

# Faraday Rotators and Isolators

## I. Introduction

The negative effects of optical feedback on laser oscillators and laser diodes have long been known. Problems include frequency instability, relaxation oscillations, amplified stimulated emission, and in some cases, optical damage. As lasers have improved, the need to protect laser oscillators and laser diodes from optical feedback has increased. A Faraday Isolator’s ability to allow light to pass unimpeded in one direction, while strongly attenuating light traveling in the opposite direction, eliminates the negative effects of optical feedback. Figures 1 and 2 demonstrate this fact. Figure 1 illustrates noise emission displaced 60 kHz from the actual laser frequency of a mode-locked laser due to reflections from an uncoated glass surface. The noise emissions correspond to relaxation oscillations in the laser being driven by residual feedback. Figure 2 illustrates the effectiveness of EOT's Faraday Isolators in eliminating this problem.

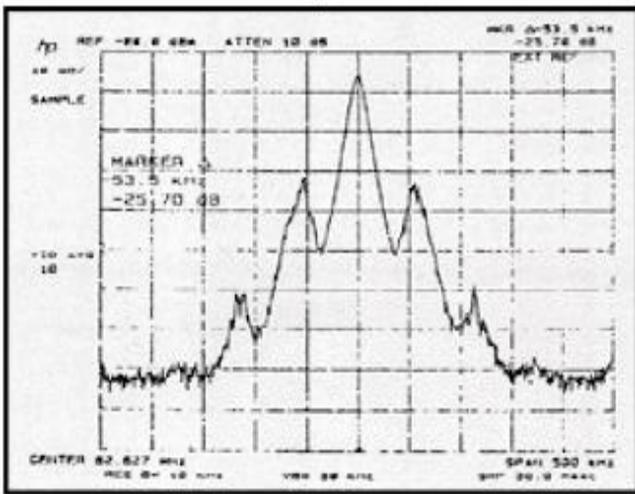


Figure 1

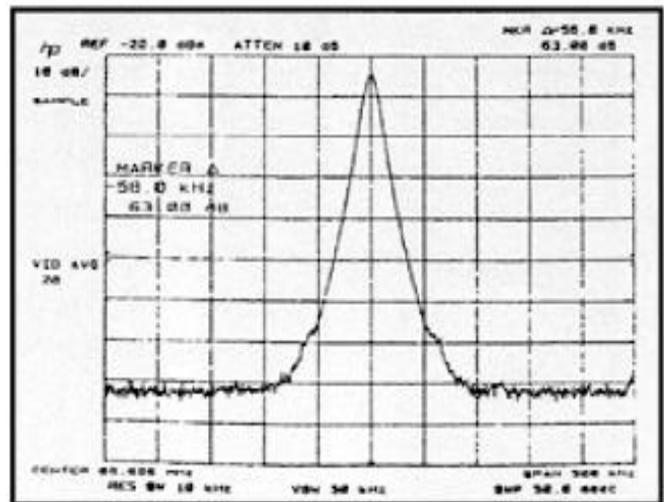


Figure 2

At the heart of a Faraday Isolator is a Faraday Rotator. Faraday Rotators utilize high strength, rare earth permanent magnets in conjunction with a high damage threshold optical element to provide a uniform 45° polarization rotation to light passing through the device. The amount of polarization rotation is,  $\theta = V \int H_z dz$  where:

- $\theta$  = polarization rotation angle
- $V$  = Verdet constant of optical element
- $H_z$  = longitudinal component of magnetic intensity vector
- $z$  = length of optical length of optical element

## II. Operation of a Faraday Isolator

A Faraday Isolator consists of three main components, an input polarizer, a Faraday Rotator and an output polarizer. As shown in Figure 3, light traveling in the forward direction passes through the input polarizer and becomes polarized in the vertical plane. Upon passing through the Faraday Rotator, the plane of polarization

will have been rotated 45° on axis. The output polarizer, which has been aligned 45° relative to the input polarizer will allow the light to pass unimpeded. As Figure 4 shows, light traveling in the reverse direction will pass through the output polarizer and become polarized at 45°. The light will then pass through the Faraday Rotator and experience an additional 45° of nonreciprocal rotation. The light is now polarized in the horizontal plane and will be rejected by the input polarizer which only allows light polarized in the vertical plane to pass unimpeded.

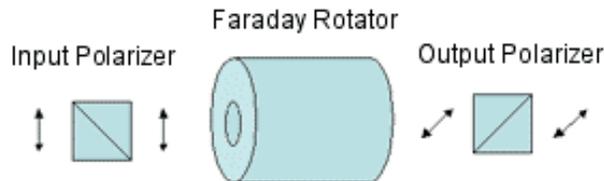


Figure 3

A Faraday Isolator’s ability to provide nonreciprocal rotation while maintaining a linear polarization is what differentiates it from a  $\lambda/4$  plate-polarizer type isolator, and allows it to provide higher isolation.

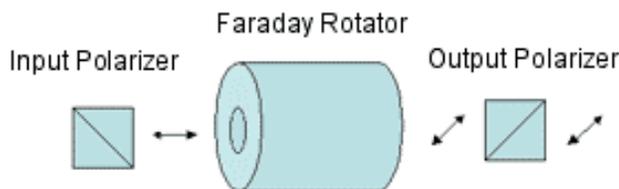


Figure 4

### III. Broadband Isolators for Ti:Sapphire and Other Tunable Lasers

Some applications, such as isolating individual amplifiers in a Ti:Sapphire amplifier chain while maintaining the ability to tune rapidly over the amplifier bandwidth or isolating a femtosecond oscillator from a Ti:Sapphire regenerative amplifier, require isolators that are wavelength independent. Unfortunately, standard isolators are only capable of providing high isolation and transmission over a narrow range of wavelengths, usually about 30 nm to 40 nm. For this reason we make broadband isolators. Broadband isolators are unique in that they are passive devices which provide high isolation and good transmission over a 250 nm range simultaneously. Other means can be used to increase an isolator’s useable wavelength range, but they require manual adjustments such as translating the Faraday Rotator optic within the magnetic field or adjusting the polarizers to compensate for the change in rotation angle. It is important to note that while these adjustments will increase an isolator’s useable wavelength range, their effective bandwidth still remains  $\pm 15$  nm at any point in time. Figure 5 shows the transmission and isolation of our broadband isolators centered at 800 nm. As these curves demonstrate, it is possible to construct a Faraday Isolator that can provide >30 dB isolation and >70% transmission simultaneously over a very large wavelength range.

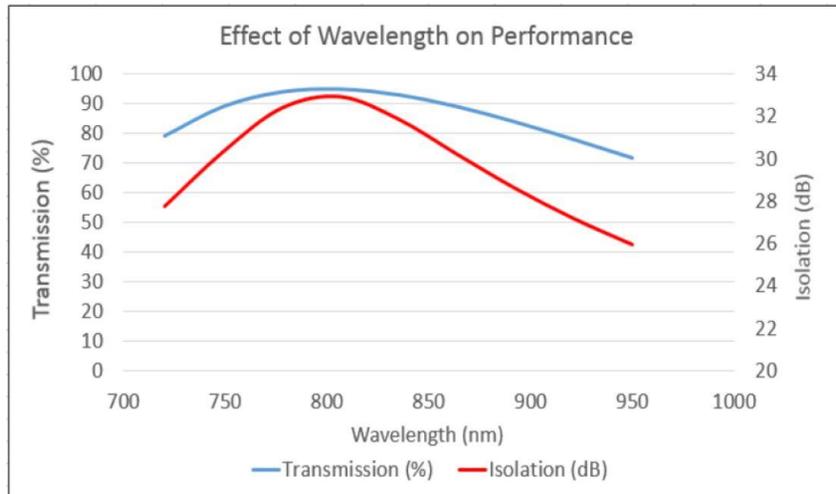


Figure 5

#### IV. Operation of Broadband Isolators

A Broadband Isolator achieves its wide bandwidth by compensating for the dispersion in the Faraday Rotator optic. While the direction of polarization rotation in a Faraday Rotator is dependent upon the direction of the rotator’s magnetic field, the direction of rotation in a crystal quartz rotator is dependent upon the direction of light propagating through it. By using a 45° crystal quartz optical rotator with its dispersion similar to the optic in the Faraday Rotator, and aligning the Faraday Rotator and crystal quartz rotator such that they rotate the polarization of back reflected light in opposite directions, the Faraday Isolator becomes less wavelength-dependent. If 45° rotation at the center wavelength is used for both the Faraday Rotator and crystal quartz rotator having the same dispersion, the net rotation will be 0° in the reverse direction and 90° (at the center wavelength only) in the forward direction. Figure 6 shows the effect of light traveling through a broadband isolator in the forward direction.

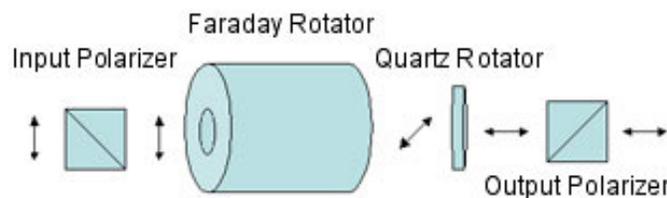


Figure 6

Figure 7 shows the effect of light traveling in the reverse direction through a broadband isolator.

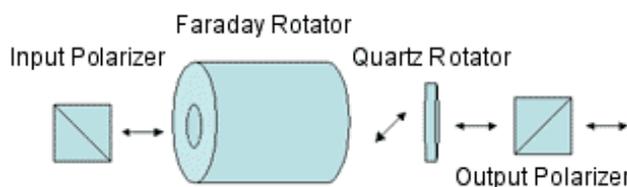


Figure 7



## V. Dispersion in Ultrafast Ti:Sapphire Lasers; Sellmeiers Equation for TGG

In femtosecond Ti:Sapphire lasers, pulse broadening caused by dispersion in the Faraday rotator optic is a major concern. Below is the Sellmeiers Equation for TGG:

$$n^2 - 1 = \frac{E_d E_o}{E_o^2 - (hc / \lambda)^2}$$

where:  $E_o = 9.223\text{eV}$  and  $E_d = 25.208\text{eV}$

### References:

1. U. Schlarb and B. Sugg, Phys. Stat. Sol. (b) 182 K91 (1994)

## VI. Key Optical Components of a Faraday Isolator

- A. Faraday Rotator optic:** The most important optical element in a Faraday Isolator is the Faraday Rotator optic. The characteristics that one looks for in a Faraday Rotator optic include a high Verdet constant, low absorption coefficient, low non-linear refractive index and high damage threshold. Also, to prevent self-focusing and other thermal-related effects, the optic should be as short as possible. The most commonly used material used for the 650 nm to 1100 nm range is terbium gallium garnet (TGG). However, terbium doped borosilicate glass can be used in certain customer products.
- B. Polarizers:** Also of critical importance in determining the performance of a Faraday Isolator are the polarizers. Desirable polarizer characteristics include high damage threshold, high extinction ratios and low transmission losses. EOT's 1010 nm to 1080 nm isolators use optically contacted fused silica cube polarizers. Broadband isolators utilize PBS Cubes. Laser diode isolators utilize Corning Polarcor™ polarizers or PBS Cubes.

## VII. Optical Component Specifications

### A. Faraday Rotator Optic Specifications:

	Tb:Glass	TGG
Pulsed Damage Threshold at 10 ns	2 J/cm <sup>2</sup>	10 J/cm <sup>2</sup>
Absorption Coefficient at 1064 nm	<0.005 cm <sup>-1</sup>	<0.0035 cm <sup>-1</sup>
Nonlinear Refractive Index	2.7 x 10 <sup>-13</sup> esu	8 x 10 <sup>-13</sup> esu
Index of Refraction at 1064 nm	1.720	1.95
Verdet Constant at 1064 nm (min/Oe-cm)	0.098	0.125



**B. Polarizer Specifications:**

	PAVOS Isolators	Eurys Isolators	TORNOS Low Power Isolators	TORNOS Medium Power Isolators
<b>Material</b>	PBS	PBS	Polarcor™	PBS
<b>Pulsed Damage Threshold at 10 ns</b>	10 J/cm <sup>2</sup>	1 J/cm <sup>2</sup>	25 W/cm <sup>2</sup> (CW)	1 J/cm <sup>2</sup>
<b>Refractive Index</b>	1.450 at 1064 nm	1.48216 at 800 nm	1.529 at 583 nm	
<b>Transmission at 22 °C</b>	>92%	>92%	>82% at 800 nm	>88% at 800 nm
<b>Isolation at 22 °C</b>	>30 dB	>30 dB	>30 dB	>27 dB

**VIII. Isolation Defined**

The two main factors which determine isolation are the extinction level of the polarizers and rotator optic, and the radial uniformity of the Faraday Rotator. The radial uniformity is the angle of rotation across a cross section of the rotator optic. The following equation gives the isolation ratio (I.R.) due to radical uniformity for a Faraday Rotator when placed between polarizers having an extinction of  $\geq 10^{-5}$  for a Gaussian beam:

I.R. =  $-10\log P \text{ Leakage}/P \text{ Incident}$   
 or: I.R. =  
 Isolation Ratio due to radial uniformity

$$I.R. = -10\log \left[ \frac{4}{w^2 \left[ 1 - e^{-\frac{2a^2}{w^2}} \right]} \int_0^a r e^{-\frac{2r^2}{w^2}} \left[ \cos^2(\pi / 2 - \beta(r)) + 10^{-5} \right] dr \right]$$

Where:

a = Clear aperture radius

w = Gaussian beam 1/e<sup>2</sup> intensity, radius = 2/3 of clear aperture

$\beta r$  = Radial variation of rotation =  $\theta(r) - \theta$  on axis

**IX. Pulsed Damage Threshold; Root "T" Scaling**

Pulsed damage thresholds for EOT's rotators can be obtained for various pulsewidths by using the Root "T" Scaling method.

For 1010 nm to 1080 nm and broadband rotators:  $10 \text{ J/cm}^2(\tau/10 \text{ nsec})^{1/2}$

Where  $\tau$  = the desired pulsewidth