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Characterization and experimental verification of actively mode-locked erbium doped fiber laser utilizing ring cavity

Charakterisierung und experimentelle Verifizierung eines aktiv modengekoppelten Erbium-dotierten Faserlasers unter Verwendung des Ringhohlraums

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Abstract: A simple active mode-locked erbium-doped fiber (EDF) ring laser is characterized and experimentally demonstrated. The active mode-locked laser can be tuned in the C-band wavelength range 1525 nm to 1565 nm using a tunable bandpass filter placed in the cavity. An intensity modulator placed inside the laser cavity is driven using a sinusoidal signal at different repetition rates. The laser can produce trains of pulses with a width that is controlled using the mode-locking order. The experiments demonstrated an active mode-locked laser that can generate pulse trains with 39 ns width at multiple cavity fundamental frequency of 0.67 MHz repetition rate. Numerical simulations are conducted to investigate the effect of the tunable filter bandwidth and the power of the EDF 980 nm pump on the mode-locking process and produced pulses width.

Keywords: Active model-locked laser, ring laser, fiber laser, intensity modulator, optical metrology.

Zusammenfassung: Ein einfacher Ringfaser mit aktivem modengekoppeltem Erbium-dotiertem Faser (EDF) wird charakterisiert und experimentell demonstriert. Der aktive modengekoppelte Laser kann im C-Band-Wellenlängenbereich von 1525 nm bis 1565 nm unter Verwendung eines abstimmbaren Bandpassfilters, das in dem Hohlraum angeordnet ist, abgestimmt werden. Ein im Laserresonator angeordneter Intensitätsmodulator wird unter Verwendung eines sinusförmigen Signals mit unterschiedlichen Wiederholungsraten angesteuert. Der Laser kann Impulsfolgen mit einer Breite erzeugen, die unter Verwendung der Modenkopplungsreihenfolge gesteuert wird. Die Experimente zeigten einen aktiven modengekoppelten Laser, der Impulsfolgen mit einer Breite von 39 ns bei einer Grundfrequenz mit mehreren Hohlräumen und einer Wiederholungsrate von 0,67 MHz erzeugen kann. Numerische Simulationen werden durchgeführt, um den Einfluss der einstellbaren Filterbandbreite und der Leistung der EDF 980 nm-Pumpe auf den Modenkopplungsprozess und die erzeugte Impulsbreite zu untersuchen.

Schlagwörter: Aktiver modellverriegelter Laser, Ringlaser, Faserlaser, Intensitätsmodulator, optische Messtechnik.

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1 Introduction

Passive and active mode-locked fiber lasers have been demonstrated in the past years for many applications ranging from optical communication, sensing metrology, and device testing. An actively mode-locking Nd-doped fiber laser with piezoelectrically induced Raman-Nath diffraction modulation was proposed by Hofer et al. in 1990 [1]. The laser produced an unwavering pulse of 2.4 ps at a central wavelength of 1054 nm. In 2004, Usechak et al. demonstrated a ytterbium fiber laser mode-locked at its 281st harmonic, thereby corresponding to a repetition rate above 10 GHz [2]. Moreover, the proposed laser generated linearly polarized 2 ps pulses with an average output power around 38 mW. Combining dispersive fibers with Lithium Niobate modulator, Tozburun et al. proposed a wavelength stepped laser operating at 1550 nm with 200 GHz wavelength-stepping and a sweep rate of 9 MHz over a 94 nm range [3]. A passively mode-locked erbium-doped fiber laser utilizing multiple graphene layers was proposed by Liu et al. in 2015 [4]. The laser is designed to operate at 1568.1 nm wavelength. The fiber laser produced pulses width of 58.8 ps. Furthermore, the obtained maximum average output power and repetition rate were found to be 7.29 MHz and 1.68 mW. In 2017, Wang et al. experimentally demonstrated a linear chirped fiber Bragg grating (LC-FBG) wavelength-swept fiber laser centered at 1550 nm [5]. The results showed that the fiber laser yields a sweep rate of 5.4 MHz in a wide range of 2.1 nm. In the same year, Khazaeinezhad et al. achieved a repetition rate of 16.3 MHz and lasing bandwidth of 62 nm at 1550 nm operating wavelength [6]. The authors achieved these results utilizing a four-path delay line at the output. In 2018, Nady et al. [7] and Chen et al. [8] proposed mode-locked and actively-locked lasers, respectively. The mode-locked laser was showcased using vanadium oxide (V2O5) as the saturable absorber and was centered at 1559.25 nm wavelength with a repetition frequency of 1 MHz. While, the actively-locked laser has a slope efficiency improvement of 2.37 % over the original 10.24 %. Furthermore, the laser repetition rate was shifted from 15.65 MHz to 626 MHz for the fundamental mode to the 40th harmonic mode-locking.

Active mode-locked lasers can be realized by implanting a modulator inside the laser cavity, which is driven using an external electrical signal. On the other hand, passive mode-locked lasers do not require an external signal to create the mode-locking. The input electrical pulses driving the modulator to cause the mode-locking inside the laser cavity and the generated laser pulse train would have much narrower pulses. Mode-locked fiber lasers have low thermal effects, high efficiency, simple architecture, high pulse power, and beam quality which makes them better than semiconductor lasers for many applications [3]. These applications include but not limited to optical metrology [8], fiber optic communication [5], sensing [10], and medical applications [11].

The cavity of mode-locked lasers is typically made of an active medium to create noise seed, which defines the operating wavelength of the laser. Different rare-earth-doped fibers have been used as the gain medium for the fiber laser such as erbium (Er), ytterbium (Yb), thulium (Tm), and praseodymium (Pr). A tunable bandpass filter placed in the cavity allows tuning the laser as it selects a specific wavelength range of the seed. Other components are also placed inside the laser cavity to massage the produced pulses and assist the mode-locking process such as alternative pieces of fibers with different dispersion profiles [12], chirped fiber Bragg grating [9, 13], or nonlinear polarization rotator [14].

The base repetition rate of the generated pulse train of the active mode-locked laser depends on the cavity length, while the width of the pulses depending on the massaging scheme and the initial electrical pluses width used to drive the modulator. Higher-order laser pulse repetition rates are multiples of the base rate, which would produce narrower laser pulses. The demonstrated mode-locked lasers' structures in the literature are either relatively complex or have a low repetition rate. In this work, we demonstrated experimentally a simple active mode-locked laser structure that has a high repetition rate and generates very narrow pulses. Numerical simulation using a commercial tool is used to analyze the laser and study the effect of filter bandwidth and laser pump power on the mode-locking and laser pulses. The laser-generated pulse train has a pulse width of 39 ns at 0.67 MHz repetition rate.

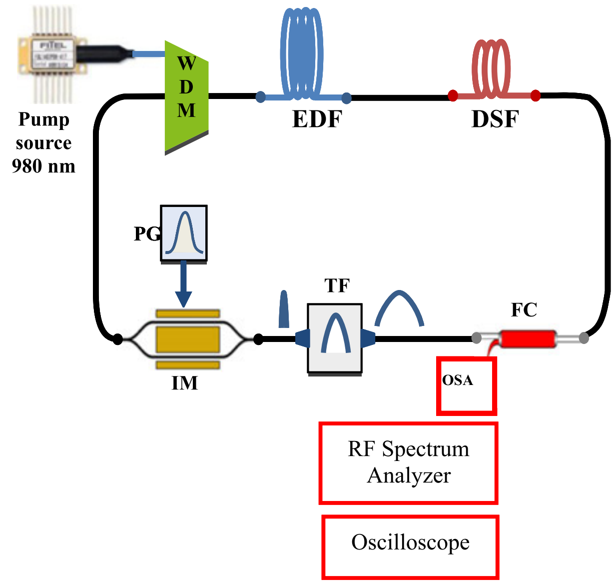

Figure 1: Active mode-locked ring fiber laser block diagram. EDF: erbium-doped fiber; DSF: dispersion-shifted fiber; PG: pulse generator; IM: intensity modulator; TOF: tunable optical filter; FC: fiber coupler.

2 Active mode-locked laser architecture and experimental verification

The investigated active mode-locked laser block diagram is shown in Fig. 1. The laser cavity is created using an erbium-doped fiber amplifier (EDFA) used as an amplified spontaneous emission (ASE) source, 250 m of polarization-maintaining dispersion-shifted fiber (PM-DSF), intensity modulator (IM) and tunable optical filter (TOF). The PM-DSF is connected using FC/APC adaptors to a non-polarization maintaining EDFA with no special arrangements. Figure 2 shows the experimental setup used to demonstrate the laser. The IM is driven using a sinu-

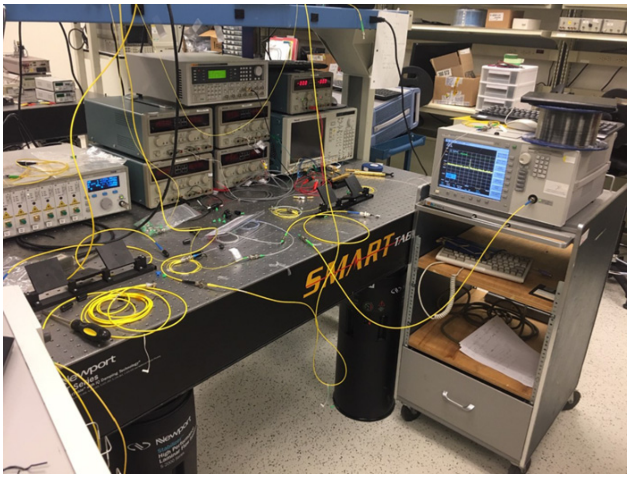

Figure 2: Active mode-locked laser experimental setup block diagram.

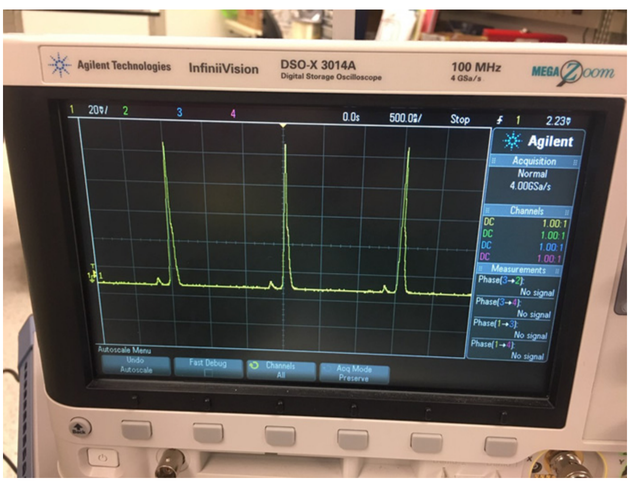

Figure 3: Active mode-locked laser output pulse train at 0.67 MHz repetition rate.

soidal electrical signal at different repetition rates. The PM-DSF fiber parameters at 1550 nm are attenuation of 0.35 dB/km, 2.2 ps/(km nm) dispersion and effective area (A_{eff}) of 26 μm^2.

The pumped EDF provides a broadband noise seed in the C-band wavelength range that is necessary for the mode-locking effect. A JDSU TB9 TOF with 3-dB bandwidth of 0.55 nm is used to control the lasing wavelength of the laser in the C-band wavelength range. Two polarization controllers are placed in the cavity after the IM and EDFA to assist in creating the mode-locking. The mode-locked laser output is monitored by tapping 20 % of the lasing signal through a fiber coupler (FC). The generated pulse train of the laser is analyzed using an optical spectrum analyzer, RF spectrum analyzer, and oscilloscope.

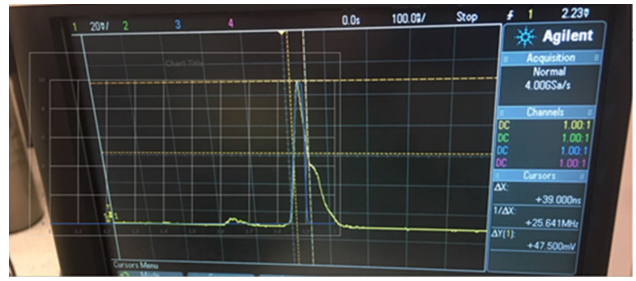

Figure 4: The generated pulse of the active mode-locked laser has a pulse width of 39 ns. The simulated pulse (blue) is superimposed over the generated pulse (yellow).

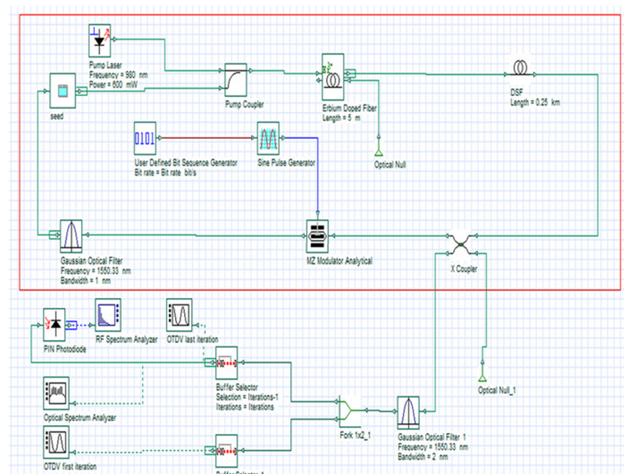

Figure 5: The active mode-locked laser block diagram in OptiSystem.

A sinusoidal signal is used to drive the intensity modulator, while the EDFA is set to maximum output power equivalent to 17 dBm as an ASE source. Figure 3 illustrates the generated active mode-locked laser output pulse train. The laser fundamental pulse repetition rate is 0.67 MHz. The estimated laser cavity that would produce such a repetition rate is approximately 307 m assuming effective fiber core refractive index 1.46. The generated pulses have full-width at half-maximum width of 39 ns as shown in Fig. 4. The generated pulses have a pedestal, which is due to a high order nonlinear effect created inside the PM-DSF fiber.

3 Numerical simulations

Numerical simulations are conducted using OptiSystem commercial software to comprehensively investigate the experimentally demonstrated laser. The simulation tool is used first to reproduce the generated pulse train with

Figure 6: Generated active mode-locked pulse train.

Table 1: Effect of pump laser power on the laser-generated pulses width.

Filter BW (nm)	Pump Power (mW)	Laser Pulse Width (ns)	Repetition Rate (MHz)
0.3	200	39.4	4
0.3	300	40	4
0.3	400	39	4
0.3	500	39.6	4
0.3	600	39	4

the same pulse width and repetition rate, then study the effect of varying different parameters of the components in the cavity on the mode-locking process and the generated laser pulse width. An initial noise seed of –30 dBm is passed through the EDF and DSF fiber pieces, modulated by the electrical sinewave in the intensity modulator, then passed through the tunable optical filter, amplified again in the EDF and continue the process until mode-locking occurred in the ring. The IM extinction ratio is 34 dB.

Figure 5 illustrates the active mode-locked laser block diagram used to simulate in OptiSystem software. The software needs to calculate the design for many iterations to reach mode-locking. It requires about fifty iterations to achieve mode-locking and produce pulse train at the output of the ring laser as shown in Fig. 6. The generated pulses have a repetition rate of 4 MHz and a pulse width of 39 ns. This rate is a 6^{th} order mode-locking. The simulated pulse is superimposed over the experimentally generated pulse of the laser as shown in Fig. 4 shown. A perfect match is achieved. A 5 m erbium-doped fiber piece with an erbium concentration of $2 \times 10^{24}\ m^{-3}$ in an Er doping radius of 2.2 µm is used in the simulations. The same parameters of PM-DSF are used in the numerical simulation with a nonlinear refractive index of $3.2 \times 10^{-20}\ m^2/W$.

Table 2: Effect of tunable optical filter on the laser-generated pulses width.

Filter BW (nm)	Pump Power (mW)	Laser Pulse Width (ns)	Repetition Rate (MHz)
0.3	400	39	4
0.6	400	39	4
1	400	39.3	4

Table 3: Order on the laser generated pulses width.

Order	Pulse Width (ns)	Laser Pulse interval (ns)	SNR (dB)	Repetition Rate (MHz)
System Practical performance	39	1.45 (µs)		4
1^{st}	11.78	50	46	20
5^{th}	5	10	62	100
10^{th}	2.5	5	60	200
40^{th}	0.5	1.25	53	800
50^{th}	**30 (ps)**	1	51	**1 (GHz)**

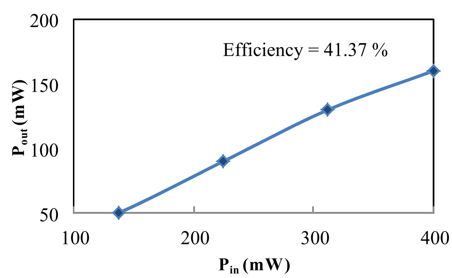

Figure 7: Output power characteristics of a mode-locked laser.

The laser output is coupled using a 20 % terminal of a fiber coupler and passed through another optical filter to minimize the optical noise level in the generated pulse train. A pin detector is then used to convert the optical signal to an electrical signal to allow using an RF spectrum analyzer. An electrical bandpass filter with a bandwidth of 0.1 MHz is used after the pin detector to clean the noise generated by the laser and detector. The noise sources assumed in the pin detector are signal-ASE beat noise, ASE-ASE beat noise, thermal, and shot noises.

The power level of the 980 nm laser pump to the EDF is varied in the simulation. It is found that the pump power does not affect the produced pulse width as shown in Table 1. Also, the effect of the bandwidth of the TOF on the laser-generated pulses width is summarized in Table 2. There is no effect of filter bandwidth on the laser-generated pulses width. Thus, the mode-locking is independent of

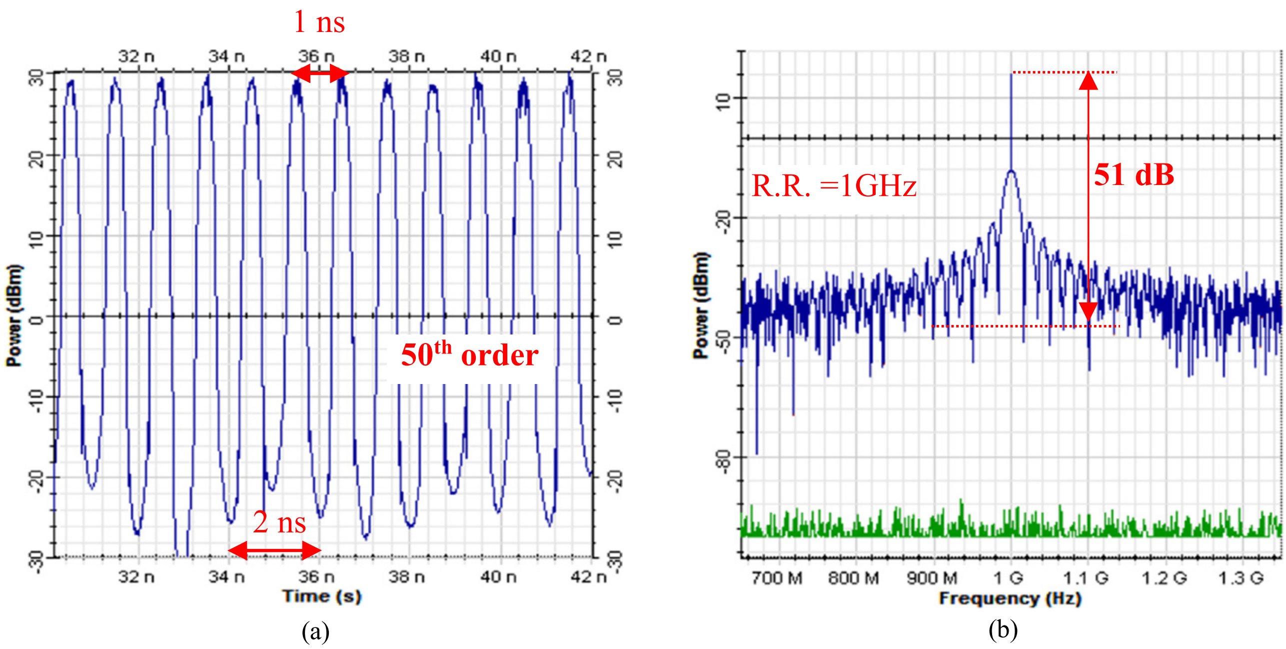

Figure 8: 40th order mode-locked laser (a) output pulse train (b) relative RF spectrum.

Table 4: Performance comparison with previous works.

reference	mode-locked type	Fiber type	repetition rates (Hz)	bandwidth	Center Wavelength (nm)
[1]	Active	Nd^{3+} Doped	/	2.4 nm	1054
[2]	Active	Ytterbium	10 G	2 nm	1053
[4]	Passive	Erbium-Doped	7.29 M	58.8 nm	1568.1
[5]	Active	Erbium-Doped	16.3 M	62 nm	1550
[6]	Passive	Erbium-Doped	1 M	3.14 nm	1559.25
[6]	Active	Dispersive	9 M	94 nm	1550
[7]	Active	Two-Mode Fiber Bragg Grating	Tuneable from 15.65 MHz to 626 MHz	6 nm	1546 to 1552
[8]	Active	Linear Chirped Fiber Bragg Grating	5.4 M	2.1 nm	1550
This work	Active	Erbium-Doped	Tuneable from 0.67 MHz to 1 GHz	30 nm	1525 to 1565

both the 980 nm laser pump power and the tunable filter bandwidth.

Generating higher-order mode-locking for the laser is possible by increasing the electrical sinewave repetition rate used to drive the modulator. The simulated active mode-locked fiber has a very high efficiency of about 41 % as illustrated in Fig. 7 even for higher-order 10th, 40th, and 50th mode-locking. The slope efficiency is calculated by measuring the generated pulse train power by varying the 980 nm pump laser power. The output of the active mode-locked laser pulse train at higher-order mode-locking is also simulated for 15 m cavity length as shown in Fig. 8. The cavity is made of 10 m DSF and 5 m EDF. A 20 MHz sinusoidal signal is used to drive the IM. Over 50 dB signal to noise ratio (SNR) is measured for the laser train of pulses using an RF spectrum analyzer and a pulse width of 30 ps is achieved for 1 GHz pulse repetition rate. Table 4 shows performance comparison with previously published works. It is clear that this demonstrated mode-locked laser design can be used in optical communication and metrology applications similar to already published work described in references 5 and 8, respectively.

4 Conclusions

A simple active mode-locked laser is experimentally demonstrated in the C-band wavelength range. Numerical simulations are conducted to further characterize the laser mode-locking process and the effect of the power level of the 980 nm laser pump power and tunable optical filter bandwidth on the generated laser pulses width. The laser cavity is created using EDFA used as ASE noise source, 250 m of PM-DSF, tunable optical filter, and an intensity modulator driven with an electrical sinusoidal signal at different repetition rates. The laser cavity fundamental rate is 0.67 MHz. The simulation was done at 4 MHz, which is the 6^{th} order harmonic mode-locking, while the experiments were done using a 5.36 MHz modulator, which gives the 8^{th} harmonic order mode-locking. The frequency of the intensity modulator was adjusted in the experiments to give the most clear and stable output, which happens to be the eight orders.

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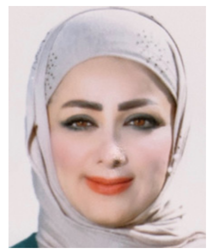

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