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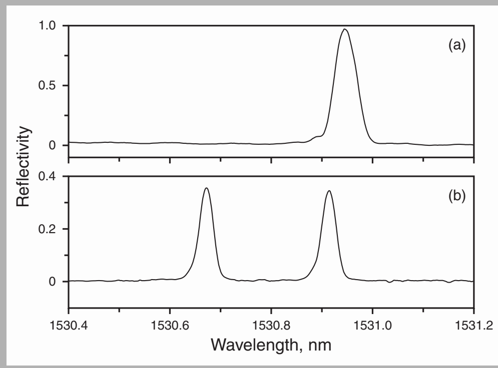
Abstract: We report an experimental study of an erbium-doped all-fiber laser with electrically switchable output polarization. Fiber Bragg grating written in a polarization maintaining optical fiber and attached to a piezo-ceramic actuator is used to commute the polarization state of the laser emission. The laser oscillates at one of two orthogonal polarizations depending on voltage applied to the actuator.



Reflection spectra of FBG written in (a) the Lo-Bi fiber and (b) in the polarization maintaining fiber

Polarization switchable Erbium-doped all-fiber laser

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1. Introduction

Erbium-doped (ED) fiber lasers (FLs) are attractive optical sources covering a broad area of the generation wavelengths, including the S, C, and L communication bands [1,2]. It has been demonstrated that ED FLs possess multiwavelength oscillation [3,4], stable Q-switch and mode-lock operation [5,6], single-frequency generation [7], and a wide range tuning of operating wavelengths [8], among other features, and they are promising light sources for applications in communications, including microwave generation [9,10], sensors [11,12], spectroscopy [13,14], etc.

ED FL usually consists of a pair of uniform fiber Bragg gratings (FBGs) as output laser couplers. If FBGs are written in a Lo-Bi fiber, the laser oscillates with random polarization. To have a single-polarization regime, one needs to produce a polarization-dependent intra-cavity loss, causing different laser thresholds for two orthogonal polarizations. For instance, the use of a FBG written in a polarization maintaining fiber (PMF) as FL output coupler, or the insertion of a long-period grating (LPG) written in PMF in the FL cavity, allows reaching single-polarization lasing [15–17]. In both cases, one needs to use an additional polarization control of the FL cavity in order to compensate for any birefringence induced inside the cavity.

In this work, we present an experimental study of a single-polarization ED FL with electrically switchable output polarization. The polarization switching is based on the use of a tunable FBG written in PMF as the output laser coupler. This FBG is fixed to a piezo-ceramic-based actuator, allowing the superposition of one of two grating reflection peaks (each peak reflects only one of the two orthogonal linear polarizations) with the reflection peak of a uniform FBG written in a Lo-Bi fiber.

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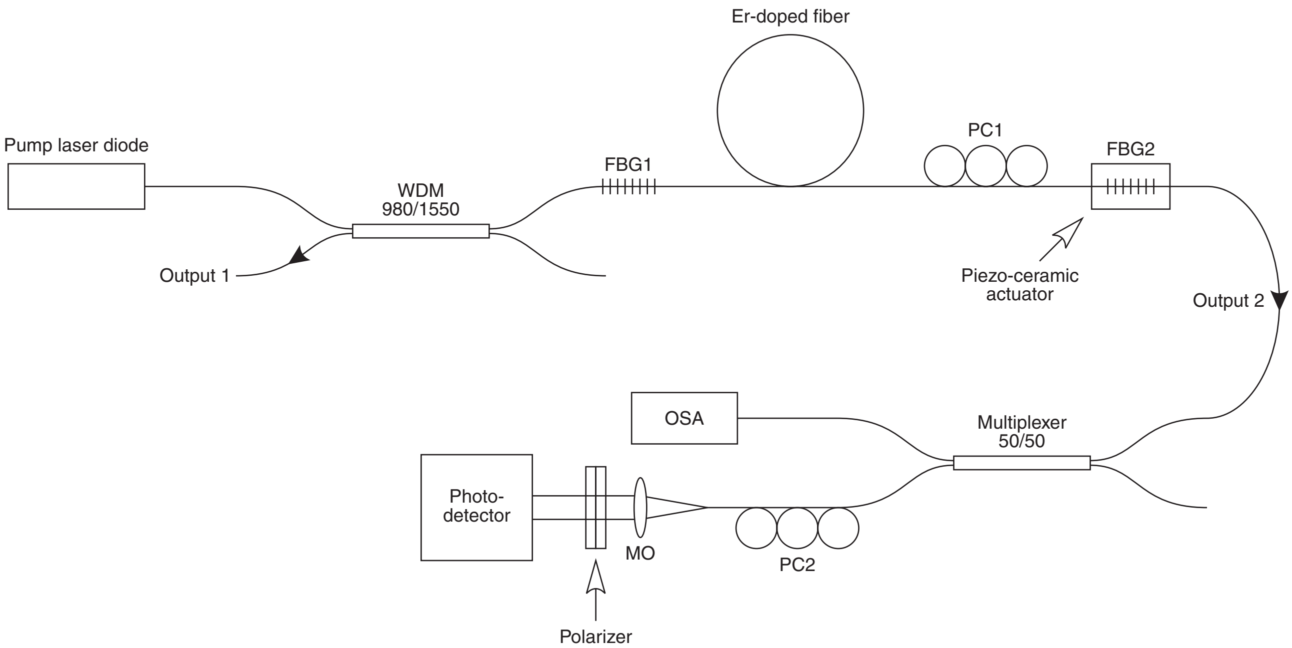

Figure 1 Experimental setup. MO – micro-objective

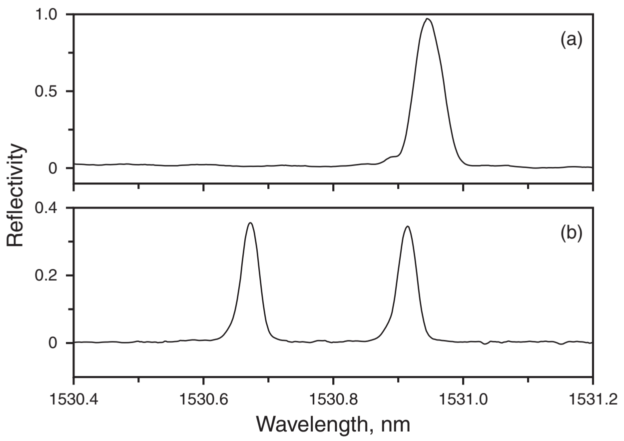

Figure 2 Reflection spectra of FBG written in (a) the Lo-Bi fiber and (b) in the polarization maintaining fiber

The output laser polarization depends on voltage applied to the piezo-ceramicbased actuator. The proposed FL with controllable polarization is suitable for sensing and other applications where one needs to make relative or differential measurements at two orthogonal polarizations [18].

2. Experimental setup

The setup of the polarization-switchable all-fiber ED laser is shown in Fig. 1. The laser was assembled using standard single-mode fiber elements. The FBGs were written in photosensitive fibers by UV-light (wavelength, 244 nm) exposure through the same phase mask. One of the gratings was written in a conventional photosensitive fiber (*Fibercore PS980*), and another one in a PMF (*Fibercore DHB1500-0980*) after photosensibilization in hydrogen atmosphere at room temperature during two weeks. Thus, the first FBG (FBG1) does not have birefringence properties, whereas the second one (FBG2) does exhibit strong polarization effects (see Fig. 2). The two reflections peaks of the birefringent FBG2 are separated by approximately 250 pm, which determines the value of the modal refractive index birefringence, $\Delta n_{mod} \approx 2.3\times10^{-4}$. The spectra presented in Fig 2 were recorded by an optical spectrum analyzer (OSA) with 18 pm-resolution (*Photonetics Walics 3651HP-12*) and a broadband unpolarized light source. The spectra widths measured at 3-dB level were approximately 35 pm for both FBGs. The length of each FBG was ~ 4 cm, and the efficiencies of the gratings were measured to be 97% (non-birefringent FBG1) and $\sim 70\%$ (birefringent FBG2). The maximum of the reflectivity spectrum of the non-birefringent FBG1 was centered at 1531.95 nm.

A low-doped erbium fiber (*Thorlabs M5-970-125*, ~ 300 ppm of Er^{3+} concentration), with a length of 2.85 m, was spliced to the non-birefringent FBG1 and the birefringent FGB2 in order to define a special polarization dependent Fabry-Perot cavity. A polarization controller (PC1) was used for compensation for birefringence induced inside the FL cavity. The total FL cavity length was about 6 m. The laser was pumped with a standard fibered semiconductor laser (978 nm, model: *JDSU 26-7702-180*) through a fused wavelength division multiplexer (WDM).

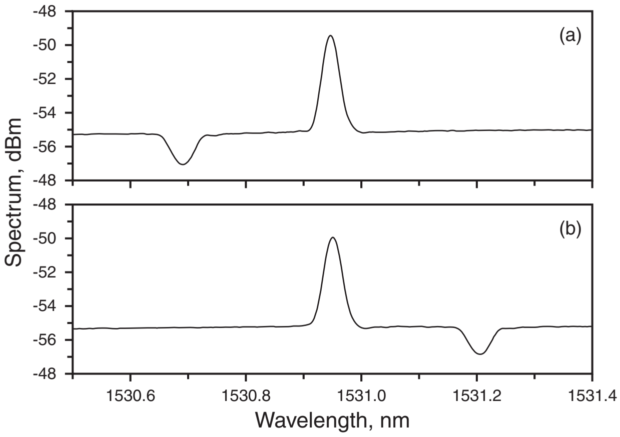

Figure 3 Output spectra of the fiber laser pumped just below the threshold: Reflection peak of FBG written in the Lo-Bi fiber is overlapped with (a) the right and (b) the left reflection peak of FBG written in the polarization maintaining fiber

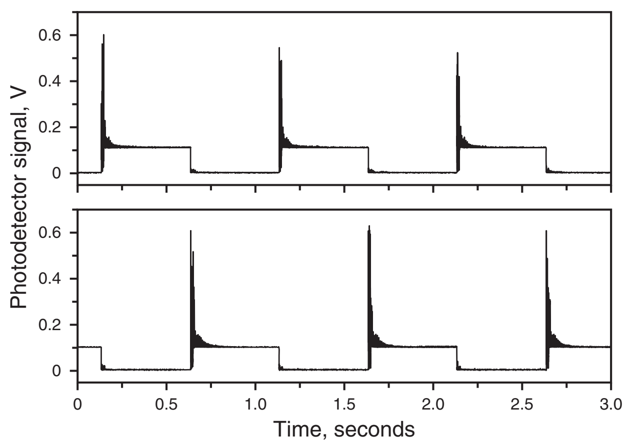

Figure 4 Fiber laser output signals measured at two orthogonal positions of the polarizer (upper and lower curves) placed at the photodetector input. The modulation frequency of the piezo-ceramic actuator is 1 Hz, the pump power is 150 mW

The birefringent FBG2 was glued to a piezo-ceramic actuator. The actuator allowed shifting the reflection peaks of FBG2 towards longer wavelengths, as a function of the applied voltage (the shift 45 pm per volt). The FL threshold was about 20 mW, and the output power, measured at the FBG2 output, was ~ 12 mW at 150 mW of pump power. The FL output power can be increased by optimization of the output coupler reflectivity and the active fiber length, and by reduction of losses of the splices between the fiber elements.

A standard fiber multiplexer (50:50) was used to divide the laser output signal in two parts, one for the OSA and another one for polarization analysis. In order to check the laser polarization properties, a second polarization controller PC2 was used to adjust the laser output polarization; for example, to demonstrate single polarization emission by matching the transmission axis of a bulk polarizer (polarization analyzer).

3. Experimental results and discussion

First, we found the optimal conditions for the electric signal driving the piezo-ceramicbased actuator. The reflection peak of FBG1 is red-shifted by 40 pm with respect to the longer wavelength peak of non-tensed FBG2, and by 290 pm with respect to the shorter wavelength peak (see Fig. 2). Thus, the driving voltage applied to the actuator should be of the value that permits to overlap the peak of FBG1, either with the first or the second peak of FBG2, depending on the polarization state to be selected.

To find the optimal driving voltage, we studied the laser spectrum measured from the second output (Output 2, see Fig. 1) when the pump power was chosen just below the threshold value (see Fig. 3). The best overlapping of FBGs' peaks was observed when the driving voltage was equal to $V_1 = 0.89$ V (Fig. 3a) or $V_2 = 6.44$ V (Fig. 3b). Note that the positive peak observed in this figure corresponds to the amplified spontaneous emission (ASE) spectrum reflected by FBG1, while the negative one corresponds to ASE spectrum partially rejected by FBG2. For both values of the optimal driving voltage (V_1 and V_2), the lasing is observed at the same wavelength (~ 1531.95 nm), but with the polarization state depending on the voltage applied to the actuator.

The second experiment was dedicated to study the temporal response of our laser system when the voltage driving the piezo-ceramic actuator switches from V_1 to V_2. Fig. 4 shows the laser output signal measured by the photodetector at two orthogonal states of the polarization analyzer. The driving voltage was modulated by a rectangular signal with 1 Hz modulation frequency, switching the voltage from to $V_1 = 0.89$ V to $V_2 = 6.44$ V and vice versa.

As it is seen from Fig. 4, the polarization of the laser emission switches between two orthogonal states with the modulation frequency of the actuator. The polarization ratio of the laser signal is limited by amplified spontaneous emission, and was measured to be better than 50:1. It is also seen that every change in the polarization state is accompanied by dumping oscillations of the laser output power, which arise, in turn, from the acoustical dumping oscillations of the piezo-ceramic actuator, which has a resonance frequency of about 120 Hz. The laser dumping oscillations are decreased by 10 dB in approximately 35 ms after switching from one polarization to another. The relaxation time of these oscillations and their amplitude can be decreased through the appropriate choice of the actuator construction.

4. Conclusions

We report an experimental study of a single-polarization Erbium-doped all-fiber laser with the output polarization controlled electrically by a piezo-ceramic actuator. The laser has a Fabry-Perot cavity defined by two fiber Bragg gratings; the first grating is written in a Lo-Bi fiber and is fixed, while the second one is written in a polarization maintaining fiber and glued to the actuator to make it tunable. The polarization state of the laser output depends on the voltage applied to the actuator. The switching time of the polarization state is ~ 35 ms. The proposed laser can be used in applications requiring relative or differential measurements at two orthogonal polarizations.

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