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Low-threshold wavelength-switchable fiber laser based on few-mode fiber Bragg grating

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ABSTRACT

We propose a backward-pump transverse mode fiber laser to generate optical beams based on few-mode fiber Bragg grating. The grating as a transverse mode filter possesses several reflection peaks by adjusting the core-offset. The transverse mode fiber laser operates at extremely low thresholds which are about 20, 16.5 and 16 mW corresponding to different operation wavelengths of 1560.98, 1562.32 and 1563.76 nm, respectively. The optical signal to noise ratios are about 72, 75.5 and 75.8 dB, when the pump power is fixed at 100 mW, respectively. The effectively exciting modes corresponding to each reflection peak interfere with each other. Different optical beams can be achieved by changing the operating wavelength or changing the state of PC. The device maybe find its applications such as sensing, transporting or manipulating microscopic particles.

1. Introduction

The optical micro-manipulating technology is a hot topic of great current interest in recent years. In which, Bessel-like beams become essential elements in various applications, such as imaging, secure communication, and remote sensing [1–3]. Besides, optical beams generating from the transverse mode fiber laser are another effective technique to apply in sensing, manipulating microscopic particles [4,5].

The generation of these beams is drawn considerable attentions based on transverse mode fiber laser. It has attracted greatly interests for the high efficiency, compactness and flexibility. In previous lasers, the volume optical elements were applied in the laser system. It made the operating system complex and could introduce some unavoidable variables [6]. Besides, the filter was not used by the former in the fiber laser cavity [7]. Despite the system was simplified, the out spectrum was instability from one peak to multi peaks by changing the polarization state via polarization controller. The collimators utilized to excite high order modes should be carefully adjusted. Besides, the operating wavelength was an important restriction by the doping concentration [8]. Another was based on the fiber filter. The simply technology for transverse mode selection was reported in a multimode fiber laser [9]. The filter was achieved by writing a fiber Bragg grating in the D-shaped Tm, Ge co-doped double-clad fiber (TDF). However, the operating system was so complex by applying a collimating lens, a volume Bragg grating (VBG), a plane mirror and an uncoated fused wedge [7]. Besides, an all fiber transverse mode laser was reported in recent years [10]. The system is more compact for the absence of volume elements. In spite of good results, the pump power for forward pump and the radiation from Yb-doped or Tm-doped fiber should be considered. Besides, low-threshold should be an effective goal whenever the fiber laser was operated at single-wavelength or multi-wavelength [11]. In additions, a single-mode fiber laser based on core-cladding mode conversion was demonstrated with Er-doped active fiber. It converted the light into a counter-propagating cladding mode that traveled inside the cladding by one of the grating and was reflected at the cleaved fiber facet. The lasing threshold was about 45 mW of pump power [12].

In the previous papers, fiber Bragg grating (FBG) plays an important role in the system. The coupling occurs between forward- and backward-propagating modes when satisfying phase-matching condition. The transverse mode fiber laser was proposed based on the few-mode fiber considering the operating wavelength less than the cutoff wavelength. Different order spatial output modes (fundamental mode, second-order mode, and hybrid modes) were obtained by controlling the oscillating wavelength through the usage of a tunable filter [11]. Optical beams for the unique properties based on the transverse mode fiber laser operating in C band are attracted attentions gradually in the operating wavelength ranges as far as we know [13].

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In this paper, we propose a backward-pump transverse mode fiber laser based on few-mode fiber Bragg grating reflector. The designed refractive index profile of the fiber leads to the number of modes down to several linear polarization modes operation in C-band. The grating as a transverse mode filter possesses several reflection peaks when adjusting the core-offset. The fiber laser operates at extremely low thresholds which are about 20, 16.5 and 16 mW, corresponding to different operation wavelengths, respectively. Meanwhile, the remarkable optical signal to noise ratios (OSNRs) more than 72 dB are achieved in the experiment. The device maybe find its applications such as trapping, transporting or manipulating microscopic particles.

2. Experimental theory and setup

The few-mode fiber (FMF) is manufactured by the optical fiber perform. It is fabricated by the modified chemical vapor deposition (MCVD) and solution-doping technique in the experiment. The photomicrograph and measured refractive index (RI) profile of the laboratory-made FMF are illustrated in Fig. 1. The outer diameter of the FMF is about 140 μm. The maximal refractive index difference (RID) of the fiber is about 1.44%.

The modes supported by the fiber are important factors for the characteristics of the device. Fig. 2 shows the effective refractive indices (ERIs) of the mode groups and the amplitude profiles of the linear polarization modes. The modes supported by the fiber can be divided into five mode groups which are degenerate modes. At the same time, the amplitude profile of the linear polarization modes correspond to the five mode groups respectively, as shown in Fig. 2(b). The modes with the linear polarization mode approximation are LP_{01}, LP_{11}, LP_{21}, LP_{02}, LP_{31}, respectively. In which, the last mode have a larger loss than the former modes.

With the UV-induced refractive index changing due to a grating written into the fiber core, the coupling can occur between the forward and backward propagating modes. The reflection spectrum of SMF-FBG can shift within a certain wavelength range when applied strain along the FBG, shown in Fig. 3(a). The reflection spectra of FMF-FBG are shown in Fig. 3(b), with the automatic splicing program and adjusting core-offset. The grating period of the FMF-FBG is 537.5 nm. In the experiment, we adjusted the core-offset and monitored the reflection spectrum at the same time. The energy is injected into the FMF-FBG through the splicing point. It is coupled into the backward propagating modes when satisfying the phase-matching condition [14]: $\lambda = (n_{eff,i} + n_{eff,j})\Lambda$, where λ, ($n_{eff,i}$, $n_{eff,j}$) and Λ represent the resonance wavelength of the grating, the ERIs of the forward or backward propagating modes, and the grating period, respectively. The main reflection peaks may be achieved from the coupling of modes with the same mode groups in forward or backward propagating directions. Meanwhile, the cross coupling could happen when the modes with different mode groups satisfy the phase-matching condition. For the splicing point in the fiber with the automatic fiber fusion splicer (Ericsson: FSU975), only the power exciting coefficients of the LP_{0n} modes could be effectively coupled for the symmetric fiber structure. The optical beam satisfying the phase-matching condition is reflected. Only a strong reflection peak appears in the reflection spectrum of the grating. The low reflection peak comes from the weak coupling to a high order mode for the imperfect coaxial splicing. In contrast, when adjusting the core-offset, the power exciting coefficients of the other modes also could be effectively improved. The multiple reflection peaks can be achieved in the reflection spectrum, shown in Fig. 3(b). The extinction ratio corresponding to the fundamental mode changes lower than that of auto-splicing.

The experimental schematic of the proposed switchable transverse mode fiber laser for the generation of optical beams is presented in Fig. 4. Pump light is provided by a semiconductor laser operating at ~980 nm and is coupled into the fiber laser cavity through a 980/1550 nm wavelength division multiplexer (WDM). The gain medium is Er-doped fiber (EDF) with the length of about 10 meters. The reflecting mirror is formed by a standard $SMF\text{-}FBG_1$ possessing a 3-dB bandwidth of 0.22 nm providing a reflectivity higher than 99%. The reflection spectrum of the grating (FBG_1) can be turned by applying strain along the fiber, as shown in Fig. 3(a). A 90/10 optical coupler is inserted into the cavity with the power of 10% coupled out. It is coupled into an optical spectrum analyzer (OSA: Ando AQ6317C) in order to monitor the output

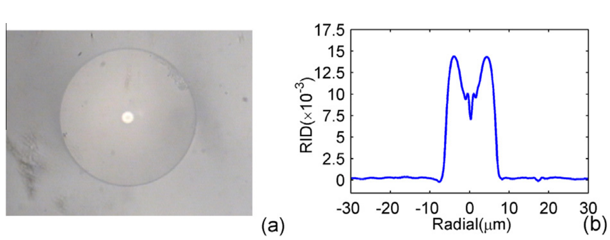

Fig. 1. (a) The photomicrograph and (b) measured RI profile of the laboratory-made FMF.

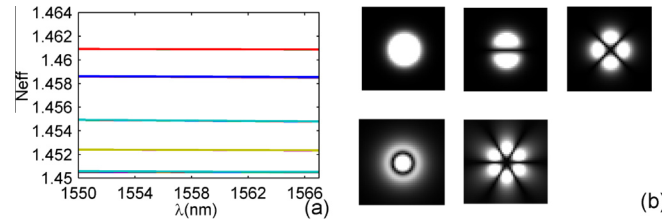

Fig. 2. (a) The effective refractive indices of the mode groups; (b) The amplitude profiles corresponding to each mode group with linear polarization mode approximation.

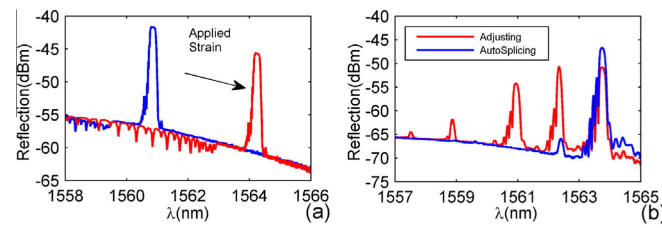

Fig. 3. (a) The reflection spectrum of the FBG_1 written in the standard SMF (Corning SMF-28 TM) as the totally reflection mirror; (b) The reflection spectra of the FBG_2 written in the FMF by adjusting the core-offset splicing and automatic splicing program as the device of the output beams.

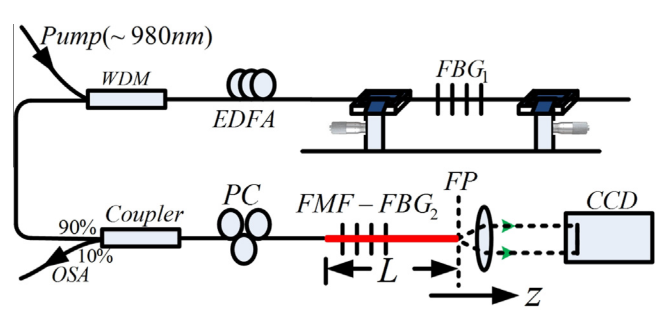

Fig. 4. Schematic of the experimental setup for switchable transverse mode fiber laser. FP: focal plane.