Wavelength and bandwidth tunable passively mode-locked fiber laser based on semiconductor saturable absorber mirror and liquid crystal on silicon device

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Abstract. Using a liquid crystal on silicon (LCoS) device as tunable filter, we experimentally demonstrate a wavelength and bandwidth tunable passively mode-locked fiber laser. The key feature of this laser is that any wavelength with any bandwidth can be tuned independently over the whole C-band, which is flexibly driven by only a single LCoS chip. The outputs exhibit excellent tuning capacity and high consistency in the C-band, using a 0.1 nm wavelength-tuning step. The filter bandwidth can be set to any width within the wavelength range, while the pulse width varies from 9 to 50 ps.

1. Introduction
Mode-locked fiber lasers with high peak power and good beam quality have attracted wide attention due to their potential applications in wavelength-division-multiplexed (WDM) communication systems, fiber sensing systems, optical signal processing, spectroscopy, optical instrumentation, and biomedical research [1–3]. Compared to conventional mode-locked lasers, a tunable-mode-locked laser with flexibly adjustable mode-locked laser parameters, such as output wavelength, pulse repetition frequency, and pulse width, obviously has a wider application potential [4–8]. Graphene and other two-dimensional (2D) noncarbon materials, including topological insulators (TIs), transition metal dichalcogenides (TMDCs), phosphorene, bismuthene, and antimonene, have witnessed a very fast development of both fundamental and practical aspects in mode-locked fiber lasers [9]. Several approaches have been proposed to achieve tunable wavelength mode-locked operation, based on a nonlinear optical loop mirror (NOLM) [10] or on polarization-maintaining fiber (PMF) [11]. However, these techniques require a few kilometers of fiber to achieve the desired non-linear effect, which increase the length of the fiber required for the constitution of the laser, resulting in a significant reduction in the stability of the laser output. The most popular approaches used to achieve tunable wavelength mode-locked operation incorporate other additional components, such as Mach–Zehnder interferometer [12], Fabry–Perot interferometer [13], and the Sagnac loop interferometer with fiber Bragg grating [14]. However, the wide range of tunable optical interference filters are sensitive to temperature, gradient, sound, vibration, and other environmental noises, which also reduce the stability of the laser operation. In addition, these commonly used tunable filters can tune the output wavelength, but they cannot change the beam bandwidth. The tunable filter based on a LCoS device
have the features of colourless, directionless, contentionless and high flexible spectrum, is very suitable as a filter for a mode-locked laser [15-17].

In this paper, we propose a liquid crystal on silicon (LCoS) device as a tunable filter and apply it to tune the wavelength and bandwidth in a passively mode-locked fiber laser for the first time. The main feature of this LCoS-based mode-locked fiber laser is that any wavelength with any bandwidth can be programmed by only one software-driven LCoS chip. All wavelengths can be tuned flexibly in the range of 1530–1560 nm with 0.1 nm steps. Any width of filter bandwidth can be selected within the wavelength range, while the pulse width varies from 9 to 50 ps.

This report is organized as follows: In Section 2, a description of the tunable filter is given. In Section 3, a system of broadband tunable mode-locked fiber lasers, based on LCoS is presented. Section 4 discusses the implementation and performance test of the experimental devices, including filter characteristics, mode-locked laser characteristics without using a filter and mode-locked laser characteristics affected by the programmed filter. Finally, conclusions are drawn in Section 5.

2. Structure and operational principle of the tunable filter

In this study, the tuning operation of the mode-locked tunable filter is based on the LCoS technology. LCoS combines the unique light-modulating properties of liquid crystal (LC) materials and the advantages of high-performance silicon complementary metal oxide semiconductor (CMOS) technology owing to its dedicated assembly processes [18–20]. This technology can be used as amplitude-only or as phase-only spatial light modulator (SLM), when the input and output polarization configurations are appropriately selected [21–22]. Figure 1 shows a schematic diagram of a wavelength and bandwidth tunable filter. The filter system includes a pair of microlens arrays, a plano-convex lens, a transmissive grating, a cylindrical mirror, and an LCoS chip. As the instrument is fixed on a stage during the experiment, the system has high stability, except for the software-controlled LCoS, which is the only variable device. The input optical signal is coupled through a microlens and it becomes divergent light. Then, the divergent light becomes parallel light after passing through a cylindrical lens with a focal length of 300 mm. Then, the transmission grating (966 lines/mm) disperses the parallel light. These light waves, passing through the cylindrical mirror, are converted into parallel light and are incident on the work area of the LCoS chip. Different wavelengths are diffracted to different positions of the LCoS chip. By controlling the position and size of the simulated flare light image the desired wavelength of light can be accurately diffracted. The LCoS chip is located on the back focal plane of a 300 mm lens, and the lens collimates the returned first order diffracted light into the output of the microlens.

![Figure 1. Schematic diagram of tunable filter based on LCoS.](image1)

![Figure 2. Grating image diagram loaded on the LCoS.](image2)
For certain required output wavelengths, we load an image, similar to figure 2 on the LCoS. The light wavelength (~1530–1560 nm) is dispersed on the x-axis after demultiplexing through the transmissive gratings. In figure 2, a represents the width of the selected light wave on the x-axis. The position of a determines the output wavelength while the width of a determines the bandwidth: the wider a is, the wider the wavelength range. In figure 2, c represents the spot diameter of the incident light beam (our experimental spot is 6 mm); a greater c generates a large volume of grating cycles, which can achieve finer spot focus. The grating period in figure 2 is represented by d, which determines the diffraction angle. As we need only one output port, the value of d does not need to be varied when the optimal diffraction angle (at which power loss is minimized) is chosen.

3. Construction of broadband tunable mode-locked fiber laser system based on LCoS
A schematic diagram of a wavelength and bandwidth tunable passively mode-locked fiber laser is shown in figure 3. It consists of a fiber loop and a bulk optics module. The fiber loop includes a 1 × 2 polarization maintaining (PM) fiber coupler with a 10/90 power splitting ratio, an erbium-doped fiber amplifier (EDFA) operating in the C-band, a polarization controller (PC), a circulator, and a semiconductor saturable absorber mirror (SESAM). By using the EDFA as a pump source, the pumping current can be controlled by the software. The mode-locked device is a SESAM for the pulsed light output. The circulator connects the SESAM with the laser cavity to ensure unidirectional light transmission. A programmable LCoS is used as a tunable filter to tune the wavelength and bandwidth of the laser. In order to obtain a higher average output power, the output coupler used in the coupling ratio is 90:10, of which the output is 10%. The laser mode-locking characteristics were observed by an oscilloscope, a spectrometer, and an autocorrelator. The wavelength resolution of the oscilloscope (model MS9740, manufactured by Agilent Technologies Inc., USA) is 0.03 nm. The pulse width measurement range of the autocorrelator (model FR-103XL, manufactured by Femtochrome Research, Inc.) is approximately form 5 fs to 90 ps.

![Figure 3. Construction of broadband tunable mode-locked fiber laser system based on LCoS.](attachment:image)

4. Experimental results and discussion

4.1. Characteristics of wavelength and bandwidth tunable filter tuning
The experimental device for a tunable broadband filter was set up as shown in figure 1. In the experiment, the spontaneous emission spectrum (ASE) generated by an EDFA was used as the signal source, with a wavelength range of the entire C-band (1530–1560 nm). Continuously adjustable wavelength and bandwidth were achieved by controlling the blazed grating image on the LCoS. Figure 4 shows the experimental result of the filter characteristics with wavelength and bandwidth values.
randomly chosen for the testing of the output (the dashed line in the figure is the ASE spectrum of the EDFA). The total loss of bulk optics from input and output collimators was \( \sim 11 \) dB, which was mainly the result of lens reflection loss, diffraction loss, and insertion loss from the blazed grating and LCoS processor.

![ASE noise and Wavelength selected by LCoS](image)

**Figure 4.** LCoS-tunable filter characteristics recorded at any wavelength and bandwidth of the output.

4.2. Performance test of a mode-locked fiber laser without LCoS filter
The laser characteristics without using an LCoS tunable filter was tested in order to observe the filter effect on the mode-locked pulse. Figure 5 shows the experimental test of the mode-locked pulse without filter with an EDFA pump current of 20 mA. The repetition frequency was 3.68 MHz and the average output power was 0.4 mW. Figure 5 (a) shows the pulse autocorrelation trace measured by the autocorrelator. The full width at half maximum (FWHM) of the autocorrelated signal is 64 µs tested by oscilloscope. According to the manual of the autocorrelator, when the pulse waveform is a Gaussian pulse, the time-domain spectral pulse width \( \tau \) is calculated as:

\[
\tau = \text{FWHM} \times 31 \times 0.707
\]

**Figure 5.** Experimental results of the mode-locked laser at a filter center wavelength of 1564 nm without filter: (a) autocorrelation curves; (b) output spectra.

Where the unit of FWHM is ms, and the unit of \( \tau \) is ps. According to formula 1, pulse width can be calculated about \( \sim 1.4 \) ps. Figure 5 (b) shows the laser spectrum measured by the spectrometer, while the center wavelength stabilizes at 1564 nm and the FWHM is 3.316 nm.
4.3. Performance test of a LCoS tunable mode-locked fiber laser

![Figure 6](image1)

**Figure 6.** Experimental results of the mode-locked tunable laser at a filter center wavelength of 1550 nm and a filter bandwidth of 3.2 nm: (a) bursts observed after the oscilloscope; (b) autocorrelation curves; (c) output spectra.

4.4. Tunable mode-locked fiber lasers output characteristics.

As the LCoS-tunable tunable filter can be tuned in both wavelength (~1530–1560 nm) and bandwidth, the mode-locked laser needs to be tested with different wavelengths and different bandwidths. When the pump drive current is greater than 7 mA, a stable mode-locked output can be observed by adjusting the cavity polarization controller. Figure 6 shows the experimental results of the mode-locked tunable laser at a filter center wavelength of 1550 nm, with an EDFA pump current of 20 mA and a filter bandwidth of 3.2 nm. Figure 6 (a) shows the optical pulse train obtained by the oscilloscope. The output waveform is very stable with little change in the amplitude. The repetition rate was 5.03 MHz and the average output power was 0.02 mW. Figure 6(b) shows the pulse autocorrelation trace measured by the autocorrelator. The FWHM of the autocorrelated signal was 440 μs and the calculated pulse width was ~9.64 ps. Figure 6 (c) shows the laser spectrum measured by the spectrometer, while the center wavelength stabilizes at 1550.15 nm and the FWHM is 1.37 nm. As the insertion loss of the LCoS-tunable filter is relatively large and the filter bandwidth of 3.2 nm reduces the pulse width, the output pulse power drops significantly compared to the result of laser without filter. The experimental
results show that due to the filter regulation, the mode-locked spectrum is confined to the selected frequency band and it is no longer a single output center wavelength of 1564 nm, but it can be flexibly selected by the filter. The basic idea of mode-locking is to use special modulation means for the laser spectrum to form a constant phase relationship between different oscillation longitudinal modes and coherently superimpose them, in order to obtain ultrashort optical pulses with very narrow pulse width and high peak power in the time domain. The filter limits the gain spectrum bandwidth so that the above process only occurs within the corresponding bandwidth, so the filter can tune the mode-locked pulse width and output wavelength, resulting in the optical spectrum in the figure 6 (c) is different from conventional soliton mode-locked lasers in the figure 5 (b).

4.4.1. Wavelength tuning performance of tunable mode-locked fiber lasers. In order to verify the tunability of the mode-locked laser in the C-band (~1530–1560 nm), we fixed the output of the filter bandwidth at 3.2 nm and the filter center wavelength at 1530 nm, 1534 nm, 1538 nm, 1542 nm, 1546 nm, 1550 nm, 1554 nm, and 1558 nm. The mode-locked output spectra are summarized in figure 7. At the same time, we measured the output pulse width and the average power of different center wavelengths respectively, by using the autocorrelator and the optical power meter. The values are shown in figure 8. When the bandwidth was fixed at 3.2 nm, the variations of the output pulse width were not very large, typically remained at 9 ps. The average optical power was also very stable, maintained typically at 0.02 mw. To protect the SESAM, although it is theoretically feasible, the EDFA pump current was not increased continuously for greater output optical power. Figure 9 shows the experimental results of the fine wavelength tuning with a tuning accuracy of 0.1 nm. In the wavelength tuning, the wavelength switching was rapid and complete without jitter and distortion.
shows Experiments spectrometer, calculating trace wavelength 0.71 nm measured was pulse laser output repetition bandwidths section. results 4.4.2.

Figure 9. Finely tuned spectrum of the mode-locked tunable laser with a tuning accuracy of 0.1 nm: (a) spectrum; (b) pulse width and average power.

(a) 
(b)

Figure 10. Experimental results of the mode-locked tunable laser at a filter center wavelength of 1550 nm and a filter bandwidth of 1.6 nm: (a) autocorrelation curves; (b) output spectra.

(a) 
(b)

4.4.2. Bandwidth tuning performance of the tunable mode-locked fiber lasers. The experimental results of the effect of the tuning filter bandwidth on the mode-locked laser are discussed in this section. Figure 10 and 11 show the mode-locked laser experimental output characteristics with filter bandwidths of 1.6 nm and 0.8 nm, respectively. As there was no change in the laser cavity length, the repetition frequency of the laser was maintained at 5.03 MHz. Only the autocorrelation curve and the output spectrum are given here. Figure 10 shows the experimental results of the mode-locked tunable laser at a filter center wavelength of 1550 nm and a filter bandwidth of 1.6 nm. Figure 10(a) shows the pulse autocorrelation trace measured by the autocorrelator. The FWHM of the autocorrelated signal was 0.66 ms and the calculated pulse width was ~14.47 ps. Figure 10(b) shows the laser spectrum measured by the spectrometer, while the center wavelength stabilizes at 1550.4 nm and the FWHM is 0.71 nm. Figure 11 shows the experimental results of the mode-locked tunable laser at a filter center wavelength of 1550 nm and a filter bandwidth of 0.8 nm. Figure 11(a) shows the pulse autocorrelation trace measured by the autocorrelator. The FWHM of the autocorrelated signal was 2.25 ms and the calculated pulse width was ~49.31 ps. Figure 11(b) shows the laser spectrum measured by the spectrometer, while the center wavelength stabilizes at 1550.22 nm and the FWHM is 0.25 nm. Experiments show that the LCoS can control the mode-locked laser output pulse width. Figure 12 shows the pulse width and average power of different filter bandwidth. Comparing figure 6, 10, 11 and
12, it can be clearly seen that as the filter bandwidth is reduced, the mode-locked bandwidth is also significantly reduced, corresponding to output pulse broadening and output power attenuating.

(a) ![Autocorrelation curves](image1.png)  
(b) ![Output spectra](image2.png)

**Figure 11.** Experimental results of the mode-locked tunable laser at a filter center wavelength of 1550 nm and a filter bandwidth of 0.8 nm: (a) autocorrelation curves; (b) output spectra.

![Pulse width and average power](image3.png)

**Figure 12.** Pulse width and average power of different filter bandwidth.

### 5. Conclusions

We experimentally demonstrate a wavelength and bandwidth tunable passively mode-locked fiber laser based on a SESAM and an LCoS device. An attractive feature of this tunable fiber laser is that wavelengths and bandwidth can be tuned flexibly and independently by only one LCoS chip. The experimental results show that the output lasing wavelength can be shifted easily over the C-band with the tuning step of 0.1 nm, which is more practical than the traditional tuning of fiber lasers. The bandwidth can also be controlled by the LCoS filter and the output pulse width varies in the range of 9–50 ps.

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