Nonreciprocal polarization converter consisting of asymmetric waveguide with ferrimagnetic Ce:YIG

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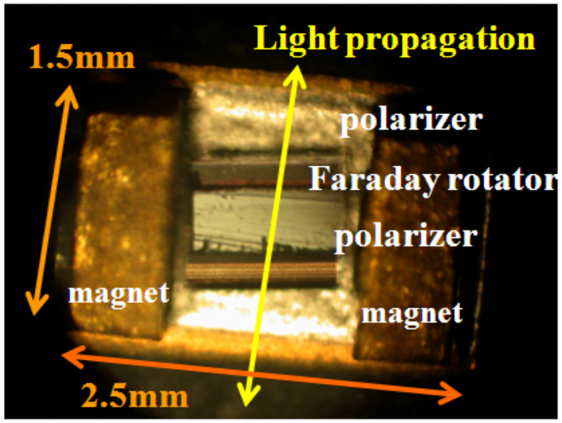
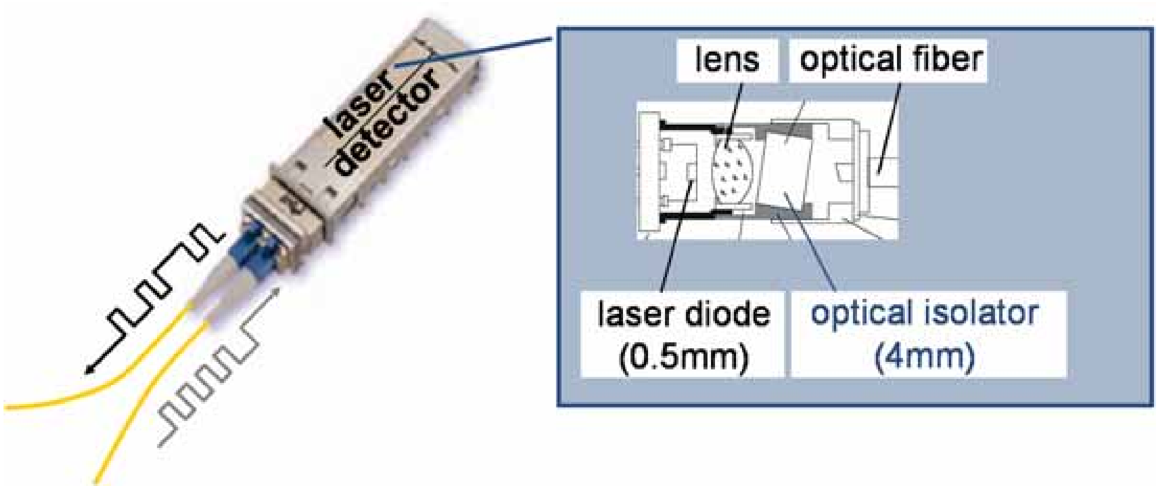
Introduction

Commercially available optical isolators

⇒ Faraday rotation of the magneto-optical materials (garnets).



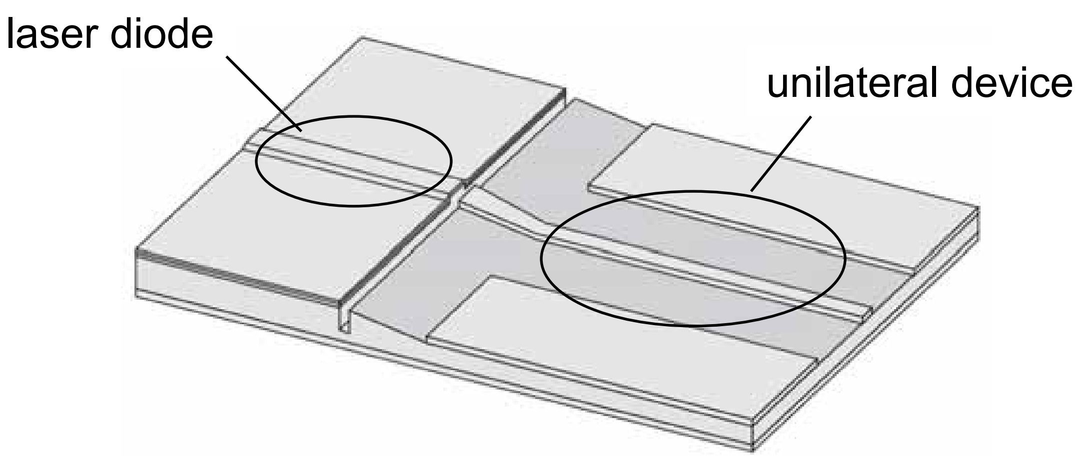


Conventional bulk isolators are not suitable for monolithic integration with other waveguide-based optical devices.

Waveguide-based unilateral devices

Waveguide-based unilateral devices

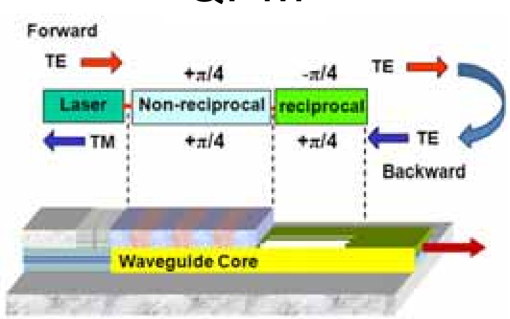
- enhancement of stability in photonic integrated circuits
- reduction of cost and size of laser diode package



Waveguide isolators studied in recent years

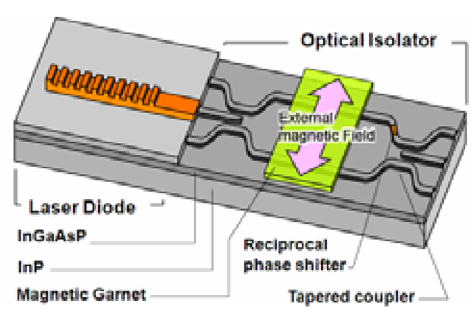
Type	Material	Performance	Fabrication	Size
QPM faraday rotation	Ce:YIG/ GaAs/AlGaAs	< 10 dB/mm	△	< 1 mm
Nonreciprocal phase shift (NRPS)	Ce:YIG/ GaInAsP/InP	30 dB/mm	×	2 - 4 mm
Nonreciprocal loss (NRL)	Fe/ GaInAsP/InP	15 dB/mm	○	< 0.5 mm

QPM



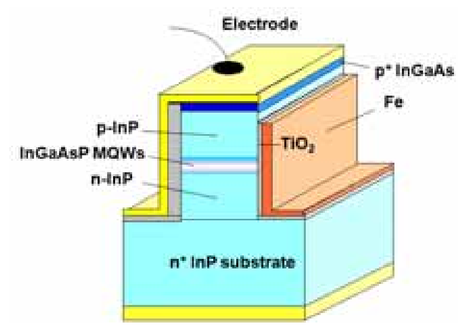
APL **88**, 061116 (2006)

NRPS



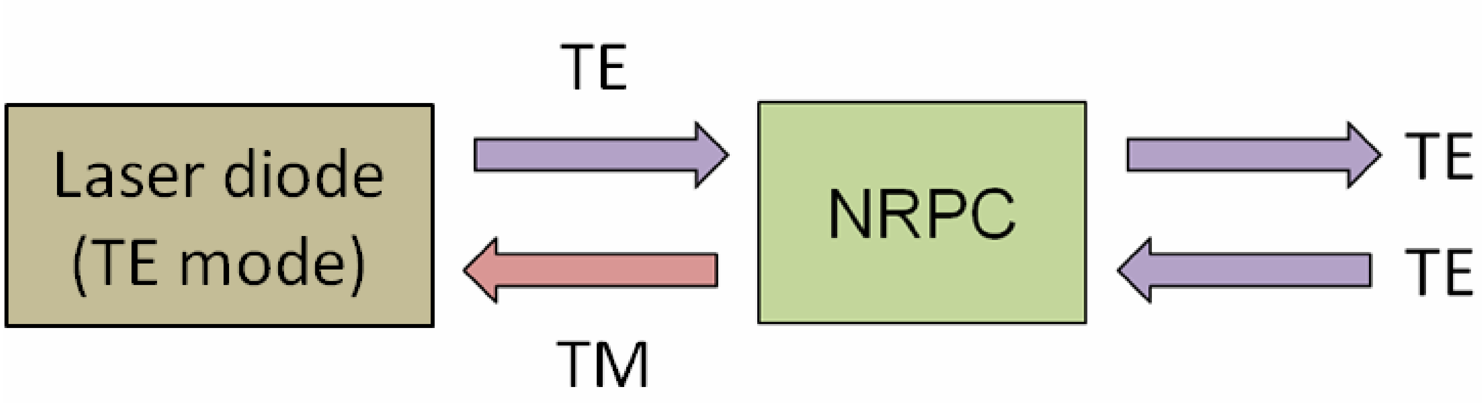
Appl. Opt. **39**, 6158 (2000)

NRL



APL **88**, 071115 (2006)
JLT **24**, 38 (2006)

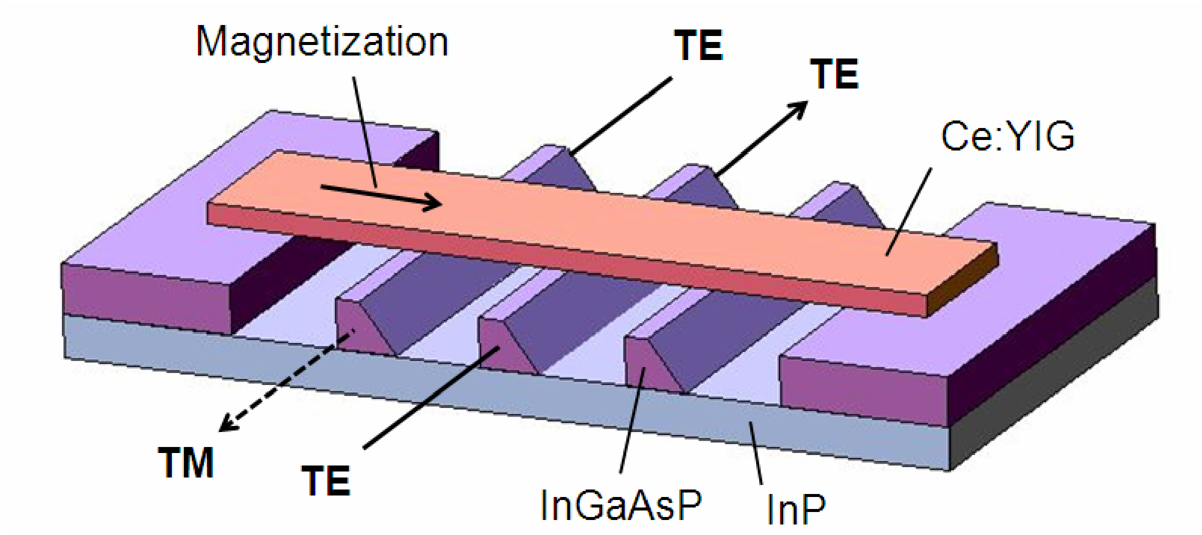
Concept of nonreciprocal polarization converter



I. By inserting a NRPC at the output port of a laser, we can suppress the coherent interference between the lasing light and back-reflected light.

II. We can also make a waveguide isolator by combining the NRPC with a waveguide polarizer or mode splitter.

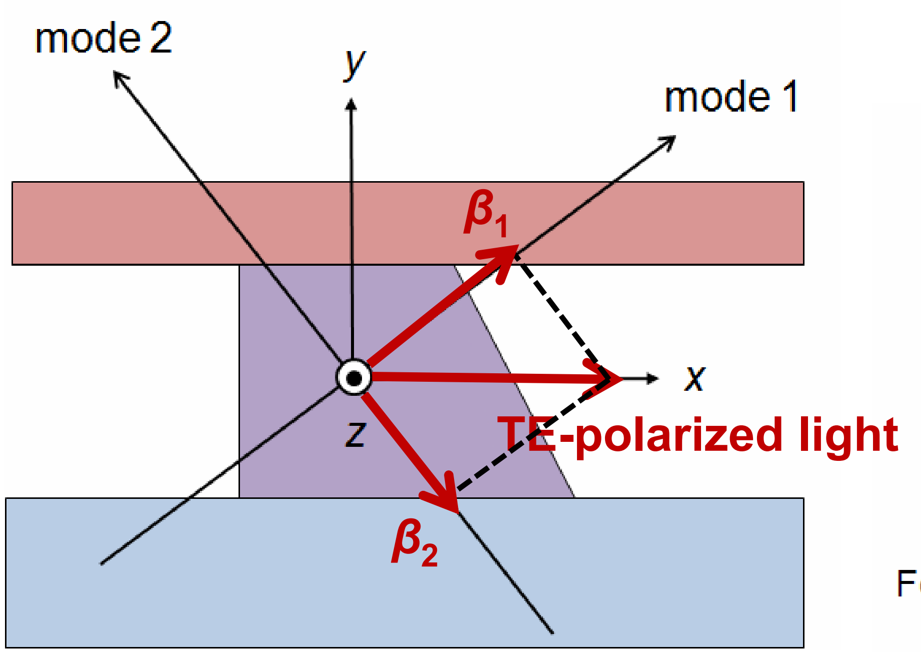
Structure of our NRPC

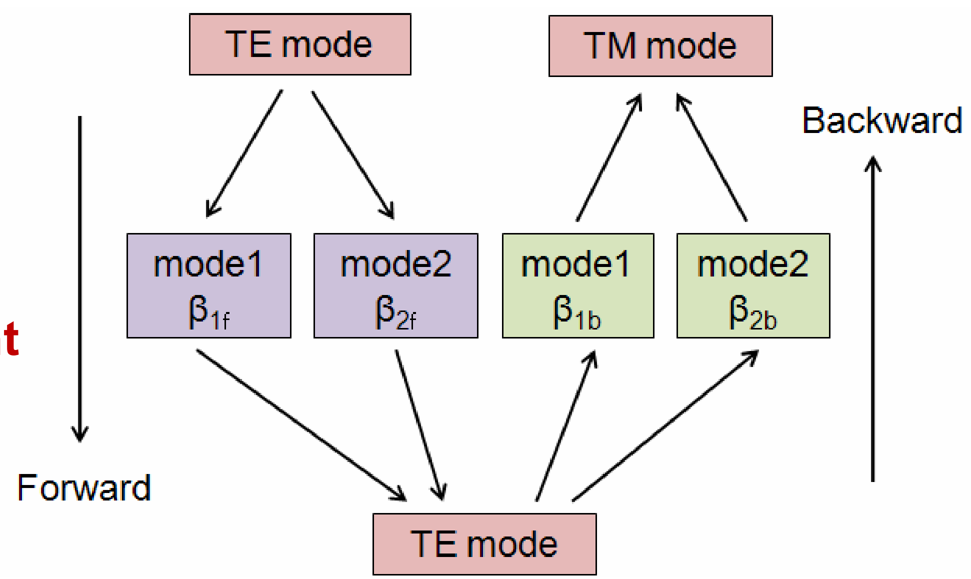


Our device has several advantages over other waveguide-based unilateral devices reported so far.

Material	Performance	Fabricatio	Size
Ce:YIG/ GaInAsP/InP	Over 90 % nonreciprocal polarization conversion (without electric power)	○	< 0.3 mm

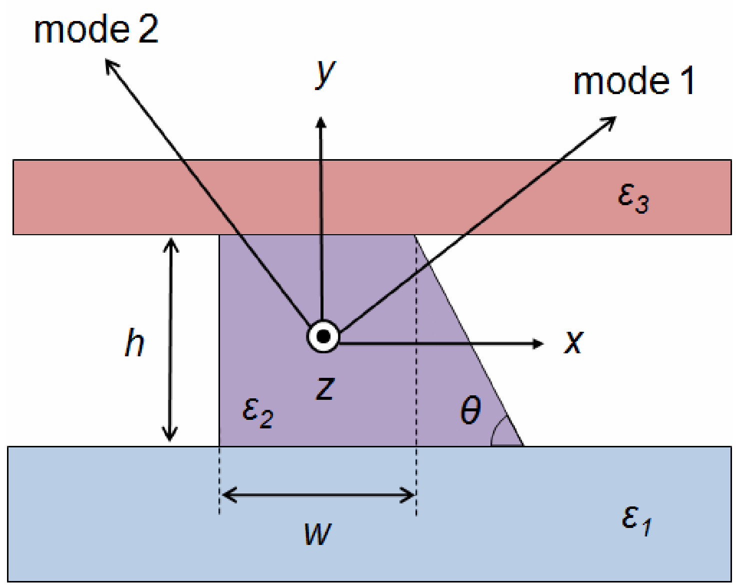
Basic principle of our NRPC





The values of β_1 and β_2 are different between forward and backward propagations because of the magneto-optic transverse Kerr effect induced by the ferrimagnetic Ce:YIG.

Parameters for simulation



@1.55μm

Symbol	Parameter	Value
ε_1	Refractive index of InP	3.16
ε_2	Refractive index of GaInAsP	3.4
ε_3	Refractive index of Ce:YIG	2.2
Θ	Magneto-optical effect for Ce:YIG	-4500 (deg/cm)
θ	Angle of the asymmetric waveguide	53°
h	Height of the device	**1.1** (μm)
w	Width of the device	**0.9 – 1.4** (μm)

Simulation process

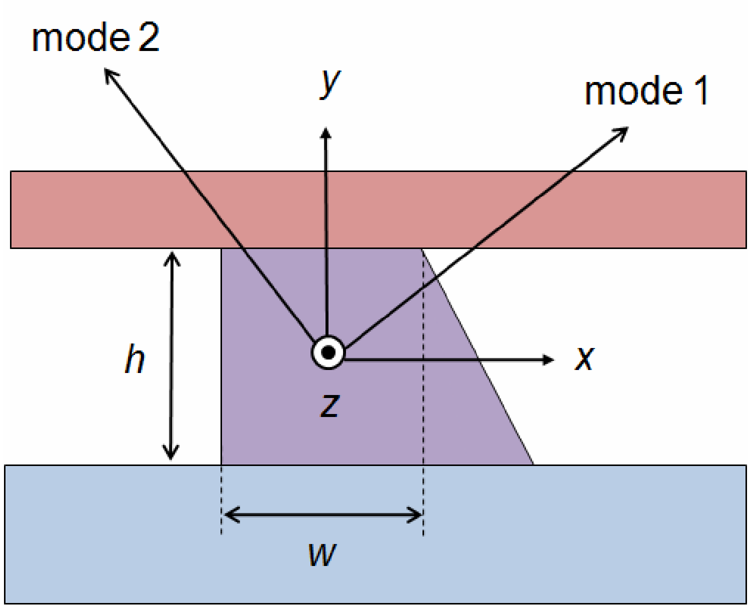
<x-y plane>

With the aid of FDM (full-vector wave equations)
(1)Propagation constant for each mode
(2)Electric field distribution

Optimize the device structure

<z-axis>

With the aid of vectorially corrected (VC) method
Power intensity along light propagation



W. P. Huang, JQE **29**, 2639 (1993)
M. Fontaine, JOSA B **15**, 964 (1998)

Full-vector wave equations (x-y plane)

Dielectric tensor of each layer
$$\varepsilon^{\mu\nu} = \begin{pmatrix} \varepsilon_r & 0 & 0 \\ 0 & \varepsilon_r & j\alpha \\ 0 & -j\alpha & \varepsilon_r \end{pmatrix}$$

Non-magnetic layer

1st
$$\partial_x{}^2 E_x + \partial_y{}^2 E_x + (k_0{}^2\varepsilon_r - \beta^2)E_x + \partial_x(\frac{1}{\varepsilon_r}\partial_x\varepsilon_r \cdot E_x) + \partial_x(\frac{1}{\varepsilon_r}\partial_y\varepsilon_r \cdot E_y) = 0$$

2nd
$$\partial_x{}^2 E_y + \partial_y{}^2 E_y + (k_0{}^2\varepsilon_r - \beta^2)E_y + \partial_y(\frac{1}{\varepsilon_r}\partial_x\varepsilon_r \cdot E_x) + \partial_y(\frac{1}{\varepsilon_r}\partial_y\varepsilon_r \cdot E_y) = 0$$

Magnetic layer

1st
$$\partial_x{}^2 E_x + \partial_y{}^2 E_x + (k_0{}^2\varepsilon_r - \beta^2)E_x + \partial_x(\frac{1}{\varepsilon_r}\partial_x\varepsilon_r \cdot E_x) + \partial_x(\frac{1}{\varepsilon_r}\partial_y\varepsilon_r \cdot E_y) + \alpha\omega\mu_0\partial_x(\frac{\Psi}{\varepsilon_r}) = 0$$

2nd
$$\partial_x{}^2 E_y + \partial_y{}^2 E_y - \beta^2 E_y + \Lambda + \partial_y(\frac{1}{\varepsilon_r}\partial_x\varepsilon_r \cdot E_x) + \partial_y(\frac{1}{\varepsilon_r}\partial_y\varepsilon_r \cdot E_y) + \alpha\omega\mu_0\partial_y(\frac{\Psi}{\varepsilon_r}) = 0$$

$$\Psi = \frac{\alpha\omega\varepsilon_0}{\varepsilon_r\beta^2 + k_0{}^2\alpha^2}[\frac{\varepsilon_r\beta}{k_0{}^2\alpha}(\partial_x{}^2 E_y - \partial_x\partial_y E_x) - \partial_x(\varepsilon_r E_x) - \partial_y(\varepsilon_r E_y) - \frac{\varepsilon_r{}^2\beta}{\alpha}E_y]$$

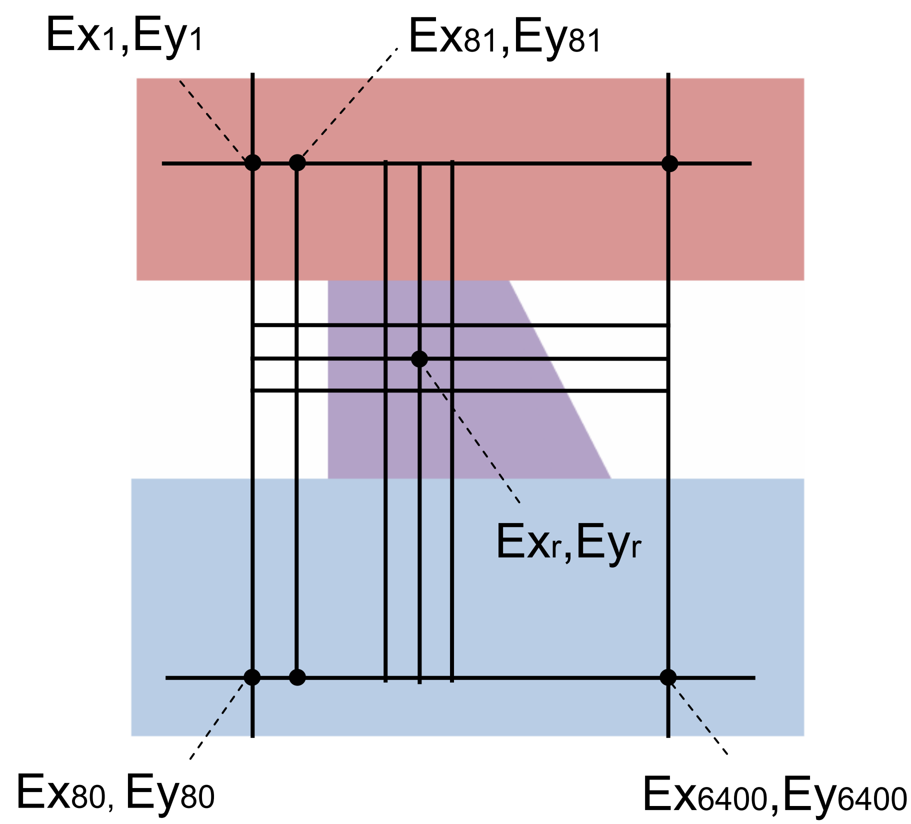
$$\Lambda = \frac{k_0{}^2\alpha^2}{\varepsilon_r\beta^2 + k_0{}^2\alpha^2}(\partial_x{}^2 E_y - \partial_x\partial_y E_x) + \frac{\alpha\beta k_0{}^2}{\varepsilon_r\beta^2 + k_0{}^2\alpha^2}[\partial_x(\varepsilon_r E_x) + \partial_y(\varepsilon_r E_y) + \frac{\varepsilon_r{}^2\beta}{\alpha}E_y]$$

FDM solution (x-y plane)

Using the discrete form of the differential operators, we obtained finite-difference equations for electric field component E_x and E_y.

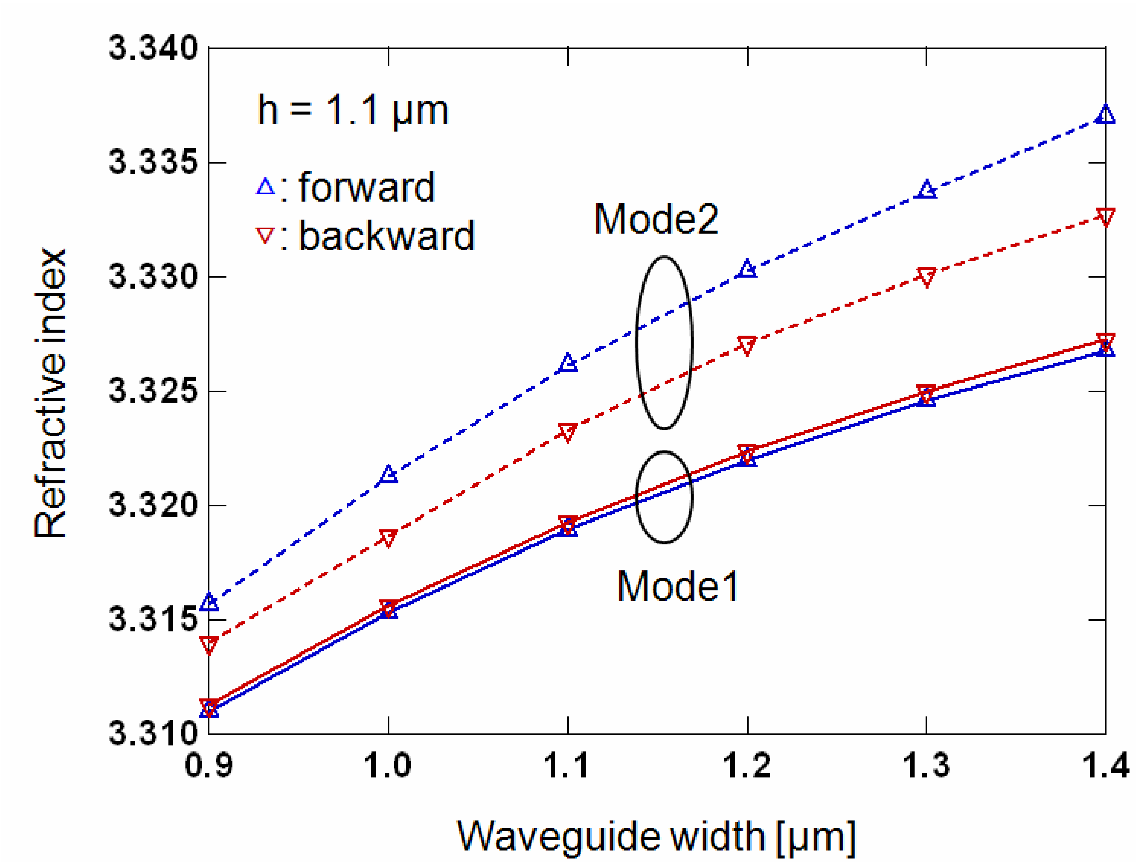
$$\begin{pmatrix} \text{1st Full-vector equation} \\ \text{2nd Full-vector equation} \end{pmatrix} \begin{pmatrix} Ex_1 \\ Ex_2 \\ \vdots \\ Ex_{6400} \\ Ey_1 \\ Ey_2 \\ \vdots \\ Ey_{6400} \end{pmatrix} = 0$$

Mesh: 80×80
Mesh width: 50 (nm)

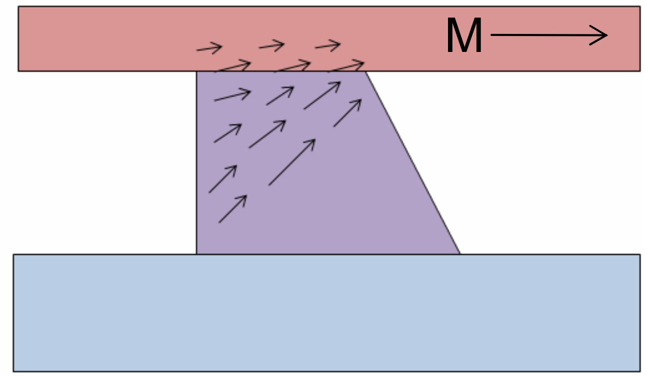


W. P. Huang, JQE **29**, 2639 (1993)

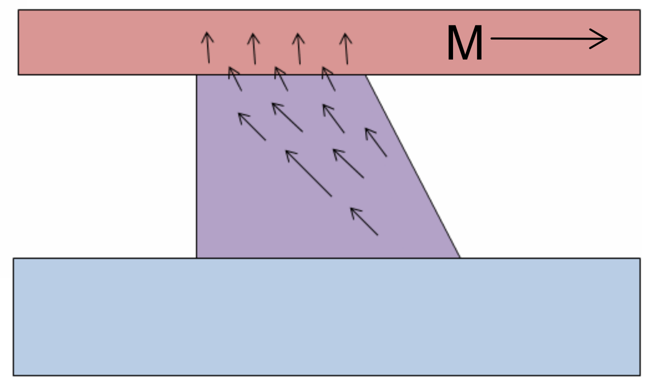
Refractive index for orthogonal two modes



Effective refractive index = β / k_0

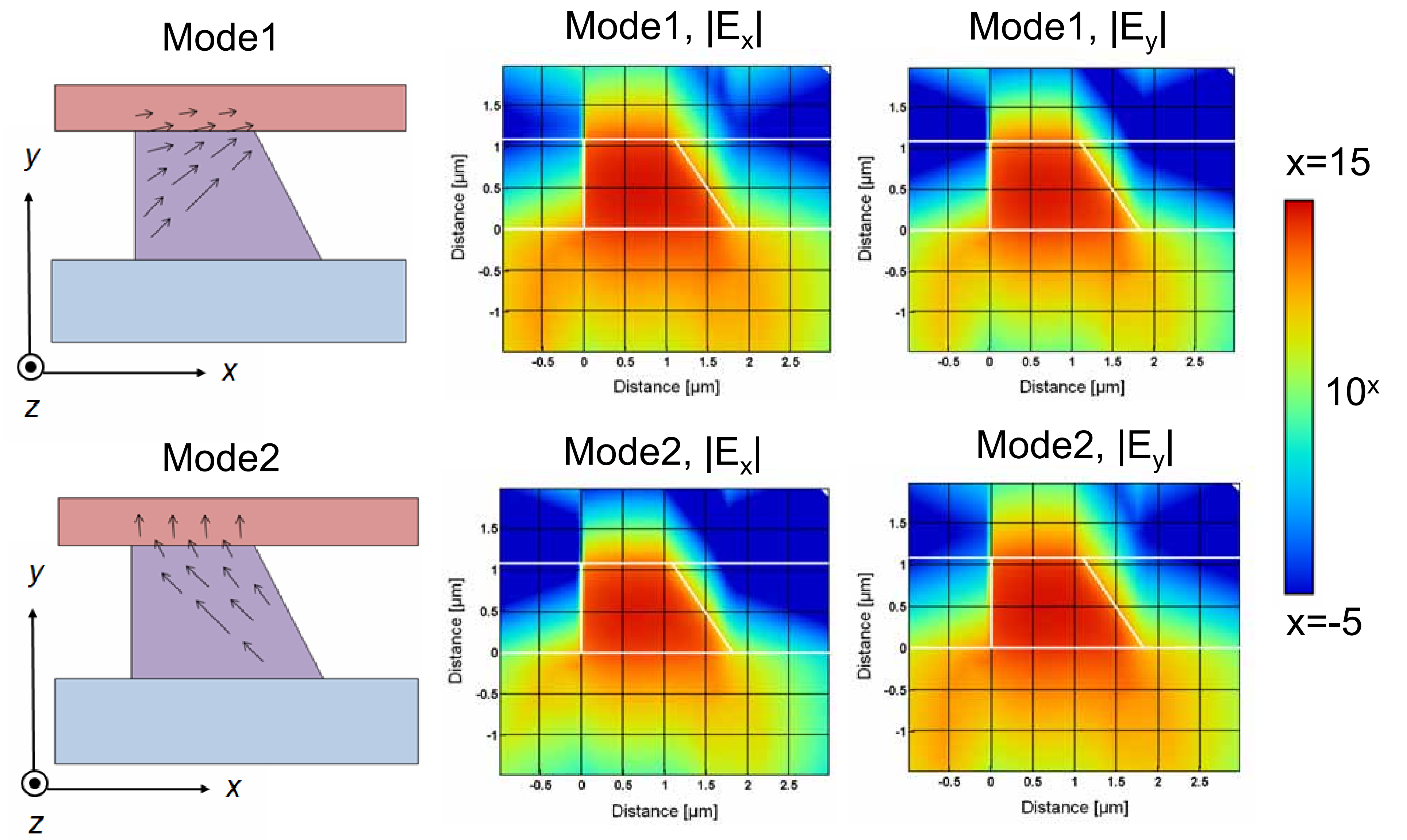


Mode1 (Electric field)



Mode2 (Electric field)

Electric field distributions in our device



Simulation process

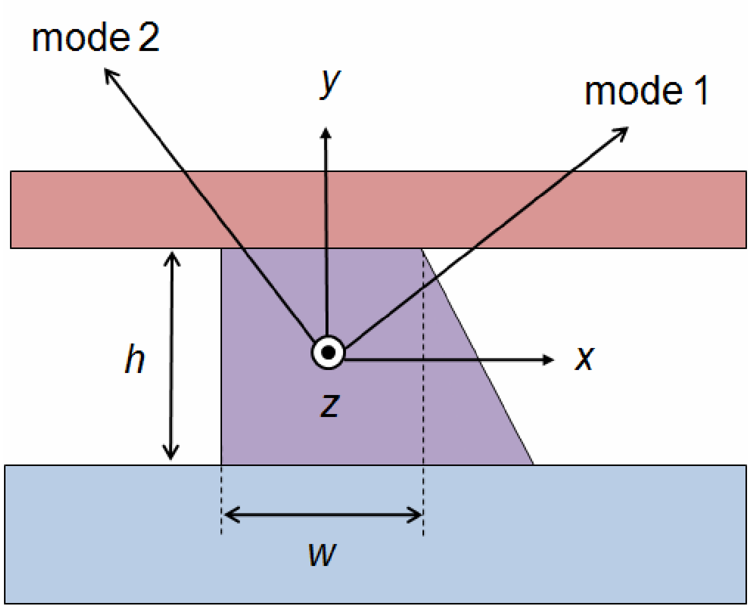
<x-y plane>

With the aid of FDM method (full-vector wave equations)
(1)Propagation constant for each mode
(2)Electric field distribution

Optimize the device structure

<z-axis>

With the aid of vectorially corrected (VC) method
Power intensity along light propagation



W. P. Huang, JQE **29**, 2639 (1993)
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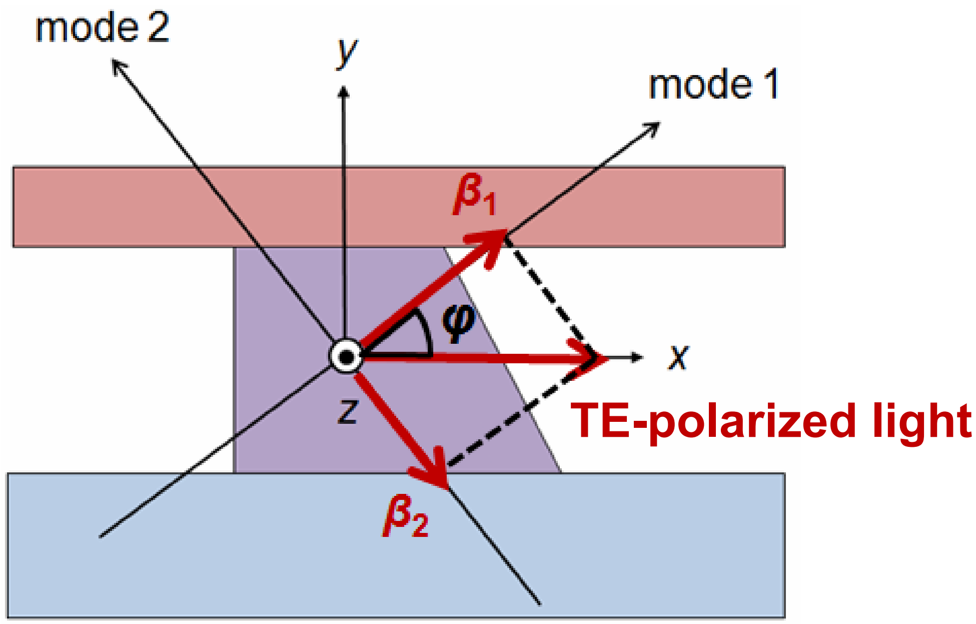
Optimizing the device structure (I)



The necessary conditions for efficient nonreciprocal conversion

✓ Backward half-beat length is twice as large as forward one.
✓ Angle φ should be almost 45°.

Half Beat length

$$L = \frac{\pi}{|\beta_1 - \beta_2|}$$

TE → TM

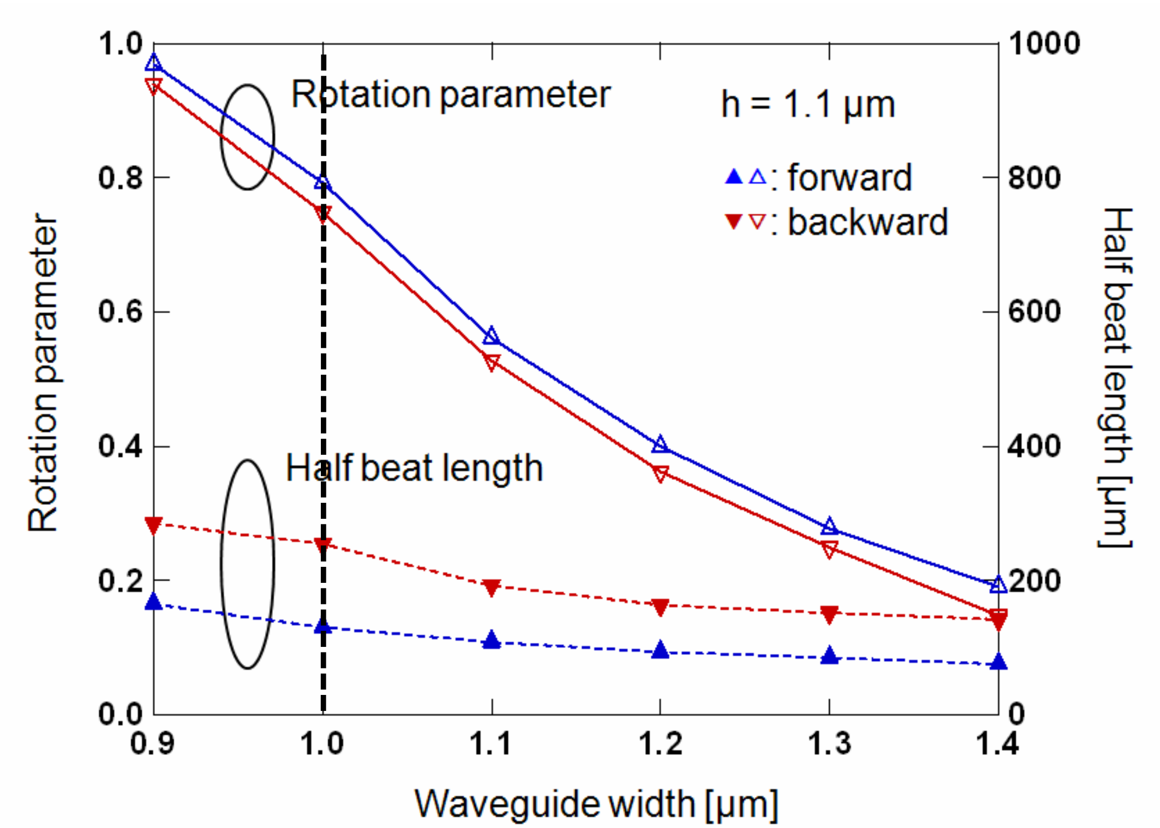
Rotation parameter

$$R = \left| \frac{\int_{A\infty} \varepsilon_r E_y{}^2 dxdy}{\int_{A\infty} \varepsilon_r E_x{}^2 dxdy} \right|$$

R=1 ⇒ φ=45°

K. Saitoh et al., JLT **19**, 405 (2001)

Optimizing the device structure (II)



To achieve an effective non-reciprocal conversion,

(I)The half-beat length for backward light must be twice as large as that for forward.

(II)The rotation parameter R should be near 1.

We optimized structure of the device.
w = 1.0 μm, *h* = 1.1 μm

Simulation process

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(1)Propagation constant for each mode
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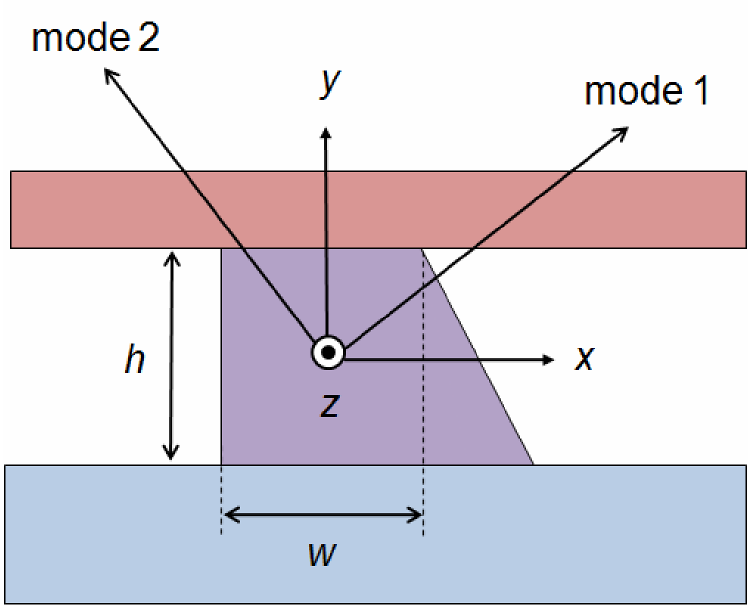

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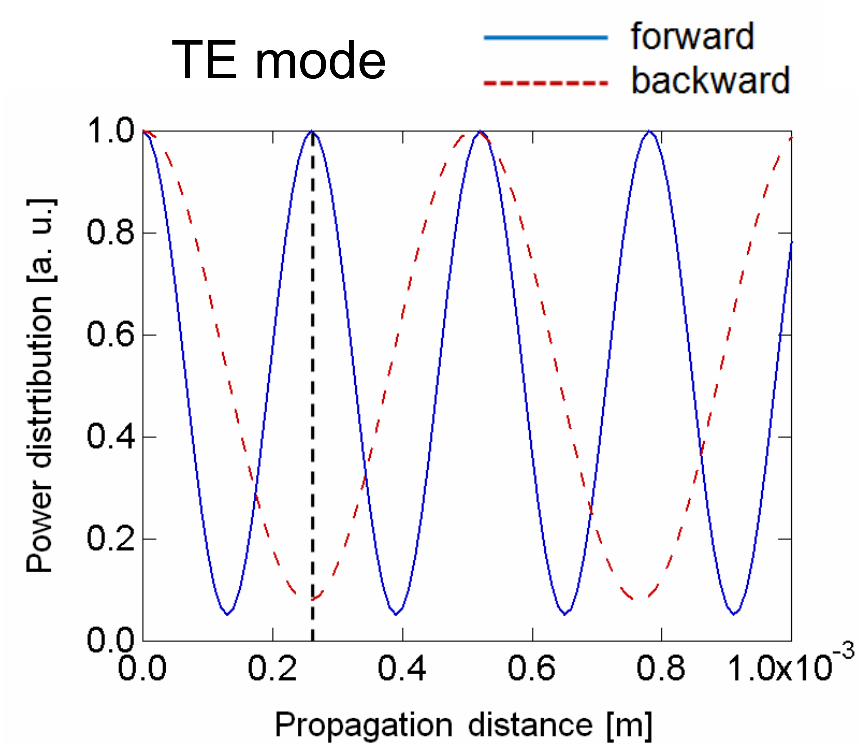
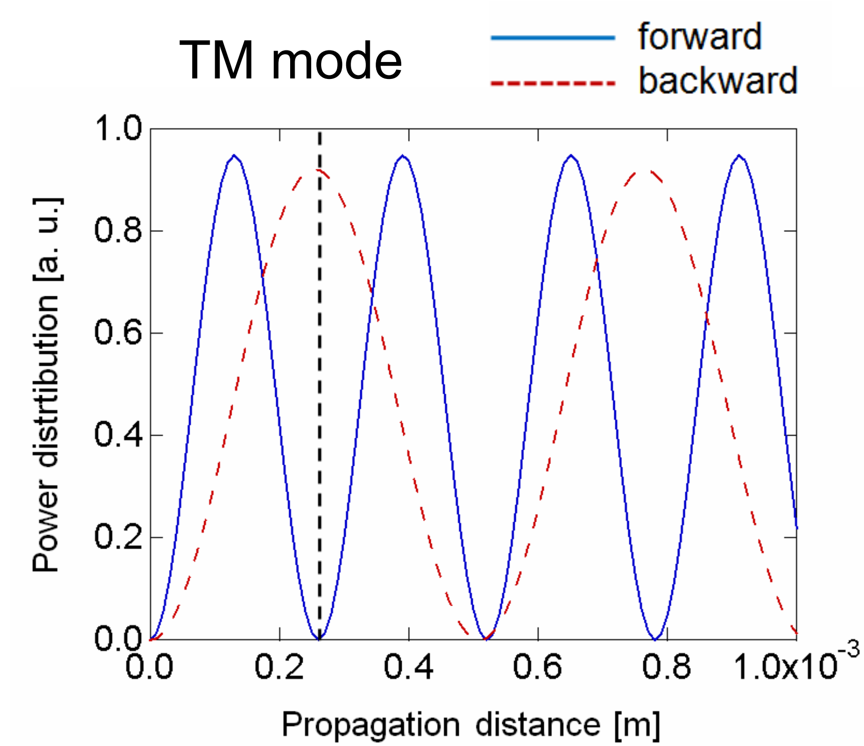
Power intensity along light propagation





$$u(z) = \frac{1 - \exp\left(iz\left|\beta_1 - \beta_2\right|\right)}{R + \frac{1}{R}\exp\left(iz\left|\beta_1 - \beta_2\right|\right)}$$

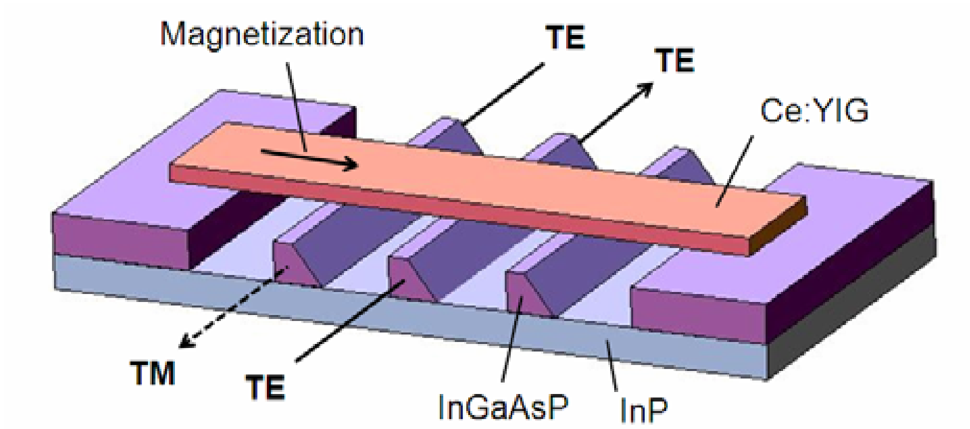
Device length: **0.27mm**
Nonreciprocal polarization conversion: **92%**

Forward light: TE→TE
Backward light: TE→TM

M. Fontaine, JOSA B **14**, 1444 (1997)
M. Fontaine, JOSA B **15**, 964 (1998)

Summary

✓ We proposed a nonreciprocal TE-TM polarization converter for avoiding the problems caused by undesired reflections of light in photonic integrated circuits.



Material	Performance	Size
Ce:YIG/ GaInAsP/InP	93 % nonreciprocal polarization conversion Forward: TE→TE Backward: TE→TM	0.27 mm