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Linear-cavity cylindrical vector lasers based on all-fiber mode converters

Xiaoqi Cui, Zhiwen He, Wending Zhang, Mingkun Li, Hua Lu, Dong Mao *, Jianlin Zhao

MOE Key Laboratory of Material Physics and Chemistry under Extraordinary Conditions, and Shaanxi Key Laboratory of Optical Information Technology, School of Science, Northwestern Polytechnical University, Xi'an 710072, China

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ABSTRACT

We propose three mode converters based on coupling of the fundamental mode and the first group higher-order modes in fiber tapers, angled fiber facets, and transversely dislocated fibers, respectively. The insertion loss and coupling efficiency of the fiber tapers are 0.541 dB and 10.6% respectively, which are much better than those of the angled fiber facets (2.4 dB and 2.9%) or the transversely dislocated fibers (1.2 dB and 5.6%). Cylindrical vector beams are delivered from an erbium-doped fiber laser after separately incorporating the mode converters into the cavity. The output spectra of three lasers are located at 1548.7 nm with the same 3-dB bandwidth of 0.03 nm, and spatial distributions are switchable between radially and azimuthally polarized states by adjusting the incident polarization state of the fundamental mode. The linear-cavity all-fiber lasers are capable of generating flexible and cost-effective cylindrical vector beams, which are quite attractive for fiber-based sensing and communications.

1. Introduction

Cylindrical vector beams (CVBs) with axially symmetric polarization distribution [1–9] and vortex beams [10] with helical phases have gained increasing attention due to their applications in fields of optical tweezer [11,12], plasmonic focusing [13], atoms guiding [14], high resolution imaging [15], material processing [16,17], *etc.* The polarization of CVBs is indeterminate at the center, resulting in the polarization singularity and doughnut-like intensity profile. In the past decades, the common methods or devices for generating CVBs included phase plate [18,19], spatial light modulator [20,21], interference technology [22], birefringent element [23,24], plasmonic metasurface [25], nanostructured hologram [26], or the integration of them [27–29]. However, most of these techniques are based on free-space elements in free space, and the generated CVBs are difficult to couple and propagate in fibers, which strongly limits their applications in long-distance fiber-based sensing and communication [30–33,3].

According to the mode coupling theory, a part of the fundamental mode (LP_{01}) will couple into the first group higher-order modes (LP_{11}) when the input optical field deviates from axial symmetry with respect to the two-mode fiber (TMF) [34,35]. It is worth noting that the first group higher-order modes LP_{11} consist of four annular vector modes (TE_{01}, TM_{01}, and HE_{21}) and the vector modes TM_{01} and TE_{01} are radially polarized beams (RPBs) and azimuthally polarized beams (APBs) respectively [1,36]. Several mode-coupling elements have been developed by splicing the transversely dislocated single-mode fiber (SMF) and TMF to excite CVBs [31,37]. By exploiting transversely dislocated fibers as mode converters and two-mode fiber Bragg gratings (TMFBG) as mode selector, continuous-wave [38], Q-switched [39,40], and mode-locked [41] RPBs and APBs have been obtained from various types of cylindrical vector fiber lasers [42,43]. However, a persistent issue is that both the coupling efficiency and the insertion loss of the mode converter increase with the transverse dislocation distance, significantly restricting the emission efficiency and output power of the laser. Moreover, the transverse dislocation distance between two fibers is several micrometers, which is difficult to precisely control in the experiment. There is an urgent need to develop high-efficiency flexible mode converters and all-fiber cylindrical vector lasers (CVLs).

Here, based on coupling of the fundamental mode in SMF and the first group higher-order modes in TMF, three all-fiber mode converters are fabricated by utilizing SMF–TMF tapers, physical contact (PC)–angled physical contact (APC) fiber facets, and transversely dislocated SMF–TMFs, respectively. Among these converters, the fiber facet based converter is flexible and convenient, whereas SMF–TMF tapers exhibit the lowest insertion loss of 0.541 dB and the highest coupling efficiency of 10.6%. Switchable RPBs and APBs are obtained from a linear-cavity erbium-doped fiber laser after the three mode converters are separately inserted into the cavity.

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* Corresponding author.
E-mail address: maodong@nwpu.edu.cn (D. Mao).

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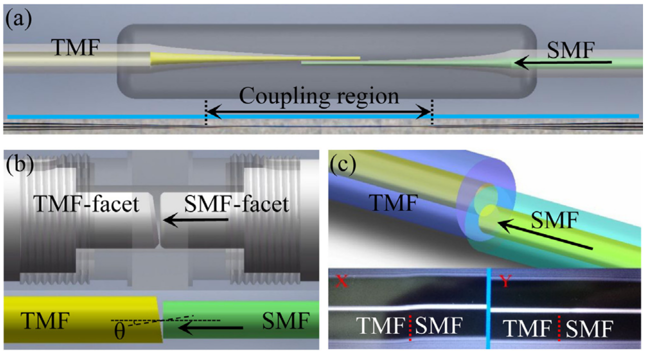

Fig. 1. Structures of the mode converters based on (a) fiber tapers, (b) angled fiber facets, and (c) transversely dislocated fibers.

2. Experimental setup

Three types of mode converters are proposed to couple the fundamental mode in SMF into the first group higher-order modes in TMF. Fig. 1 shows the schematic of the mode converters based on fiber tapers, angled fiber facets, and transversely dislocated fibers, respectively. The TMF (OFS: two mode step-index fiber) has a step index difference of 0.005, a cladding radius of 62.5 μm, and a core radius of 7 μm. The first mode converter is based on SMF (Corning: SMF-28)-TMF tapers, which are fabricated by heating two fibers with a CO_2 laser and then stretching them with a stepping motor, as shown in the upper diagram in Fig. 1(a). The lower picture in Fig. 1(a) is captured by a microscopy, from which the coupling region and waist diameter are measured as 2 mm and 15.3 μm, respectively. The coupling mechanism of the fiber-tapers can be described as follows. The effective mode field increases when the guided mode propagates into the tapered region of the SMF. The separation between the two fiber tapers is very small, and thus the light field couples from one taper to the other due to the existence of a strong evanescent field. Because the input light field deviates from axial symmetry with respect to the TMF, a part of the fundamental mode transforms into the first group higher-order modes with the increase in the fiber taper diameter.

Fig. 1(b) shows the structure of the mode converter based on PC–APC fiber facets. The custom-made two-mode APC facet has a tilt angle of 8°, and the single-mode PC connector is flat on the facet. The two facets are connected by an adaptor, which provides an angle and a distance between the SMF and TMF surfaces. The incident light has a small angle with respect to the axis of TMF, resulting in coupling between the fundamental mode and the first group higher-order modes.

Transversely dislocated SMF–TMFs is also fabricated to compare the coupling behavior with that of fiber tapers and angled fiber facets with those based on fiber tapers and angled fiber facets. As shown in Fig. 1(c), a lateral misalignment between the SMF and the TMF is clearly observed in the X-axis direction. Because the two fibers are shifted in the transverse direction, the first group higher-order modes can be excited from the fundamental mode [31]. The insertion loss of the three devices are measured by a 1550 nm laser and a power meter. The SMF–TMF taper has the lowest insertion loss of 0.541 dB, compared with 2.383 dB for the PC–APC fiber facets and 1.235 dB for the transversely dislocated SMF–TMF. All of these mode converters aim to achieve axial asymmetry between the input optical field and the TMFs to excite the desired CVBs.

Another essential element is the transverse mode selector, which extracts the desired CVB from hybrid modes. In our experiment, a chirped TMFBG, fabricated by applying the phase-mask technique, plays a triple role as transverse-mode selector, output terminal, and reflection element. As shown in Fig. 2(a), the reflection spectrum is measured by a 3-port circulator and a broadband light source. The TMFBG exhibits two reflection peaks at 1548.49 nm (Peak 1) and at 1547.22 nm (Peak 2), as indicated by the black curve in Fig. 2(b). Peak 1 denotes the reflection of the fundamental mode to the fundamental mode, whereas Peak 2 represents that of the fundamental mode to the first group higher-order modes, and Peak 3 indicates the reflection between hybrid higher-order modes. As a result, when the laser spectrum is located at Peak 1 of the chirped TMFBG, the fundamental mode is reflected back, whereas the higher-order modes are exported. The reflection spectrum is further tested by adding three mode converters separately in front of the TMFBG. The normalized reflection spectra in Fig. 2(b) show that Peak 2 becomes much clearer and the third peak appears on the spectrum, suggesting the successful excitation of the first group higher-order modes [41]. Here, Peak 2 achieves the highest intensity by using SMF–TMF tapers, indicating that this mode converter possesses the largest coupling efficiency between the fundamental mode and the first group higher-order modes. In Fig. 2(b), the background of the blue curve is much higher than that of other curves, which could be attributed to the reflection of the ultrathin air wedge in PC–APC fiber facets. In this device, the broadband light source is output from PC fiber facet and transformed into the APC fiber facet after passing through an ultrathin air wedge, which means a portion of light will be firstly reflected to port 3 of the circulator. For other devices, the reflection is much lower, and thus the reflection spectrum has a smaller noise background.

Based on the mode converter and selector, an all-fiber linear-cavity CVL is constructed, as shown in Fig. 3. The fiber laser consists of a 980 nm pump laser, a 980/1550 nm wavelength division multiplexer, a 2-m SMF, a 1.2-m erbium-doped fiber (EDF; Nufen: EDFC-980-HP), a single-mode fiber Bragg gratings (SMFBG), a mode converter, two polarization controllers (PCs), and a TMFBG. PC_1 controls the polarization state of the fundamental mode in SMF to selectively excite the TE_{01} or TM_{01} mode, and PC_2 slightly adjusts the polarization state of the output beam. The TMFBG acts as a transverse mode selector, which reflects the fundamental mode and passes the desired vector mode. The generated CVL is exported by a custom-made two-mode fiber facet. After passing through a collimator, the spatial distribution of the CVBs is captured by an infrared CCD camera. The SMFBG works as the other output terminal for comparison with that of the TMFBG.

3. Results and discussions

The spatial distribution of the output beam always has a Gaussian profile before the insertion of the mode converter. CVLs can be obtained after SMF–TMF tapers, PC–APC fiber facets, or transversely dislocated fibers are separately inserted into the cavity. By adjusting the input polarization with PC_1, the CVL can be simply switched between radially and azimuthally polarized states. This phenomenon could be explained by noting that the tangential electric field is continuous across the coupling regime between the SMF and TMF. Fig. 4 shows the spatial distributions of the RPB and APB at a pump power of 150 mW by using the aforementioned mode converters. Due to the existence of polarization singularity, both types of CVBs have annular intensity profiles with dark spots at their centers. The polarization state of the CVB is investigated by inserting a linear polarizer in front of the CCD. By tuning the linear polarizer from 0° to 180° with a step of 45°, the dark band is perpendicular to the polarization direction, confirming the operation of the RPB (TM_{01} mode), as described in Fig. 4(a), (c) and (e). In contrast to the RPB, the dark band of the APB (TE_{01} mode) is parallel to the polarization direction, as described in Fig. 4(b), (d) and (f) respectively. The experiment results demonstrate that these mode converters can effectively excite the RPB and APB in the all-fiber EDF laser.

Fig. 5(a)–(c) show the evolution of the output power versus the pump power for the three mode converters. The blue (red) sphere represents the output power of the RPB (APB) measured from TMFBG terminal, while the blue (red) triangle represents the output power measured from the SMFBG with 95% attenuation. It is obvious that the output