Integrated Isolators

Class: Integrated Photonic Devices
Time: Fri. 8:00am ~ 11:00am.
Classroom: 資電206
Lecturer: Prof. 李明昌(Ming-Chang Lee)

Optical Isolators

An optical isolator is a nonreciprocal device that transmits an optical wave in one direction but blocks it in the reverse direction

Key specifications:

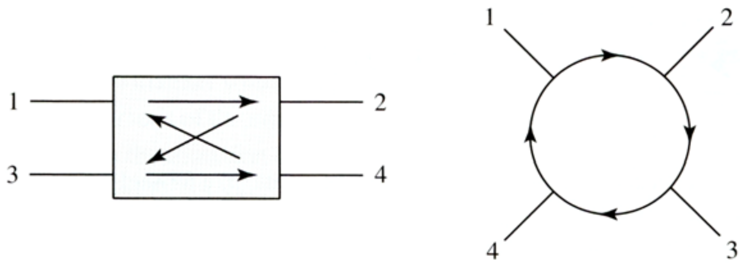
$$Insertion\ loss = -10\log\frac{p_t^{\ f}}{p_{in}^{\ f}}$$

$$Return\ loss = -10\log\frac{p_r^{\ b}}{p_{in}^{\ f}}$$

$$Reverse\ isolation = -10\log\frac{p_t^{\ b}}{p_{in}^{\ b}}$$

Optical Circulators

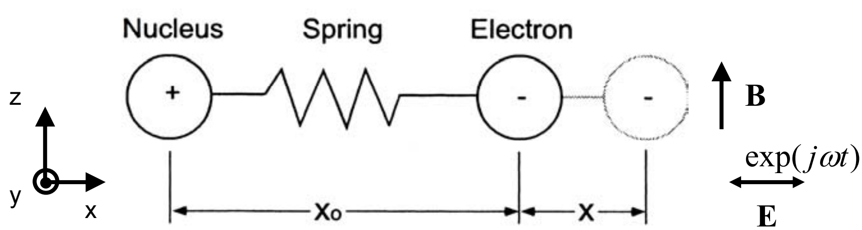
An optical circulator loops an optical signal through successive ports while blocks backscattered and reflected light.



(a) (b)

The key components of optical isolators and circulators require the nonreciprocal transmission which usually relies on magneto-optic effects

Faraday's Effect



Consider the equation of motion of the bound electrons in the presence of the static magnetic field and the oscillating electric field

$$m\frac{d^2\mathbf{r}}{dt^2} + k\mathbf{r} = -e\mathbf{E} - e\left(\frac{d\mathbf{r}}{dt}\right)\times\mathbf{B}$$

displacement

Faraday's Effect

E is harmonic time dependence $\exp(j\omega t)$ and r also has the same harmonic dependence

$$-m\omega^2\mathbf{r} + k\mathbf{r} = -e\mathbf{E} + j\omega e\mathbf{r} \times \mathbf{B}$$

The polarization P of the medium is just a constant times r, namely, -Ner, hence the above equation becomes

$$(-m\omega^2 + k)\mathbf{P} = Ne^2\mathbf{E} + j\omega e\mathbf{P} \times \mathbf{B}$$

The polarization can be solved and written as a function of E

$$\mathbf{P} = \varepsilon_0 \boldsymbol{\chi} \mathbf{E}$$

Faraday's Effect

The solution of χ

$$\boldsymbol{\chi} = \begin{bmatrix} \chi_{11} & +j\chi_{12} & 0 \\ -j\chi_{12} & \chi_{11} & 0 \\ 0 & 0 & \chi_{33} \end{bmatrix}$$

Where

$$\begin{cases} \chi_{11} = \dfrac{Ne^2}{m\varepsilon_0}\left[\dfrac{\omega_0{}^2 - \omega^2}{(\omega_0{}^2 - \omega^2)^2 - \omega^2\omega_c{}^2}\right] \\ \chi_{33} = \dfrac{Ne^2}{m\varepsilon_0}\left[\dfrac{1}{\omega_0{}^2 - \omega^2}\right] \\ \chi_{12} = \dfrac{Ne^2}{m\varepsilon_0}\left[\dfrac{\omega\omega_c}{(\omega_0{}^2 - \omega^2)^2 - \omega^2\omega_c{}^2}\right] \end{cases}$$

and

$$\omega_0 = \sqrt{\frac{k}{m}}$$

(resonance frequency due to spring)

$$\omega_c = \frac{eB}{m}$$

(resonance frequency due to magnetic force)

Faraday's Effect

Suppose a plane wave propagating along the z direction; that is,

$$\vec{E} = \vec{E_0}\exp(jkz)$$

(The propagation direction is parallel to the magnetic field)

E has to be subjected to Helmholtz Eq. $\nabla^2 \vec{E} + (I+\chi)\dfrac{\omega^2}{c^2}\vec{E} = 0$

$$\begin{cases} -k^2 E_x + \dfrac{\omega^2}{c^2}E_x = -\dfrac{\omega^2}{c^2}(\chi_{11}E_x + j\chi_{12}E_y) \\ -k^2 E_y + \dfrac{\omega^2}{c^2}E_y = -\dfrac{\omega^2}{c^2}(-j\chi_{12}E_x + \chi_{11}E_y) \\ \dfrac{\omega^2}{c^2}E_z = -\dfrac{\omega^2}{c^2}\chi_{33}E_z \qquad \text{(}E_z = 0\text{ since E propagate along z)} \end{cases}$$

Faraday's Effect

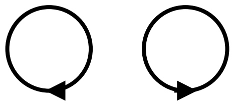
To have nontrivial solution of E, the determinant should be zero

$$\begin{vmatrix} -k^2 + (\omega^2/c^2)(1+\chi_{11}) & j(\omega^2/c^2)\chi_{12} \\ -j(\omega^2/c^2)\chi_{12} & -k^2 + (\omega^2/c^2)(1+\chi_{11}) \end{vmatrix} = 0$$

Then

$$\begin{cases} k = \dfrac{\omega}{c}\sqrt{1+\chi_{11} \pm \chi_{12}} \qquad \text{(Eigenvalue)} \\ E_x = \pm jE_y \qquad \text{(Eigenvector)} \end{cases}$$

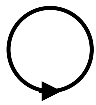
Physical Meanings of Eigenvalue and Eigenvector



$$E_x = \pm jE_y$$

(left-hand rotation and right-hand rotation)

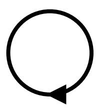
Left hand rotation:



$$n_R = \sqrt{1+\chi_{11}+\chi_{12}}$$
$$k_R = \frac{\omega}{c} n_R$$

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} 1 \\ j \end{bmatrix} \exp(jk_L z)$$

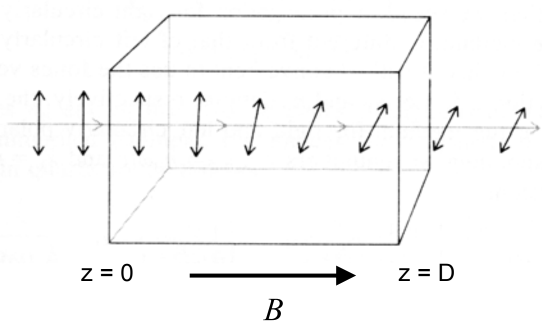
Right hand rotation:



$$n_L = \sqrt{1+\chi_{11}-\chi_{12}}$$
$$k_L = \frac{\omega}{c} n_L$$

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} 1 \\ -j \end{bmatrix} \exp(jk_R z)$$

Optical Activity by Faraday's Effect



At z = 0

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 \\ -j \end{bmatrix} + \frac{1}{2}\begin{bmatrix} 1 \\ j \end{bmatrix}$$

At z = D

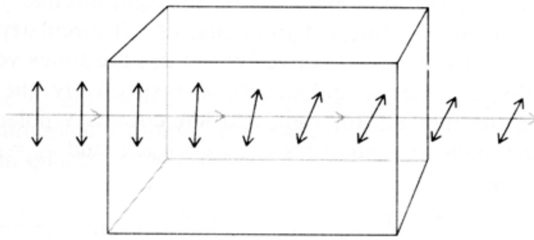
$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 \\ -j \end{bmatrix}\exp(jk_R D) + \frac{1}{2}\begin{bmatrix} 1 \\ j \end{bmatrix}\exp(jk_L D)$$

$$= \frac{1}{2}\exp[j\phi]\left\{\begin{bmatrix} 1 \\ -j \end{bmatrix}\exp(j\theta) + \begin{bmatrix} 1 \\ j \end{bmatrix}\exp(-j\theta)\right\}$$

where

$$\begin{cases} \theta = \frac{1}{2}(k_R - k_L)D \\ \phi = \frac{1}{2}(k_R + k_L)D \end{cases}$$

Optical Activity by Faraday's Effect



z = 0 → z = D

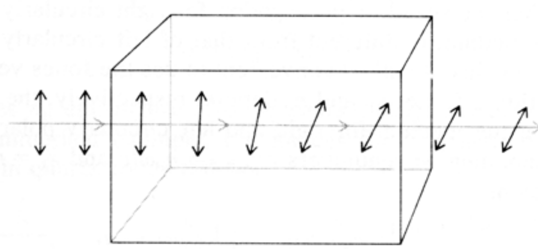
B

This represents a linearly polarized wave in which the direction of polarization is turned through an angle θ with respect to the original direction of polarization

$$\frac{1}{2}\exp[j\phi]\left\{\begin{bmatrix}1\\-j\end{bmatrix}\exp(j\theta)+\begin{bmatrix}1\\j\end{bmatrix}\exp(-j\theta)\right\}$$

$$=\exp[j\phi]\begin{bmatrix}\frac{1}{2}[\exp(j\theta)+\exp(-j\theta)]\\ \frac{j}{2}[\exp(j\theta)-\exp(-j\theta)]\end{bmatrix}=\exp[j\phi]\begin{bmatrix}\cos\theta\\ \sin\theta\end{bmatrix}$$

Optical Activity by Faraday's Effect



z = 0 → z = D

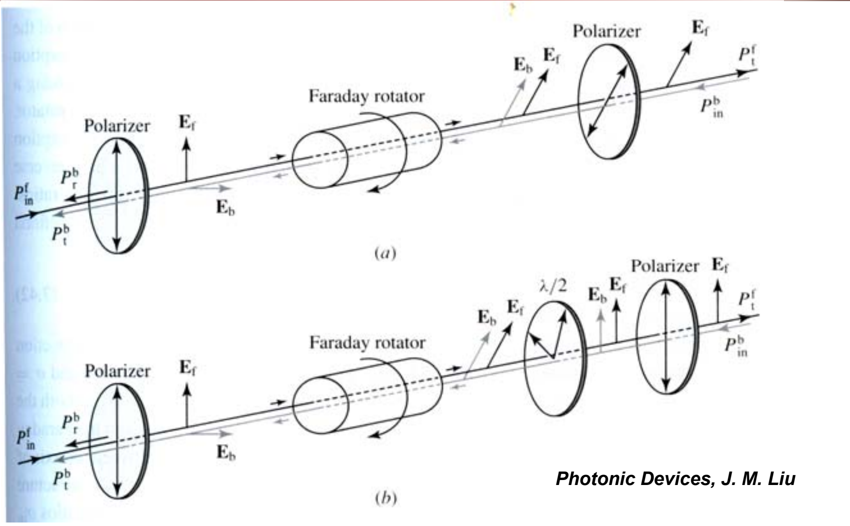
B

Faraday's Effect

$$\begin{cases} n_R - n_L \approx \dfrac{\chi_{12}}{\sqrt{1+\chi_{11}}} = \dfrac{\chi_{12}}{n_0} \\[2ex] k_R - k_L = (n_R - n_L)\dfrac{\pi}{\lambda} = \dfrac{\chi_{12}\pi}{n_0\lambda} \end{cases}$$

$$\chi_{12} \propto B$$

Polarization-Dependent Isolators (Bulk Optics)



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The Faraday's rotation is nonreciprocal

Polarization-Dependent Isolators (Bulk Optics)

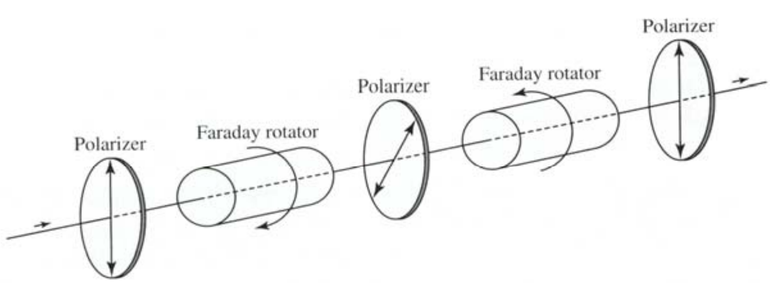

Figure 7.8 Two-stage cascaded optical isolator.

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Polarization-Independent Isolators (Bulk Optics)

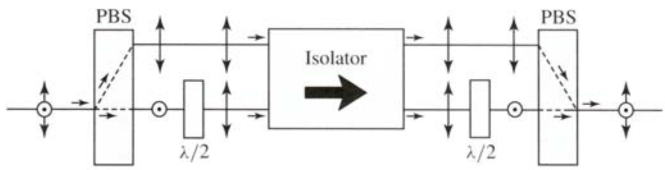
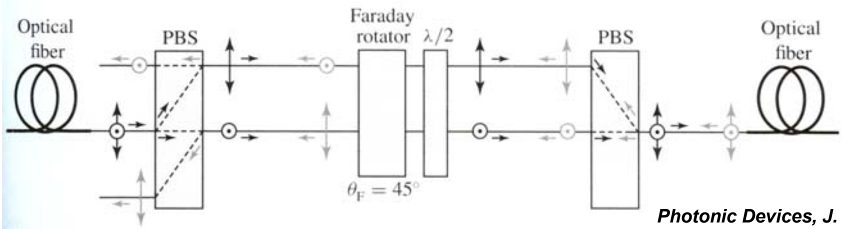


Figure 7.9 Polarization-independent optical isolator and its principle of operation. The polarization-dependent isolator used in this design maintains input polarization direction at the output. PBS indicates a polarizing beam splitter. $\lambda/2$ labels a half-wave plate.



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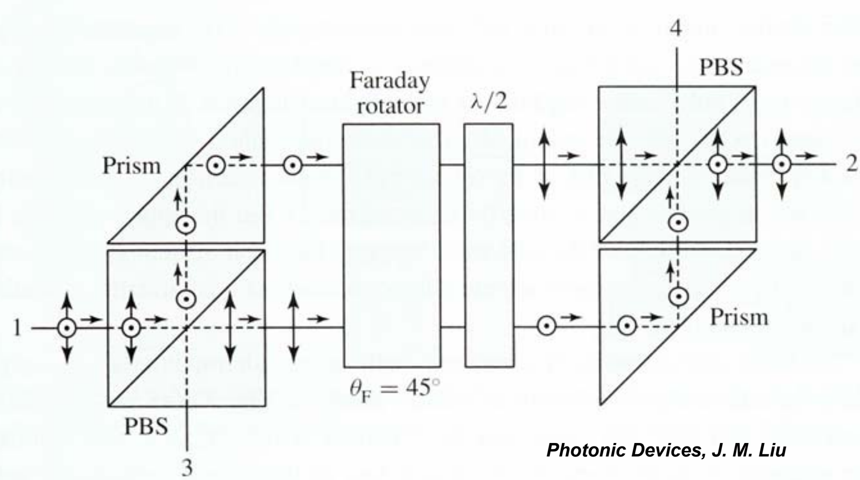
Polarization-Independent Circulators (Bulk Optics)



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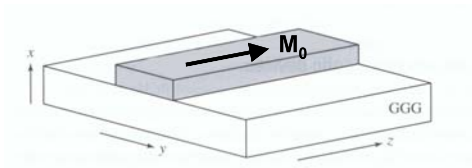
Nonreciprocal Phase Shifter

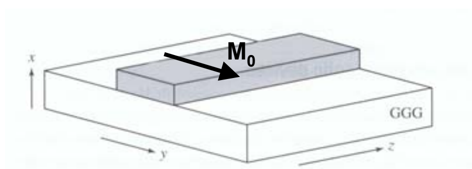
- **For guide-wave optics, the Faraday's rotation is difficult to be realized due to phase-mismatched between TE-like and TM-like modes**



$$\chi = \begin{bmatrix} \chi_{11} & +j\chi_{12} & 0 \\ -j\chi_{12} & \chi_{22} & 0 \\ 0 & 0 & \chi_{33} \end{bmatrix}$$

1:x, 2:y, 3:z

- **Nonreciprocal phase shifter is suitable to realized the integrated isolators and circulators.**

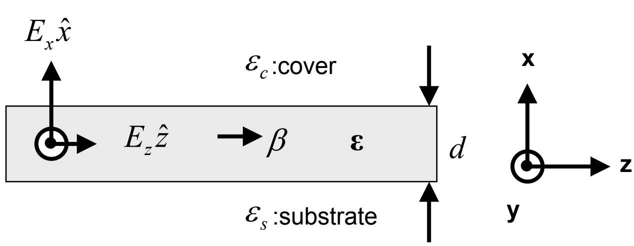


$$\chi = \begin{bmatrix} \chi_{11} & 0 & j\chi_{13} \\ 0 & \chi_{22} & 0 \\ -j\chi_{13} & 0 & \chi_{33} \end{bmatrix}$$

1:x, 2:y, 3:z

Nonreciprocal Phase Shifter

- **The nonreciprocal phase shifter exhibits in magneto-optic waveguides which has one polarization parallel to the magnetic field**
- **However, the nonreciprocal phase shift only works on the polarization perpendicular to the magnetic field**



$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_{11} & 0 & j\varepsilon_{13} \\ 0 & \varepsilon_{22} & 0 \\ -j\varepsilon_{13} & 0 & \varepsilon_{33} \end{bmatrix}$$

magneto-optic dielectric tensor

The TM wave:
$$\begin{cases} \mathbf{E} = (E_x, 0, E_z)\exp[j(\beta z - \omega t)] \\ \mathbf{H} = (0, H_y, 0)\exp[j(\beta z - \omega t)] \end{cases}$$

Nonreciprocal Phase Shifter

The wave equation of magnetic field for TM waves

$$\frac{\partial^2 H_y}{\partial x^2} + (k_0^2 \varepsilon_{eff} - \frac{\varepsilon_{33}}{\varepsilon_{11}} \beta^2) H_y = 0 \qquad \text{where} \qquad \varepsilon_{eff} = \varepsilon_{33} - \frac{\varepsilon_{13}{}^2}{\varepsilon_{11}}$$

Assume $\varepsilon_{11} = \varepsilon_{33}$. For the TM$_0$ mode, the eigenvalue equation is

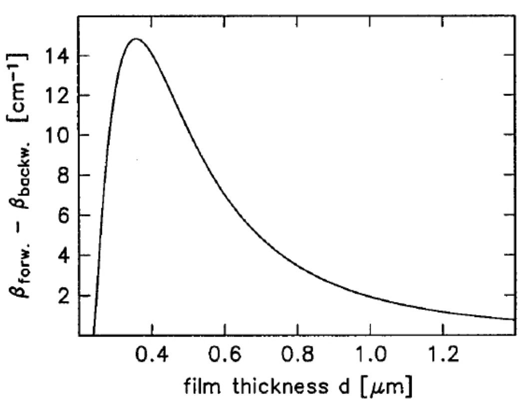
$$d \cdot \sqrt{k_0^2 \varepsilon_{eff} - \beta^2} = \tan^{-1}\left[\frac{\varepsilon_{eff}}{\sqrt{k_0^2 \varepsilon_{eff} - \beta^2}}\left(\frac{\sqrt{\beta^2 - k_0^2 \varepsilon_c}}{\varepsilon_c} - \frac{\beta \varepsilon_{13}}{\varepsilon_{11}\varepsilon_{eff}}\right)\right] + \tan^{-1}\left[\frac{\varepsilon_{eff}}{\sqrt{k_0^2 \varepsilon_{eff} - \beta^2}}\left(\frac{\sqrt{\beta^2 - k_0^2 \varepsilon_s}}{\varepsilon_s} + \frac{\beta \varepsilon_{13}}{\varepsilon_{11}\varepsilon_{eff}}\right)\right]$$

The solution of β
$$\begin{cases} \boxed{\beta_{forward} = \beta_0 + \Delta\beta} \\ \boxed{\beta_{back} = \beta_0 - \Delta\beta} \end{cases}$$
β_0 : propagation constant without magnetic field

To have the reciprocal birefringence, the waveguide should be asymmetric.

Nonreciprocal Phase Shifter

For a YIG (yttrium ion garnet)



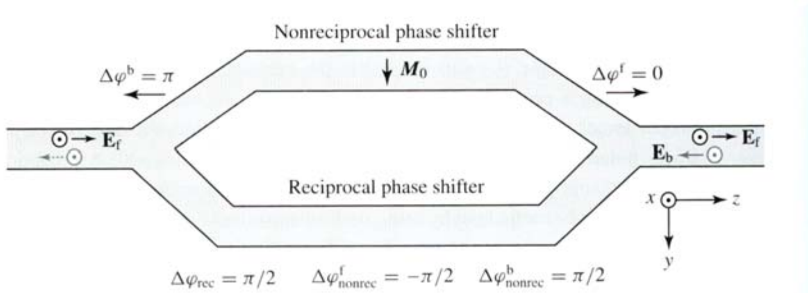
H. Dotsch, et al., IEEE Trans. on Magnet.

PARAMETERS USED IN THE CALCULATIONS

ϵ_c	ϵ_s	ϵ_{xx}	ϵ_{xz}^*	k_0 [μm^{-1}]	d [μm]
1.0	3.8025	5.3	$\pm$ 0.005	2 π/1.3	0.5

*): + = forward, − = backward propagation.

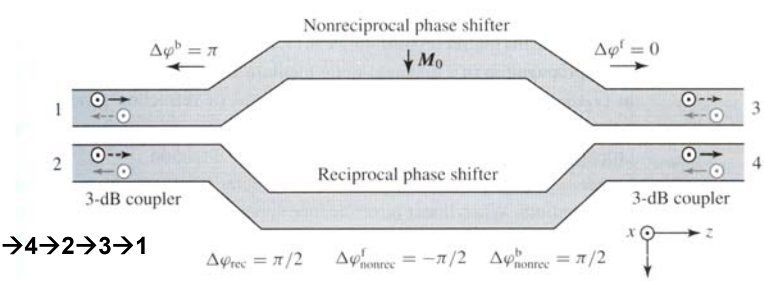
Guide-Wave Optical Isolators



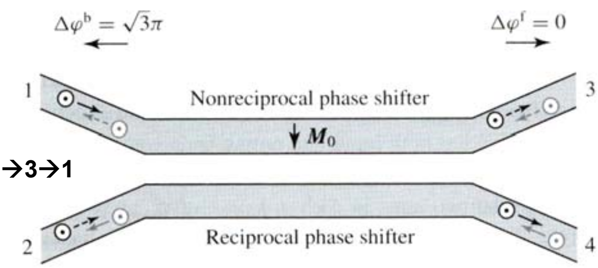
Forward: $\Delta\varphi^f = \Delta\varphi_{rec} + \Delta\varphi^f{}_{nonrec} = 0$ → Total transmission

Backward: $\Delta\varphi^f = \Delta\varphi_{rec} + \Delta\varphi^f{}_{nonrec} = \pi$ → Destructive interference

Guide-Wave Optical Circulators



1→4→2→3→1



1→4→2→3→1