# Characterization of nonlinear saturation and mode-locking potential of ionically-doped colored glass filter for short-pulse fiber lasers

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**Abstract:** The nonlinear saturable absorption of an ionically-doped colored glass filter is measured directly using a Z-scan technique. For the first time, we demonstrate the potential of this material as a saturable asborber in fiber lasers. We achieve mode-locking of an ytterbium doped system. Mode-locking of cavities with all-positive and net-negative group velocity dispersion are demonstrated, achieving pulse durations of 60 ps and 4.1 ps, respectively. This inexpensive and optically robust material, with the potential for broadband operation, could surplant other saturable absorber devices in affordable mode-locked fiber lasers.

**OCIS codes:** (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers; (160. 2750) Glass and other amorphous materials.

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## 1. Introduction

Passively mode-locked fiber laser sources have been extensively developed in recent years. This has led to their deployment across a broad range of applications requiring ultrashort pulses, because of their compactness, simplicity, and low cost. The use of intra-cavity saturable absorber devices (SADs) in laser systems to initiate and stabilize mode-locking is ubiquitous, with the first demonstration just six years after the development of the laser [1].The parameters that characterize a SAD, and govern mode-locking performance, differ depending on the round-trip gain and loss, dispersion and nonlinearity of a laser system. Thus, SADs used in bulk and fiber lasers have differing properties. Typically, a larger modulation depth is required for fiber lasers, where the round-trip gain and loss is high, and dispersion and nonlinearity strongly influence pulse formation. The recovery time can strongly influence the pulse duration, particularly in a bulk laser without dispersion management. A short recovery time, while supporting short pulses, can lead to unreliable self-starting performance [2]. To date, a number of SADs, with parameters specific for use in fiber lasers, have been investigated and widely employed to achieve reliable mode-locked performance including, semiconductor-based absorbers [3]; carbon nanotubes (CNTs) [4, 5]; and more recently, graphene [5–8]. Although these technologies offer many advantages, such as broadband and reliable operation, they are not without limitation, having drawbacks, namely, high production costs and relatively low damage thresholds. In contrast, ionically-doped colored glasses [9–11] used as a saturable absorber in fiber lasers may resolve these issues, providing a more thermally robust solution allowing potential for higher achievable output powers, supported by performance of mode-locked solid-state lasers based on this approach [12, 13], as well as offering the potential for broadband operation. In this paper, using a Z-scan technique we measure the nonlinear transmission of a low-cost, commericially available ionically-doped colored glass filter (RG1000). We demonstrate, for the first time to the best of our knowledge, that this device offers sufficient intensity contrast to promote mode-locking in a low-power ytterbium- (Yb-) doped fiber system. This proof-of-concept demonstration of mode-locking a fiber laser, importantly, where the requirements on the absorber differ significantly to solid-state counterparts due to differences in the gain dynamics and the magnitude of the nonlinearity and dispersion, could open the possiblity of achieving elavated output energies from all-fiber, passively mode-locked pulsed lasers.

## 2. Characterization of the nonlinear absorption by Z-scan

The configuration used to perform the Z-scan measurements is shown in Fig. 1(a). A commercial Yb-doped mode-locked fiber laser was amplified by an inline Yb-doped fiber amplifier unit, and used as the pump source centred at 1063 nm. The pump light was split using a fused fiber coupler to support a 7% reference port, monitored by a power meter; the remaining 93% was coupled into a small core, high numerical aperture fiber (Nufern UHNA 3), the output of which was imaged by a pair of 10 mm focal length lenses. A 2×2 mm square piece of ionically-doped colored glass, with a thickness of 240 $\mu$m, attached to the sample arm was moved through the focal point by an automated translation stage. A third lens collected the light transmitted

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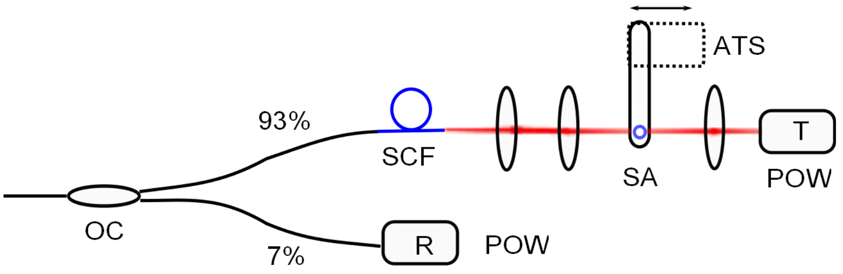
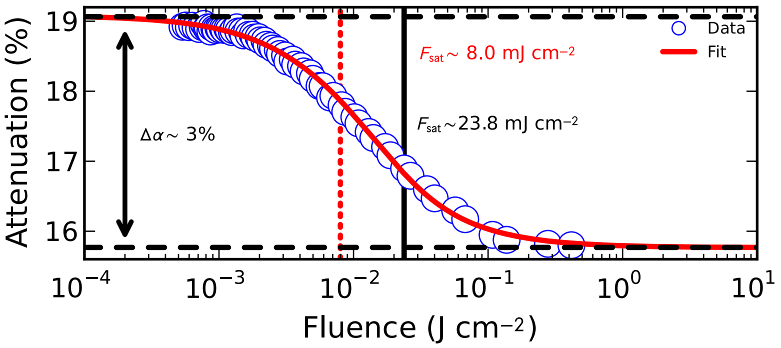
through the test sample and focussed it through the entrance aperture of a second power meter. In order to fully saturate the sample, the pump source was amplified to 0.5 W, after which it produced pulses with a duration of 8.9 ps at a repetition rate of 50 MHz. The beam waist was 1.3 $\mu$m, resulting a peak intensity at the Z-scan focus of approximately 46 GW cm$^{-2}$.

The sample and reference power, at each spatial increment through the focal plain, was recorded using a fully automated approach, and was integrated with the precision stepper motor that controlled the position of the sample. This allowed rapid, accurate and reproducible aquisition of multiple datasets.



(a) Z-scan setup.



(b) Representative nonlinear saturable absorption curve.

Fig. 1. (a) OC-output coupler; SCF-small core fiber; SA-scanning arm; ATS-automated translation stage; POW-power meter; T-transmitted; R-reference. (b) Typical dataset from Z-scan experiment.

A typical dataset from a single Z-scan measurement, at a fixed transverse position on the test sample, is shown in Fig. 1(b). The red curve is a fit to the experimental data based on the slow saturable absorption model [14]:

$$\alpha(t) = \frac{\Delta\alpha\left[1-\exp\left(-\frac{F(t)}{F_{\mathrm{sat}}}\right)\right]}{\frac{F(t)}{F_{\mathrm{sat}}}} \tag{1}$$

where $\Delta\alpha$ is equivalent to the modulation depth, $F(t)$ and $F_{\mathrm{sat}}$ are the instantaneous and saturation fluence, respectively. This model of saturable absorption is appropriate due to the fact that the relaxation time of the ionically-doped glass which could be estimated based on Chen et al and Yumashev et al [11,15,16] to be on the order of tens of picoseconds, is expected to be much longer than the duration of pump pulse [15]. The corresponding saturation fluence, based

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on the slow absorber model, is 8.0 mJ $\mathrm{cm}^{-2}$. We also highlight, with a solid black line, the $1/e$ value of 23.8 mJ $\mathrm{cm}^{-2}$. The modulation depth – the contrast between the fully absorbing and fully saturated state of the device, and highlighted in Fig. 1(b) with a solid black line – of the test sample is $\sim$3%.

The density of active ions, however, was not homogeneous across the test sample. We mapped this inhomogeneity by raster scanning the sample, measuring the nonlinear saturation curve at 0.5 mm spatial increments in the XY plain, across a $2\times2$ mm section, with a uniform thickness of 240 $\mu$m. Figure 2 shows the resulting data, processed to display the variation in the modulation depth and saturation fluence, presented on a two-dimensional grid. The resolution, and the resulting minimal spatial increment, was limited by the spot size through the Z-scan optics.

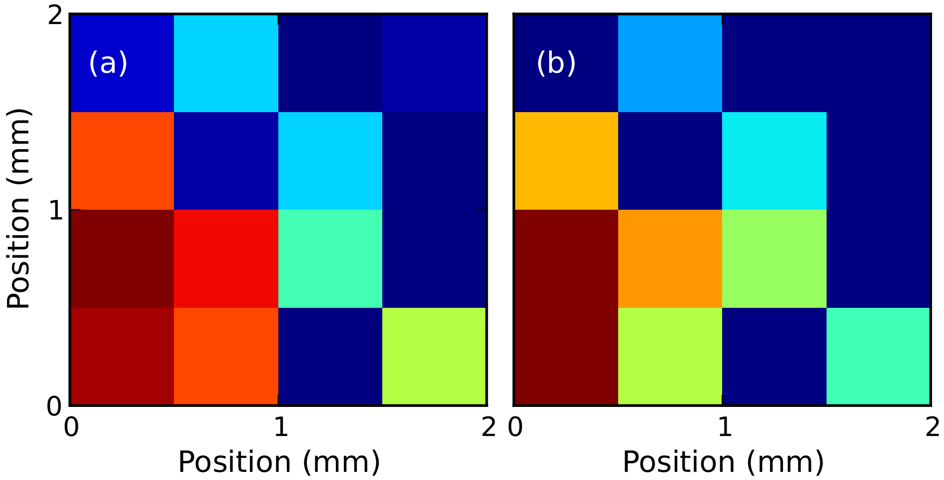

Fig. 2. Mapping of the inhomogeneity. Variation in modulation depth (a). Colorbar: 0 3%. Variation in saturation fluence (b). Colorbar: 0 25 mJ $\mathrm{cm}^{-2}$.

It is clear that the density of absorbing ions, present in the glass host, is concentrated in the lower left corner of this particular test sample. It should be noted that, improved doping control during the fabrication process would result in a greater homogeneity, and improved device performance.

In addition to measuring the nonlinear saturation, the linear spectral transmission was also recorded using a commerical spectrophotometer (Fig. 3). The dashed black line shows that at the wavelength of 1063 nm, the spectral region where nonlinear saturation measurements were performed using the Z-scan technique, where pump light was provided by a Yb-doped fiber laser, the corresponding linear transmission of the sample, with a thickness of 240 $\mu$m, is $\sim$80%.

## 3. Demonstration of mode-locking a fiber laser

We constructed an Yb-doped fiber laser, using a travelling wave ring cavity design, to test the mode-locking potential of the ionically-doped colored glass filter – well known to be an effective saturable absorber in bulk systems [12, 13].

The configuration of the all-fiber laser is shown in Fig. 4. A fiber amplifier module was used to provide a noise seed and amplification in a band around 1060 nm; a polarization independent inline fiber circulator ensured unidirectional propagation and allowed dispersion control

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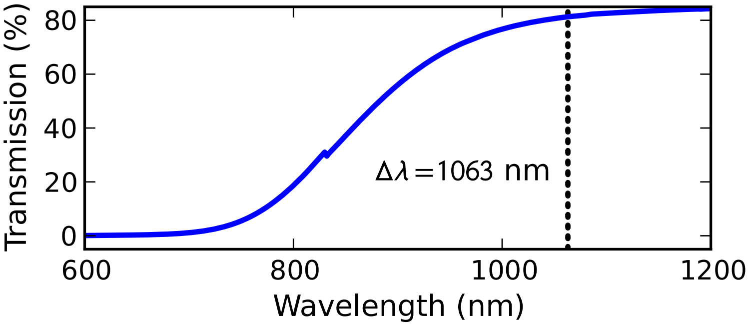

Fig. 3. Linear transmission spectrum of the ionically-doped glass sample. The vertical dashed line denotes the pump laser operation wavelength at 1063 nm, used in the Z-scan experiment.

of the cavity to be achieved with the inclusion of chirped and unchirped fiber Bragg gratings (FBGs). The FBG also provided spectral filtering, stabilizing the mode-locking. An unchirped FBG, with a 0.2 nm bandwidth, was used to operate with an all-positive cavity dispersion. A chirped FBG, with a passband of 3.8 nm, was used for dispersion control, and operation in the average soliton regime, with net-anomalous dispersion. A fiber-based polarization controller (PC) was added to the cavity. The output was delivered through a 20% fused-fiber coupler to both spectral (optical spectrum analyzer) and temporal diagnostics (50 GHz Tektronix sampling scope and back-ground free intensity autocorrelator). Mode-locking was initiated with the inclusion of the commerically available ionically-doped glass filter (RG1000); the nonlinear and linear absorption characteristics of which were characterized in Section 2. The device comprised three layers, each polished to a uniform thickness of 240 $\mu$m, integrated into the cavity by sandwiching it between two fiber connectors, with index matching gel.

### 3.1. All-positive cavity dispersion

The laser cavity consisted of entirely isotropic, single-mode fiber with positive dispersion at the operation wavelength of 1064 nm. With the unchirped grating included to provide only spectral narrowing, and no dispersion compensation the mode-locking dynamics were non-solitonic. Mode-locking was achieved at the fundamental repetition frequency of the cavity of 7.4 MHz, with a corresponding single-pulse energy of 0.96 pJ. The spectrum (Fig. 5(a)) was

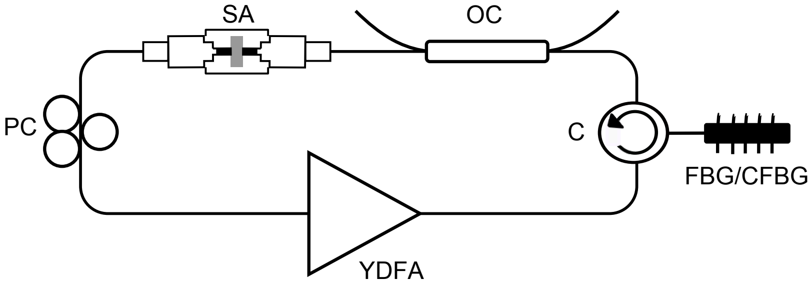

Fig. 4. Laser setup for testing the mode-locking potential of the ionically-doped glass SAD. YDFA, Yb-doped fiber amplifier; C, circulator; FBG, fiber Bragg grating; CFBG, chirped fiber Bragg grating; OC, output coupler; SA, saturable absorber; PC, polarization controller.

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centered at 1064 nm, and had a full width at half maximum (FWHM) of 0.05 nm, corresponding to a transform-limited pulse duration of 24.8 ps. The temporal pulse profile, recorded using a fast photodiode, with a 15 ps risetime and a 50 GHz sampling oscilloscope, is plotted in Fig. 5(b). When fitted with a $\mathrm{sech}^2$ pulse-shape, the pulse duration can be seen to be ∼60 ps. The fundamental and higher harmonic frequencies are shown in Fig. 6(a) and 6(b), respectively.

### *3.2. Net-anomalous cavity dispersion*

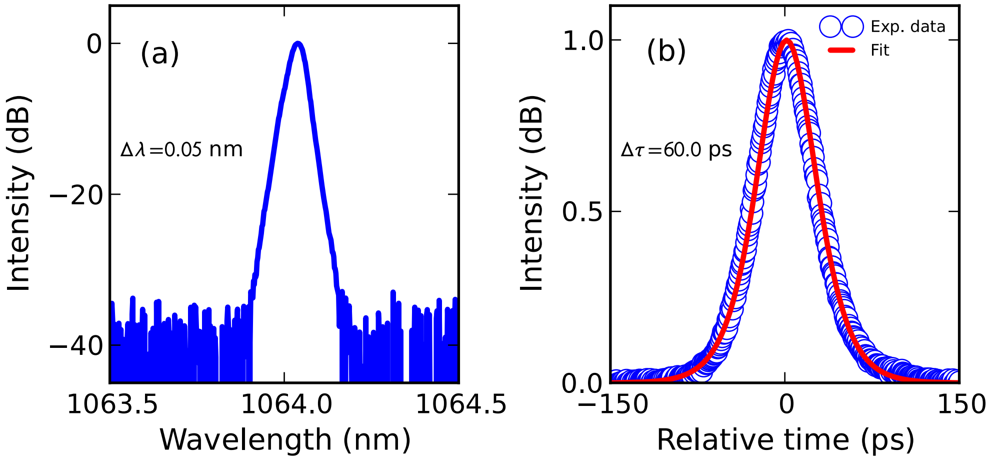

Fig. 5. (a) Measured optical spectrum, and (b) the corresponding experimentally measured temporal intensity profile.

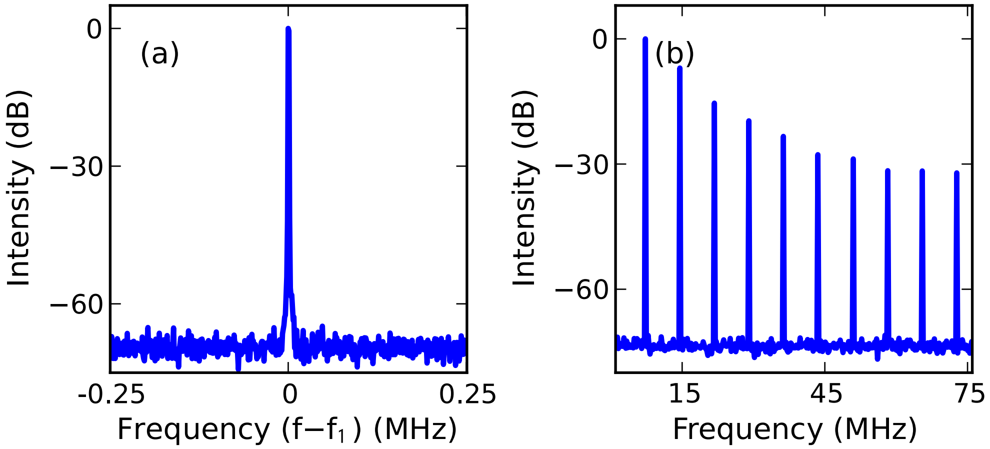

Fig. 6. Radio frequency spectra.(a) Fundamental on a span of 500 kHz, and (b) harmonics on a span of 75 MHz.

To compensate the normal dispersion, a chirped FBG, with a negative dispersion of $-35.71$ ps $\mathrm{nm}^{-1}$, was employed. The laser operated in the average soliton regime at the fundamental cavity repetition rate of 7.3 MHz, with a corresponding single-pulse energy of

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0.28 pJ. The spectral FWHM of 0.37 nm, centered at 1065.2 nm (Fig. 7(a)), corresponds to a transform limit of 3.2 ps. Figure 7(b) shows the back-ground free intensity autocorrelation trace. Assuming a sech$^2$ profile, the deconvolved pulse duration is 4.1 ps. The fundamental and higher harmonic frequencies are shown in Fig. 8(a) and 8(b), respectively.

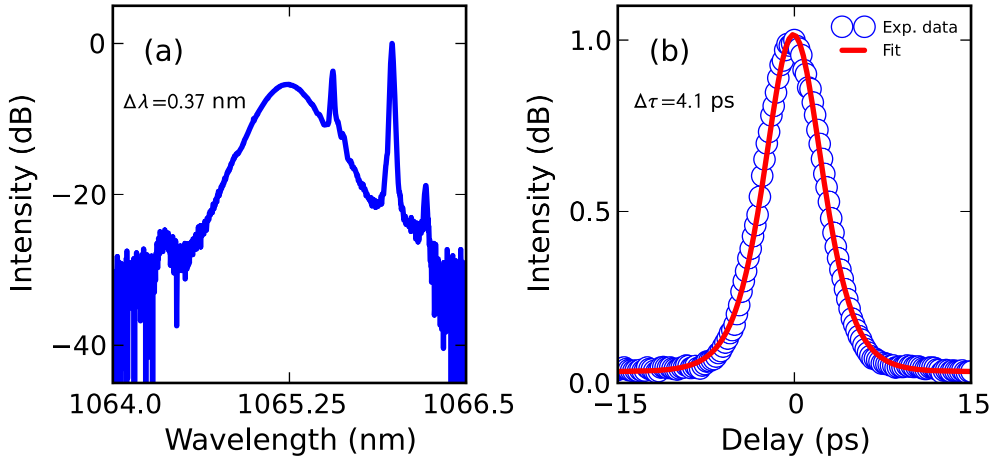

Fig. 7. (a) Measured optical spectrum, and (b) the corresponding intensity autocorrelation.

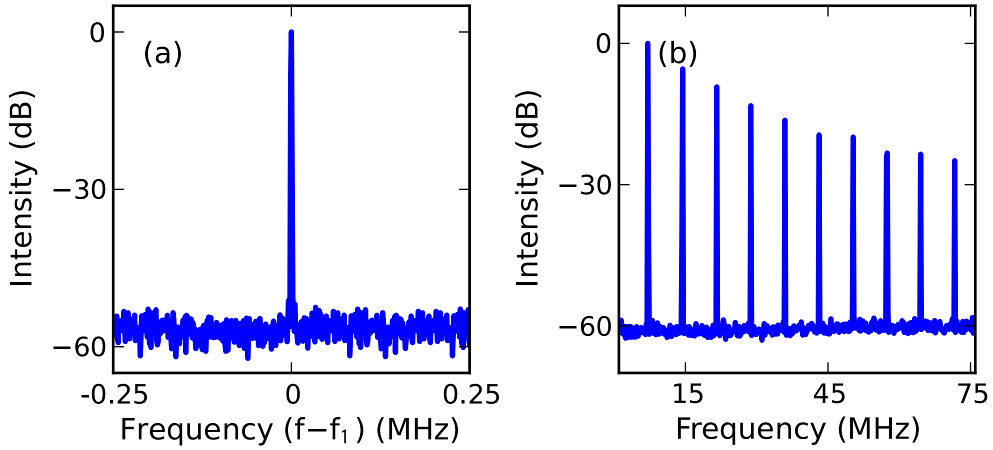

Fig. 8. Radio frequency spectra.(a) Fundamental on a span of 500 kHz, and (b) harmonics on a span of 75 MHz.

It was confirmed that in both dispersion regimes, mode-locking was initiated by the saturable action of the ionically-doped glass by removing the sample and observing no mode-locked operation. It should be noted that in this case, because a device consisting of multiple layers was used, a large insertion loss was introduced due to the finite separation (∼720 $\mu$m) between containing fiber connectors. This resulted in low average output powers, and small pulse energies, but could be readily circumvented with improvements to the sample doping concentation (reducing the need for such a thick SAD), and the method of integration.

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## 4. Conclusion

In conclusion, we have characterized the intensity dependent absorption properties of a commercially available, ionically-doped colored glass filter (RG1000). We have demonstrated that this simple, cost-effective device can be effectively employed as an optically robust saturable asborber in a fiber laser. Basic, low system power results of passive mode-locking an Yb-doped fiber laser, operating with all-positive and net-anomalous cavity dispersion, were reported for the first time.

While it has been well known that ionically-doped glasses can be used to mode-lock solid-state systems, their potential application in fiber lasers has not be studied, until now. The results reported here could have significance in the ongoing development of low-cost and compact turn-key sources of picosecond-scale pulses, delivered by all-fiber systems. In particular, overcoming issues related to damage that occurs at relatively modest power levels in current saturable absorber devices.

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