

# Feedback Prevention in Optical Fiber-Based Ultrafast Lasers using EOT Optical Isolators

## 1 The Effect of Feedback on Femtosecond Fiber Laser Systems

*A little (optical) feedback can go a long way . . .*

As rare-earth doped optical fiber becomes a more widespread medium for ultrafast laser systems, used in both fiber-only and hybrid (fiber and bulk) lasers, issues specific to design with fiber-based oscillators and amplifiers have emerged. Because fiber is a high gain medium, any light that is inadvertently injected into the ultrafast oscillator, as well as into amplifiers, can degrade and potentially irreversibly affect system performance by causing instability (at best) or damage (at worst). Optical feedback, caused by back-reflections off of downstream optics or by amplified spontaneous emission (ASE) from amplifier stages, is literally amplified by the high gain in doped optical fibers. Small signal, single-pass gains of  $\sim 20$  dB or more are typical in optical fibers, as opposed to the relatively lower gain of  $\sim 5$  dB in bulk doped materials. That, and the relatively smaller size of the beam at the end of a fiber compared to bulk gain material, leading to a higher intensity at the end face, allows fiber systems to reach the damage threshold at lower optical powers.

**Glass fiber** host laser media are “high gain”

- Geometry allows for more gain in a single pass than in bulk systems
- Gain can be up to 100x or more
- For Oscillators, output coupler can be  $\sim 70\%$  or more

→ ***Very susceptible to external feedback***

Ultrafast laser systems, generating pulses below 10 picoseconds (ps) and into the femtosecond (fs) range, can be designed for different operating regimes, depending upon target pulse energies and repetition rates. Two typical configurations are: an optical Master Oscillator Power Amplifier (MOPA) scheme (for ps pulses and often with hybrid bulk-fiber design) and a Chirped Pulse Amplifier (CPA) scheme (for fs pulses). Examples of these designs can be seen in Figures 1 and 2.

Practically speaking, whenever a laser system is designed using a mode-locked fiber oscillator as the pulse source, the oscillator typically provides only mW level output while system requirements can go to the 10s of Watts and beyond. Amplifiers are required to achieve performance targets, and often use large-mode area (LMA) amplifiers producing 1W to even up to more than 100W, but the oscillator can only remain stable with feedback on the microwatt ( $\mu\text{W}$ ) level or less. Otherwise, noise that disturbs the spectral content can inhibit mode-locking or even cause Q-switching—the power that is fed back must be smaller than the ASE that pulses build from; this often means that an oscillator requires  $\ll 60$  dB of feedback to remain stably mode-locked. In contrast, solid-state mode-locked oscillators can still operate with many times that amount of feedback. At the same time, if the seed pulse from the oscillator is interrupted at the input of an amplifier, Q-switching can result, which invariably leads to optical damage on a fiber end face. A mechanism to prevent feedback from entering ultrafast fiber oscillators, and to protect the subsequent chain of amplifiers, is essential.

*Fortunately, there is a solution to the problems arising from optical feedback – the use of EOT Optical Isolators.*

## 2 Protection from Feedback Using a Faraday Isolator

A Faraday Isolator is an optical device that provides high transmission of signal light in the forward direction, but strongly blocks light from the reverse direction. The main component in an optical isolator is the Faraday Rotator, made of a magneto-optic material that has special properties - the way a Faraday Rotator operates is to rotate the plane of polarized light 45 ° in the forward direction and an additional 45 degrees of non-reciprocal rotation in the reverse direction while maintaining the light's linear polarization. When placed between crossed polarizers, a Faraday Rotator becomes a Faraday isolator. A Faraday Isolator protects laser oscillators and laser amplifiers from the deleterious effects of back reflections. Containing low absorption, high damage threshold optics, EOT's Faraday Rotators and Isolators are ideally suited for use with average power levels of up to 50W for ultrafast laser systems.

When selecting an isolator, there are several criteria to keep in mind: the incident beam size, the incident optical power on the isolator, the required transmitted power for the next stage, and the amount of isolation required. See <http://www.eotech.com/cart> to find the EOT product best suited for your requirements at every stage.

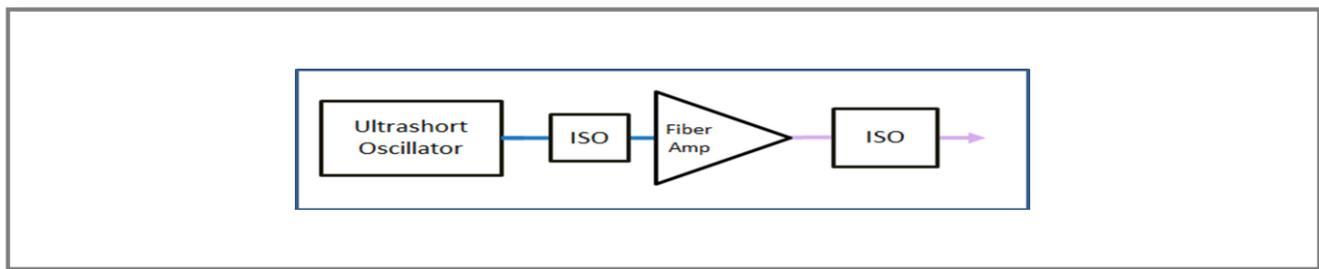


Figure 1. Typical MOPA Design, showing the use of isolators (denoted ISO) and their locations in the beam path.

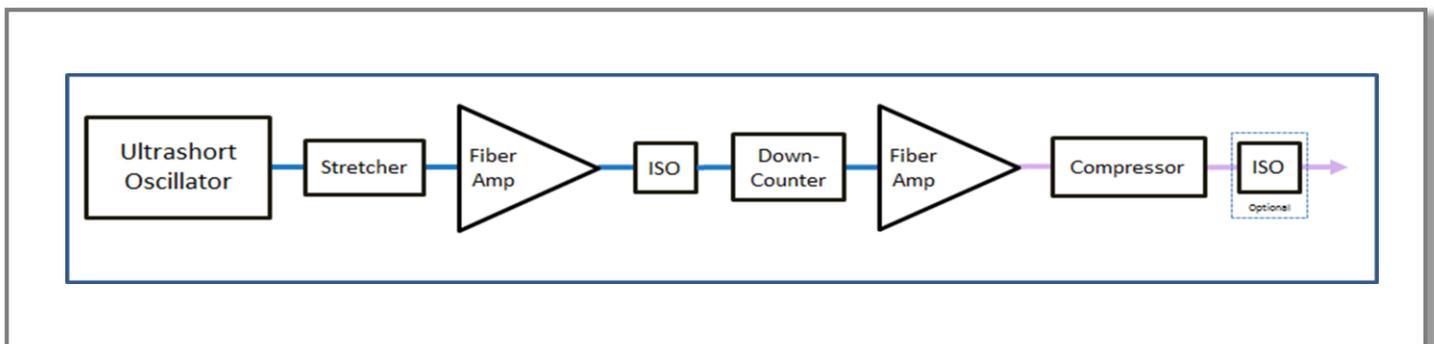


Figure 2. Typical CPA Design, showing the use of isolators (denoted ISO) and their locations in the beam path.

## 3 Installing a Faraday Isolator

Installing a Faraday Isolator in the optical path of a fiber laser system is relatively straight forward. Each EOT Isolator comes with a User's Manual<sup>i</sup>, which describes how to align the device in the beam path. Consideration of the optical beam size, optical power and center wavelength and bandwidth must be taken into account when selecting the

appropriate isolator. EOT Faraday Isolators are factory aligned as per the Model Number specified in a Purchase Order. See Figures 1 and 2 for examples of where to install isolators in MOPA and CPA systems. An example of a real-world application can be found in reference 2<sup>ii</sup>.

## 4 Considerations Related to Dispersion

Dispersion is a significant issue for ultrafast lasers, one that can affect the pulse duration and therefore, the peak power, of ultrashort pulses. Dispersion occurs when light pulses travel in a medium where the phase velocity depends on its frequency (or wavelength). The Faraday material used to make an optical isolator is dispersive, and therefore pulses traversing through an isolator can broaden in length, although the magnitude and relevance of that effect depends on both the initial pulse and the application.

Generally, fiber laser systems produce pulses on the order of 100 fs or longer, with an optical bandwidth in the range of 10 - 30 nm or more. The actual system bandwidth, along with the length of the Faraday Rotator used in the isolator, will dictate the amount of pulse broadening that will occur. The amount of dispersion typically will not cause enough pulse distortion to negatively impact applications.

However, it is important to note that for pulses < 100 fs (pulses with broader bandwidth), the amount of dispersion will be greater and this becomes an important consideration in many applications. As an example, in nonlinearly broadened systems, including certain CPA systems, it is possible to produce < 100 fs pulses. If an isolator is required at the output of the laser system because there can be feedback that arises from the application (for instance, when the laser is used for material processing), this will add to the overall group velocity dispersion budget. In some cases, the effects of dispersion caused by the output isolator can be mitigated or removed by balancing it with dispersion in other parts of the system.

An example of how a Faraday Isolator using 8 mm of TGG can affect the pulse duration of ~ 1050 nm ultrashort pulses over the range from 10 – 10,000 fs, is shown in Figure 3. The graph was generated by determining how much group velocity dispersion (GVD) occurs for 1050 nm pulses. This was done using the Sellmeier Equation for TGG<sup>iii</sup>,

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

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

and  $h$  (Planck's constant) =  $4.135667516 \times 10^{-15}$  eV·s and  $c$  (the speed of light) =  $3 \times 10^8$  m/s.

The group velocity dispersion (GVD), which introduces a frequency dependent delay to the different spectral components of the pulse (typically in units of  $\text{fs}^2/\text{m}$ ) is expressed as<sup>iv</sup>:

$$GVD = \frac{\lambda^3}{2\pi c^2} \left( \frac{d^2 n}{d\lambda^2} \right)$$

Solving analytically for the 2<sup>nd</sup> derivative of the refractive index, it is possible to calculate GVD and then the actual second order dispersion for a specific device (here denoted as  $\beta_2$ , the second-order group delay dispersion), related to GVD by multiplying GVD by the length of the material – in this case, the TGG used in the isolator. This information can in turn be used to calculate the output pulse duration for given input pulse duration, after traveling through the length of TGG isolator material. For the case where the input pulse length squared,  $\tau_0^2 \ll \beta_2$ , an equation to express the pulse broadening proportional to  $\beta_2$  can be used.<sup>v</sup>

By performing these calculations, the amount of dispersion,  $\beta_2$ , over the range of 1030 - 1080 nm was found to be  $\sim 1100 \text{ fs}^2$  for 8 mm long TGG. The estimated broadening from that amount of second order dispersion for pulses in the range of 10 – 10,000 fs is shown in the graph below.

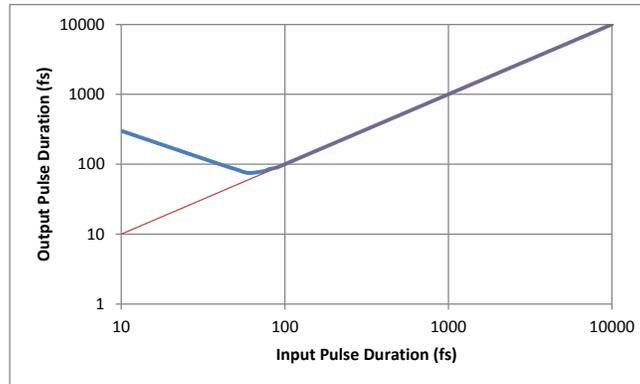


Figure 3. Broadening of a femtosecond pulse at  $\sim 1050 \text{ nm}$  after propagation through 8 mm of TGG (blue curve); the red curve shows the output for undistorted pulses.

## 5 Conclusions

When designing ultrafast laser systems with fiber sub-systems, the use of protective optical isolators is key to achieving the best performance and product lifetime possible. The use of EOT Optical Isolators at critical points in the system, as described in this Application Note (i.e. after a seed fiber oscillator and between amplifier stages) will allow for designers to realize the best possible performance with respect to stability, robustness, long term reliability, and to avoid damage that would cause system failure.

*Contact EOT for more information on how to protect your fiber-based laser system from optical feedback.*

### References:

- <sup>i</sup> EOT User Manual: <http://www.eotech.com/9/user-guides/faraday-rotators-and-isolators>
- <sup>ii</sup> J. Limpert, T. Schreiber, S. Nolte, H. Zellmer, and A. Tünnermann, "All fiber chirped-pulse amplification system based on compression in air-guiding photonic bandgap fiber," in *Advanced Solid-State Photonics (TOPS)*, G. Quarles, ed., Vol. 94 of *OSA Trends in Optics and Photonics (Optical Society of America, 2004)*, paper 9.
- <sup>iii</sup> U. Schlarb and B. Sugg, "Refractive Index of Terbium Gallium Garnet", *Phys. Stat. Sol. (b)* 182 K91 (1994)
- <sup>iv</sup> As one source, see "Nonlinear Fiber Optics" by G. P. Agrawal for more details on group velocity dispersion
- <sup>v</sup> See the section on Dispersive Pulse Broadening and Chirping at: [http://www.rp-photonics.com/chromatic\\_dispersion.html](http://www.rp-photonics.com/chromatic_dispersion.html)