Optics and Laser Technology 108 (2018) 273–278

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

# Five-wavelength-switchable all-fiber erbium-doped laser based on few-mode tilted fiber Bragg grating

Kang Yang [a,b], Yan-Ge Liu [a,*], Zhi Wang [a], Guo-Yu Li [b], Ya Han [a], Hong-Wei Zhang [a], Jie Yu [a]

[a] Key Laboratory of Optoelectronic Sensor and Sensing Network Technology, Institute of Modern Optics, Nankai University, Tianjin, China
[b] The Institute of Information Technology, Handan University, Handan, Hebei, China

ARTICLE INFO

*Article history:*
Received 7 March 2018
Received in revised form 14 June 2018
Accepted 6 July 2018
Available online 18 July 2018

*Keywords:*
Mode coupling
Tilted fiber Bragg grating (TFBG)
Wavelength-switchable lasing

ABSTRACT

We demonstrate a five-wavelength-switchable erbium-doped few-mode fiber laser based on a few-mode tilted fiber Bragg grating (TFBG). The TFBG was written in a few-mode graded-index fiber and has multiple resonance characteristics. Theoretical investigations reveal that these resonances originate from mode couplings among the $LP_{01}$, $LP_{11}$, and $LP_{21}$ modes. Switchable five-wavelength lasing with different transverse modes is obtained by careful adjustment of the polarization controller and the lateral offset between the single-mode fiber (SMF) and the few-mode fiber (FMF) located before the TFBG in the laser cavity. This wavelength-switchable laser offers the advantages of a simple structure, stable lasing and ease of operation. The proposed structure can be potentially used in applications including communications, sensing and manipulation of microscopic particles.



## 1. Introduction

All-fiber methods for control of the lasing wavelength and modes in fiber lasers have a variety of potential applications including optical communication systems, fiber sensing, and manipulation of microscopic particles [1–4]. Wavelength-switchable lasers can be obtained using four-wave mixing in a highly nonlinear photonic crystal fiber (PCF) [5], an in-line fiber Mach-Zehnder interferometer in PCF [6] and few-mode fiber Bragg gratings (FM-FBGs) for tunable and switchable multiwavelength laser operation [7,8].

FM-FBG-based mode selection and wavelength-switchable lasers have been demonstrated both theoretically and experimentally. Zhou et al. [9], Zhang et al. [10] and Sun et al. [11] demonstrated all-fiber lasers emitted cylindrical vector beams. The intra-cavity FM-FBGs inscribed in few-mode fibers are employed to provide both mode selection and wavelength switching functions. Jin et al. [7] proposed a ring fiber laser that contained a core-offset spliced point between the single-mode fiber (SMF) and the dual-mode ring-core fiber. Bending of the FM-FBG written in a dual-mode fiber generated fundamental mode and second-order mode lasing at two different wavelengths, either individually or simultaneously. A low-threshold-switchable transverse-mode fiber laser using a standard single-mode FBG (SM-FBG) and an FM-FBG was presented by Qi et al. [8]. The FM-FBG also can be regarded as a transverse-mode filter that can process multiple reflection peaks by adjusting the core offset between the SMF and the few-mode fiber (FMF).

When compared with the FM-FBG, the few-mode tilted fiber Bragg grating (FM-TFBG) has two different properties. The first is that the FM-TFBG enhances coupling of the light from the fundamental core mode to the higher-order modes, which are much more sensitive to polarization. Because of this property, the FM-TFBG has been widely used in optical sensing applications [12,13]. The second property is that the resonant dips of the device can be tuned by using TFBGs with different tilt angles. The tunable resonant wavelengths in FM-TFBGs allow wavelength-division multiplexing (WDM) to be obtained in optical systems [14,15].

In this paper, based on use of the superior properties of the FM-TFBG, a novel FM-TFBG-based erbium-doped fiber laser that realizes four different transverse modes with five corresponding oscillating wavelengths is demonstrated and investigated for the first time, to the best of our knowledge. The output modes of the laser include $LP_{01}LP_{11}$, $LP_{21}$ and a hybrid mode composed of $LP_{01}$ and $LP_{11}$, where $LP_{mn}$ refers to a linearly polarized mode, with m = 0, 1, 2, and n = 1, 2. Switching among the different output modes is achieved by adjusting the laser cavity polarization state and the lateral offset between the SMF and the FMF. Furthermore, the $LP_{01}$ and $LP_{11}$ hybrid mode at the second wavelength (1553.37 nm) can be separated using a polarizer placed before a charge-coupled device (CCD) camera.

* Corresponding author.
*E-mail address:* ygliu@nankai.edu.cn (Y.-G. Liu).

https://doi.org/10.1016/j.optlastec.2018.07.005
0030-3992/

## 2. Experimental setup and operating principle

A schematic diagram of the proposed switchable linear-cavity erbium-doped fiber laser is shown in Fig. 1(a). A 980 nm laser diode with a pump protector acts as the pump light source. A highly $Er^{3+}$-doped SMF with an absorption coefficient of 80 dB/m at 980 nm and length of 50 cm is used as the gain medium. A fiber loop of 3 dB coupler is used as a high-level reflector. An FM-TFBG with a 1.5° tilt angle that was manufactured using the phase-mask technique with a 193 nm ultraviolet (UV) excimer laser serves as the output reflector. The TFBG was written in a graded-index few-mode fiber (GI-FMF) that supports $LP_{01}$, $LP_{11}$, $LP_{21}$, and $LP_{02}$ modes in the fiber core (OFS, Four-mode graded-index fiber). The core radius is ∼12 µm and the cladding radius is ∼62.5 µm. The output mode profile and spectrum of the TFBG were recorded using a CCD camera and an optical spectrum analyzer (OSA) simultaneously via a non-polarizing beam splitter (NPBS). The lateral offset splicing (OSS) was formed by splicing the SMF and the FMF with a small lateral misalignment to produce efficient coupling from the fundamental mode to the desired higher-order core modes.

In the proposed laser, OSS is used to achieve efficient mode coupling from the fundamental mode to the higher-order modes, as shown in Fig. 1(a). Before OSS, the fiber only supports the propagation of the fundamental mode. After OSS, the fundamental mode is partially transformed into higher-order modes, which can be supported for propagation in the FMF. Therefore, the fundamental mode oscillates in the resonant cavity and is transformed into the higher-order modes after it passes through the OSS. In addition, the TFBG written in the FMF supports coupling between the fundamental mode and the higher-order modes. Using the polarization controller (PC), the TFBG can select both the lasing wavelength and the output spatial mode.

Because of the lateral offset between the SMF and the FMF, several modes, including the $LP_{01}$, $LP_{11}$, and $LP_{21}$ modes, can oscillate in the proposed cavity. In theory, the $LP_{02}$ mode will participate in the lasing process, as shown in Fig. 1(b). However, the higher-order modes are excited via the lateral offset between the SMF and the FMF, which breaks the cylindrically symmetrical structure of the incident light. Unlike the $LP_{21}$ mode, the $LP_{02}$ mode is strictly cylindrically symmetrical. Therefore, the $LP_{02}$ mode can be excited, but is mostly repressed by the lateral offset. The rate equation

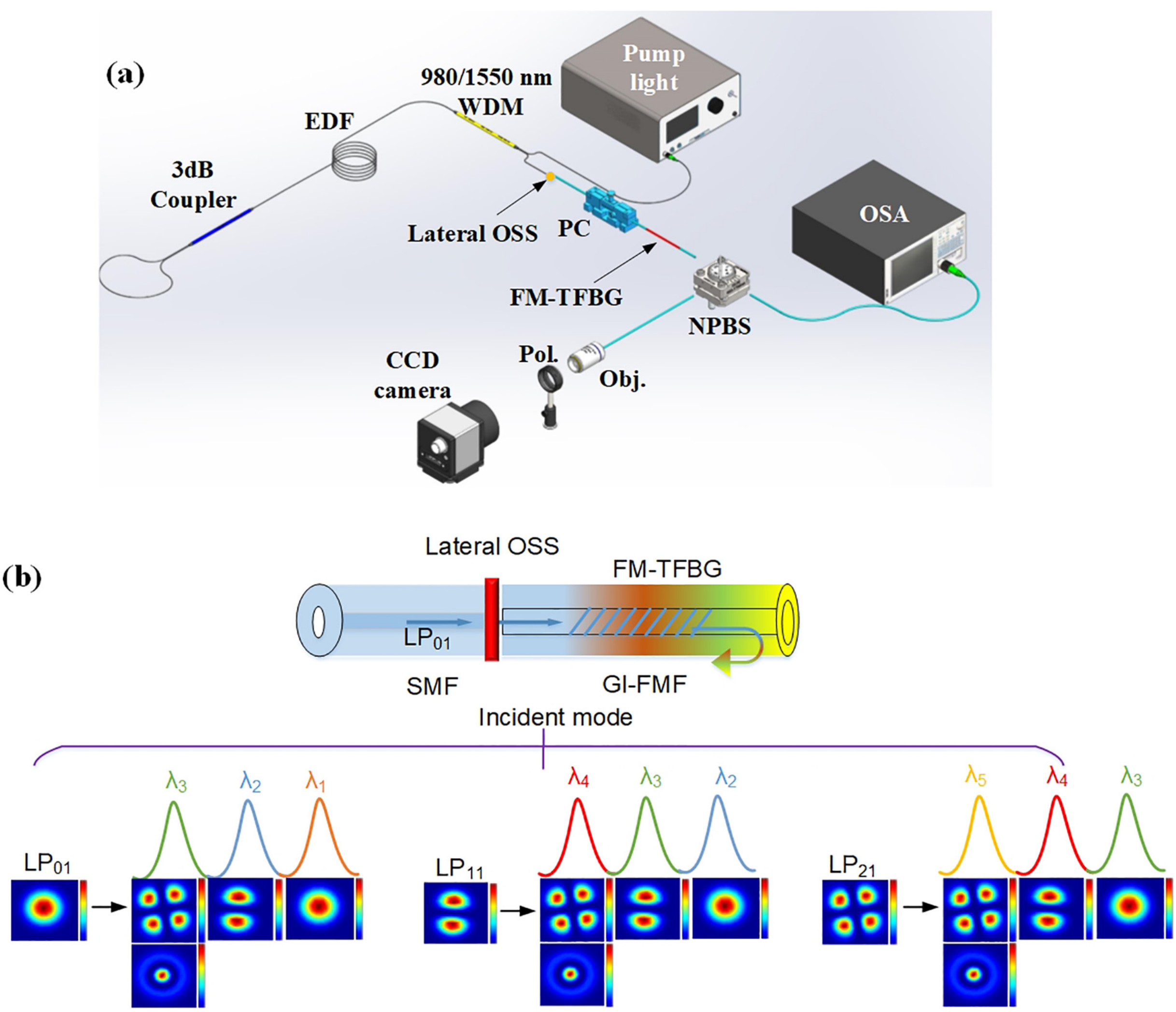


**Fig. 1.** Schematic of wavelength-switching process in fiber laser. (a) Experimental setup for the proposed laser design. EDF: $Er^{3+}$-doped fiber; Pol.: polarizer; Obj.: Object lens; PC: polarization controller; 980/1550 nm WDM: 980/1550 nm wavelength division multiplexer; NPBS: non-polarizing beam splitter. (b) Concept of wavelength switching based on the few-mode TFBG. The legend bars beside the mode patterns indicate the intensity changed from high to low. Red color presents high intensity and blue color presents low intensity.