Single- and Dual-Wavelength Switchable Erbium-Doped Fiber Ring Laser based on Intra-Cavity Polarization Selective Tilted Fiber Gratings

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We have proposed and demonstrated a single- and dual-wavelength switchable Erbium doped fiber laser (EDFL) by utilizing intra-cavity polarization selective filters based on tilted fiber gratings (TFGs). In the cavity, one 45°-TFG is functioning as an in-fiber polarizer and the other 77°-TFG is used as a fiber polarization dependent loss (PDL) filter. The combined polarization effect from these two TFGs enables the laser to switch between the single- and dual-wavelength operation with single polarization state at room temperature. The laser output at each wavelength shows an optical signal to noise ratio (OSNR) of > 60dB and a side mode suppression ratio (SMSR) >50dB and a polarization extinction ratio of ~35dB. The proposed EDFL can give stable output under laboratory condition.

OCIS codes: 060.2410, 060.3510, 060.3735, 140.3500, 140.3510.

1. Introduction

Optical fiber lasers with switchable multi-wavelength output are useful in many applications, such as wavelength division multiplexed (WDM) optical fiber communication systems, fiber sensors, optical instrument and system diagnostics and so on. Fiber Bragg gratings (FBGs) are ideal wavelength selective components for fiber lasers due to their advantages of intrinsic fiber compatibility, ease of use, and low cost etc. Erbium-doped fiber (EDF) has been developed and widely used for commercial fiber lasers and amplifiers owing to its high optical gain and low noise figure in 1550nm region. Because of its relatively broad homogeneous excitation, it is difficult to obtain stable and relatively close wavelength spacing oscillations in EDF lasers (EDFLs) at room temperature. Various techniques have been developed to suppress the mode competition induced by the homogeneous broadening of EDF, such as cooling down EDF in liquid nitrogen [1], incorporating a frequency shifter in the cavity [2], employing a hybrid gain medium [3] and utilizing spatial hole burning by inserting a multi-phase shift FBG in a linear cavity fiber laser [4]. Special laser cavity configurations for multi-wavelength operation by incorporating a segment of highly nonlinear photonic crystal fiber or dispersion-shifted fiber have also been reported [5-7]. In recent years, multi-wavelength fiber lasers operating at room temperature by utilizing polarization hole burning (PHB) effect from polarization maintaining (PM) FBGs have been studied extensively and various setups have been demonstrated [8-10]. However, in all these setups, the PHB effect has only been studied with PM fiber based devices. We report here a stable, single- and dual-wavelength switchable fiber laser by utilizing two special tilted fiber gratings (TFGs) in an EDF ring laser cavity without any PM fiber based device. The two TFGs include one with the structure tilted at 45°, which is used as an in-fiber polarizer [11] and the other at 77° as a polarization dependent loss filter. The optical signal to noise ratio of >60dB has been obtained in such an EDFL system, which is higher than that in the previous reports [8-10]. In this configuration, the separation between the switchable wavelengths can be more flexibly designed with potential tuning capability.

2. Fabrication and Characterization of the polarization selective tilted gratings

Two fiber gratings with structures tilted at 45° and 77° (named as 45°-TFG and 77°-TFG) were fabricated by the standard scanning UV-inscription technique using two different phase masks. The 45°-TFG was UV-inscribed in the single mode B/Ge co-doped photosensitive fiber and the 77°-TFG was in the standard telecom fiber (SMF-28). Both fibers were photosensitized by high pressure H_2-loading at 100° C for 2 days prior to the UV-inscription.

In order to induce slanted index fringe structure at ~77° in the fiber core, we used a phase mask with 6.6μm period (from Edmund Optics) and oriented it at 73° in the UV-inscription system. According to our previous work, TFGs with excessively tilted structures exhibit polarization dependent loss property, giving a series of paired polarization loss peaks in 1550nm region [12]. The transmission spectrum of this 77°-TFG was first examined using a broadband source (Agilent 83437A) and an optical spectrum analyzer, which is shown in Fig.1(a). From the figure we can see that all paired loss peaks exhibit near-3dB strength, indicating the light is coupled almost equally to the two sets of cladding modes with orthogonal polarization states. We then examined the 77°-TFG under polarized lights by using another source (AFC BBS

1550A-TS) with even lower degree of polarization and inserted an in-fiber polarizer and a polarization controller between the light source and the 77°-TFG. As the zoomed spectra of one paired modes shown in Fig. 1 (b), when the light is polarized at P1 state, the fast-axis loss peak is fully excited to ~12dB whereas the slow-axis peak almost disappeared, and vice versa when the light is switched to P2 state (90° to the P1). This proves that although the 77°-TFG was made in standard telecom fiber, the excessively tilted structure makes it behaving as a PM-like device, i.e. a polarization dependent loss filter.

The 45° -TFG used as an in-fiber polarizer in the EDFL system was fabricated previously using concatenation method employing a phase mask with 1.8μm period (from QPS) [11]. We examined the polarization dependent loss (PDL) of the 45°-TFG using a commercial EXFO PDL characterization kit that incorporated a tuneable laser to provide optimization measurement over 100nm range. The measured PDL is shown in Fig.2 and from which we can see that the 45°-TFG is a near-ideal polarizer with a polarization extinction ratio close to 35dB over 100nm bandwidth from 1520nm to 1620nm.

In addition to the two TFGs, two standard FBGs (G1 and G2 in Fig. 3), as seeding wavelength selectors, were also UV-inscribed in H_2-loaded SMF-28 fiber with their Bragg wavelengths matching the two loss peaks of the 77°-TFG. The reflectivities of the two FBGs are 2.51dB and 2.28dB at 1547.07nm and 1553.24nm, respectively, and the bandwidths are of ~0.1nm.

3. Principle of the EDFL system and experimental results

The set-up for the proposed EDFL is shown in Fig.3. In this configuration, the gain medium is a 6m of highly Erbium doped fiber (from Lucent Technology), which has an absorption coefficient of 12dB/m. A 976nm laser diode (from SDL) controlled by a set of commercial laser diode driver (Newport 505B) and temperature controller (Newport 300 Series) is used to pump the EDFL through a 980/1550 WDM coupler. An optical isolator (OIS) ensures an anticlockwise ring cavity. The 30% arm of the coupler is used as the output port of the laser. A fiber polarization controller (PC) is placed between the 77^{o}-TFG and the 45^{o}-TFG. Two standard FBGs (G1 and G2) functioning as seeding wavelength selectors are coupled into the laser cavity via a circulator. The end of the FBG array is terminated by index matching gel in order to eliminate any unwanted background ASE noise.

The operation principle of this EDFL is described as follows. The intracavity 45^{o}-TFG has a very high polarization extinction ratio, which can guarantee that the fiber ring laser will oscillate in single polarization regime [13]. The 77^{o}-TFG will induce polarization dependent loss to the ring cavity around its paired attenuation band region, thus imposing PHB effect to the gain medium in this region. The amplitude of the loss depends on the polarization state of the light travelling in the 77^{o}-TFG.

By adjusting the PC to control the polarization state of the light entering the 77^{o}-TFG, i.e. polarized in the equivalent fast- or slow-axis of the 77^{o}-TFG, single-polarization and single-wavelength lasing at either 1547nm or 1553nm can be realized. Fig. 4 (a) and (b) show the single wavelength oscillation of the fiber ring laser at the two seeding wavelengths, respectively.

The laser output amplitude variation was measured to be less than 0.5dB within 1 hour at laboratory condition and the spectra were recorded every 5min and are plotted in Fig. 4(c) and (d). From these two figures we can see that the optical signal to noise ratio (OSNR) is more than 65dB and the side mode suppression ratio (SMSR) is larger than 50dB for both laser lines. These two values are higher than that of the EDFLs reported in references [8-10]. The higher OSNR and SMSR are mainly attributed to the ASE suppression function of the 45°-TFG and the low reflectivities of the two seeding FBGs, respectively.

Single polarization operation was verified by connecting the laser output to a polarization controller followed by a commercial grade polarizer. The measured degree of polarization (DOP) was ~35dB for 1547.07nm and ~30dB for 1553.24nm laser lines, indicating a marked high degree of single polarization operation. If we change the polarization direction of the launching light to at 45° to the fast- and slow-axis of the 77°-TFG, as shown in inset in Fig. 2, dual-wavelength laser output with two orthogonal polarization states can be achieved. Fig.5 shows the dual-wavelength output at ~1547.07nm and ~1553.24nm of the fiber ring laser. We have also monitored the dual wavelength operation continuously for 20mins, and no noticeable amplitude variation was observed for a fixed PC position at room temperature (shown in Fig. 5(b)). The OSNR for both lasing lines was more than 60dB.

The slope efficiencies of the proposed fiber laser have also been characterized for both single- and dual-wavelength operation. Fig. 6(a) shows that for single wavelength operation, the threshold pump power is just slightly lower than ~15mW and the slope efficiencies are 0.22% and 0.12% for 1547.07nm and 1553.24nm lasing lines, respectively. The difference in slope efficiency could be due to the variation of the polarization dependent gain of the EDF. While the laser working in dual-wavelength operation, equal power distribution at ~1547nm and ~1553nm regions can be obtained by carefully tuning the PC. As shown in Fig. 6 (b), for dual-wavelength operation, the threshold pump power is just slightly higher than 15mW and the slope efficiency is ~0.065% which is much lower than that in the single wavelength operation. This is because in dual-wavelength operation, 77°-TFG induces some losses at the two lasing wavelengths, inevitably resulting in lower output for each wavelength. Since there were several fiber slices in the cavity, the TFGs may have some small extra loss and the reflectivities of the two seeding FBGs are relatively low, we expect that the slope efficiencies of the proposed EDFL system are to be low. By reducing the loss and employing FBGs with higher reflectivity, the slope efficiency can be improved.

4. Discussion and Conclusion

One may notice from Fig.4 and Fig.5, there is a small reflection peak at 1546.5nm adjacent to the lasing line at 1547.07nm. This reflection was proved to be induced by the 45°-TFG. We experimentally verified this by monitoring the laser output port when the 77°-TFG and the two seeding FBGs were removed from the cavity. As shown in Fig. 7, we see a strong reflection around 1546.5nm when the cavity was containing only the 45°-TFG. If the 45°-TFG is a perfect in-fiber polarizer no feedback will be provided in the laser cavity, thus only strong ASE should be seen from the laser output port. Because this 45°-TFG was fabricated by concatenation technique, stitch error could thus induce unwanted back reflection. We believe this unexpected noise line can be eliminated by employing a 45°-TFG made from a longer phase mask without concatenation.

Although we have only demonstrated single- and dual-wavelength operation at fixed wavelengths, the system potentially has a capability of tuning operation since the reflection bandwidths of the seeding FBGs are much narrower than the paired loss peaks of the 77°-TFG.

In addition, switchable multi-wavelength (more than two) output may be realized by using two large angle tilted TFGs with un-overlapped spectra.

In summary, we have demonstrated a novel, stable, single-polarization and single- and dual-wavelength switchable fiber ring laser by using TFGs acting as a polarizer and a polarization dependent loss filter. The TFGs were all made in single mode fibers, thus giving low splicing loss advantage for the proposed laser system. The laser output can be switched between two single wavelengths and a dual-wavelength operation regimes by simply adjusting the polarization controller in the system. The measured OSNR and SMSR were as high as 65dB and 50dB and the lasing operation was very stable in laboratory environment condition.

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Figure 1 (a) Transmission spectrum of the 77°-TFG over wavelength range 1200nm – 1700nm; (b) Zoomed spectra of one paired polarization loss peaks of the 77°-TFG around 1550nm measured with randomly and fully polarized light.

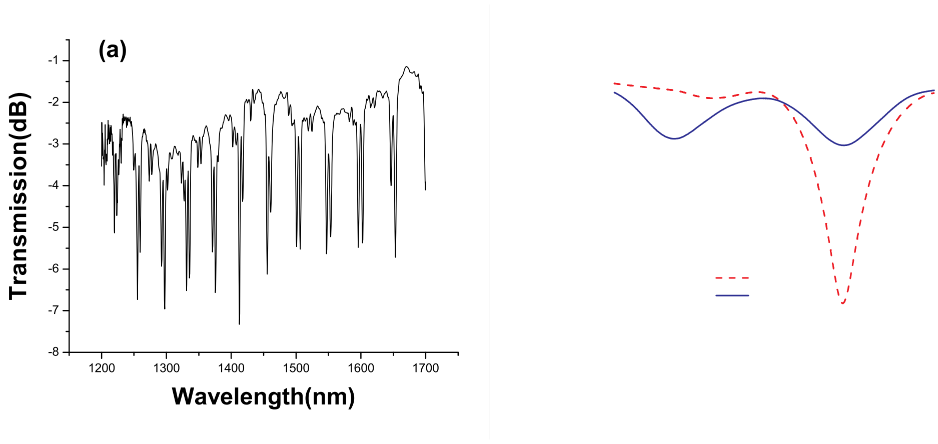

Figure.2 PDL of the used 45°-TFG measured by the EXFO PDL characterization tool kit

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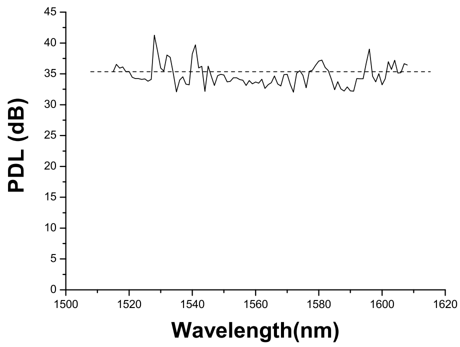

Figure.3 Schematic diagram of TFG based single- and dual-wavelength switchable EDFL. The inset describes the polarization directions of the light launching to the 77° -TFG.

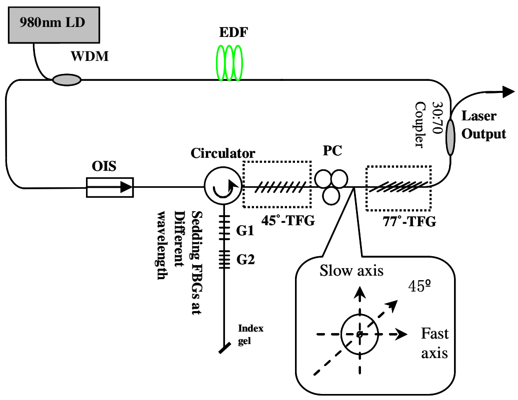

Figure.4 Single wavelength lasing oscillation of the propose fiber ring laser at two seeding wavelengths at (a) 1547.07nm and (b) 1553.24nm; (c) and (d) stability measurement of the two laser lines.

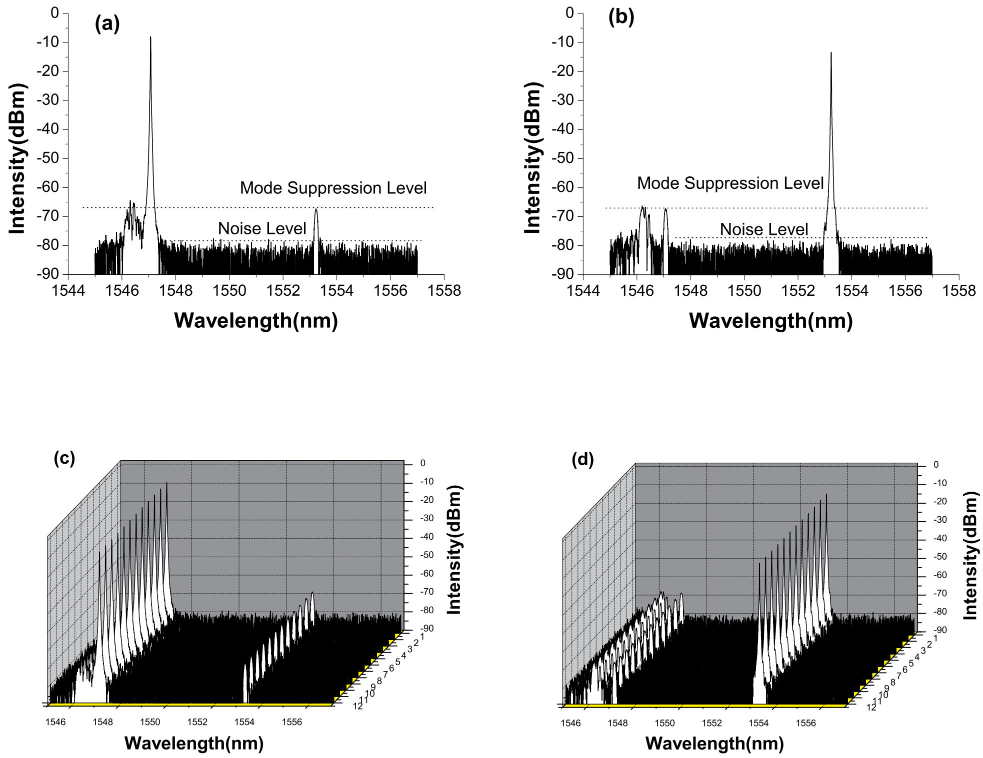

Figure.5. (a) Dual wavelength lasing oscillation of the proposed fiber ring laser, (b) stability of dual wavelength oscillation (20 times repeated scan).

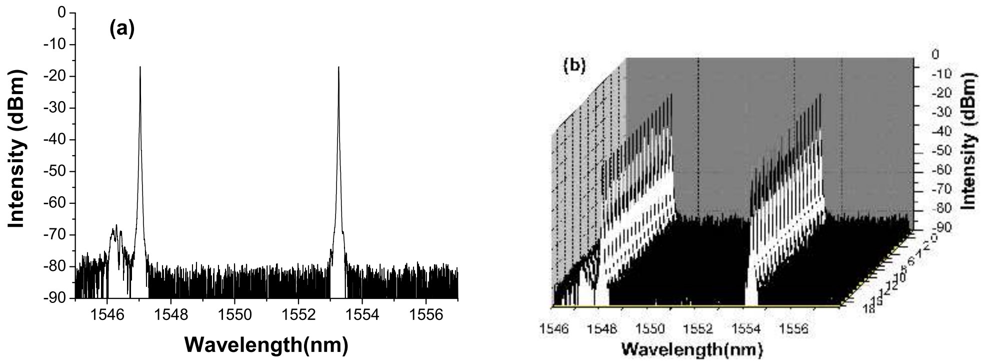

Figure.6 Slope efficiencies of the fiber laser at (a) single wavelength output and (b) dual wavelength output.

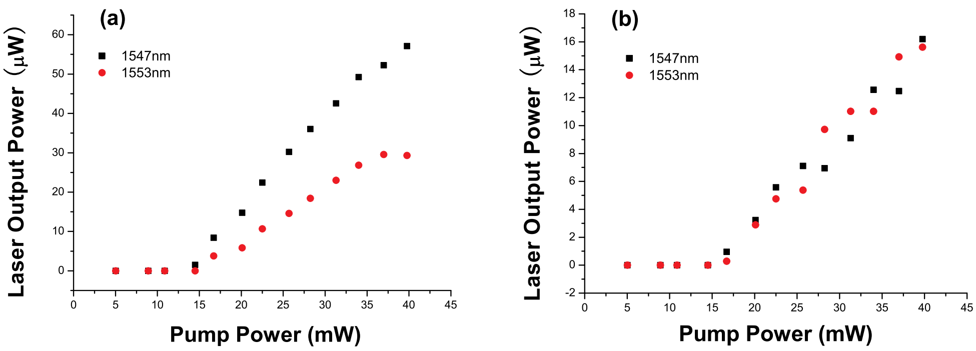

Figure.7 45^o −TFG induced unwanted reflection at 1546.5nm in the fiber ring laser.