An All-Fiber Mode-Locked Pulse Laser Based on Acoustically-Induced Fiber Grating

Qingsong Zhang
The Key Laboratory of Specialty Fiber Optics and Optical Access Network
Shanghai University
Shanghai, China
15623789182@163.com

Jiangtao Xu
The Key Laboratory of Specialty Fiber Optics and Optical Access Network
Shanghai University
Shanghai, China
tsyjxjt@shu.edu.cn

Meiting Xie
The Key Laboratory of Specialty Fiber Optics and Optical Access Network
Shanghai University
Shanghai, China
xiemeiting@shu.edu.cn

Yi Zhu
The Key Laboratory of Specialty Fiber Optics and Optical Access Network
Shanghai University
Shanghai, China
18949553293@163.com

Tao Han
The Key Laboratory of Specialty Fiber Optics and Optical Access Network
Shanghai University
Shanghai, China
2717467775@qq.com

Xianglong Zeng*
The Key Laboratory of Specialty Fiber Optics and Optical Access Network
Shanghai University
Shanghai, China
*zenglong@shu.edu.cn

***Abstract*—We experimentally demonstrated a high-order LP11 mode-locked fiber laser based on frequency-shifted feedback mechanism， which uses acoustically-induced fiber grating (AIFG) to realize frequency shift and mode conversion.**

Keywords—frequency-shifted feedback laser, acoustically-induced fiber grating, high-order mode, mode conversion

I. INTRODUCTION

Temporal mode-locking (ML) is achieved in a frequency shifted feedback laser (FSFL) by incorporating a frequency shifter into the fiber laser cavity, which can deliver short pulses independent of net dispersion within the cavity [1]. The pulse widths ranged from a hundred femtoseconds to a few nanoseconds [2, 3], and the wavelengths involved near-infrared to mid-infrared bands [4, 5]. Passive fiber mode-locked laser is widely used in physics and biology experiments by virtue of its advantages of simple structure and compactness. The mode-locking mechanism of the FSFL can overcome the limitations in the gain wavelength coverage [6], and the FSFL has been applied in the fields of atomic cooling and slowing [7], dispersion measurement [8], etc.

Because of the unique phase and polarization distribution, high-order mode (HOM) in fibers has important application value in optical communication, plasma excitation, material processing and other fields. Compared with other fiber mode conversion devices, acoustically-induced fiber grating (AIFG) can be used to realize not only mode conversion but also frequency shift.

In this paper, we propose an all-fiber mode-locked frequency-shift feedback laser based on the cascaded AIFGs. The AIFG in the cavity continuously changes the frequency of the light during each round trip [9]. The FSFL principle is new phase components induced by nonlinear self-phase modulation (SPM), which is inherently different from the spectral component of the spontaneous emission effect. All spectral components are finally phase correlated, hence resulting in a mode-locked output in the time domain.

II. EXPERIMENTAL SETUP AND RESULTS

The schematic of measuring the AIFG is shown in Fig. 1(a). The conversion efficiency spectrum of the AIFG is shown in Fig. 1(b), which reaches -15 dB (>95%) at 1550 nm. When the ultrasonic wave generated by the piezoelectric transducer (PZT) is transmitted to the unjacketed FMF through the mechanical connection between the aluminum cone and the FMF, the axial micro perturbation of the core will accordingly modulate the refractive index, leading to index-modulation characteristic of dynamic long-period grating. The frequency shift and resonant wavelength of mode conversion can be changed by adjusting the frequency of the signal.

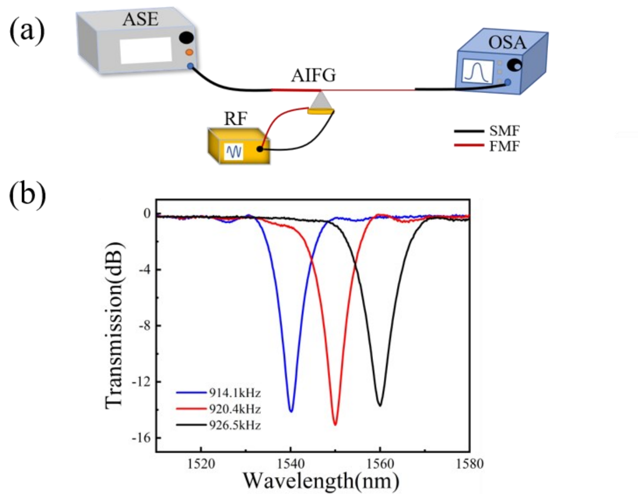

Fig. 1. (a) Schematic of measuring the AIFG; (b) Transmission spectra of mode conversion efficiency.

The HOM FSFL experimental structure is depicted in Fig. 2(a). The cavity length of the all-fiber linear cavity is 34 m. A segement of Erbium-doped fiber (EDF, 2m long) pumped by a 980 nm laser is used as the gain medium. An 26 m-long single-mode fiber is used to enhance the nonlinear effect in the cavity. When the light is transmitted through the AIFG, the AIFG acts as a mode converter and frequency shifter, and a mirror use to play the role of high-order mode output and reflect the light back into the cavity. A Charge-coupled device (CCD) is used to capture the output mode and optical spectrum analyzer (OSA), oscilloscope and radio frequency spectrum analyzer are used to detect the performance of the laser. The spectrum of the laser is shown in Fig. 2(b) with the central wavelength and 3 dB bandwidth are 1549.9 nm and 0.1 nm. The pulse oscilloscope track is shown in Fig. 2(c), the repetition frequency is 2.97 MHz. The frequency spectrum measured by the RF spectrum analyzer is shown in Fig. 2(d), the obtained sideband rejection ratio is 22 dB, indi-

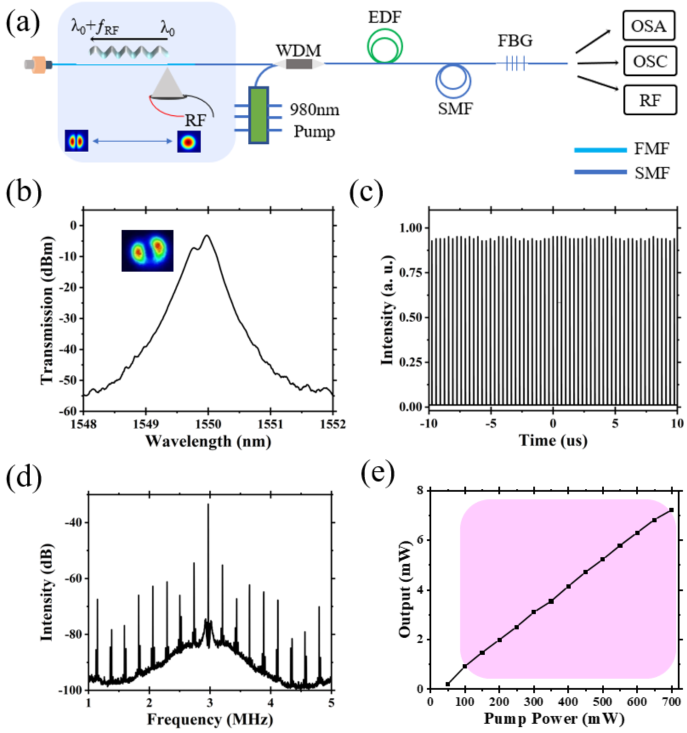

Fig. 2. (a) The experimental setup for the HOM FSFL based on AIFG; (b) Spectrum of laser operating in a mode-locked state; (c) Time domain sequence of mode-locked pulses; (d) The radio spectrum at the base frequency of 2.97 MHz; (e) The variation of output power with pump power.

cating that the laser has good stability. Fig. 2(e) shows the relationship between the output power and pump input power of the laser. When the pump input power reaches 100 mW, the laser can enter the mode locking state.

In the experiment, we found that as the pump power is set to 70 mW, the phenomenon of Q-switched mode-locking is observed, and the spectrum at this time is shown in the red line in Fig. 3(a). It can be clearly seen that the spectrum at this time is slightly narrower than that obtained at the time of mode-locked, and the pulse output waveform is shown in Fig. 3(b), showing the pulse sequence with significant peak intensity fluctuation.

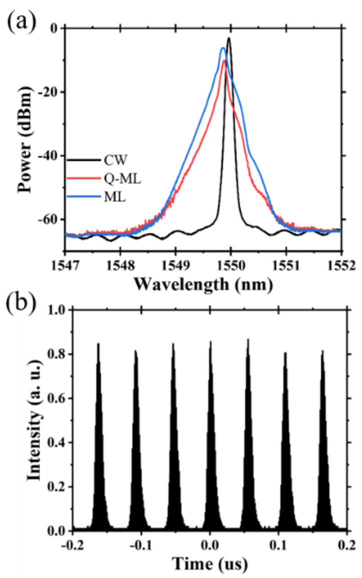

Fig. 3. (a) Spectrum of laser operating in different state; (b) Time domain sequence of Q-switched pulses.

III. Conclusion

The experimental results show that mode-locked FSFL can output LP_{11} mode, in which mode conversion and frequency migration are realized by the AIFG. This work greatly enriches the methods of high-order mode-locked laser.

References

[1] R. Gumenyuk, D. A. Korobko, I. O. Zolotovsky, and O. G. Okhotnikov, "Role of cavity dispersion on soliton grouping in a fiber lasers," Opt. Express, vol. 22, no. 1, pp. 1896-1905, 2014.

[2] A. M. Heldt, J. P. Burger, J.-N. Maran, and N. Traynor, "High power and high energy ultrashort pulse generation with a frequency shifted feedback fiber laser," Opt. Express, vol. 15,no. 24, pp. 15892-15897, 2007.

[3] Z. Gao, L. Sun, and T. Mei, "An All-Fiber Mode-Locked Pulse Laser by Fiber Bragg Grating-Based Acousto-Optic Frequency Shifter," J. Lightwave Technol. vol. 39, no. 19, pp. 6288-6293, 2021.

[4] O. Henderson-Sapir, N. Bawden, M. R. Majewski, R. I. Woodward, D. J. Ottaway, and S. D. Jackson, "Mode-locked and tunable fiber laser at the 3.5 µm band using frequency-shifted feedback," Opt. Lett., vol. 45, no. 1, pp. 224-227, 2020.

[5] W. Fu, L. G. Wright, P. Sidorenko, S. Backus, and F. W. Wise, "Several new directions for ultrafast fiber lasers," Opt. Express, vol. 26, no. 8, pp. 9432-9463, 2018.

[6] M. R. Majewski, R. I. Woodward, and S. D. Jackson, "Ultrafast mid-infrared fiber laser mode-locked using frequency-shifted feedback," Opt. Lett., vol. 44, no. 7, pp. 1698-1701, 2019.

[7] I. C. M. Littler, H.-M. Keller, U. Gaubatz, and K. Bergmann, "Velocity control and cooling ofan atomic beam using a modeless laser," ZPhys-e.D:At. Mol. Clusters., vol. 18, pp. 307-308, 1991.

[8] M. Yoshida, K. Nakamura, and H. Ito, "A new method for measurementof group velocity dispersion of optical fibers by using a frequency-shifted feedback fiber laser," IEEE Photon. Technol. Lett, vol. 13, no. 3, pp. 227-229, 2001.

[9] F. V. Kowalski, P. D. Hale, and S. J. Shattil, "Broadband continuous-wave laser," Opt. Lett., vol. 13, no. 8, pp. 622-624, 1988.