An introduction to integrated optical isolators

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Avoid reflections

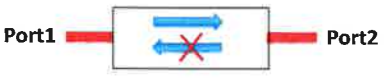
Lasers are sensitive to light injection
- change of power
- change of wavelength
- increase of linewidth
- increase of intensity noise
- chaos

Two reflections: interferometric ripple in transmission
- distorts spectroscopic functions
- distorts modulated signals

Two reflections + gain ⇒ oscillation!

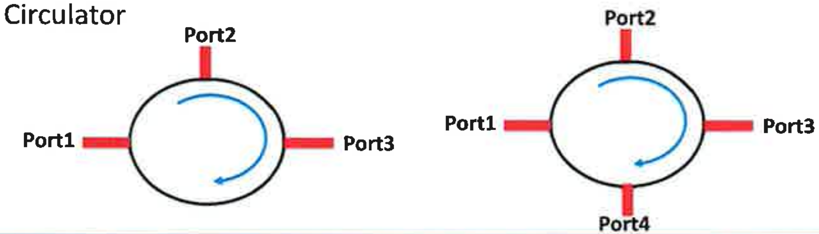
The standard solution

Isolator



Performance metrics
- isolation
- forward losses
- optical bandwidth
- number of modes at input and output
- power consumption
- price

Circulator



Integration of isolators in photonic IC's

Integration of many functions on a chip:
- increasing need to incorporate isolators
- especially in the presence of lasers or amplifiers

Major photonic integration platforms:
- InP
- silicon photonics
- siliconoxide/siliconnitride waveguide ICs

Trend towards higher refractive index contrast
- more spurious reflections!

Outline

Lorentz reciprocity

Avoiding reflections

Reciprocal "isolators", "diodes"…

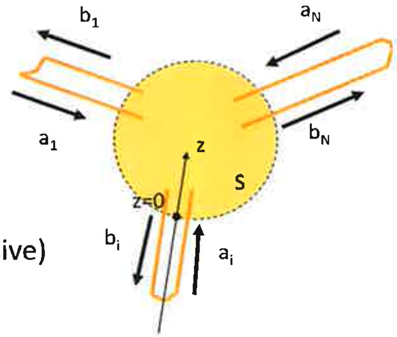
Breaking reciprocity by magneto-optic effects

Breaking reciprocity by nonlinear effects

Breaking reciprocity by time-variant modulation

Open questions

Lorentz reciprocity



We consider a system:

which is <u>linear</u>

which is <u>time-invariant</u>

which has <u>no internal sources</u> (passive)

for which the influx and outflux of electromagnetic waves occurs through well-defined modes

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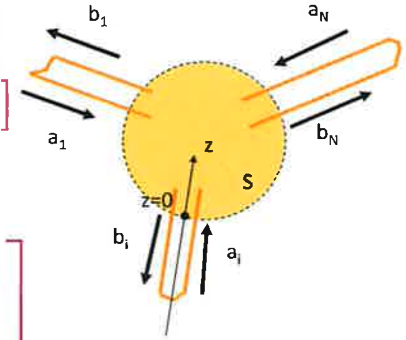
Lorentz reciprocity

$$\mathbf{E}_{T,i}(x,y,t)=\mathrm{Re}\left[(a_i+b_i)\,\mathbf{e}_T(x,y)\,e^{j\omega t}\right]$$

$$\mathbf{H}_{T,i}(x,y,t)=\mathrm{Re}\left[(a_i-b_i)\,\mathbf{h}_T(x,y)\,e^{j\omega t}\right]$$



$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

Lossless and lossy circuits

Lossless circuits: no absorption

$$P = \mathbf{A}^+\mathbf{A} - \mathbf{B}^+\mathbf{B} = \mathbf{A}^+\left(1 - \mathbf{S}^+\mathbf{S}\right)\mathbf{A} = 0$$

$$\Downarrow$$

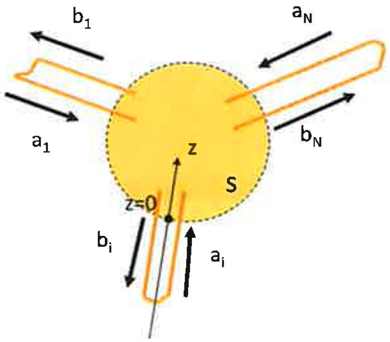
$$\mathbf{S}^+\mathbf{S} = 1 \quad (\mathbf{S} \text{ is unitary})$$

Lossy circuits: $P > 0$

$$\mathbf{A}^+\mathbf{S}^+\mathbf{S}\mathbf{A} \le \mathbf{A}^+\mathbf{A}$$

$$\Downarrow$$

$$\sum_{j=1}^{\mu} \left|S_{jk}\right|^2 \le 1$$



Lorentz reciprocity

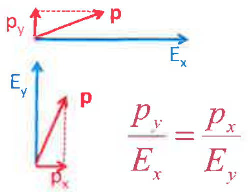
If all materials in the system have symmetric permittivity and permeability tensors:

$\varepsilon^T = \varepsilon$ **and** $\mu^T = \mu$

⇩

"Reciprocal circuit"

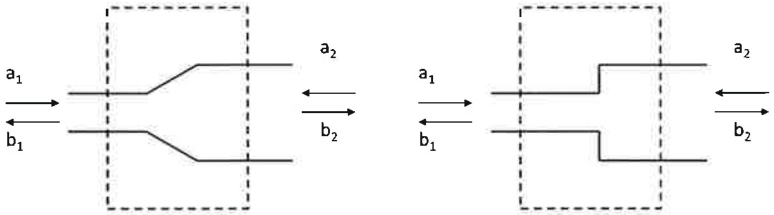
Symmetric S-matrix ($s_{ij} = s_{ji}$) :
Transmission between ports is independent of the propagation direction



$$\frac{p_y}{E_x} = \frac{p_x}{E_y}$$

This also holds in the presence of absorption (ε complex)!

Reciprocity



Reciprocity: $S_{21} = S_{12}$!!!!!!!

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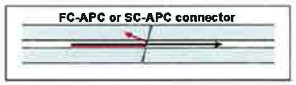
Avoiding reflections : better prevent than cure

Many approaches to avoid reflections

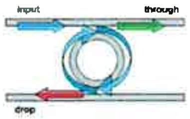
AR-coatings

Angled facets

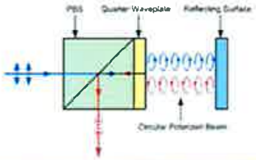


Resonators:

ring resonators rather than Fabry-Perot



Exploit polarization



Avoiding reflections in photonic IC's

High index contrast allows for very compact photonic functions

BUT

Leads to high scattering losses and strong reflections

Solution: smart design + high precision manufacturing

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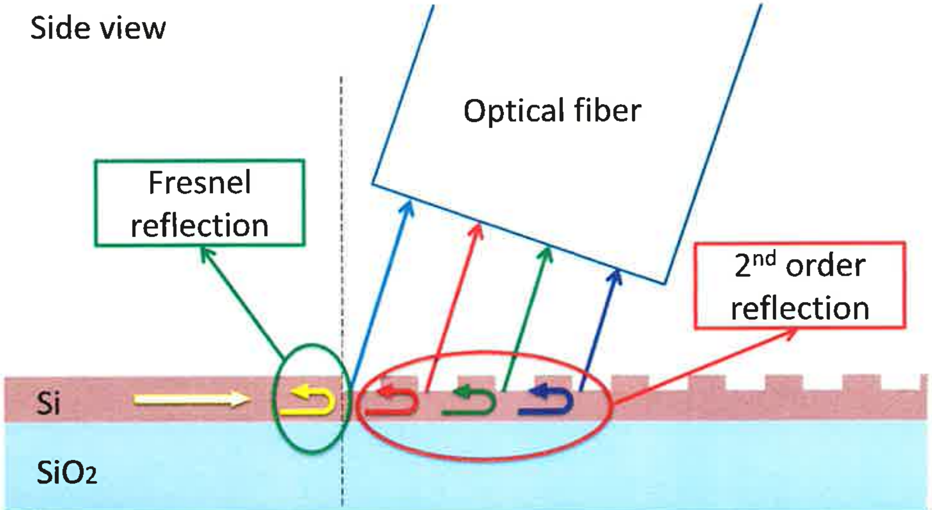
grating couplers and reflections

Side view



Optical fiber

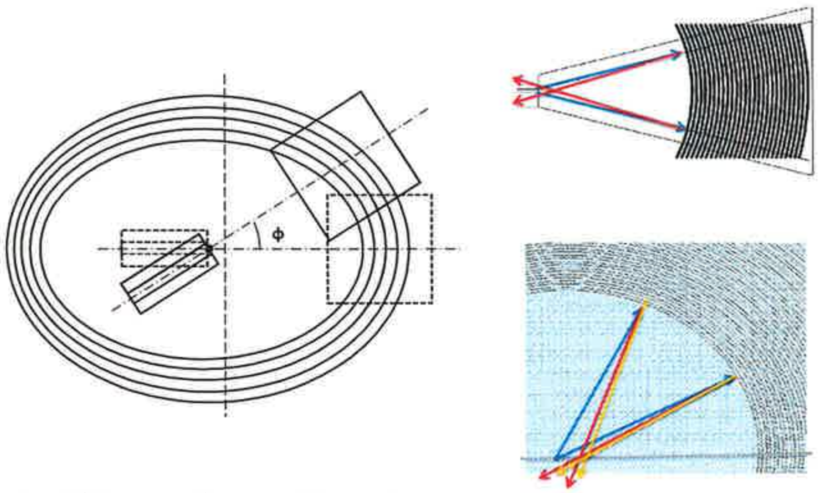
Fresnel reflection

2^{nd} order reflection

Si

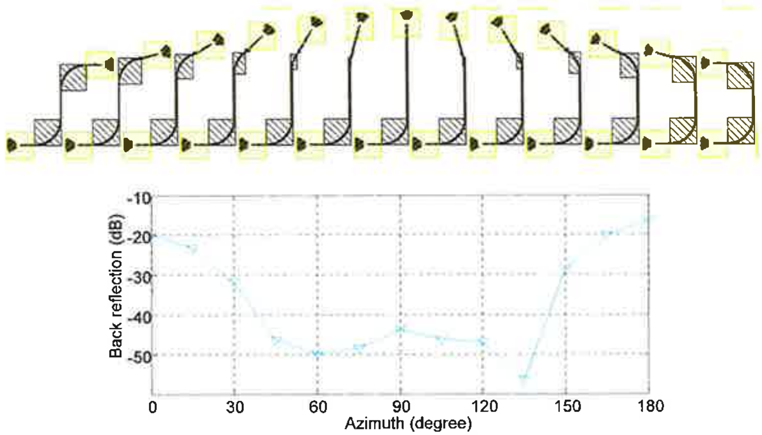
SiO_2

Tilted focusing grating couplers (TFGCs)



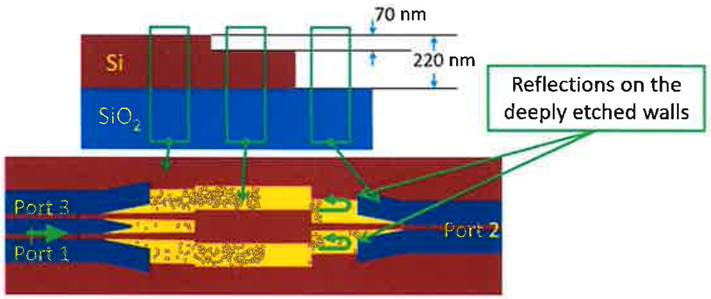
D. Vermeulen, Y. De Koninck, Y. Li, W. Bogaerts, R. Baets, G. Roelkens, Optics Express, p.22278-22283 (2012)

Reflectionless grating couplers



Y. Li, D. Vermeulen, Y. De Koninck, G. Yurtsever, G. Roelkens, R. Baets, Optics Letters, 37(21), p.4356-4358 (2012)

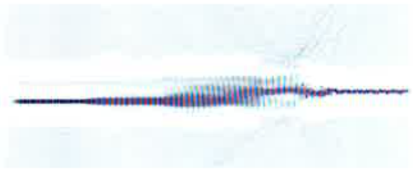
Multimode interferometers and reflections



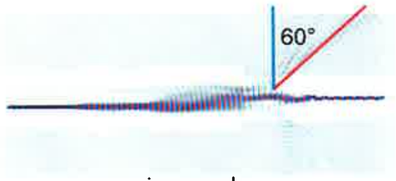
Reflections on the deeply etched walls

How to reduce MMI reflections?

Simulation:

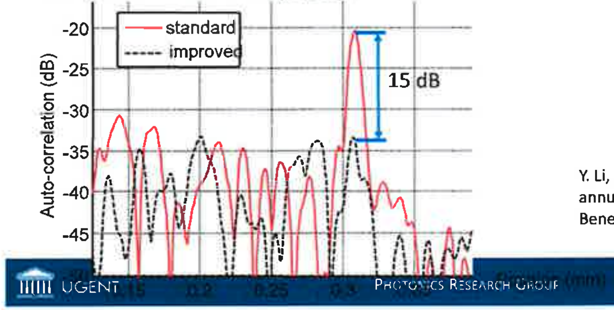


standard:
The wall is perpendicular to the incoming light



improved:
the wall is oblique to the incoming light

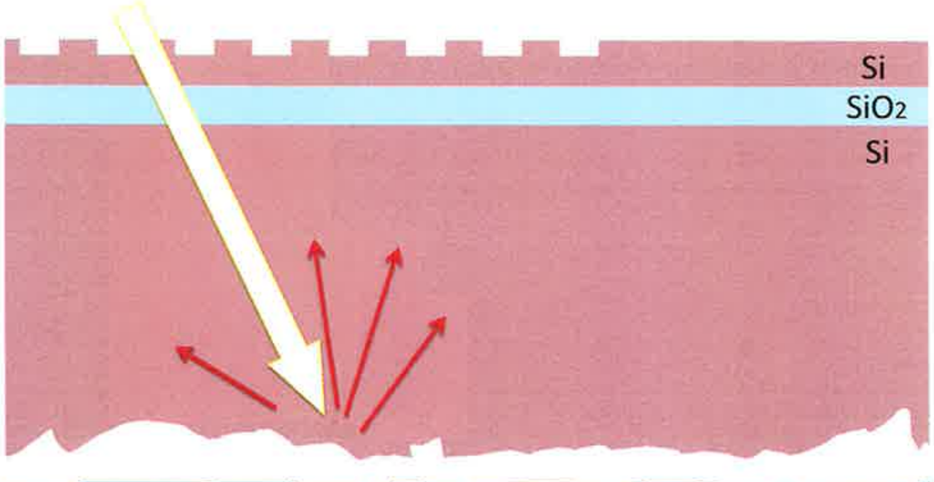
Reflection measurement (OFDR):



Y. Li, R. Baets, Proceedings of the 2011 annual symposium of the IEEE Photonics Benelux Chapter, p.205-208 (2011)

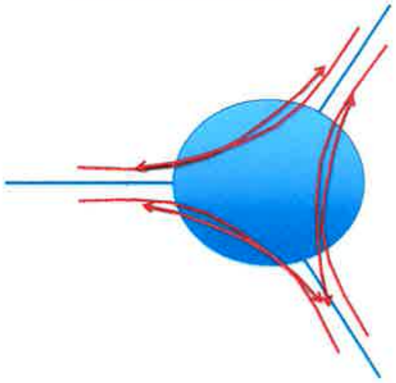
Topography of the chip backside

From fiber



Reflectionless power splitter?

Is it physically possible to have a lossless N-port that splits up power entering any port without reflection equally to all N-1 other ports?



Reflectionless power splitter?

Is it physically possible to have a lossless N-port that splits up power entering any port without reflection equally to all N-1 other ports?

N=2: trivially YES (simple waveguide)

N=3: PHYSICALLY IMPOSSIBLE!!

N=4: possible, but NOT with reciprocal solution

N=5: possible, with reciprocal solution,
but which physical implementation???

N=6: possible, with reciprocal solution

N>6: ???

$$\frac{1}{\sqrt{3}}\begin{bmatrix} 0 & 1 & 1 & -1 \\ 1 & 0 & 1 & 1 \\ -1 & 1 & 0 & 1 \\ -1 & -1 & 1 & 0 \end{bmatrix}. \tag{1}$$

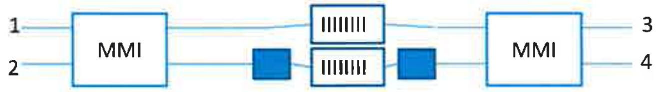
$$\frac{1}{2}\begin{bmatrix} 0 & 1 & a & a & 1 \\ 1 & 0 & 1 & a & a \\ a & 1 & 0 & 1 & a \\ a & a & 1 & 0 & 1 \\ 1 & a & a & 1 & 0 \end{bmatrix}$$

$$a = e^{2j\pi/3}, \tag{2}$$

$$\frac{1}{\sqrt{5}}\begin{bmatrix} 0 & 1 & 1 & -1 & 1 & 1 \\ 1 & 0 & 1 & 1 & -1 & 1 \\ 1 & 1 & 0 & 1 & 1 & -1 \\ -1 & 1 & 1 & 0 & -1 & -1 \\ 1 & -1 & 1 & -1 & 0 & -1 \\ 1 & 1 & -1 & -1 & -1 & 0 \end{bmatrix}. \tag{3}$$

V. Belevitch, IRE Transactions on Circuit Theory, pp. 295, 1962

Three-way-splitting four-port

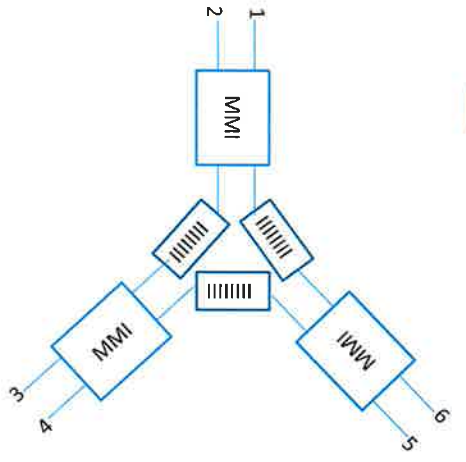


🟦 Non-reciprocal phase shift: pi/4 in forward and −pi/4 in backward direction

▥ Reflector (eg DBR) with power reflection of 1/3 and power transmission of 2/3

$$S = \tfrac{1}{\sqrt{6}}\begin{bmatrix} 0 & -\sqrt{2} & 1+j & 1+j \\ -\sqrt{2} & 0 & 1+j & -(1+j) \\ 1-j & -(1-j) & 0 & -\sqrt{2} \\ -(1-j) & -(1-j) & -\sqrt{2} & 0 \end{bmatrix}$$

Five-way-splitting six-port



▥ Reflector (eg DBR) with power reflection of 1/5 and power transmission of 4/5

$$S = \tfrac{1}{\sqrt{5}}\begin{bmatrix} 0 & -1 & j & -1 & j & 1 \\ -1 & 0 & 1 & j & -1 & j \\ j & 1 & 0 & -1 & j & -1 \\ -1 & j & -1 & 0 & 1 & j \\ j & -1 & j & 1 & 0 & -1 \\ 1 & j & -1 & j & -1 & 0 \end{bmatrix}$$

Outline

Lorentz reciprocity

Avoiding reflections

Reciprocal "isolators", "diodes"…

Breaking reciprocity by magneto-optic effects

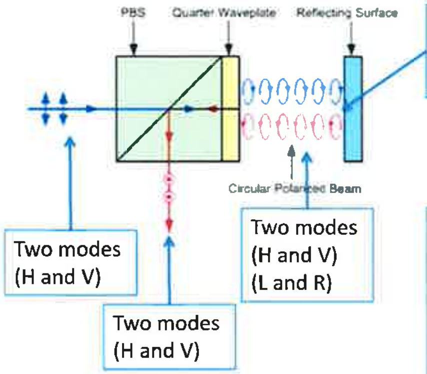
Breaking reciprocity by nonlinear effects

Breaking reciprocity by time-variant modulation

Open questions

Reciprocal “isolators”, “optical diodes”, …

Is this an isolator?



Two modes (H and V)

Two modes (H and V)

Two modes (H and V) (L and R)

Specular reflector that converts one particular incident mode into one specific reflected mode

$$S = \begin{bmatrix} 0 & r \\ r & 0 \end{bmatrix}$$

If the reflector can convert polarisation in an arbitrary way (eg reflection by rough surface), then some power will go back to the source

$$S = \begin{bmatrix} a & b \\ b & a' \end{bmatrix}$$

Reciprocal “isolators”, “optical diodes”, …

Is this an isolator?

Two modes (e and o)

Extra phase shift of $\pi/2$

Two modes (e and o)

One mode (e)

Cut-off of o-mode

Reflector that converts one particular incident mode into one specific reflected mode (e to e; o to o)

$$S = \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix}$$

If the reflector can convert polarisation in an arbitrary way (eg reflection by rough surface), then some power will go back to the source

$$S = \begin{bmatrix} a & b \\ b & a' \end{bmatrix}$$

Core message

An isolator should block reflections irrespective of the mode conversion by the reflector

This is fundamentally impossible with a
Linear
Time-independent
Reciprocal
device

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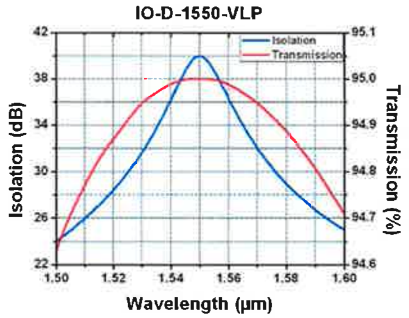
Open questions

Non-reciprocity by magneto-optic effect

Faraday rotator



Sources: wikipedia, Thorlabs

Non-reciprocity by magneto-optic effect

In magnetic materials and in the presence of a static magnetic field **H,** the permittivity tensor changes into

$$\varepsilon = \begin{pmatrix} \varepsilon'_{xx} & \varepsilon'_{xy} + ig_z & \varepsilon'_{xz} - ig_y \\ \varepsilon'_{xy} - ig_z & \varepsilon'_{yy} & \varepsilon'_{yz} + ig_x \\ \varepsilon'_{xz} + ig_y & \varepsilon'_{yz} - ig_x & \varepsilon'_{zz} \end{pmatrix}$$

with $\mathbf{g} = \varepsilon_0 \chi^{(m)} \mathbf{H}$

In other words: if **H** is in the z-direction, then E_x and E_y get coupled.

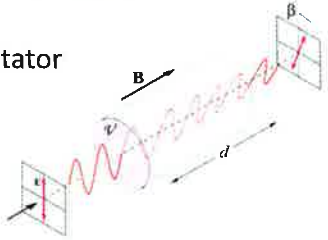
Physical origin: Lorentz force **F**=q **v** x **B**

These materials are called magneto-optic or gyrotropic

Faraday configuration

This is different from optical activity in chiral materials!!

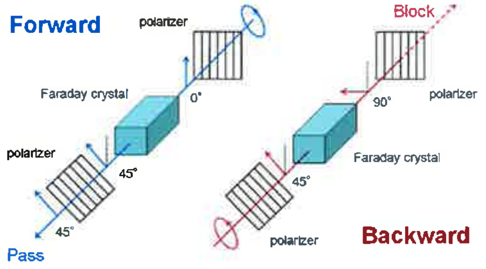
Faraday rotator



$$\beta = VBd$$

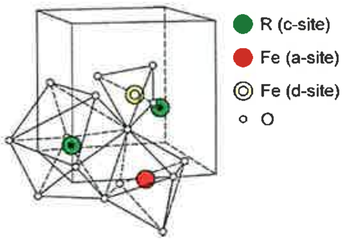
$$\text{V : Verdet constant } (\sim g)$$

Optical isolator



Magneto-optic materials

Desired properties
- large magneto-optic (MO) effect
- low optical absorption
- temperature insensitive



Rare earth iron garnets ($R_3Fe_5O_{12}$)
- $Y_3Fe_5O_{12}$ (YIG)
- $(Y_{3-x}Bi_x)Fe_5O_{12}$, $(Y_{3-x}Ce_x)Fe_5O_{12}$
  - enhancement of Faraday rotation
- can be deposited with good crystalline quality on GGG (Gadolinium Gallium garnet)
- ferrimagnetic
- needs magnet on top to saturate magnetization

Faraday rotation in waveguides?

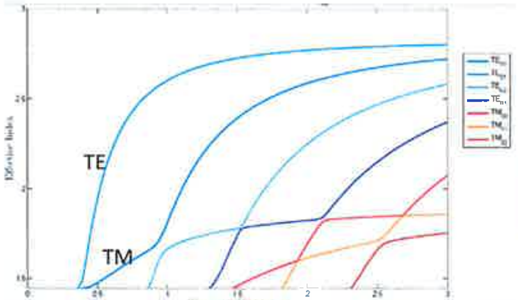
Longitudinal static magnetic field:

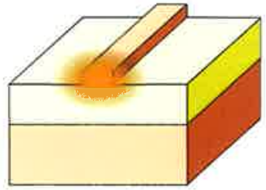
TE and TM mode exchange power

But they are not easily phase matched

Hence total polarisation is not a simple rotation of linear polarisation

Isolation is poor





Voigt configuration in waveguides

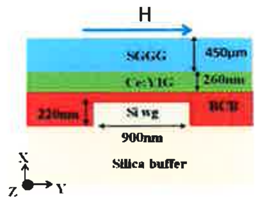
Transverse magnetic field induces nonreciprocal phase shift

$$\Phi = k_0 n_{eff} L \pm \Delta\Phi \text{ (+ for forward, - for backward)}$$

Case 1: H-field along y

$$\Delta\Phi \propto g_y \iint_{YIG} E_x E_z \, dxdy$$

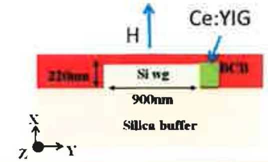
Works only for TM-mode



Case 2: H-field along x

$$\Delta\Phi \propto g_x \iint_{YIG} E_y E_z \, dxdy$$

Works only for TE-mode



Integration of YIG on waveguide platform

Bonding of YIG-dies on photonic IC

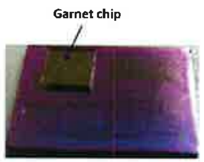
not a wafer scale technology

direct molecular bonding

adhesive BCB bonding

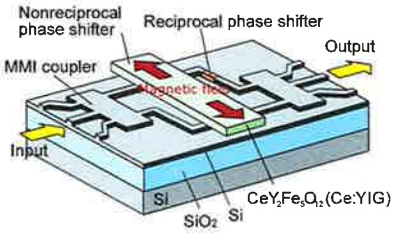
Sputter deposition or pulsed laser deposition

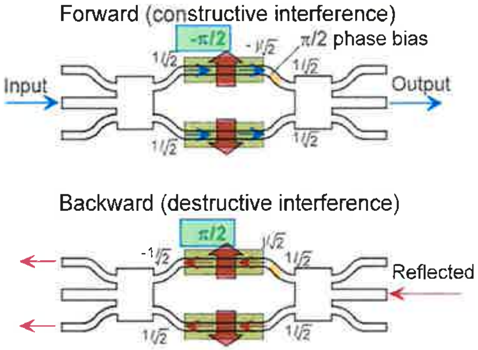
wafer scale technology



Interferometric isolator: operation principle

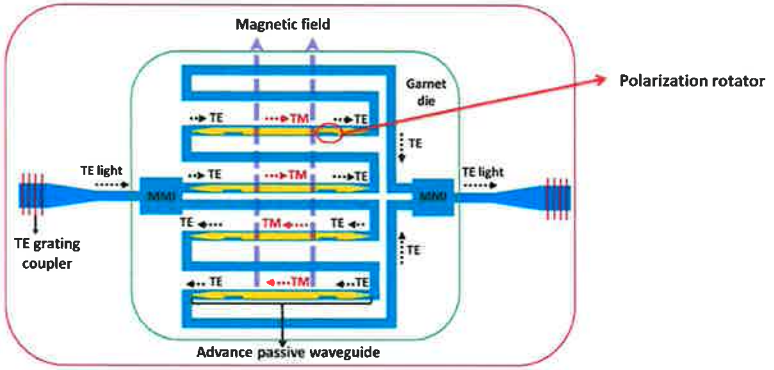
Interferometric isolator



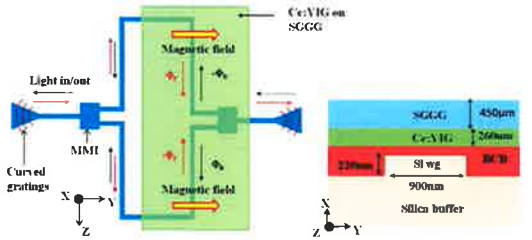


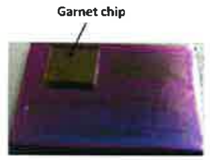
- Single polarization operation
  - → No need for phase matching
  - → Fabrication tolerant
- Simple in-plane magnetization

TE-Isolator: Design

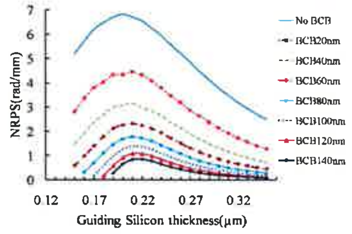


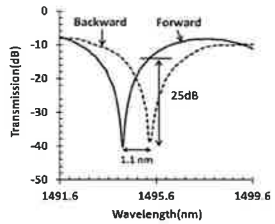
Push-Pull MZI type Isolator





NRPS = (Forward - Backward) nonreciprocal Phase = 2*($\phi_F + \phi_B$)





Results:

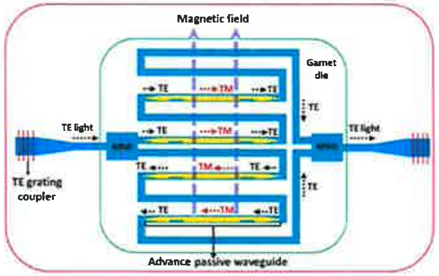
Isolation: 25 dB

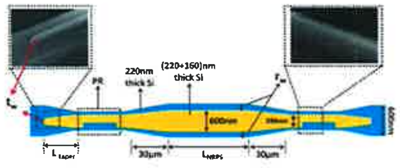
Insertion loss: ~10 dB

BCB thickness: ~ 100nm

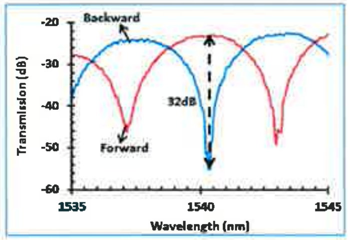
S. Ghosh *et.al*, Optics Express **20**(2), 1839-1848(2012)

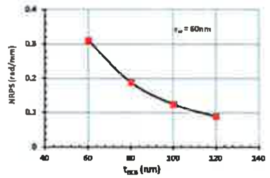
TE Isolator

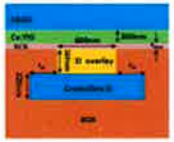




Advance passive waveguide





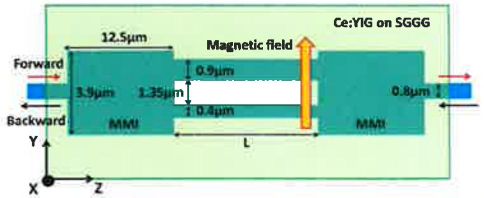


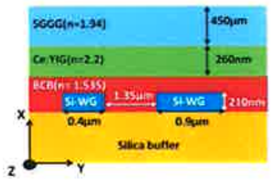
Isolation: ~ 32dB, NRPS: ~ 0.27 rad/mm

Insertion loss: ~22 dB

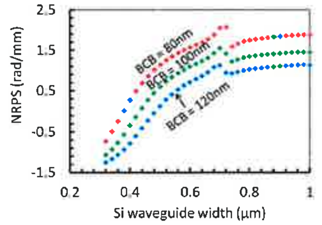
S. Ghosh *et.al*, IEEE Photonics Journal, 2013

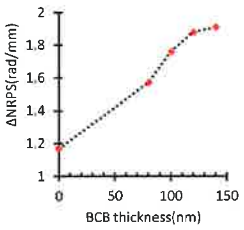
Asymmetric Arm widths type MZI Isolator

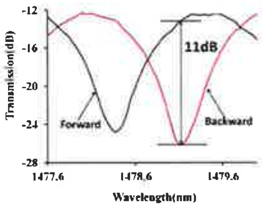




ΔNRPS = NRPS in (Wider arm – Narrower arm)



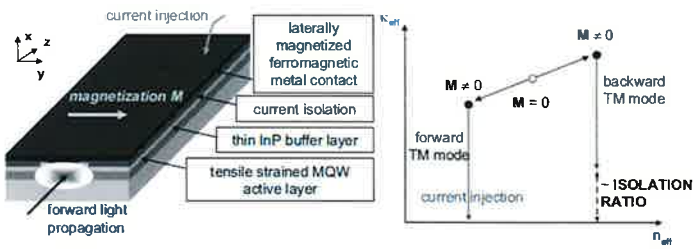


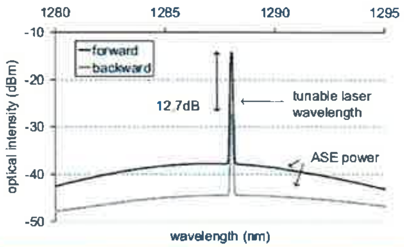


11 dB isolation for L = 1.49mm

S. Ghosh *et.al*, Photonics Technology Letters **24**(18), 1653-1656(2012)

FeCo ferromagnetic isolator on InP SOA





Outline

Lorentz reciprocity

Avoiding reflections

Reciprocal “isolators”, “diodes”…

Breaking reciprocity by magneto-optic effects

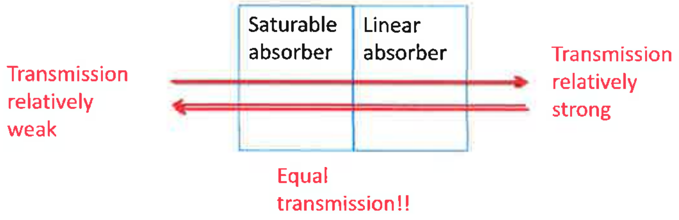
Breaking reciprocity by nonlinear effects

Breaking reciprocity by time-variant modulation

Open questions

Breaking reciprocity by nonlinear effects

Third order nonlinear effects (Kerr-effect, two-photon absorption, saturable absorption…)


Saturable absorber

Linear absorber

Transmission relatively weak

Transmission relatively strong

Equal transmission!!

Problems

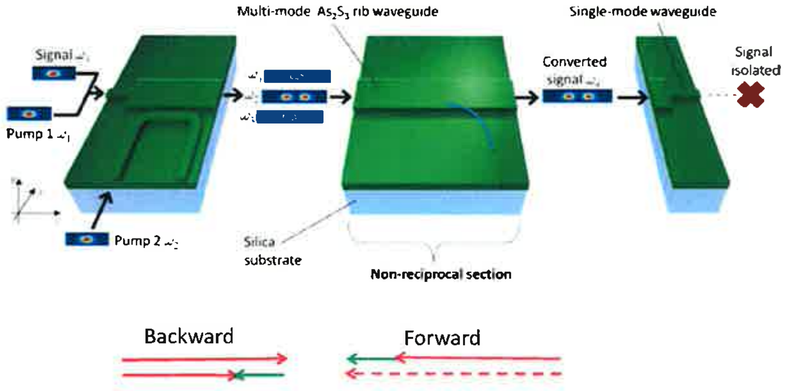
- Isolation in non-presence of forward beam is mostly useless
- operation is signal power dependent
- time-varying signal power ⇒ time-varying isolation

Breaking reciprocity by nonlinear effects

Need an effect that is
- linear in the signal
- nonlinear in a pump
- different for forward signal and backward signal

Stimulated Brillouin scattering
- two optical pump beams with frequency difference $\Delta\omega$ create a travelling beating pattern
- electrostriction creates an acoustic wave
- acoustic wave creates a moving grating that diffracts the signal
- forward and backward signal have opposite Doppler shift
- phase matching and mode selection can do the rest

Breaking reciprocity by nonlinear effects



Poulton et al, Optics Express p. 21235, 2012

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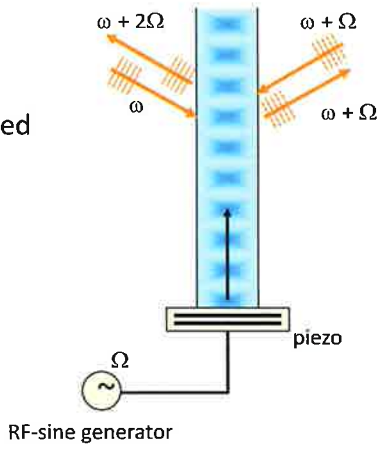
Acousto-optic diffraction leads to frequency shift

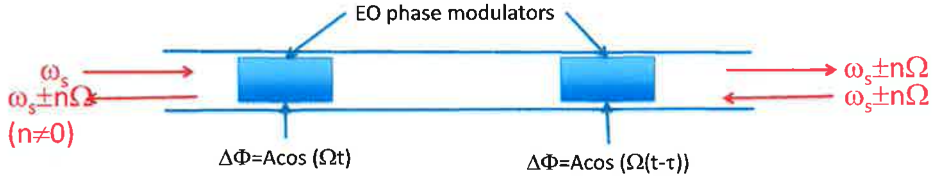
Reflected signal is frequency shifted

Filtering can do the rest



Breaking reciprocity by time-variant modulation

At least two electrooptical modulators with time delay between modulating signals



By smart design one can ensure minimal distortion of forward signal and maximum rejection of backward signal.

Rejection: filters, mode filters, absence of phase matching

This will only work if:

- Ω larger than optical bandwidth of signal
- 1/Ω of same order as propagation time of optical signals on chip (~100ps)

Hence Ω in GHz range!

Outline

Lorentz reciprocity

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Breaking reciprocity by nonlinear effects

Breaking reciprocity by time-variant modulation

Open questions

Conclusions on isolators integrated on PIC platform

A lot of progress in recent years

Many novel ideas

Need for good understanding of reciprocity and isolator functionality

None of the reported approaches has good enough performance for practical use

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Conclusion: many open questions

Bonded YIG isolators (on silicon, InP,…)
  losses (5-10 dB): cause to be identified; outcome uncertain
  manufacturability
Sputtered or laser deposited YIG isolators (on silicon, InP,…)
  performance considerably poorer than bonded isolators
  material quality to be improved; outcome uncertain
Nonlinear isolators
  nonlinear in signal: no future
  nonlinear in pump: implementation on silicon or InP needed; operating at low power
  is (expensive) optical pump acceptable for an optical isolator function?
Dynamic isolators
  performance rather poor so far in most implementations;
  requires very high speed modulation
  is associated power dissipation and complexity acceptable for an optical isolator function?

Acknowledgements

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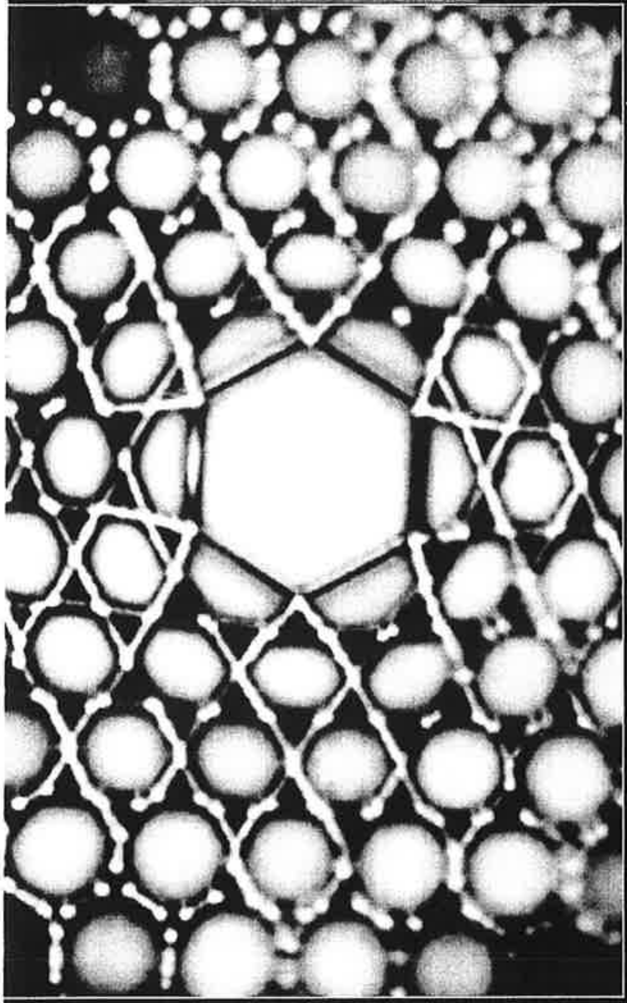
14–17
July 2013



Conference Program

Advanced Photonics

OSA Optics & Photonics Congress

Integrated Photonics Research, Silicon, and Nano-Photonics (IPR)

Optical Sensors (Sensors)

Photonic Networks and Devices (Networks)

Signal Processing in Photonic Communications (SPPCom)

Image credit: Chromatic dispersion in the cladding of a kagome-lattice hollow core photonic crystal fiber when white light is launched into its core (courtesy Max Planck Institute for the Science of Light, Erlangen, Germany)

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www.osa.org/advancedphotonics

Congress Highlights

Recent Developments in Silicon Photonics Symposium

Monday, 15 July, 13:30–15:30 and 16:00–18:00
Caribbean 2 & 3

This symposium, organized by IPR Program Committee members, focuses on new and upcoming developments in silicon photonics for tele- and data communications and features speakers from both academia and industry. This symposium will be held in two parts on Monday (13:30–15:30 and 16:00–18:00) with a coffee break between the sessions. Invited Speakers include the following individuals:

- **Photonics-Electronics Convergent System Technology,** Yasuhiko Arakawa; *Univ. of Tokyo, Japan*
- **Towards Large-scale Silicon Photonics Integration**, Michael Watts; *MIT, USA*
- **High Speed GeSi Electro-absorption Modulator: Technology and Applications,** Dazeng Feng; *Kotura, Inc., USA*
- **Ge/SiGe Quantum Well Optical Modulators,** Delphine Marris-Morini; *Institut d'Electronique Fondamentale, France*
- **III-V on Silicon Hybrid Tunable Lasers,** Alban Leliepvre; *Alcatel-Thales III-V Lab, France*
- **Towards High-Performance Monolithic Ge-on Si Lasers for Integrated Photonics,** Jifeng Liu; *Dartmouth College, USA*
- **Photonic Wire Bonding: An Enabling Technology for Heterogeneous Multi-chip Integration,** Christian Koos; *Karlsruhe Inst. of Tech., Germany*
- **Silicon Integrated Quantum Photonics**, Mark Thompason, *Univ. of Bristol, Australia*

Joint Poster Session

Tuesday, 16 July, 13:30-15:00
Rio Mar 6

Posters are an integral part of the technical program and offer a unique networking opportunity, where presenters can discuss their results one-to-one with interested parties. Light refreshments will be served.

Congress Reception

Tuesday, 16 July, 19:00–20.30
Ocean Terrace

Join your fellow attendees for the Congress Reception. Enjoy delectable fare while networking. The reception is open to committee members, presenting authors, students and full conference attendees. Conference attendees may purchase extra tickets for their guest for US$ 75 per person.

Workshop on Integrated Isolators

Wednesday, 17 July, 09:15–10:00 and 10:30–12:00
Caribbean 2 & 3

This workshop, organized by the IPR Program Committee will be held in two parts on Monday (09:15–10:00 and 10:30–12:00) with a coffee break between the sessions. Invited speakers include the following individuals:

- **Tutorial: Integrated Optical Isolators: An Introduction**, Roel G. Baets; *Universiteit Gent, Belgium*
- **Nonreciprocal Phase Shift Isolator,** Fan Shanhui; *Stanford Univ., USA*
- **Magnetooptical Materials for Integrated Nonreciprocal Devices,** Caroline Ross; *MIT, USA*
- **On-chip Isolator for Telecom**, Christopher Doerr; *Acacia Communications, USA*

Plenary Speakers

Brutally-efficient Photonics for Future Intra-system Communications
Tuesday, 16 July 2013
JT1A.1 • 08:30, *Caribbean 2 & 3*

Ashok V. Krishnamoorthy, *Oracle Labs, USA*

Dr. A. V. Krishnamoorthy is an Oracle Architect and Chief Technologist, Photonics. He also serves as Principle Investigator for the Oracle Labs DARPA UNIC/POEM initiatives on silicon "photonics-to-the-processor". Previously, he was a Distinguished Engineer and Director at Sun Microsystems responsible for advanced optical interconnect and silicon photonics development. He also spent several years as CTO and President of AraLight, a Lucent technologies spinout developing high-density parallel optical products and technologies. Prior to that he was an entrepreneur-in-residence at Lucent New Ventures group, and before that a member of technical staff in the Advanced Photonics research department at Bell Labs, in Holmdel, NJ. He has worked over two decades on the packaging and integration of photonic devices with silicon CMOS circuits - including electro-optic modulators on silicon, quantum well devices, VCSELs, and, most recently, Si/Ge photonics - and on creating transceivers, switching systems, and computing systems based on these components.

He has published over 200 technical papers and 8 book chapters, has presented over 90 conference invited and plenary lectures, and holds 90 US patents. He has served as member or chair of over 35 international conferences, and has been guest editor for several technical journals. He is currently serving as co-General Chair for the IEEE Optical Interconnects conference, and guest co-editor for the IEEE Journal of Selected Topics in Quantum Electronics. He continues to serve on the advisory board of several technology startups and early-stage venture funds. His honors include the ICO international prize in Optics, the IEEE Distinguished Lecturer award, Eta Kappa