Design and Demonstration of Semiconductor Active Waveguide Optical Isolators

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Profs. Yoshiaki NAKANO and Masaaki TANAKA of Univ. of Tokyo

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· *Introduction*

Photonic Integrated Circuits (PICs) issues

· *Operation principle of*

Semiconductor Active Waveguide Optical Isolators

based on the "Nonreciprocal loss".

Difference from conventional "Free space" Optical Isolators

How to take magneto-optic effect into semiconductor waveguide

· *TE mode Waveguide Optical Isolator*

Design, Device structure, Analysis, Fabrication, Measurements

· *Towards optical isolator integrated telecommunication lasers*

Comparison with conventional "Free space" optical isolators and applicability

Photonic Integrated Circuits (PICs)

>EA modulator monolithically integrated DFB LDs are well known and widely available.

>InP based AWGs can be monolithically integrated with SOAs, PDs etc.

>Large scale PIC transmitters and receivers are demonstrated.
AWG, VOA, EAM, DFB LDs, PDs.

R. Nagarajan et al., IEEE J. Select. Topics Quantum Electron. **11**, pp. 50-62, (2005).

However, Optical Isolators are not monolithically integrated.

Introduction

Commercially available ***Optical Isolators***

⇒ Free space type

Faraday rotation of MO materials. ex. garnets ($Ce:Y_2Fe_5O_{12}$ etc.).

:necessary for stable operation of telecommunication semiconductor lasers.

Insertion loss < 0.6dB

Backward loss > 50dB

Compact: W2.5mm D1.5mm H1.5mm

Price in market:

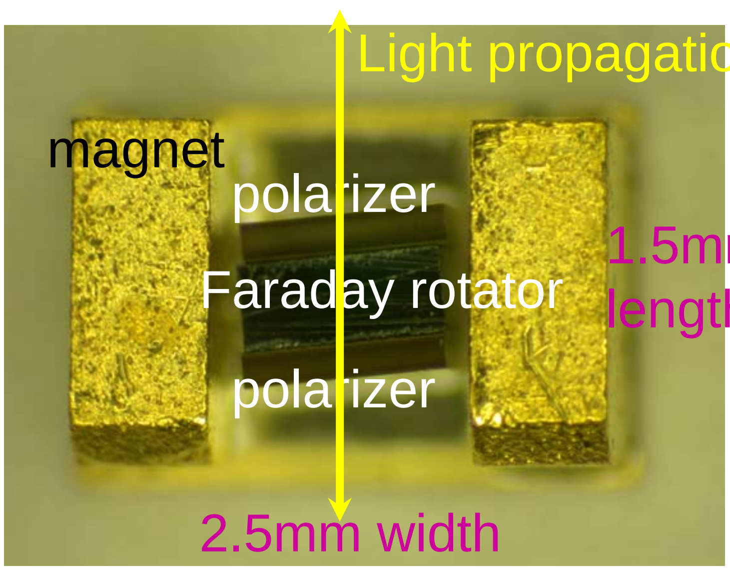
$15 – 20 (not including assembly cost on Transmitter modules)

But,

two polarizers are necessary,

material and device structure are not compatible with semiconductor LDs.

Conventional Faraday Isolator



Namiki

http://www.namiki.co.jp/nqt/index.html

Need of integrable optical isolators

Assembly cost of optical isolators is high.

⇒Semiconductor Waveguide Optical isolators are strongly desired.

for

· monolithic integration with laser diodes.

· robust operation of highly functional PICs (cascadability is allowed).

All optical devices
・ Wavelength converters,
・ All Optical Switches,
・ Optical Flip-Flops, etc.
are vulnerable to undesired external light noise.

Nonreciprocal functions are unique to magnetic materials…
Normal semiconductors can not handle nonreciprocal function…
Some solutions are necessary…

Previously reported Waveguide Optical Isolators

· Nonreciprocal TE-TM mode conversion type (YIG)

K. Ando et al., Appl. Phys. Lett., **53**, 4, (1988).

· Nonreciprocal radiation type (YIG)

T. Shintaku, Appl. Phys. Lett., **73**, 1946, (1998).

· Nonreciprocal phase shift type (YIG)

(Wafer bonding on **InP** substrate) H. Yokoi et al., Appl. Opt., **38**, 7409 (1999).

J. Fujita et al., Appl. Phys. Lett., **75**, 998, (1999).

· **"Nonreciprocal loss" type**

(Co and GaAs substrate, design)

W. Zaets et al., IEEE., Photon. Tech. Lett., **11**, 1012, (1999).

(Fe and **InP** substrate, design)

M. Takenaka and Y. Nakano IPRM1999.

Waveguide optical isolator based on the nonreciprocal loss

= Ferromagnetic metal + Semiconductor Optical Amplifier (SOA)

Research history

· Fe + InGaAsP SOA, Transverse Magnetic (TM) mode, design. M. Takenaka and Y. Nakano. IPRM (1999).

· Co + GaAs SOA, TM mode, design. W. Zaets et al., IEEE. Photon. Tech. Lett., **11**, 1012, (1999).

demonstration, 1dB/mm Appl. Phys. Lett. 86, 261105, (2005).

· Fe + InGaAsP SOA, Transverse Electric (TE) mode, design,

H. Shimizu and Y. Nakano., first demonstration, TE and TM mode

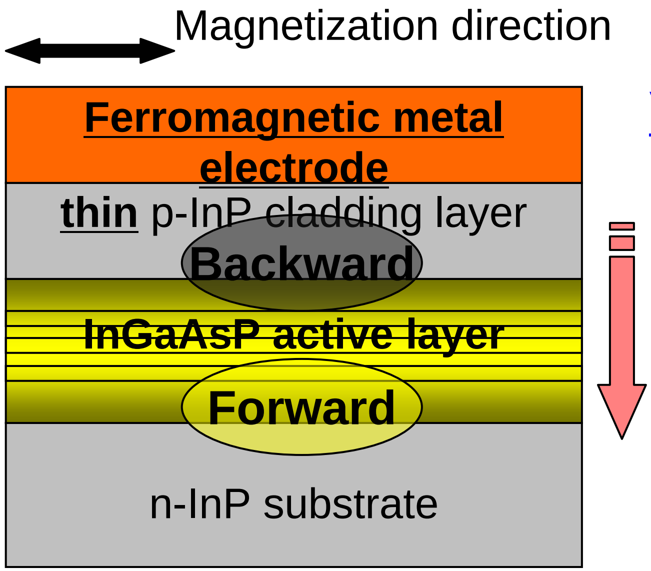
IEEE. J. Lightwave Tech., **24**, 38, (2006), Appl. Phys. Lett., **89**, 021104 (2006),

Jpn. J. Appl. Phys., **43**, L1561, (2004).

· FeCo + InGaAlAs SOA, TM mode, Nonreciprocal propagation (8.1dB/mm).

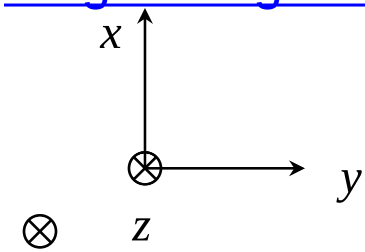
W. V. Parys et al., Appl. Phys. Lett.,**88**, 071115, (2006)

Operation principle



H_y // M for TM mode (essential for nonreciprocal loss)

Voigt configuration, not Faraday configuration



Light // z

M // y

M. Takenaka et al., IPRM 1999.
W. Zaets et al.,
IEEE., Photon. Tech. Lett., **11**, 1012, (1999)

N_{eff}*changes between the forward and backward in the magneto-optical waveguide (SOA)

(Transverse magneto-optical Kerr effect).

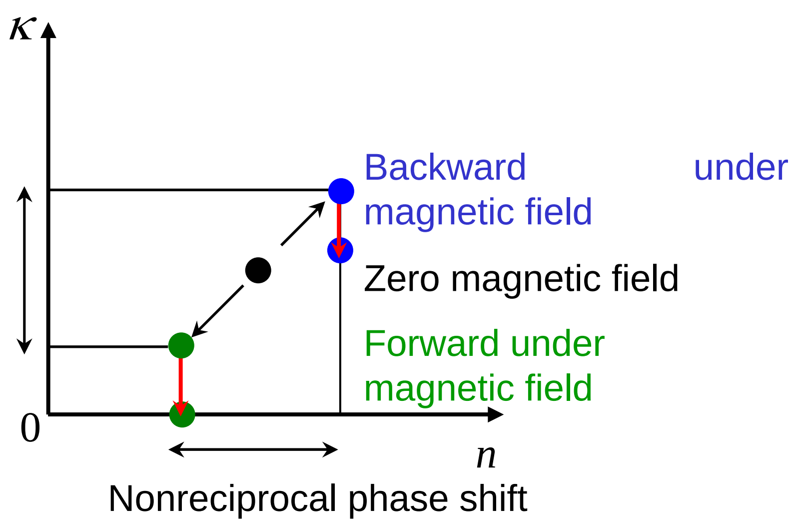
Compensation of the forward light loss by SOA gain.

⇒Optical isolator operation.

TM mode operation.

$$N_{eff}^* = n - i\kappa$$

Nonreciprocal loss shift
⇒isolation ratio



Please note that…

Completely different from “free space” optical isolators.

>Ferromagnetic + semiconductor waveguide provides the nonreciprocal loss.
>Novel research in semiconductor optical waveguides and their numerical simulations.
Significance of the Nonreciprocity

>No polarization rotations. Polarizers are not necessary.

>Great advantage for simple fabrication and monolithic integration.

>Operational wavelength: SOA gain wavelength (depends on semiconductor material and ferromagnetic metal).

InP / InGaAsP, InGaAlAs for λ =1.3 - 1.55μm,

GaAs / InGaAlP, AlGaAs for red,

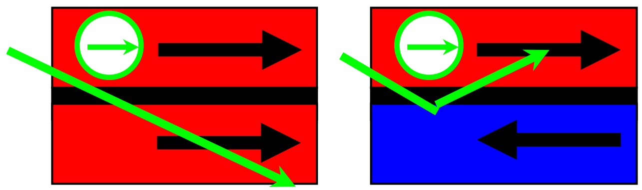
GaN / InGaN for blue and UV.

Analogy with Spin dependent transport phenomena

Giant Magneto Resistance

Conducting electrons (spin polarized)

FM 1
NM
FM 2



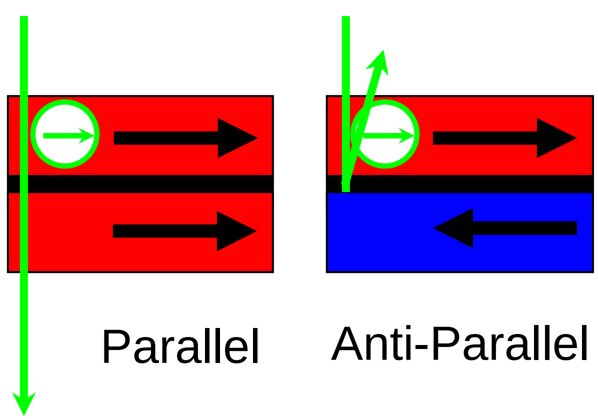
Parallel Anti-Parallel

$R_P < R_{AP}$

Tunneling Magneto Resistance in Magnetic Tunnel Junctions

Conducting electrons (spin polarized)

FM 1
Tunnel barrier
FM 2

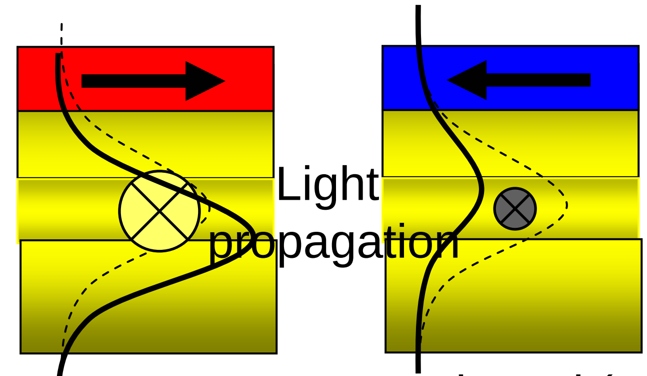


Parallel Anti-Parallel

$R_P << R_{AP}$

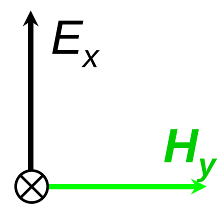
Nonreciprocal loss in optical waveguides with FMs

FM
Clad
Core
Clad



Forward (+H) Backward (-H)

TM-mode propagating light



$H_x = H_z = E_y = 0$

***H_y* (Magnetic field vector)**

Forward: ***Hy*** and ***M*** : Parallel
Backward: ***Hy*** and ***M*** : Anti-Parallel
Propagation loss: Forward < Backward

Optical isolator operation

How to take magneto-optic effect into semiconductor waveguides

Maxwell's equations

$$\nabla \times E = -\mu_0 \frac{\partial H}{\partial t}$$

$$\nabla \times H = \varepsilon_0 \tilde{\varepsilon} \frac{\partial E}{\partial t}$$

$$\tilde{\varepsilon} = \begin{pmatrix} \varepsilon_x & 0 & \varepsilon_{xz} \\ 0 & \varepsilon_x & 0 \\ -\varepsilon_{xz} & 0 & \varepsilon_x \end{pmatrix}$$

ε : dielectric tensor

ε_{xz} : source of magneto-optic effect, proportional to Magnetization

zero for nonmagnetic materials

$\varepsilon_{xz} = 3.15 + 1.8\,i$, $n - ik = 3.27 - 5.27\,I$ $(\varepsilon_x = n^2 - k^2 - 2nk\,i)$

for Fe at $\lambda = 1550nm$

(P. B. Johnson et al., PRB. **9**, 5056, (1974), and G. S. Krinchik et al., JAP. 39, 1276, (1968).)

Magnetic field direction // *y*

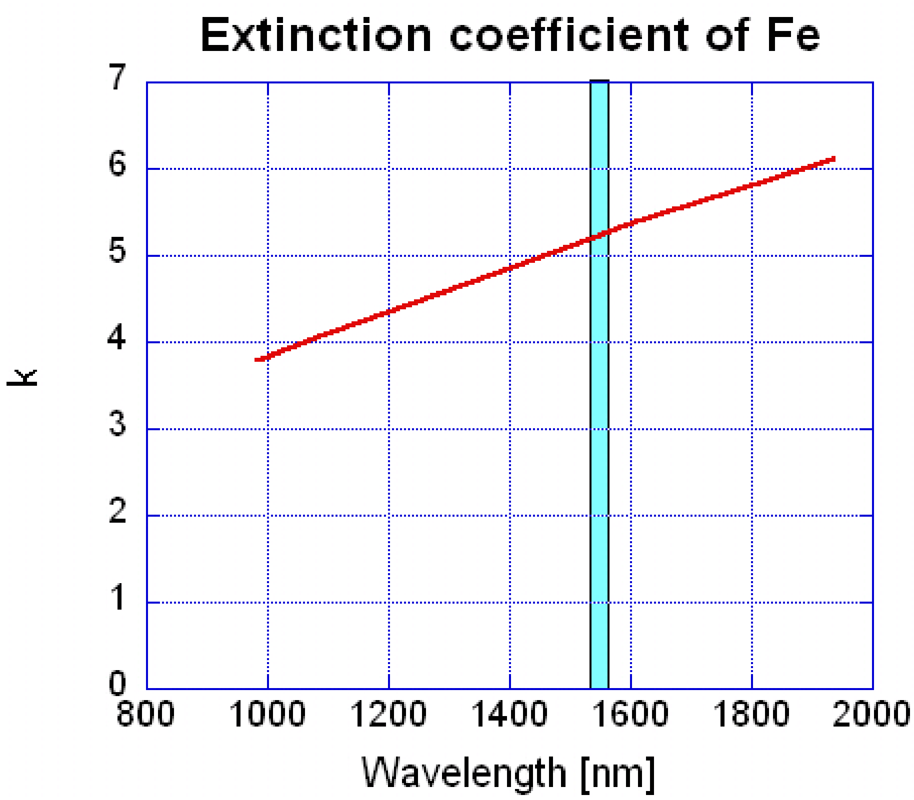
Nonreciprocal propagation: $\Delta\alpha$

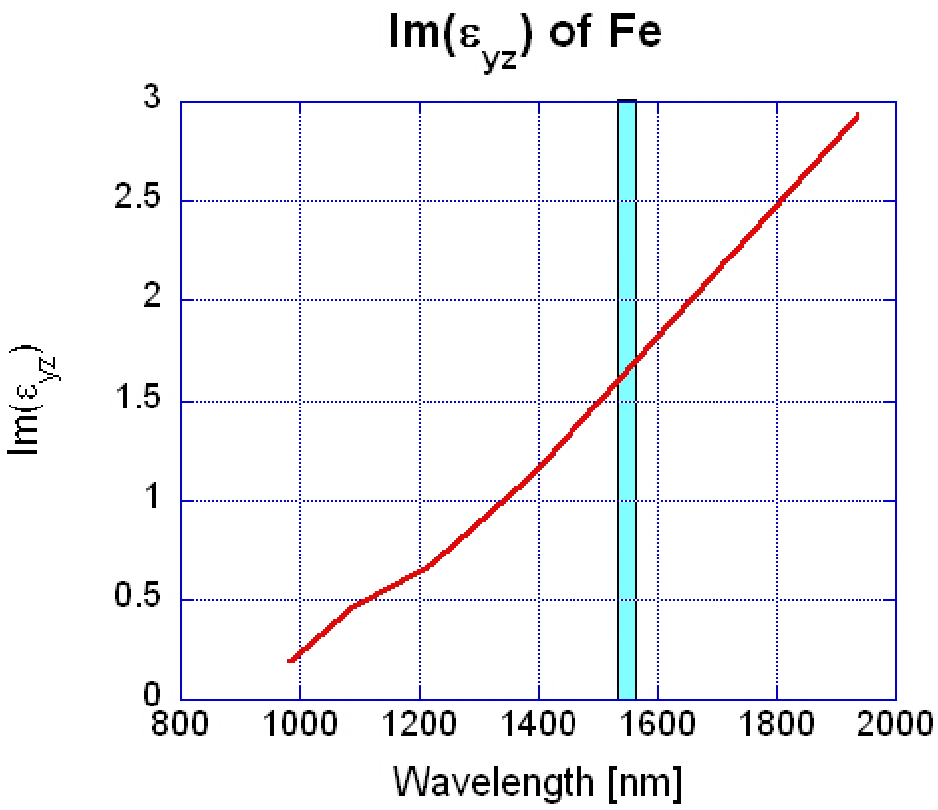
= difference between forward and backward

: inversion of the ε_{xz} sign

$\Delta\alpha$ [dB/mm] = 0.02 Log[e] k_0 Im[$n_{eff.\ forward} - n_{eff.\ backward}$]

Wavelength dependence of the absorption and MO effect of Fe





For longer wavelength,
Both the absorption and MO effect are larger.

P. B. Johnson et al., PRB. **9**, 5056, (1974), and G. S. Krinchik et al., JAP. 39, 1276, (1968)..

TE mode waveguide optical isolator

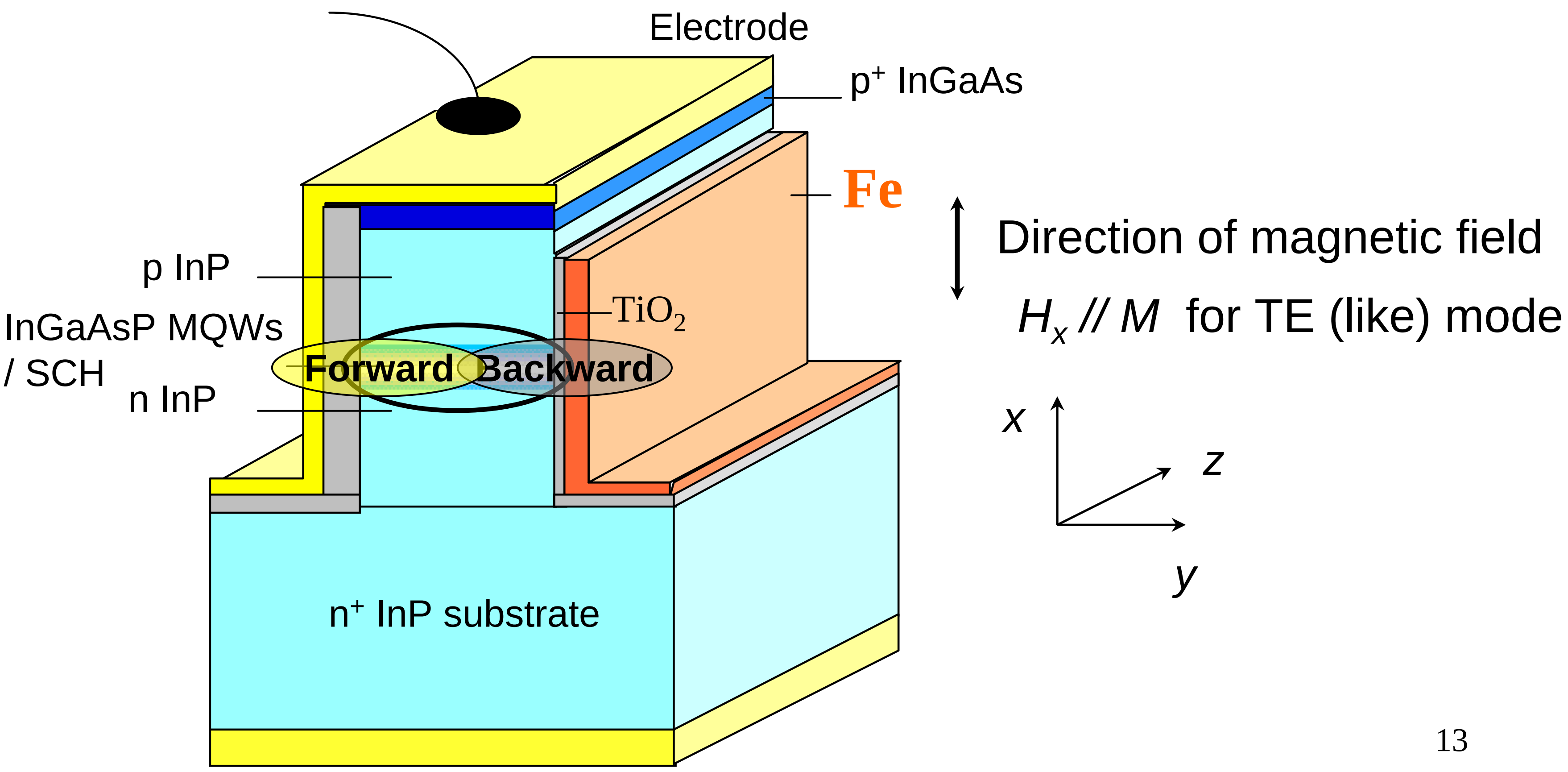
Almost all the edge emitting LDs operate in the TE mode.

⇒

TE mode waveguide optical isolator based on the “nonreciprocal loss”.

Ferromagnetic metal (Fe) on a **sidewall** of the SOA waveguide

λ = 1.55μm



Simulation method, TE mode waveguide optical isolator

“Nonreciprocal loss”: the Effective index method and the perturbation approximation. (Rough estimation)

Nonreciprocal propagation: $\Delta\alpha$

= difference between forward and backward

$\Delta\alpha$ [dB/mm] = 0.02 Log[e] k_0 Im[$\Delta n_{eff,\,TE}$]

$$\Delta n_{eff,TE} = -\frac{i}{2k_0}\frac{\iint_{Fe}\frac{\varepsilon_{yz}}{\varepsilon}H_x^*\frac{\partial H_x}{\partial y}dxdy}{\iint_{all}\left|H_x\right|^2 dxdy}$$

To increase the optical isolation,,,

>large optical confinement in Fe -> thicker core layer

>large magneto-optic effect, MO effect @1550nm Fe > Co >Ni

>small absorption, absorption @1550nm Fe < Co <Ni

->-> Fe is the best for 1550nm

>of course, large SOA gain is necessary

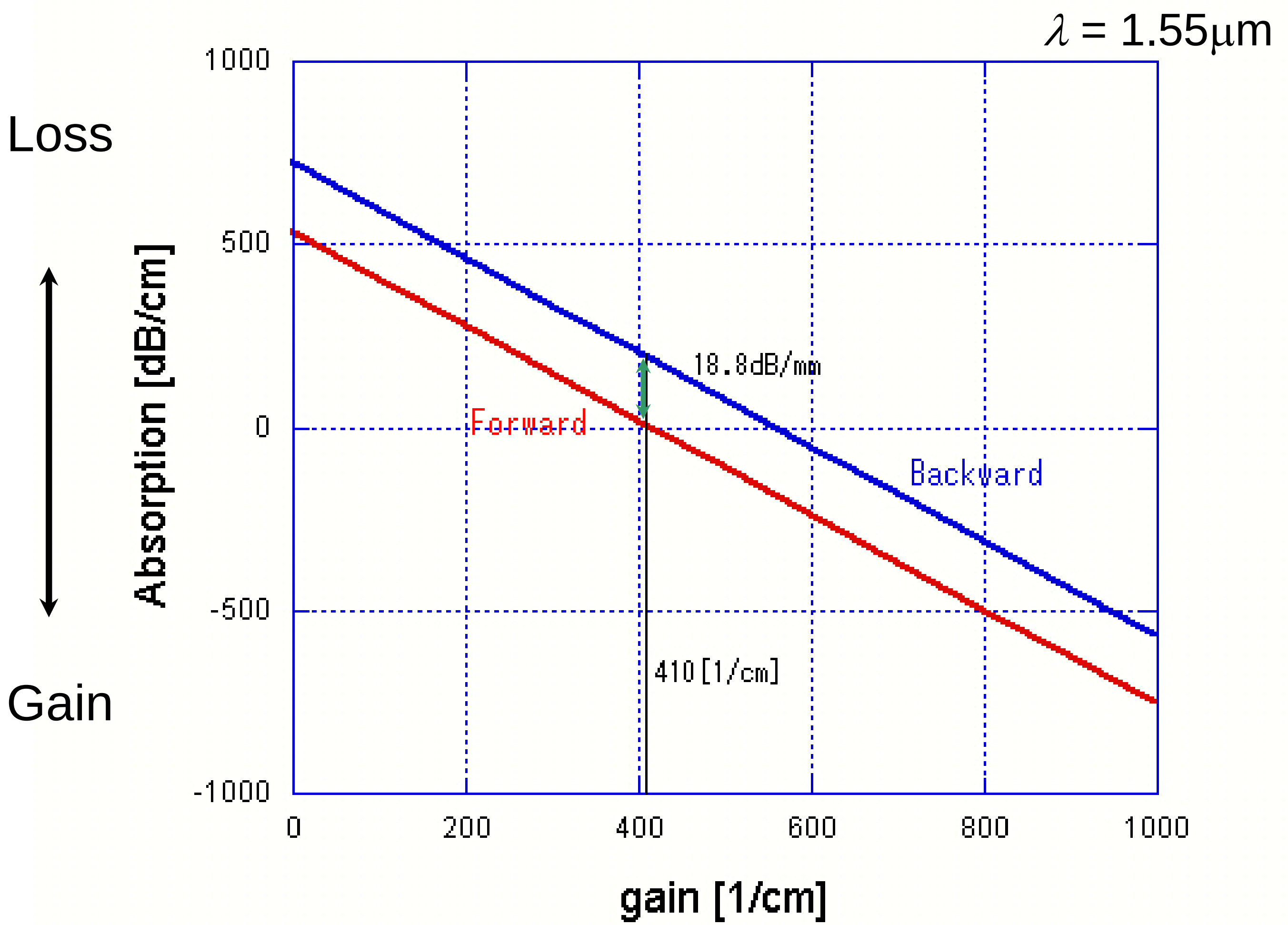
Simulation results

d_{TiO2}=50nm, Waveguide width = 1.5μm

⇒**"Nonreciprolcal loss": 18.8dB/mm**

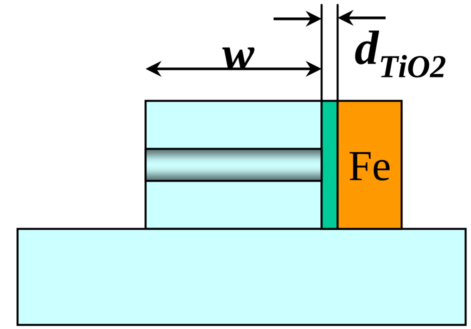
(Device length for 30dB isolation: **1.6mm**).

The MQW gain necessary for transparent forward light: **410cm^{-1}**



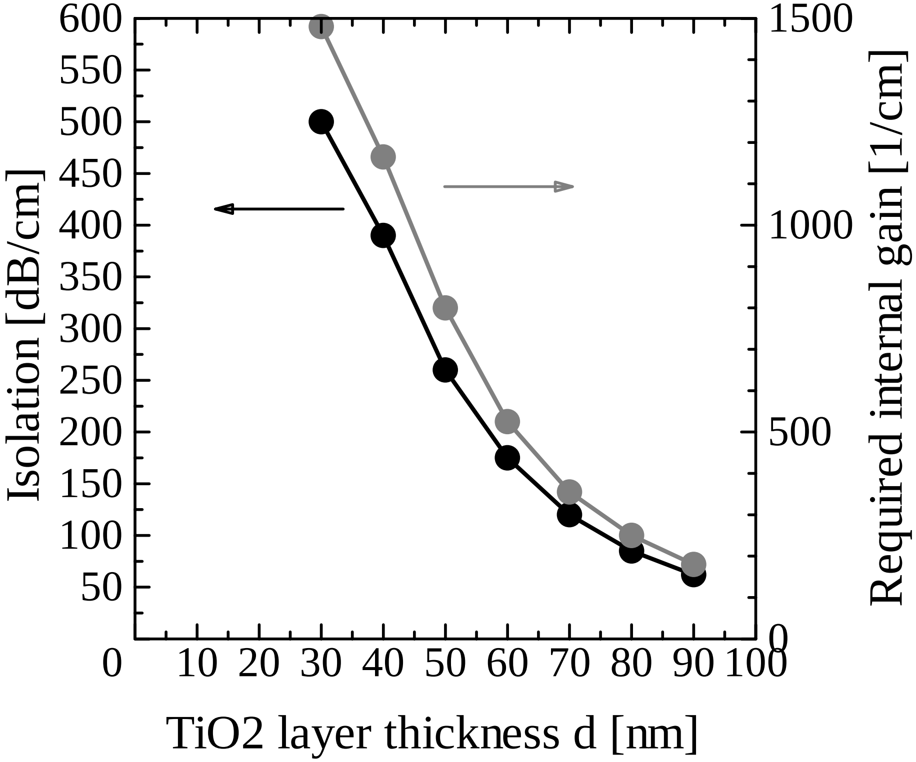
Simulation results

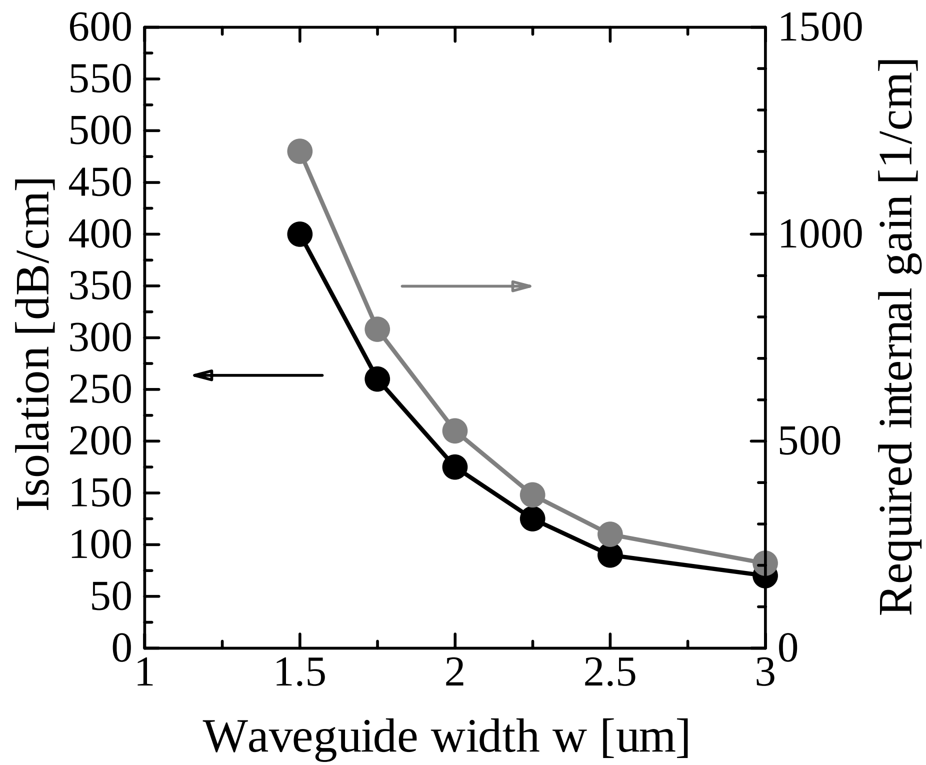
λ = 1.55μm



dTiO2 = 60nm

Waveguide width = 2um





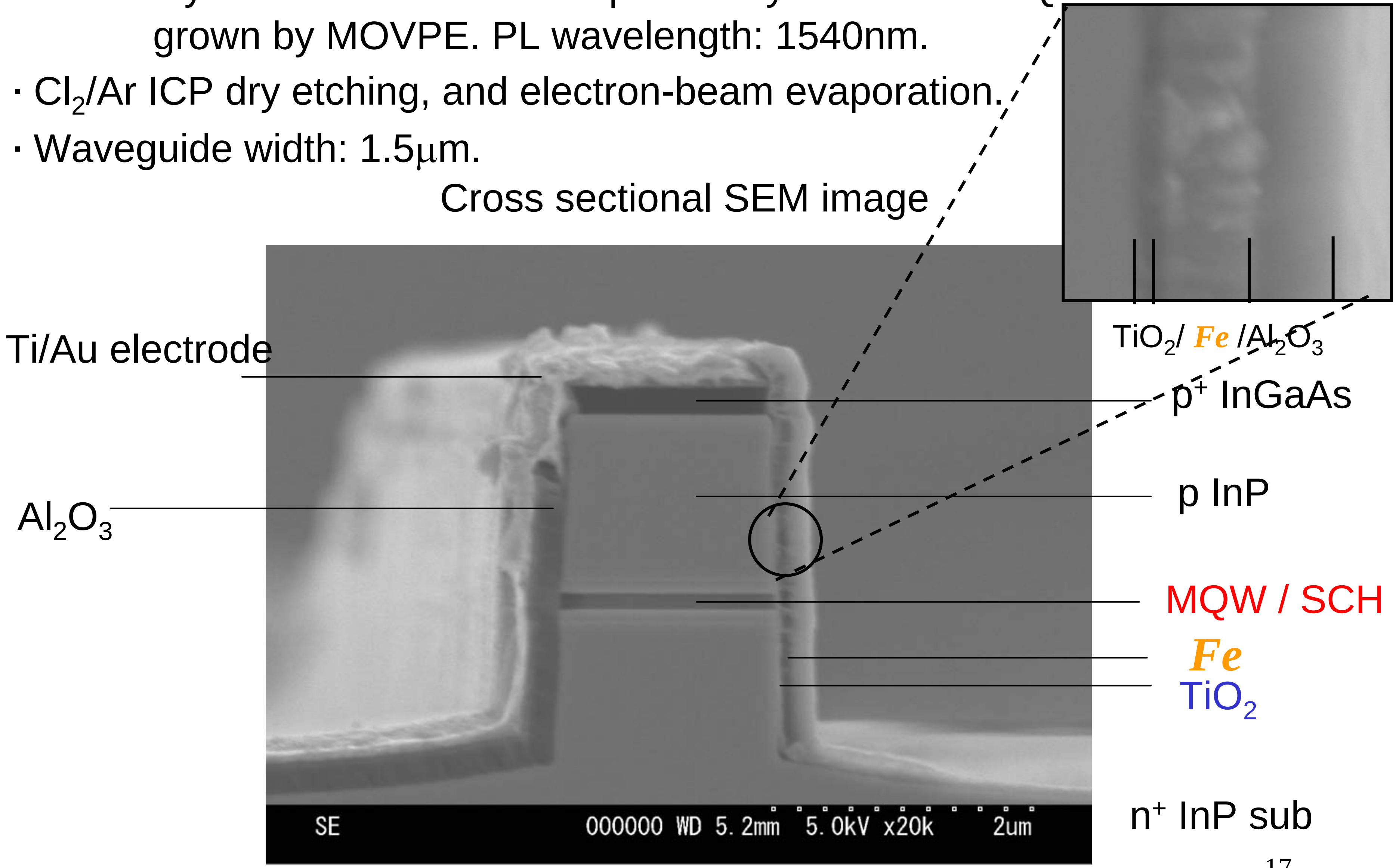
Narrower TiO_2 layer thickness and waveguide width -> larger optical isolation

Optical confinement factor Γ in the Fe layer: 0.1-0.5%

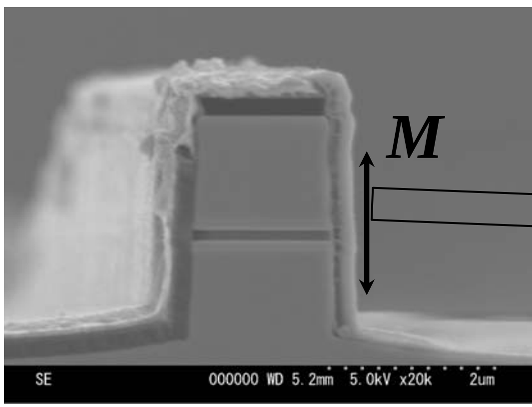
Fabrication

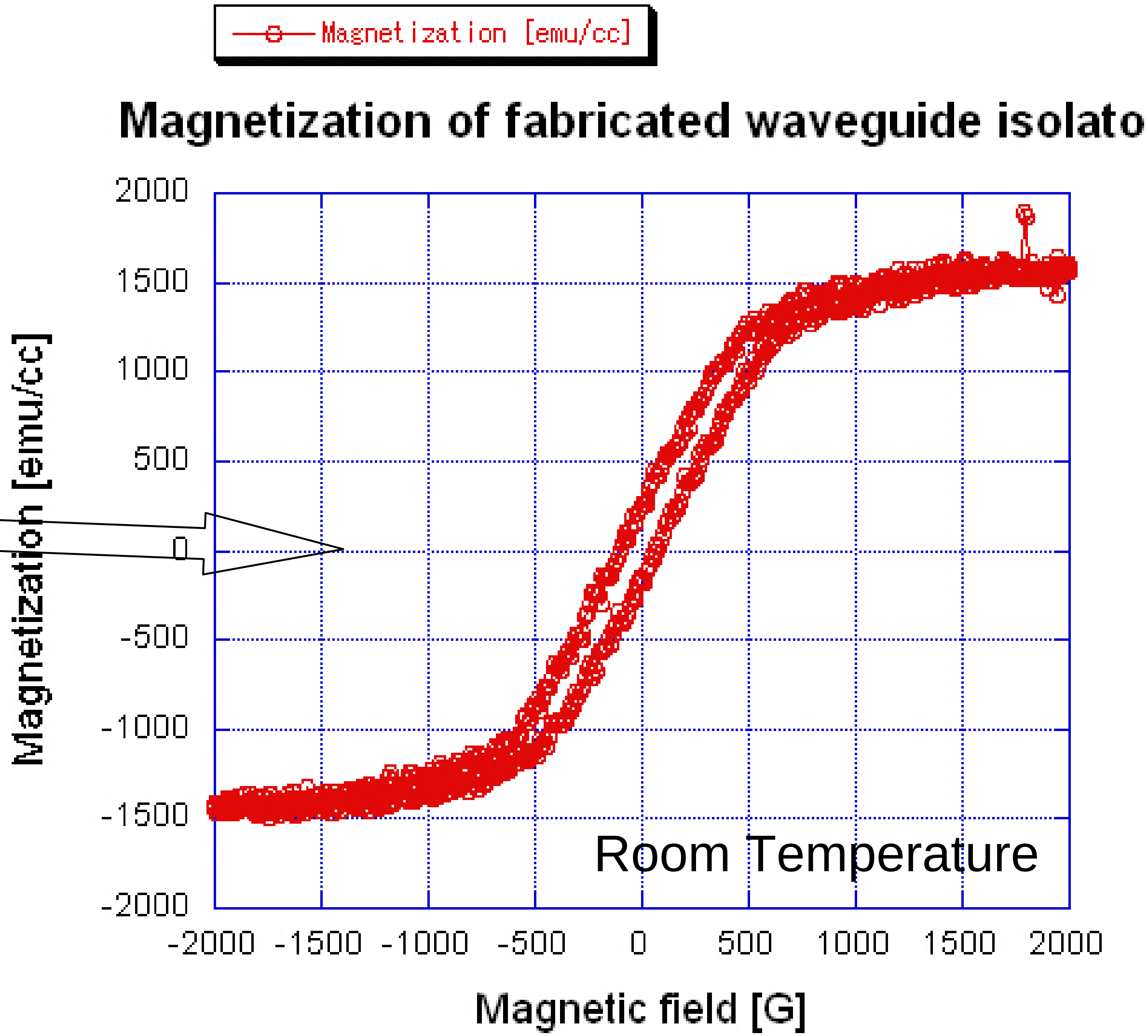
- Active layer: InGaAsP 0.7% compressively strained 14MQW. grown by MOVPE. PL wavelength: 1540nm.
- Cl_2/Ar ICP dry etching, and electron-beam evaporation.
- Waveguide width: 1.5μm.

Cross sectional SEM image



Magnetization





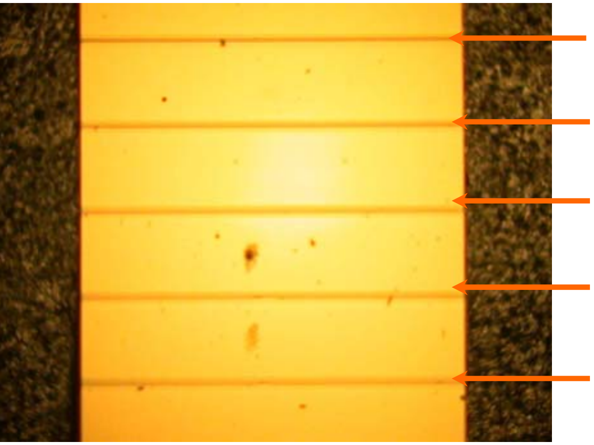
The magnetization of the device saturated at 1kG.
Permanent magnet can provide sufficient magnetic field for operation.

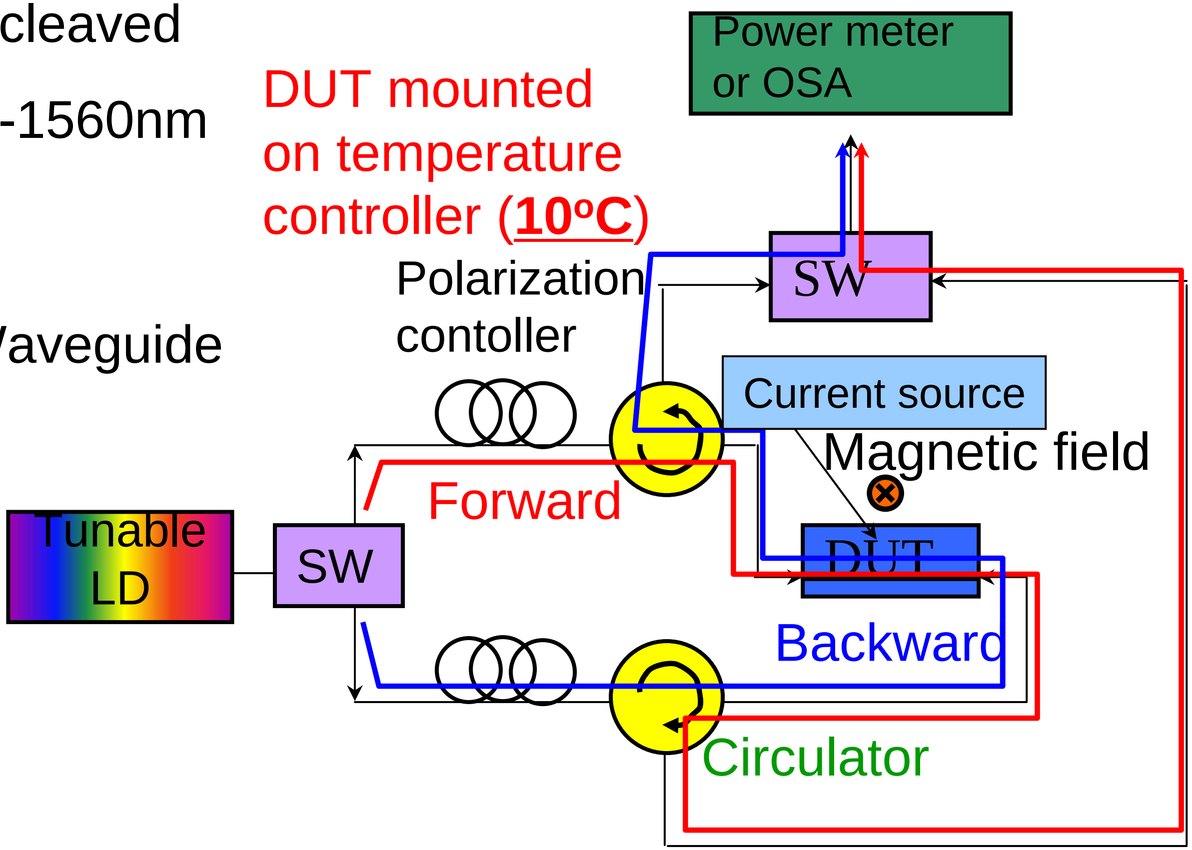
Nonreciprocal loss measurements

Device length: 0.7mm, as cleaved

Incident light: 5dBm, 1530-1560nm

Bias current: 100-200mA





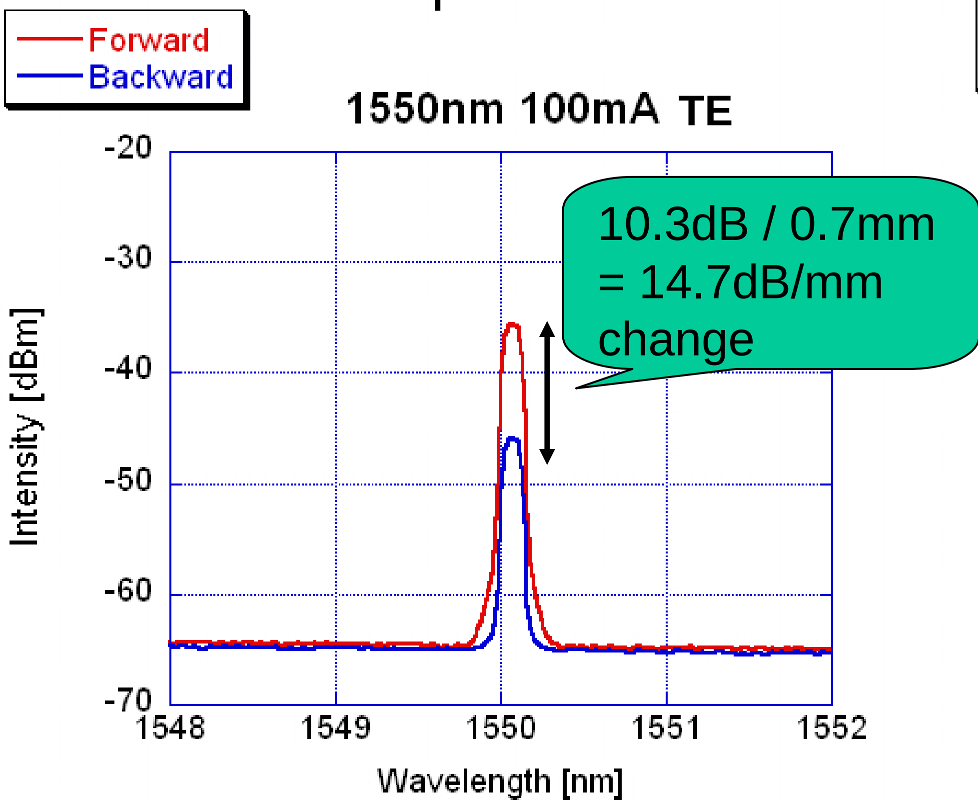
Measurement system

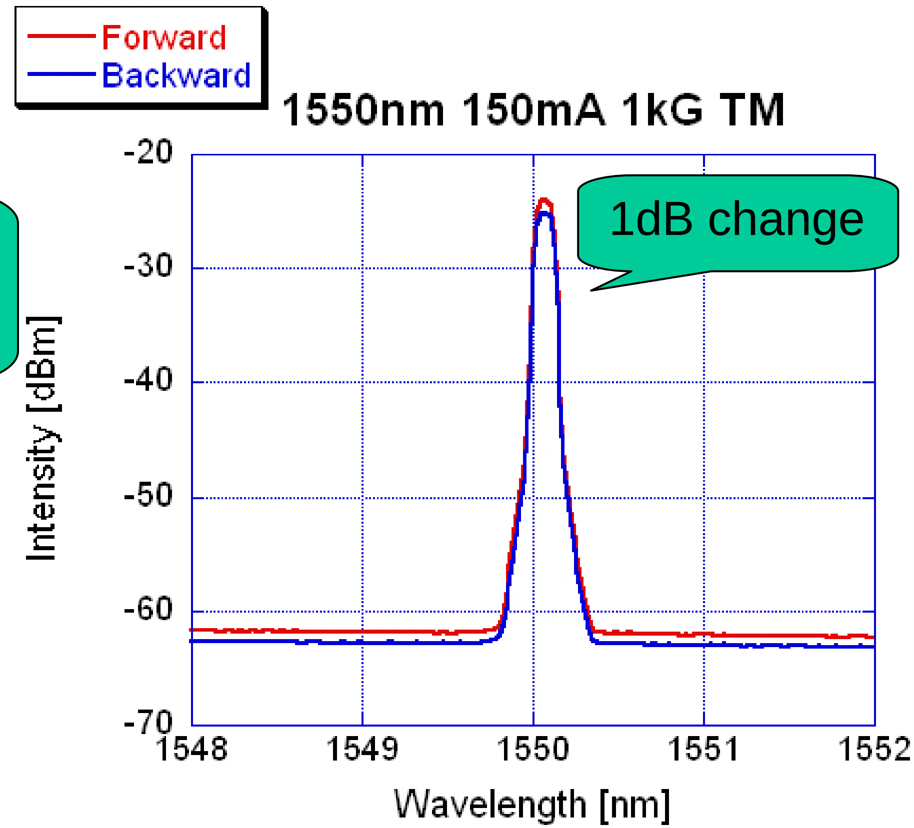
· Magnetic field (1kG) applied by a permanent magnet.

· Changed the propagation direction using two optical switches and circulators.

Nonreciprocal loss measurement results

Polarization dependence





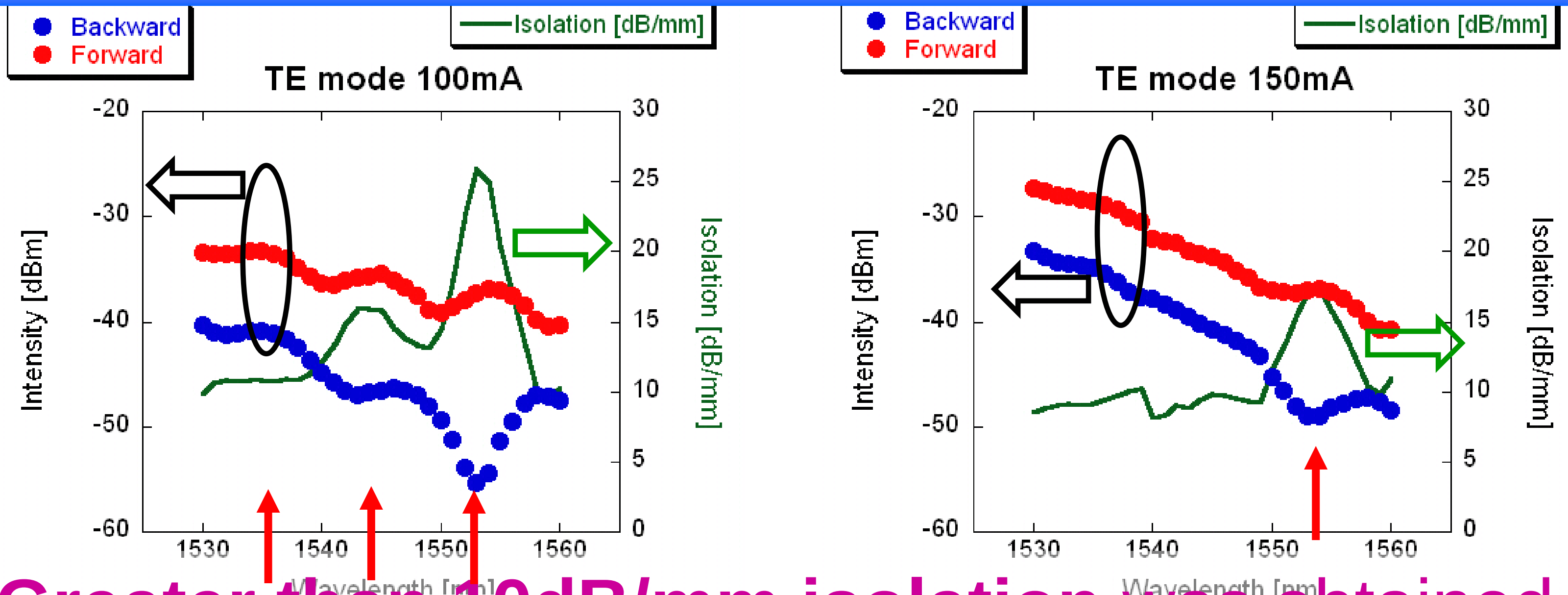
Our device operates only in TE mode

⇒clear evidence of the nonreciprocal loss propagation.

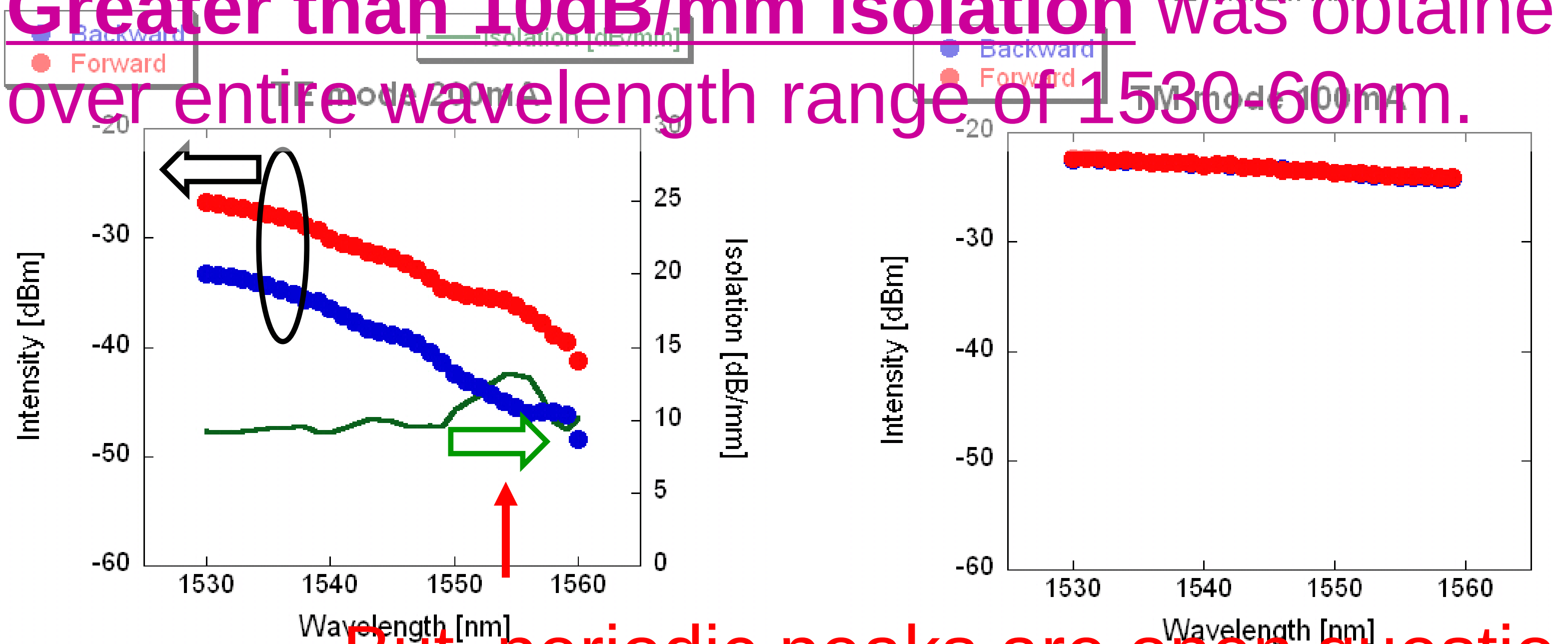
- Nonreciprocal loss (isolation ratio) : 14.7dB/mm.
- Propagation loss : 7-14dB/mm (can be reduced).

IEEE J. Lightwave Technol. **24**, 38, (2006).

Wavelength and bias current dependence



Greater than 10dB/mm isolation was obtained, over entire wavelength range of 1530-60nm.



But, periodic peaks are open questions.

Applicability

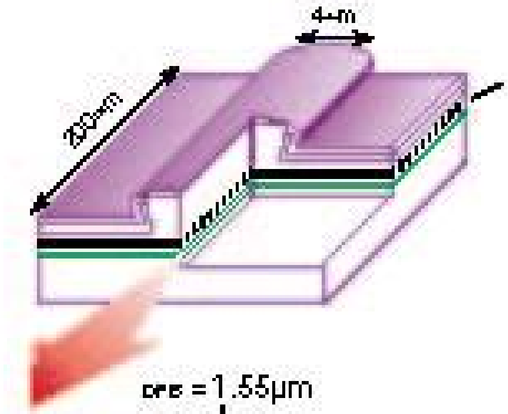
Our *Active* Waveguide Optical Isolators are based on SOA having Amplified Spontaneous Emission (ASE) noise.

To get advantage over conventional *Passive* “Faraday”Optical Isolators, *Integrated devices are required.*

	Passive “Faraday” Optical Isolator	Active “Waveguide” Optical Isolator
Temperature characteristics	Temperature dependence on Faraday rotation	Temperature control is required for SOA
Bias current	Not necessary	Necessary, ASE noise.
Monolithic Integration	*Difficult*	***Possible.*** ***Temperature control and bias current become easier by Integration.***

Integration

⇒Monolithic Integration with Distributed FeedBack (DFB) LD or installation to PICs.



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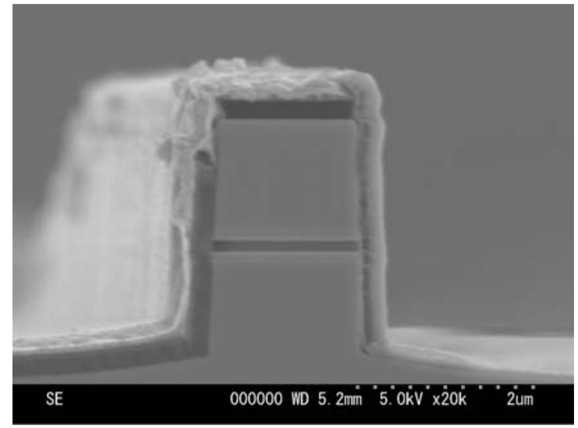

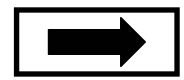

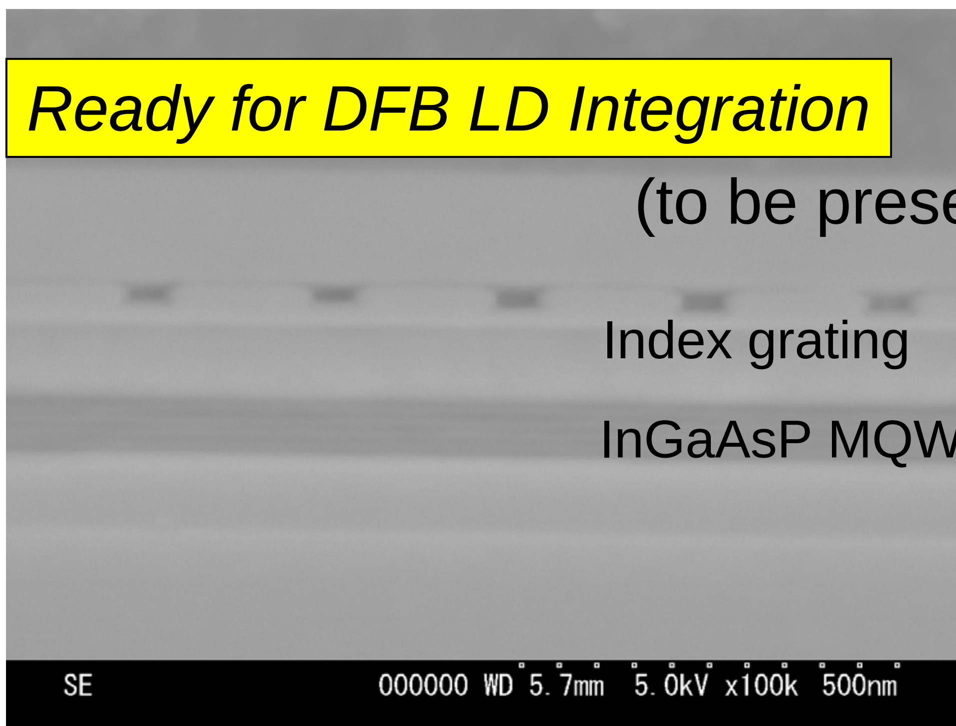

Ready for DFB LD Integration

(to be present at ISLC2006)

Index grating

InGaAsP MQW

Other tasks, problems towards application

・ Transparent waveguide

Dry etching process to be optimized.

AR coatings

・ Smaller size

At present, isolation: 14.7dB/mm -> ~2mm

⇒ preferably < 1mm

Comparable size with DFB LD

・ Buried Heterostructure waveguide for higher reliability

・ ASE noise of SOA

Summary

· TE mode waveguide optical isolator based on the "nonreciprocal loss". Simulation and fabrication.

How to take the magneto-optic effect into semiconductor waveguides

·Demonstrated large "Nonreciprocal loss" (***14.7dB/mm @1550nm***).

·Wavelength and bias dependence. (***Greater than 10dB/mm Isolation over 1530-60nm***)

·Discussion on Applicability.

Monolithically integrated device is necessary, and ready for integration. (to be present at ISLC2006)