Femtosecond Similariton Pulse Generation from an All-Fiber Erbium Doped Fiber Laser

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ABSTRACT

Mode-locked fiber lasers with femtosecond pulse durations have become attractive for numerous applications in science and industry. Amplifier similariton shaped pulses typically have pulse energies of a few nanojoules and sub-100 fs pulse width. The work presented seeks to demonstrate the generation of femtosecond amplifier similariton pulses from an all-fiber erbium doped fiber laser cavity. Mode-locking in the erbium-doped fiber laser was achieved by nonlinear polarization evolution which produced pulses at a wavelength of 1572 nm with an average output power of 24 mW and a pulse energy of 0.46 nJ. These pulses at transform limit have a pulse duration of 73 fs.

Keywords: Fiber laser, amplifier similariton, erbium-doped, femtosecond pulse, ultrashort pulse, nonlinear polarization evolution

1.0 INTRODUCTION

Fiber lasers have become increasingly popular over the years due to their alignment-free operation, high beam quality, low intensity noise, stability, ease of use, compact nature and low cost as compared to bulkier solid-state lasers. There has been significant progress in the development of ultrashort pulse fiber lasers, making them suitable for a broad range of applications such as material processing (Voisiat et al., 2015), ultrafast spectroscopy (Liao et al., 2018), biomedical applications (Erdoğan et al., 2011; Kong et al., 2017), optical imaging (Charan et al., 2018; Murashova et al., 2017), surgery (Morin et al., 2009; Traxer & Keller, 2020), metrology (Lazarev et al., 2016), and optical communications (Lopera et al., 2021). Generation of ultrashort pulses in fiber lasers can be achieved through either Q-switching (Laroche et al., 2002; Williams et al., 2010), or mode-locking (Ilday et al., 2003; Nie et al., 2011; Wang, Zhan, et al., 2016). Mode- locking techniques however have proven to yield the shortest pulse durations, on the order of femtoseconds, while Q-switched techniques typically yield pulses in the range of nanoseconds. Mode-locked pulses are generated either by active mode-locking or by passive mode-locking. In active mode-locking, an external periodic signal is used to modulate the optical resonant cavity parameters (Koliada et al., 2013; Tahhan et al., 2019). Passive mode-locking uses the nonlinear absorption characteristics of the laser cavity, either by a real saturable absorber (Gomes et al., 2004; Shtyrina et al., 2009), or by an artificial saturable absorber (Fermann et al., 1993; Mahmoodi et al., 2021; Zhang et al., 2022) inside the resonant cavity which modulates the optical field and generates the short pulses.

The major physical parameters for pulse shaping are nonlinearity and group velocity dispersion (GVD). The soliton pulse is the most common pulse shape resulting from a balance of the nonlinear self-phase modulation and anomalous GVD yielding stable, almost transform limited pulses (Chen et al., 1992; Richardson et al., 1991). Pulse parameters are in the typical range of picojoules, with nanosecond to femtosecond pulse duration. Dispersion managed soliton pulses are produced from a cavity with a dispersion map, where pulses are stretched and compressed as they propagate through anomalous and normal dispersion portions of the cavity (Dvoretskiy et al., 2015; Tamura et al., 1993). The shortest pulses are obtained when the net group dispersion is close to zero. Average energies of these pulses are in nanojoules, with sub-100 fs pulse durations. An all-normal GVD cavity with the addition of a spectral filter yields dissipative solitons which are highly up-chirped and have a cat-ear spectral profile (Chong et al., 2006; Chong et al., 2007; Peng et al., 2012) . High pulse energies of 20 nJ and beyond are achievable with pulse widths in the hundreds of femtoseconds. Sub 100 fs pulses can be generated but have lower energies, typically a few nanojoules.

Another category of mode-locked pulse is the similariton or passive self-similar pulse (Aguergaray et al., 2010; Chong et al., 2015; Renninger et al., 2010). These are generated in optical cavities that have normal dispersion fibers and are characterized by a parabolic temporal and spectral profile with linear frequency chirp which mainly evolve in a long passive fiber section. The gain fiber is kept short to limit additional pulse evolution to maintain the parabolic shape. After each round trip, the parabolic pulse is restored to its initial shape through an anomalous dispersive element. Fiber laser cavities that have appreciable lengths of normal GVD gain fiber have also been used to generate optical pulses with parabolic profiles known as amplifier similaritons or active self-similar pulses (Fermann et al., 2000; Nie et al., 2011; Oktem et al., 2010). This pulse type is obtained by pulse shaping within the gain section of the cavity and is a nonlinear attractor; that is, any pulse shape eventually evolves to the self-similar parabolic pulse profile. The net cavity dispersion is therefore not of importance and a dispersion map similar to the map for dispersion managed soliton can be used to generate dispersion managed amplifier similaritons (DMAS) (Olivier & Piché, 2016; Renninger et al., 2011; Wang, Zhan, et al., 2016). We present a DMAS all-fiber laser that generates femtosecond amplifier similariton pulses using non-linear polarization rotation. An all-fiber laser cavity that uses off the shelf telecommunication components is implemented. Er-doped fiber is used for the gain section and mode locking is achieved by non-linear polarization evolution in the gain fiber.

2.0 EXPERIMENTAL SETUP

The schematic diagram for the DMAS Er-doped fiber laser cavity is given in figure 1. The cavity is made-up of a normal group velocity dispersion section and an anomalous group velocity dispersion section. The anomalous group velocity dispersion in the cavity arises from a combination of 151 cm of single-mode fiber, 21 cm of polarization maintaining fiber ($\beta_2 = 23\ \mathrm{ps}^2\ \mathrm{km}^{-1}$), and 63 cm of HI1060 fiber ($\beta_2 = -5.8\ \mathrm{ps}^2\ \mathrm{km}^{-1}, \gamma = 4.0 \times 10^{-3}\ \mathrm{W}^{-1}\ \mathrm{m}^{-1}$). The HI1060 fiber is the pigtail of an isolating wavelength division multiplexer (IWDM) used to couple pump light into the cavity. The single-mode fiber has a group velocity dispersion of $-22\ \mathrm{ps}^2\ \mathrm{km}^{-1}$ and a nonlinearity of $1.4 \times 10^{-3}\ \mathrm{W}^{-1}\ \mathrm{m}^{-1}$. The gain fiber, which is an erbium doped fiber (EDF-150), provides normal group velocity dispersion of $59\ \mathrm{ps}^2\ \mathrm{km}^{-1}$ and has a nonlinear parameter value of $6.2 \times 10^{-3}\ \mathrm{W}^{-1}\ \mathrm{m}^{-1}$. The EDF-150 gain fiber has a high erbium concentration, with an absorption of $103.56\ \mathrm{dB\ m}^{-1}$ near $980\ \mathrm{nm}$. Its core radius is $1.24\ \mu\mathrm{m}$ with a numerical aperture of 0.268. The length of EDF-150 used in this laser cavity is 120 cm giving a total cavity length of 355 cm with a net cavity dispersion of $0.029\ \mathrm{ps}^2$. The laser cavity therefore operates in the normal dispersion regime.

The EDF-150 erbium doped fiber is pumped bi-directionally by two separate diode lasers: a QPhotonics diode laser which operates at a wavelength of 974 nm at a maximum power of 450 mW, and a second diode laser operating at a wavelength of 977 nm with maximum power of 600 mW. Pumping at both ends of the erbium doped fiber ensures that population inversion occurs along as much of the doped fiber length as possible. The 974 nm diode pump laser is coupled to the EDF-150 fiber through a high-power fused wavelength division multiplexer (FWDM). The 977 nm pump laser is coupled to the Er-doped gain fiber by the HI1060 fiber pigtail port of a hybrid isolating wavelength division multiplexer (IWDM). The single-mode fiber pigtailed pass-port of the IWDM is used to form a quarter wave-plate and a half wave-plate by wrapping it round a Thorlabs FPC020 fiber paddle polarization controller. One loop of single-mode fiber around a paddle corresponds to a quarter-wave plate and two loops of fiber corresponds to a half-wave plate. The fiber pigtail of the FWDM pass-port is also used to form a quarter wave-plate. A2×2 polarizing beam splitter (PBS) is spliced to the quarter wave-plate leading to the FWDM. One of the

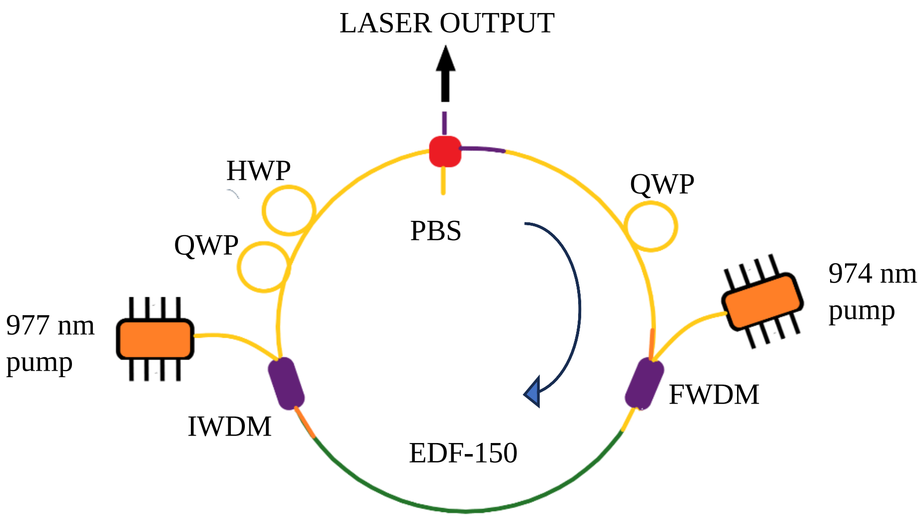

Figure 1: Experimental setup for 355 cm erbium-doped fiber laser cavity. QWP: quarter waveplate; HWP: half waveplate; PBS: polarization beam splitter; IWDM: isolating WDM; FWDM: fused WDM. The generated pulse propagates in the clockwise direction.

output ports of the PBS is made with SMF and the other with PM fiber. A length of 30 cm of the SMF output port is spliced to the halfwave-plate, closing the ring cavity. The PM fiber port of the PBS is the output for the laser cavity. Because of the sensitivity to high power of most monitoring equipment, a 1:99 fused PM fiber splitter is spliced to this output port and laser signal from the 1 percent port of this splitter is divided by a 50:50 single-mode coupler. One arm of the 50:50 coupler goes to an InGaAs photodetector from Thorlabs (DETO1CFC) which has a specified maximum input peak power of 70 mW. The photodetector converts the optical signals and gives corresponding electrical signals which are monitored with a Picoscope6 oscilloscope paired with Signal Hound spectrum analyser software. The other arm of the 50:50 coupler is connected to a Yokogawa AQ6370 optical spectrum analyser.

3.0 RESULTS AND DISCUSSION

With a pump power of 450 mW from the 974 nm pump diode and 290 mW of power from the 977 nm pump diode, the polarization controllers are adjusted till mode-locked pulses are observed. Characteristics of the generated mode-locked pulses are shown in Figures 2, 3 and 4. The pulse spectrum (Figure 2) has a centre peak at 1572 nm and an FWHM of 50 nm. A pulse with this spectral breadth yields a calculated transform-limited pulse width of 72.7 fs. As pump power is increased towards the most stable mode-locked condition, a spectral bandwidth increase is observed. This spectrum expansion is due to self-

-phase modulation (SPM) in the gain fibre, indicating that the propagating pulse is an amplifier similariton rather than a stretched pulse or dispersion managed soliton. The pulse train shown in Figure 3, has a period of 19.18 ns which gives a repetition rate of 52.13 MHz, as confirmed by the RF analyzer measurement (Figure 4). The pulses are stable and self-starting, giving an average power of 24 mW. The pulse energy is calculated to be 0.46 nJ. Usually, long lengths of gain fiber are used for amplifier similariton generation, allowing the asymptotic limits of the pulse energy to be reached well within the limits of the gain fiber. A gain fiber length of 5.6 m was used to generate 60 fs pulses (Wang, Qian, et al., 2016). It has however been shown (Olivier & Piché, 2016), that it is possible for amplifier similaritons to be generated with fiber lengths as short as 0.65 m, nearly half the length of gain fiber used in the setup reported here.

Even without the actual physical presences of a spectral filter in the cavity, as has been suggested as necessary for their generation (Renninger et al., 2010), amplifier similaritons have nonetheless been generated in a manner similar to that of (Olivier & Piché, 2016). The polarising beam splitter is a major factor in the similariton pulse shaping: Despite the absence of a spectral filter, the PBS can function as a filter in its own right, excluding some wavelengths while permitting others to be used for mode locking. In the same manner, the WDMs can exhibit spectral filtration. Indeed, the isolating WDM has a pass bandwidth of 20 nm and is similarly wavelength dependent and can also contribute to the pulse shaping.

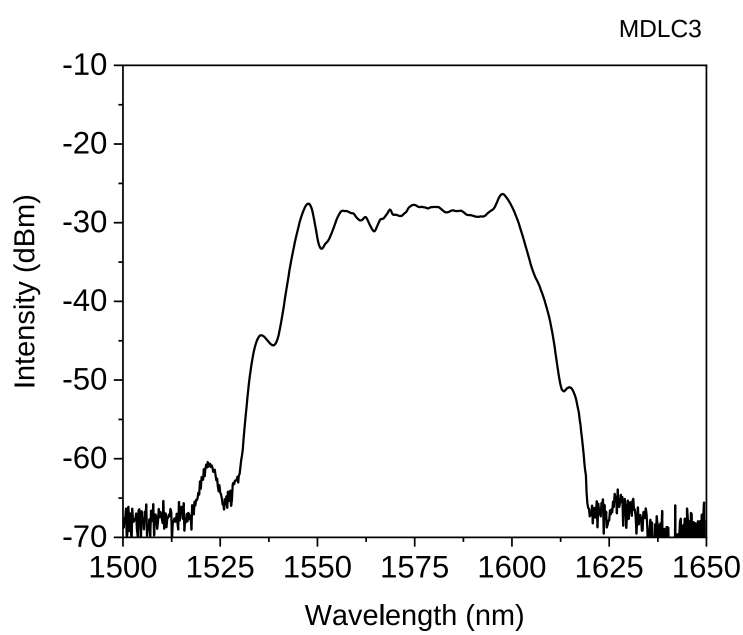

Figure 2: Pulse spectrum of the mode-locked fiber laser.

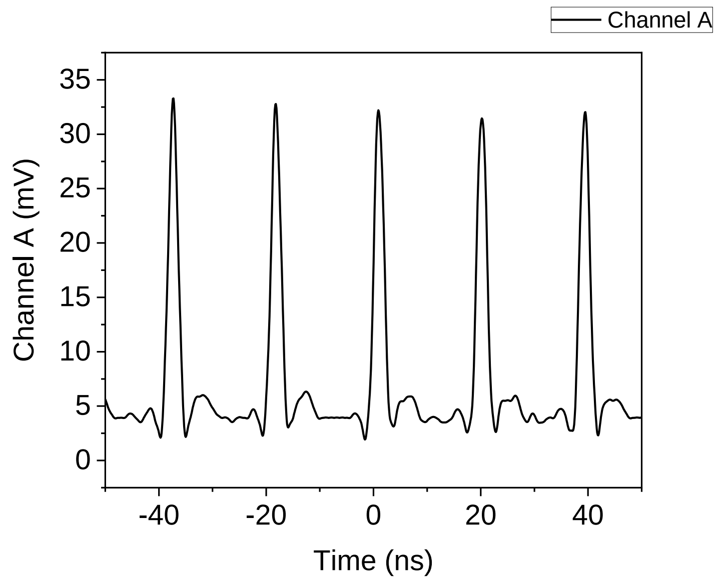

Figure 3: Oscilloscope display of the pulse train from the Er-doped fiber laser.

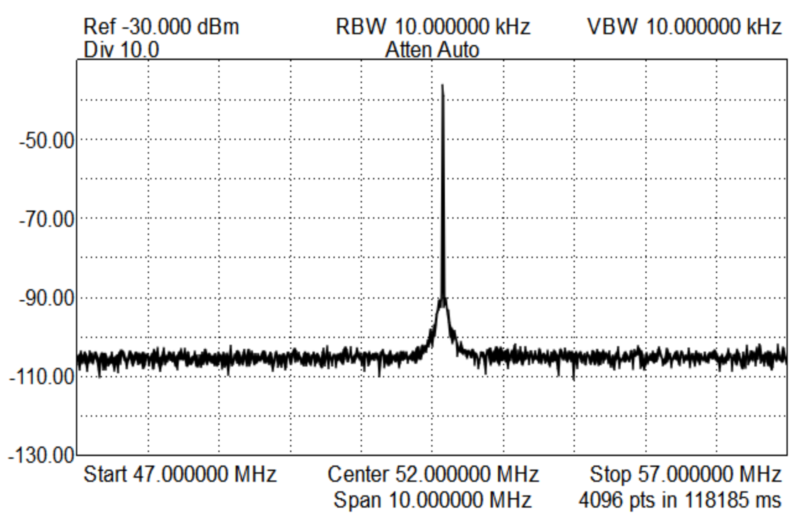

Figure 4: RF spectrum of generated pulse.

ISSN: 2821-9007 (Online)

4.0 CONCLUSION

We demonstrate the generation of amplifier similariton pulses from an all-fiber-erbium-doped fiber laser with a total cavity dispersion of 0.029 ps^2. The fiber laser operates at a wavelength of 1572 nm and gives transform limited pulses of duration 72.7 fs as estimated from the pulse spectrum which implies a pulse energy of 0.46 nJ. The pulse spectral shape and spectral broadening as pump power is increased are indicative of amplifier similariton pulse shaping.

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