PATENT ASSIGNMENT COVER SHEET

Electronic Version v1.1
Stylesheet Version v1.2

EPAS ID: PAT5605503

SUBMISSION TYPE:	NEW ASSIGNMENT
NATURE OF CONVEYANCE:	ASSIGNMENT

CONVEYING PARTY DATA

Name	Execution Date
THE GOVERNING COUNCIL OF THE UNIVERSITY OF TORONTO	03/02/2019

RECEIVING PARTY DATA

Name:	FINISAR CORPORATION
Street Address:	1308 MOFFET PARK DRIVE
City:	SUNNYVALE
State/Country:	CALIFORNIA
Postal Code:	94089

PROPERTY NUMBERS Total: 1

Property Type	Number
Application Number:	15977907

CORRESPONDENCE DATA

Fax Number: (435)252-1361

Correspondence will be sent to the e-mail address first; if that is unsuccessful, it will be sent using a fax number, if provided; if that is unsuccessful, it will be sent via US Mail.

Email: acorwell@mabr.com
Correspondent Name: ERIC L. MASCHOFF/ MASCHOFF BRENNAN
Address Line 1: 1389 CENTER DRIVE
Address Line 2: SUITE 300
Address Line 4: PARK CITY, UTAH 84098

ATTORNEY DOCKET NUMBER:	F1002.12712US02
NAME OF SUBMITTER:	ERIC L. MASCHOFF
SIGNATURE:	/Eric L. Maschoff, Reg. #36596/
DATE SIGNED:	07/05/2019

Total Attachments: 160
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ASSIGNMENT OF RIGHTS AGREEMENT

THIS AGREEMENT is made and effective as of the 27th day of November, 2018 (the "**Effective Date**")

B E T W E E N:

THE GOVERNING COUNCIL OF THE UNIVERSITY OF TORONTO, a corporation vested with the government, management and control of the University of Toronto by the *University of Toronto Act, 1971* and having offices at Banting Institute, 100 College Street, Suite 413, Toronto, ON M5G 1L5, Canada

(hereinafter the "**Assignor**")

- and -

FINISAR CORPORATION, a manufacturer of optical communication components and subsystems with an office located at 1389 Moffett Park Drive, Sunnyvale, CA, U.S.A.

(hereinafter the "**Assignee**")

(individually a "**Party**", collectively the "**Parties**")

WHEREAS the University entered into a Sponsored Research and Collaboration Agreement ("**SRA**") with the Assignee, effective November 23, 2015, *as further amended October 23, 2016 and October 27, 2017*, for a project entitled "*Si photonic platform SiN for a low cost Course Wavelength Division Multiplexing (CWDM) solution*" (the "**Project**"); and

WHEREAS the Project sponsored by the Assignee was led by Prof. Joyce K. Poon of the Department of Electrical and Computer Engineering at the University, and

WHEREAS under the terms of the SRA and in the performance of the Project, Joyce Kai See Poon, Jared Carl Mikkelson, Antoine Bois, Zheng Yong ("**University Inventors**") while employed by the University of Toronto in collaboration with certain co-inventors from Finisar Corporation created a series of inventions as listed and more fully set forth in the Confidential Invention Disclosures under Schedule "A" appended hereto (collectively, the "**Inventions**"); and

WHEREAS pursuant to Section 2.2 (c) of the SRA, *herein incorporated by reference*, the

Parties understand that these Inventions developed under the joint collaboration are Jointly Owned with the Assignee on an equal and undivided basis; and

WHEREAS pursuant to Section 2.2 (f) of the SRA, the Assignee has been granted an exclusive option to purchase all right, title and interest in the Jointly Owned Inventions and related Intellectual Property Rights; and

WHEREAS the Assignee is desirous of acquiring all of the Assignor's right, title and interest, world-wide in the Jointly Owned Inventions and related Intellectual Property Rights for commercial exploitation; and

WHEREAS the University is willing to assign its entire right, title and interest in the Jointly Owned Inventions and related Intellectual Property Rights to the Assignee for the pre-approved purchase price set forth in the SRA; and

WHEREAS to facilitate this assignment of rights by the University to the Assignee, the University Inventors have assigned all of their rights, title and interest in and to their respective Inventions to the University by way of separate internal assignments to the University ("**Inventors' Assignments**"), appended hereto under Schedule "B".

NOW THEREFORE in consideration of the premises and the mutual covenants, terms, conditions and agreements contained herein, and other good and valuable consideration, the sufficiency of which is hereby acknowledged, the Parties hereto agree as follows:

1. **Definitions**

The following terms have the following meanings in this Agreement:

"**Affiliate**" shall mean, with respect to any Person, any other Person directly or indirectly controlling, controlled by or under common control with the first Person. The term "control" means the ability to direct the management and policies of such Person, whether through ownership of equity, by contract or otherwise;

"**Assigned Assets**" mean the Inventions and related Intellectual Property Rights;

"**Confidential Information**" means the specific terms and conditions set forth in this Agreement, the know-how, and any information, which is non-public, confidential or proprietary in nature, including, without limitation, business information, trade secrets, and any information related to the Inventions, related technology, Patents or Intellectual Property Rights, whether written, oral or in electronic form, provided that tangible materials are marked as confidential, and provided that information given orally is identified as confidential at the time of disclosure, and confirmed as confidential in writing within fifteen (15) days, but shall not include information that: (i) is or becomes generally available to the public other than as a result of any act by a receiving Party to this Agreement; (ii) is rightfully received from a third party without similar restriction or

without breach of this Agreement; (iii) a receiving Party is able to demonstrate, in writing, was known to it on a non-confidential basis; or (iv) was independently developed by a receiving Party without the use of any of the Confidential Information;

"**Patents**" means the patents and/or patent applications listed in Schedule "C" and includes divisions, re-examination or renewals based on the foregoing patents and/or patent applications, any patents which may issue on, from or as a result of any of the foregoing and any reissue of said patents. The Parties hereto may, by mutual written agreement, amend Schedule "C" to include or update the details of any Patent filed for the Inventions. Any such amended Schedule "C" shall be appended to this Agreement and shall form an integral part of this Agreement;

"**Patent Costs**" means the legal and other fees incurred directly in the process of establishing and maintaining the legal protection of the rights in the Inventions;

"**Intellectual Property Rights**" means all Patents, copyrights, trade names and other intellectual property rights related to the Inventions, whether registered or not, owned by or licensed to the Assignor and further set forth under Schedule "C";

"**Inventions**" means the inventions listed and set forth under Schedule "A" hereof; and

"**University**" means the University of Toronto.

2. Assignment of Rights

Subject to the terms and conditions of this Agreement, the Assignor hereby assigns to the Assignee, all right, title and interest in and to the Assigned Assets (*but without any representation or warranty as to the nature, extent or validity thereof*), the right to apply for patents in every country, the right to sublicense to its Affiliates, receive any letters patent that may issue from any such applications, and the right to sell or license the Assigned Assets.

3. Retained Licenses

Notwithstanding the rights granted above, the Parties confirm, acknowledge and agree that the Assignor retains a royalty-free, non-exclusive, perpetual, irrevocable license to use the Assigned Assets for non-commercial, research, educational and administrative purposes, without cost and in perpetuity.

4. Patent Prosecution

(a) **Patent Prosecution by Assignee**: Assignee shall continue to bear the responsibility to prosecute and maintain the Patents in accordance with its standard practices. Assignee shall have sole discretion with regard to patent filing and patent

prosecution matters. All Patent Costs associated with the prosecution, maintenance of any Patents filed for the Inventions and listed in Schedule "C" and any other patent applications filed thereon, including provisional, regular, continuation, continuation-in-part and divisional applications, patents issuing thereon and any reissue or extension thereof, occurring on or after the Effective date of this Agreement shall be the responsibility of the Assignee. Assignee shall also be responsible, at its own discretion for the costs associated with the enforcement and defense of any patents that issue for the Inventions.

(b) **Patent Prosecution Support**: Assignor shall provide input and such assistance to Assignee, as Assignee may reasonably request, with regard to patent prosecution matters, and will also co-operate with Assignee on the signing of all patent and legal documents and such other matters without unreasonable delay to affect the transfer of Intellectual Property Rights to the Assignee.

5. Consideration

(a) **Payment.** As consideration for the assignment of the Assigned Assets to the Assignee, the Assignee shall pay the Assignor a purchase price (the "**Fee**") of One hundred and fifty thousand United States dollars (US$150,000.00) within ninety (90) days from the date of last signature on the Agreement. For greater certainty, the Fee shall not include any liens or encumbrances, or any deductions for third party payments, disbursements, patent expenses, legal costs, or taxes.

(b) **Payment to Assignor.** The Fee set out herein shall be made via a cheque made payable to *"The Governing Council of the University of Toronto"*.

(c) **Payment to University Inventors**. Assignor shall be solely responsible for calculating and distributing to the University Inventors their share of income in accordance with Assignor's own policy. The Assignee shall not be responsible for any payment to the University Inventors under or in connection with this Agreement.

6. Confidential Information

It is contemplated that, from time to time during the course of the performance of this Agreement, either Party may disclose its Confidential Information to the other Party. Each Party shall not: (a) use or disclose Confidential Information received from the other Party for any purpose other than the performance of the receiving Party's obligations hereunder; or (b) disclose Confidential Information to any third party. Each Party shall take such reasonable measures to maintain the other Party's Confidential Information as confidential as it takes to protect its own proprietary and confidential information, and in any event no less than a reasonable degree of care. Each Party shall be responsible for

the imposition of the confidentiality provisions provided for herein upon its own staff, consultants and other advisors prior to disclosing any Confidential Information to such representatives.

7. Disclaimers

The Assigned Assets are assigned to the Assignee by the Assignor on an "*as is*" basis, and the Assignor disclaims all representations, warranties and conditions of any kind, whether express or implied, statutory or otherwise, including without limitation:

(a) all representations, warranties and conditions as to the patentability, validity, scope or enforceability of the Assigned Assets;

(b) all representations, warranties and conditions that any use of the Assigned Assets will be free from infringement of intellectual property rights of any third party; and

(c) all representations, warranties and conditions as to quality, merchantable quality, merchantability or fitness of the Assigned Assets for any particular purpose.

8. Termination

(a) In the event that the Assignee fails to pay the Fee as outlined under Section 5 and is not able to cure the breach within ninety (90) days of notification of the failure to pay by the Assignor, the Parties hereto acknowledge and agree that any portion of the Fee which has been paid to the Assignor shall be forfeited by the Assignee and shall remain the property of the Assignor. Further, any rights granted herein by the Assignor to the Assignee shall immediately terminate.

(b) Termination of this Agreement shall not relieve any of the Parties of obligations accrued under this Agreement prior to the date of termination.

9. Indemnity

The Assignee shall indemnify and save the Assignor harmless from and against any loss arising out of or pursuant to any claims or demands in connection with the Assigned Assets and all costs, damages and expenses (including reasonable legal fees) incurred by the Assignor and in connection therewith, except where such claims are caused by the Assignor's use of the Assigned Assets contemplated under Section 3 herein.

10. Release

Save and except for the right to enforce the terms of this Agreement, the Assignor releases the Assignee from any and all claims that the Assignor may now have or may in

future have in respect of the Assigned Assets.

11. Further Assurances

The Assignor agrees to do all acts necessary and to execute all documents necessary or desirable, at the Assignee's cost and expense, to fulfill the provisions of this Agreement, to give the Assignee the full benefit of this Agreement and to secure and evidence ownership of the Assigned Assets in favour of the Assignee.

12. Notices

Notices under this Agreement will be sent to the Parties as follows or to such other person as a Party may designate in writing:

(a) **In the case of a notice to the Assignor:**

The Governing Council of the University of Toronto
Innovations & Partnerships Office
Banting Institute, 413-100 College Street,
Toronto, ON M5G 1L5, Canada

Attention: Jennifer Fraser
Title: Director, Innovations

Tel: 416.946-5515
E-mail: jen.fraser@utoronto.ca

(b) **In the case of a notice to the Assignee:**

For Technical/Scientific Matters:

Finisar Corporation
1389 Moffett Park Drive
Sunnyvale, CA 94089, U.S.A.

Attention: Daniel Mahgerefteh
Title: Director of Technology

Tel: 310-721-1955
Email: daniel.mahgerefteh@finisar.com

With a copy to (for Patent/Legal Matters):

Finisar Corporation
1389 Moffett Park Drive
Sunnyvale, CA 94089, U.S.A.

Attention: Christopher E. Brown
Title: Executive Vice President and Chief Counsel

Tel: 781-453-8948
Email: chris.brown@finisar.com

Any notice given by personal delivery shall be conclusively deemed to have been given on the day of actual delivery thereof and, if given by registered mail, on the second business day following the deposit thereof in the mail.

13. Miscellaneous

(a) Titles used in this Agreement are for the purposes of convenience only and shall not be used in the interpretation of this Agreement. The attached schedules form part of this Agreement.

(b) This Agreement supersedes any discussions or other agreements between the Parties and is the entire agreement of the Parties with respect to its subject matter. No change or modification will be valid unless it is in writing and signed by both Parties.

(c) The Parties are independent contractors, and there is no joint venture or partnership formed hereby.

(d) This Agreement will be governed by and construed in accordance with the laws of the Province of Ontario in Canada. In the event that a court of competent jurisdiction holds any provision of this Agreement to be invalid, such holding will have no effect on the remaining provisions of this Agreement, which will continue in full force and effect.

(e) This Agreement binds and inures to the benefit of the Parties hereto and their respective heirs, successors and permitted assigns.

(f) This Agreement may be executed by signatures delivered by facsimile transmission or delivered electronically in optically scanned form; and/or it may be simultaneously executed by the Parties in multiple counterparts, each of which will be considered to be an original instrument, and all of which taken together, where each Party has executed at least one counterpart, will constitute one and the same instrument.

(g) In the event that any terms or any part of any term of this Agreement is determined to be void or unenforceable by a court of competent jurisdiction, such term or part of a term shall be considered separate and severable from this Agreement and the remaining terms shall continue in full force and effect.

[REMAINDER OF PAGE LEFT INTENTIONALLY BLANK; SIGNATURE PAGE FOLLOWS]

IN WITNESS WHEREOF, the Parties have caused this Agreement to be executed as of the Effective Date.

THE GOVERNING COUNCIL OF THE UNIVERSITY OF TORONTO

Per: _____
Name: Jennifer Fraser
Title: Director, Innovations

Date: 2 March 2019

FINISAR CORPORATION

Per: _____
Name: Christopher R. Cole
Title: Vice President, Advanced Development

Date: 1 March 2019

Finisar Legal

SCHEDULE "A"

LIST OF CONFIDENTIAL INVENTION DISCLOSURES

(See attached for copies of Disclosures)

Disclosure ID	Invention Title	Disclosure Date
10003189	High Efficiency Grating-to-Grating Optical Coupling for Multi-chip Integration	Jul 28, 2016
10003194	Birefringence Control of Silicone Nitride-on-Silicon Optical Waveguides and Photonic Circuits	Aug 3, 2016
10003215	Birefringence Compensation by Serially Varying the Waveguide Width	Aug 29, 2016
10003351	Wavelength Filtering and Polarization (de)multiplexing via Non-Adiabatic Transitions	May 5, 2017
10003606	Adiabatic Polarization Rotator-Splitter	May 10, 2018
10003607	Adiabatic Polarization Rotator Combiner	May 10, 2018

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OFFICE OF THE VICE-PRESIDENT, RESEARCH AND INNOVATION

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1. Title of Invention:

High efficiency grating-to-grating optical coupling for multi-chip integration

2. Inventors and Contributors:

a. Inventors at the University of Toronto: List all individuals who have made an inventive contribution to this disclosure through the use of U of T resources (i.e. faculty, students, postdocs, staff, visiting scientist, etc). Attach separate pages if necessary.

SURNAME, GIVEN NAMES	U of T PERSONNEL NO (if applicable)	DEPARTMENT *(List any cross appointments or affiliated institutions)*	AFFILIATION WITH U of T *(i.e. faculty, research assoc., post-doc, student, staff, visitor, etc.)*	EMAIL ADDRESS	CONTACT INFORMATION *(non-U of T mailing address, phone, fax)*	% CONTRIBUTION *(*optional)*
Poon, Joyce Kai See	993899	Electrical and Computer Engineering	Faculty	joyce.poon@utoronto.ca	24 Wellesley St. W., #2212, Toronto, ON, M4Y 2X6 416-262-0571	
Mikkelsen, Jared Carl	1092195	Electrical and Computer Engineering	PhD student	jared.mikkelsen@mail.utoronto.ca	2155 Mayflower Blvd., Oakville, ON, L6H 4E6 905-399-3109	

* If invention is assigned to UofT, percentage will be used as a basis for sharing future revenues. Revenue distribution agreed to by the parties in an assignment agreement will govern.

FOR IPO USE ONLY:
Disclosure Date: July 28, 2016 **Disclosure No:** 10003189

For more information, see our Disclosure Guide.

b. External Inventors: List all individuals who have made an inventive contribution to this disclosure using non-U of T resources (i.e. sponsor employees, academic collaborators, etc). Please include names, organization, contact information and email address.

Daniel Mahgerefteh, Finisar Corporation
1389 Moffett Park Dr., Sunnyvale, CA 94089, USA
daniel.mahgerefteh@finisar.com 1-310-721-1955

c. Contributors (Non-Inventors): List all individuals at or external to U of T who have not made an inventive contribution but have contributed to the development of the invention. Please include name, organization and email address.

3. Location(s) of Work:

Please list all locations (U of T and external) of the work leading to this invention, be specific (i.e. department, building, hospital, etc).

Department of Electrical and Computer Engineering, Galbraith building
Finisar Corporation, 48800 Milmont Dr., Fremont CA, 94538
Finisar Corporation, 1389 Moffett Park Dr., Sunnyvale, CA 94089, USA

4. Invention Description:

Please provide a description of this invention for evaluation, highlighting its novel or patentable aspects. Attach separate pages if necessary.

The invention is a grating coupler configuration that improves the optical coupling between two chips using a pair of grating couplers.

Background: In the field of silicon (Si) integrated photonics, one of the major challenges is the low-cost and efficient integration of a semiconductor laser (typically realized in compound semiconductor materials, like indium phosphide (InP)) onto a Si photonic chip. Finisar Corp. has been working on a solution in which an InP laser is integrated on top of a Si photonic chip using a transmitter grating coupler defined in the InP that sends the light to a large-area receiver grating coupler in the Si photonic die. The receiver grating coupler scatters the light from the laser into an in-plane waveguide.

In their previous work (Finisar background IP), the receiver grating coupler had a "positive angle" design, in which the light propagation in the in-plane waveguide (in the Si die) is in the same direction as the lateral component of the propagation direction of the incident light.

This invention is a receiver grating coupler with a "negative angle" design, in which the light propagation in the in-plane waveguide (in the Si die) is in a direction opposite to the lateral component of the propagation of the incident light. The negative angle reduces high order scattering directions to improve the coupling efficiency in the fundamental order (i.e., agnle). In a specific implementation using silicon nitride (SiN), the coupling efficiency is improved by about 1dB compared to previous approach using a "positive angle". The negative angle modifies the configuration of the coupled system of two chips.

An added benefit of the negative angle grating is that the electric fields in the transmitter and receiver grating couplers decrease in the same direction. This should lead to simpler apodization procedure of the gratings for

mode matching, providing a further boost to the coupling efficiency.
Please see the enclosed slides.

5. Dissemination:

List all publications, abstracts, presentations or any other forms of public dissemination regarding this work, including dates.

○ **None** ○ **Yes (please provide details)**

None

6. Funding:

Provide details regarding any funding used in the development of this invention (i.e..salary or stipend support, materials, equipment etc.).

SPONSOR	PROJECT TITLE	RIS FUND #
Finisar Corporation	Si Photonics for Coarse Wavelength Division Multiplexing (CWDM)	500138
NSERC	Postgraduate scholarship – doctoral level	

7. Related Agreements:

Was the work leading to this invention subject to any written or oral contract(s) or other agreement(s) such as: material transfer, data transfer, software licence, confidentiality, collaboration, and/or sponsored research?

○ **No** ○ **Yes (please provide details)**

Yes. This invention has been made under a sponsored research agreement between Finisar and U of T. The U of T reference number is 2015-1761.

8. Patent Applications:

Have any patent applications or other intellectual property protections been filed in respect of this invention?

○ **No** ○ **Yes (please provide details)**

Yes – Finisar has background IP and filed for a provisional application F1002-12677US01.

9. Warranty:

I/We, the Inventors listed in Section 2(a), have read, understood and agree to all of the preceding, and declare that all of the information provided in this disclosure is complete and correct. To the best of our knowledge, all persons who might legally make an ownership claim in this Invention are identified in Section 2(a) and 2(b).

NAME (typed):	SIGNATURE:	DATE :
Joyce Poon	Joyce Poon	July 21, 2016
Jared Mikkelsen	Jared Mikkelsen	July 21st, 2016

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If you need any assistance, please contact the IP Officer.

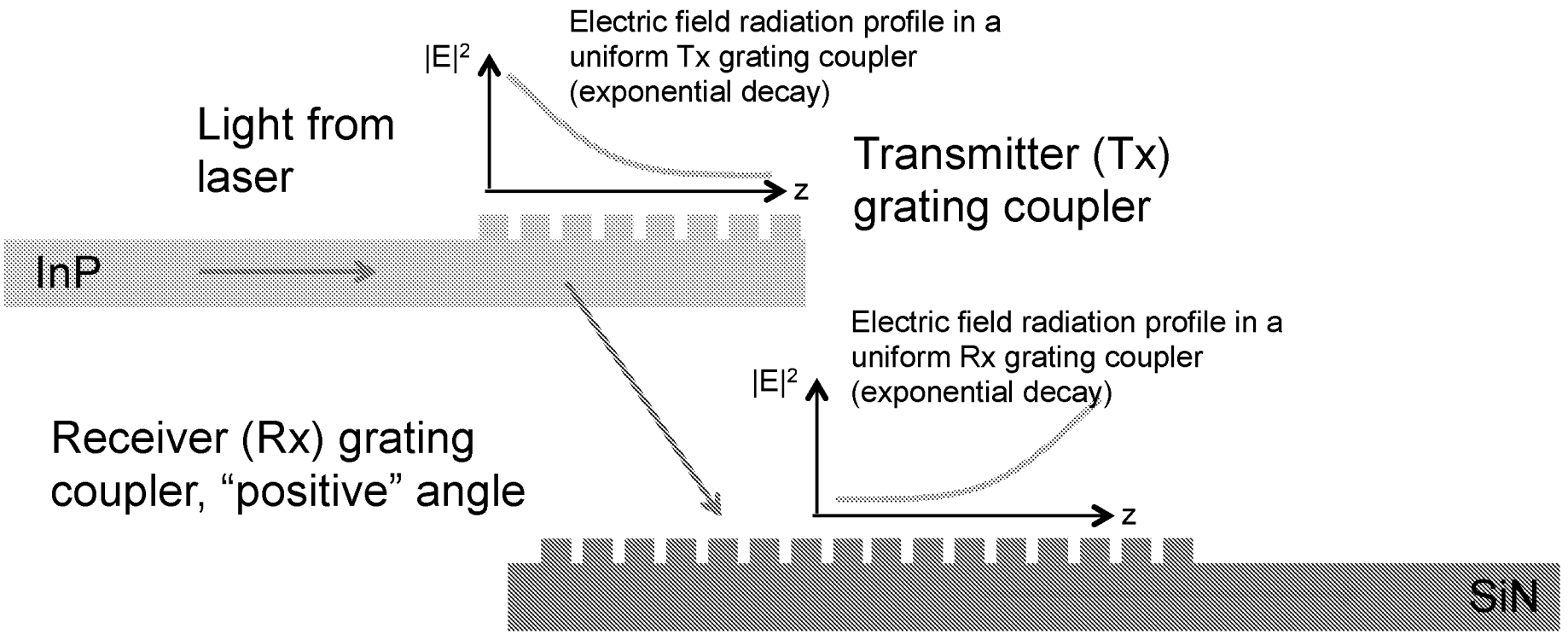
High efficiency grating-to-grating optical coupling for multi-chip integration

Invention Disclosure

July 19, 2016

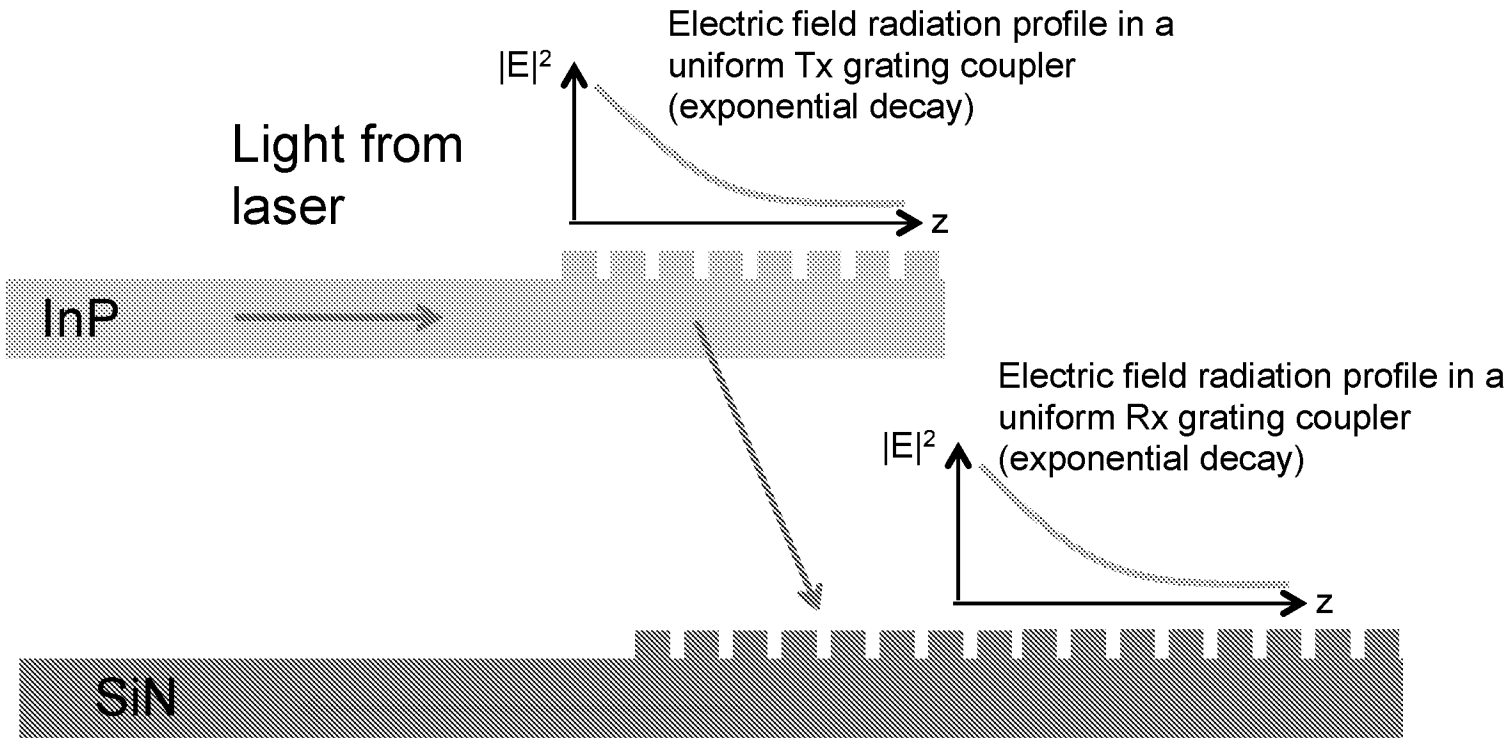
Finisar Background IP

- Two chip integration solution using a pair of grating couplers
  - For laser (InP) integration onto silicon (Si) photonic die containing a silicon nitride (SiN) layer



Invention

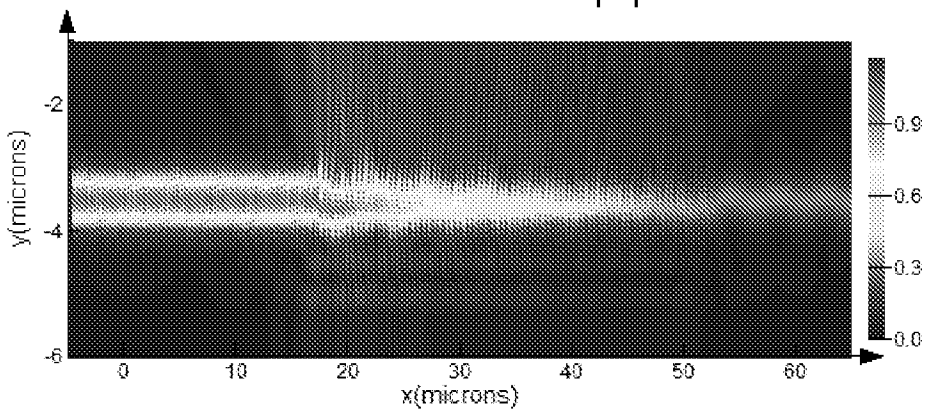
- Negative angle Rx grating coupler



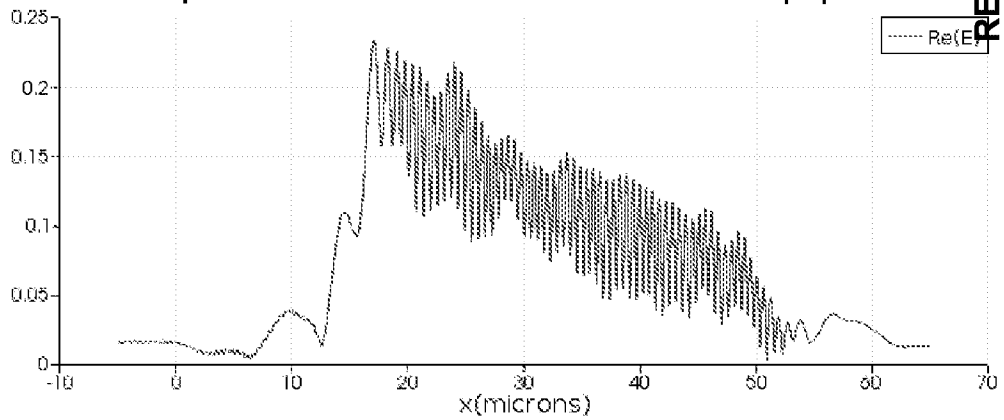
Example Receiver Grating Coupler

- Max. upward directionality: -1.35 dB
- Emission angle: -37.56 degrees

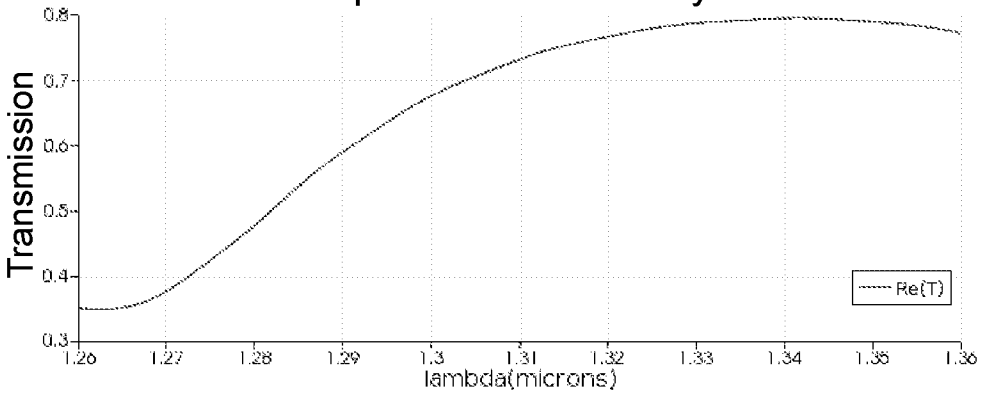
Full Field Profile |E|



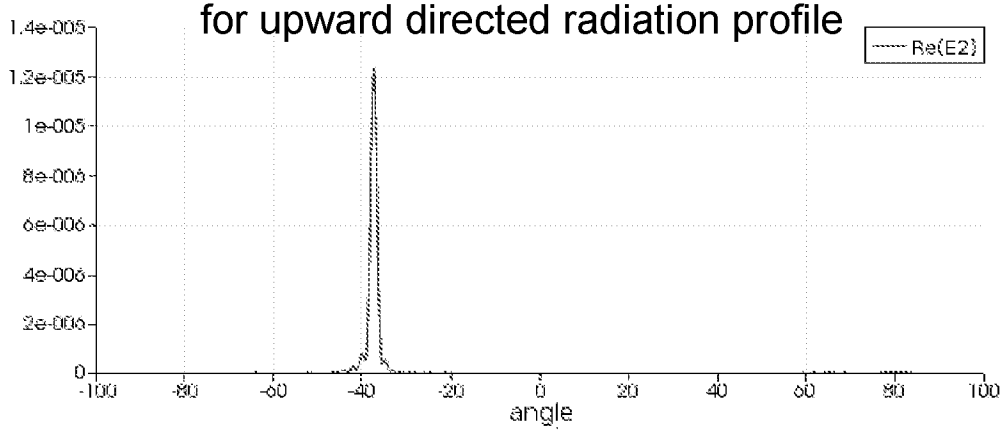
Upward Directed Radiation Profile |E|



Upward Directionality



Far-Field Projection
for upward directed radiation profile



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1. Title of Invention:

Birefringence control of silicon nitride-on-silicon optical waveguides and photonic circuits

2. Inventors and Contributors:

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List all individuals who have made an inventive contribution to this disclosure through the use of U of T resources (i.e. faculty, students, postdocs, staff, visiting scientist, etc). Attach separate pages if necessary.

SURNAME, GIVEN NAMES	U of T PERSONNEL NO (if applicable)	DEPARTMENT *(List any cross appointments or affiliated institutions)*	AFFILIATION WITH U of T *(i.e. faculty, research assoc., post-doc, student, staff, visitor, etc.)*	EMAIL ADDRESS	CONTACT INFORMATION *(non-U of T mailing address, phone, fax)*	% CONTRIBUTION *(*optional)*
Poon, Joyce Kai See	993899	Electrical and Computer Engineering	Faculty	joyce.poon@utoronto.ca	24 Wellesley St. W., #2212, Toronto, ON, M4Y 2X6 416-262-0571	
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FOR IPO USE ONLY:
Disclosure Date: August 3, 2016 **Disclosure No:** 10003194

For more information, see our Disclosure Guide

b. External Inventors: List all individuals who have made an inventive contribution to this disclosure using non-U of T resources (i.e. sponsor employees, academic collaborators, etc). Please include names, organization, contact information and email address.

c. Contributors (Non-Inventors): List all individuals at or external to U of T who have not made an inventive contribution but have contributed to the development of the invention. Please include name, organization and email address.

3. Location(s) of Work:

Please list all locations (U of T and external) of the work leading to this invention, be specific (i.e. department, building, hospital, etc).

Department of Electrical and Computer Engineering, Galbraith building

4. Invention Description:

Please provide a description of this invention for evaluation, highlighting its novel or patentable aspects. Attach separate pages if necessary.

The invention is the birefringence compensation in silicon nitride (SiN) waveguides using a thin silicon (Si) region under the SiN. The Si is usually separated from the SiN by silicon dioxide (SiO_2), which encapsulates the waveguides. The birefringence is controlled by the choice of the widths of the SiN and Si layers at the given thicknesses of the fabrication process.

In the field of high index contrast integrated photonics (which includes Si and SiN photonics), polarization management is a critical issue. The high index contrast leads to strongly birefringent waveguides, where the transverse electric (TE) and transverse magnetic (TM) modes experience different effective and group indices. Meanwhile, the incoming light from an optical fiber can be of an arbitrary polarization. Therefore, it is necessary to make photonic circuits that function as a receiver or inline component (in the middle of a fiber optic communication link) polarization insensitive.

This invention is to control, mitigate, and cancel the polarization sensitivity using SiN-on-Si waveguides. In a SiN waveguide with a width greater than the height (as is typical), the TM mode has a lower effective index than the TE mode. Introducing Si under the SiN can preferentially increase the effective index of the TM mode over the TE mode, due to the higher refractive index of Si than SiN and the greater overlap of the TM mode with the Si than the TE mode. By choosing the widths of the SiN and Si regions, the birefringence can be adjusted.

Waveguides and photonic circuits can be made polarization insensitive in a couple of ways. First, waveguide cross-sections with zero or near zero birefringence are possible for combinations of SiN and Si widths, leading to waveguides and photonic circuits that would be polarization insensitive. Another approach is to combine two cross-sections – one with slightly positive birefringence with one with slightly negative birefringence. A photonic device/circuit would comprise of equal lengths of these two cross-sections.

In a full design and circuit implementation, light primarily propagates in the SiN layer. The fiber-to-chip coupler should be in the SiN level, and the Si feature should be adiabatically introduced under the SiN. This reduces losses

and adiabatically transforms the TM0 mode of the SiN waveguide into the hybrid TM mode of the SiN-on-Si waveguide.

Please see the enclosed slides for details.

5. Dissemination:

List all publications, abstracts, presentations or any other forms of public dissemination regarding this work, including dates.

○ None ○ Yes (please provide details)

None

6. Funding:

Provide details regarding any funding used in the development of this invention (i.e. salary or stipend support, materials, equipment, etc.).

SPONSOR	PROJECT TITLE	RIS FUND #
Finisar Corporation	Si Photonics for Coarse Wavelength Division Multiplexing (CWDM)	500138
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No.

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NAME (typed):	SIGNATURE:	DATE :
Joyce Poon	Joyce Poon	July 25, 2016
Jared Mikkelsen	Jared Mikkelsen	July 25, 2016

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If you need any assistance, please contact the IP Officer.

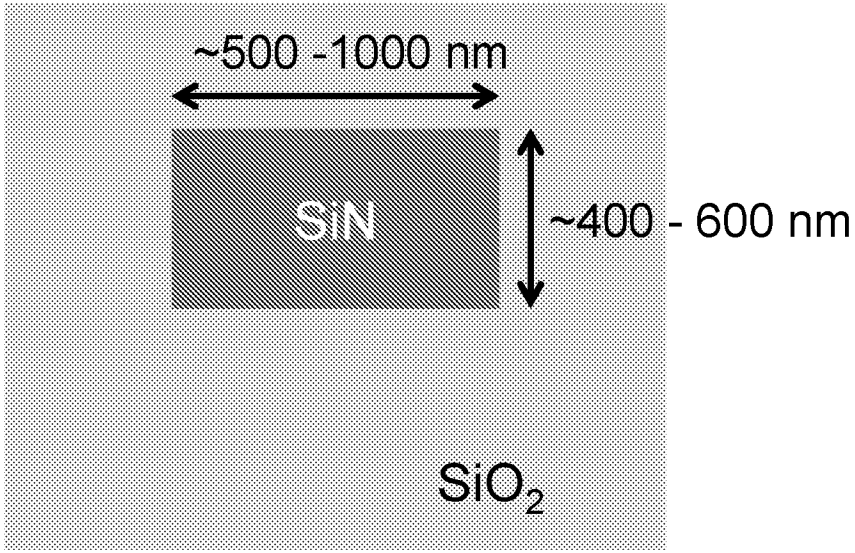
Birefringence control of silicon nitride-on-silicon optical waveguides and photonic circuits

Invention Disclosure

July 26, 2016

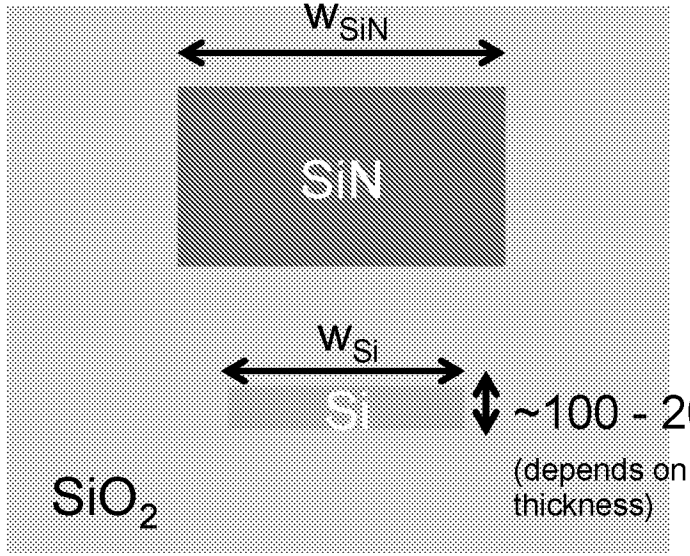
Concept

Conventional high index contrast/
high confinement silicon nitride (SiN)
waveguide cross-section



Birefringent
$n_{eff,TE} - n_{eff,TM} \sim O(10^{-1})$

Birefringence control with
SiN-on-Si waveguide



Controllable birefringence
$n_{eff,TE} - n_{eff,TM}$: positive, negative or 0
Heights are typically set by the
fabrication process

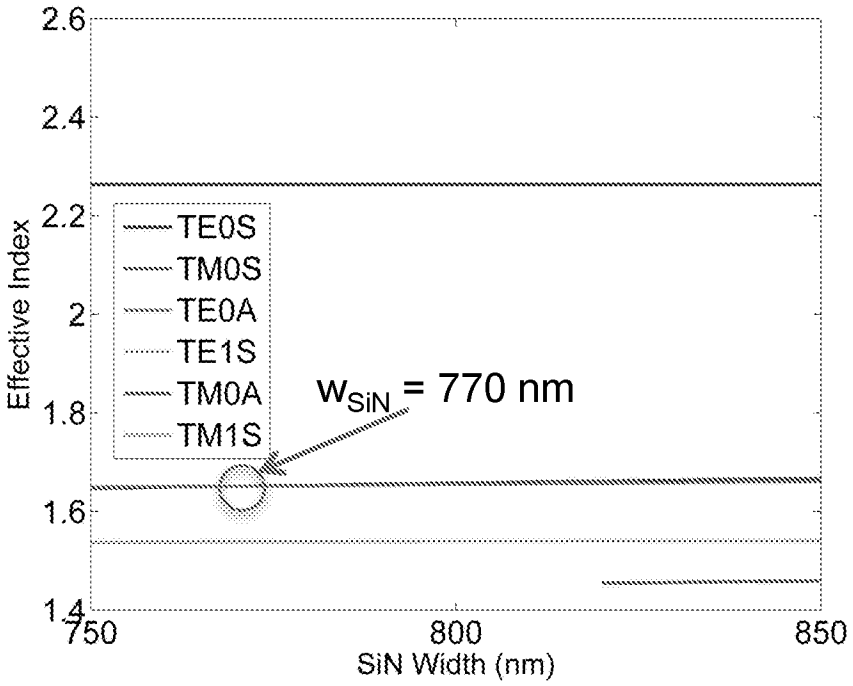
Si increases $n_{eff,TM}$ more than $n_{eff,TE}$ since TM mode is slightly more delocalized and the electric field points vertically.

Example design

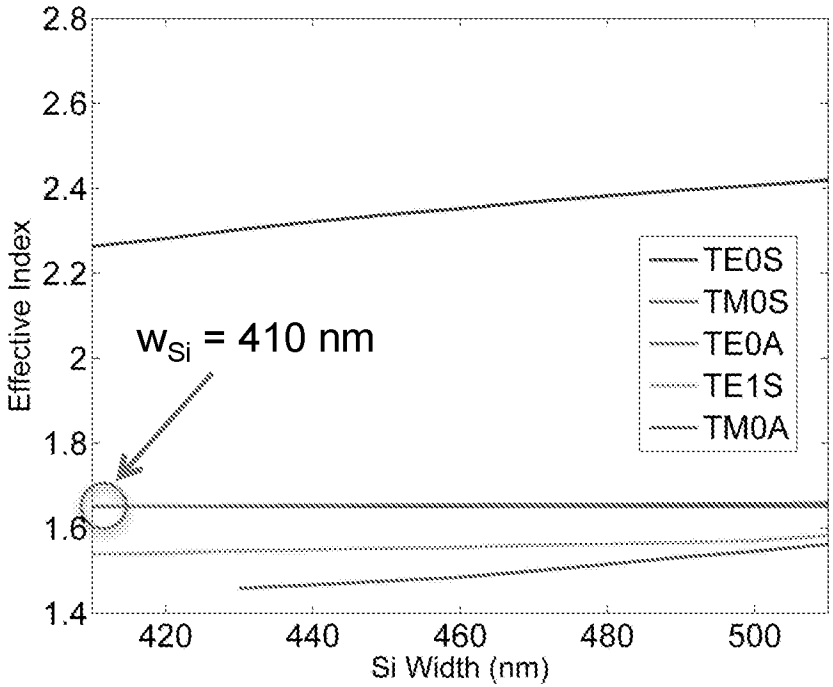
- Thicknesses
  - Si: 150 nm
  - SiO_2 spacer between SiN and Si: 350 nm
  - SiN: 600 nm (refractive index 1.9)

- The plots below show the effective indices of the first several modes vs. SiN or Si widths (with the Si or SiN width fixed)
- Zero birefringence point is circled
- Note: The highest blue line (TE0S) corresponds to a mode confined solely in the Si

Si Width: 410 nm

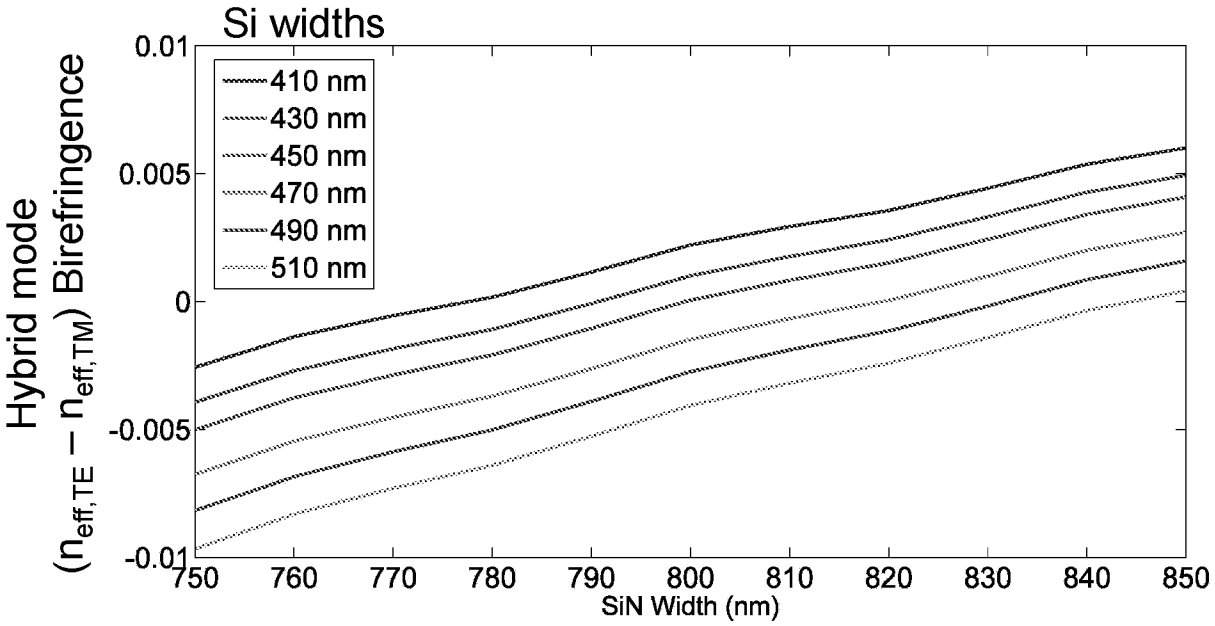


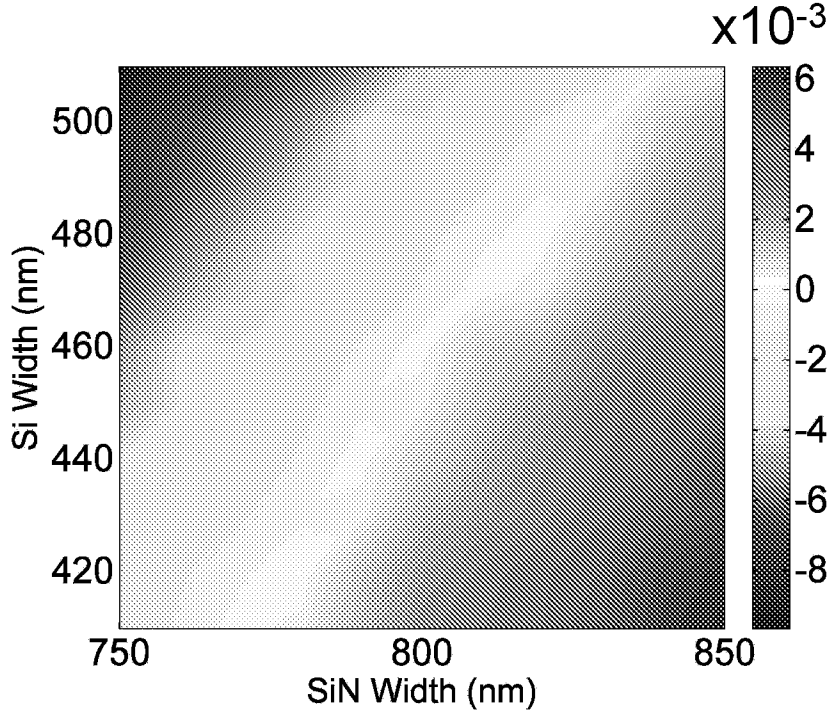
SiN Width: 770 nm



Birefringence dependence

- TE hybrid SiN-Si mode
- TM hybrid SiN-Si mode

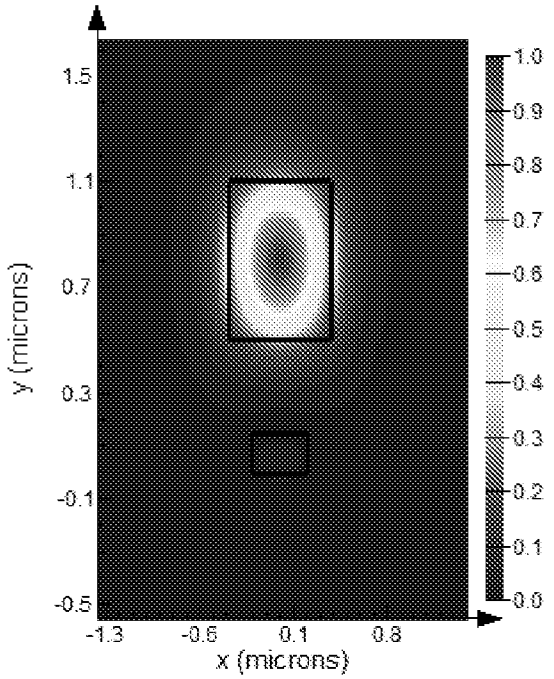




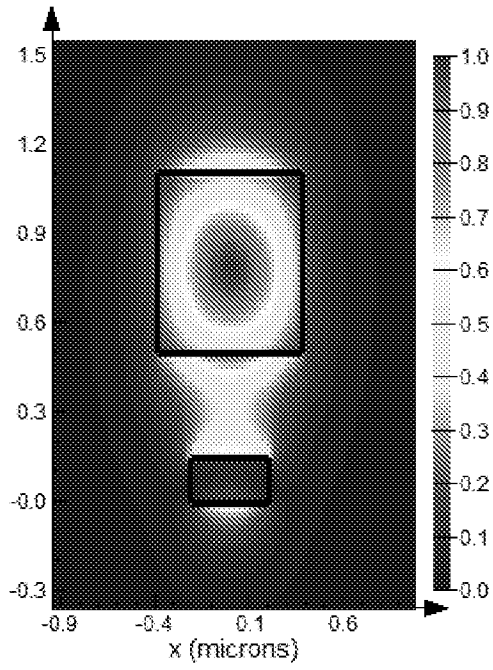
Modal Profiles

- Profiles shown for Si width of 410 nm, SiN width of 770 nm
- TM hybrid mode interacts with both SiN and Si

TE hybrid mode

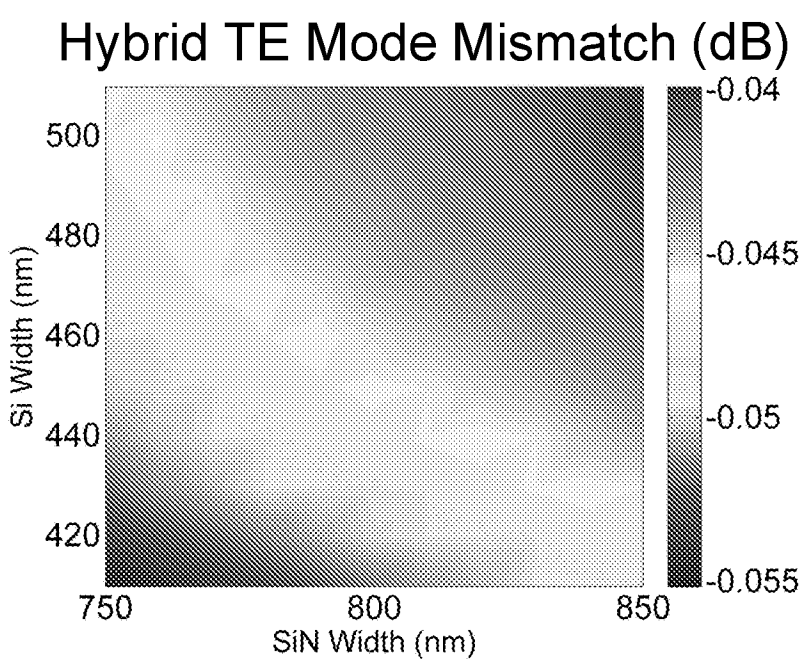


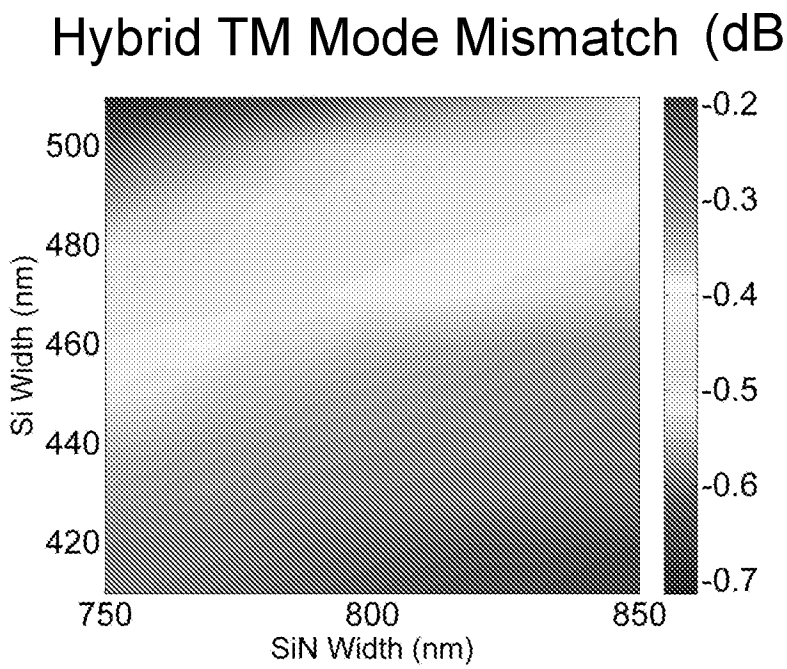
TM hybrid mode



Mode overlap loss, adiabatic tapers

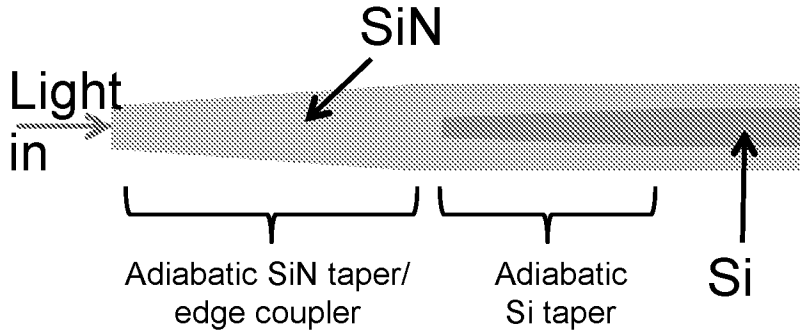
- If Si is abruptly introduced below an SiN waveguide, there is loss due to modal mismatch





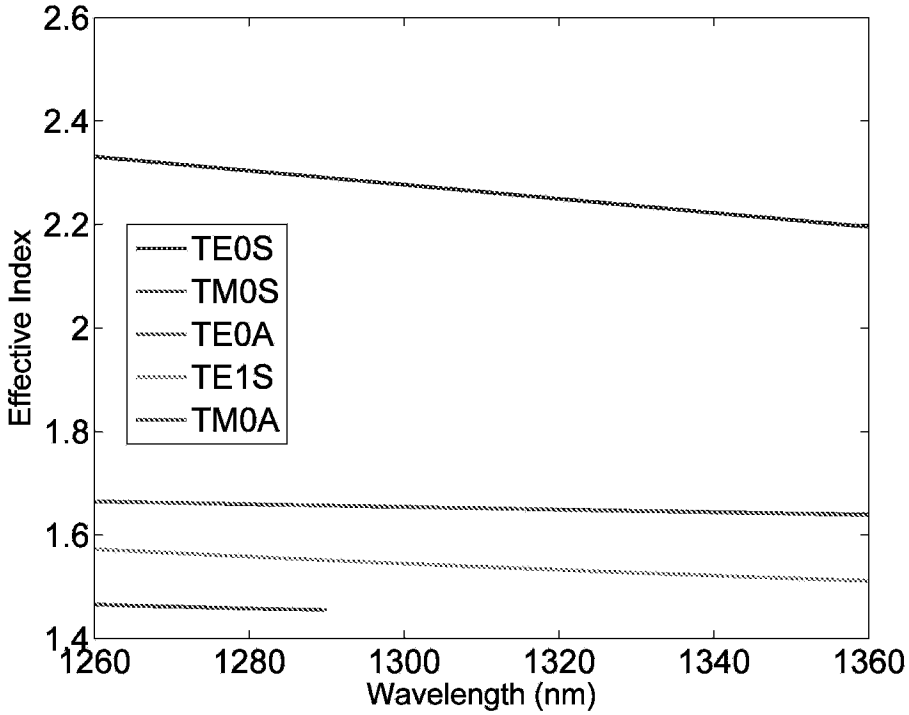
- To reduce loss, the Si can be adiabatically introduced under the SiN. Si tip width cannot be too narrow to transform the TE mode in the SiN waveguide into the TE mode of the Si

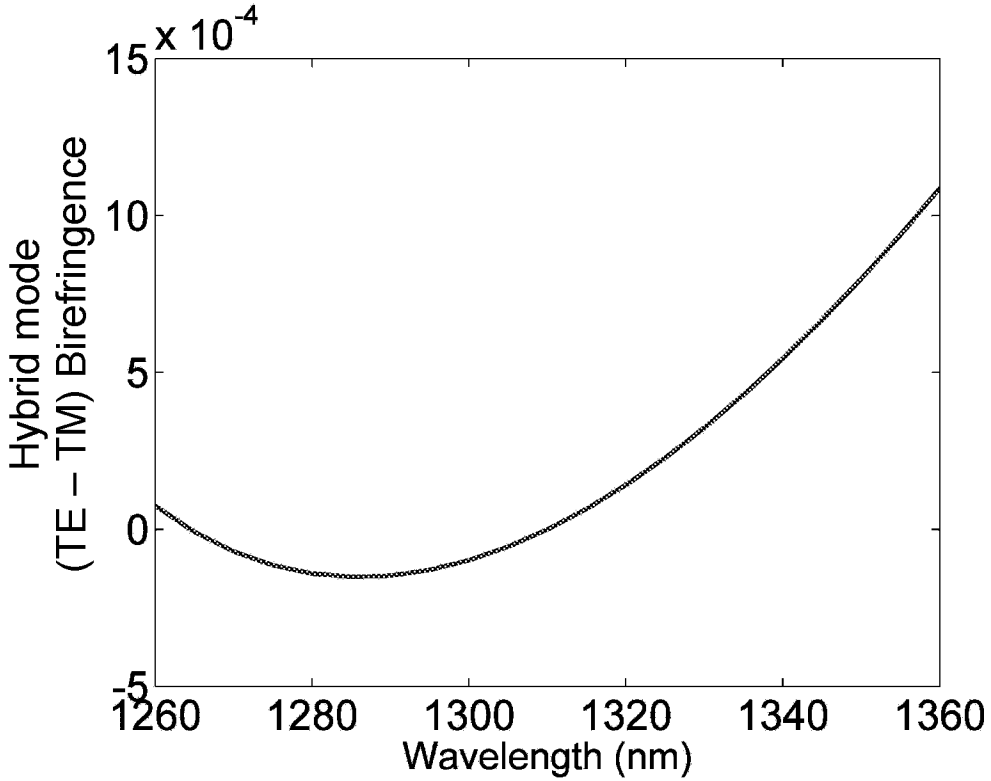
Top view



Dispersion Characteristics

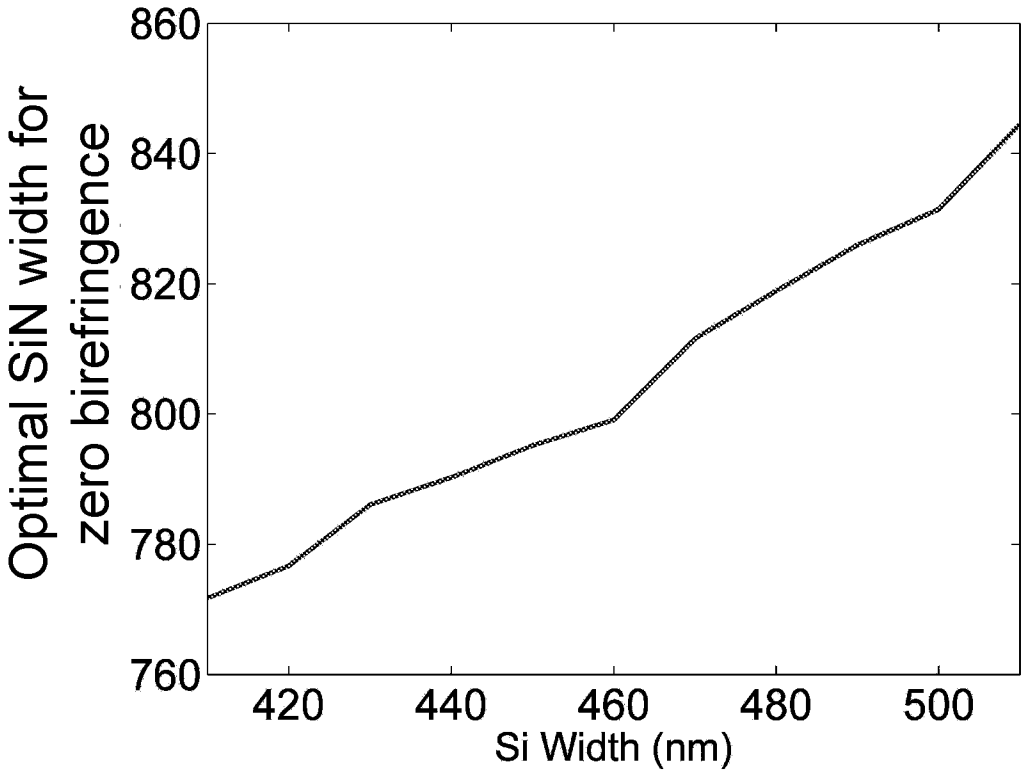
- Birefringence < 10^{-3} can be maintained over entire O-band
  - Designs shown are for SiN width of 770 nm and Si width of 410 nm





Tolerance to thickness variations

- For Si widths between 400-500 nm, there is always a corresponding SiN width which makes the birefringence zero for the thicknesses on p.3



Thicknesses

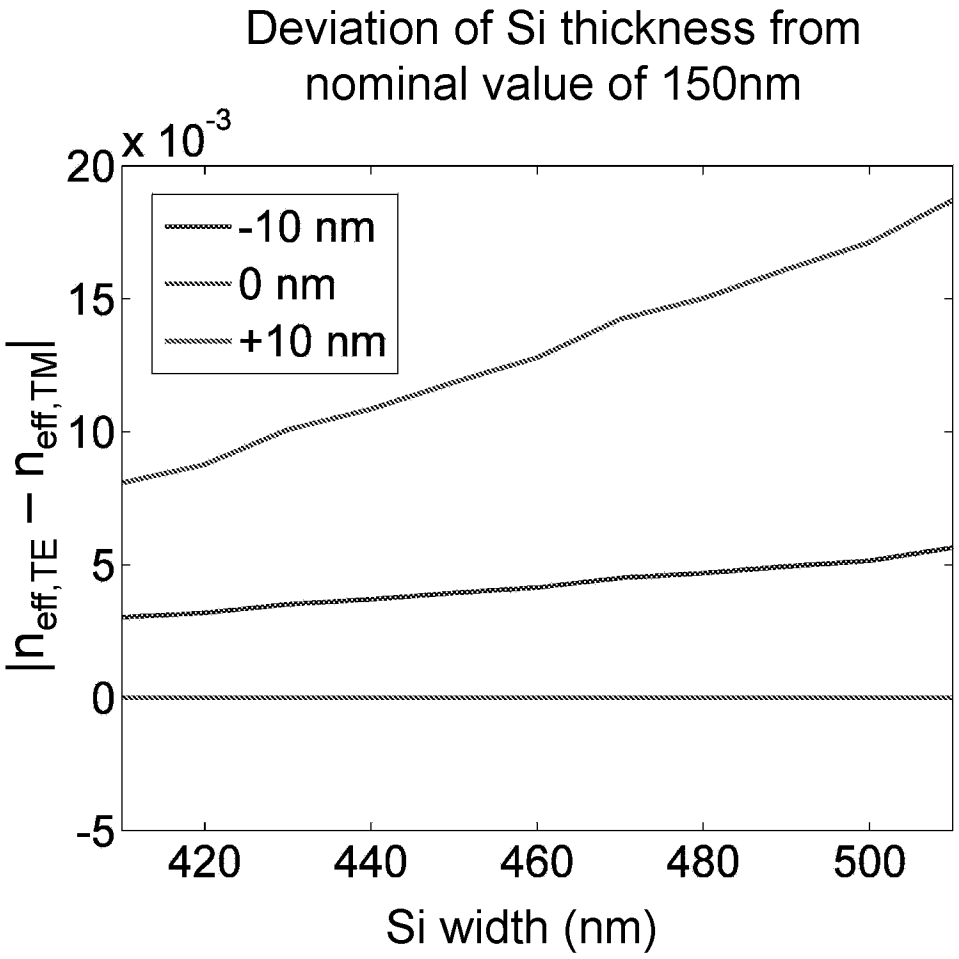
Si: 150 nm

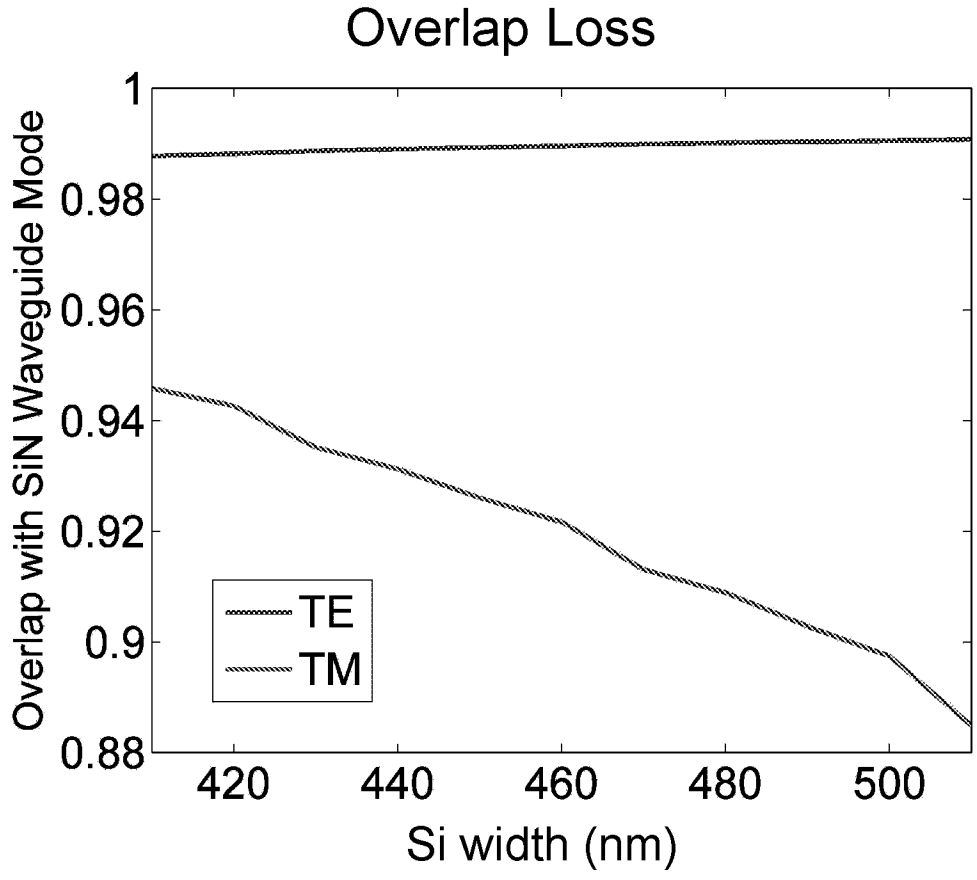
SiO_2 spacer: 350 nm

SiN: 600 nm (refractive index 1.9)

Tolerance to thickness variations

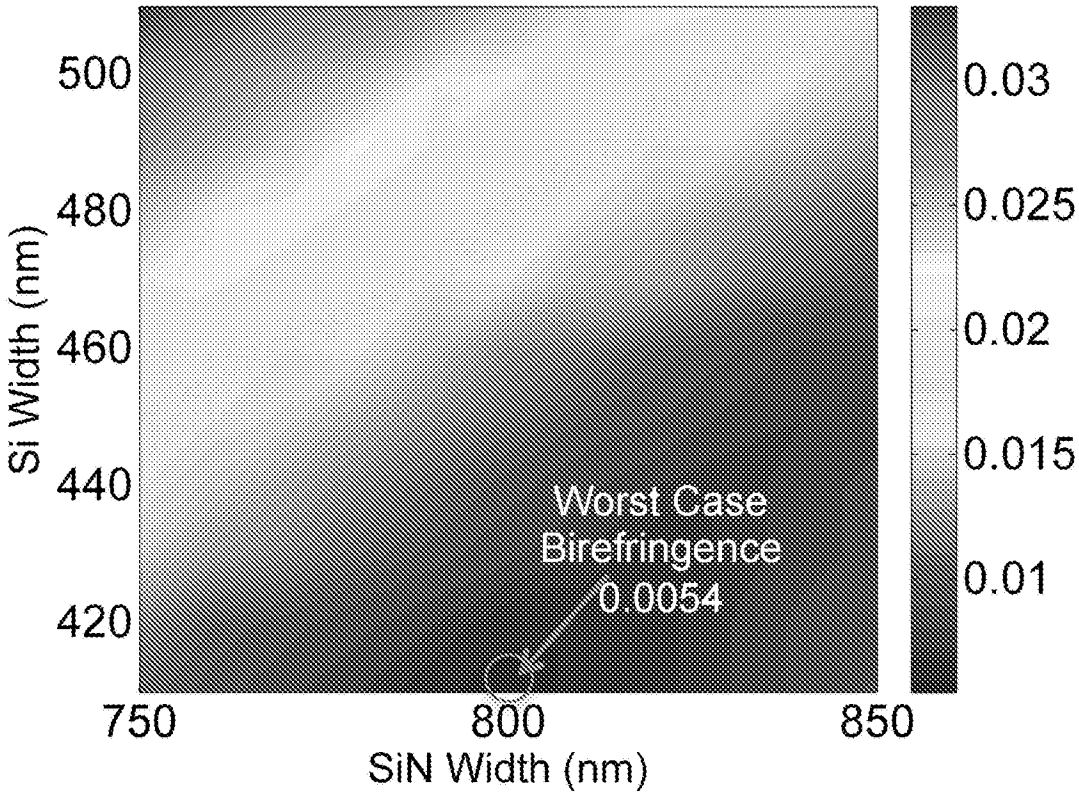
- Birefringence mainly sensitive to Si thickness variation
  - Reason: hybrid TM mode migrates more into Si if Si layer is thicker





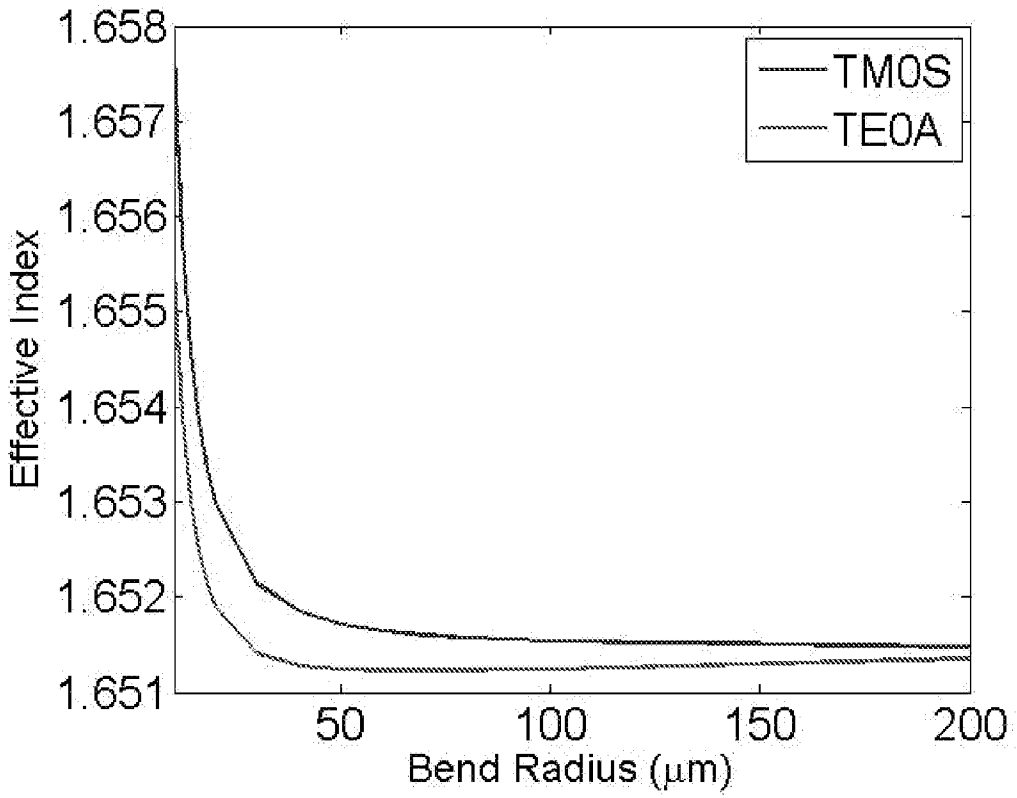
Birefringence Worst Case Deviation

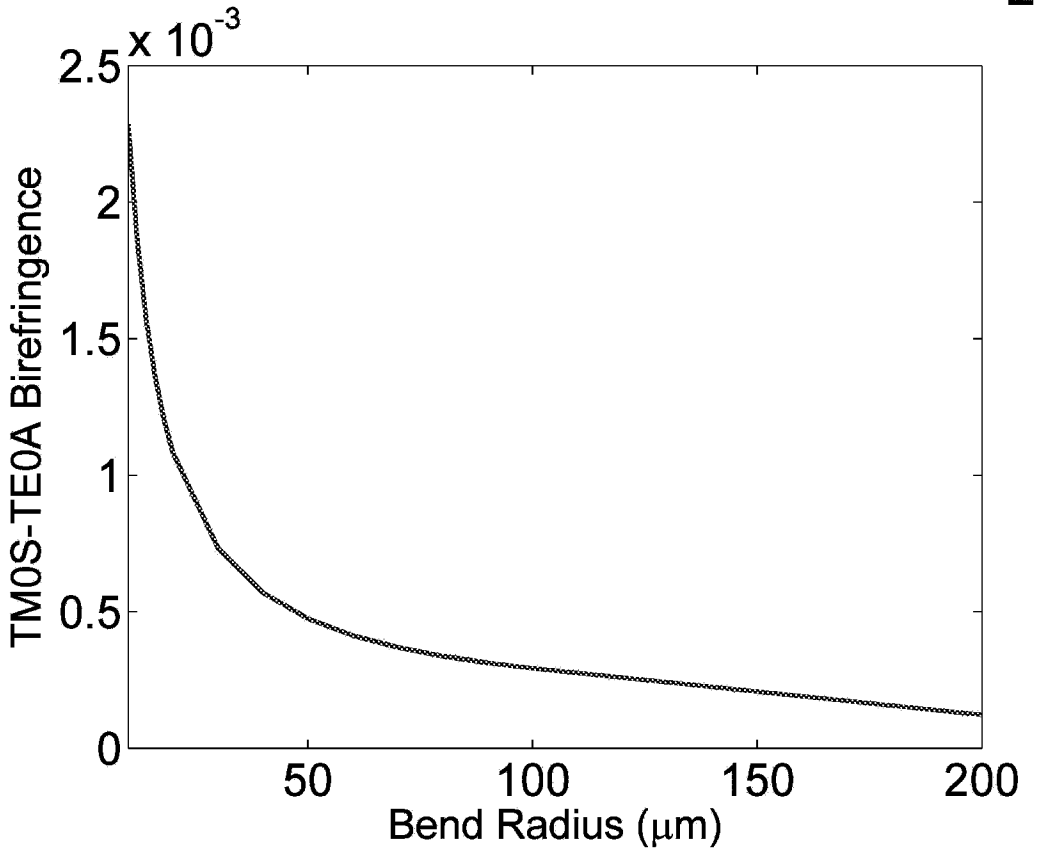
- Since increases in Si thickness are more detrimental than decreases, it may be beneficial to bias design away from optimal point to minimize the “worst case” birefringence
- Considering a +/- 10 nm Si thickness variation:
  - Minimal worst case birefringence so far is **0.0054** for SiN width of 800 nm and Si width of 410 nm. This sets an upper limit on the allowable delay line lengths for the MZI arms



Bent Waveguide Birefringence

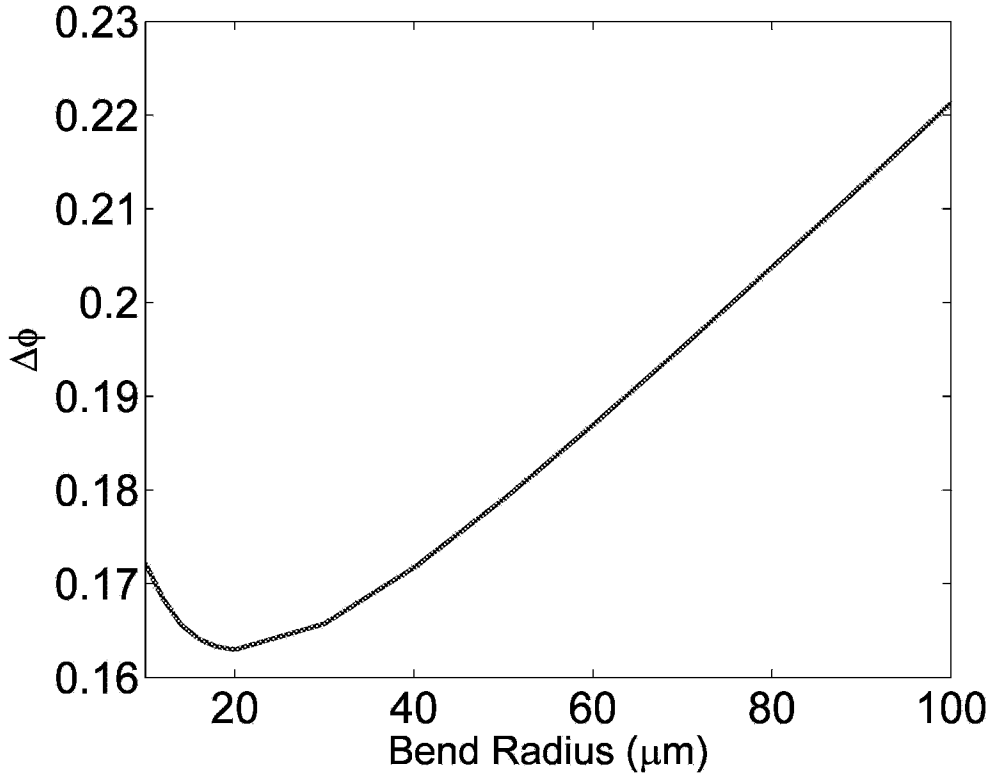
- Birefringence increases as bend radius decreases
- Plots below are for SiN width of 770 nm, Si width 410 nm





Bent Waveguide Birefringence

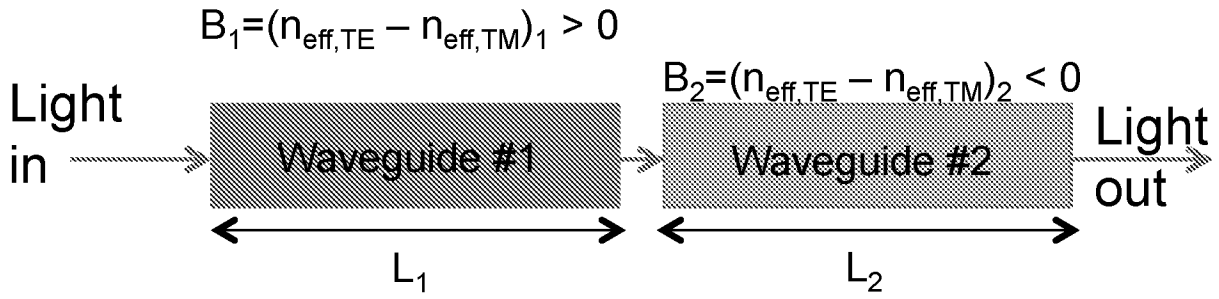
- Phase accumulation difference $\Delta\phi = 2\pi/\lambda\ \Delta n_{eff}(\pi R/2)$ vs. bend radius R
  - Indicates that R = 20 μm is optimal for this waveguide cross-section (w_{SiN} = 770 nm, w_{Si} = 410 nm)



Reducing polarization dependence

- 1. Choose waveguide cross-section with near zero birefringence
  - Bias design point at slightly thinner Si
  - The operation point is sensitive to waveguide dimensions (especially thickness variations)

- 2. Equalize the birefringence by using two types of waveguide cross-sections, one with positive birefringence and one with negative birefringence, so the overall birefringence cancels.
  - Can choose widths that are more variation tolerant
  - Broader band operation may also be possible



$$B_1L_1 = B_2L_2$$

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1. Title of Invention:

Birefringence compensation by serially varying the waveguide width

2. Inventors and Contributors:

a. Inventors at the University of Toronto: List all individuals who have made an inventive contribution to this disclosure through the use of U of T resources (i.e. faculty, students, postdocs, staff, visiting scientist, etc). Attach separate pages if necessary.

SURNAME, GIVEN NAMES	U of T PERSONNEL NO (if applicable)	DEPARTMENT *(List any cross appointments or affiliated institutions)*	AFFILIATION WITH U of T *(i.e. faculty, research assoc., post-doc, student, staff, visitor, etc.)*	EMAIL ADDRESS	CONTACT INFORMATION *(non-U of T mailing address, phone, fax)*	% CONTRIBUTION *(*optional)*
Poon, Joyce Kai See	993899	Electrical and Computer Engineering	Faculty	joyce.poon@utoronto.ca	24 Wellesley St. W., #2212, Toronto, ON, M4Y 2X6 416-262-0571	80
Bois, Antoine	15823349	Electrical and Computer Engineering	MASc student	antoine.bois@mail.utoronto.ca	181 rue de l'Affluent, Lévis, QC, G7A 5C1, 647-639-1086	20

* If invention is assigned to UofT, percentage will be used as a basis for sharing future revenues. Revenue distribution agreed to by the parties in an assignment agreement will govern.

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Disclosure Date: August 29, 2016 **Disclosure No:** 10003215

b. External Inventors: List all individuals who have made an inventive contribution to this disclosure using non-U of T resources (i.e. sponsor employees, academic collaborators, etc). Please include names, organization, contact information and email address.

c. Contributors (Non-Inventors): List all individuals at or external to U of T who have not made an inventive contribution but have contributed to the development of the invention. Please include name, organization and email address.

3. Location(s) of Work:

Please list all locations (U of T and external) of the work leading to this invention, be specific (i.e. department, building, hospital, etc).

Department of Electrical and Computer Engineering, Galbraith building

4. Invention Description:

Please provide a description of this invention for evaluation, highlighting its novel or patentable aspects. Attach separate pages if necessary.

The invention is the birefringence compensation in photonic circuits by varying the waveguide width in a serial way.

For a given thickness, h, of a waveguide layer, two waveguide cross-sections with widths, w_1 and w_2 are chosen. The cross-section with width w_1 will have a birefringence, $B_1 = (n_{TE,1} - n_{TM,1})$, where $n_{TE,1}$ and $n_{TM,1}$ are the effective indices of the transverse electric (TE) and transverse magnetic polarized fundamental mode, respectively, of the waveguide. The cross-section with width w_2 will have a birefringence, $B_2 = (n_{TE,2} - n_{TM,2})$. Concatenating these two types of waveguides serially in a photonic device, can allow for the overall birefringence to be compensated. Waveguide lengths of L_1 and L_2 are chosen for widths of w_1 and w_2, respectively, such that $B_1L_1 + B_2L_2 = m\lambda$. This type of strategy can also be incorporated into designs that use differential (or "parallel") architectures for birefringence compensation in devices such as Mach-Zehnder interferometer filters.

Please see the enclosed slides for details.

5. Dissemination:

List all publications, abstracts, presentations or any other forms of public dissemination regarding this work, including dates.

○ **None** ○ **Yes (please provide details)**

None

6. Funding:

Provide details regarding any funding used in the development of this invention (i.e..salary or stipend support, materials, equipment, etc.).

SPONSOR	PROJECT TITLE	RIS FUND #
Finisar Corporation	Si Photonics for Coarse Wavelength Division Multiplexing (CWDM)	500138

7. Related Agreements:

Was the work leading to this invention subject to any written or oral contract(s) or other agreement(s) such as: material transfer, data transfer, software licence, confidentiality, collaboration, and/or sponsored research?

○ **No** ○ **Yes (please provide details)**

Yes. This invention has been made under a sponsored research agreement between Finisar and U of T. The U of T reference number is 2015-1761.

8. Patent Applications:

Have any patent applications or other intellectual property protections been filed in respect of this invention?

○ **No** ○ **Yes (please provide details)**

No.

9. Warranty:

I/We, the Inventors listed in Section 2(a), have read, understood and agree to all of the preceding, and declare that all of the information provided in this disclosure is complete and correct. To the best of our knowledge, all persons who might legally make an ownership claim in this Invention are identified in Section 2(a) and 2(b).

NAME (typed):	**SIGNATURE:**	**DATE :**
Joyce Poon	Joyce Poon	August 12, 2016
Antoine Bois	Antoine Bois	August 12, 2016

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If you need any assistance, please contact the IP Officer.

Birefringence compensation by serially varying the waveguide width

Invention Disclosure

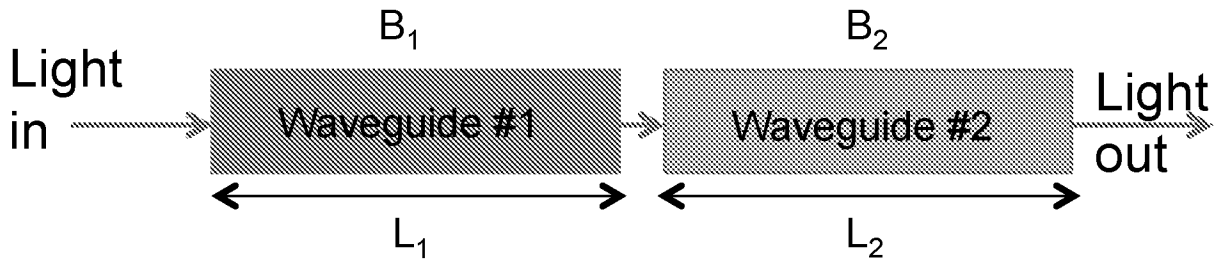
August 12, 2016

Concept

- Consider two waveguides sections with the same height that are concatenated with each other
  - 1. height = h, width = w_1, length = L_1
  - 2. height = h, width = w_2, length = L_2

Birefringence: $B_1 = n_{TE,1} - n_{TM,1}$

$B_2 = n_{TE,2} - n_{TM,2}$



Phase-shift of TE component after propagating through both sections

$$\phi_{TE} = \frac{2\pi}{\lambda}(n_{TE,1}L_1 + n_{TE,2}L_2)$$

Phase-shift of TM component after propagating through both sections

$$\phi_{TM} = \frac{2\pi}{\lambda}(n_{TM,1}L_1 + n_{TM,2}L_2)$$

The birefringence of the total system is compensated if $\phi_{TE} = \phi_{TM} + 2m\pi$ m = integer

This implies $B_1L_1 + B_2L_2 = m\lambda$

- There are many ways to achieve $B_1L_1 + B_2L_2 = m\lambda$
- An example is m = 0, B_1 and B_2 have opposite sign
  - Choose $w_1 > h$, $w_2 < h$
- Also possible for B_1, $B_2 > 0$ through choice of *m*, L_1, L_2
- For a variation tolerant design, we seek

$$\min(\Delta B_1 L_1 + \Delta B_2 L_2)$$

Assuming the variation in the length is negligible

where

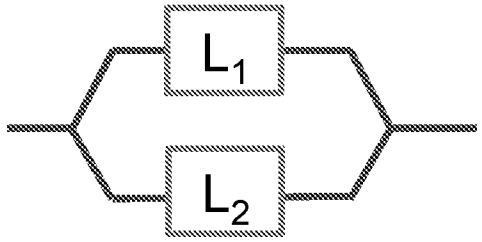
$$\Delta B_{1,2} = \frac{\partial B_{1,2}}{\partial w_{1,2}} \Delta w_{1,2} + \frac{\partial B_{1,2}}{\partial h} \Delta h + \frac{\partial B_{1,2}}{\partial n} \Delta n + \ldots$$

is the possible variation in $B_{1,2}$

Extensions

- Such a concept can also be combined with the differential birefringence compensation scheme proposed by Finisar for polarization-insensitive Mach-Zehnder interferometer filters

- Finisar concept



Consider a MZI with extra lengths L_1 and L_2 in each arm respectively. (Note: a similar width and length in both arms automatically compensate both polarizations. This is why nothing particular must be done about the bends.) It follows then that:

$$\phi_{TE} = \frac{2\pi}{\lambda}\left(n_{TE_1}L_1 - n_{TE_2}L_2\right), \tag{1}$$

$$\phi_{TM} = \frac{2\pi}{\lambda}\left(n_{TM_1}L_1 - n_{TM_2}L_2\right). \tag{2}$$

We require:

$$\phi_{TE} = \phi_{TM} + m2\pi, \quad m \in \mathbb{N}. \tag{3}$$

We choose $m = 0$ such that we automatically satisfy all λ, and as such do not depend on a specific central wavelength. Choosing $m = 0$ also leads to shorter delay lengths, without any downside. With $B = n_{TE} - n_{TM}$, this translates to:

$$B_1L_1 = B_2L_2. \tag{4}$$

Another condition must also be satisfied on the free spectral range. With $\Delta L n_g \approx n_{gTE_1}L_1 - n_{gTE_2}L_2$ and $\delta\lambda$ the channel spacing, this gives:

$$n_{gTE_1}L_1 - n_{gTE_2}L_2 = \lambda^2/(2\delta\lambda). \tag{5}$$

Note: For the TM FSR to match also

$$n_{gTM1}L_1 - n_{gTM2}L_2 = \lambda^2/(2\delta\lambda)$$

Eqs. (4) and (5) are the two conditions that must be satisfied. At first glance, this is a system of two equations and eight variables. However, since we have control only over the widths w, we essentially have n_{TE_1}, n_{TM_1}, n_{gTE_1}, $n_{gTM_1} \propto w_1$ and n_{TE_2}, n_{TM_2}, n_{gTE_2}, $n_{gTM_2} \propto w_2$, reducing the system to four variables, namely w_1, w_2, L_1, L_2. Having an underdetermined system is actually beneficial in that it allows us to apply other optimization criteria.

For each pair $\{w_1, w_2\}$, the following linear system can be solved:

$$\begin{bmatrix} n_{TE_1} - n_{TM_1} & n_{TM_2} - n_{TE_2} \\ n_{gTE_1} & -n_{gTE_2} \end{bmatrix} \begin{bmatrix} L_1 \\ L_2 \end{bmatrix} = \begin{bmatrix} 0 \\ \lambda^2 / (2\delta\lambda) \end{bmatrix}$$

From the set of solutions $\{w_1, w_2\} \mapsto \{L_1, L_2\}$, we can then look at minimizing the sensitivity, through $\min(L_1 + L_2)$, since err $\phi \propto (L)^{1/2}$, at least from sidewall roughness, or at minimizing the difference in group indices, through $\min([n_{gTE_1} - n_{gTM_1}] L_1 - [n_{gTE_2} - n_{gTM_2}] L_2)$, in order to have consistent channel spacings.

- For a MZI, having $B_1L_1 = B_2L_2$ is robust to dimensional variations, but because $L_1 \neq L_2$, there is some leftover sensitivity.
  - For a MZI, using the differential compensation is generally better than the series approach, which requires $B_1L_1 = -B_2L_2$ (L_1 and L_2 in series).

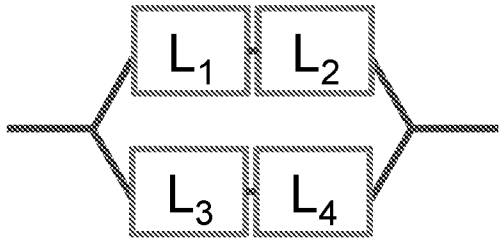
- Because B_1 and B_2 are the same sign, it is also robust to variations of the waveguide material index, though this can be achieved better with the series approach that has $B_1 < 0$ and $B_2 > 0$ and comparable L_1 and L_2.
  - Choice of series or parallel approach depends on which variation (dimension vs. index) is likely to be stronger.

- For the MZI directional couplers: use square cross-section waveguides for simplicity.

Combine Series and Parallel Birefringence Compensation

- L_1 and L_2 in series in one arm, and L_3 and L_4 in series in the other in a MZI

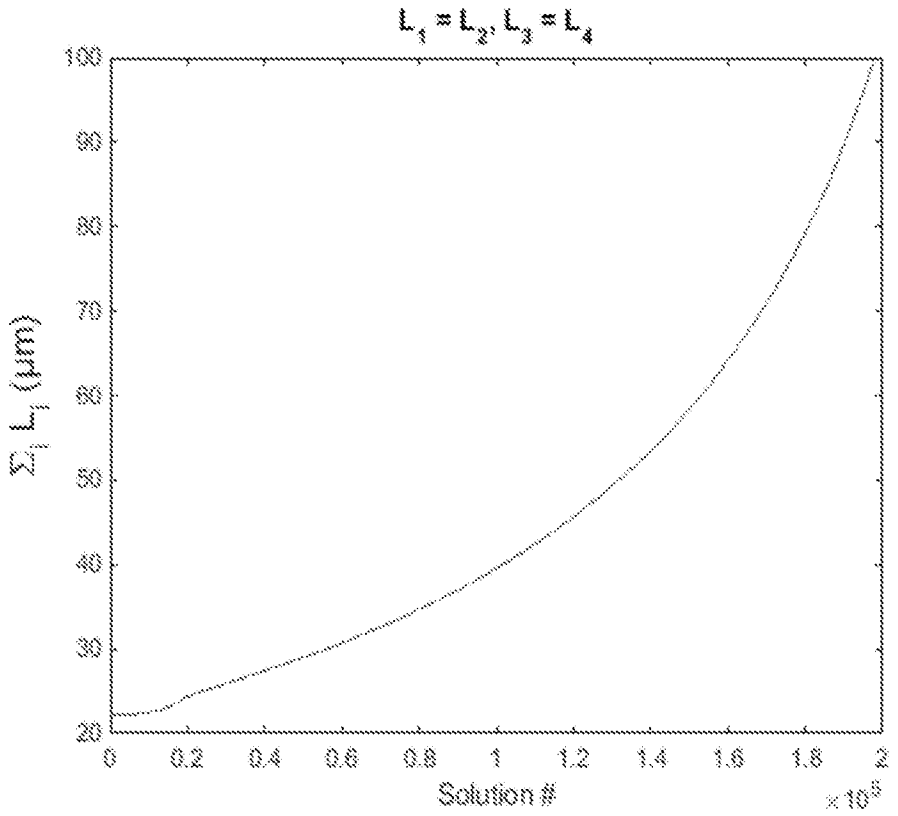
- Combines parallel and series approaches
  - To solve the residual birefringence variation due to ΔL in a MZI



- Needs two more conditions to solve the linear system. Examples can be:
  - $L_1 = L_2$,
  - $L_1 + L_2 = L_3 + L_4$,
  - L_1, L_2, L_3, or L_4 to specific values,
  - Or any other variation.

Example

SiN waveguide, 600nm tall
Channel spacing of 20nm, near a wavelength of 1310nm



The shortest solution converges to series case.

$L_1 = L_2 = 11$ μm
$L_3 = L_4 = 0$ μm

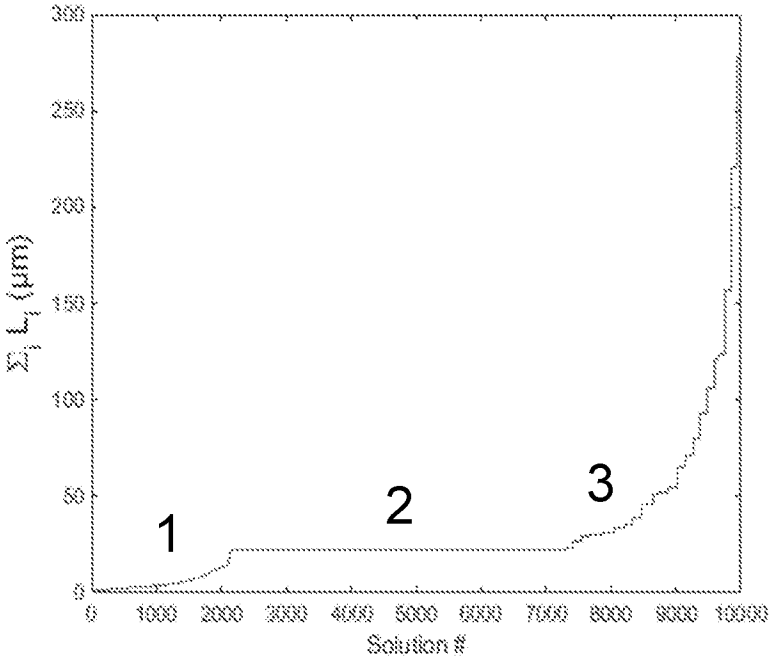
Other solutions are of the form:

$L_1 = L_2 = 11 + x_1$ μm
$L_3 = L_4 = x_2$ μm
with $(x_1 - x_2) / x_1 << 1$

Nonlinear optimization (with L_1, L_2, L_3, L_4)

- With nonlinear optimization criterion as min(ΣL_i) and linear optimization criterion maintained as:

$$\begin{bmatrix} n_{TE_1} - n_{TM_1} & n_{TE_2} - n_{TM_2} & n_{TM_3} - n_{TE_3} & n_{TM_4} - n_{TE_4} \\ n_{qTE_1} & n_{qTE_2} & -n_{qTE_3} & -n_{qTE_4} \end{bmatrix} \begin{bmatrix} L_1 \\ L_2 \\ L_3 \\ L_4 \end{bmatrix} = \begin{bmatrix} 0 \\ \lambda^2/(2\delta\lambda) \end{bmatrix}$$



1. Failed to converge
2. Converge to series case with $L_1 + L_2 = 22$ μm, $L_3 = L_4 = 0$ μm
3. Most solutions of the form $L_1 = x_1 + 22$ μm, $L_2 = 0$, $L_3 = x_2$, $L_4 = 0$ with $(x_1 - x_2) / x_1 << 1$

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1. Title of Invention:

Wavelength filtering and polarization (de)multiplexing via non-adiabatic transitions

2. Inventors and Contributors:

a. Inventors at the University of Toronto: List all individuals who have made an inventive contribution to this disclosure through the use of U of T resources (i.e. faculty, students, postdocs, staff, visiting scientist, etc). Attach separate pages if necessary.

SURNAME, GIVEN NAMES	U of T PERSONNEL NO (if applicable)	DEPARTMENT *(List any cross appointments or affiliated institutions)*	AFFILIATION WITH U of T *(i.e. faculty, research assoc., post-doc, student, staff, visitor, etc.)*	EMAIL ADDRESS	CONTACT INFORMATION *(non-U of T mailing address, phone, fax)*	% CONTRIBUTION *(*optional)*
Bois, Antoine	1160940	Electrical and Computer Engineering	Graduate student	antoine.bois@mail.utoronto.ca	181 rue de l'Affluent, Lévis, QC, G7A 5C1 418-836-0436	90%
Poon, Joyce Kai See	993899	Electrical and Computer Engineering	Faculty	joyce.poon@utoronto.ca	24 Wellesley St. W., #2212, Toronto, ON, M4Y 2X6 416-262-0571	10%

* If invention is assigned to UofT, percentage will be used as a basis for sharing future revenues. Revenue distribution agreed to by the parties in an assignment agreement will govern.

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Disclosure Date: May 5, 2017 **Disclosure No:** 10003351

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c. Contributors (Non-Inventors): List all individuals at or external to U of T who have not made an inventive contribution but have contributed to the development of the invention. Please include name, organization and email address.

3. Location(s) of Work:

Please list all locations (U of T and external) of the work leading to this invention, be specific (i.e. department, building, hospital, etc).

Department of Electrical and Computer Engineering, Galbraith building

4. Invention Description:

Please provide a description of this invention for evaluation, highlighting its novel or patentable aspects. Attach separate pages if necessary.

The invention is a polarization diverse wavelength demultiplexer/multiplexer which uses a unique wavelength-sensitive polarization rotator (PR). The PR relies on a polarization-based Mach-Zehnder interferometer that uses a non-adiabatic coupler. The non-adiabatic coupler has an L-shaped cross-section, for which the two lowest order modes have 50:50 TE:TM polarization mixtures. Incident TE or TM polarized light excite these hybrid modes, which are then converted into TE and TM modes of a birefringent waveguide. The TE and TM modes accumulate different phase-shifts in this waveguide, and are then recombined using a second non-adiabatic coupler with mode converters. Depending on the phase-shift accumulated in the birefringent waveguide, the interference is used to demultiplex signal according to wavelength and polarization. Different configurations are possible with the addition of standard broadband polarizations splitters or polarization-splitter-rotators.

Please see the enclosed slides.

5. Dissemination:

List all publications, abstracts, presentations or any other forms of public dissemination regarding this work, including dates.

○ **None** ○ **Yes (please provide details)**

None

6. Funding:

Provide details regarding any funding used in the development of this invention (i.e..salary or stipend support, materials, equipment, etc.).

SPONSOR	PROJECT TITLE	RIS FUND #
Finisar Corporation	Si Photonics for Coarse Wavelength Division Multiplexing (CWDM)	500138

7. Related Agreements:

Was the work leading to this invention subject to any written or oral contract(s) or other agreement(s) such as: material transfer, data transfer, software licence, confidentiality, collaboration, and/or sponsored research?

○ **No** ○ **Yes (please provide details)**

Yes. This invention is being disclosed under a sponsored research agreement between Finisar and U of T. The U of T reference number is 2015-1761.

8. Patent Applications:

Have any patent applications or other intellectual property protections been filed in respect of this invention?

○ **No** ○ **Yes (please provide details)**

No.

9. Warranty:

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NAME (typed):	**SIGNATURE:**	**DATE :**
Antoine Bois	Antoine Bois	April 21, 2017
Joyce Poon	Joyce Poon	April 21, 2017

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Wavelength filtering and polarization (de)multiplexing via non-adiabatic transitions

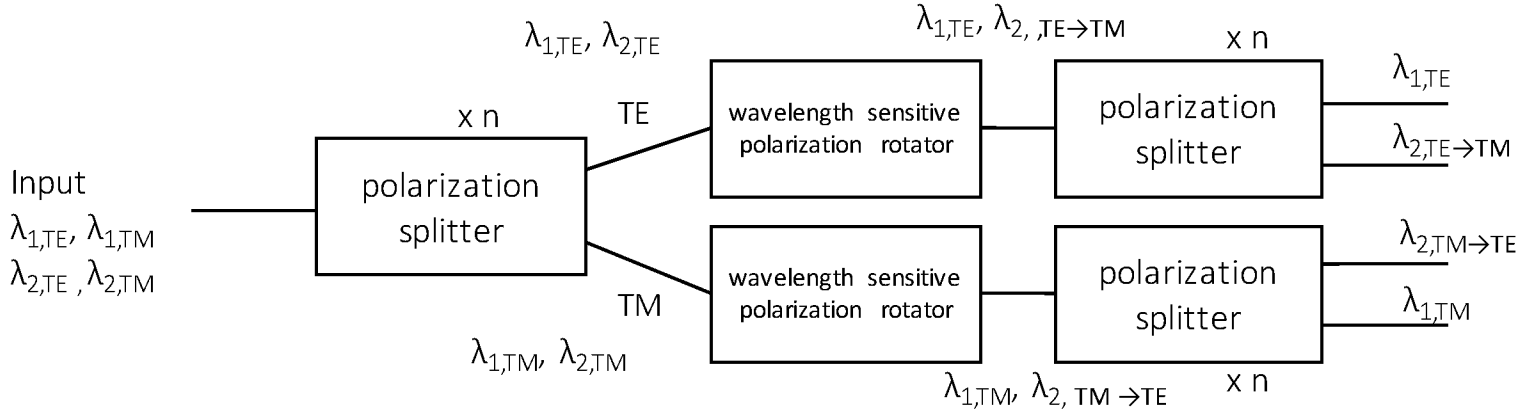
21/04/2017

Antoine Bois
Joyce Poon

UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE & ENGINEERING

Wavelength DEMUX concept

- Use wavelength sensitive polarization rotator
- Only 2nd wavelength channel is polarization rotated:

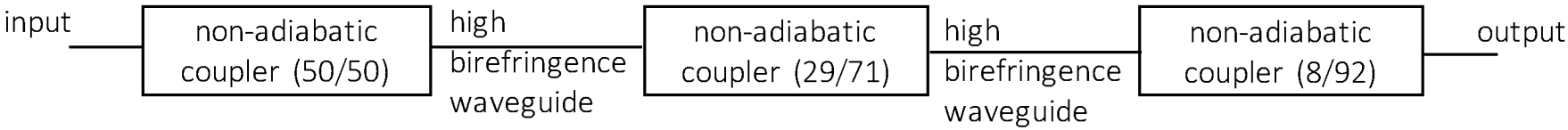


Can further rotate the polarization of λ_2 to obtain only TE outputs.

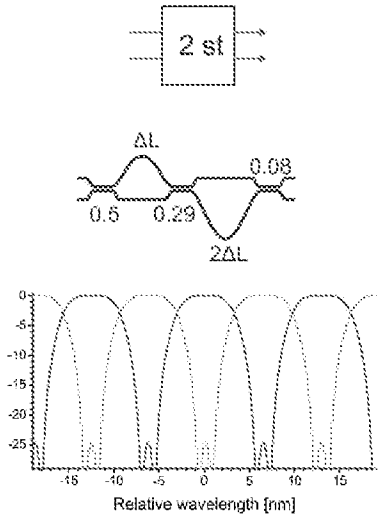
Can add a polarization combiner for each wavelength in a receiver for a polarization insensitive design.

Wavelength sensitive polarization rotator

- Based on a second order lattice filter, but uses non-adiabatic couplers



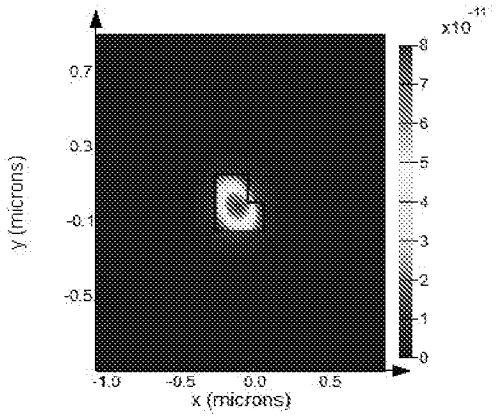
- Equivalent to



Horst, Folkert, et al. "Cascaded Mach-Zehnder wavelength filters in silicon photonics for low loss and flat pass-band WDM (de-) multiplexing." *Optics express* 21.10 (2013): 11652-11658.

Non-adiabatic coupler

- Example of cross-section (L-shaped Si):
- Tapering down too fast induces mode mixing.
- The lowest order 2 modes are TE-TM hybrid, with nearly 50:50 TE:TM mixtures.

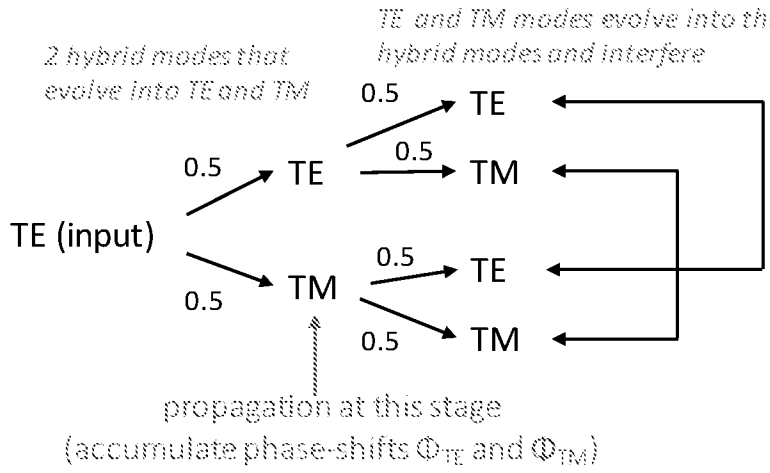


Mode list

mode #	effective index	wavelength (μm)	loss (dB/cm)	TE polarization fraction (Ex)
1	2.430637	1.31	0.00000	48
2	2.230070	1.31	0.00000	52

- Combining two such couplers leads to a birefringence-based MZI:

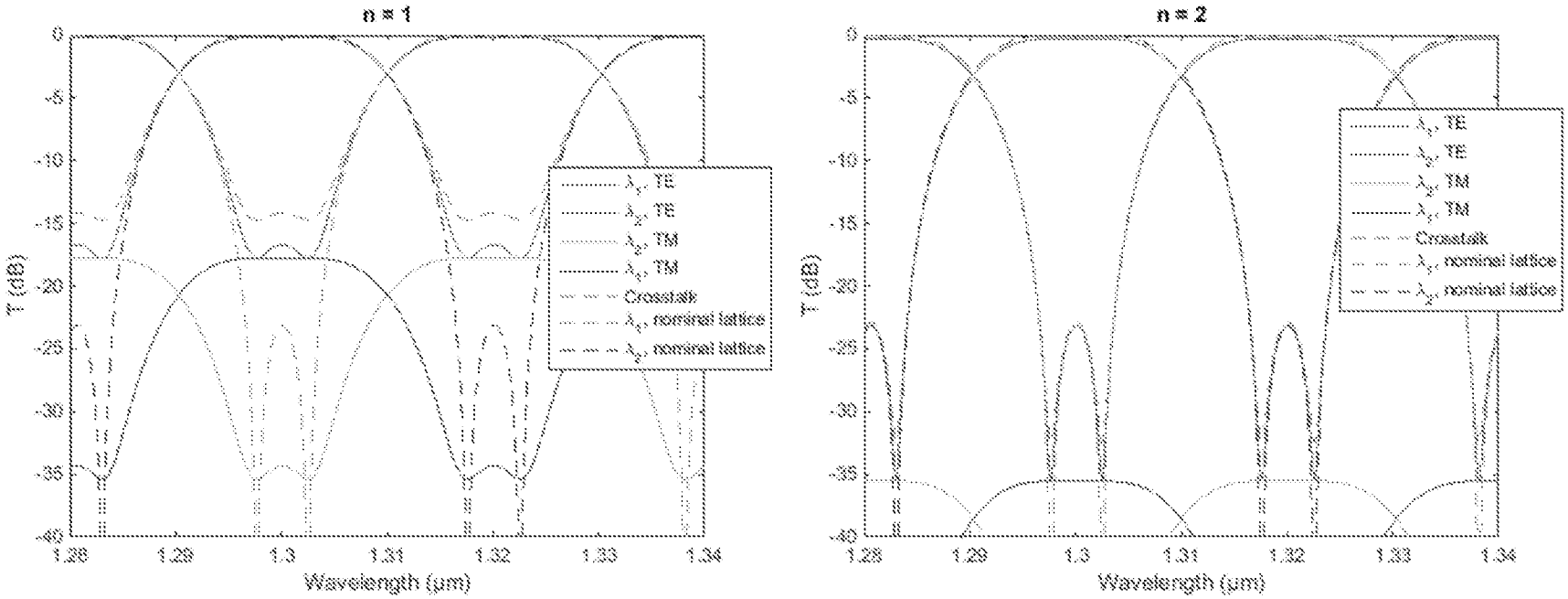
Consider TE input (TM is input is the reciprocal)



Interference
depends on the phase difference accumulated through the intermediate waveguide

Transfer matrix model (for pure TE input)

- Nominal lattice parameters, with *n* the number of polarization splitters in series.
- -17.7 dB crosstalk assumed for polarization splitters (based on some early simulations).

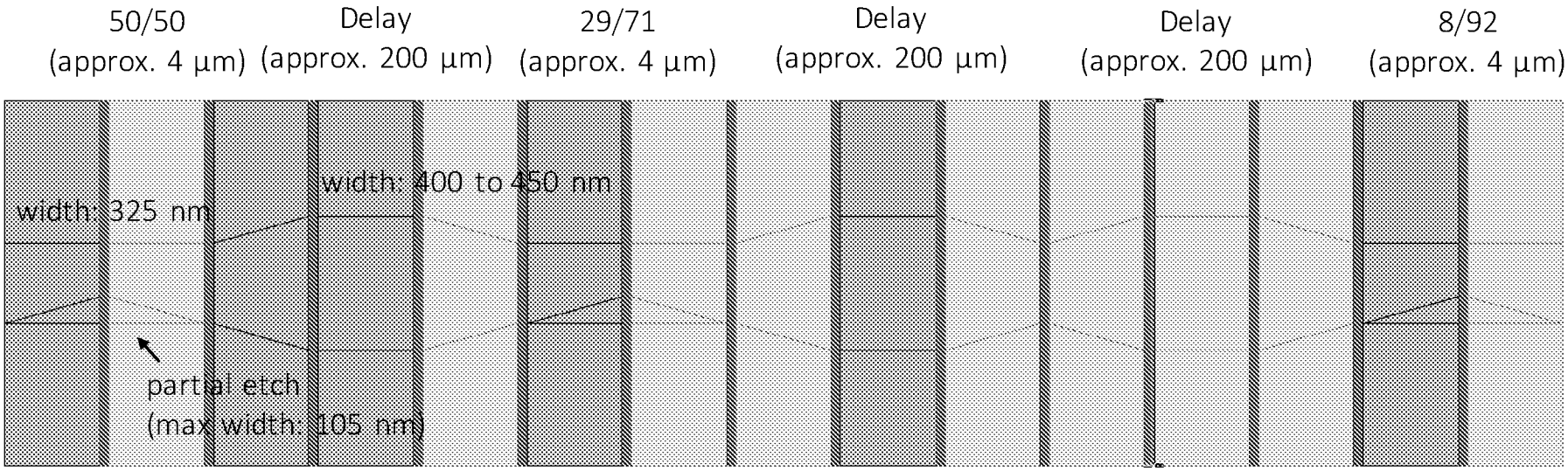


Notes

- High birefringence waveguides can be used to shorten nominal MZI lengths
- Couplers are short due to the non-adiabatic design -> compact implementation
- Non-adiabatic couplers have a broadband operation

Example topology for lattice block (in Si)

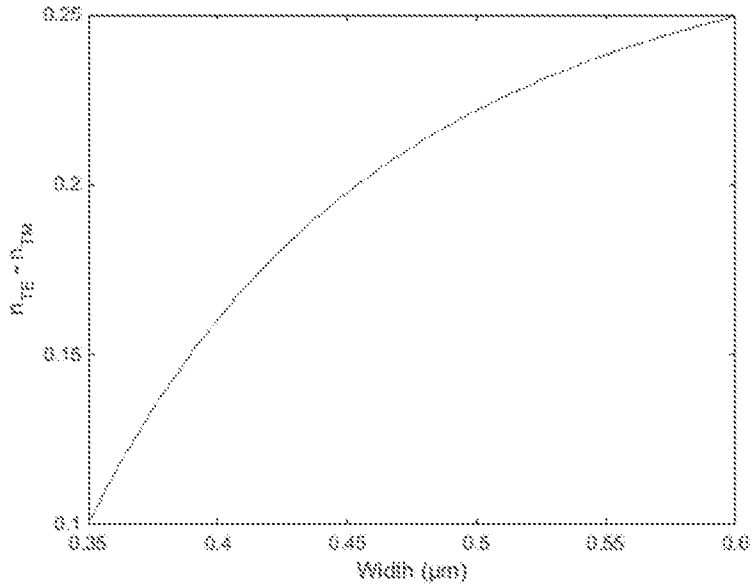
Non-adiabatic transitions to cross-sections with 50:50 hybrid modes is mirrored to achieve arbitrary coupling ratios between 0 and 100%. Robustness, coupler length, and wavelength sensitivity are not compromised.

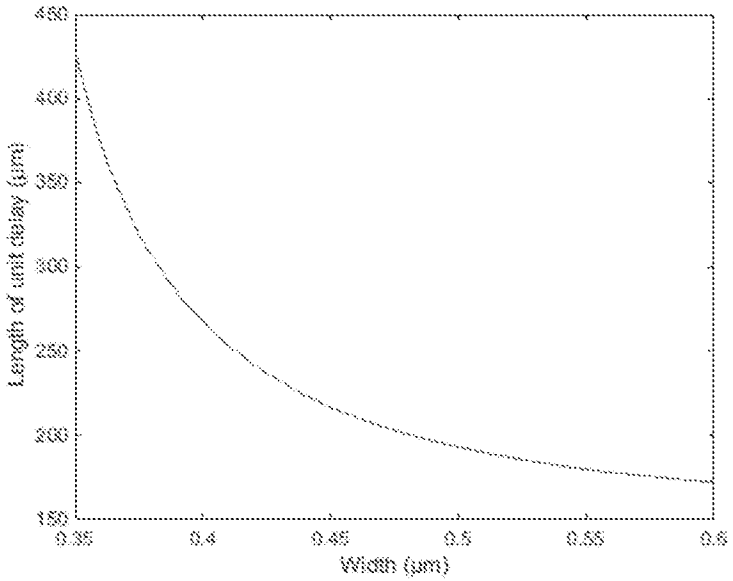


Full etch height: 300 nm
Partial etch height: 165 nm

Width of delay sections

- A high birefringence leads to multimode waveguides, but shorten the necessary delays.
- n is the group index.





Width of delay sections

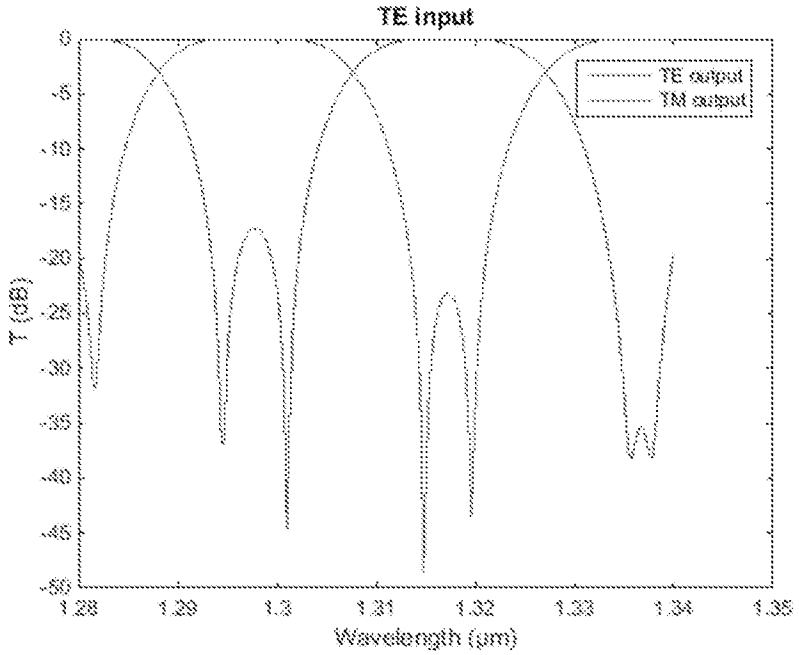
- 440 nm x 300 nm cross-section supports 4 modes with reasonable index separation:

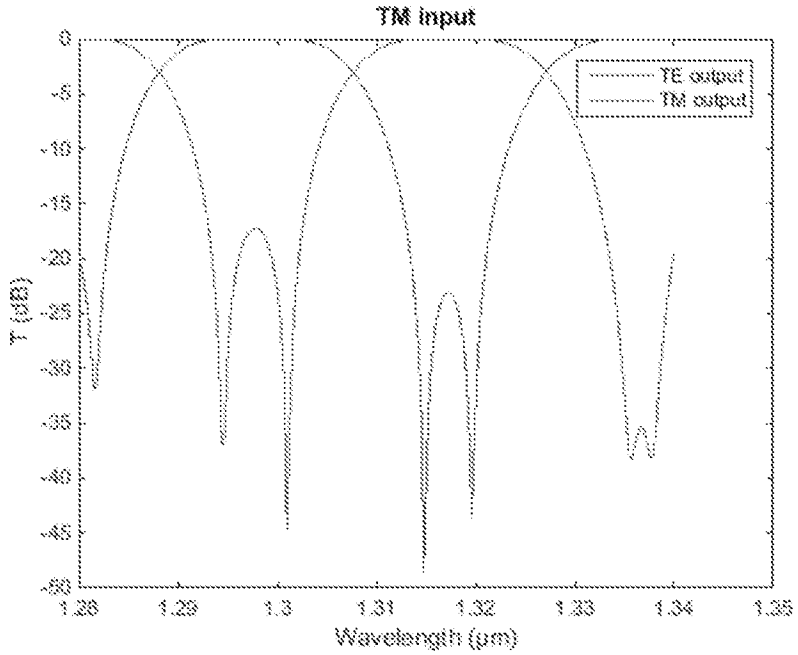
Mode list

mode #	effective index	wavelength (μm)	loss (dB/cm)	TE polarization fraction (Ex)
1	2.833647	1.31	0.00000	99
2	2.643459	1.31	0.00000	2
3	1.973490	1.31	0.00000	35
4	1.782133	1.31	0.00000	79

- Few mode waveguides can be manageable using adiabatic transitions that do not excite higher order modes
  - Widening the delay waveguides is a common technique for phase error mitigation:
    - "In these CMZ devices we have reduced the sensitivity to width variations by widening the waveguides in the delay arms [14], from the standard width of 500 nm to a width of 1.0 μm. In the widened waveguides, the sensitivity of the optical phase to width-variations is reduced by a factor of 5. This also makes the delay line waveguides multi-modal, but we use 10 μm long parabolic tapers to couple adiabatically between the multi-mode and mono-mode sections of the device to avoid excitation of the higher order modes." (same ref. as on slide #3)

Polarization rotation – simulation example



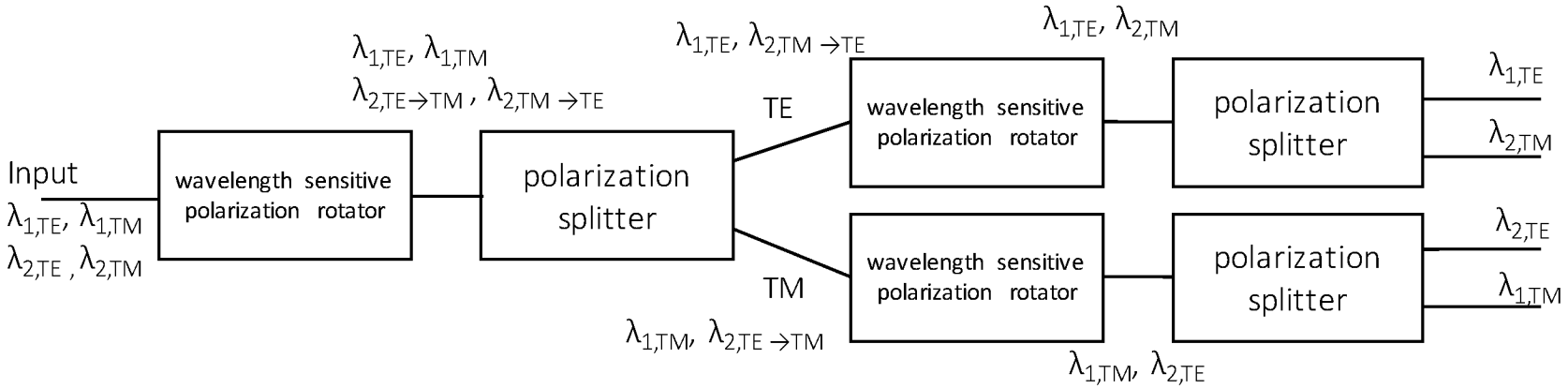


Sensitivity – Delay sections

- Dimensional variations will likely to lead to a similar increase or decrease in both the TE and TM effective indices, leading to the same overall birefringence. This is unlike a conventional interferometer with different waveguides with their own set of independent, uncorrelated perturbations.

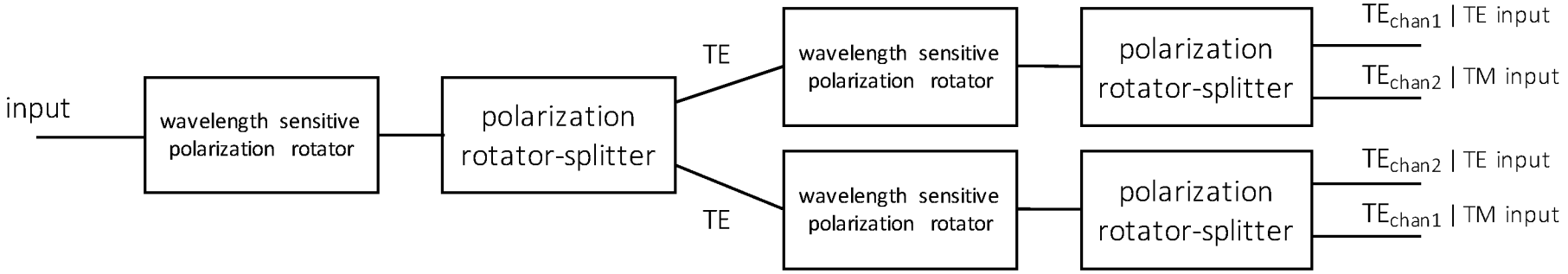
- Any perturbation that affects all delay lines equally lead to the same filter shape, but shifted in wavelength. This is unlike a filter that actively tries to match the TM and TE responses, with their own wavelength sensitivity to this shift. Here, the birefringence is the only wavelength sensitive element, so this problem is eliminated.

Alternate versions (1)

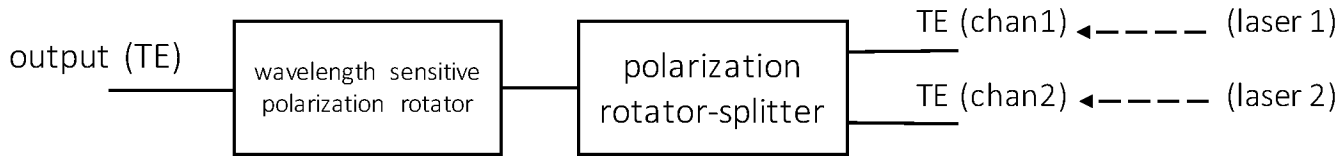


Can add a polarization combiner for each wavelength

Alternate versions (2)



- MUX at the transmitter end



UNIVERSITY OF TORONTO

OFFICE OF THE VICE-PRESIDENT, RESEARCH AND INNOVATION

CONFIDENTIAL INVENTION DISCLOSURE

Innovations & Partnerships Office | Banting Institute, Room 413 | 100 College St. Toronto ON M5G 1L5
Tel: (416) 978-7833 | Fax: (416) 978-6052 | email: ip.officer@utoronto.ca

This form is used to record inventions made using U of T resources, facilities and/or funds managed by U of T and is to be completed by the inventor(s) to satisfy their obligations under **U of T's Inventions Policy**. For step by step information on how to complete the form, please refer to the **invention disclosure guide**.

1. Title of Invention:

ADIABATIC POLARIZATION ROTATOR-SPLITTER

2. Inventors and Contributors:

a. Inventors at the University of Toronto: List all individuals who have made an inventive contribution to this disclosure through the use of U of T resources (i.e. faculty, students, postdocs, staff, visiting scientist, etc). Attach separate pages if necessary.

SURNAME, GIVEN NAMES	U of T PERSONNEL NO (if applicable)	DEPARTMENT *(List any cross appointments or affiliated institutions)*	AFFILIATION WITH U of T *(i.e. faculty, research assoc., post-doc, student, staff, visitor, etc.)*	EMAIL ADDRESS	CONTACT INFORMATION *(non-U of T mailing address, phone, fax)*	% CONTRIBUTION *(*optional)*
Yong, Zheng	1136946	Electrical and Computer Engineering	PhD student	zheng.yong@mail.utoronto.ca	925 Bay street, Apt. 1104, Toronto, ON M5S 3L4 6479946871	90
Poon, Joyce Kai See	993899	Electrical and Computer Engineering	Faculty	Joyce.poon@utoronto.ca	24 Wellesley St. W., #2212, Toronto, ON, M4Y 2X6 416-262-0571	10

* If invention is assigned to UofT, percentage will be used as a basis for sharing future revenues. Revenue distribution agreed to by the parties in an assignment agreement will govern.

For more information, see our Disclosure Guide.

FOR IPO USE ONLY:
Disclosure Date: May 10, 2018 Disclosure No: 10003606

b. External Inventors: List all individuals who have made an inventive contribution to this disclosure using non-U of T resources (i.e. sponsor employees, academic collaborators, etc). Please include names, organization, contact information and email address.

Bryan Park

c. Contributors (Non-Inventors): List all individuals at or external to U of T who have not made an inventive contribution but have contributed to the development of the invention. Please include name, organization and email address.

3. Location(s) of Work:

Please list all locations (U of T and external) of the work leading to this invention, be specific (i.e. department, building, hospital, etc).

Department of Electrical and Computer Engineering, Galbraith building

4. Invention Description:

Please provide a description of this invention for evaluation, highlighting its novel or patentable aspects. Attach separate pages if necessary.

The invention is an adiabatic polarization rotator-splitter (PRS) based on silicon nitride (SiN) waveguide. The proposed PRS receives an input optical signal in one SiN waveguide, and the input is a mixture of the two polarization modes, TE00 and TM00. The PRS first convert the incoming TM00 light to TE01 light and then separate it as the TE00 mode in a second waveguide while the input TE00 mode is not converted and maintained in the original waveguide. The adiabatic PRS is optimized to be insensitive to the geometric variations of the SiN waveguide (e.g., waveguide height, side wall angle). This device can be implemented in the platform where fabrication precision of SiN waveguide is not high. The design uses a partially etched layer in the SiN waveguide (i.e., SiN rib waveguides) to reduce the polarization crosstalk.

5. Dissemination:

List all publications, abstracts, presentations or any other forms of public dissemination regarding this work, including dates.

(•) None ( ) Yes (please provide details)

None

6. Funding:

Provide details regarding any funding used in the development of this invention (i.e. salary or stipend support, materials, equipment, etc.).

SPONSOR	PROJECT TITLE	RIS FUND #
Finisar Corporation	Si Photonics for Coarse Wavelength Division Multiplexing (CWDM)	500138

7. Related Agreements:

Was the work leading to this invention subject to any written or oral contract(s) or other agreement(s) such as: material transfer, data transfer, software licence, confidentiality, collaboration, and/or sponsored research?

○ No ○ Yes (please provide details)

Yes. This invention is being disclosed under a sponsored research agreement between Finisar and U of T. The U of T reference number is 2015-1761.

8. Patent Applications:

Have any patent applications or other intellectual property protections been filed in respect of this invention?

○ No ○ Yes (please provide details)

Yes. A non-provisional patent application was submitted on Nov. 29, 2017. US Patent Application number: 15/826,636

9. Warranty:

I/We, the inventors listed in Section 2(a), have read, understood and agree to all of the preceding, and declare that all of the information provided in this disclosure is complete and correct. To the best of our knowledge, all persons who might legally make an ownership claim in this invention are identified in Section 2(a) and 2(b).

NAME (typed):	SIGNATURE:	DATE :
Zheng Yong	Zheng Yong	May 10, 2018
Joyce Kai See Poon	Joyce Poon	May 10, 2018

SUBMISSION INSTRUCTIONS:

Please send an electronic draft of the disclosure form to the IP Officer for review prior to obtaining signatures.

Once reviewed for completeness and accuracy, the completed and signed form should be returned to the IP Officer via email at ip.officer@utoronto.ca, in-person, or by mail.

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UNIVERSITY OF TORONTO

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1. Title of Invention:

Adiabatic Polarization Rotator Combiner

2. Inventors and Contributors:

a. Inventors at the University of Toronto: List all individuals who have made an inventive contribution to this disclosure through the use of U of T resources (i.e. faculty, students, postdocs, staff, visiting scientist, etc). Attach separate pages if necessary.

SURNAME, GIVEN NAMES	U of T PERSONNEL NO (if applicable)	DEPARTMENT *(List any cross appointments or affiliated institutions)*	AFFILIATION WITH U of T *(i.e. faculty, research assoc., post-doc, student, staff, visitor, etc.)*	EMAIL ADDRESS	CONTACT INFORMATION *(non-U of T mailing address, phone, fax)*	% CONTRIBUTION *(*optional)*
Yong, Zheng	1136946	Electrical and Computer Engineering	PhD student	zheng.yong@mail.utoronto.ca	925 Bay street, Apt. 1104, Toronto, ON M5S 3L4 6479946871	90
Poon, Joyce Kai See	993699	Electrical and Computer Engineering	Faculty	Joyce.poon@utoronto.ca	24 Wellesley St. W., #2212, Toronto, ON, M4Y 2X6 416-262-0571	10

FOR IPO USE ONLY:
Disclosure Date: May 10, 2018 Disclosure No: 10003607

* If invention is assigned to UofT, percentage will be used as a basis for sharing future revenues. Revenue distribution agreed to by the parties in an assignment agreement will govern.

For more information, see our Disclosure Guide.

b. External Inventors: List all individuals who have made an inventive contribution to this disclosure using non-U of T resources (i.e. sponsor employees, academic collaborators, etc). Please include names, organization, contact information and email address.

Bryan Park, Daniel Mahgerefteh – Finisar Corp.

c. Contributors (Non-Inventors): List all individuals at or external to U of T who have not made an inventive contribution but have contributed to the development of the invention. Please include name, organization and email address.

3. Location(s) of Work:

Please list all locations (U of T and external) of the work leading to this invention, be specific (i.e. department, building, hospital, etc).

Department of Electrical and Computer Engineering, Galbraith building

4. Invention Description:

Please provide a description of this invention for evaluation, highlighting its novel or patentable aspects. Attach separate pages if necessary.

The invention is an adiabatic polarization rotator combiner (PRC) based on silicon nitride (SiN) waveguides. The proposed PRC is a polarization multiplexing device that can receive two optical signals with TE00 polarization in two SiN waveguides. The second optical signal is first converted to TE01 mode and then TM00 mode. Then the converted TM00 mode is combined with the other input TE00 optical signal. The adiabatic PRC is optimized to be insensitive to the geometric variations of the SiN waveguide (e.g., waveguide height, side wall angle) for the given integrated photonic platform. This device can be implemented in the platform where fabrication precision of SiN waveguide is not high. The design uses a partially etched layer in the SiN waveguide (i.e., SiN rib waveguides) to reduce the polarization crosstalk.

5. Dissemination:

List all publications, abstracts, presentations or any other forms of public dissemination regarding this work, including dates.

(•) None ( ) Yes (please provide details)

None

6. Funding:

Provide details regarding any funding used in the development of this invention (i.e..salary or stipend support, materials, equipment, etc.).

SPONSOR	PROJECT TITLE	RIS FUND #
Finisar Corporation	Si Photonics for Coarse Wavelength Division Multiplexing (CWDM)	500138

7. Related Agreements:

Was the work leading to this invention subject to any written or oral contract(s) or other agreement(s) such as: material transfer, data transfer, software licence, confidentiality, collaboration, and/or sponsored research?

○ No ○ Yes (please provide details)

Yes. This invention is being disclosed under a sponsored research agreement between Finisar and U of T. The U of T reference number is 2015-1761.

8. Patent Applications:

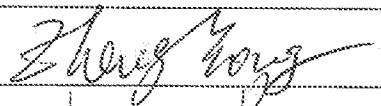
Have any patent applications or other intellectual property protections been filed in respect of this invention?

○ No ○ Yes (please provide details)

Yes. A non-provisional patent application was submitted on Nov. 29, 2017. US Patent Application number: 15/826,673

9. Warranty:

I/We, the inventors listed in Section 2(a), have read, understood and agree to all of the preceding, and declare that all of the information provided in this disclosure is complete and correct. To the best of our knowledge, all persons who might legally make an ownership claim in this Invention are identified in Section 2(a) and 2(b).

NAME (typed):	SIGNATURE:	DATE :
Zheng Yong		May 10, 2018
Joyce Kai See Poon		May 10, 2018

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If you need any assistance, please contact the IP Officer.

SCHEDULE "B"

INVENTORS' ASSIGNMENTS TO THE UNIVERSITY

(See Attached)

UNIVERSITY OF TORONTO

OFFICE OF THE VICE-PRESIDENT, RESEARCH AND INNOVATION

ASSIGNMENT TO THE UNIVERSITY FROM INVENTOR AND REVENUE SHARING AGREEMENT

This assignment and revenue sharing agreement (the **"Agreement"**) is between Joyce K Poon, Jared C Mikkelsen, their respective heirs, executors, administrators and assigns (collectively, the **"Inventor"**) and The Governing Council of the University of Toronto, its successors and assigns (collectively, the **"University"**).

WHEREAS, the Inventor has created certain intellectual property entitled **"High Efficiency Grating-to-Grating Optical Coupling for Multi-chip Integration" (Disclosure No. 10003189)** as more particularly described in the disclosure form attached as Appendix 1 (the **"Invention"**);

AND WHEREAS, the University and the Inventor jointly own the Invention under the University's *Inventions Policy* (the **"Policy"**, including any successor policy thereto);

AND WHEREAS, rights are being granted to the research sponsor, Finisar Corporation, as a condition of the Sponsored Research and Collaboration Agreement dated, November 23, 2015;

AND WHEREAS, in order to offer such rights to the sponsor, the Inventor wishes to assign its interest in the Invention to the University;

NOW THEREFORE this Agreement witnesses that in consideration of the mutual covenants contained herein and other good and valuable consideration, the receipt and sufficiency of which are hereby acknowledged by each of the parties, the parties covenant and agree as follows:

1. **Definitions.** In addition to any terms defined above, in this Agreement:

   (a) **"Commercialization Costs"** means the legal and other fees incurred directly in the process of establishing and maintaining the legal protection of rights in the Invention;

   (b) **"Management Fee"** means a fee for services provided by the University in connection with its commercialization of the Invention; and,

   (c) **"Net Revenue"** means the royalty, licensing and other income or equivalent financial return received by the University from the assignment or licensing of the rights in the Invention, less any: (i) Commercialization Costs; and (ii) amounts payable to third parties under prior written agreements that directly relate to the Invention, including but not limited to funding and collaboration agreements.

2. **Assignment.** The Inventor hereby assigns to the University all right, title and interest, whatever the same may be (but without any representation or warranty as to the nature, extent or validity thereof) which the Inventor now has or may in the future have in the Invention, including, without limitation, the right to apply for patents in Canada, the United States of America and any other country, the right to receive any letters

patent that may be issued from any such applications and the right to sell, license or assign the Invention or the rights thereto.

3. **Disclosure.** The Inventor shall make full and complete disclosure of the Invention to the University, and shall make available to the University any physical embodiments of the Invention and other data that will be or that may be useful to the University in exercising its rights in the Invention.

4. **Assistance.** The Inventor shall execute, acknowledge and deliver all such further assurances and do all such acts as may be necessary to carry out the intent and purpose of this Agreement, including without limitation, to execute powers of attorney and other documents required to maintain intellectual property protection of the Invention, and shall review and provide comments with respect to such intellectual property protection as and when requested by the University.

5. **Revenue Sharing.**

   (a) Subject to 5(b), the University shall distribute sixty percent (60%) of the Net Revenue to the Inventor. The remaining forty percent (40%) of the Net Revenue shall be retained by the University and distributed in accordance with the Policy.

   (b) If the Inventor is also the founder of a company and the University assigns or licenses the Invention to that company, the Inventor agrees to waive all right to receive its share of the Net Revenue.

6. **Equivalent Revenue.** If an arrangement for commercialization of the Invention is made which provides consideration other than cash, the University may liquidate the non-cash assets to the extent it deems necessary to recover Commercialization Costs. The parties shall share the proceeds of such non-cash consideration in the same proportion as provided in section 5.

7. **Payments.** Any money to be paid by the University under this Agreement shall be paid to the Inventor in Canadian funds in the proportions set out in the attached Appendix 2, annually on or before the thirtieth (30th) day following the anniversary of the Effective Date.

8. **Term and Termination.** This Agreement enters into force as of the Effective Date and shall continue until terminated in accordance with this section. Unless otherwise agreed in writing by the parties:

   (a) the University may terminate this Agreement by providing ninety (90) days written notice to the Inventor; or,

   (b) if the University has not made reasonable efforts to enter into an agreement with a third party to commercialize the Invention within two (2) years of the Effective Date, the Inventor may request the termination of this Agreement and reassignment of the Invention to the Inventor by providing ninety (90) days written notice to the University;

   In either case, the parties shall execute an assignment of the University's rights in the Invention to the Inventor on terms to be negotiated by the parties in good faith.

9. **Indemnity.** The University shall indemnify and save the Inventor harmless from and against any loss arising out of or pursuant to any claims or demands in connection with the Invention and all costs, damages and expenses (including reasonable legal fees) incurred by the Inventor in connection therewith, except to the extent caused by the breach of any obligations of the Inventor herein or of any representations or warranties given by the Inventor in the disclosure form attached as Appendix 1.

10. **Acknowledgement and Release.** The Inventor acknowledges that, because of the speculative nature of the undertaking to commercialize the Invention, the University cannot guarantee that the results will meet the objectives sought. The University may enter into an Agency Agreement in its sole discretion and, if so, shall provide a copy of the Agency Agreement to the Inventor. Save and except for the right to enforce the terms contained in this Agreement, the Inventor releases the University from any and all claims that the Inventor may now have or may in future have in respect of the Invention. Any disputes arising under this Agreement shall be resolved by the parties in accordance with the dispute resolution procedures set out in the Policy.

11. **Counterparts.** This Agreement may be executed by signatures delivered by facsimile transmission or delivered electronically in optically scanned form; and/or it may be simultaneously executed by the Inventors in multiple counterparts, each of which will be considered to be an original instrument, and all of which taken together, where each Inventor has executed at least one counterpart, will constitute one and the same instrument.

REMAINDER OF THIS PAGE INTENTIONALLY LEFT BLANK

Witness

TORREY THIESSEN

Inventor

Joyce K Poon

Antoine Bois

Jared C Mikkelsen

The Governing Council of the University of Toronto

Derek Newton
Assistant Vice-President, Innovation, Partnerships and Entrepreneurship

Executed at Toronto, Ontario this 9th day of October, 2016 (the "**Effective Date**")

APPENDIX 1

Invention Disclosure Form

APPENDIX 2

Distribution of Net Revenue

The Inventor directs the University to distribute 60% of the Net Revenue to each Inventor in the following proportions:

Joyce K Poon:	75%
Jared C Mikkelsen:	25%
Total:	100%

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CONFIDENTIAL INVENTION DISCLOSURE

Innovations & Partnerships Office | Banting Institute, Room 413 | 100 College St. Toronto ON M5G 1L5
Tel: (416) 978-7833 | Fax: (416) 978-6052 | email: ip.officer@utoronto.ca

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1. Title of Invention:

High efficiency grating-to-grating optical coupling for multi-chip integration

2. Inventors and Contributors:

a. Inventors at the University of Toronto: List all individuals who have made an inventive contribution to this disclosure through the use of U of T resources (i.e. faculty, students, postdocs, staff, visiting scientist, etc). Attach separate pages if necessary.

SURNAME, GIVEN NAMES	**U of T PERSONNEL NO (if applicable)**	**DEPARTMENT** *(List any cross appointments or affiliated institutions)*	**AFFILIATION WITH U of T** *(i.e. faculty, research assoc., post-doc, student, staff, visitor, etc.)*	**EMAIL ADDRESS**	**CONTACT INFORMATION** *(non-U of T mailing address, phone, fax)*	**% CONTRIBUTION** *(*optional)*
Poon, Joyce Kai See	993899	Electrical and Computer Engineering	Faculty	joyce.poon@utoronto.ca	24 Wellesley St. W., #2212, Toronto, ON, M4Y 2X6 416-262-0571	
Mikkelsen, Jared Carl	1092195	Electrical and Computer Engineering	PhD student	jared.mikkelsen@mail.utoronto.ca	2155 Mayflower Blvd., Oakville, ON, L6H 4E6 905-399-3109	

* If invention is assigned to UofT, percentage will be used as a basis for sharing future revenues. Revenue distribution agreed to by the parties in an assignment agreement will govern.

FOR IPO USE ONLY:
Disclosure Date: July 28, 2016 **Disclosure No:** 10003189

For more information, see our Disclosure Guide.

b. External Inventors: List all individuals who have made an inventive contribution to this disclosure using non-U of T resources (i.e. sponsor employees, academic collaborators, etc). Please include names, organization, contact information and email address.

Daniel Mahgerefteh, Finisar Corporation
1389 Moffett Park Dr., Sunnyvale, CA 94089, USA
daniel.mahgerefteh@finisar.com 1-310-721-1955

c. Contributors (Non-Inventors): List all individuals at or external to U of T who have not made an inventive contribution but have contributed to the development of the invention. Please include name, organization and email address.

3. Location(s) of Work:

Please list all locations (U of T and external) of the work leading to this invention, be specific (i.e. department, building, hospital, etc).

Department of Electrical and Computer Engineering, Galbraith building
Finisar Corporation, 48800 Milmont Dr., Fremont CA, 94538
Finisar Corporation, 1389 Moffett Park Dr., Sunnyvale, CA 94089, USA

4. Invention Description:

Please provide a description of this invention for evaluation, highlighting its novel or patentable aspects. Attach separate pages if necessary.

The invention is a grating coupler configuration that improves the optical coupling between two chips using a pair of grating couplers.

Background: In the field of silicon (Si) integrated photonics, one of the major challenges is the low-cost and efficient integration of a semiconductor laser (typically realized in compound semiconductor materials, like indium phosphide (InP)) onto a Si photonic chip. Finisar Corp. has been working on a solution in which an InP laser is integrated on top of a Si photonic chip using a transmitter grating coupler defined in the InP that sends the light to a large-area receiver grating coupler in the Si photonic die. The receiver grating coupler scatters the light from the laser into an in-plane waveguide.

In their previous work (Finisar background IP), the receiver grating coupler had a "positive angle" design, in which the light propagation in the in-plane waveguide (in the Si die) is in the same direction as the lateral component of the propagation direction of the incident light.

This invention is a receiver grating coupler with a "negative angle" design, in which the light propagation in the in-plane waveguide (in the Si die) is in a direction opposite to the lateral component of the propagation of the incident light. The negative angle reduces high order scattering directions to improve the coupling efficiency in the fundamental order (i.e., agnle). In a specific implementation using silicon nitride (SiN), the coupling efficiency is improved by about 1dB compared to previous approach using a "positive angle". The negative angle modifies the configuration of the coupled system of two chips.

An added benefit of the negative angle grating is that the electric fields in the transmitter and receiver grating couplers decrease in the same direction. This should lead to simpler apodization procedure of the gratings for

mode matching, providing a further boost to the coupling efficiency.
Please see the enclosed slides.

5. Dissemination:

List all publications, abstracts, presentations or any other forms of public dissemination regarding this work, including dates.

○ **None** ○ **Yes (please provide details)**

None

6. Funding:

Provide details regarding any funding used in the development of this invention (i.e..salary or stipend support, materials, equipment etc.).

SPONSOR	PROJECT TITLE	RIS FUND #
Finisar Corporation	Si Photonics for Coarse Wavelength Division Multiplexing (CWDM)	500138
NSERC	Postgraduate scholarship – doctoral level	

7. Related Agreements:

Was the work leading to this invention subject to any written or oral contract(s) or other agreement(s) such as: material transfer, data transfer, software licence, confidentiality, collaboration, and/or sponsored research?

○ **No** ○ **Yes (please provide details)**

Yes. This invention has been made under a sponsored research agreement between Finisar and U of T. The U of T reference number is 2015-1761.

8. Patent Applications:

Have any patent applications or other intellectual property protections been filed in respect of this invention?

○ **No** ○ **Yes (please provide details)**

Yes – Finisar has background IP and filed for a provisional application F1002-12677US01.

9. Warranty:

I/We, the Inventors listed in Section 2(a), have read, understood and agree to all of the preceding, and declare that all of the information provided in this disclosure is complete and correct. To the best of our knowledge, all persons who might legally make an ownership claim in this Invention are identified in Section 2(a) and 2(b).

NAME (typed):	SIGNATURE:	DATE :
Joyce Poon	Joyce Poon	July 21, 2016
Jared Mikkelsen	Jared Mikkelsen	July 21st, 2016

SUBMISSION INSTRUCTIONS:

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If you need any assistance, please contact the IP Officer.

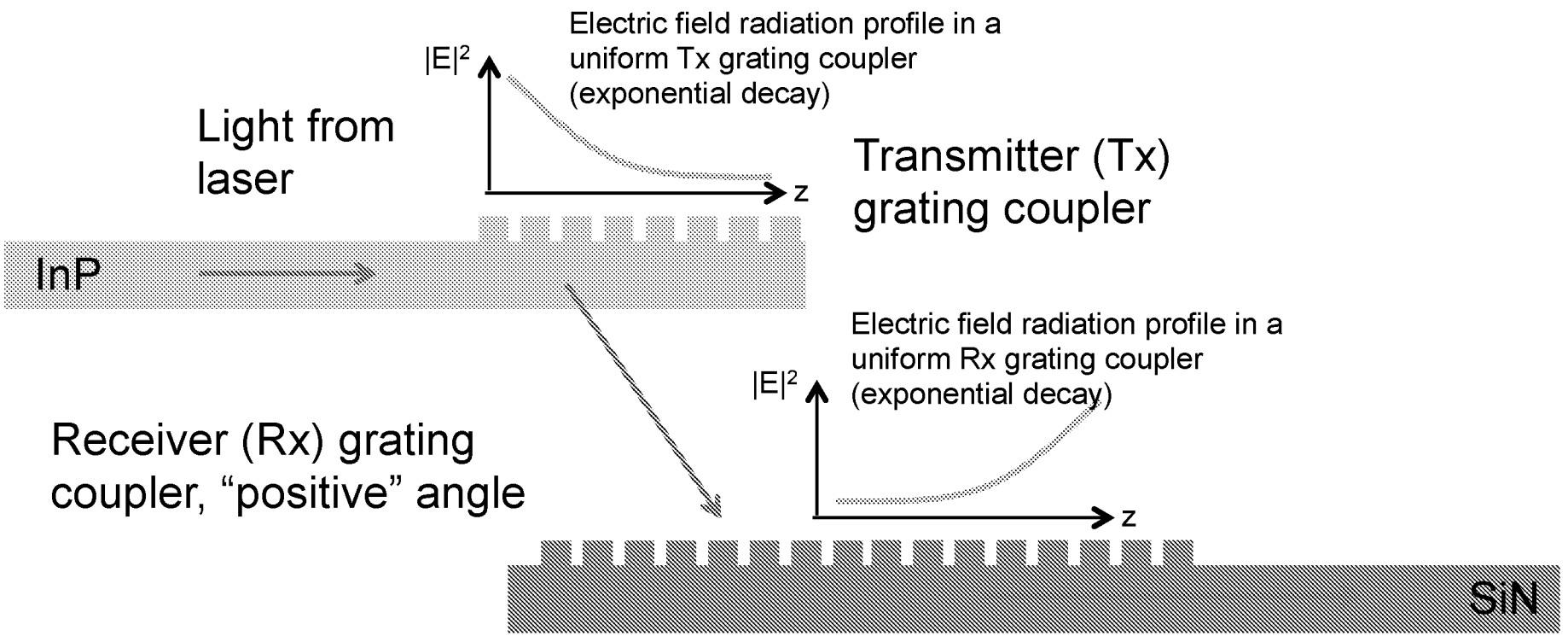
High efficiency grating-to-grating optical coupling for multi-chip integration

Invention Disclosure

July 19, 2016

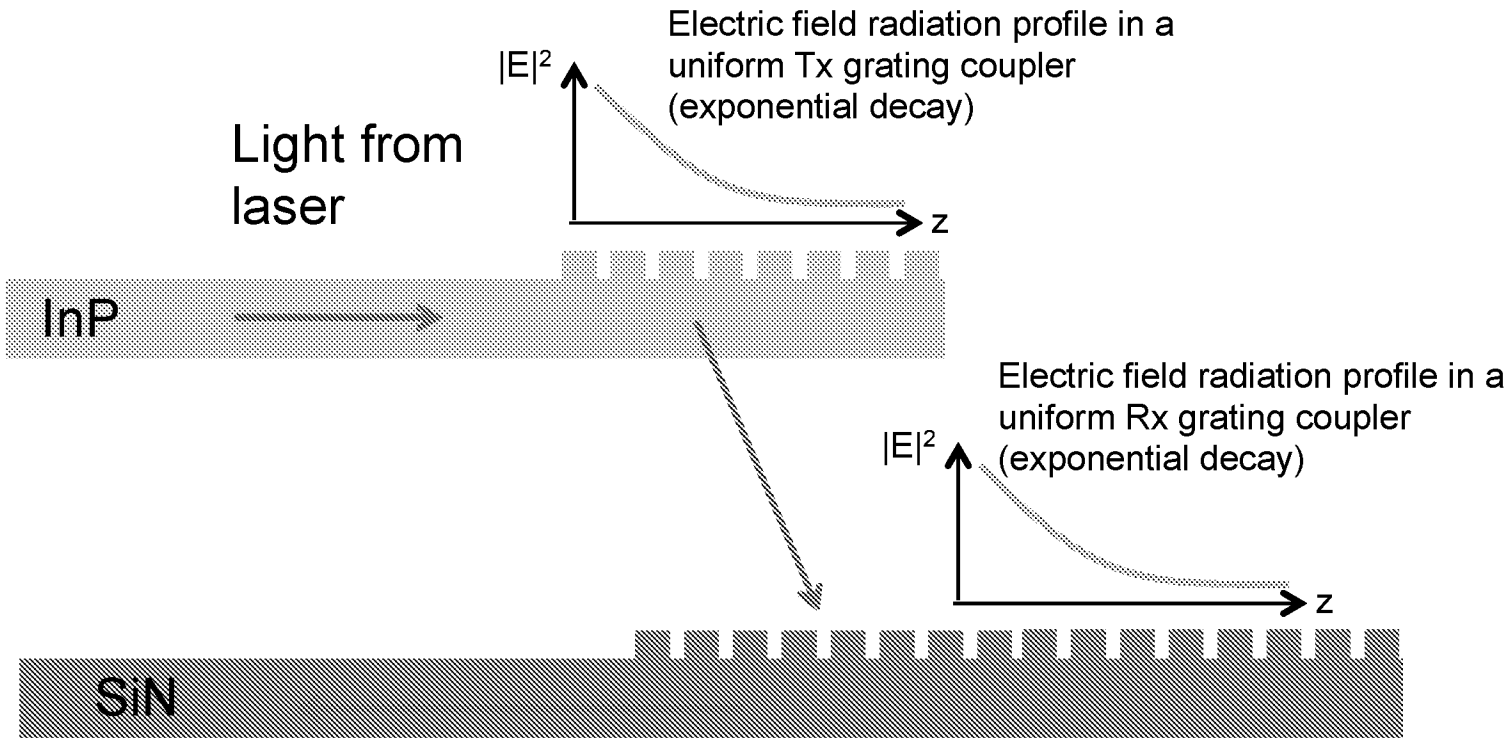
Finisar Background IP

- Two chip integration solution using a pair of grating couplers
  - For laser (InP) integration onto silicon (Si) photonic die containing a silicon nitride (SiN) layer



Invention

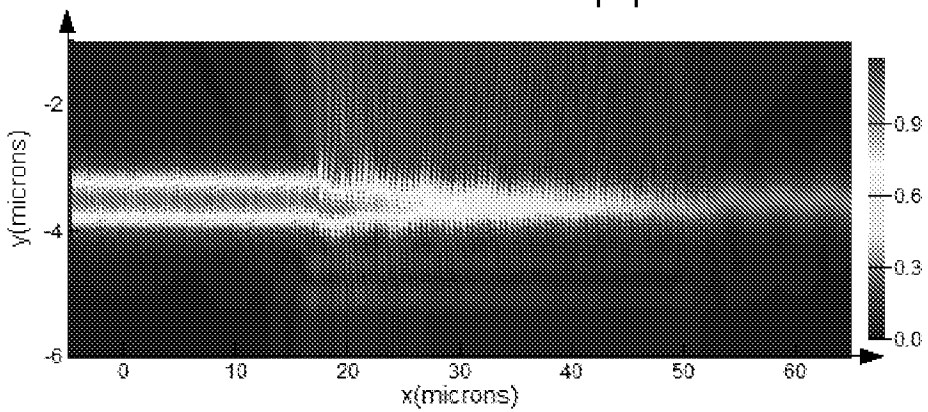
- Negative angle Rx grating coupler



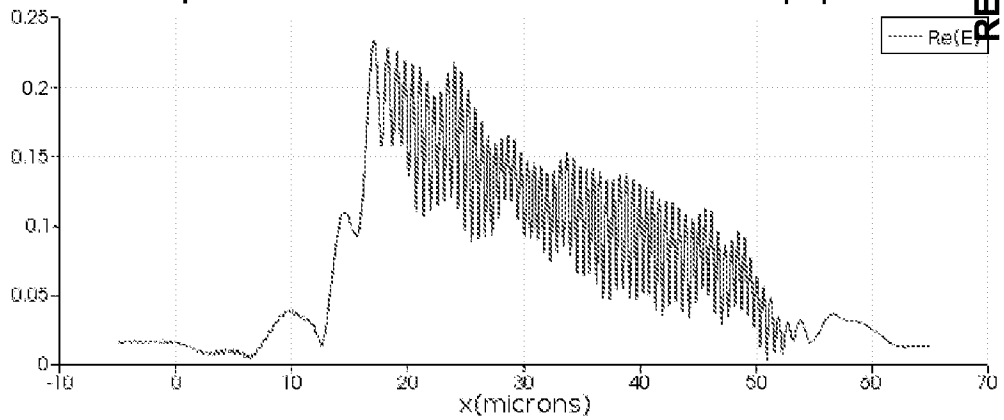
Example Receiver Grating Coupler

- Max. upward directionality: -1.35 dB
- Emission angle: -37.56 degrees

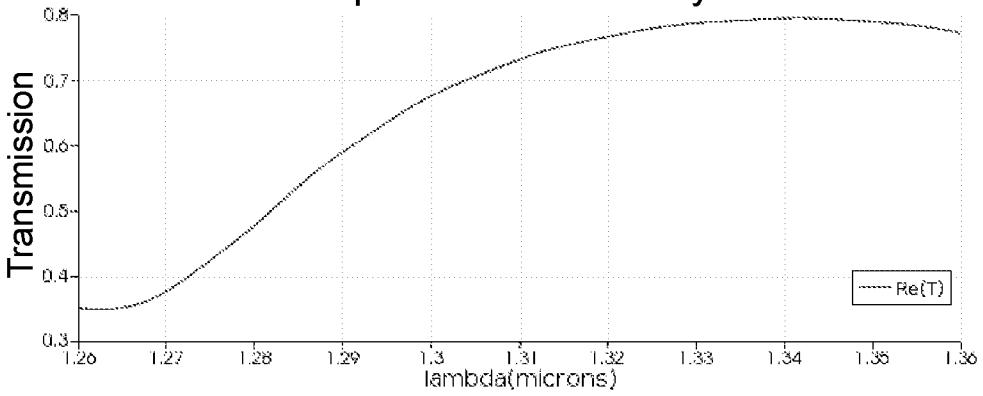
Full Field Profile |E|



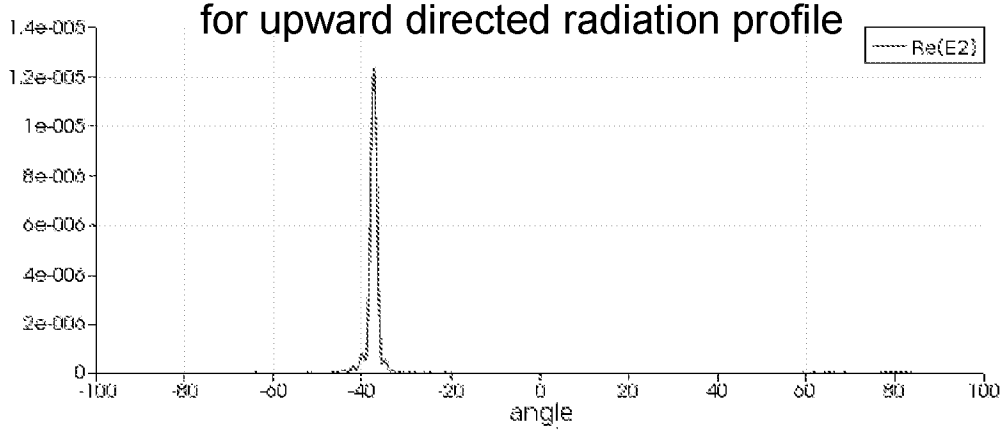
Upward Directed Radiation Profile |E|



Upward Directionality



Far-Field Projection
for upward directed radiation profile



ASSIGNMENT TO THE UNIVERSITY FROM INVENTOR AND REVENUE SHARING AGREEMENT

This assignment and revenue sharing agreement (the **"Agreement"**) is between Joyce K Poon, Jared C Mikkelsen, their respective heirs, executors, administrators and assigns (collectively, the **"Inventor"**) and The Governing Council of the University of Toronto, its successors and assigns (collectively, the **"University"**).

WHEREAS, the Inventor has created certain intellectual property entitled **"Birefringence Control of Silicone Nitride-on-Silicon Optical Waveguides and Photonic Circuits" (Disclosure No. 10003194)** as more particularly described in the disclosure form attached as Appendix 1 (the **"Invention"**);

AND WHEREAS, the University and the Inventor jointly own the Invention under the University's *Inventions Policy* (the **"Policy"**, including any successor policy thereto);

AND WHEREAS, rights are being granted to the research sponsor, Finisar Corporation, as a condition of the Sponsored Research and Collaboration Agreement dated, November 23, 2015;

AND WHEREAS, in order to offer such rights to the sponsor, the Inventor wishes to assign its interest in the Invention to the University;

NOW THEREFORE this Agreement witnesses that in consideration of the mutual covenants contained herein and other good and valuable consideration, the receipt and sufficiency of which are hereby acknowledged by each of the parties, the parties covenant and agree as follows:

1. **Definitions.** In addition to any terms defined above, in this Agreement:

   (a) **"Commercialization Costs"** means the legal and other fees incurred directly in the process of establishing and maintaining the legal protection of rights in the Invention;

   (b) **"Management Fee"** means a fee for services provided by the University in connection with its commercialization of the Invention; and,

   (c) **"Net Revenue"** means the royalty, licensing and other income or equivalent financial return received by the University from the assignment or licensing of the rights in the Invention, less any: (i) Commercialization Costs; and (ii) amounts payable to third parties under prior written agreements that directly relate to the Invention, including but not limited to funding and collaboration agreements.

2. **Assignment.** The Inventor hereby assigns to the University all right, title and interest, whatever the same may be (but without any representation or warranty as to the nature, extent or validity thereof) which the Inventor now has or may in the future have in the Invention, including, without limitation, the right to apply for patents in Canada, the United States of America and any other country, the right to receive any letters

patent that may be issued from any such applications and the right to sell, license or assign the Invention or the rights thereto.

3. **Disclosure.** The Inventor shall make full and complete disclosure of the Invention to the University, and shall make available to the University any physical embodiments of the Invention and other data that will be or that may be useful to the University in exercising its rights in the Invention.

4. **Assistance.** The Inventor shall execute, acknowledge and deliver all such further assurances and do all such acts as may be necessary to carry out the intent and purpose of this Agreement, including without limitation, to execute powers of attorney and other documents required to maintain intellectual property protection of the Invention, and shall review and provide comments with respect to such intellectual property protection as and when requested by the University.

5. **Revenue Sharing.**

   (a) Subject to 5(b), the University shall distribute sixty percent (60%) of the Net Revenue to the Inventor. The remaining forty percent (40%) of the Net Revenue shall be retained by the University and distributed in accordance with the Policy.

   (b) If the Inventor is also the founder of a company and the University assigns or licenses the Invention to that company, the Inventor agrees to waive all right to receive its share of the Net Revenue.

6. **Equivalent Revenue.** If an arrangement for commercialization of the Invention is made which provides consideration other than cash, the University may liquidate the non-cash assets to the extent it deems necessary to recover Commercialization Costs. The parties shall share the proceeds of such non-cash consideration in the same proportion as provided in section 5.

7. **Payments.** Any money to be paid by the University under this Agreement shall be paid to the Inventor in Canadian funds in the proportions set out in the attached Appendix 2, annually on or before the thirtieth (30th) day following the anniversary of the Effective Date.

8. **Term and Termination.** This Agreement enters into force as of the Effective Date and shall continue until terminated in accordance with this section. Unless otherwise agreed in writing by the parties:

   (a) the University may terminate this Agreement by providing ninety (90) days written notice to the Inventor; or,

   (b) if the University has not made reasonable efforts to enter into an agreement with a third party to commercialize the Invention within two (2) years of the Effective Date, the Inventor may request the termination of this Agreement and reassignment of the Invention to the Inventor by providing ninety (90) days written notice to the University;

   In either case, the parties shall execute an assignment of the University's rights in the Invention to the Inventor on terms to be negotiated by the parties in good faith.

9. **Indemnity.** The University shall indemnify and save the Inventor harmless from and against any loss arising out of or pursuant to any claims or demands in connection with the Invention and all costs, damages and expenses (including reasonable legal fees) incurred by the Inventor in connection therewith, except to the extent caused by the breach of any obligations of the Inventor herein or of any representations or warranties given by the Inventor in the disclosure form attached as Appendix 1.

10. **Acknowledgement and Release.** The Inventor acknowledges that, because of the speculative nature of the undertaking to commercialize the Invention, the University cannot guarantee that the results will meet the objectives sought. The University may enter into an Agency Agreement in its sole discretion and, if so, shall provide a copy of the Agency Agreement to the Inventor. Save and except for the right to enforce the terms contained in this Agreement, the Inventor releases the University from any and all claims that the Inventor may now have or may in future have in respect of the Invention. Any disputes arising under this Agreement shall be resolved by the parties in accordance with the dispute resolution procedures set out in the Policy.

11. **Counterparts.** This Agreement may be executed by signatures delivered by facsimile transmission or delivered electronically in optically scanned form; and/or it may be simultaneously executed by the Inventors in multiple counterparts, each of which will be considered to be an original instrument, and all of which taken together, where each Inventor has executed at least one counterpart, will constitute one and the same instrument.

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Witness

TORLEY THIESSEN

Antoine Bois

Inventor

Joyce K Poon

Jared C Mikkelsen

The Governing Council of the University of Toronto

Derek Newton
Assistant Vice-President, Innovation, Partnerships and Entrepreneurship

Executed at Toronto, Ontario this 3rd day of October, 2016 (the "**Effective Date**")

APPENDIX 1

Invention Disclosure Form

APPENDIX 2

Distribution of Net Revenue

The Inventor directs the University to distribute 60% of the Net Revenue to each Inventor in the following proportions:

Joyce K Poon:	75%
Jared C Mikkelsen:	25%
Total:	100%

UNIVERSITY OF TORONTO

OFFICE OF THE VICE-PRESIDENT, RESEARCH AND INNOVATION

CONFIDENTIAL INVENTION DISCLOSURE

Innovations & Partnerships Office | Banting Institute, Room 413 | 100 College St. Toronto ON M5G 1L5
Tel: (416) 978-7833 | Fax: (416) 978-6052 | email: ip.officer@utoronto.ca

This form is used to record inventions made using U of T resources, facilities and/or funds managed by U of T and is to be completed by the inventor(s) to satisfy their obligations under **U of T's Inventions Policy**. For step by step information on how to complete the form, please refer to the **invention disclosure guide**.

1. Title of Invention:

Birefringence control of silicon nitride-on-silicon optical waveguides and photonic circuits

2. Inventors and Contributors:

a. Inventors at the University of Toronto:

List all individuals who have made an inventive contribution to this disclosure through the use of U of T resources (i.e. faculty, students, postdocs, staff, visiting scientist, etc). Attach separate pages if necessary.

SURNAME, GIVEN NAMES	U of T PERSONNEL NO (if applicable)	DEPARTMENT *(List any cross appointments or affiliated institutions)*	AFFILIATION WITH U of T *(i.e. faculty, research assoc., post-doc, student, staff, visitor, etc.)*	EMAIL ADDRESS	CONTACT INFORMATION *(non-U of T mailing address, phone, fax)*	% CONTRIBUTION *(*optional)*
Poon, Joyce Kai See	993899	Electrical and Computer Engineering	Faculty	joyce.poon@utoronto.ca	24 Wellesley St. W., #2212, Toronto, ON, M4Y 2X6 416-262-0571	
Mikkelsen, Jared Carl	1092195	Electrical and Computer Engineering	PhD student	jared.mikkelsen@mail.utoronto.ca	2155 Mayflower Blvd., Oakville, ON, L5H 4E6 905-399-3109	

* If invention is assigned to UofT, percentage will be used as a basis for sharing future revenues. Revenue distribution agreed to by the parties in an assignment agreement will govern.

FOR IPO USE ONLY:
Disclosure Date: August 3, 2016 **Disclosure No:** 10003194

For more information, see our Disclosure Guide

b. External Inventors: List all individuals who have made an inventive contribution to this disclosure using non-U of T resources (i.e. sponsor employees, academic collaborators, etc). Please include names, organization, contact information and email address.

c. Contributors (Non-Inventors): List all individuals at or external to U of T who have not made an inventive contribution but have contributed to the development of the invention. Please include name, organization and email address.

3. Location(s) of Work:

Please list all locations (U of T and external) of the work leading to this invention, be specific (i.e. department, building, hospital, etc).

Department of Electrical and Computer Engineering, Galbraith building

4. Invention Description:

Please provide a description of this invention for evaluation, highlighting its novel or patentable aspects. Attach separate pages if necessary.

The invention is the birefringence compensation in silicon nitride (SiN) waveguides using a thin silicon (Si) region under the SiN. The Si is usually separated from the SiN by silicon dioxide (SiO_2), which encapsulates the waveguides. The birefringence is controlled by the choice of the widths of the SiN and Si layers at the given thicknesses of the fabrication process.

In the field of high index contrast integrated photonics (which includes Si and SiN photonics), polarization management is a critical issue. The high index contrast leads to strongly birefringent waveguides, where the transverse electric (TE) and transverse magnetic (TM) modes experience different effective and group indices. Meanwhile, the incoming light from an optical fiber can be of an arbitrary polarization. Therefore, it is necessary to make photonic circuits that function as a receiver or inline component (in the middle of a fiber optic communication link) polarization insensitive.

This invention is to control, mitigate, and cancel the polarization sensitivity using SiN-on-Si waveguides. In a SiN waveguide with a width greater than the height (as is typical), the TM mode has a lower effective index than the TE mode. Introducing Si under the SiN can preferentially increase the effective index of the TM mode over the TE mode, due to the higher refractive index of Si than SiN and the greater overlap of the TM mode with the Si than the TE mode. By choosing the widths of the SiN and Si regions, the birefringence can be adjusted.

Waveguides and photonic circuits can be made polarization insensitive in a couple of ways. First, waveguide cross-sections with zero or near zero birefringence are possible for combinations of SiN and Si widths, leading to waveguides and photonic circuits that would be polarization insensitive. Another approach is to combine two cross-sections – one with slightly positive birefringence with one with slightly negative birefringence. A photonic device/circuit would comprise of equal lengths of these two cross-sections.

In a full design and circuit implementation, light primarily propagates in the SiN layer. The fiber-to-chip coupler should be in the SiN level, and the Si feature should be adiabatically introduced under the SiN. This reduces losses

and adiabatically transforms the TM0 mode of the SiN waveguide into the hybrid TM mode of the SiN-on-Si waveguide.

Please see the enclosed slides for details.

5. Dissemination:

List all publications, abstracts, presentations or any other forms of public dissemination regarding this work, including dates.

○ None ○ Yes (please provide details)

None

6. Funding:

Provide details regarding any funding used in the development of this invention (i.e. salary or stipend support, materials, equipment, etc.).

SPONSOR	PROJECT TITLE	RIS FUND #
Finisar Corporation	Si Photonics for Coarse Wavelength Division Multiplexing (CWDM)	500138
NSERC	Postgraduate scholarship – doctoral level	

7. Related Agreements:

Was the work leading to this invention subject to any written or oral contract(s) or other agreement(s) such as: material transfer, data transfer, software licence, confidentiality, collaboration, and/or sponsored research?

○ No ○ Yes (please provide details)

Yes. This invention has been made under a sponsored research agreement between Finisar and U of T. The U of T reference number is 2015-1761.

8. Patent Applications:

Have any patent applications or other intellectual property protections been filed in respect of this invention?

○ No ○ Yes (please provide details)

No.

9. Warranty:

I/We, the Inventors listed in Section 2(a), have read, understood and agree to all of the preceding, and declare that all of the information provided in this disclosure is complete and correct. To the best of our knowledge, all persons who might legally make an ownership claim in this invention are identified in Section 2(a) and 2(b).

NAME (typed):	SIGNATURE:	DATE :
Joyce Poon	Joyce Poon	July 25, 2016
Jared Mikkelsen	Jared Mikkelsen	July 25, 2016

SUBMISSION INSTRUCTIONS:

Please send an electronic draft of the disclosure form to the IP Officer for review prior to obtaining signatures.

Once reviewed for completeness and accuracy, the completed and signed form should be returned to the IP Officer via email at ip.officer@utoronto.ca, in-person, or by mail.

If you need any assistance, please contact the IP Officer.

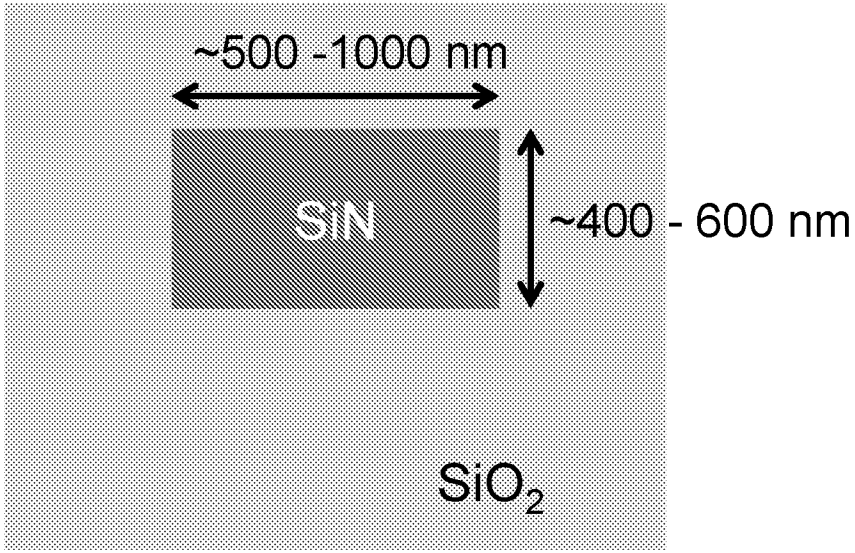
Birefringence control of silicon nitride-on-silicon optical waveguides and photonic circuits

Invention Disclosure

July 26, 2016

Concept

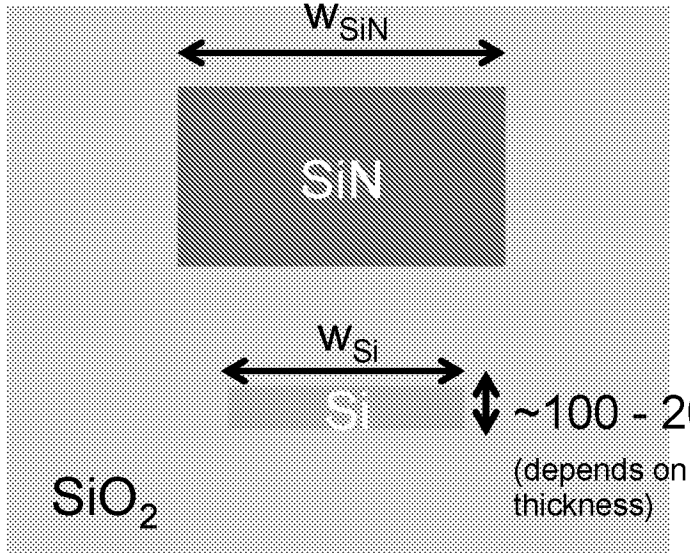
Conventional high index contrast/ high confinement silicon nitride (SiN) waveguide cross-section



Birefringent

$n_{eff,TE} - n_{eff,TM} \sim O(10^{-1})$

Birefringence control with SiN-on-Si waveguide



Controllable birefringence

$n_{eff,TE} - n_{eff,TM}$: positive, negative or 0

Heights are typically set by the fabrication process

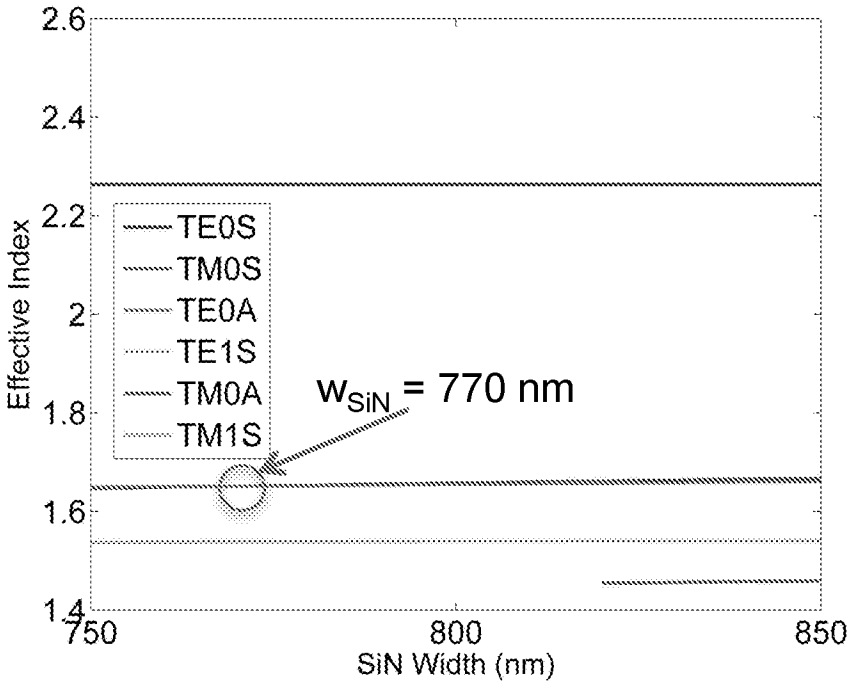
Si increases $n_{eff,TM}$ more than $n_{eff,TE}$ since TM mode is slightly more delocalized and the electric field points vertically.

Example design

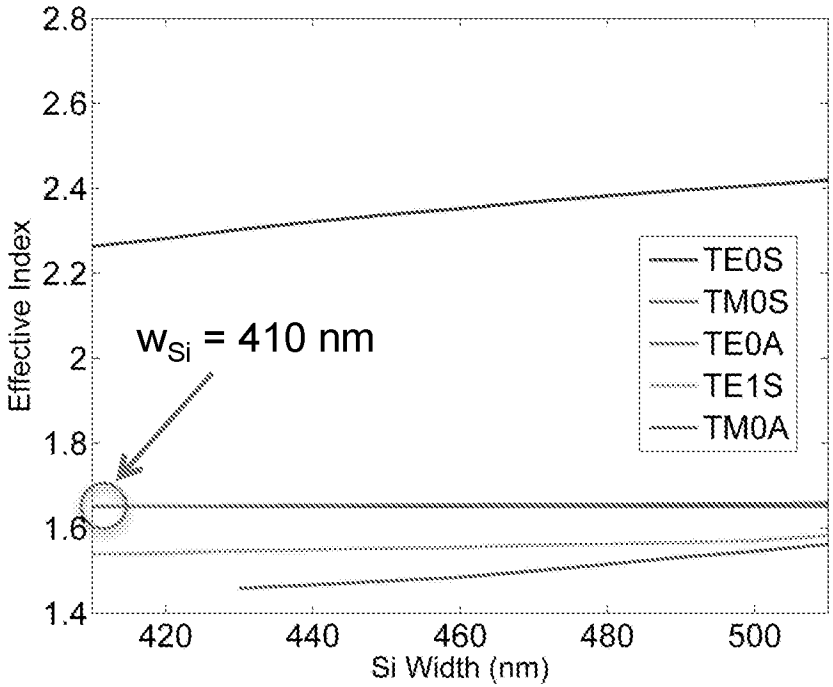
- Thicknesses
  - Si: 150 nm
  - SiO_2 spacer between SiN and Si: 350 nm
  - SiN: 600 nm (refractive index 1.9)

- The plots below show the effective indices of the first several modes vs. SiN or Si widths (with the Si or SiN width fixed)
- Zero birefringence point is circled
- Note: The highest blue line (TE0S) corresponds to a mode confined solely in the Si

Si Width: 410 nm

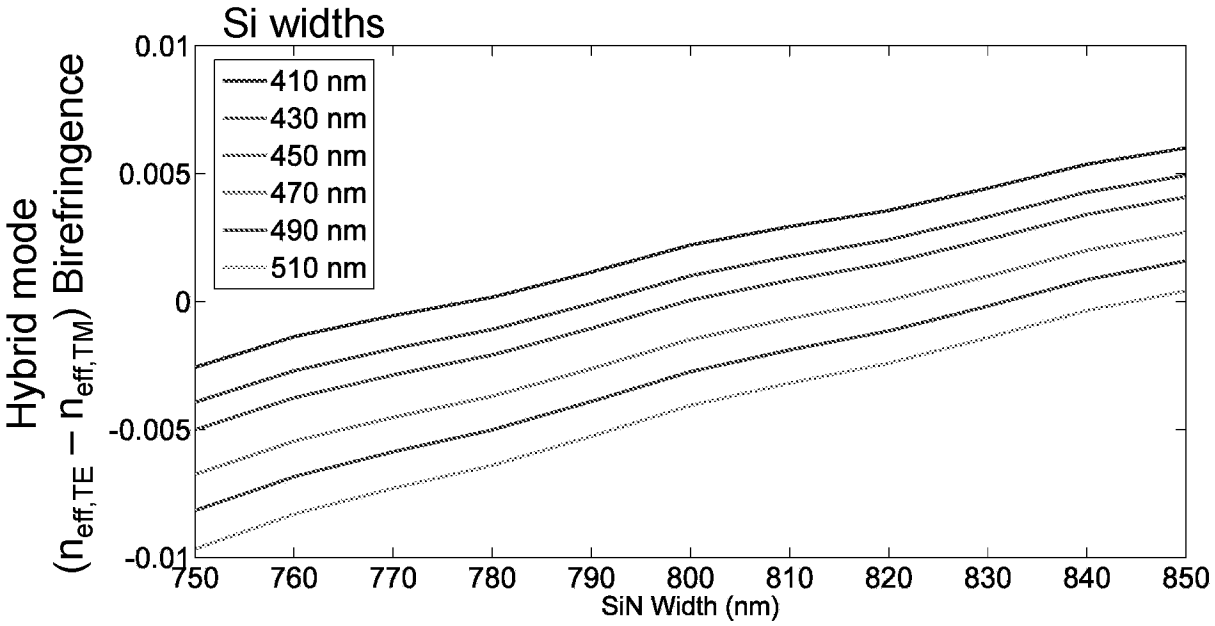


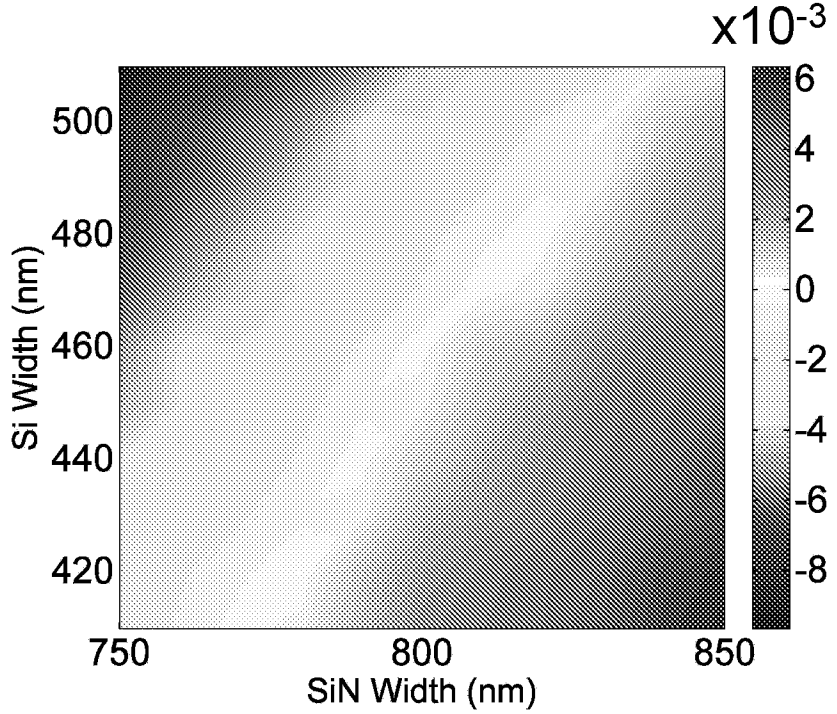
SiN Width: 770 nm



Birefringence dependence

- TE hybrid SiN-Si mode
- TM hybrid SiN-Si mode

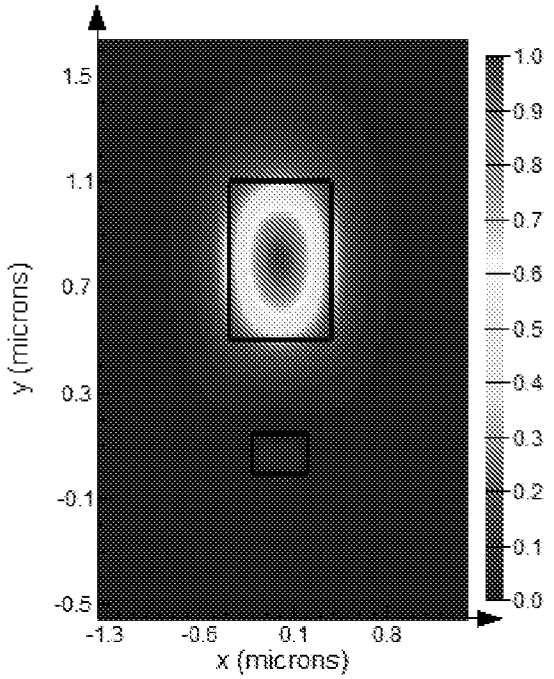




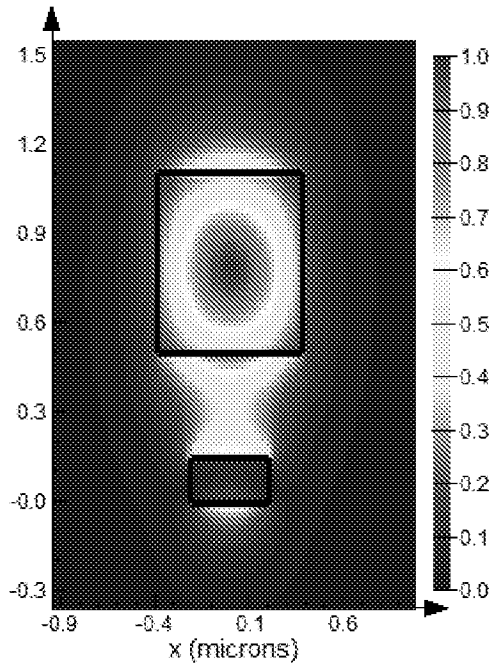
Modal Profiles

- Profiles shown for Si width of 410 nm, SiN width of 770 nm
- TM hybrid mode interacts with both SiN and Si

TE hybrid mode

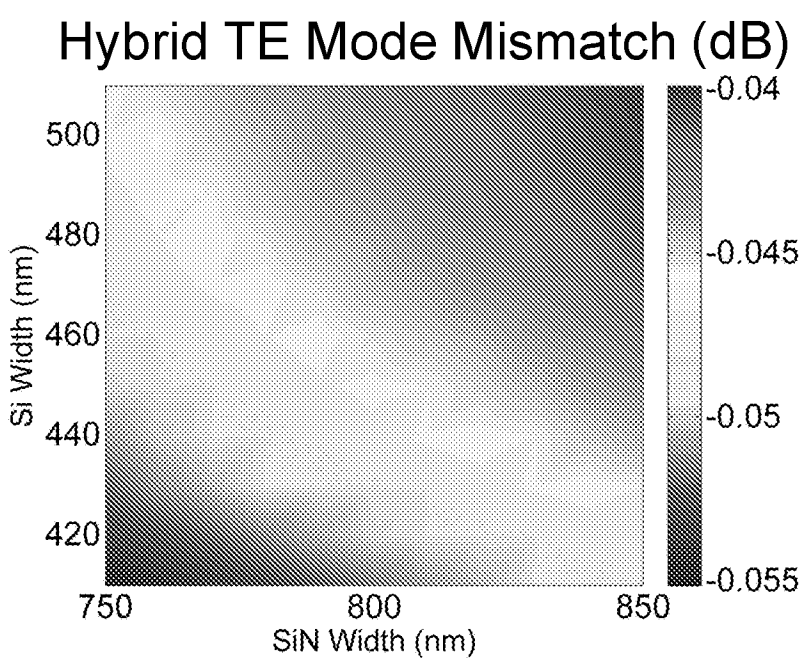


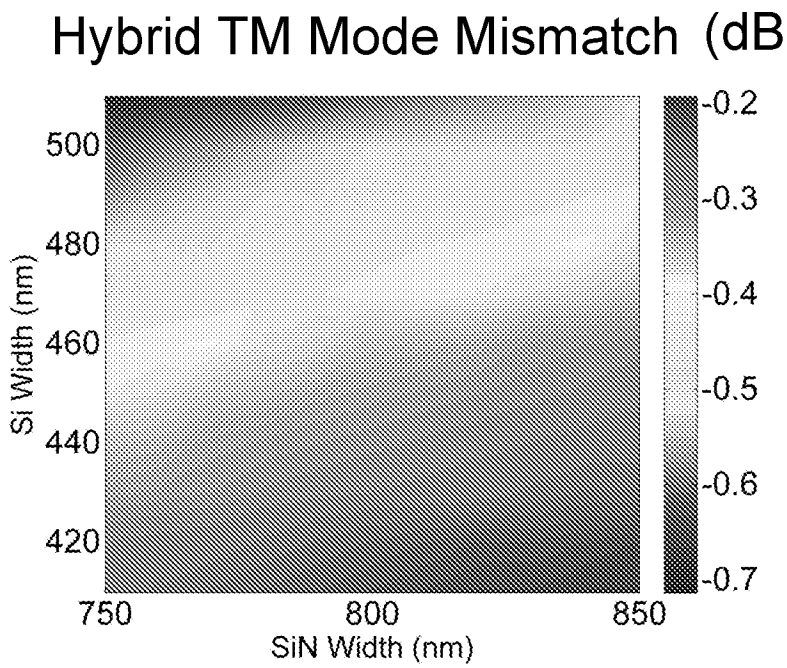
TM hybrid mode



Mode overlap loss, adiabatic tapers

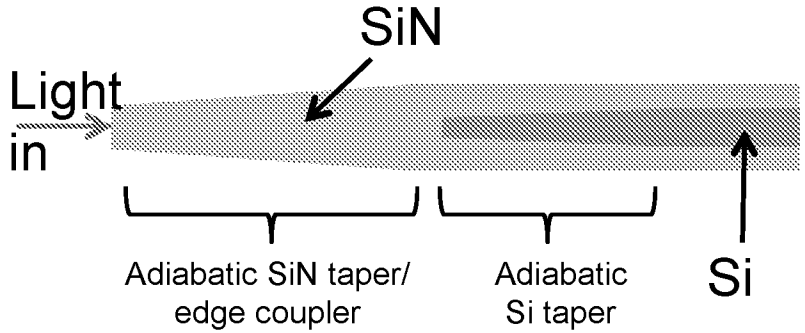
- If Si is abruptly introduced below an SiN waveguide, there is loss due to modal mismatch





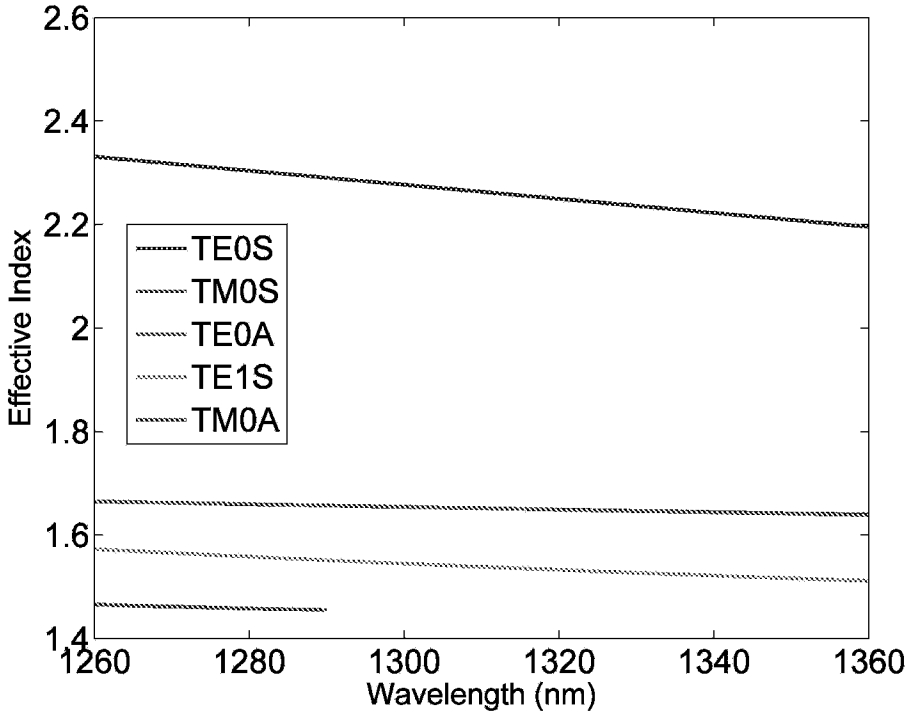
- To reduce loss, the Si can be adiabatically introduced under the SiN. Si tip width cannot be too narrow to transform the TE mode in the SiN waveguide into the TE mode of the Si

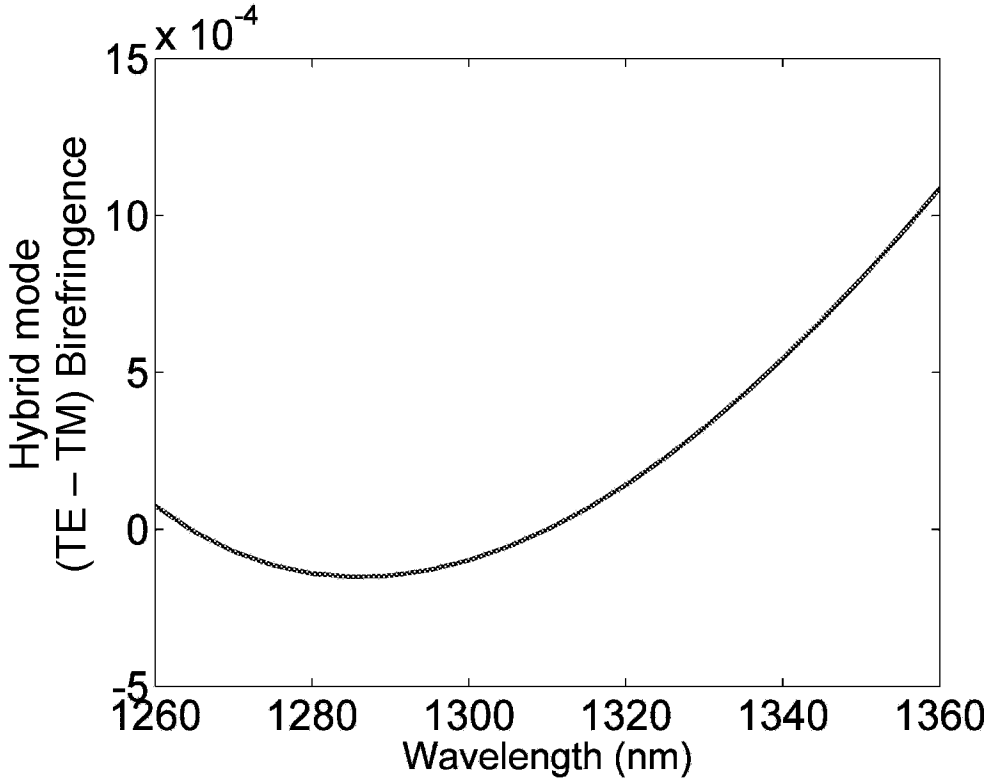
Top view



Dispersion Characteristics

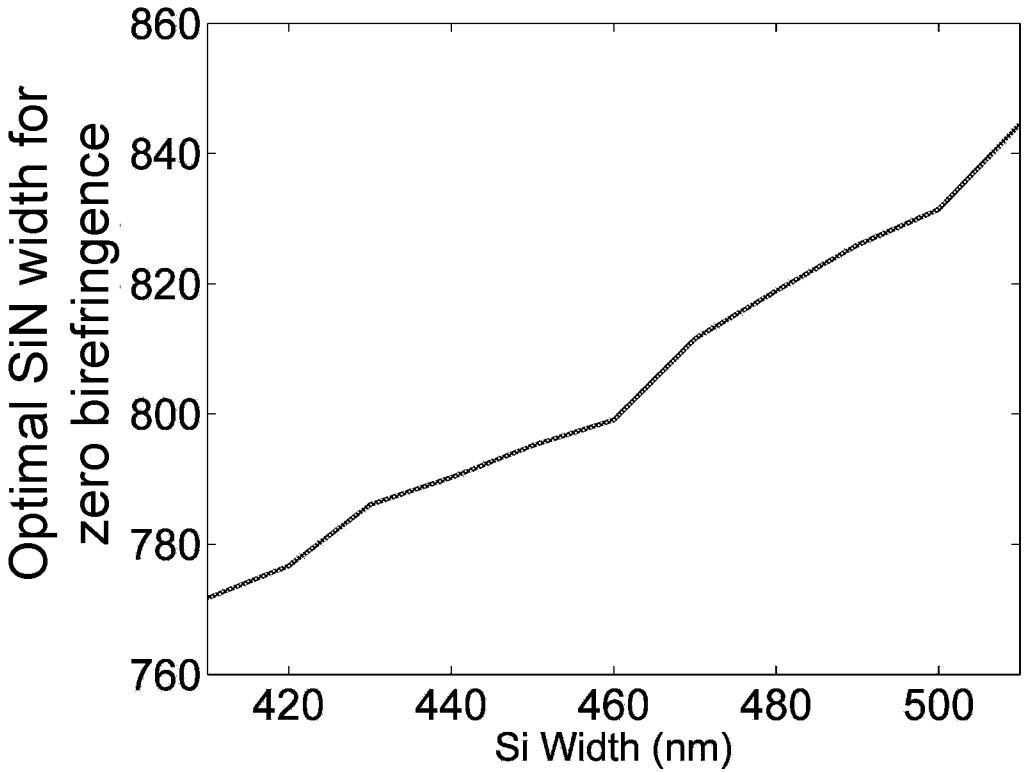
- Birefringence < 10^{-3} can be maintained over entire O-band
  - Designs shown are for SiN width of 770 nm and Si width of 410 nm





Tolerance to thickness variations

- For Si widths between 400-500 nm, there is always a corresponding SiN width which makes the birefringence zero for the thicknesses on p.3



Thicknesses

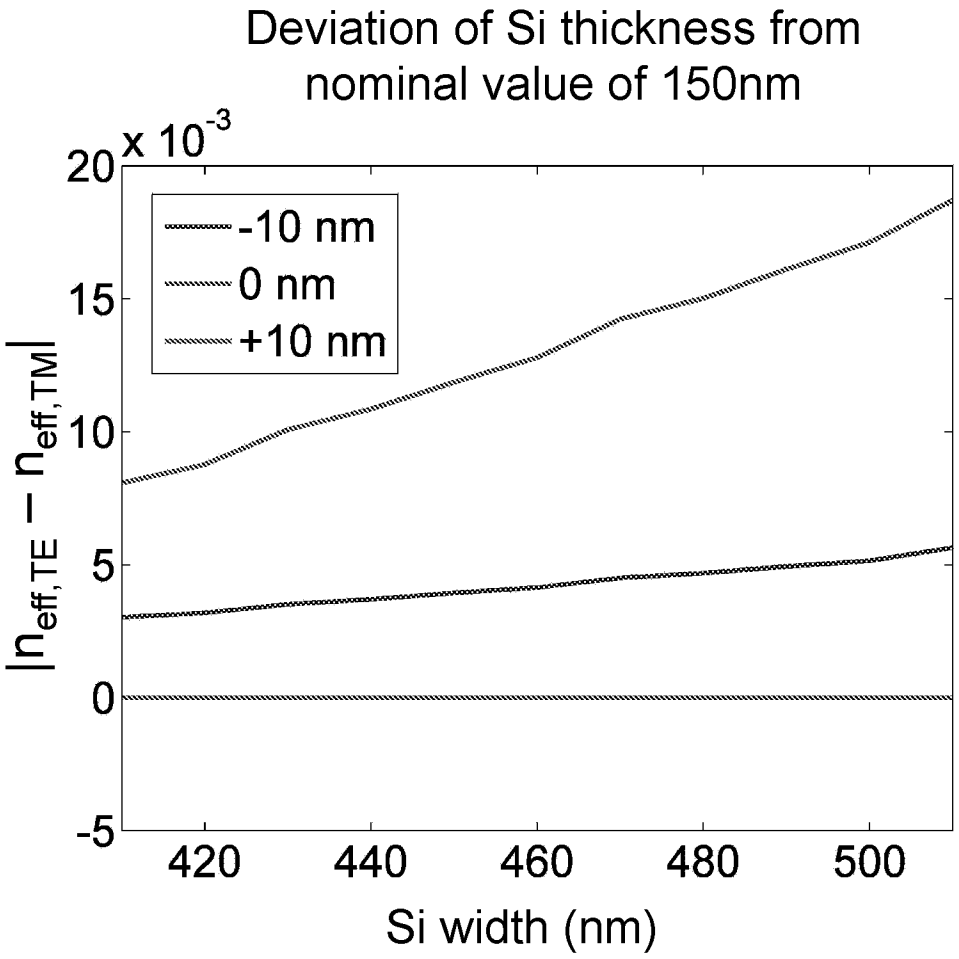
Si: 150 nm

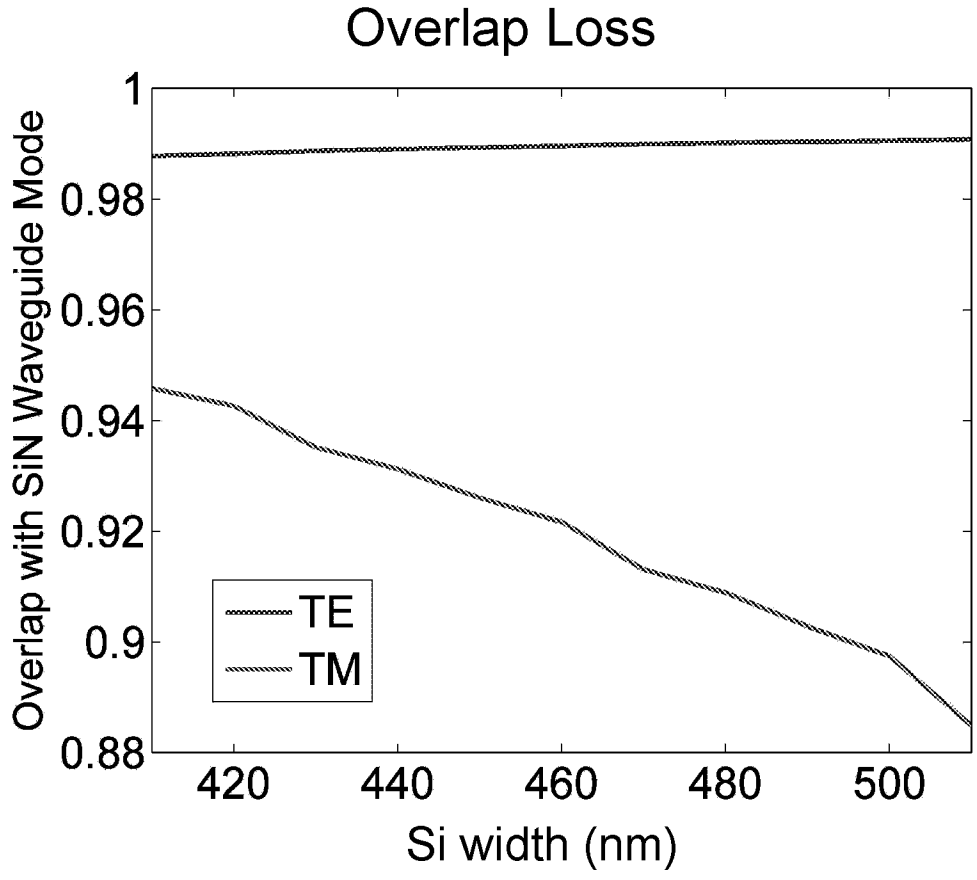
SiO_2 spacer: 350 nm

SiN: 600 nm (refractive index 1.9)

Tolerance to thickness variations

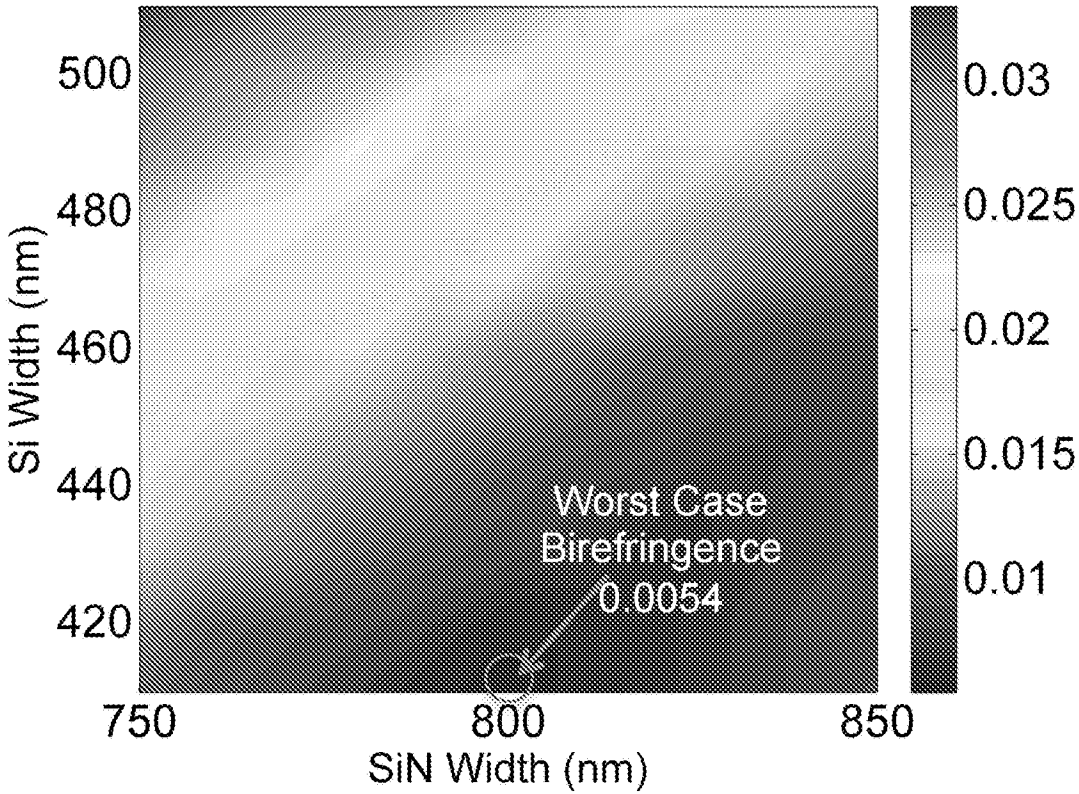
- Birefringence mainly sensitive to Si thickness variation
  - Reason: hybrid TM mode migrates more into Si if Si layer is thicker





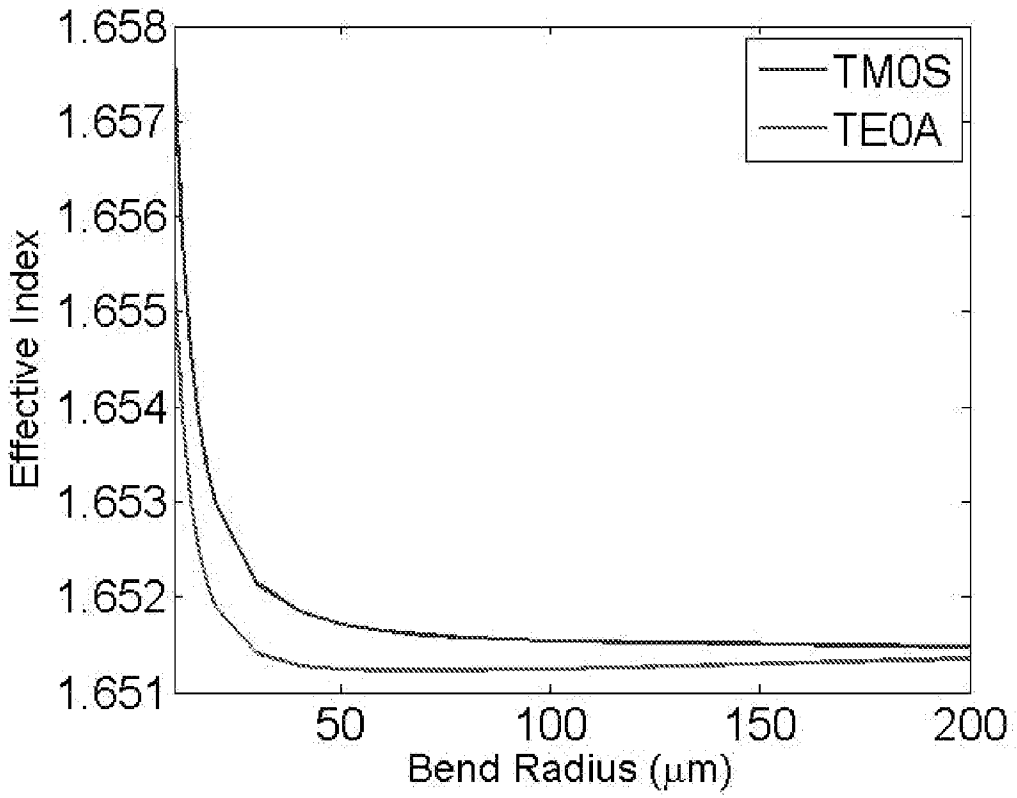
Birefringence Worst Case Deviation

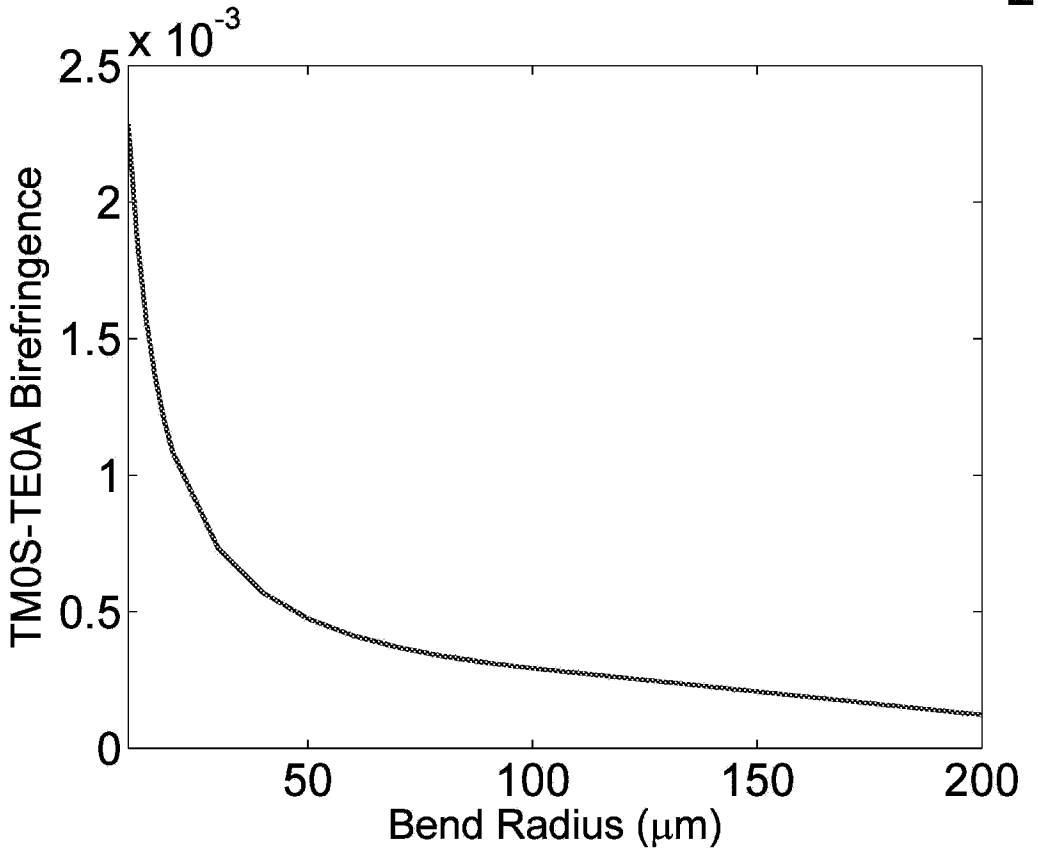
- Since increases in Si thickness are more detrimental than decreases, it may be beneficial to bias design away from optimal point to minimize the “worst case” birefringence
- Considering a +/- 10 nm Si thickness variation:
  - Minimal worst case birefringence so far is **0.0054** for SiN width of 800 nm and Si width of 410 nm. This sets an upper limit on the allowable delay line lengths for the MZI arms



Bent Waveguide Birefringence

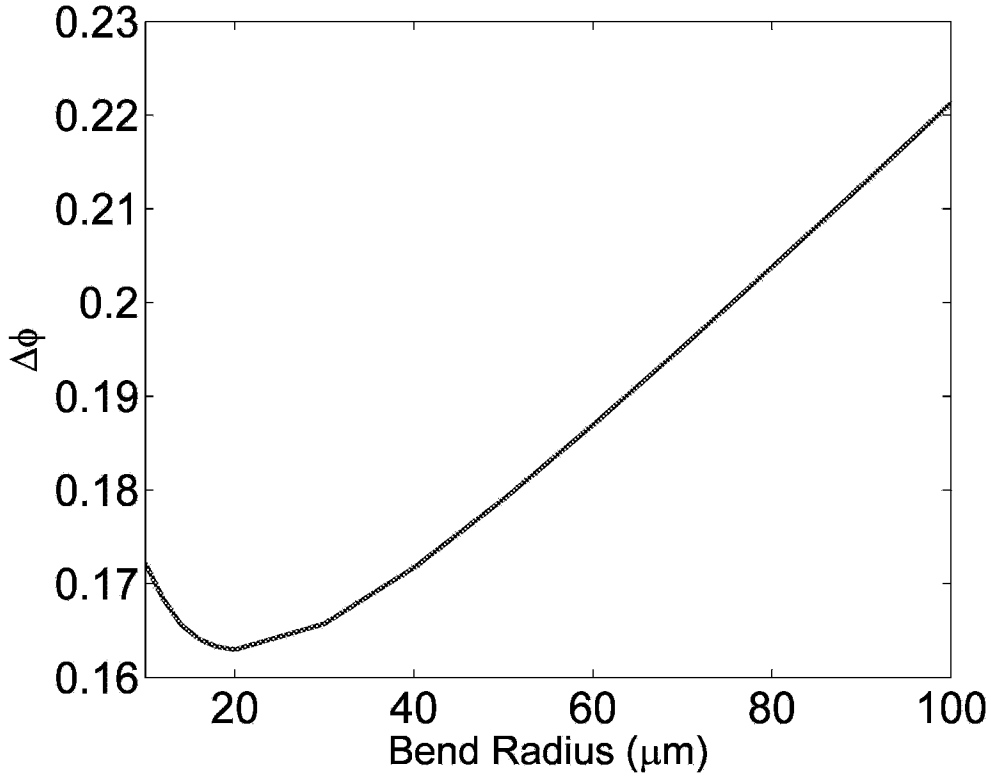
- Birefringence increases as bend radius decreases
- Plots below are for SiN width of 770 nm, Si width 410 nm





Bent Waveguide Birefringence

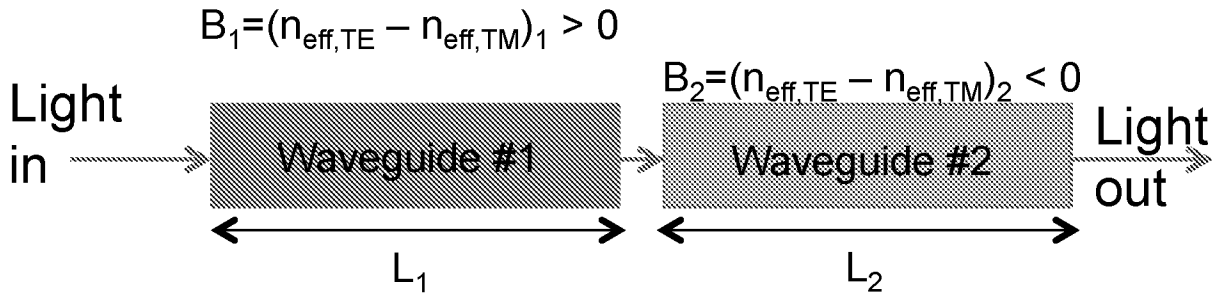
- Phase accumulation difference $\Delta\phi = 2\pi/\lambda\ \Delta n_{eff}(\pi R/2)$ vs. bend radius R
  - Indicates that R = 20 μm is optimal for this waveguide cross-section (w_{SiN} = 770 nm, w_{Si} = 410 nm)



Reducing polarization dependence

- 1. Choose waveguide cross-section with near zero birefringence
  - Bias design point at slightly thinner Si
  - The operation point is sensitive to waveguide dimensions (especially thickness variations)

- 2. Equalize the birefringence by using two types of waveguide cross-sections, one with positive birefringence and one with negative birefringence, so the overall birefringence cancels.
  - Can choose widths that are more variation tolerant
  - Broader band operation may also be possible



$$B_1L_1 = B_2L_2$$

UNIVERSITY OF TORONTO

OFFICE OF THE VICE-PRESIDENT, RESEARCH AND INNOVATION

ASSIGNMENT TO THE UNIVERSITY FROM INVENTOR AND REVENUE SHARING AGREEMENT

This assignment and revenue sharing agreement (the **"Agreement"**) is between Joyce K Poon, Antoine Bois, their respective heirs, executors, administrators and assigns (collectively, the **"Inventor"**) and The Governing Council of the University of Toronto, its successors and assigns (collectively, the **"University"**).

WHEREAS, the Inventor has created certain intellectual property entitled **"Birefringence Compensation by Serially Varying the Waveguide Width" (Disclosure No. 10003215)** as more particularly described in the disclosure form attached as Appendix 1 (the **"Invention"**);

AND WHEREAS, the University and the Inventor jointly own the Invention under the University's *Inventions Policy* (the **"Policy"**, including any successor policy thereto);

AND WHEREAS, certain rights are being granted to the research sponsor, Finisar Corporation, as a condition of the Sponsor Research and Collaboration Agreement dated, November 23, 2015;

AND WHEREAS, in order to offer such rights to the sponsor, the Inventor wishes to assign its interest in the Invention to the University;

NOW THEREFORE this Agreement witnesses that in consideration of the mutual covenants contained herein and other good and valuable consideration, the receipt and sufficiency of which are hereby acknowledged by each of the parties, the parties covenant and agree as follows:

1. **Definitions.** In addition to any terms defined above, in this Agreement:

   (a) **"Commercialization Costs"** means the legal and other fees incurred directly in the process of establishing and maintaining the legal protection of rights in the Invention;

   (b) **"Management Fee"** means a fee for services provided by the University in connection with its commercialization of the Invention; and,

   (c) **"Net Revenue"** means the royalty, licensing and other income or equivalent financial return received by the University from the assignment or licensing of the rights in the Invention, less any: (i) Commercialization Costs; and (ii) amounts payable to third parties under prior written agreements that directly relate to the Invention, including but not limited to funding and collaboration agreements.

2. **Assignment.** The Inventor hereby assigns to the University all right, title and interest, whatever the same may be (but without any representation or warranty as to the nature, extent or validity thereof) which the Inventor now has or may in the future have in the Invention, including, without limitation, the right to apply for patents in Canada, the United States of America and any other country, the right to receive any letters

patent that may be issued from any such applications and the right to sell, license or assign the Invention or the rights thereto.

3. **Disclosure.** The Inventor shall make full and complete disclosure of the Invention to the University, and shall make available to the University any physical embodiments of the Invention and other data that will be or that may be useful to the University in exercising its rights in the Invention.

4. **Assistance.** The Inventor shall execute, acknowledge and deliver all such further assurances and do all such acts as may be necessary to carry out the intent and purpose of this Agreement, including without limitation, to execute powers of attorney and other documents required to maintain intellectual property protection of the Invention, and shall review and provide comments with respect to such intellectual property protection as and when requested by the University.

5. **Revenue Sharing.**

   (a) Subject to 5(b), the University shall distribute sixty percent (60%) of the Net Revenue to the Inventor. The remaining forty percent (40%) of the Net Revenue shall be retained by the University and distributed in accordance with the Policy.

   (b) If the Inventor is also the founder of a company and the University assigns or licenses the Invention to that company, the Inventor agrees to waive all right to receive its share of the Net Revenue.

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   In either case, the parties shall execute an assignment of the University's rights in the Invention to the Inventor on terms to be negotiated by the parties in good faith.

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10. **Acknowledgement and Release.** The Inventor acknowledges that, because of the speculative nature of the undertaking to commercialize the Invention, the University cannot guarantee that the results will meet the objectives sought. The University may enter into an Agency Agreement in its sole discretion and, if so, shall provide a copy of the Agency Agreement to the Inventor. Save and except for the right to enforce the terms contained in this Agreement, the Inventor releases the University from any and all claims that the Inventor may now have or may in future have in respect of the Invention. Any disputes arising under this Agreement shall be resolved by the parties in accordance with the dispute resolution procedures set out in the Policy.

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Witness

Inventor

Joyce K Poon

Antoine Bois

The Governing Council of the University of Toronto

Derek Newton
Assistant Vice-President, Innovation, Partnerships and Entrepreneurship

Executed at Toronto, Ontario this 21st day of November, 2016 (the "**Effective Date**")

APPENDIX 1

Invention Disclosure Form

UNIVERSITY OF TORONTO

OFFICE OF THE VICE-PRESIDENT, RESEARCH AND INNOVATION

CONFIDENTIAL INVENTION DISCLOSURE

Innovations & Partnerships Office | Banting Institute, Room 413 | 100 College St. Toronto ON M5G 1L5
Tel: (416) 978-7833 | Fax: (416) 978-8052 | email: ip.officer@utoronto.ca

This form is used to record inventions made using U of T resources, facilities and/or funds managed by U of T and is to be completed by the inventor(s) to satisfy their obligations under **U of T's Inventions Policy.** For step by step information on how to complete the form, please refer to the **invention disclosure guide.**

1. Title of Invention:

Birefringence compensation by serially varying the waveguide width

2. Inventors and Contributors:

a. Inventors at the University of Toronto: List all individuals who have made an inventive contribution to this disclosure through the use of U of T resources (i.e. faculty, students, postdocs, staff, visiting scientist, etc). Attach separate pages if necessary.

SURNAME, GIVEN NAMES	U of T PERSONNEL NO (if applicable)	DEPARTMENT *(List any cross appointments or affiliated institutions)*	AFFILIATION WITH U of T *(i.e. faculty, research assoc., post-doc, student, staff, visitor, etc.)*	EMAIL ADDRESS	CONTACT INFORMATION *(non-U of T mailing address, phone, fax)*	% CONTRIBUTION *(*optional)*
Poon, Joyce Kai See	993899	Electrical and Computer Engineering	Faculty	joyce.poon@utoronto.ca	24 Wellesley St. W., #2212, Toronto, ON, M4Y 2X6 416-262-0571	80
Bois, Antoine	15823349	Electrical and Computer Engineering	MASc student	antoine.bois@mail.utoronto.ca	181 rue de l'Affluent, Lévis, QC, G7A 5C1, 647-639-1086	20

* If invention is assigned to UofT, percentage will be used as a basis for sharing future revenues. Revenue distribution agreed to by the parties in an assignment agreement will govern.

For more information, see our Disclosure Guide.

FOR IPO USE ONLY:
Disclosure Date: August 29, 2016 **Disclosure No:** 10003215

b. External Inventors: List all individuals who have made an inventive contribution to this disclosure using non-U of T resources (i.e. sponsor employees, academic collaborators, etc). Please include names, organization, contact information and email address.

c. Contributors (Non-Inventors): List all individuals at or external to U of T who have not made an inventive contribution but have contributed to the development of the invention. Please include name, organization and email address.

3. Location(s) of Work:

Please list all locations (U of T and external) of the work leading to this invention, be specific (i.e. department, building, hospital, etc).

Department of Electrical and Computer Engineering, Galbraith building

4. Invention Description:

Please provide a description of this invention for evaluation, highlighting its novel or patentable aspects. Attach separate pages if necessary.

The invention is the birefringence compensation in photonic circuits by varying the waveguide width in a serial way.

For a given thickness, h, of a waveguide layer, two waveguide cross-sections with widths, w_1 and w_2 are chosen. The cross-section with width w_1 will have a birefringence, $B_1 = (n_{TE,1} - n_{TM,1})$, where $n_{TE,1}$ and $n_{TM,1}$ are the effective indices of the transverse electric (TE) and transverse magnetic polarized fundamental mode, respectively, of the waveguide. The cross-section with width w_2 will have a birefringence, $B_2 = (n_{TE,2} - n_{TM,2})$. Concatenating these two types of waveguides serially in a photonic device, can allow for the overall birefringence to be compensated. Waveguide lengths of L_1 and L_2 are chosen for widths of w_1 and w_2, respectively, such that $B_1L_1 + B_2L_2 = m\lambda$. This type of strategy can also be incorporated into designs that use differential (or "parallel") architectures for birefringence compensation in devices such as Mach-Zehnder interferometer filters.

Please see the enclosed slides for details.

5. Dissemination:

List all publications, abstracts, presentations or any other forms of public dissemination regarding this work, including dates.

○ **None** ○ **Yes (please provide details)**

None

6. Funding:

Provide details regarding any funding used in the development of this invention (i.e..salary or stipend support, materials, equipment, etc.).

SPONSOR	PROJECT TITLE	RIS FUND #
Finisar Corporation	Si Photonics for Coarse Wavelength Division Multiplexing (CWDM)	500138

7. Related Agreements:

Was the work leading to this invention subject to any written or oral contract(s) or other agreement(s) such as: material transfer, data transfer, software licence, confidentiality, collaboration, and/or sponsored research?

○ **No** ○ **Yes (please provide details)**

Yes. This invention has been made under a sponsored research agreement between Finisar and U of T. The U of T reference number is 2015-1761.

8. Patent Applications:

Have any patent applications or other intellectual property protections been filed in respect of this invention?

○ **No** ○ **Yes (please provide details)**

No.

9. Warranty:

I/We, the Inventors listed in Section 2(a), have read, understood and agree to all of the preceding, and declare that all of the information provided in this disclosure is complete and correct. To the best of our knowledge, all persons who might legally make an ownership claim in this Invention are identified in Section 2(a) and 2(b).

NAME (typed):	**SIGNATURE:**	**DATE :**
Joyce Poon	Joyce Poon	August 12, 2016
Antoine Bois	Antoine Bois	August 12, 2016

SUBMISSION INSTRUCTIONS:

Please send an electronic draft of the disclosure form to the IP Officer for review prior to obtaining signatures.

Once reviewed for completeness and accuracy, the completed and signed form should be returned to the IP Officer via email at ip.officer@utoronto.ca, in-person, or by mail.

If you need any assistance, please contact the IP Officer.

Birefringence compensation by serially varying the waveguide width

Invention Disclosure

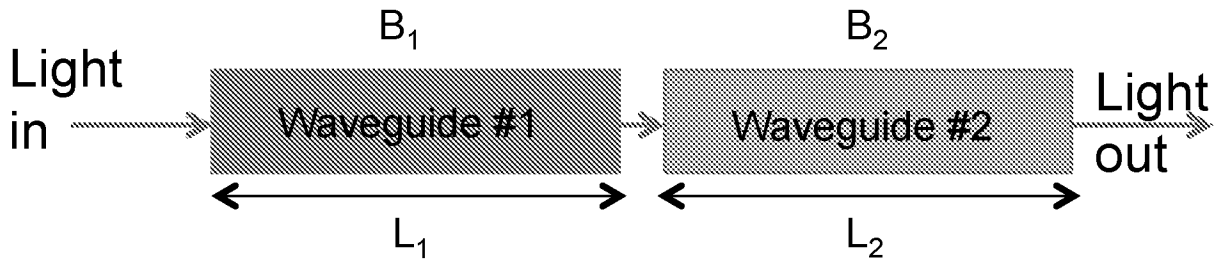
August 12, 2016

Concept

- Consider two waveguides sections with the same height that are concatenated with each other
  - 1. height = h, width = w_1, length = L_1
  - 2. height = h, width = w_2, length = L_2

Birefringence: $B_1 = n_{TE,1} - n_{TM,1}$

$B_2 = n_{TE,2} - n_{TM,2}$



Phase-shift of TE component after propagating through both sections

$$\phi_{TE} = \frac{2\pi}{\lambda}(n_{TE,1}L_1 + n_{TE,2}L_2)$$

Phase-shift of TM component after propagating through both sections

$$\phi_{TM} = \frac{2\pi}{\lambda}(n_{TM,1}L_1 + n_{TM,2}L_2)$$

The birefringence of the total system is compensated if $\phi_{TE} = \phi_{TM} + 2m\pi$ m = integer

This implies $B_1L_1 + B_2L_2 = m\lambda$

- There are many ways to achieve $B_1L_1 + B_2L_2 = m\lambda$
- An example is m = 0, B_1 and B_2 have opposite sign
  - Choose $w_1 > h$, $w_2 < h$
- Also possible for B_1, $B_2 > 0$ through choice of *m*, L_1, L_2
- For a variation tolerant design, we seek

$$\min(\Delta B_1 L_1 + \Delta B_2 L_2)$$

Assuming the variation in the length is negligible

where

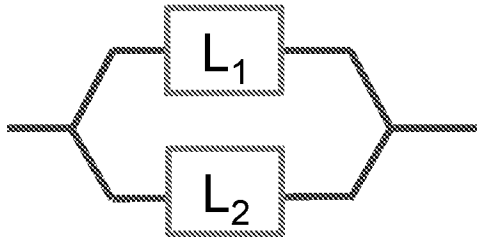
$$\Delta B_{1,2} = \frac{\partial B_{1,2}}{\partial w_{1,2}} \Delta w_{1,2} + \frac{\partial B_{1,2}}{\partial h} \Delta h + \frac{\partial B_{1,2}}{\partial n} \Delta n + \ldots$$

is the possible variation in $B_{1,2}$

Extensions

- Such a concept can also be combined with the differential birefringence compensation scheme proposed by Finisar for polarization-insensitive Mach-Zehnder interferometer filters

- Finisar concept



Consider a MZI with extra lengths L_1 and L_2 in each arm respectively. (Note: a similar width and length in both arms automatically compensate both polarizations. This is why nothing particular must be done about the bends.) It follows then that:

$$\phi_{TE} = \frac{2\pi}{\lambda}\left(n_{TE_1}L_1 - n_{TE_2}L_2\right), \tag{1}$$

$$\phi_{TM} = \frac{2\pi}{\lambda}\left(n_{TM_1}L_1 - n_{TM_2}L_2\right). \tag{2}$$

We require:

$$\phi_{TE} = \phi_{TM} + m2\pi, \quad m \in \mathbb{N}. \tag{3}$$

We choose $m = 0$ such that we automatically satisfy all λ, and as such do not depend on a specific central wavelength. Choosing $m = 0$ also leads to shorter delay lengths, without any downside. With $B = n_{TE} - n_{TM}$, this translates to:

$$B_1L_1 = B_2L_2. \tag{4}$$

Another condition must also be satisfied on the free spectral range. With $\Delta L n_g \approx n_{gTE_1}L_1 - n_{gTE_2}L_2$ and $\delta\lambda$ the channel spacing, this gives:

$$n_{gTE_1}L_1 - n_{gTE_2}L_2 = \lambda^2/(2\delta\lambda). \tag{5}$$

Note: For the TM FSR to match also

$$n_{gTM1}L_1 - n_{gTM2}L_2 = \lambda^2/(2\delta\lambda)$$

Eqs. (4) and (5) are the two conditions that must be satisfied. At first glance, this is a system of two equations and eight variables. However, since we have control only over the widths w, we essentially have n_{TE_1}, n_{TM_1}, n_{gTE_1}, $n_{gTM_1} \propto w_1$ and n_{TE_2}, n_{TM_2}, n_{gTE_2}, $n_{gTM_2} \propto w_2$, reducing the system to four variables, namely w_1, w_2, L_1, L_2. Having an underdetermined system is actually beneficial in that it allows us to apply other optimization criteria.

For each pair $\{w_1, w_2\}$, the following linear system can be solved:

$$\begin{bmatrix} n_{TE_1} - n_{TM_1} & n_{TM_2} - n_{TE_2} \\ n_{gTE_1} & -n_{gTE_2} \end{bmatrix} \begin{bmatrix} L_1 \\ L_2 \end{bmatrix} = \begin{bmatrix} 0 \\ \lambda^2 / (2\delta\lambda) \end{bmatrix}$$

From the set of solutions $\{w_1, w_2\} \mapsto \{L_1, L_2\}$, we can then look at minimizing the sensitivity, through $\min(L_1 + L_2)$, since err $\phi \propto (L)^{1/2}$, at least from sidewall roughness, or at minimizing the difference in group indices, through $\min([n_{gTE_1} - n_{gTM_1}] L_1 - [n_{gTE_2} - n_{gTM_2}] L_2)$, in order to have consistent channel spacings.

- For a MZI, having $B_1L_1 = B_2L_2$ is robust to dimensional variations, but because $L_1 \neq L_2$, there is some leftover sensitivity.
  - For a MZI, using the differential compensation is generally better than the series approach, which requires $B_1L_1 = -B_2L_2$ (L_1 and L_2 in series).

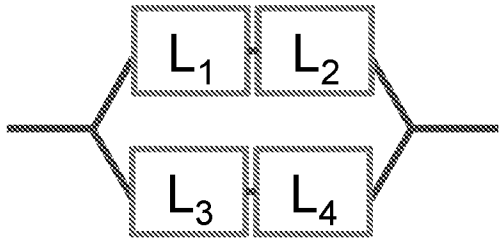
- Because B_1 and B_2 are the same sign, it is also robust to variations of the waveguide material index, though this can be achieved better with the series approach that has $B_1 < 0$ and $B_2 > 0$ and comparable L_1 and L_2.
  - Choice of series or parallel approach depends on which variation (dimension vs. index) is likely to be stronger.

- For the MZI directional couplers: use square cross-section waveguides for simplicity.

Combine Series and Parallel Birefringence Compensation

- L_1 and L_2 in series in one arm, and L_3 and L_4 in series in the other in a MZI

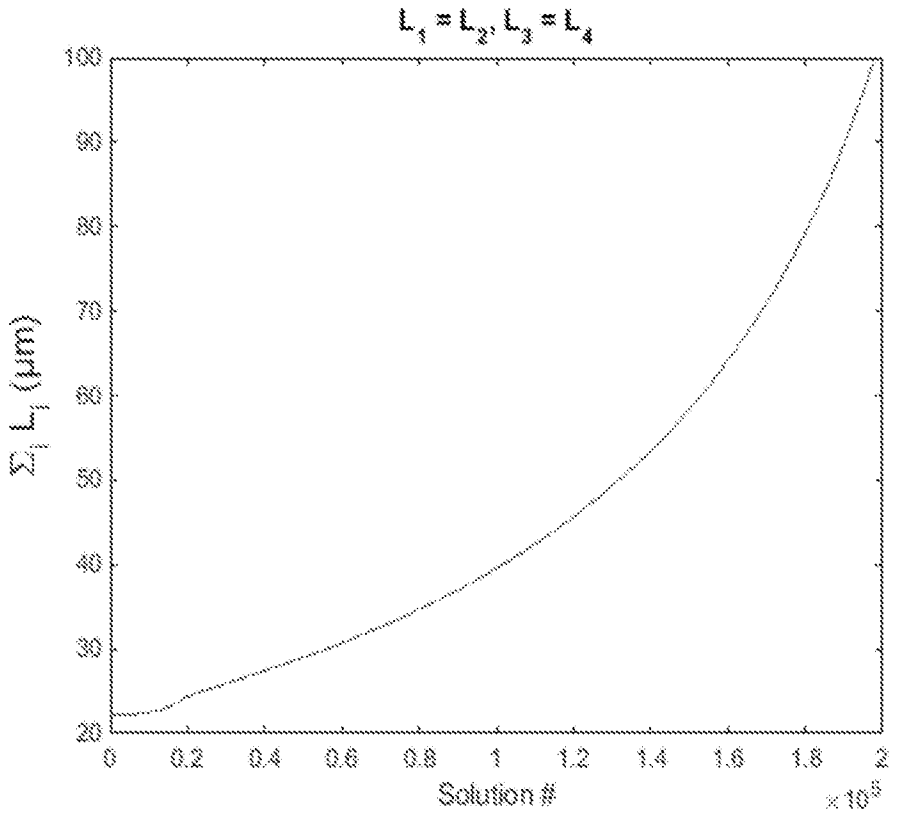
- Combines parallel and series approaches
  - To solve the residual birefringence variation due to ΔL in a MZI



- Needs two more conditions to solve the linear system. Examples can be:
  - $L_1 = L_2$,
  - $L_1 + L_2 = L_3 + L_4$,
  - L_1, L_2, L_3, or L_4 to specific values,
  - Or any other variation.

Example

SiN waveguide, 600nm tall
Channel spacing of 20nm, near a wavelength of 1310nm



The shortest solution converges to series case.

$L_1 = L_2 = 11$ μm
$L_3 = L_4 = 0$ μm

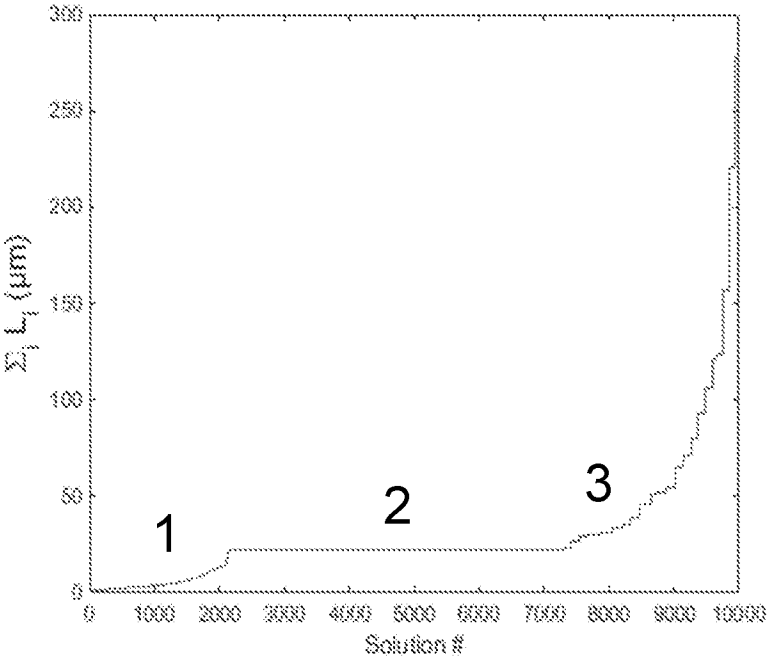
Other solutions are of the form:

$L_1 = L_2 = 11 + x_1$ μm
$L_3 = L_4 = x_2$ μm
with $(x_1 - x_2) / x_1 << 1$

Nonlinear optimization (with L_1, L_2, L_3, L_4)

- With nonlinear optimization criterion as min(ΣL_i) and linear optimization criterion maintained as:

$$\begin{bmatrix} n_{TE_1} - n_{TM_1} & n_{TE_2} - n_{TM_2} & n_{TM_3} - n_{TE_3} & n_{TM_4} - n_{TE_4} \\ n_{qTE_1} & n_{qTE_2} & -n_{qTE_3} & -n_{qTE_4} \end{bmatrix} \begin{bmatrix} L_1 \\ L_2 \\ L_3 \\ L_4 \end{bmatrix} = \begin{bmatrix} 0 \\ \lambda^2/(2\delta\lambda) \end{bmatrix}$$



1. Failed to converge
2. Converge to series case with $L_1 + L_2 = 22$ μm, $L_3 = L_4 = 0$ μm
3. Most solutions of the form $L_1 = x_1 + 22$ μm, $L_2 = 0$, $L_3 = x_2$, $L_4 = 0$ with $(x_1 - x_2) / x_1 << 1$

APPENDIX 2

Distribution of Net Revenue

The Inventor directs the University to distribute 60% of the Net Revenue to each Inventor in the following proportions:

Joyce K Poon:	80%
Antoine Bois:	20%
Total:	100%

UNIVERSITY OF TORONTO

OFFICE OF THE VICE-PRESIDENT, RESEARCH AND INNOVATION

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WHEREAS, the Inventor has created certain intellectual property entitled **"Wavelength Filtering and Polarization (de)Multiplexing via Non-Adiabatic Transitions" (Disclosure No. 10003351)** as more particularly described in the disclosure form attached as Appendix 1 (the **"Invention"**);

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patents in Canada, the United States of America and any other country, the right to receive any letters patent that may be issued from any such applications and the right to sell, license or assign the Invention or the rights thereto.

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   (a) if the University has not made reasonable efforts to enter into an agreement with a third party to commercialize the Invention within two (2) years of the Effective Date, the Inventor may request the termination of this Agreement and reassignment of the Invention to the Inventor by providing ninety (90) days written notice to the University;

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Witness

Inventor

Joyce K Roon

Antoine Bois

The Governing Council of the University of Toronto

Derek Newton
Assistant Vice-President, Innovation, Partnerships and Entrepreneurship

Executed at Toronto, Ontario this 29 day of May, 2017(the "**Effective Date**")

APPENDIX 1

Invention Disclosure Form

UNIVERSITY OF TORONTO

OFFICE OF THE VICE-PRESIDENT, RESEARCH AND INNOVATION

CONFIDENTIAL INVENTION DISCLOSURE

Innovations & Partnerships Office | Banting Institute, Room 413 | 100 College St. Toronto ON M5G 1L5
Tel: (416) 978-7833 | Fax: (416) 978-8052 | email: ip.officer@utoronto.ca

This form is used to record inventions made using U of T resources, facilities and/or funds managed by U of T and is to be completed by the inventor(s) to satisfy their obligations under **U of T's Inventions Policy**. For step by step information on how to complete the form, please refer to the **invention disclosure guide**.

1. Title of Invention:

Wavelength filtering and polarization (de)multiplexing via non-adiabatic transitions

2. Inventors and Contributors:

a. Inventors at the University of Toronto: List all individuals who have made an inventive contribution to this disclosure through the use of U of T resources (i.e. faculty, students, postdocs, staff, visiting scientist, etc). Attach separate pages if necessary.

SURNAME, GIVEN NAMES	U of T PERSONNEL NO (if applicable)	DEPARTMENT *(List any cross appointments or affiliated institutions)*	AFFILIATION WITH U of T *(i.e. faculty, research assoc., post-doc, student, staff, visitor, etc.)*	EMAIL ADDRESS	CONTACT INFORMATION *(non-U of T mailing address, phone, fax)*	% CONTRIBUTION *(*optional)*
Bois, Antoine	1160940	Electrical and Computer Engineering	Graduate student	antoine.bois@mail.utoronto.ca	181 rue de l'Affluent, Lévis, QC, G7A 5C1 418-836-0436	90%
Poon, Joyce Kai See	993899	Electrical and Computer Engineering	Faculty	joyce.poon@utoronto.ca	24 Wellesley St. W., #2212, Toronto, ON, M4Y 2X6 416-262-0571	10%

* If invention is assigned to UofT, percentage will be used as a basis for sharing future revenues. Revenue distribution agreed to by the parties in an assignment agreement will govern.

For more information, see our Disclosure Guide.

FOR IPO USE ONLY:
Disclosure Date: May 5, 2017 **Disclosure No:** 10003351

b. External Inventors: List all individuals who have made an inventive contribution to this disclosure using non-U of T resources (i.e. sponsor employees, academic collaborators, etc). Please include names, organization, contact information and email address.

c. Contributors (Non-Inventors): List all individuals at or external to U of T who have not made an inventive contribution but have contributed to the development of the invention. Please include name, organization and email address.

3. Location(s) of Work:

Please list all locations (U of T and external) of the work leading to this invention, be specific (i.e. department, building, hospital, etc).

Department of Electrical and Computer Engineering, Galbraith building

4. Invention Description:

Please provide a description of this invention for evaluation, highlighting its novel or patentable aspects. Attach separate pages if necessary.

The invention is a polarization diverse wavelength demultiplexer/multiplexer which uses a unique wavelength-sensitive polarization rotator (PR). The PR relies on a polarization-based Mach-Zehnder interferometer that uses a non-adiabatic coupler. The non-adiabatic coupler has an L-shaped cross-section, for which the two lowest order modes have 50:50 TE:TM polarization mixtures. Incident TE or TM polarized light excite these hybrid modes, which are then converted into TE and TM modes of a birefringent waveguide. The TE and TM modes accumulate different phase-shifts in this waveguide, and are then recombined using a second non-adiabatic coupler with mode converters. Depending on the phase-shift accumulated in the birefringent waveguide, the interference is used to demultiplex signal according to wavelength and polarization. Different configurations are possible with the addition of standard broadband polarizations splitters or polarization-splitter-rotators.

Please see the enclosed slides.

5. Dissemination:

List all publications, abstracts, presentations or any other forms of public dissemination regarding this work, including dates.

○ **None** ○ **Yes (please provide details)**

None

6. Funding:

Provide details regarding any funding used in the development of this invention (i.e..salary or stipend support, materials, equipment, etc.).

SPONSOR	PROJECT TITLE	RIS FUND #
Finisar Corporation	Si Photonics for Coarse Wavelength Division Multiplexing (CWDM)	500138

7. Related Agreements:

Was the work leading to this invention subject to any written or oral contract(s) or other agreement(s) such as: material transfer, data transfer, software licence, confidentiality, collaboration, and/or sponsored research?

○ **No** ○ **Yes (please provide details)**

Yes. This invention is being disclosed under a sponsored research agreement between Finisar and U of T. The U of T reference number is 2015-1761.

8. Patent Applications:

Have any patent applications or other intellectual property protections been filed in respect of this invention?

○ **No** ○ **Yes (please provide details)**

No.

9. Warranty:

I/We, the Inventors listed in Section 2(a), have read, understood and agree to all of the preceding, and declare that all of the information provided in this disclosure is complete and correct. To the best of our knowledge, all persons who might legally make an ownership claim in this Invention are identified in Section 2(a) and 2(b).

NAME (typed):	SIGNATURE:	DATE :
Antoine Bois	Antoine Bois	April 21, 2017
Joyce Poon	Joyce Poon	April 21, 2017

SUBMISSION INSTRUCTIONS:

Please send an electronic draft of the disclosure form to the IP Officer for review prior to obtaining signatures.

Once reviewed for completeness and accuracy, the completed and signed form should be returned to the IP Officer via email at ip.officer@utoronto.ca, in-person, or by mail.

If you need any assistance, please contact the IP Officer.

Wavelength filtering and polarization (de)multiplexing via non-adiabatic transitions

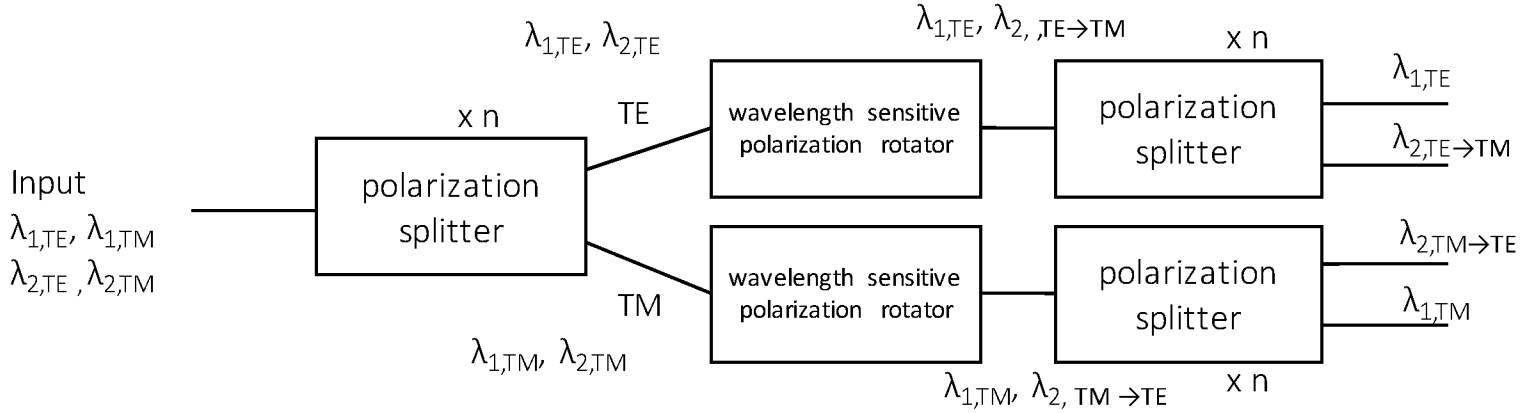
21/04/2017

Antoine Bois
Joyce Poon

UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE & ENGINEERING

Wavelength DEMUX concept

- Use wavelength sensitive polarization rotator
- Only 2nd wavelength channel is polarization rotated:

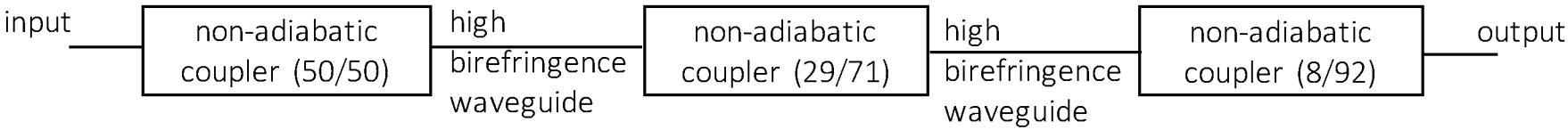


Can further rotate the polarization of λ_2 to obtain only TE outputs.

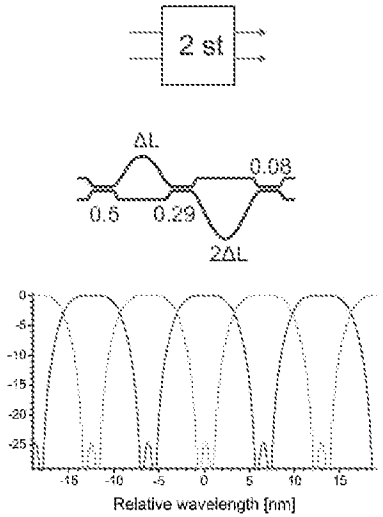
Can add a polarization combiner for each wavelength in a receiver for a polarization insensitive design.

Wavelength sensitive polarization rotator

- Based on a second order lattice filter, but uses non-adiabatic couplers



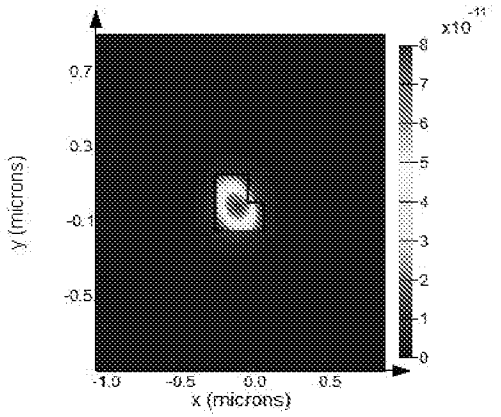
- Equivalent to



Horst, Folkert, et al. "Cascaded Mach-Zehnder wavelength filters in silicon photonics for low loss and flat pass-band WDM (de-) multiplexing." *Optics express* 21.10 (2013): 11652-11658.

Non-adiabatic coupler

- Example of cross-section (L-shaped Si):
- Tapering down too fast induces mode mixing.
- The lowest order 2 modes are TE-TM hybrid, with nearly 50:50 TE:TM mixtures.

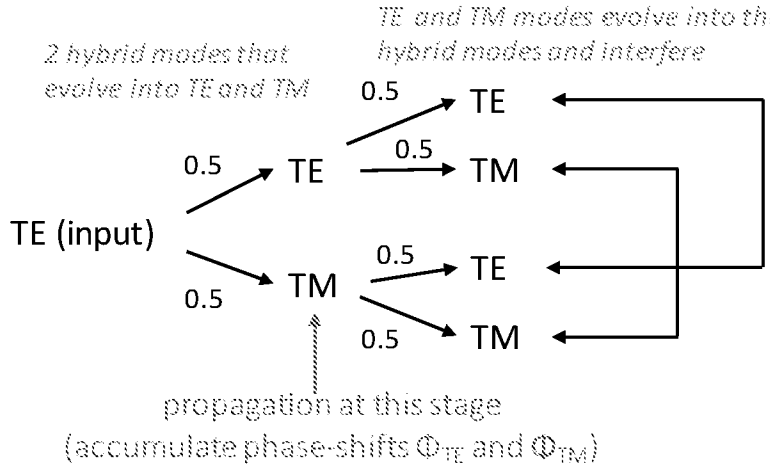


Mode list

mode #	effective index	wavelength (μm)	loss (dB/cm)	TE polarization fraction (Ex)
1	2.430637	1.31	0.00000	48
2	2.230070	1.31	0.00000	52

- Combining two such couplers leads to a birefringence-based MZI:

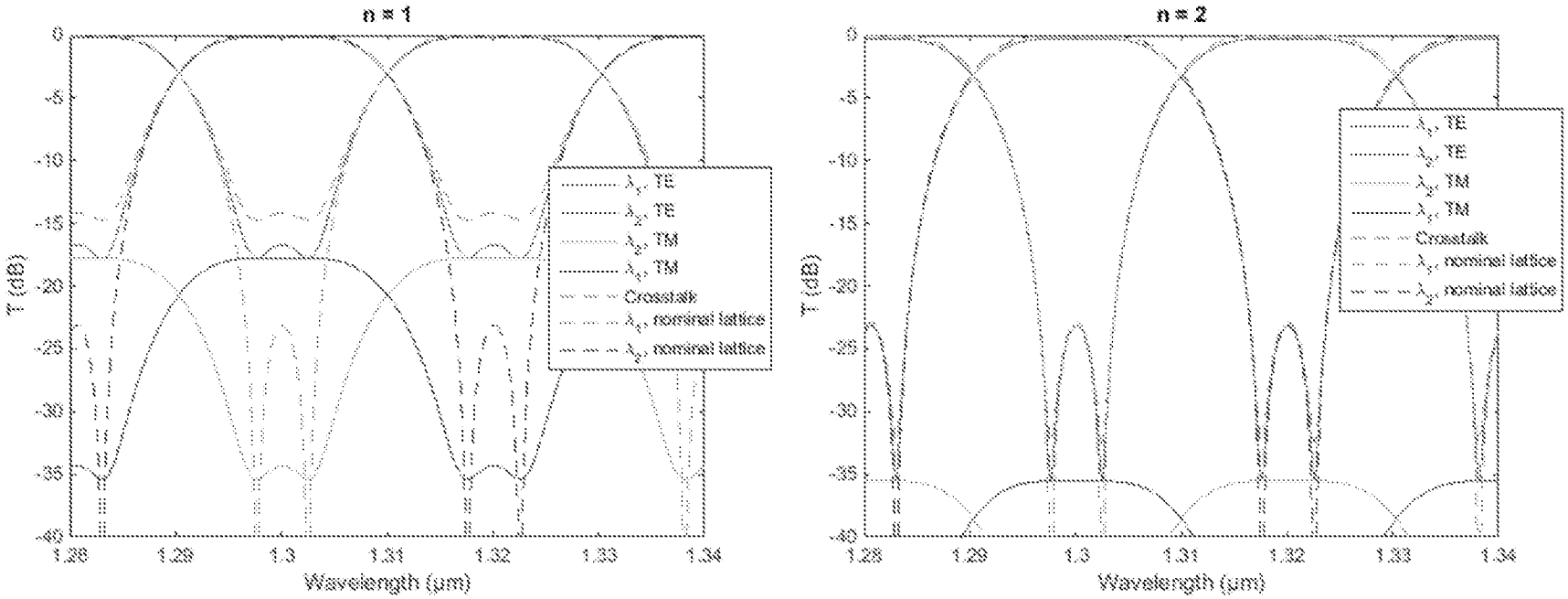
Consider TE input (TM is input is the reciprocal)



Interference
depends on the phase difference accumulated through the intermediate waveguide

Transfer matrix model (for pure TE input)

- Nominal lattice parameters, with *n* the number of polarization splitters in series.
- -17.7 dB crosstalk assumed for polarization splitters (based on some early simulations).

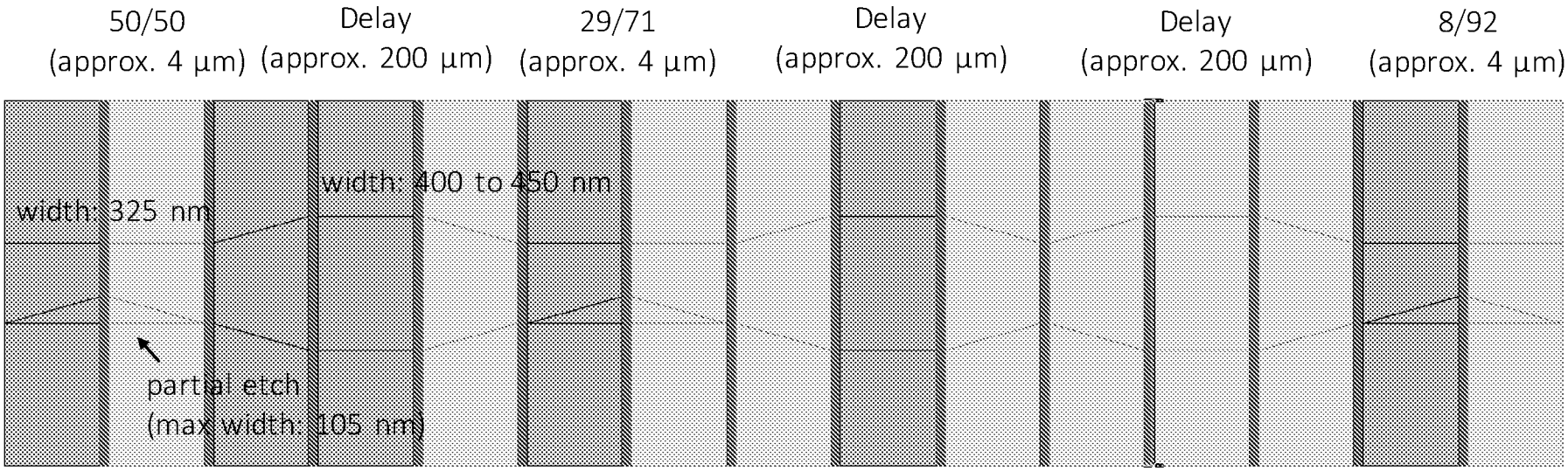


Notes

- High birefringence waveguides can be used to shorten nominal MZI lengths
- Couplers are short due to the non-adiabatic design -> compact implementation
- Non-adiabatic couplers have a broadband operation

Example topology for lattice block (in Si)

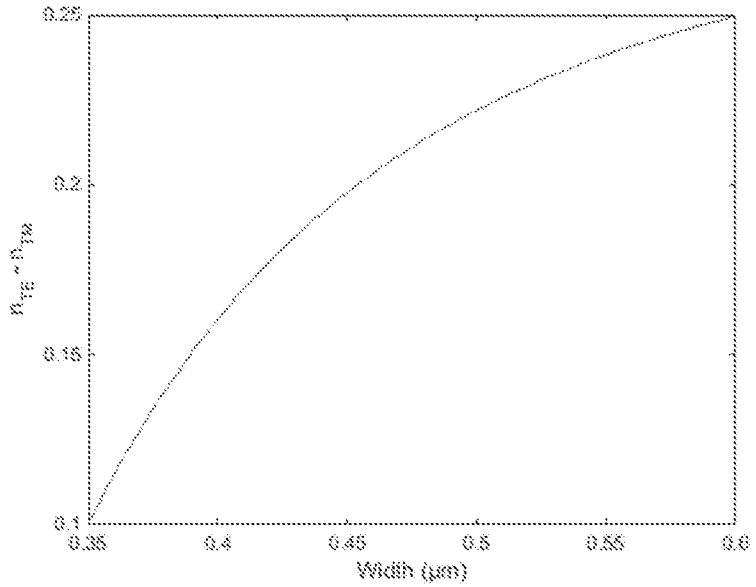
Non-adiabatic transitions to cross-sections with 50:50 hybrid modes is mirrored to achieve arbitrary coupling ratios between 0 and 100%. Robustness, coupler length, and wavelength sensitivity are not compromised.

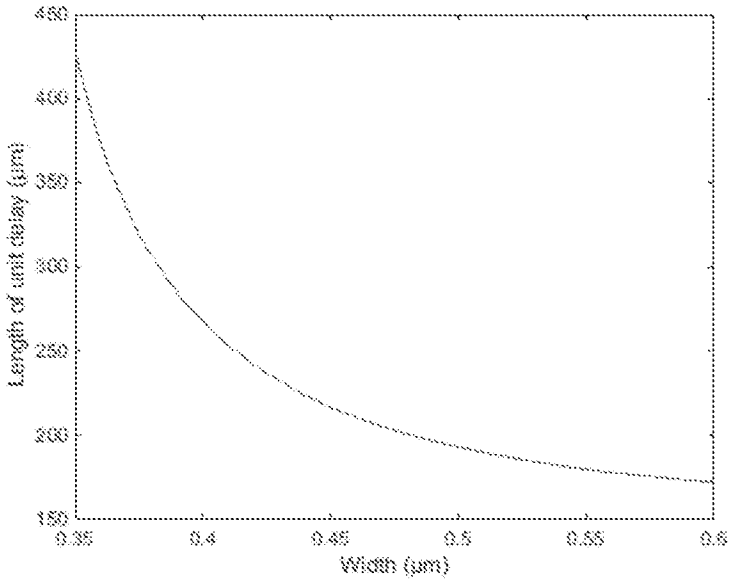


Full etch height: 300 nm
Partial etch height: 165 nm

Width of delay sections

- A high birefringence leads to multimode waveguides, but shorten the necessary delays.
- n is the group index.





Width of delay sections

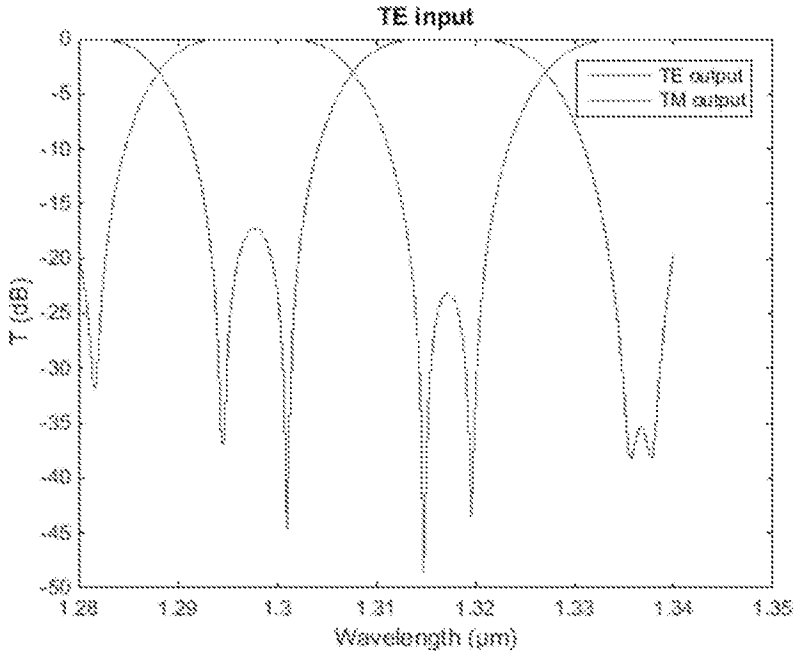
- 440 nm x 300 nm cross-section supports 4 modes with reasonable index separation:

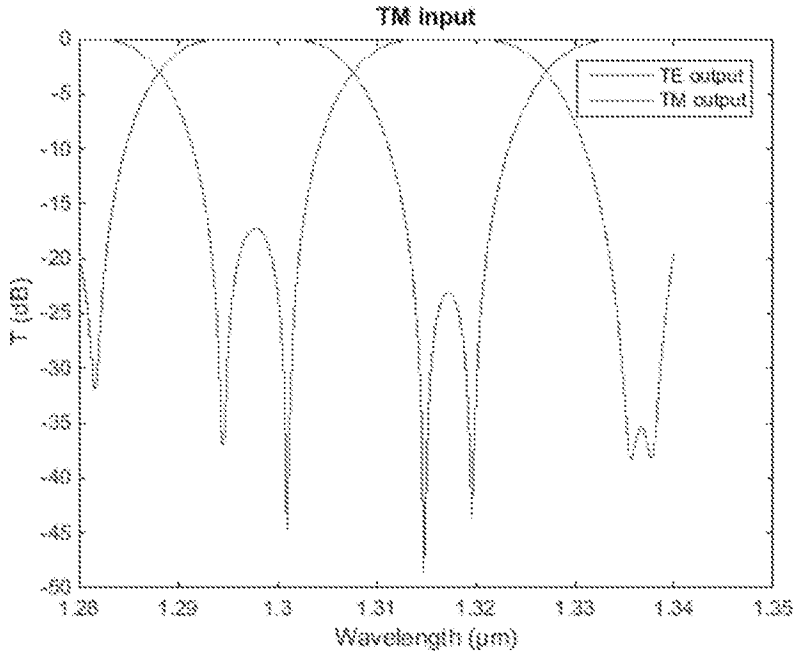
Mode list

mode #	effective index	wavelength (μm)	loss (dB/cm)	TE polarization fraction (Ex)
1	2.833647	1.31	0.00000	99
2	2.643459	1.31	0.00000	2
3	1.973490	1.31	0.00000	35
4	1.782133	1.31	0.00000	79

- Few mode waveguides can be manageable using adiabatic transitions that do not excite higher order modes
  - Widening the delay waveguides is a common technique for phase error mitigation:
    - "In these CMZ devices we have reduced the sensitivity to width variations by widening the waveguides in the delay arms [14], from the standard width of 500 nm to a width of 1.0 μm. In the widened waveguides, the sensitivity of the optical phase to width-variations is reduced by a factor of 5. This also makes the delay line waveguides multi-modal, but we use 10 μm long parabolic tapers to couple adiabatically between the multi-mode and mono-mode sections of the device to avoid excitation of the higher order modes." (same ref. as on slide #3)

Polarization rotation – simulation example



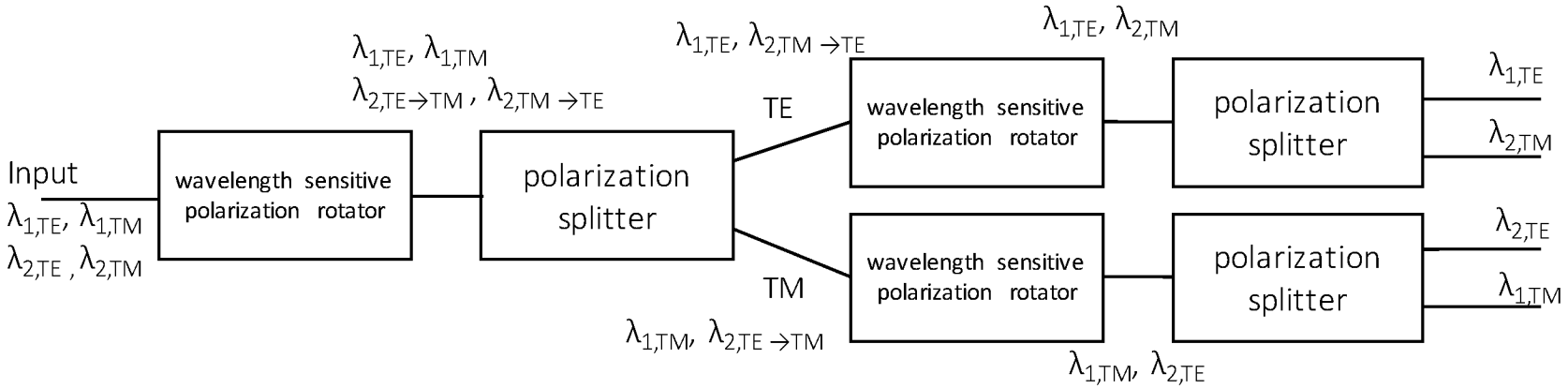


Sensitivity – Delay sections

- Dimensional variations will likely to lead to a similar increase or decrease in both the TE and TM effective indices, leading to the same overall birefringence. This is unlike a conventional interferometer with different waveguides with their own set of independent, uncorrelated perturbations.

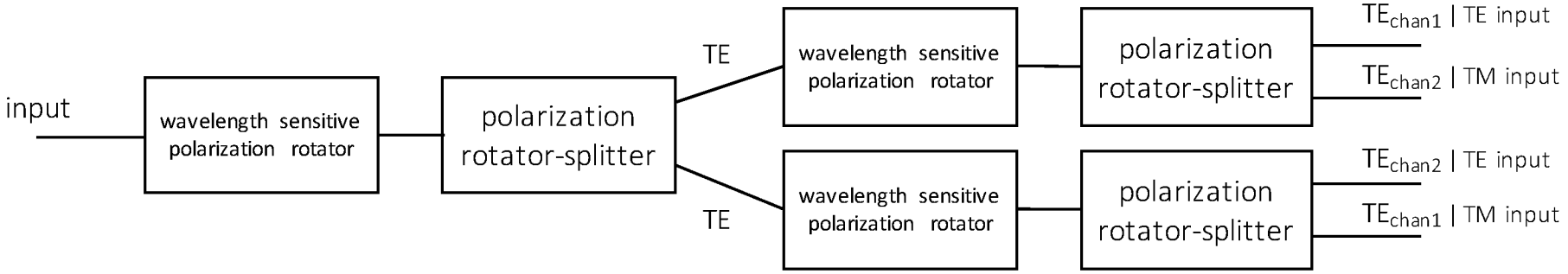
- Any perturbation that affects all delay lines equally lead to the same filter shape, but shifted in wavelength. This is unlike a filter that actively tries to match the TM and TE responses, with their own wavelength sensitivity to this shift. Here, the birefringence is the only wavelength sensitive element, so this problem is eliminated.

Alternate versions (1)

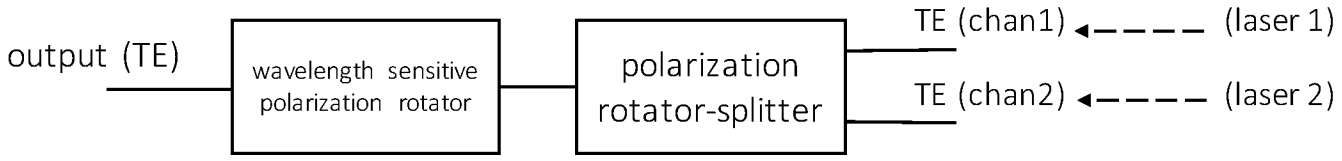


Can add a polarization combiner for each wavelength

Alternate versions (2)



- MUX at the transmitter end



APPENDIX 2

Distribution of Net Revenue

The Inventor directs the University to distribute 60% of the Net Revenue to each Inventor in the following proportions:

Joyce K Poon:	10 %
Antoine Bois:	90 %
Total:	100%

UNIVERSITY OF TORONTO

OFFICE OF THE VICE-PRESIDENT, RESEARCH AND INNOVATION

ASSIGNMENT TO THE UNIVERSITY FROM INVENTOR AND REVENUE SHARING AGREEMENT

This assignment and revenue sharing agreement (the **"Agreement"**) is between Joyce K Poon and Zheng Yong, their respective heirs, executors, administrators and assigns (collectively, the **"Inventor"**) and The Governing Council of the University of Toronto, its successors and assigns (collectively, the **"University"**).

WHEREAS, the Inventor has created certain intellectual property entitled **"Adiabatic Polarization Rotator-Splitter" (Disclosure No. 10003606)** as more particularly described in the disclosure form attached as Appendix 1 (the **"Invention"**);

AND WHEREAS, the University and the Inventor jointly own the Invention under the University's *Inventions Policy* (the **"Policy"**, including any successor policy thereto);

AND WHEREAS, rights are being granted to the research sponsor, Finisar Corporation, as a condition of the Sponsored Research & Collaboration Agreement dated, November 23, 2015;

AND WHEREAS, in order to offer certain rights to the sponsor, the Inventor wishes to assign its interest in the Invention to the University;

NOW THEREFORE this Agreement witnesses that in consideration of the mutual covenants contained herein and other good and valuable consideration, the receipt and sufficiency of which are hereby acknowledged by each of the parties, the parties covenant and agree as follows:

1. **Definitions.** In addition to any terms defined above, in this Agreement:

   (a) **"Commercialization Costs"** means the legal and other fees incurred directly in the process of establishing and maintaining the legal protection of rights in the invention;

   (b) **"Management Fee"** means a fee for services provided by the University in connection with its commercialization of the Invention; and,

   (c) **"Net Revenue"** means the royalty, licensing and other income or equivalent financial return received by the University from the assignment or licensing of the rights in the Invention, less any: (i) Commercialization Costs; and (ii) amounts payable to third parties under prior written agreements that directly relate to the Invention, including but not limited to funding and collaboration agreements.

2. **Assignment.** The Inventor hereby assigns to the University all right, title and interest, whatever the same may be (but without any representation or warranty as to the nature, extent or validity thereof) which the inventor now has or may in the future have in the invention, including, without limitation, the right to apply for patents in

Canada, the United States of America and any other country, the right to receive any letters patent that may be issued from any such applications and the right to sell, license or assign the Invention or the rights thereto.

3. **Disclosure.** The Inventor shall make full and complete disclosure of the Invention to the University, and shall make available to the University any physical embodiments of the Invention and other data that will be or that may be useful to the University in exercising its rights in the Invention.

4. **Assistance.** The Inventor shall execute, acknowledge and deliver all such further assurances and do all such acts as may be necessary to carry out the intent and purpose of this Agreement, including without limitation, to execute powers of attorney and other documents required to maintain intellectual property protection of the Invention, and shall review and provide comments with respect to such intellectual property protection as and when requested by the University.

5. **Revenue Sharing.**

   (a) Subject to 5(b), the University shall distribute sixty percent (60%) of the Net Revenue to the Inventor. The remaining forty percent (40%) of the Net Revenue shall be retained by the University and distributed in accordance with the Policy.

   (b) If the Inventor is also the founder of a company and the University assigns or licenses the Invention to that company, the Inventor agrees to waive all right to receive its share of the Net Revenue.

6. **Equivalent Revenue.** If an arrangement for commercialization of the Invention is made which provides consideration other than cash, the University may liquidate the non-cash assets to the extent it deems necessary to recover Commercialization Costs. The parties shall share the proceeds of such non-cash consideration in the same proportion as provided in section 5.

7. **Payments.** Any money to be paid by the University under this Agreement shall be paid to the Inventor in Canadian funds in the proportions set out in the attached Appendix 2, annually on or before the thirtieth (30th) day following the anniversary of the Effective Date.

8. **Term and Termination.** [THIS SECTION IS INTENTIONALLY DELETED]

9. **Indemnity.** The University shall indemnify and save the Inventor harmless from and against any loss arising out of or pursuant to any claims or demands in connection with the Invention and all costs, damages and expenses (including reasonable legal fees) incurred by the Inventor in connection therewith, except to the extent caused by the breach of any obligations of the Inventor herein or of any representations or warranties given by the Inventor in the disclosure form attached as Appendix 1.

10. **Acknowledgement and Release.** The Inventor acknowledges that, because of the speculative nature of the undertaking to commercialize the Invention, the University cannot guarantee that the results will meet the objectives sought. Save and except for the right to enforce the terms contained in this Agreement, the Inventor releases the University from any and all claims that the Inventor may now have or may in future have in respect of the Invention. Any disputes arising under this Agreement shall be resolved by the parties in accordance with the dispute resolution procedures set out in the Policy.

11. **Counterparts.** This Agreement may be executed by signatures delivered by facsimile transmission or delivered electronically in optically scanned form; and/or it may be simultaneously executed by the Inventors in multiple counterparts, each of which will be considered to be an original instrument, and all of which taken together, where each Inventor has executed at least one counterpart, will constitute one and the same instrument.

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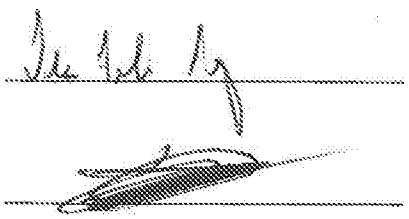
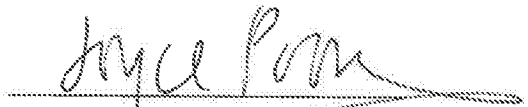
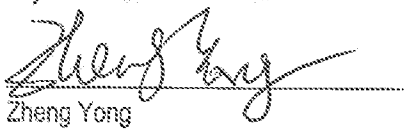
Witness



Inventor

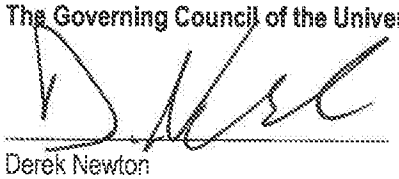


Joyce K Podn



Zheng Yong

The Governing Council of the University of Toronto



Derek Newton
Assistant Vice-President, Innovation, Partnerships and Entrepreneurship

Executed at Toronto, Ontario this 24th day of Aug., 2018 (but made effective **08 May 2018**, the "**Effective Date**")

APPENDIX 1

Invention Disclosure Form

UNIVERSITY OF TORONTO

OFFICE OF THE VICE-PRESIDENT, RESEARCH AND INNOVATION

CONFIDENTIAL INVENTION DISCLOSURE

Innovations & Partnerships Office | Banting Institute, Room 413 | 100 College St. Toronto ON M5G 1L5
Tel: (416) 978-7833 | Fax: (416) 978-6052 | email: ip.officer@utoronto.ca

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1. Title of Invention:

ADIABATIC POLARIZATION ROTATOR-SPLITTER

2. Inventors and Contributors:

a. Inventors at the University of Toronto: List all individuals who have made an inventive contribution to this disclosure through the use of U of T resources (i.e. faculty, students, postdocs, staff, visiting scientist, etc). Attach separate pages if necessary.

SURNAME, GIVEN NAMES	U of T PERSONNEL NO (if applicable)	DEPARTMENT *(List any cross appointments or affiliated institutions)*	AFFILIATION WITH U of T *(i.e. faculty, research assoc., post-doc, student, staff, visitor, etc.)*	EMAIL ADDRESS	CONTACT INFORMATION *(non-U of T mailing address, phone, fax)*	% CONTRIBUTION *(*optional)*
Yong, Zheng	1136946	Electrical and Computer Engineering	PhD student	zheng.yong@mail.utoronto.ca	925 Bay street, Apt. 1104, Toronto, ON M5S 3L4 6479946871	90
Poon, Joyce Kai See	993899	Electrical and Computer Engineering	Faculty	Joyce.poon@utoronto.ca	24 Wellesley St. W., #2212, Toronto, ON, M4Y 2X6 416-262-0571	10

* If invention is assigned to UofT, percentage will be used as a basis for sharing future revenues. Revenue distribution agreed to by the parties in an assignment agreement will govern.

For more information, see our Disclosure Guide.

FOR IPO USE ONLY:
Disclosure Date: May 10, 2018 Disclosure No: 10003606

b. External Inventors: List all individuals who have made an inventive contribution to this disclosure using non-U of T resources (i.e. sponsor employees, academic collaborators, etc). Please include names, organization, contact information and email address.

Bryan Park

c. Contributors (Non-Inventors): List all individuals at or external to U of T who have not made an inventive contribution but have contributed to the development of the invention. Please include name, organization and email address.

3. Location(s) of Work:

Please list all locations (U of T and external) of the work leading to this invention, be specific (i.e. department, building, hospital, etc).

Department of Electrical and Computer Engineering, Galbraith building

4. Invention Description:

Please provide a description of this invention for evaluation, highlighting its novel or patentable aspects. Attach separate pages if necessary.

The invention is an adiabatic polarization rotator-splitter (PRS) based on silicon nitride (SiN) waveguide. The proposed PRS receives an input optical signal in one SiN waveguide, and the input is a mixture of the two polarization modes, TE00 and TM00. The PRS first convert the incoming TM00 light to TE01 light and then separate it as the TE00 mode in a second waveguide while the input TE00 mode is not converted and maintained in the original waveguide. The adiabatic PRS is optimized to be insensitive to the geometric variations of the SiN waveguide (e.g., waveguide height, side wall angle). This device can be implemented in the platform where fabrication precision of SiN waveguide is not high. The design uses a partially etched layer in the SiN waveguide (i.e., SiN rib waveguides) to reduce the polarization crosstalk.

5. Dissemination:

List all publications, abstracts, presentations or any other forms of public dissemination regarding this work, including dates.

(•) None ( ) Yes (please provide details)

None

6. Funding:

Provide details regarding any funding used in the development of this invention (i.e. salary or stipend support, materials, equipment, etc.).

SPONSOR	PROJECT TITLE	RIS FUND #
Finisar Corporation	Si Photonics for Coarse Wavelength Division Multiplexing (CWDM)	500138

7. Related Agreements:

Was the work leading to this invention subject to any written or oral contract(s) or other agreement(s) such as: material transfer, data transfer, software licence, confidentiality, collaboration, and/or sponsored research?

○ No ○ Yes (please provide details)

Yes. This invention is being disclosed under a sponsored research agreement between Finisar and U of T. The U of T reference number is 2015-1761.

8. Patent Applications:

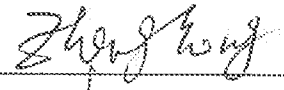
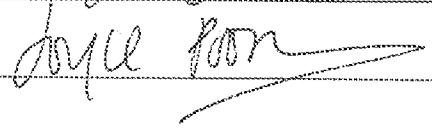
Have any patent applications or other intellectual property protections been filed in respect of this invention?

○ No ○ Yes (please provide details)

Yes. A non-provisional patent application was submitted on Nov. 29, 2017. US Patent Application number: 15/826,636

9. Warranty:

I/We, the inventors listed in Section 2(a), have read, understood and agree to all of the preceding, and declare that all of the information provided in this disclosure is complete and correct. To the best of our knowledge, all persons who might legally make an ownership claim in this invention are identified in Section 2(a) and 2(b).

NAME (typed):	SIGNATURE:	DATE :
Zheng Yong		May 10, 2018
Joyce Kai See Poon		May 10, 2018

SUBMISSION INSTRUCTIONS:

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APPENDIX 2

Distribution of Net Revenue

The Inventor directs the University to distribute 60% of the Net Revenue to each Inventor in the following proportions:

Joyce K Poon:	10 %
Zheng Yong:	90 %
Total:	100%

UNIVERSITY OF TORONTO

OFFICE OF THE VICE-PRESIDENT, RESEARCH AND INNOVATION

CONFIDENTIAL INVENTION DISCLOSURE

Innovations & Partnerships Office | Banting Institute, Room 413 | 100 College St. Toronto ON M5G 1L5
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This form is used to record inventions made using U of T resources, facilities and/or funds managed by U of T and is to be completed by the inventor(s) to satisfy their obligations under **U of T's Inventions Policy**. For step by step information on how to complete the form, please refer to the **invention disclosure guide**.

1. Title of Invention:

Adiabatic Polarization Rotator Combiner

2. Inventors and Contributors:

a. Inventors at the University of Toronto: List all individuals who have made an inventive contribution to this disclosure through the use of U of T resources (i.e. faculty, students, postdocs, staff, visiting scientist, etc). Attach separate pages if necessary.

SURNAME, GIVEN NAMES	U of T PERSONNEL NO (if applicable)	DEPARTMENT *(List any cross appointments or affiliated institutions)*	AFFILIATION WITH U of T *(i.e. faculty, research assoc., post-doc, student, staff, visitor, etc.)*	EMAIL ADDRESS	CONTACT INFORMATION *(non-U of T mailing address, phone, fax)*	% CONTRIBUTION *(*optional)*
Yong, Zheng	1136946	Electrical and Computer Engineering	PhD student	zheng.yong@mail.utoronto.ca	925 Bay street, Apt. 1104, Toronto, ON M5S 3L4 6479946871	90
Poon, Joyce Kai See	993699	Electrical and Computer Engineering	Faculty	Joyce.poon@utoronto.ca	24 Wellesley St. W., #2212, Toronto, ON, M4Y 2X6 416-262-0571	10

FOR IPO USE ONLY:
Disclosure Date: May 10, 2018 Disclosure No: 10003607

* If invention is assigned to UofT, percentage will be used as a basis for sharing future revenues. Revenue distribution agreed to by the parties in an assignment agreement will govern.

For more information, see our Disclosure Guide.

b. External Inventors: List all individuals who have made an inventive contribution to this disclosure using non-U of T resources (i.e. sponsor employees, academic collaborators, etc). Please include names, organization, contact information and email address.

Bryan Park, Daniel Mahgerefteh – Finisar Corp.

c. Contributors (Non-Inventors): List all individuals at or external to U of T who have not made an inventive contribution but have contributed to the development of the invention. Please include name, organization and email address.

3. Location(s) of Work:

Please list all locations (U of T and external) of the work leading to this invention, be specific (i.e. department, building, hospital, etc).

Department of Electrical and Computer Engineering, Galbraith building

4. Invention Description:

Please provide a description of this invention for evaluation, highlighting its novel or patentable aspects. Attach separate pages if necessary.

The invention is an adiabatic polarization rotator combiner (PRC) based on silicon nitride (SiN) waveguides. The proposed PRC is a polarization multiplexing device that can receive two optical signals with TE00 polarization in two SiN waveguides. The second optical signal is first converted to TE01 mode and then TM00 mode. Then the converted TM00 mode is combined with the other input TE00 optical signal. The adiabatic PRC is optimized to be insensitive to the geometric variations of the SiN waveguide (e.g., waveguide height, side wall angle) for the given integrated photonic platform. This device can be implemented in the platform where fabrication precision of SiN waveguide is not high. The design uses a partially etched layer in the SiN waveguide (i.e., SiN rib waveguides) to reduce the polarization crosstalk.

5. Dissemination:

List all publications, abstracts, presentations or any other forms of public dissemination regarding this work, including dates.

(•) None ( ) Yes (please provide details)

None

6. Funding:

Provide details regarding any funding used in the development of this invention (i.e..salary or stipend support, materials, equipment, etc.).

SPONSOR	PROJECT TITLE	RIS FUND #
Finisar Corporation	Si Photonics for Coarse Wavelength Division Multiplexing (CWDM)	500138

7. Related Agreements:

Was the work leading to this invention subject to any written or oral contract(s) or other agreement(s) such as: material transfer, data transfer, software licence, confidentiality, collaboration, and/or sponsored research?

○ No ○ Yes (please provide details)

Yes. This invention is being disclosed under a sponsored research agreement between Finisar and U of T. The U of T reference number is 2015-1761.

8. Patent Applications:

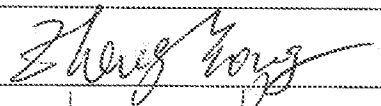
Have any patent applications or other intellectual property protections been filed in respect of this invention?

○ No ○ Yes (please provide details)

Yes. A non-provisional patent application was submitted on Nov. 29, 2017. US Patent Application number: 15/826,673

9. Warranty:

I/We, the inventors listed in Section 2(a), have read, understood and agree to all of the preceding, and declare that all of the information provided in this disclosure is complete and correct. To the best of our knowledge, all persons who might legally make an ownership claim in this invention are identified in Section 2(a) and 2(b).

NAME (typed):	SIGNATURE:	DATE :
Zheng Yong		May 10, 2018
Joyce Kai See Poon		May 10, 2018

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SCHEDULE "C"

INTELLECTUAL PROPERTY RIGHTS

List of Patents filed for the Inventions

Disclosure ID	Serial No	App. Type	Country	Title	Filing Date
10003189	62/410,293	Provisional	United States	Negative Angle Grating Coupler	10/19/2016
10003194	-	-	-	-	-
10003215	62/430,788	Provisional	United States	Waveguides with serially varying birefringence	12/06/2016
10003351	62/508,927	Provisional	United States	Optical assemblies for wavelength and polarization multiplexing and demultiplexing	05/19/2017
10003189	15/977,907	Non-Provisional	United States	Negative Angle Grating Coupler	05/11/2018
10003606	15/826,636	Non-Provisional	United States	Adiabatic Polarization Rotator-Splitter	11/29/2017
10003607	15/826,673	Non-Provisional	United States	Adiabatic Polarization Rotator Combiner	11/29/2017