Broadband femtosecond orbital angular momentum fiber laser with high repetition

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***Abstract*—In this paper, a mode-locked fiber laser generating orbital angular momentum beam based on a mode selective coupler is experimentally demonstrated. The 10 dB bandwidth is 88.7 nm and the repetition rate is 113.8 MHz.**

Keywords—orbital angular momentum, mode selective coupler, mode-locked fiber laser

I. Introduction

Orbital angular momentum (OAM) beams with helical phase front of exp($il\varphi$) have wide applications [1]. Recently, different techniques have been developed to demonstrate OAM lasers, which can be divided into non-all-fiber and all-fiber approaches. In the first one, OAM beams are generated by applying a helical phase front, such as metasurface [2], Q-plate [3], and spatial light modulator (SLM) [4]. In the second one, the generation of OAM beams usually depends on the excitation of higher order modes, such as long period fiber grating (LPFG) [5] and fiber Bragg grating (FBG) [6] mode converters. Compared with the former, the all-fiber OAM lasers have the advantages of low-cost, compactness and high stability, and thus attracting much attention. Besides, OAM ultrashort pulses [7] are suitable for applications that need high peak power and short pulse duration, for example, material processing. However, the repetition of the lasers based on mode selective couplers (MSCs) in [7] is limited by the length of the cavity, and the bandwidth is less than 70 nm, which is not favorable for applications that need OAM beams with high repetition and broad spectrum.

In this work, we report an all-fiber mode-locked first-order OAM beam laser using a MSC. By managing both the dispersion and the nonlinearity inside the laser cavity, femtosecond pulse train with wide bandwidth and high repetition is achieved.

II. Devise Design and Fabrication

In all fiber devices, OAM$_{\pm l}$ beams can be formed by linear combinations of orthogonal LP$_{l,m}$ modes with $\pi/2$ phase shift [8]. So it is critical to generate the LP$_{11}$ mode in our experiment, and MSC is a good choice. The fused type MSC

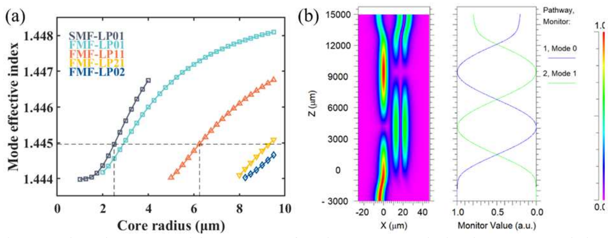

Fig. 1. The phase matching curves for the LP$_{01}$ mode in the SMF and the LP$_{11}$ mode in the FMF. (b) Simulation result for the conversion between the LP$_{01}$ mode in the SMF and the LP$_{11}$ mode in the FMF.

consists of a single mode fiber (SMF, step index, core/cladding diameter = 8/125 μm, NA = 0.13) and a few mode fiber (FMF, step index, core/cladding diameter = 19/125 μm, NA = 0.12). When the two modes meet the phase matching condition, the fundamental mode in the SMF can excite the higher order mode in the FMF. Phase matching can be achieved by tapering fibers.

The phase matching graphs for the LP$_{01}$ mode in the SMF and the LP$_{11}$ mode in the FMF obtained from the simulation software COMSOL are shown in Fig. 1 (a). In order to confirm the possibility of coupling between the two modes, the simulation software RSOFT is then used. In the simulation, the core radius of the SMF and the FMF are 2.5 μm and 6.25 μm, respectively. From Fig. 1 (b), it is obvious that the LP$_{01}$ mode in the SMF can efficiently excite the LP$_{11}$ mode in the FMF under the phase matching condition. The

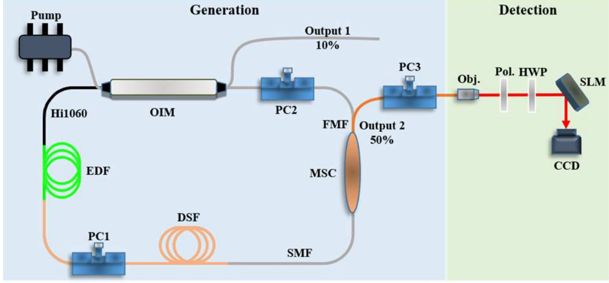

Fig. 2. Experimental setup of OAM$_{\pm1}$ beam laser. OIM, optical integrated module; EDF, erbium-doped fiber; PC, polarization controller; DSF, dispersion compensating fiber; MSC, mode selective coupler; Obj., Objective; Pol., polarizer; HWP, half-wave plate; SLM, spatial light modulator; CCD, charge-coupled device.

power of the two modes changes periodically, so different coupling ratio (CR) can be obtained by controlling the length of the coupling region.

The schematic diagram of the mode-locked fiber laser with 50% LP_{11} mode output is shown in Fig. 2. In order to achieve wide bandwidth and high repetition rate, we carefully design the length of different kinds of fibers in the laser. A 0.27m-long Erbium-doped fiber (EDF) is used as the gain medium and its group velocity dispersion (GVD) is 26.77 ps^2/km. The total length of SMF with GVD of -21.67 ps^2/km is 0.69 m. Besides, a 0.68m-long dispersion compensating fiber (DSF) with GVD of 5.74 ps^2/km is used to manage the net cavity dispersion of the laser. Here, we use two polarization controllers (PCs) and an optical integrated module (OIM) incorporating an optical coupler (OC), a 980/1550 nm wavelength division multiplexer and a polarization dependent isolator to realize nonlinear polarization rotation technique. In addition, one of the two ports connected to the laser cavity in OIM is a 0.17m-long Hi1060 with GVD of -11.47 ps^2/km. The total length of the cavity is about 1.81 m and the net cavity dispersion is estimated to be -0.00577 ps^2. Since 50% power is tapped out of the cavity by the FMF, the CR of the OC is chosen as 90:10 with 10% output to observe the characteristics of pulses of the laser.

III. Characterization Results and Discussion

Fig. 3 shows the pulse characteristics of output 1. The mode-locked optical spectrum is shown in Fig. 3 (a). The 10 dB bandwidth is 88.7 nm with the central wavelength of 1549.3 nm. As shown in Fig. 3 (b), the time interval of the pulse train is 8.78 ns, and the corresponding repetition rate is 113.8 MHz. The radio frequency (RF) spectrum is shown in Fig. 3 (c). We can observe that the signal/noise ratio (SNR) is 70 dB approximately, indicating that the laser is in a stable mode-locked state. Fig. 3 (d) shows the pulse autocorrelation trace of the laser. The full width at half maximum (FWHM) of the autocorrelation trace using Lorentzian fitting is 415 fs, with a deconvolved pulse width of 198 fs.

Fig. 4 shows the far field mode patterns of output 2. We can see clearly two lobes in Fig. 4 (a) (LP_{11a}) and (b) (LP_{11b}). When carefully adjusting PC3, a $\pi/2$ phase difference can be achieved between the two orthogonal modes. Then so-called donut-beam with a hole in the center can be observed, as shown in Fig. 4 (c) and Fig. 4 (d). To confirm that the

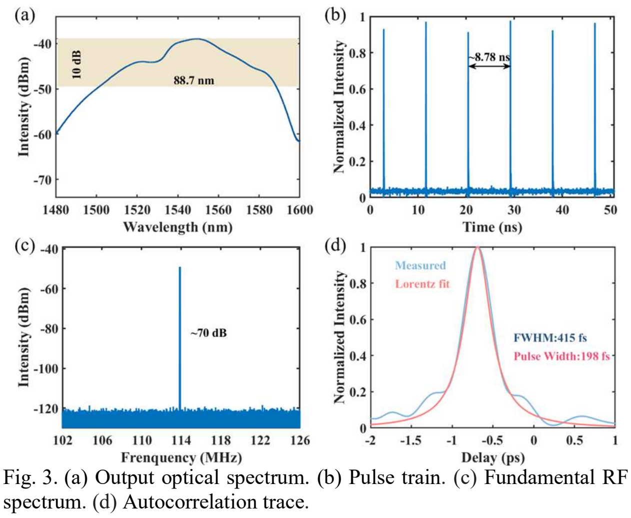

Fig. 3. (a) Output optical spectrum. (b) Pulse train. (c) Fundamental RF spectrum. (d) Autocorrelation trace.

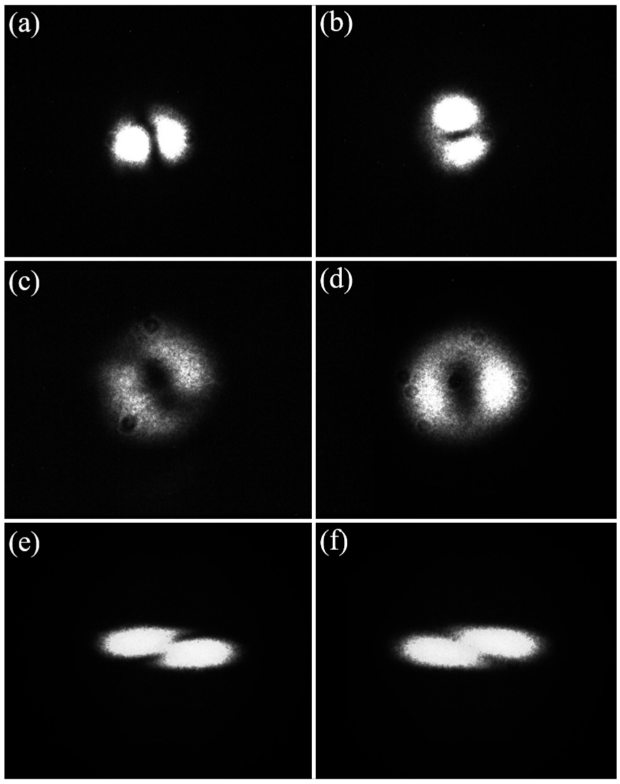

Fig. 4. Intensity profile of (a) the LP_{11a} mode. (b) the LP_{11b} mode. (c) the OAM_{-1} beam. (d) the OAM_{+1} beam. (e) the verification result for OAM_{-1}. (f) the verification result for OAM_{+1}.

generated donut-shaped beams are $OAM_{\pm 1}$, we use the method of coordinate transformation to compress the annular beam into a linear-shaped beam [9]. The output light is compressed and diffracted by the SLM, and then goes straight to a charge-coupled device (CCD). It is very important to have the polarization of the incident beam to be aligned with the slow axis of the liquid crystal, which can be achieved by a polarizer (Pol.) and a half-wave plate (HWP). The verification results with two bright fringes and one dark fringe aligning to different directions are shown in Fig. 4 (e) and Fig. 4 (f), corresponding to OAM_{+1} beam and OAM_{-1} beam, respectively.

IV. Conclusion

In conclusion, we experimentally demonstrate an all-fiber mode-locked laser generating the first-order OAM beam. By managing both the dispersion and the nonlinearity of the cavity, 88.7 nm bandwidth and 113.8 MHz repetition rate are shown. The time duration of the pulse train is measured to be 198 fs and the SNR is about 70 dB. We believe the all-fiber $OAM_{\pm 1}$ laser could be applied in wide applications including optical communication and material processing. Higher order OAM beam fiber laser may be implemented using the same principle.

Acknowledgment

This research was funded by National Natural Science Foundation of China (Grant Nos. 61927817, 61735006 and 62005090).

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