All-fiber passively mode-locked femtosecond laser using a 45°-tilted fiber grating polarization element

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Abstract: We report on the demonstration of an all-fiber femtosecond erbium doped fiber laser passively mode-locked using a 45°tilted fiber grating as an in-fiber polarizer in the laser cavity. The laser generates 600 fs pulses with output pulse energies ~1nJ. Since the 45° tilted grating has a broad polarization response, the laser output has shown a tunabilty in wavelength from 1548nm to 1562nm by simply adjusting the polarization controllers in the cavity.

OCIS codes: (140.4050) Mode Locked Lasers; (060.3735) Fiber Bragg Gratings.

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1. Introduction

Passively mode-locked lasers have evolved from fundamental science to commercial instruments, with a wide variety of applications in telecom, optical frequency comb generation, metrology, microscopy and in general, nonlinear science. Femtosecond pulse generation in mode-locked lasers relies on a variety of physical effects including group-velocity dispersion (GVD), self-phase modulation (SPM), and amplification. Further, it is necessary to have some form of intensity discrimination to promote pulse formation from initial white emission. Over the past two decades, a variety of different methods have been used to realize mode-locking pulse generation including, among others, nonlinear polarization rotation (NPR) [1-4], nonlinear interferometry [5,6], semi-conductor saturable absorber mirrors (SESAM) [7-9] and more recently, single-walled carbon nanotubes (CNTs) [10-12]. Although solid-state mode-locked lasers remain the current workhorse for high-power, ultra-short pulse generation for applications, there has been great interest in mode-locked fiber lasers due to the practical advantages they offer, such as superior wave-guide properties, reduced thermal effects, power scalability, and integrability with other telecom components. In general, a mode-locked fiber laser that is made from all-fiber components would be ideal. Although there are some examples where this is achieved, such as those using polarizing fibers [4], the majority rely on bulk objects in the laser cavity, thus reducing the benefits of an all-fiber format. For instance, a common method to experimentally achieve intensity discrimination in a mode-locked fiber laser is through NPR. Because the optical Kerr effect induces a change in polarization that is dependent on the intensity of the pulse, when the light is coupled from the fiber to a polarizer the transmission through the polarizer is intensity dependent. By appropriately selecting the polarization state of light through polarization controllers, one can maximize the transmission for the highest pulse intensity thus creating an artificial saturable absorber. Usually, a bulk optic polarizer is used in this scheme, necessitating the coupling between fiber and bulk segments and also inducing insertion loss.

Compared with bulk form polarizers, in-fiber polarizers are more desirable in fiber systems due to their light weight, low insertion loss, and high coupling efficiency. Several types of in-fiber polarizers have been demonstrated [13,14], however they lack the robustness and integrity necessary to take full advantage of an all-fiber device. Recently, 45º tilted fiber gratings (45°-TFGs) have been shown to exhibit strong polarization-dependent loss (PDL) properties. In principle, the light through such a grating shows small transmission loss of the *p*-light whereas the *s*-light loss remains significant. The 45°-TFGs have been implemented as both a PDL equalizer [15] and a broadband polarizer [16] in optical communications systems. Further, these polarizing gratings have been successfully used to generate single polarization continuous output in an all-fiber laser structure [17]. In this paper, we use a 45°-TFG as a polarization element in a mode-locked laser that relies on nonlinear polarization rotation for mode-locking. The laser outputs 600 fs soliton pulses with pulse energies of ~1 nJ. The use of a 45°-TFG in such a laser configuration could potentially have several advantages when compared to bulk polarizers, including low insertion loss, high stability and integrability.

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The paper is outlined as follows: Section 2 describes the fabrication and characterization of 45°-TFGs used in the experiment. Section 3 discusses the operation of the 45°-TFG in an all-fiber mode-locked laser. Finally, we conclude in Section 4.

2. Fabrication and characterization of 45º tilted fiber gratings

The 45°-TFGs used in the experiment were UV inscribed in a commercial B/Ge co-doped photosensitive fiber (from Fibercore PS1200/1500) using the standard phase mask scanning technique and a 244 nm UV source from a CW frequency doubled Ar^+ laser (Coherent Sabre Fred®). The B/Ge fiber samples were hydrogen loaded at 150 bar and 80°C for two days prior to the UV inscription to further enhance the fiber photosensitivity. The phase mask has a uniform period of 1800 nm (from IBSEN) and was designed to have the period pattern tilted at 33.7º with respect to the fiber axis, which would produce internal tilted index fringes at 45º in the fiber core with a broad radiation response around 1550 nm. A typical microscopic image of the UV inscribed grating under a 100× oil immersion microscopic lens is given in Fig.1(a), showing that the tilted index fringes cover the entire fiber core region and are tilted at 44.65°. The effective length of the phase mask is ~23.8 mm which corresponds to the length of the grating. Previously, such gratings have shown strong polarization dependency properties and linear polarization output can be obtained when the light passes through the grating [16]. In order to examine the PDL of the 45°-TFG, a commercial PDL test system (from LUNA system) incorporating a tunable laser was used to characterize the grating for a

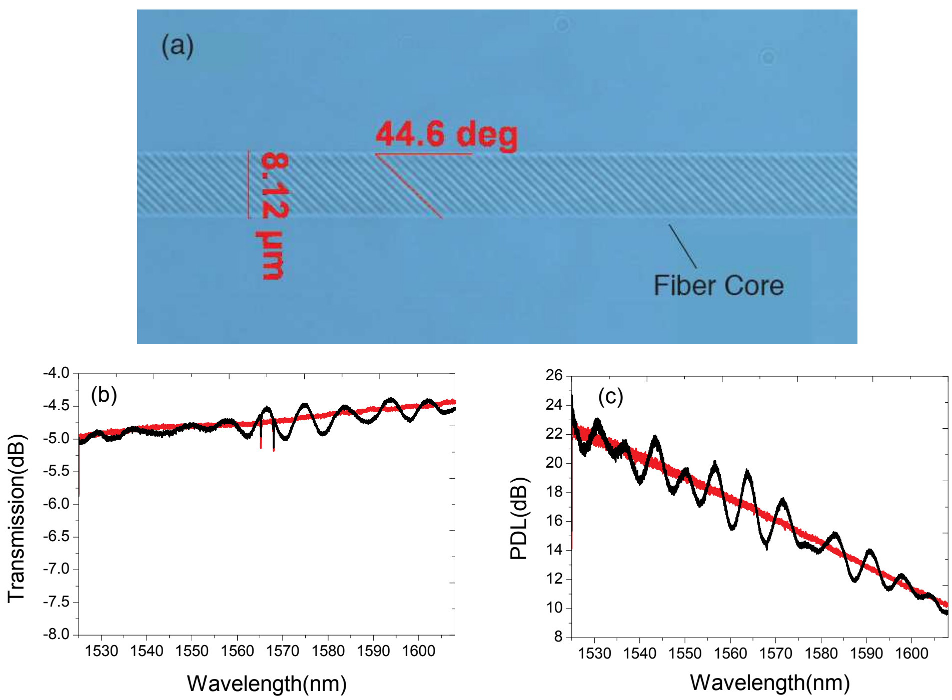

Fig. 1. (a) Microscope image of the 45°-TFG UV-inscribed in B/Ge fiber. Measured (b) transmission spectrum and (c) PDL response of the 45°-TFG from 1525 nm to 1608 nm. Note: in (b,c) black curves show the spectra when grating was exposed to air while the red smooth lines are the measured spectral responses when the grating was immersed in index matching liquid.

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range from 1525 nm to 1608 nm. The measured spectral range was limited by the range of the tunable laser. Figure 1(b) shows the transmission spectrum of the 45°-TFG, illustrating there is an average ~4.5 dB insertion loss across the entire spectrum (this includes 3 dB loss to *s*-light and additional loss due to both bad connection and splicing). As described in Ref. [16], due to the Brewster angle effect, a 45°-TFG functions as an in-fiber polarizer, thus there is no Bragg reflection as expected in normal fiber Bragg gratings. In principle, the light through the 45°-TFG shows small transmission loss of the *p*-light whereas the *s*-light loss remains significant, giving an overall strong PDL. This is in contrast to a non-tilted fiber grating where no noticeable PDL can be observed. Fig. 1(c) shows the characteristic PDL of the 45°-TFG over a large wavelength range (~80 nm) that almost covers a typical gain bandwidth of erbium doped fiber. It is clear that the PDL depends on wavelength and the maximum PDL value at 1550 nm is ~20 dB. It is interesting to note that there is an inherent oscillation in the transmission spectra and PDL profile. The 45°-TFG couples the *s*-light to both the cladding and radiation modes in a direction orthogonal to the fiber axis. Due to the finite thickness of the cladding, the radiated modes are reflected back via the cladding/air boundary which in turn forms the cladding mode oscillation [17]. However, this oscillation can be eliminated by immersing the 45º-TFG in the index matching gel, as clearly shown by the red smooth plots in Fig.1(b,c). We also notice from the transmission spectrum the existence of weak second-order Bragg reflection and small ghost mode peaks, which do not affect the polarization functionality of the grating.

3. Fiber laser configuration and experimental results

Here we use the polarization functionality of the 45°-TFG in an erbium-doped fiber laser shown in Fig. 2. The laser consists of ~6 m conventional erbium doped fiber (EDF, from Lucent Technologies) with nominal absorption coefficient of ~12 dB/m at 1530 nm and normal dispersion -8.6 ps/nm/km. The rest of the cavity consists of 12 m standard telecom fiber with anomalous dispersion of ~+17 ps/nm/km and a 50 cm B/Ge fiber, incorporating the 45°-TFG, with dispersion of ~+10 ps/nm/km. Thus, the net-anomalous dispersion of the laser cavity is ~+8.5 ps/nm/km. Two polarization independent optical isolators (OIS) are used to ensure single direction oscillation. The fiber laser is pumped through a 980/1550 wavelength division multiplexing (WDM) from a grating stabilized 975 nm laser diode (LD, from SDL), which can provide up to 300 mW pump power. A commercial laser diode driver and controller (Newport 505B & 300) are used for stabilizing the pump laser. Two fiber polarization controllers (PC1 & PC2) are located before and after the 45°-TFG. A 10:90 fiber coupler is employed to couple out the laser light.

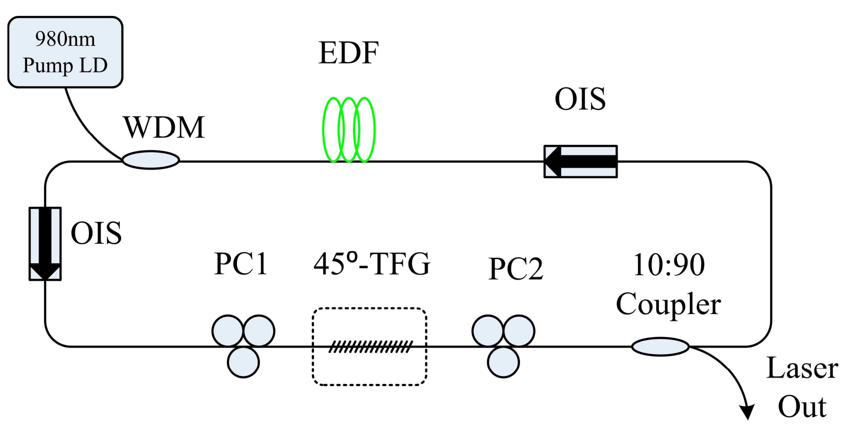

Fig. 2. Schematic configuration of the 45°-TFG based mode-locked fiber laser.

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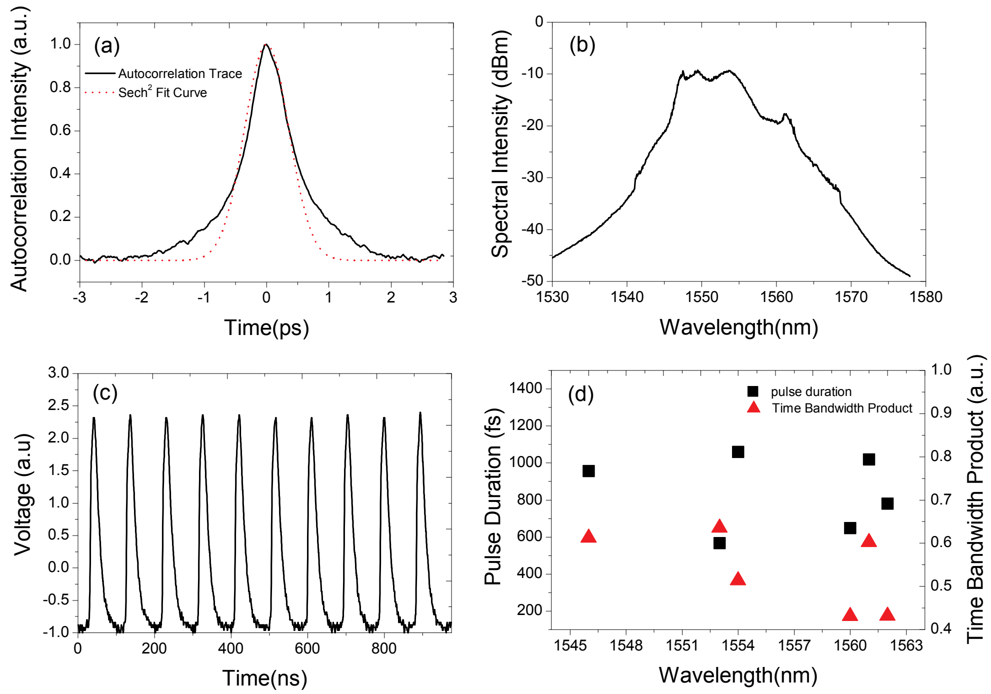

Fig. 3. (a) Measured auto-correlation trace and the corresponding sech^2 fit; (b) optical spectrum of the ~ 600 fs output pulse; (c) a typical output pulse train of the mode-locked fiber laser showing a repetition rate of ~ 10.34 MHz; (d) measured pulse width and time-bandwidth products as a function of the wavelength.

The effect of nonlinear polarization evolution (NPE) with the 45°-TFG in-line polarizer provides the necessary intensity discrimination for mode locking. Since the net GVD is anomalous, GVD and SPM counter-balance to give soliton-like pulses. By properly adjusting the two fiber polarization controllers in the system, stable mode-locked pulses can be obtained. The optical pulses have been amplified and then fed through to an autocorrelator whose resolution is 44 fs (from INRAD Inc. MODEL 5-14B). Fig. 3(a) shows the auto-correlation trace of the pulse corresponding to a pulse duration of ~600 fs. Fig. 3(b) shows the optical spectrum profile of centered at 1553 nm with a spectral bandwidth at full-width half-maximum (FWHM) of ~ 9 nm, thus giving a time-bandwidth product of ~0.6, indicating the pulse is slightly chirped. A typical pulse train is shown in Fig. 3(c) with a 90 ns interval between two adjacent pulses, giving a repetition rate of 10.34 MHz. Note, the negative value of the signal is due to the AC coupling to the oscilloscope. The output pulse power is 12 mW which corresponds to the output energy of ~ 1 nJ. The laser is stable under laboratory condition for > 1 hour. By adjusting the two polarization controllers, the mode-locked wavelength exhibits a certain degree of tunability from 1548 nm to 1562 nm with pulse durations from ~ 600 fs to ~ 1 ps. The measured pulse width and time-bandwidth product (TBP) as a function of the wavelength are shown in Fig. 3(d) and also demonstrates the tunability of the fiber laser. Since the TBP of the output pulses is larger than 0.3 the output pulses are not transform limited [18]. Although many modern mode-locked lasers provide higher energy pulses with shorter durations, here we have not optimized the laser cavity using the 45°-TFG. However, it is interesting to note that the pulse energies obtained from this laser are ~10 times that of typical soliton mode-locked lasers [21]. Future research will consist of comparisons between similar cavity designs only differing from the use of commercial polarizers and 45°-TFG, highlighting the effects on key pulse characteristics. Further, the 45°-TFG can be used in a variety of different mode-locked fiber laser configurations. For

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example, future studies will pursue the use of this all-fiber configuration in all-normal dispersion mode locked fiber lasers [19-21] to achieve high pulse energies.

4. Conclusions

In conclusion, we have experimentally demonstrated a passively mode-locked erbium doped fiber laser using a 45°-TFG as an in-fiber polarization element. 600 fs mode-locked pulses have been obtained with energy ~1 nJ. The simplicity of UV inscription allows producing highly repeatable gratings at low cost and the 45°-TFG can be directly written into compatible fiber for the laser cavity. In our work, the photosensitive fiber used is a commercial product which has mode-field optimization for splicing with telecom fibers and comparable dispersion parameters, allowing for easy performance optimization in all-fiber formats. The use of a 45°-TFG as an in-fiber polarizer in a mode-locked fiber laser could provide several advantages when compared to current mode-locked fiber lasers using bulk polarizers, including low insertion loss, high integrability and less temperature sensitivity.

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