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Numerical modeling of mode-locked fiber lasers with a fiber-based saturable-absorber

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ABSTRACT

We report fiber laser simulations with a fiber compatible, self-focusing, saturable absorber (SA) device. The SA device consists of two tapered fiber ends separated by a bulk, nonlinear medium. An optical beam transmitted from one tapered fiber end, propagate through the nonlinear medium (chalcogenide glass $As_{40}Se_{60}$) and couples back into the other tapered fiber end. Pulse propagation in the fiber laser cavity is performed using the Split Step Method. Stable pulses are generated with energies around 0.3 nJ and a transform limited pulse width around 200 *fs*.

1. Introduction

A saturable absorber (SA) device is placed in a laser cavity to suppress continuous wave operation and to promote cooperation between many modes to sustain ultrashort pulse operation. A saturable absorber imparts losses to pulses within the cavity. The losses are relatively large at low intensities, but are significantly smaller for higher intensities. A pulse becomes shorter in time after passing through the SA, since the high intensity at the peak of the pulse saturates the absorber more strongly than its low intensity wings. Even in the presence of SAs the pulses can grow from intensity noise fluctuations in the cavity to achieve self-starting mode locking action.

Various SA mechanisms have been proposed to achieve the desired range intensity discrimination. Current commercial ultrafast lasers generally use semiconductor saturable absorber mirrors (SESAMs) [1,2]. Due to the well-established nanofabrication technology, they provide good control of the critical SA parameters, i.e. modulation depth, non-saturable loss and saturation power. However, due to the use of highly complex equipment in the fabrication process, a SESAM is generally pricy and bulky, which are not desirable characteristics for devices in fiber laser cavities. Other SA examples, based on a material nonlinearity, include: carbon based absorbers such as single-walled carbon nanotubes (SWCNTs) [3], graphene based absorbers [4] and so on. All these SAs have technical drawbacks. For example, CNTs generally suffer high non-saturable losses and graphene based absorbers have low modulation depth [5].

The disadvantages of the SAs mentioned above have spurred scientists' interest to develop artificial SAs based on nonlinear effects. These efforts give rise to the Kerr lens mode locking based on Optical Kerr effect [6] and nonlinear polarization evolution (NPE) based on the nonlinear effect in fibers [7,8]. Fiber lasers with NPE are inherently environmentally unstable and subtle fiber distortions can result in different output pulses from the same cavity. Furthermore, NPE effect is not accessible in cavities where polarization maintaining (PM) fibers are used. In contrast, Kerr lens mode locking based on optical Kerr effect is also suitable where PM fibers are needed.

Kerr lens mode locking was first reported for Ti: sapphire lasers in 1991 by Spence's group [9] and achieved pulses as short as 60 fs pulses. The reason ultra-short pulses can be generated with Kerr effect is due to the ultrafast response time of the electronic effect, which has enabled the generation of the shortest pulses with pulse width of ~5 fs [10]. The realization of Kerr lens mode locking action involves using the third order nonlinearity in conjunction with a hard (soft) aperture and has not been used in a fiber laser cavity. We recently report a new fiber-based saturable absorber design based on focusing the Kerr Effect [11]. The new SA design has two tapered fiber ends separated by a space with a nonlinear Kerr medium between them. The SA characteristics of the device were calculated using carbon disulfide ($\mathbf{CS_2}$) and chalcogenide glass $\mathbf{As_2S_3}$ as the nonlinear medium [11]. The materials were chosen because of their large Kerr nonlinearity. As shown in Ref. ([11]), the new proposed SA design enjoys high modulation depth, ultrafast response time and has very low manufacturing cost. In this paper, we replace the nonlinear medium by another type of chalcogenide glass $\mathbf{As_{40}Se_{60}}$ and calculate the SA action following the same procedure as in [11]. Once SA action is obtained, we investigate its pulse shaping performance in a fiber

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laser cavity using standard simulation technique – split step method.

2. Saturable absorber action with $As_{40}Se_{60}$

As shown in reference [11] (see Fig. 2 in [11]), the SA action of the proposed design is a function of the beam sizes at the fiber ends, nonlinear coefficient and the thickness of the nonlinear medium (D). In this paper, we assume both the transmitting and receiving fibers are tapered from a normal single mode fiber, which has an outer diameter of 125 µm and core diameter of 8.2 µm. The fibers are tapered to have an outer diameter of 40 µm, which has the largest mode radius among different tapered fibers which in turn effectively reduces the need for high nonlinearity. The gap between fiber ends is D=3 mm and is filled with a plate of chalcogenide glass $As_{40}Se_{60}$. At tele-communication wavelength of $1.55\mu m$, $As_{40}Se_{60}$ has been found to have both high nonlinearity and figure of merit {FOM[$= n_2/\beta\lambda$, with β the two photon absorption coefficient]}, $2.3\times10^{-17} m^2/W$ and 11, respectively [12,13]. It is worth to mentioning that extremely large third order nonlinearity, including material ablation, has been reported near $1\mu m$; $9.0 \pm 1.4\times10^{-16} m^2/W$ using a $4.8\mu m$ thick $Te_{20}As_{30}Se_{50}$ thin film [14] at $1064 nm$. Published values of n_2 vary from 2000 to 27000 times larger than n_2 values for fused silica ($n_{2\_fused\_silica}=3.0\times10^{-20} m^2/W$) at $1.05\mu m$ in Ag doped $As_{40}Se_{60}$ [15]. Specially in [15], higher dopant of silver generally results in higher nonlinearity. However, high percentage of dopant of silver inevitably increases the linear absorption rate.

For our simulations we apply the reported values from Reference [12]; the nonlinear index and the refractive index for $As_{40}Se_{60}$ at $\lambda = 1.55\mu m$ are $n_2=2.3\times10^{-17} m^2/W$ and $n_0=2.81$, respectively. The corresponding critical power for self-focusing an optical beam is given by the following estimated expression [16,17]:

$$P_{cr}=0.148\frac{\lambda^2}{n_0 n_2}=5.43kW, \qquad (1)$$

where n_0 is the refractive index, λ is the vacuum wavelength and n_2 is the Kerr nonlinearity, as given above.

Following the same procedure in [11], one can calculate the SA action for the proposed SA device, which is plotted in Fig. 1. In this paper, all the powers used are taken to be smaller than the critical power, since beyond the critical power the beam becomes unstable and collapse to a filament can occur [18].

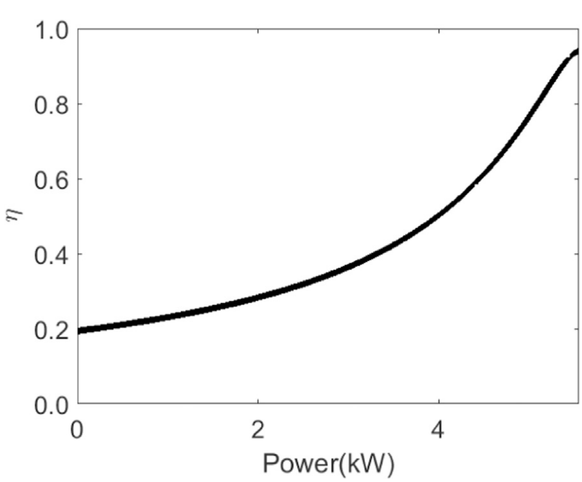

Fig. 1. Transmission (η) for ChG $As_{40}Se_{60}$ fiber-based SA at $D = 3mm$. See Reference [11] for details about the calculations.

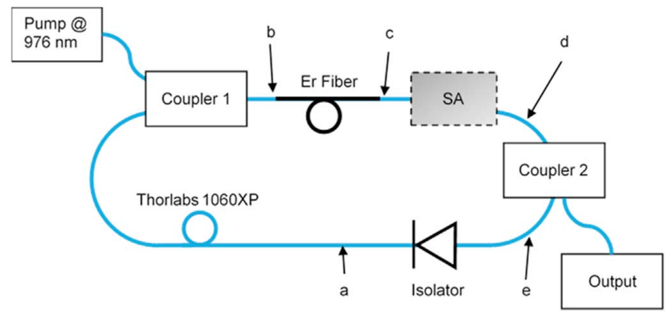

Fig. 2. Conceptual fiber laser cavity with the new saturable absorber design. Coupler1 transmits wavelengths near 976 nm, which co-propagate with the 1550 nm wavelength. Coupler 2 splits the input into two parts: one passes to the output port and the other couples the pulse back into the fiber cavity. In the fiber cavity, the black fiber is the Er-doped gain fiber and the blue fiber parameters use data for the Thorlabs 1060XP. Point *a* is chosen at the beginning of the PF, *b* at the beginning of the AF, *c* before the SA, *d* before the output coupler and *e* after the output coupler. An isolator is used to ensure that the pulse is propagating clockwise. Pigtails for couplers and the isolator are assumed to be short and ignored in our simulations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

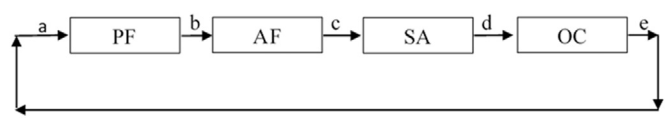

Fig. 3. Effective laser cavity for the simulation. PF=passive fiber, AF=active fiber, SA=saturable absorber, and OC=output coupler.

Table 1
Polynomial coefficients of SA action for $As_{40}Se_{60}$.

Coefficient	$As_{40}Se_{60}$
c_4	5.4223×10^{-4}
c_3	8.3644×10^{-5}
c_2	9.70522×10^{-4}
c_1	0.038705
c_0	0.1922079

Table 2
Simulation details.

Passive Fiber	$lengthL_{pf}(cm)$	600
	$\beta_2(ps^2/cm)$	-9.77×10^{-5}
(*Thorlabs 1060XP*)	$\gamma(1/cm\_W)$	1.3×10^{-5}
	$\alpha(1/cm)$	0
Gain Fiber	$lengthL_{af}(cm)$	55
	$\beta_2(ps^2/cm)$	16.5×10^{-5}
	$\gamma(1/cm\_W)$	2.8×10^{-5}
	$\alpha(1/cm)$	0
(*Thorlabs Er30 4/125*)	$g_0(1/cm)$	0.069077
	$\Delta\lambda(nm)$	40
	$E_{sat}(nJ)$	1.4
OC	R	0.8 or 0.7
Initial Pulse	$T_{max}(ps)$	120
	n_t	2^{14}
	$P_0(W)$	1
	$F_0(ps)$	1
	m_0	1
	C_0	0