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All-fiber CW cylindrical vector beam fiber laser based on few-mode fiber Bragg grating

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Abstract. An all-fiber CW cylindrical vector beam (CVB) fiber laser based on a few-mode fiber Bragg grating (FW-FBG) with switchable radially and azimuthally polarized beam generation has been demonstrated. The CVB fiber laser operates at a wavelength of 1053.95 nm with a 3 dB line width of 0.1 nm, a signal-to-background ratio of more than 50 dB. The CVB output power can reach 75 mW, and the mode purity is measured to be >95.5%. This compact CVB fiber laser has potential applications in many areas such as optical tweezers, optical trapping and optical sensing systems.

Keywords: fiber laser, cylindrical vector beam, fiber Bragg grating.

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1 Introduction

Cylindrical vector beam (CVB) with unique axial symmetry in both field amplitude and polarization has attracted significant attention recently[1,2], due to their diverse applications, such as optical tweezers[3,4], single molecule imaging[5], optical trapping[6], optical sensing[7], and material processing[8]. A variety of methods for CVB generation have been reported[9-12]. Devices with spatially variant polarization properties inside or outside the laser cavity, such as axial birefringent component, axial dichroic component, and phase plate, can facilitate polarization mode discrimination against the fundamental mode, and thus force the laser to oscillate in CVB mode[2]. However, the use of bulky intracavity devices in this technique seems a roadblock to develop compact laser configuration. Compact fiber based components with a function of transverse mode selection is another simple and easy-to-realize technique for CVB generation. Few-mode fiber Bragg grating (FM-FBG), accordingly with several Bragg wavelengths, can act as a mode discriminator in multimode fiber lasers, resulting in specific higher-order mode output[13]. For instance, Sun reported an all-fiber laser generating cylindrical vector beams using a FM-FBG as

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both the feedback element and the mode filter[14]. However, the output power was limited to several milliwatts.

In this paper, we propose and demonstrate an all-fiber CVB laser using a FM-FBG for mode selection and a dual-cladding fiber as gain medium with relatively high output power. In order to efficient excitation of the desired high-order cylindrically polarized modes from the fundamental mode, a lateral offset splicing between single-mode fiber and few-mode fiber is introduced in the laser cavity. Just by simply adjusting two fiber polarization controllers, the output polarization can furthermore be switched between radially and azimuthally polarized modes. The output power of the CVB fiber laser operating in a single wavelength of 1053.95 nm with a 3 dB line width of 0.1 nm, signal-to-background ratio of 50 dB, and a polarization purity of >95.5%, can reach 75 mW.

2 Experiment and Results

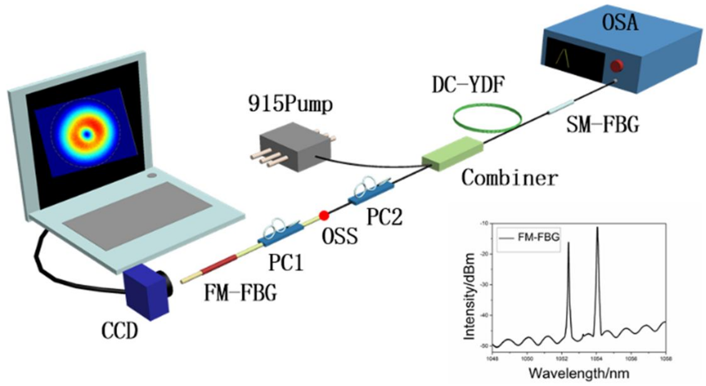

Fig. 1. Schematic of the proposed CVB fiber laser (inset is a typical reflective spectrum of the used few-mode fiber Bragg grating). OSS: offset splicing spot; PC: polarization controller; SM-FBG: single-mode fiber Bragg grating; FM-FBG: few-mode fiber Bragg grating, DC-YDF: dual-cladding ytterbium-doped fiber.

The experimental setup of our proposed all-fiber integrated laser with CVB generation is illustrated in Fig. 1. A length of 4 m dual-cladding ytterbium-doped fiber (DC-YDF) with core diameter of

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10 μm and NA of 0.07, and inner clad diameter of 125 μm and NA of 0.46, is used as the gain medium, which can support higher output power in comparison with single-mode gain fiber. A 915nm laser diode with maximal power of 8 W is utilized to pump DC-YDF through a 915/1060 nm pump/signal combiner. Besides, the fiber laser consists of one few-mode FBG written on SMF-28e fiber, one single-mode FBG written on Hi-1060 single-mode fiber, and two fiber polarization controllers (PC1 and PC2). The Corning SMF-28e fiber has a core diameter of 8.2 μm and NA of 0.14. Its normalized V-number is calculated to be 3.4 at the wavelength of 1054 nm, and thus can function as few-mode fiber in this wavelength band. A lateral offset splicing spot (OSS) with a small lateral misalignment of 4.5 μm between the SMF and the FMF is deliberately introduced for exciting the second-order modes efficiently. The OSS enables mode coupling from the fundamental mode to high order modes[14]. Two fiber polarization controllers (PC1 and PC2) are adjusted carefully as to obtain TM01 and TE01 mode by removing the degeneracy of the second-order modes. The optical spectrum of the laser is measured by an optical spectrum analyzer (OSA, YOKOGAWA, AQ6370C). The output beam profiles are captured by a CCD camera (CinCam IR).

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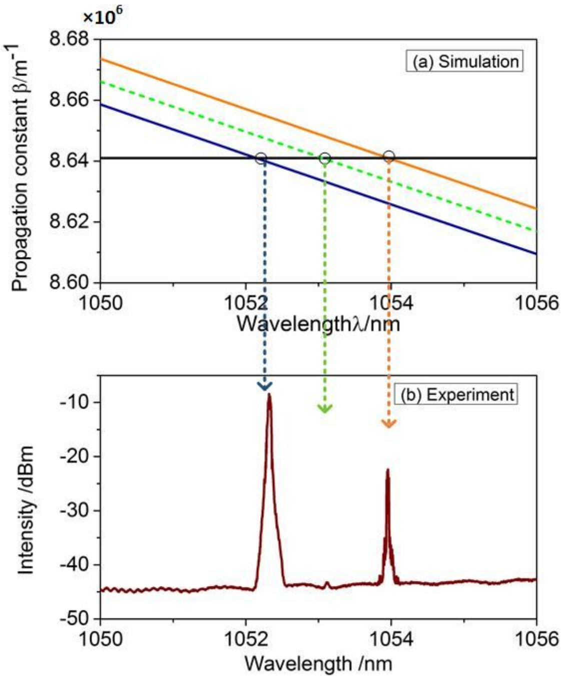

Fig. 2. Simulation and experiment of the FM-FBG. (a) Calculated propagation constants for LP01 mode (N=0, orange line), LP11 mode (N = 1, blue line), the average of N=0 and N=1(green line), and corresponding Bragg wavelengths of the FM-FBG (indicated by the three intersection points), (b) reflection spectra of the FM-FBG.

Firstly, a simple analysis about the modal profile of our used FM-FBG was carried out. The Bragg reflection condition of the FM-FBG with the period Λ is given by $\beta_f - \beta_b = 2\pi / \Lambda$, where β_f and β_b are the propagation constants of forward and backward propagating modes, respectively. Considering only the self-coupling, i.e. the case of reflection to the same mode, there is $\beta_f = -\beta_b = \beta$. Then the phase-matching condition can be simplified as $\beta = \pi / \Lambda$. An approximate expression of the propagation constant β for the Nth principal mode is given by[15]

$$\beta = \frac{2\pi}{\lambda} n_{core} \sqrt{1 - 4\Delta \frac{N+1}{V}}$$

(1)

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Where $V = (2\pi aNA) / \lambda$ presents the normalized frequency, NA presents the numerical aperture, N presents the mode order, and $\Delta = (n_{core} - n_{cladding}) / n_{core}$ presents the normalized core-cladding index difference. The calculated propagation constants for our FMF are shown in Fig. 2(a). The three intersection points in Fig. 2(a) exactly correspond to the measured wavelengths (1052.25 nm, 1053.95 nm) of our used FM-FBG in Fig. 2(b) with the grating period Λ=363.3 nm. The middle peak is negligible because of the little influence on the modal behavior of the laser,

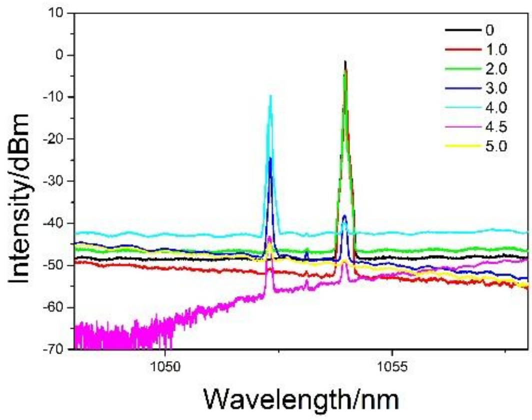

Fig. 3. Reflection spectra of the few-mode FBG under the different values(0~5 μ m) of the OSS, corresponding oscillating wavelengths: 1052.25 nm and 1053.95 nm.

Then, the reflection spectra of the few-mode FBG under the different values of the OSS have been experimentally measured, as shown in Fig. 3. When there is no lateral misalignment, the left peak of FM-FBG cannot be seen, which means the high-order mode was not excited. The LP01 reflectivity of the FM-FBG is about 90%. With the amount of OSS increasing, the second-order mode source is excited, corresponding to the leftmost reflection peak (1052.25 nm) in Fig. 3. When the OSS amount is above 5 μm, two peaks almost disappear due to the excessive loss. Thus, the amount of the lateral misalignment has effects on the reflection of the FM-FBG at two different

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Bragg wavelengths. The oscillation cavity of the proposed CVB fiber laser is formed using the few-mode FBG and the single-mode FBG as cavity mirrors. The measured transmission spectra of the few-mode FBG and the single-mode FBG are in shown Fig. 4. Two dips in the transmission spectrum of the FM-FBG corresponding to two peaks in reflection spectrum are obvious. The right one overlaps with the transmission dip of the SM-FBG. That is to say, the cylindrically polarized modes would be excited by the OSS, and transmit through the few-mode FBG, while most of the fundamental mode would be reflected back to the cavity. With the aid of SM-FBG, the high mode purity CVBs can be obtained through filtering out the fundamental mode. The few-mode FBG serves as a mode selection, and reflects back the fundamental mode.

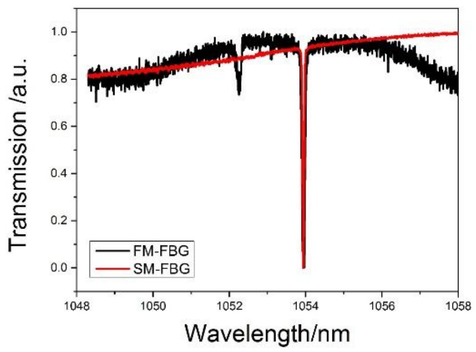

Fig. 4. Transmission spectra of the few-mode FBG (black line) and the single-mode FBG (red line).

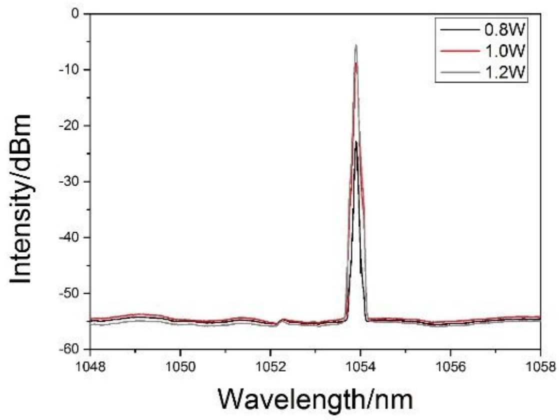

Fig. 5. The laser output spectra under different pump power.

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Fig. 5 shows the laser output spectra under the different pump power measured with the optical spectrum analyzer. The resonance wavelength is 1053.95 nm with a 3 dB line width of less than 0.1 nm. With the pump power increasing, the signal-to-background ratio becomes higher (more than 50 dB under 1.2 W pump power).

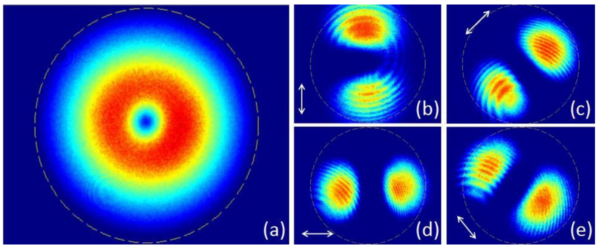

Fig. 6. Intensity distribution of the radially polarized beam (a) without a polarizer and (b)–(e) after passing through a linear polarizer with transmission axis orientation denoted by the arrows.

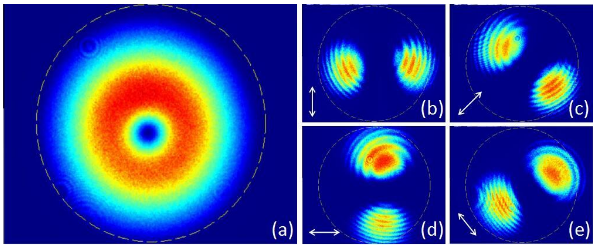

Fig. 7. Intensity distribution of azimuthally polarized beam (a) without a polarizer and (b)–(e) after passing through a linear polarizer with transmission axis orientation denoted by the arrows.

It is known that the CVB laser beam has a doughnut-shaped like intensity pattern. The full beam intensity profile recorded with a CCD camera of the radially polarized beam (TM01) is shown in Fig. 6(a). The radial polarization of the output mode is recorded by the intensity images with a linear polarizer inserted between the CCD camera and the few-mode fiber port. The images in Figs. 6(b)-(e) give the intensity distributions of the radially polarized output mode beams after passing a polarizer. An azimuthally polarized (TE01) output mode (shown in Fig. 7) has also been obtained with careful adjustment of the polarization controllers. It is indicated that there are

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switchable transverse modes through adding polarization controllers in the laser cavity in both sides of the OSS. Furthermore, we estimate the purity of the radially polarized beam to be 96.04% with the method of bending the fiber[14] to attenuate CVB modes. Similarly, the purity of the azimuthally polarized output is calculated to be 95.5%.

The laser output power has been measured with a power meter. The threshold pump power of the fiber laser was found to be 0.8 W with a slope efficiency of 1.08%. The relatively low slope efficiency is due to the large cavity loss induced by the offset splicing (OSS) between single-mode fiber and few-mode fiber, and relatively high reflectivity of both FM-FBG and SM-FBG. The output power increases linearly with the increase in the pump power. And the maximum CVB output power of 75 mW has been attained, which is limited by the available pump power.

We also adopt a vertical cut to replace the SM-FBG. The vertical cut is used as a low reflective surface (about 4%) to compare the performances of two different lasers. The output power of the CVB fiber laser operating in a single wavelength of 1053.95 nm with a 3 dB line width of less than 0.12 nm, signal-to-background ratio of 35 dB, and a polarization purity of 84.9%, can reach the highest CVB power 100 mW. By comparison, CVB modes with polarization purity using a SM-FBG are higher and perform well. What is more, the laser cavity we proposed based on two FBGs can also be used to generate mode-locked or Q-switching laser pulses. Acoustic optical modulator (AOM) is predicted to be an ideal modulator to achieve an all-fiber Q-switching CVBs, and this realistic and interesting structure will expand the prospect of applications in the future.

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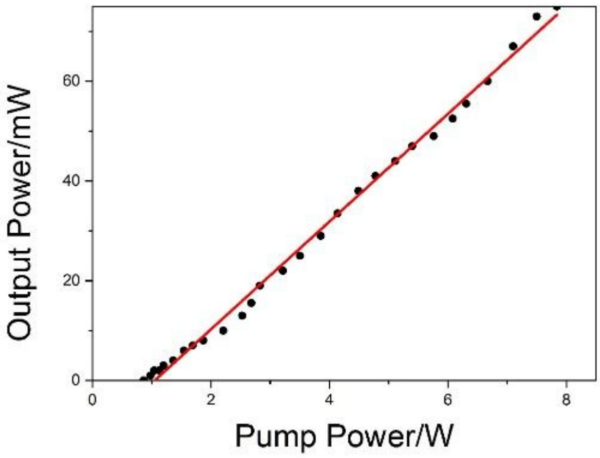

Fig.8. CVB laser output power versus pump power. The solid red line is a linear fit for the output power over the threshold.

3 Conclusion

In summary, we have presented an all-fiber CVB laser with high power and mode purity. A FM-FBG is used as the transverse mode selector in a linear fiber cavity. Both radially and azimuthally polarized beams can be obtained with high mode purity which is measured to be >95.5%. The CVB fiber laser operates near a wavelength of 1053.95 nm with a 3 dB bandwidth of 0.1 nm and a signal-to-background ratio of more than 50 dB. This compact CVB fiber laser may find applications in many areas such as optical tweezers, optical trapping and optical sensing systems

Acknowledgments

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