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Widely-tunable harmonic mode-locked fiber laser by the combination of spectral filtering and gain management

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\begin{abstract}
Controlled flexible ultrafast pulses are of great importance in many application fields, such as metrology. Here, we report a compact pulse width tunable passively harmonic mode-locked fiber laser by exploiting the combination effect of spectral filtering and gain management. The spectral filtering is achieved by adopting a band-width tunable filter, resulting in pulse width tunable and changing the harmonic order (i.e., repetition rate). On the other hand, gain management can tune the harmonic order, while the emission pulse width typically remains the same. Thus, a combination of these two effects can make the pulse width tunable in a broad range at a fixed repetition rate. At the 6th-order harmonic mode-locking (76.8 MHz), the pulse width can be tuned from ~0.8 ps to 4.3 ps by adjusting the bandwidth and pump strength. The development of pulse width tunable laser sources at a high-repetition rate would find potential applications in fields such as optical sensing and biomedical imaging.
\end{abstract}

\section{Introduction}
Pulsed fiber lasers have been researched extensively in recent years owing to their inherent advantages such as high peak power, high beam quality, and compact physical size [1–4]. In particular, the laser source with a high repetition rate has critical applications in laser imaging, microwave photonics, optical communications, optical frequency metrology, and so on [5–8]. Generally, three methods have been adopted to generate a high repetition rate pulse train: shortening cavity length, active modulation, and harmonic mode-locking. Shortening cavity length is one of the most straightforward ways to achieve high repetition rate pulses owing that the fundamental repetition rate of a mode-locked fiber laser is proportional to the cavity length [9,10]. The cavity length should be at the centimeter-long level to realize GHz mode-locking, while the output power is limited by the doping concentration restrictions in such a short cavity [11–13]. The active modulation method also exhibits the potential to obtain high repetition rate laser pulses, however, it suffers from the disadvantages of a complex structure and relatively large pulse width compared with the passive modulation method [14–15].

Harmonic mode-locking has been widely employed to produce high repetition rate pulses. According to the soliton area theorem (\(E_r \propto \beta^2/n_2\)) where \(E_r\), \(\tau\), \(\beta^2\) and \(n_2\) are pulse energy, pulse width, group velocity dispersion (GVD) coefficient, and nonlinear index of the fiber), the soliton energy is limited to \(\sim 0.1\) nJ [16–17]. Once the pulse energy exceeds the value, the extra energy will be shed from the soliton and form a new soliton pulse. Such a process is called harmonic mode-locking. Several methods have been proven to achieve harmonic mode-locking. A piece of tiny core fiber can be inserted into the cavity to enhance the nonlinear effect and decrease the splitting threshold. 144.3 GHz mode-locked pulses can be obtained based on a hybrid plasmonic microfiber knot resonator device [18]. Beyond that, the harmonic mode-locking can also be obtained by changing the cavity net dispersion. 2.5 GHz repetition rate femtosecond pulses were generated by adjusting the distance between a grating pair in the cavity [19]. However, the most practical way is to boost the pulse energy beyond the splitting
threshold by over pumping the laser owing to its simple structure and high operating stability [20–21].

As the pump power increases, the harmonic order increases yet the pulse width nearly remains the same [22]. Pulse width tunable and high repetition rate fiber lasers have versatile applications such as in optical sensing and biomedical imaging, whereas most of the research is just focused on how to increase the harmonic order but seldom on the pulse width tunability. To address this issue, a promising solution is to combine a bandwidth tunable filter (TF) with a broadband saturable absorber (SA), in which the optical spectrum filtering effect can change the bandwidth of the output pulse spectrum, and then, the output pulse width of the harmonic mode-locking can be changed accordingly [23].

In this work, we report a pulse width tunable harmonic mode-locked Er-doped fiber laser induced by the combination of spectral filtering and gain management. The gain management technique changes the order of harmonic mode-locking, while the optical spectrum filtering effect tunes the output pulse width and harmonic order. Thus, combining the optical spectrum filtering effect with gain management can significantly tune the pulse width of a harmonic mode-locked laser at a fixed repetition rate. Inserting a ~ 1.6 nm bandwidth TF and a broadband carbon nanotube (CNT) SA into the cavity, the pulse width at 6th-order harmonic mode-locking increases from ~ 0.84 ps to 4.3 ps. Our experimental results provide an advanced method for the development of practical light sources with controllable performance at a high repetition rate.

2. Experimental setup

Fig. 1 shows the schematic of the harmonic mode-locked Er-doped fiber laser. The 980 nm pump light is injected into the ring cavity through the wavelength division multiplexer (WDM). 2.5 m Er-doped fiber (I-25(980/125), from Fibercore) whose absorption coefficient is ~25 dB m$^{-1}$ at 980 nm provides gain. A CNT film is utilized to modulate the oscillating laser owing to its broadband absorption spectrum at ~1.5 μm wavelength. A polarization-insensitive optical isolator (ISO) is used to ensure the unidirectional propagation of the light in the ring cavity. A tunable bandpass filter (TB-TWF-1550, PriTel) is employed inside the cavity to selectively confine the gain bandwidth of the laser. Thus, the pulse width can be tuned in a wide range in this setup by simultaneously adopting the broadband SA and TF. Except for the gain fiber, all the other fibers in the cavity are standard single-mode fiber (SMF-28e, Corning). The mode-locked fiber laser operates at an anomalous net dispersion regime whose total net dispersion is ~ -0.31 ps$^2$. A 20 % optical coupler (OC) is employed to extract the signal from the oscillating laser beam.

The optical spectrum is measured by an optical spectrum analyzer (Anritsu MS9740A). The pulse train is detected by a high-speed photodiode detector (EOT ET-5000F) and monitored by an oscilloscope (Siglent SDS5104X) and a radio-frequency (RF) spectrum analyzer (Anritsu MS2692A). The pulse width is measured by a commercial autocorrelator (APE PulseCheck 150).
and 8th-order harmonic mode-locking with a 4.2 nm bandwidth TF inserted into the cavity.

3. Results and discussion

3.1. A. Mode-locking without TF

In order to test the pulse width tunability, the emission performance without the TF inserted into the cavity is measured firstly for comparison. When the pump power is set between ~ 17.7 mW and 29.0 mW, stable fundamental harmonic mode-locking can be observed as shown in Fig. 2. Fig. 2(a) presents the measured pulse train with a peak-to-peak period of ~ 78.1 ns. The corresponding repetition rate is ~ 12.8 MHz, which agrees well with the cavity length. Fig. 2(b) demonstrates the emission optical spectrum of the mode-locked pulses, which is centered at ~ 1564.4 nm with a 5.6 nm 3-dB bandwidth. Thus, the optical spectrum is wide enough to be filtered by the TF to tune the pulse width in the following experiments. Notably, the presence of the symmetric Kelly sidebands at both sides of the optical spectrum suggests that the output pulse is a conventional soliton [24,25]. The full width at half maximum of the correlation trace in Fig. 2(c) is ~ 1.4 ps, which suggests that the pulse width of the mode-locked pulse is ~ 913 fs based on the sech² fitting. The time-bandwidth product is 0.63 and higher than the typical value (0.315) of a transform-limited pulse waveform, which is mainly induced by the large net dispersion of the cavity. Fig. 2(d) demonstrates the RF spectrum of the laser output. The signal-to-noise ratio (SNR) is about 49 dB and the frequency peak is located at the repetition rate of ~ 12.8 MHz. The oscilloscope trace and the RF spectrum suggest that the mode-locking is operated under fundamental mode-locking.

With the pump power increased from ~ 29.0 mW to 63.1 mW, harmonic mode-locking operation can be obtained. Fig. 3(a) shows the 3rd-, 4th-, 6th- and 8th-order harmonic mode-locking under ~ 31.2 mW, 41.4 mW, 52.3 mW, and 63.1 mW pump power, respectively, whose repetition rate are ~ 38.4 MHz, 51.2 MHz, 76.8 MHz, and 102.4 MHz. Notably that the harmonic order can be increased further but with poor stability. The autocorrelation traces corresponding to Fig. 3(a) is shown in Fig. 3(b). With the increase of the pump power, the pulse widths at 3rd-, 4th-, 6th-, and 8th-order harmonic mode-locking nearly remain the same, which are ~ 0.84 ps, 0.90 ps, 0.84 ps, and 0.84 ps respectively. Fig. 3(c) demonstrates the four emission optical spectra at the different orders, which nearly have the same central wavelength and the 3-dB bandwidth. Fig. 3(d) shows the four corresponding RF spectra. The peak-to-peak intervals are coincidence with the repetition rate of the 3rd-, 4th-, 6th-, and 8th-order harmonic mode-locking, which proves the generation of the harmonic mode-locking.

B. Harmonic mode-locking with TF

The above experimental results demonstrate that the pulse width is not affected by the gain management effect (i.e., the pump power). To address this, a TF with ~ 4.2 nm bandwidth is inserted into the cavity to selectively control the output pulse performance in spectral and time domains. A piece of single-mode fiber is removed from the cavity to compensate for the fiber patch cord of the TF, so the cavity parameters (such as the net dispersion value and repetition rate) remain unchanged. When the pump power increases from ~ 34.5 mW to 67.0 mW, the harmonic mode-locking operation from 3rd-order to 8th-order can be achieved, as shown in Fig. 4(a). It can be concluded that the insertion of the TF can increase the threshold of harmonic mode-locking, which is mainly induced by two factors. One is that the optical spectrum filtering effect can reduce the oscillating power in the cavity. The other one is that the confinement of the bandwidth can increase the emission pulse width according to the Fourier transform, which can further increase the harmonic mode-locking threshold based on the soliton area theorem.

Fig. 4(b) shows the autocorrelation traces corresponding to Fig. 4(a). The pulse width remains the same with the pump level increasing, which also proves that the gain management cannot change the pulse width of the harmonic mode-locking. However, the emission pulse width increased from ~ 0.8 ps (without the TF) to 1.6 ps with a TF inserted, which suggests the optical filtering effect has an obvious effect on the laser pulse width. It is worthy to note that in the case of fixed pump strength, although the emission pulse width changes with the insertion of TF, the repetition rate is also reduced due to the increase in the harmonic mode-locking threshold.

Only the optical spectrum filtering effect cannot achieve the pulse width tunable harmonic mode-locked laser at a fixed repetition rate because the harmonic order decreased owing to the insertion of the TF. Thus, if one wants to increase the order of harmonic mode-locking, several methods could be adopted, such as insertion of a high nonlinear fiber such as the tiny core fiber and changing the net GVD value such as adjusting the distance between an intracavity grating pair. In comparison with these two methods, the gain management technique is simple but most effective and will not reduce the cavity compactness. The specific approach is to increase the pump strength when a bandwidth TF is inserted.

Fig. 5 demonstrates the emission pulse width and the pump strength with different bandwidth TF inserted into the cavity at (a) 2nd-, (b) 4th-, (c) 6th-, and (d) 8th-order harmonic mode-locking under different pump level.
two can achieve a pulse width tunable emission from a harmonic mode-locking. The optical spectrum filtering effect can be obtained by adopting the combination of optical spectrum filtering and the gain management technique. With the increase in harmonic order, there is a large demand for the pump strength to maintain the harmonic order unchanged. At the 2nd order harmonic mode-locking, the pump power should increase by an additional 12.6 mW to avoid reducing the harmonic order when the bandwidth of TF decreases from 9.1 nm to 1.6 nm. However, the demand for the extra pump strength is $\sim 19.1$ mW, $22.8$ mW, and $29.5$ mW respectively at 4th, 6th, and 8th order harmonic mode-locking as shown in Fig. 5(b-d). Thus, the pump level must reach up to 90.4 mW which can achieve 8th-order harmonic mode-locking with a 1.6 nm bandwidth TF.

It can be concluded that the bandwidth of TF makes a crucial role in the emission pulse width of harmonic mode-locking. Fig. 6 shows the optical spectrum and autocorrelation trace at the 6th-order harmonic mode-locking with a 1.6 nm and 9.1 nm TF respectively. With a 1.6 nm TF inserted into the cavity, the 3-DW bandwidth of optical spectrum is smaller than that with a 9.1 nm TF. According to the Fourier transform, the emission pulse width with a 1.6 nm TF should be larger than that with a 9.1 nm TF. The measured pulse widths with these two TF inserted into the cavity are $\sim 4.3$ ps and 1.0 ps respectively. In this experiment, the broadband CNT SA plays an important role in the wide tunability, which may not be achieved by adopting other SAs [26–28]. The higher-order harmonic mode-locking can also be observed in our experiment yet it is less stable and noisier than the lower-order harmonic mode-locking.

4. Conclusion

In summary, we have demonstrated a passively harmonic mode-locked fiber laser which can generate pulse width tunable ultrafast pulses. A novel approach via the combination of optical filtering and gain management is presented. The optical spectrum filtering effect can tune the emission pulse width yet cause the harmonic order decreased. The gain management technique can change the harmonic order, but keeps the pulse width nearly the same. Thus, the combination of these two can achieve a pulse width tunable emission from a harmonic mode-locked fiber laser at a fixed harmonic order. Without the TF insertion, the emission pulse width is 0.84 ps at 6th-order harmonic locking. When a TF with 9.1 nm or 1.6 nm bandwidth inserted into the cavity, pulse widths are 1.0 ps at 52.3 mW pump power and 4.3 ps at 75.1 mW pump power, respectively. We believe that the pulse width tunable laser presented here has enormous potential and could be an outstanding ultrafast seed laser for optics sensing and laser communications.

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