Optical Isolators

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I. Optical Isolators

Introduction

An optical isolator is a device that allows light to travel in only one direction. Isolators have two ports and are made for free-space and optical fiber applications. Lasers benefit from isolators by preventing backscatter into the laser, which is detrimental to their performance. Other applications include fiber optic communication systems, such as CATV and RF over fiber, and gyroscopes. Isolators are magneto-optic devices that use Faraday rotators and polarizers to achieve optical isolation. The magneto-optic effect was discovered by Michael Faraday, when he observed that polarized light rotates when propagating through a material with a magnetic charge.

Types of Isolators

Two categories of optical isolators are free-space and fiber isolators. Isolators in both these categories see use in a wide range of applications and for many wavelengths from ultraviolet to long-wavelength infrared. Isolators can be fixed for isolation at a single wavelength, tunable for multiple wavelengths, or wideband. Adjustable isolators come with a tuning ring to adjust the Faraday rotator's position and effect in the isolator. Adjustable isolators can be narrowband for specific wavelengths or broadband adjustable.

Polarization-dependent isolators and polarization-independent isolators are two different operation concepts that are used to achieve isolation. Polarization-dependent isolators use polarizers and faraday rotators, while polarization-independent isolators use a Faraday rotator, a have-wave plate, and birefringent beam displacers. In either case, polarization is used in both systems to achieve isolation, exploiting the magneto-optic effect using the Faraday rotator.

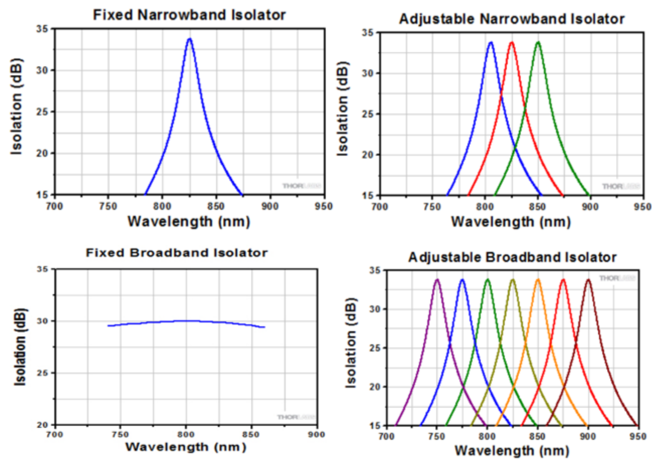


Figure 1. Broadband, Adjustable, and Narrowband Isolators from Thorlabs

Key Parameters of Isolators

An isolator's performance is measured by its transmission loss, insertion loss, isolation, and return loss. The transmission loss or S(1,2) should be low, meaning that there is no loss in optical power from the direction of port 1 to port 2. Optical power should not be transmitted from port 2 to port 1. The reduction in optical power from port 2 to port 1 is termed insertion or S(2,1) and should be high. Optical isolators can have 50 dB or higher isolation [1]. Insertion loss is reflected optical power from port 1 and should be reduced.

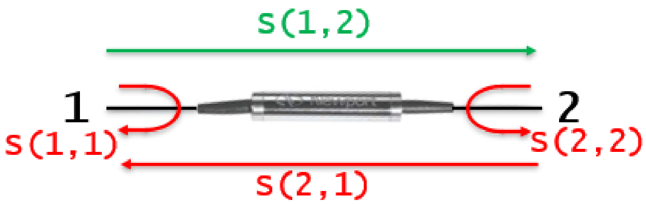


Figure 2. Optical isolator as 2-port Element

Pulse dispersion is a relevant parameter in the design of isolators for specific pulsed laser uses, such as an ultrafast laser. This is measured as a ratio between pulse time width before the isolator and the pulse time width after leaving the isolator [1].

For fiber isolators, the type of fiber will need to be considered for its application. Size is a consideration for many applications. The design of the magnet in the isolator often a major limiting factor in size reduction. Operating temperature and accepted optical power are two other considerations to ensure the isolator is in acceptable operating conditions and is not damaged. This information can be found in datasheets for common isolators.

Concept of Operation

Polarization is an important concept in the operation of an optical isolator. Polarization refers to the orientation of waves transverse to the direction of propagation. Polarization can be written as a vector sum of components in two directions perpendicular to the direction of propagation.

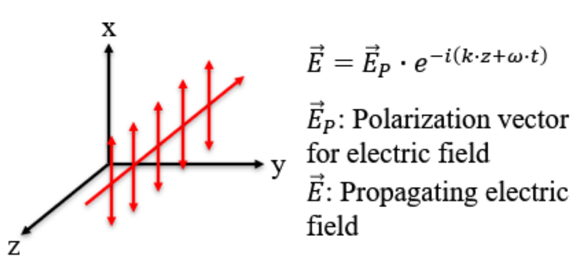


Figure 3. Wave polarized in the x-direction and propagating in the -z-direction

A polarizer changes the polarization of an incident wave to that of the polarizer. However, light is only allowed to pass through the polarizer to the extent that the incident wave shares a level of polarization in the direction of the polarizer. The output intensity from the polarizer is defined using Malus' Law, where θ is the angle between the polarization of the incident wave and the polarizer's direction:

$$I_{out} = I_{in} \cos^2 \theta.$$

For example, a wave polarized in the x-direction propagating in the negative z-direction may enter a polarizer positioned in the x-direction. In this case, the angle difference between the polarizer and the incident wave is zero, meaning that full optical power is transmitted. If an angle is introduced between the polarizer and incident wave, the output intensity is reduced. Two polarizers are used in an optical isolator, as well as a Faraday rotator.

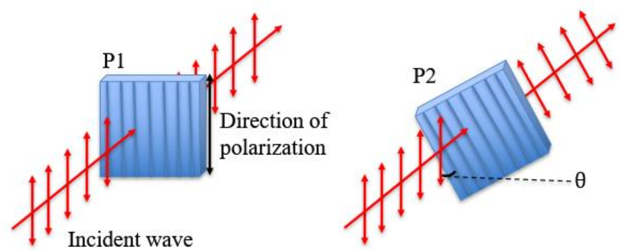


Figure 4. The angle between polarizers and incident waves

When light propagates through a magnetic material, the plane of polarization is rotated. This is termed the Faraday effect or the magneto-optic effect [2]. The Verdet constant measures the strength of the Faraday Effect in a material. The Verdet effect units are radians per Tesla per meter, and it is a function of the wavelength, electron charge and mass, dispersion, and speed of light.

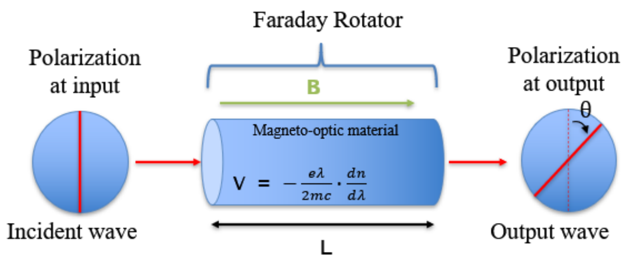


Figure 5. Rotation of Polarization using Faraday Effect

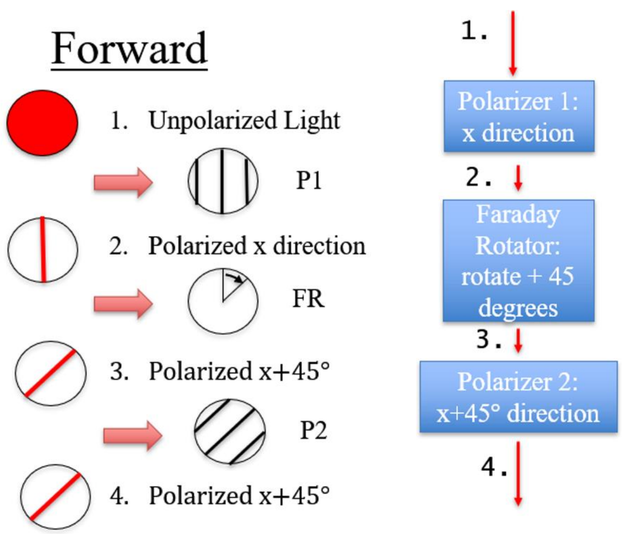


Figure 6. Optical Isolator in Forward Direction

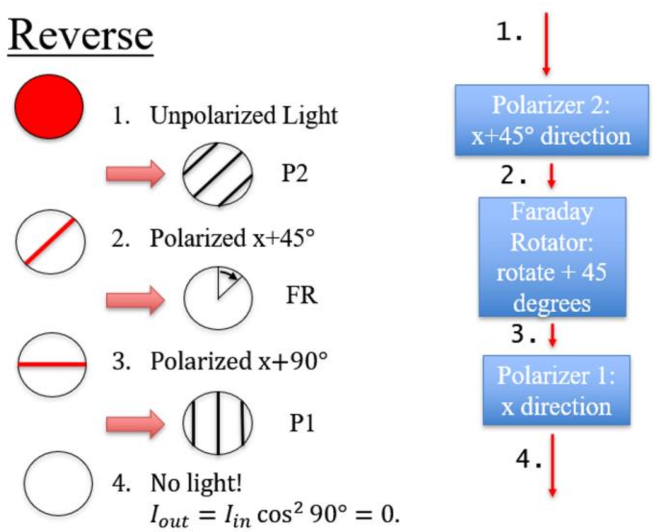


Figure 7. Optical Isolator in Reverse Direction

Using the Faraday rotator and two polarizers, a non-reciprocal isolator is made. The forward and reverse directions for an isolator are demonstrated below, made of a Faraday rotator and two polarizers. The Faraday rotator is made to rotate the polarization 45 degrees in a clockwise direction.

Since the clockwise rotation is different respective to the direction of light in the Faraday rotator, a non-reciprocal effect is expected. The two polarizers are positioned at 45 degrees from one another. In the forward direction, the direction of polarization of the optical wave matches that of the second polarizer, meaning that full optical power is present at the isolator's output. In the reverse direction, the 45 degrees difference from the Faraday rotator and 45 degrees angle difference from the polarizers are applied constructive, producing a 90-degree difference in polarization direction for the second polarizer. Using Malus's law, the resultant intensity for the outgoing light wave is zero. Since the Verdet constant is dependent on wavelength, there is a variety of materials that can be used to demonstrate the Faraday effect. For 1550 nm light, widely used in telecommunications, Yttrium Iron Garnet has a strong effect and sees use in optical isolators [3].

Designing an Isolator

To design an isolator, we must first consider the wavelength that we are using, the material that we are using for Faraday rotation, and the electromagnet output B field. Recall that the Verdet constant is a function of the wavelength. For Yttrium Iron Garnet, the Verrdet constant is 304 radians/Tesla/meter for 1550 nm-wavelength light [4]. The rotation of the polarization plane for linearly polarized light is:

$$\beta = \int_0^L BV dl,$$

where L is the length of the magneto-optic material and B is the applied magnetic field to the magneto-optic material. Given that we are looking for a Faraday rotation of 45 degrees, we can either solve for the required magnet field strength B given a certain length L, or we can determine how long (L the Faraday rotator should be given an applied magnetic field strength, B. An optical isolator can be described using the following formations. The first polarizer is for polarization in the x direction.

The Faraday rotator rotates the polarization by $\beta = BVL$ radians and then goes through the second polarizer, which is 45 degrees to the first polarizer.

$$P1 = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix},$$

$$FR = \begin{bmatrix} cos\beta & -sin\beta \\ sin\beta & cos\beta \end{bmatrix},$$

$$P2 = \begin{bmatrix} \cos(\frac{\pi}{2}) & -sin(\frac{\pi}{2}) \\ sin(\frac{\pi}{2}) & cos(\frac{\pi}{2}) \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} \sqrt{2}/2 & 0 \\ \sqrt{2}/2 & 0 \end{bmatrix}$$

The forward and reverse polarization can be calculated as follows:

$$Forward = P2 * FR * P1,$$

$$Reverse = P1 * FR * P2$$

The components of the resulting Jones' Matrices for forward and reverse directions are plotted, while varying the magnetic field strength to find the optimal strength B for reverse isolation.

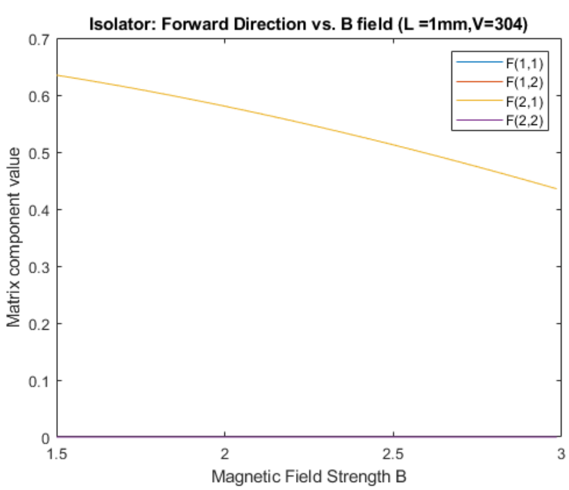


Figure 8. Forward Direction, Polarization from Isolator vs. Magnetic Field Strength

The Faraday rotator is 1 mm long, rotates polarization by pi/4 radians, and is made of Ytterbium Iron Garnet with a Verdet constant of 304 radians/Tesla/meter, I can find what strength magnetic field should be applied. The result shows that the optimal field strength is 2.584 Tesla to achieve full isolation.

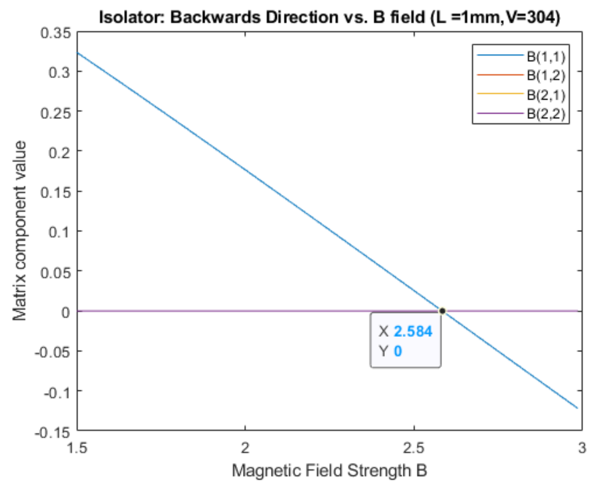


Figure 9. Backward Direction, Polarization from Isolator vs. Magnetic Field Strength

The output matricies for the forward, reverse directions and the Faraday rotation matrix are then found to be:

$$Forwards = \begin{bmatrix} 0.499 & 0 \\ 0.499 & 0 \end{bmatrix}$$

$$Backwrds = \begin{bmatrix} 1.0e^{-3} & 0 \\ -0.137 & 0 \end{bmatrix}$$

$$FR = \begin{bmatrix} 0.7070 & -0.7072 \\ 0.7072 & 0.7070 \end{bmatrix}.$$

N that the dimensions of the isolator have been calculated, these numbers can be loaded into an optical simulation for the permittivity tensor of the material. Simulation as an approach to designing an isolator is also useful to measure at which length the polarization has rotated the desired amount.

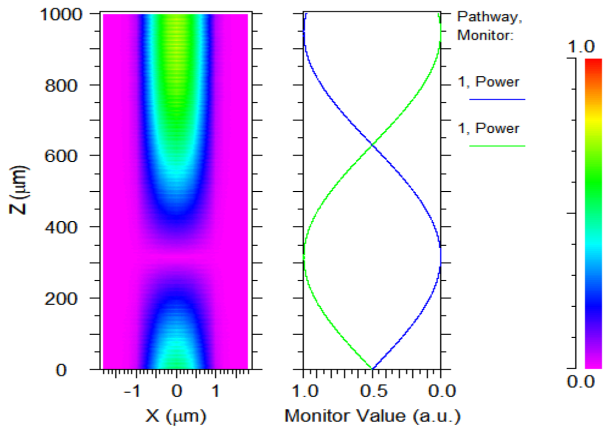
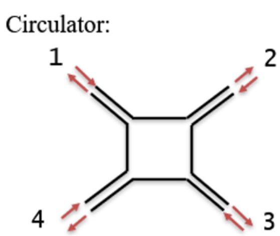


Figure 10. Faraday Rotation

Other Magneto-Optic Devices

The optical isolator is a magneto-optic component. Closely related is the circulator. The circulator is a non-reciprocal component with multiple ports and is commonly used for transceivers and radar receivers. When light enters a four-port circulator, the output port is dependent on the input port. A simple diagram and S-matrix are shown below for a four-port circulator, where the columns denote where light entered, and the row denotes which port light exits. Like the isolator, the circulator also uses Faraday rotation.



$$S = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Figure 11. Circulator Concept and S-Matrix

Other magneto-optic devices include beam-deflectors, multiplexers, displays, magneto-optic modulators [5]. Magneto-optic memory devices, including disks, tapes, and films, were commonplace but have been largely replaced by solid-state memory. Thin-film magneto-optic waveguides have also been demonstrated [6]. Magnetic-tunable optical lenses allow for a dynamically tunable focal length [7].

II. Photonic Integrated Isolators

Introduction

Integrated photonics is a technology that, like integrated electronics, allows for many components to be made on a single semiconductor chip, allowing for more complex systems with reduces size and improved reliability. The photonic IC market was about $190M in 2013 and is estimated between $1.3B and $1.8B in 2022 [8]. An integrated isolator is a highly sought technology, currently in the beginning stages of commercial availability and still in research and development. Photonic integrated circuits are usually developed on Silicon, Indium Phosphide and Gallium Arsenide; each having advantages. Indium Phosphide is of particular importance for the telecommunications wavelength (C-band at 1550nm) because this platform is used for lasers as well as photodetectors. Other methods to include active components such as lasers made on Indium Phosphode onto a Silicon wafer have been realized with limited success. Given the benefit of an isolator to a laser, an integrated isolator, if designed well could improve the performance of the semiconductor laser on Indium Phoshide.

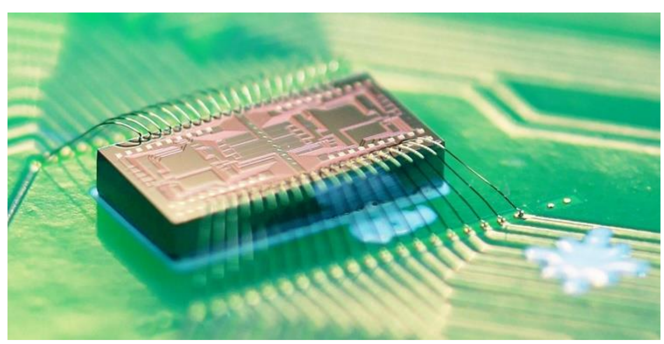


Figure 12. Photonic Integrated Circuit

As mentioned previously, the circulator is based on the same non-reciprical Faraday Effect. When conducting research on integrated isolators, it is of interest to consider that advancements in integrated isolator technology can be applied to design an integrated circulator. However, the circulator is also used for a very different purpose, which may be more compatible to passive integrated photonics on a platform such as silicon. Integrated circulators can enable the realization of miniaturized receivers and a wide range of applications.

Advantages and Demand

Integrated isolators can improve the performance of semiconductor lasers by reducing backscattering. Laser backscattering can reduce the laser linewidth and relative intensity noise (RIN), a limiting factor for next-generation high dynamic-range microwave photonic systems. Improving the signal to noise ratio by reducing RIN noise in a microwave photonic link can therefor allow for an overall signal-to-noise ratio (SNR).

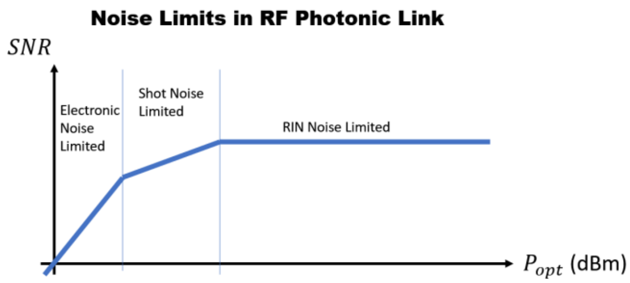


Figure 13. Noise Limits in an RF Photonic Link

Benchtop laser units typically come packaged with isolating components as needed to improve performance, but to design an entire high dynamic range microwave photonic system on a chip, the integrated lasers will need sufficient isolation to ensure that the system works properly. For a fully integrated system, an integrated isolator therefore can reduce the noise floor and enable high dynamic range system operation.

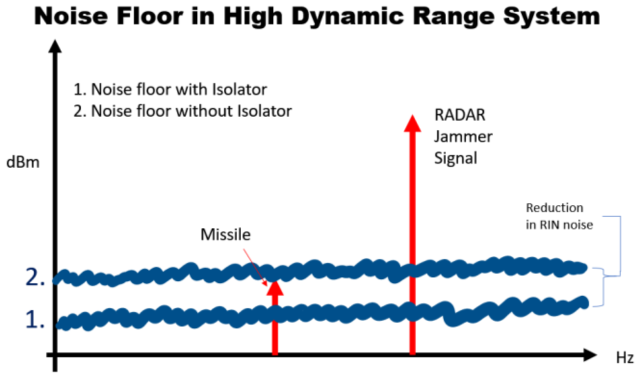


Figure 14. High Dynamic Range Integrated Microwave Photonic System

Because of the potential of integrated isolators, the US Air Force has taken an interest in this technology and sought to introduce this technology to the AIM Photonics Foundry in Albany, New York [9]. AIM Photonics currently includes an integrated isolator in its process design kit.

Challenges: Faraday Rotation

The first challenge in making an integrated isolator is the question of making an integrated Faraday rotator. Since the magneto-optic effect is dependent on the length of the Faraday Rotator, this may cause an issue with the size of the component. Semiconductor platforms do not exhibit a magneto-optic effect. One main material used for the magneto-optic effect at the 1550 nm wavelength is Yttrium Iron Garnet (YIG). For fiber isolators and free-space isolators, light propagates through the magneto-optic material. Two solutions were made for the issue of using YIG on a photonic IC: YIG waveguides [10] and layering YIG on top of the optical waveguides [11], each including the use of an electromagnet for the magnetic field. When layering YIG on top of the optical waveguides, the magneto-optic effect is applied to the evanescent waves outside of the waveguide, producing a weaker effect. The advantage of layering YIG rather than using YIG waveguides is its relative ease of fabrication.

Challenges: Fabrication

Fabrication with garnets and semiconductors is one challenge for integrated isolators. One issue is that garnets are not typically used in semiconductor fabrication, presenting several unique challenges specific to their material properties. It has found to be unreliable especially in the deposition process [11]. When growing semiconductor materials, the wafer is exposed to very high temperatures. Thermal expansion mismatch between garnets and semiconductors makes growing YIG on semiconductor difficult without cracking. To avoid thermal expansion mismatch, alternate methods using lower temperatures are used such as rapid annealing (RTA) [12]. While direct bonding techniques are preferred over YIG waveguides, YIG waveguides on deposited films are made using a H_3PO_4 wet etch [12].

Polarizers in integrated photonics are achieved using waveguide polarizers. Waveguide polarizers have been realized using a variety of approaches, including metal-cladding and birefrinfence waveguides [13], photonic crystal slab waveguides [14]. Polarizers have been fabricated using ion beam lithography [10] [15].

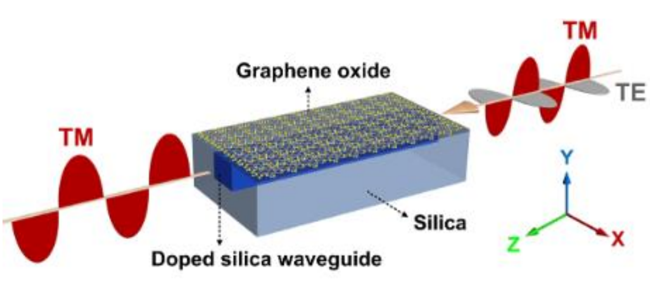


Figure 15. Integrated Waveguide Polarizer Example

Another question related to the exploitation of Faraday rotation on an integrated isolator is the design of the optical waveguide structure and phase shift or use of polarizers to reduce optical power in the reverse direction. Two designs are a microring resonator and a Mach-Zehnder interferometer. Due to the challenges of desigon developing integrated isolators that do not use the magneto-optic effect [16] [17]. A non-magneto-optic isolator was designed as a Mach-Zehnder Interferometer, providing some backwards isolation [16].

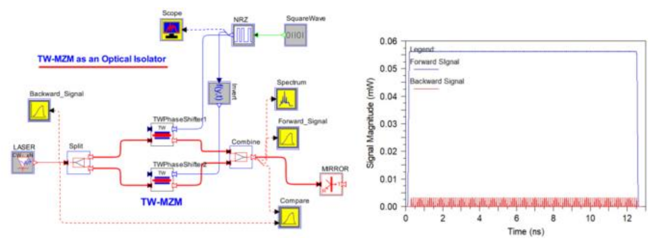


Figure 16. Travelling-Wave MZ Modulator as Isolator

Challenges: TE and TM Polarization

One issue with integrated isolators is that they require light to be TM polarized for operation, making them incompatible with TE polarized lasers. To circumvent this issue, some isolator designs are being optimized for TE polarization, or include polarization rotators between the laser and isolator [11]. The polarization rotator between the laser and isolator would then need to have low loss and a high polarization extinction ratio. Below is a model for an integrated waveguide polarization converter from TE1 to TM0 modes [11], which would follow after a TE0 to TE1 mode coupler:

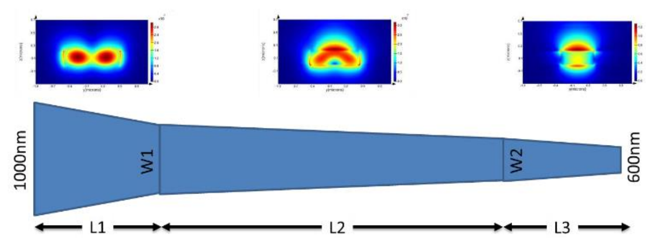


Figure 17. TE1 to TM0 Converter for Integrated Isolators

Challenges: Performance

The performance of current integrated isolator designs is a major drawback. Integrates isolators should provide wide band isolation across the C-band, have high isolation, and low insertion loss. Wideband operation ensures that the isolator will prevent backscattering from all wavelengths from a C-band laser. Achieving low insertion loss is needed to prevent optical loss. Finally, isolation measures how much loss is provided in the reverse direction, which for an isolator should be high.

Discrete component isolators can offer up to 60 dB isolation with <1dB insertion loss. Integrated isolators have been shown with much lower isolation and often large insertion loss, while being too narrowband for some applications. Improving their performance is a research topic still being explored. Large optical loss hass been theorized to be due to the loss from scattering of the YIG layered above the waveguide, the interface of the bond and losses in YIG material. Other methods for improving on previous designs include electromagnet design and waveguide design, especially for coupling of the electromagnet and a microring resonator insolator design [11].

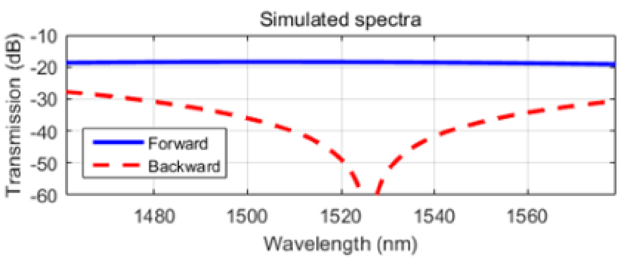


Figure 18. Integrated Isolator Performance

<u>Design on Indium Phosphide</u>

Design of integrated isolators on the Indium Phosphide platform has the advantage of being integrated directly after a 1550 nm wavelength laser, providing numerous benefits to the integrated laser. There remains an interest in integrating isolators on this platform with the laser rather than a separate, discrete component. One design uses Yttrium Iron Garnet as the magneto-optic material with a Mach-Zehnder interferometer structure and a reciprocal phase shifter [18] [11]. A design on the indium phosphide platform was proposed in 2007, utilizing the magneto-optic effect on an MZI design and achieving greater than 25 dB isolation over the telecommunications wavelength C-band [19]. Another was proposed and developed in 2008 as an interferometric isolator on the indium phosphide platform based on non-reciprocal phase shifts in the modulator's arms [20]. The YIG magneto-optic material was bonded using a surface activated direct bonding technique [20].

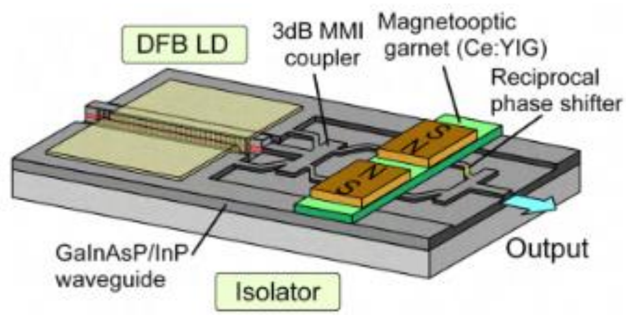


Figure 19. Integrated Isolator Design on InP with DFB Laser

The above design also features a 3x2 MMI coupler, so that the backward light wave is radiated out of the sides of the coupler, avoiding backscatter to the laser.

<u>Design on Silicon</u>

Microring resonator isolators and Mach-Zehnder Interferometers (MZI) utilizing the magneto-optic effect have been developed on heterogeneous silicon integration platforms. Integrated micro-ring resonator isolators provide isolation with low insertion loss, but the isolation is too narrow for most applications [9]. An advantage to the MZI integrated isolator is its high isolation. However, this is largely offset by its large optical insertion loss, making them impractical for most RF Photonics applications [9].

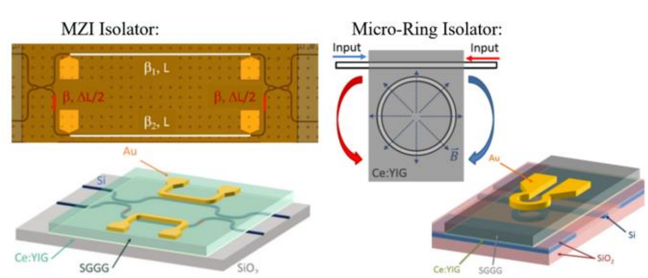


Figure 20. Integrated MZI and Micro-ring Isolator

Integrated Circulator

Designing an integrated circulator has several similarities to an integrated isolator, since they are both based on the non-reciprical magneto-optic effect.

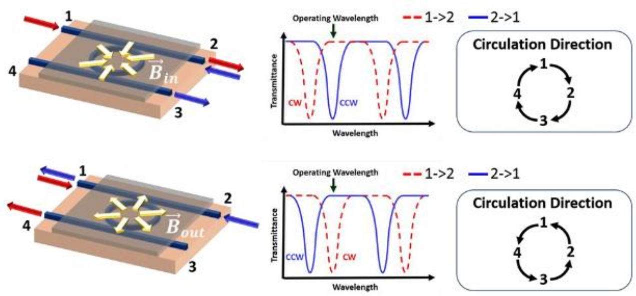


Figure 21. Integrated Isolator Design using Mircoring Resonator

Conclusion

In conclusion, isolators, and particularly integrated isolators, show a promising future for enabling photonics technology in the future. There is a clear demand for isolators to enable narrow-linewidth lasers with low RIN noise and considerable effort to apply new approaches to integration technology to realize an isolator that is wideband with high isolation and low insertion loss.

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MATLAB Code

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%Faraday Rotator
%Michael Benker
%ECE591 Photonic Devices
clf;
A_P2 = pi/4 %Polarization shift of P2
P1 = [1,0;0,0] %P1 Matrix
P2=[0.7071,0;0.7071,0] %P2 Matrix
B=2.584; %Magnetic Field
L = 0.001; %Length
V = 304; %Verdet Constant
beta = B*V*L; %Polarization shift
FR= [cos(beta),-
sin(beta);sin(beta),cos(beta)] %Faraday
Rotator
Forward = P2*FR*P1
Backward = P1*FR*P2

h=101; %Number of points on the plot
for x=1:h
    B=1.5+(x-1)*(3-1.5)/h;
    Bvect(x) = B;
    beta = B*V*L;
    FR= [cos(beta),-
sin(beta);sin(beta),cos(beta)];

    Forward = P2*FR*P1;
    Backward = P1*FR*P2;
    Forw11(x) = Forward(1,1);
    Forw21(x) = Forward(2,1);
    Forw12(x) = Forward(1,2);
    Forw22(x) = Forward(2,2);

    Back11(x) = Backward(1,1);
    Back21(x) = Backward(2,1);
    Back12(x) = Backward(1,2);
    Back22(x) = Backward(2,2);

end
figure(1)
plot(Bvect,Forw11)
hold on
plot(Bvect,Forw12)
plot(Bvect,Forw21)
plot(Bvect,Forw22)
legend(['F(1,1)';'F(1,2)';'F(2,1)';'F(2,2)'])
title(['Isolator: Forward Direction vs. B
field (L =1mm,V=304)'])
ylabel('Matrix component value')
xlabel('Magnetic Field Strength B')

figure(2)
plot(Bvect,Back11)
hold on
plot(Bvect,Back12)
plot(Bvect,Back21)
plot(Bvect,Back22)
legend(['B(1,1)';'B(1,2)';'B(2,1)';'B(2,2)'])
title(['Isolator: Backwards Direction vs. B
field (L =1mm,V=304)'])
ylabel('Matrix component value')
xlabel('Magnetic Field Strength B')
```