nb-photonics
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imec
PHOTONICS RESEARCH GROUP

The quest for integrated on-chip optical isolators

Can we do without magneto-optic materials?

Roel Baets

Ghent University – imec

IMRC2013, Cancun

Avoid reflections

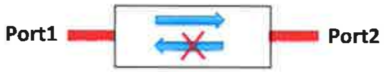
Lasers are sensitive to light injection
  change of power
  change of wavelength
  increase of linewidth
  increase of intensity noise
  chaos

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

Two reflections + gain ⇒ oscillation!

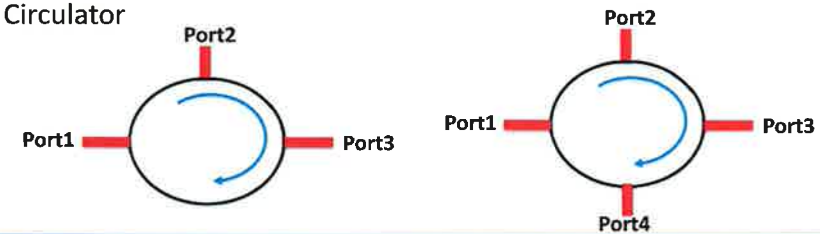
The standard solution

Isolator



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

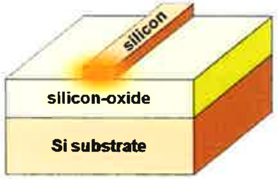
Circulator



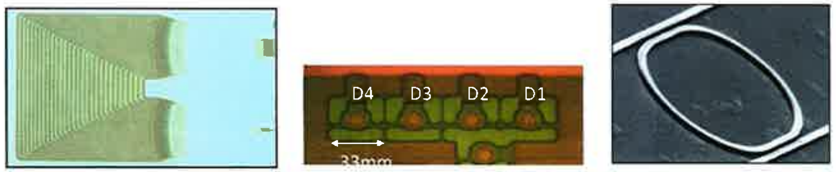
Integration of isolators in photonic IC’s

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!

Silicon photonics



High index contrast ⇒ very compact PICs
CMOS technology ⇒ low cost, high yield
High performance passive devices
High performance Ge photodetectors
High performance modulators
Integration with electronics
Wafer-level automated testing
Design tools and packaging tools
Light sources and optical isolators?



Outline

Lorentz reciprocity

Reciprocal “isolators”, “diodes”…

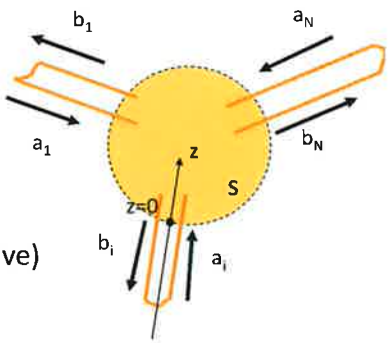
Breaking reciprocity by magneto-optic effects

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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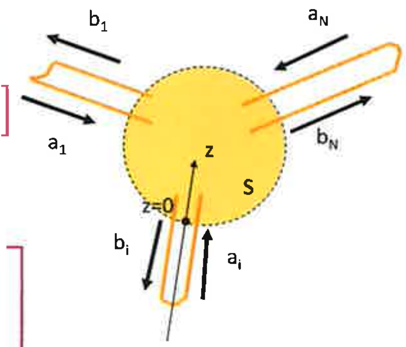
Lorentz reciprocity



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

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

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

Lossless and lossy circuits

Lossless circuits: no absorption

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

$$\Downarrow$$

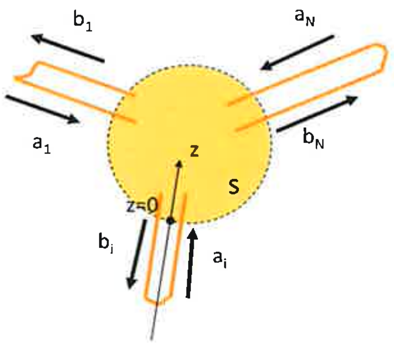
$$\mathbf{S}^+\mathbf{S} = 1 \quad (\mathbf{S} \text{ is unitary})$$

Lossy circuits: P > 0

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

$$\Downarrow$$

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



Lorentz reciprocity

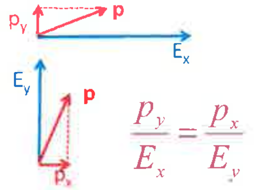
If all materials in the system have symmetric permittivity and permeability tensors:

$$\varepsilon^T = \varepsilon \quad \text{and} \quad \mu^T = \mu$$

$$\Downarrow$$

"Reciprocal circuit"

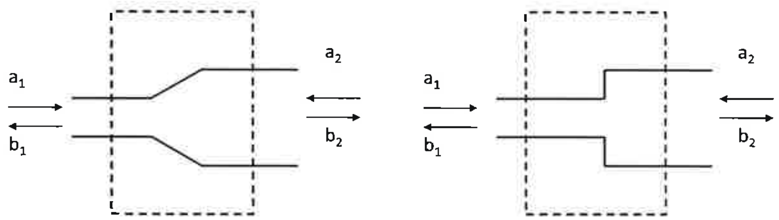
Symmetric S-matrix ($s_{ij} = s_{ji}$) :
Transmission between ports is independent of the propagation direction



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

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

Reciprocity



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

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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

D. Jalas et al, *What is – and what is not – an optical isolator, Nature Photonics 7, pp 579–582(2013)*

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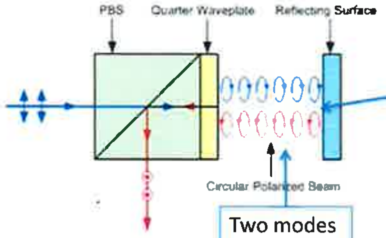
Reciprocal "isolators", "optical diodes", …

Is this an isolator?



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)

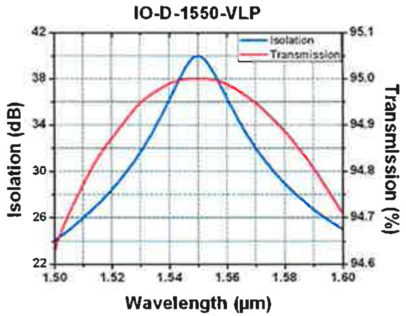
$$S = \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix}$$

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

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

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

$$\varepsilon = \begin{pmatrix} \varepsilon'_{xx} & \varepsilon'_{xy} + i g_z & \varepsilon'_{xz} - i g_y \\ \varepsilon'_{xy} - i g_z & \varepsilon'_{yy} & \varepsilon'_{yz} + i g_x \\ \varepsilon'_{xz} + i g_y & \varepsilon'_{yz} - i g_x & \varepsilon'_{zz} \end{pmatrix}$$

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.

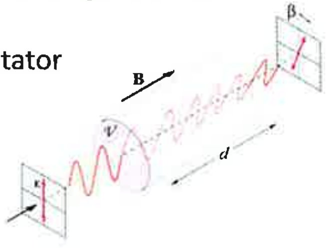
Physical origin: Lorentz force **F**=q **v** x **B**

These materials are called magneto-optic or gyrotropic

Faraday configuration

This is different from optical activity in chiral materials!!

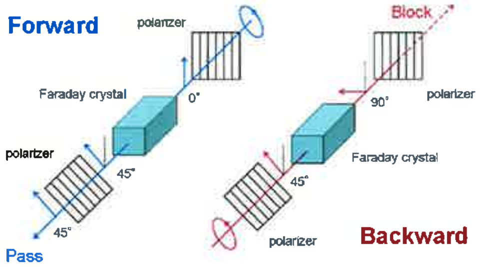
Faraday rotator



$$\beta = VBd$$

V : Verdet constant ($\sim g$)

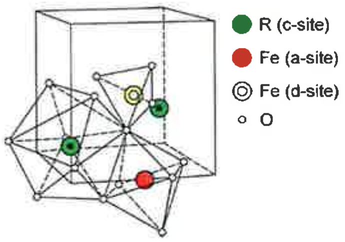
Optical isolator



Magneto-optic materials

Desired properties

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



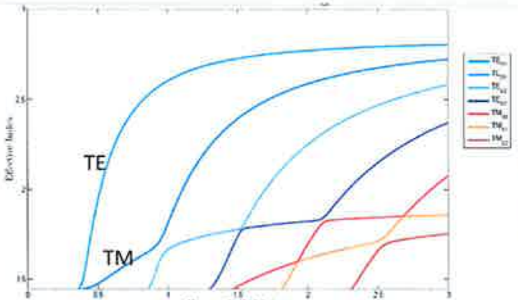
Rare earth iron garnets ($R_3Fe_5O_{12}$)

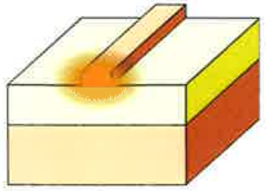
- $Y_3Fe_5O_{12}$ (YIG)
- $(Y_{3-x}Bi_x)Fe_5O_{12}$, $(Y_{3-x}Ce_x)Fe_5O_{12}$
  - enhancement of Faraday rotation
- can be deposited with good crystalline quality on GGG (Gadolinium Gallium garnet)
- ferrimagnetic

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

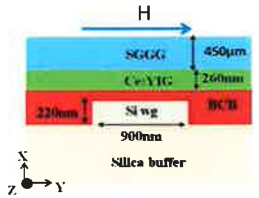
$$\Delta\Phi \propto g_y \iint_{YIG} E_x E_z\, dxdy$$

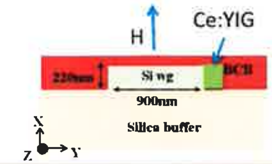
Works only for TM-mode

Case 2: H-field along x

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

Works only for TE-mode





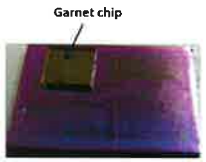
Integration of YIG on waveguide platform

Bonding of YIG-dies on photonic IC

- **not a wafer scale technology**
- direct molecular bonding
- adhesive BCB bonding

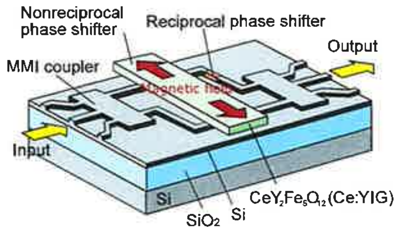
Sputter deposition or pulsed laser deposition

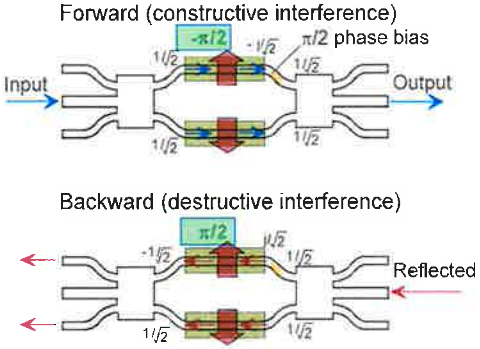
- wafer scale technology



Interferometric isolator: operation principle

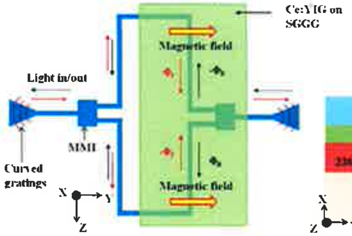
Interferometric isolator

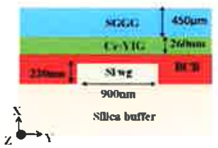


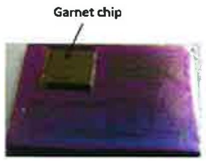


- Single polarization operation
  - → No need for phase matching
  - → Fabrication tolerant
- Simple in-plane magnetization

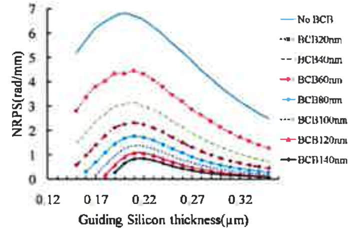
Push-Pull MZI type Isolator

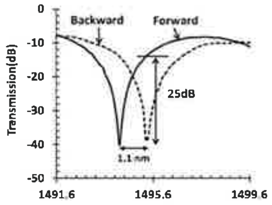






NRPS = (Forward - Backward) nonreciprocal Phase = 2*(ϕ_F + ϕ_B)



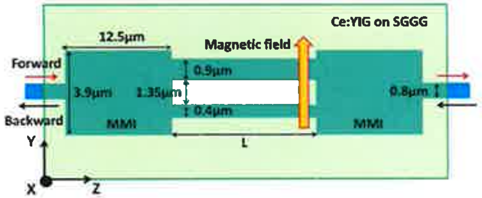


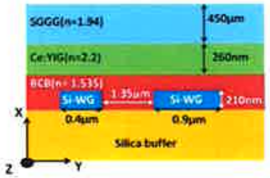
Results:

Isolation: 25 dB
Insertion loss: ~10 dB
BCB thickness: ~ 100nm

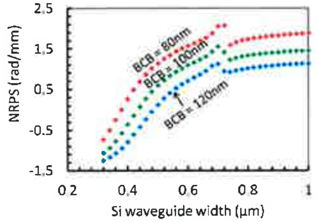
S. Ghosh *et.al*, Optics Express **20**(2), 1839-1848(2012)

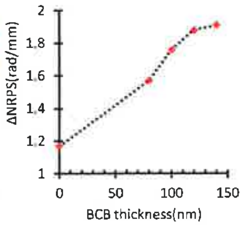
Asymmetric Arm widths type MZI Isolator

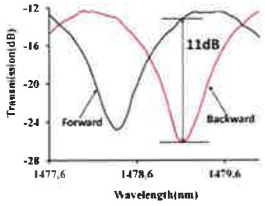




ΔNRPS = NRPS in (Wider arm – Narrower arm)



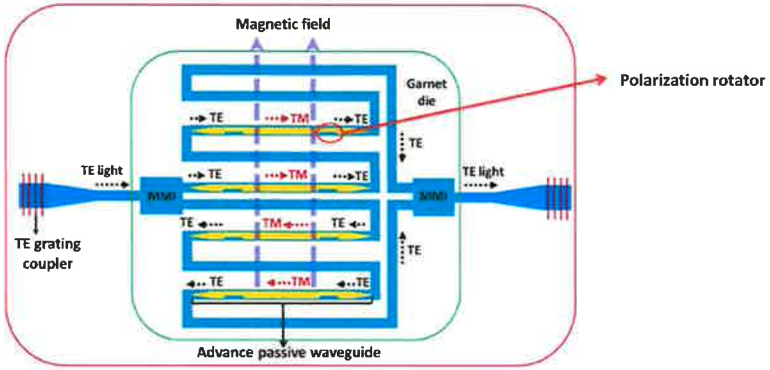




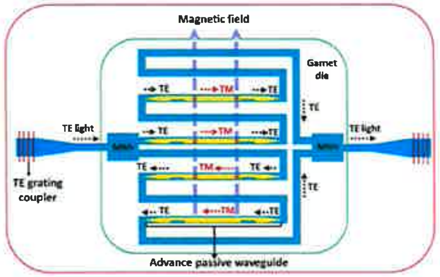
11 dB isolation for L = 1.49mm

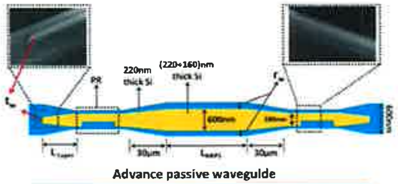
S. Ghosh *et.al*, Photonics Technology Letters **24**(18), 1653-1656(2012)

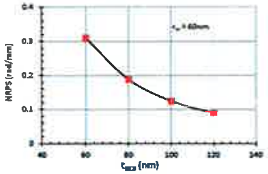
TE-Isolator: Design

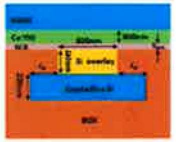


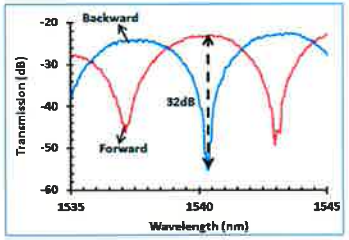
TE Isolator







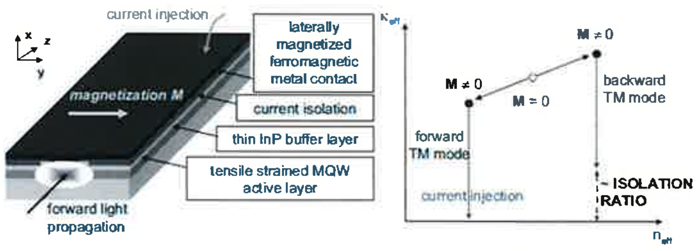


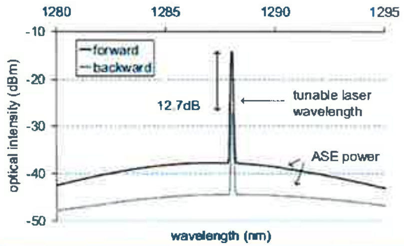


Isolation: ~ 32dB, NRPS: ~ 0.27 rad/mm
Insertion loss: ~22 dB

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

FeCo ferromagnetic isolator on InP SOA





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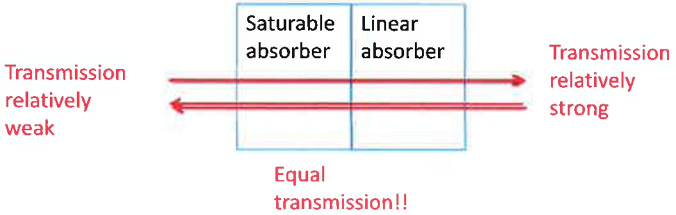
Open questions

Breaking reciprocity by nonlinear effects

Third order nonlinear effects (Kerr-effect, two-photon absorption, saturable absorption…): $n=n_0 + n_2|E|^2$



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

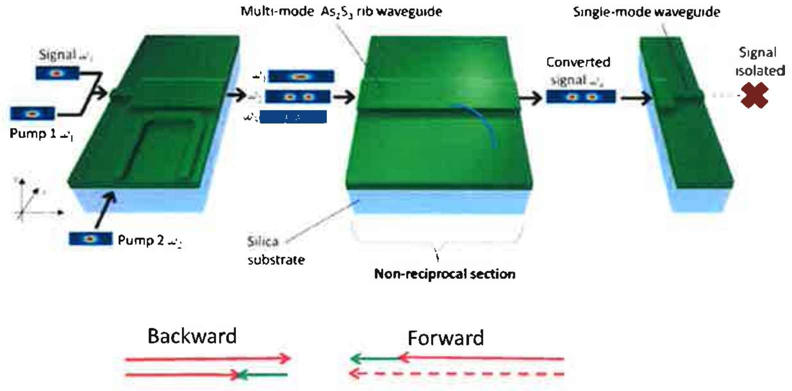
Need an effect that is

- linear in the signal
- nonlinear in combination of pump and signal
- different for forward signal and backward signal

Example: 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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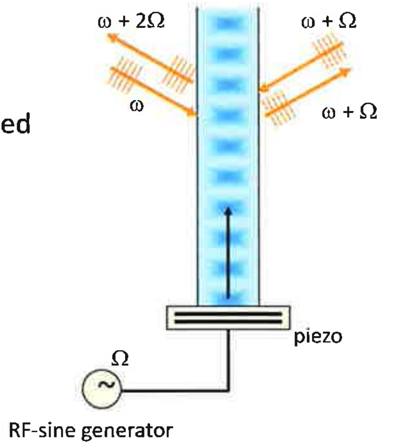
Acousto-optic diffraction leads to frequency shift

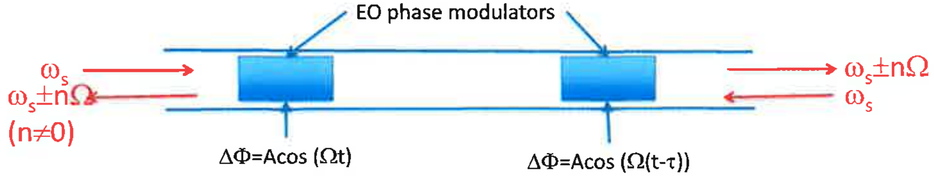
Reflected signal is frequency shifted

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 is large enough:

$1/\Omega$ < propagation time of optical signals on chip (~100ps)

Hence Ω in GHz range!

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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

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; thermal budget problem
- 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?

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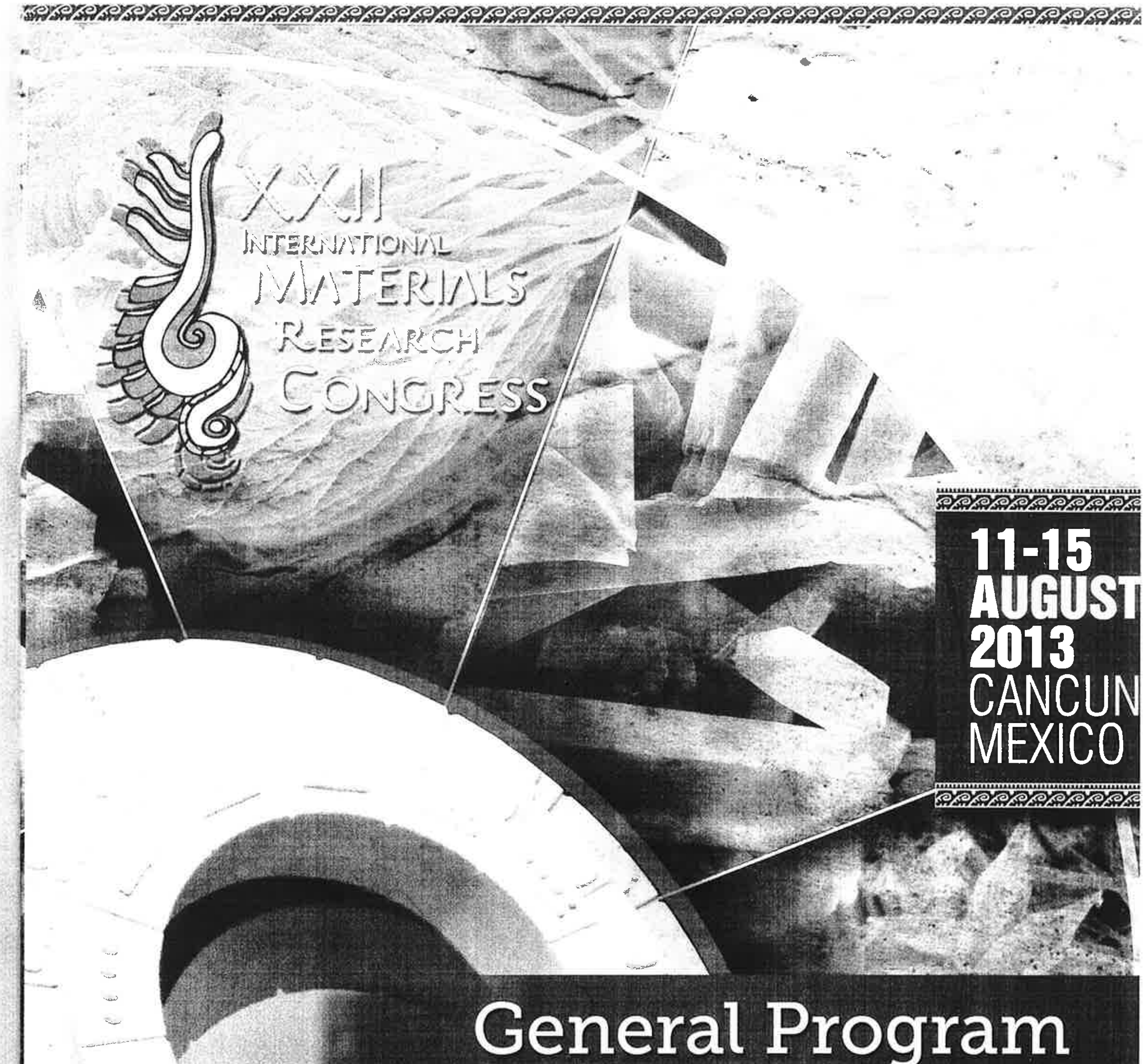
Dirk Jalas, Alexander Petrov, Manfred Eich, Wolfgang Freude, Shanhui Fan, Zongfu Yu, Miloš Popović, Andrea Melloni, John D. Joannopoulos, Mathias Vanwolleghem, Christopher R. Doerr and Hagen Renner
What is – and what is not – an optical isolator, Nature Photonics 7, pp 579–582(2013)



XXII International Materials Research Congress

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Monday

Isolator Session

9:30 Welcome Comments

9:45	Mizumoto, Tetsuya	Tokyo Institute of Technology	SILICON WAVEGUIDE MAGNETO-OPTICAL NONRECIPROCAL DEVICES
10:15	Levy, Miguel	Michigan Technological University	OPTICAL ISOLATION VIA NONRECIPROCAL BLOCH OSCILLATIONS AND RESONANT DELOCALIZATION
10:45	Block, Andrew	University of Minnesota	Achieving Phase-Purity in Substituted Yttrium Iron Garnet Thin films on Silicon Substrates

11 Coffee

11:30-12:30 Plenary

12:30	Ross, Caroline	Massachusetts Institute of Technology	MAGNETOOPTICAL THIN FILM MATERIALS FOR INTEGRATED NONRECIPROCAL PHOTONIC DEVICES
1pm	Hutchings, David	University of Glasgow	QUASI-PHASE-MATCHED FARADAY ROTATION IN SEMICONDUCTOR WAVEGUIDES WITH A MAGNETO_OPTIC CLADDING FOR MONOLITHICALLY INTEGRATED OPTICAL ISOLATORS
1:30	Dulal, Prabesh	University of Minnesota	UNIQUE MAGNETO-OPTICAL GARNETS THIN FILMS

2pm-4pm Lunch

Novel Applications for Garnet

4pm	Baryshev, Alexander	Toyohashi University of Technology	FARADAY ROTATION ENHANCEMENT, CANCELATION AND POLARIZATION CONVERSION BY PLASMONIC GARNET&ndashGOLD STRUCTURES
4:30	Zayets, Vadym	Advanced Institute Industrial Technology	OPTICAL ISOLATOR UTILIZING SURFACE PLASMONS
5pm	Aragão de Carvalho, Carlos Alberto	Universidade Federal do Rio de Janeiro	METRIC SIGNATURES WITH DISPERSIVE METAMATERIALS
→ 5:15	Baets, Roel	University of Ghent, IMEC	Integrated Isolators for Photonics
5:45	Ordonez-Romero,	Universidad Nacional Autónoma de México	Optical Control of Spin Waves in Yttrium Iron Garnet Films

Tuesday

Garnet Films for Imaging

9am	Nikitenko, Valerian	National Institute of Standards and Technology	MAGNETO-OPTICAL IMAGING OF MAGNETIZATION REVERSAL PROCESSES: ASYMMETRY IN QUASI TWO-DIMENSIONAL NANOMAGNETS
9:30	Polyanskii, Anatolii	Florida State University	MAGNETO-OPTICAL STUDY OF SUPERCONDUCTORS BY USING GARNET INDICATORS WITH HIGH FARADEY ROTATION
10am	Tamegai, Tsuyoshi	The University of Tokyo	FLUX PENETRATIONS INTO THREE-DIMENSIONAL SUPERCONDUTING NANOSTRUCTURES
10:30	Ortiz, Wilson Aires	Universidade Federal de São Carlos	MAGNETO-OPTICAL IMAGING OF FLUX AVALANCHES IN SUPERCONDUCTING FILMS DECORATED WITH LATTICES OF ANTIDOTS – MORPHOLOGY STUDIES

11 Coffee

11:30-12:30 Plenary

12:30	Yeshurun, Yosef via Michael Baziljevich	Bar-Ilan University (and U. Oslo)	MAGNETO-OPTICAL IMAGING OF FINGER-LIKE FLUX FRONT PATTERNS IN PARTIALLY IRRADIATED $Bi_2Sr_2CaCu_2O_{8+\&delta}$ CRYSTALS
1pm	Wenzel, Benjamin	INNOVENT e.V. Technology Development	APPLICATIONS FOR MAGNETO-OPTICAL IMAGING USING IRON GARNET FILMS
1:30	Johansen, Tom	University of Oslo	MAGNETO-OPTICAL IMAGING OF THE EFFECT OF STOP-HOLES ON THERMO-MAGNETIC AVALANCHE PROPAGATION IN SUPERCONDUCTING FILMS