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Switchable dual-wavelength erbium-doped fibre laser utilizing two-channel fibre Bragg grating fabricated by femtosecond laser

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Abstract: We propose and demonstrate a switchable dual-wavelength erbium-doped fibre ring laser. Competition between the lasing wavelengths in erbium-doped fibre laser at room temperature is suppressed by incorporating a two-channel fibre Bragg grating (TC-FBG), which consists of two highly localized sub-gratings fabricated by femtosecond laser in single mode fibre. Wavelengths and polarization states of the lasing lines are selected by the TC-FBG. Laser output can be switched between single- and dual-wavelength operations by simply adjusting the polarization controller. Stable dual-wavelength output is verified at room temperature with a power fluctuation less than 0.27 dB, and wavelength fluctuation less than 0.004 nm.

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1. Introduction

Multiwavelength fibre lasers have attracted considerable attention due to their potential applications in optical sensing and wavelength division multiplexed (WDM) systems [1-3]. Erbium-doped fibre (EDF) has been extensively studied and used in commercial fibre lasers and amplifiers owing to its low cost and high gain in the telecom C-L band. However, it’s not easy to achieve stable multiwavelength fibre laser utilizing erbium-doped fibre because of the severe competition between the lasing wavelengths resulting from the large homogeneous line broadening of EDF at room temperature. By cooling EDF in liquid nitrogen, the homogeneous line broadening of EDF can be reduced [4], but such an approach is not suitable for practical use. To realize stable multiwavelength fibre laser at room temperature, various techniques have been developed, such as incorporating a frequency shifter [5], employing hybrid gain medium [6], [7], use of nonlinear polarization rotation[8], using highly nonlinear fibre[9], and most recently, by means of microfibre[10].

Fibre gratings are ideal components to select lasing wavelength for fibre laser due to the full compatibility with fibre, many fibre gratings based schemes for multiwavelength fibre laser have been proposed, such as using long period grating(LPG) or large angle tilted fibre grating as polarization dependent loss element[11, 12], turning the central wavelengths of the gratings to match or mismatch the selected lasing wavelengths[13, 14], in fibre Lyot filter based on 45 degree tilted fibre Bragg gratings(FBGs)[15], cascaded long period gratings[16, 17], fibre gratings in Sagnac loop mirrors[18], [19], and use of gratings in special fibres [20-22].

However, as the LPG is sensitive to ambient environment, multiwavelength laser based on LPG suffers from unstable output, FBG based scheme gives a more stable performance, but conventional fabrication of FBG using the UV laser always calls for photosensitivity of the fibre, which requires hydrogen loading, making the fabrication cumbersome, or use of the relatively expensive photosensitive fibre.

To relieve the need of photosensitation, femtosecond laser has emerged as a powerful tool for FBG inscription [23]. Gratings inscribed by femtosecond laser can be highly localized in the fibre core with a width of ~0.3 μm and depth of ~1.9 μm[24], rather small compared with the core of single mode fibre (SMF), so two gratings co-located parallel, e. g. two-channel fibre Bragg grating (TC-FBG), can be inscribed in the core of SMF as previously reported [25]. Figure 1 shows the schematic of the TC-FBG. As the two sub-gratings are centered at different wavelengths, they can work almost independently with each other.

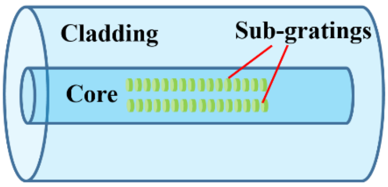

Figure 1 Schematic of the proposed two-channel fibre Bragg grating

In this work, we propose and demonstrate a stable and switchable dual-wavelength EDF laser at room temperature utilizing TC-FBG, which selects the lasing wavelengths and the polarization state at the same time. Compared with other techniques mentioned above, this method requires only one section of grating, needs no special fibre except EDF, and is easily switchable by simply adjusting the polarization controller apart from the intrinsic advantages of FBG. Moreover, as no photosensitivity is required for femtosecond laser inscription [23], TC-FBG can be written into gain fibre directly, making it promising candidate for more compact dual-wavelength fibre laser.

2. Experiment

Point-by-point (PbP) method [26] is employed to fabricate TC-FBG, an amplified Ti: Sapphire laser (center wavelength = 800 nm, pulse duration = 150 fs, repetition rate = 1KHz) is focused into the fibre core by a 100× microscopic objective with a NA of 0.55 and working distance of 13mm. The fibre is immersed in a micro-slot filled with index matching gel to alleviate the defocusing-induced distortions resulting from the curved front surface of the fibre [27]. Both the fibre and the micro-slot are mounted on a high resolution air bearing translation stage that will move along the fibre axis at a constant speed, and each focused laser pulse will produce a localized grating pitch in the core of the fibre during the translation. Grating period can be changed flexibly using the PbP method by simply adjusting the translation speed of the fibre, here the periods of the two sub-gratings are set to be 1.07μm and 1.072μm respectively, corresponding to second order Bragg wavelengths of ~1548.9 nm and ~1551.9 nm. During the fabrication, the air bearing stage moves back to the start position after the inscription of the first sub-grating is finished, and moves by ~2μm vertically to the fibre axis before inscribing the second one to separate the two sub-gratings transversely.

Figure 2 shows the transmission spectra of the TC-FBG when light sources with orthogonal polarization states are introduced. Bragg wavelength differences between the two polarizations are measured to be 0.088 nm at ~1548.9 nm and 0.056 nm at ~1551.9 nm, while differences of transmission dips for the two Bragg wavelengths are 4.35 dB and 4.56 dB respectively. We can see that the grating strength at the shorter wavelength is always stronger than the other, whatever state of the PC is, which is like the situation in previous report [21] and won't be a problem for dual-wavelength lasing as will be explained below. Cladding mode coupling, especially at ~1548.9 nm where the FBG dip centered, can be accounted as insert loss, which can be optimized by positioning the FBG dip at wavelengths with weaker cladding mode coupling. The out of peak insert loss of the TC-FBG is around 2 dB, which is related to scattering losses and depends on FBG strength [28]. As a higher loss will lead to a higher lasing threshold and a lower slope efficiency for laser application, trade-off between grating strength and the scattering loss should be considered to get a better laser performance. As the polarization dependence of each sub-grating is related to its transverse position [29], we believe by inscribing each sub-grating with different offset from the center of the fibre core, a controllable polarization dependence can be realized. The inset in figure 2 depicts the view of the fabricated TC-FBG under the microscope, and two highly localized sub-gratings parallel with each other can be seen clearly in the core. We can see that the two localized sub-gratings just occupy part of the fibre core, which means even more sub-gratings can be inscribed in the core to further improve its capacity.

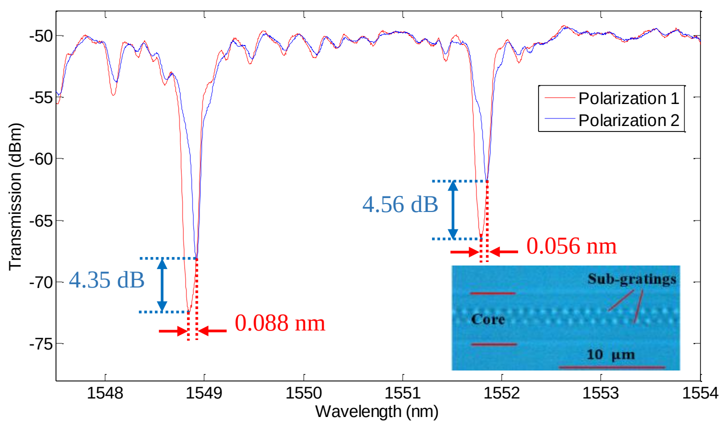

Figure 2 Measured transmission spectra of two-channel fibre Bragg grating along two orthogonal polarization states, inset shows the microscope view of the fabricated TC-FBG

The schematic of the proposed EDF laser is shown in figure 3, a 2m long EDF (Fibrecore, I-25) is employed as the gain medium, and is pumped by a 976 nm laser diode connected to the 980/1550 WDM coupler. The TC-FBG is incorporated into the cavity by an optical circulator, which also guarantees the unidirectional operation, and the unused end of TC-FBG is immersed into index matching gel (IMG) to eliminate unwanted reflection of amplified spontaneous emission (ASE). A 10:90 optical coupler (OC) is used to couple 10% of laser power to an optical spectrum analyzer (OSA) with a resolution of 0.02 nm.

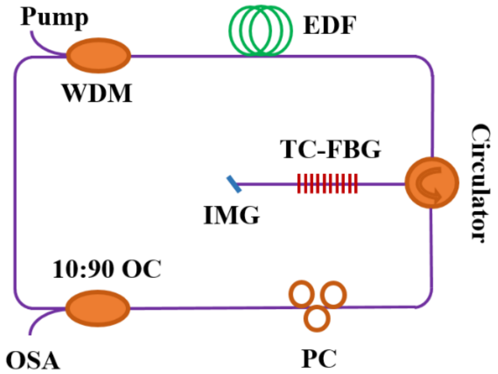

Figure 3 Schematic of proposed laser with the fabricated TC-FBG

The working principle of the proposed laser can be described briefly as follows: light reflected by the TC-FBG is partly polarized, and substantially modify its polarization state as it propagates along the fibre before re-approaching the TC-FBG. The polarization state of light at different wavelengths after the propagation will be different due to the birefringence chromatic dispersion, which means the light re-approaching the TC-FBG differs in polarization state at different wavelengths, note that not only the reflectivity, but the central wavelengths of the TC-FBG are polarization dependent (Fig. 2), so the central wavelengths of the TC-FBG before and after the propagation mismatch due to the change of polarization, and additional cavity loss can be introduced due to the mismatching. In this way, the cavity loss can be balanced by controlling the wavelength mismatching through the PC, and dual wavelength lasing can be achieved.

During the experiment, switchable dual-wavelength lasing can be obtained by adjusting the PC, output of single-wavelength and dual-wavelength lasing around 1548.9 nm and 1551.9 nm is shown in figure 4. Though side mode is not totally eliminated for single wavelength operation, the side mode suppression ratio (SMSR) is more than 42 dB at ~1548.9 nm and 46 dB at ~1551.9 nm.

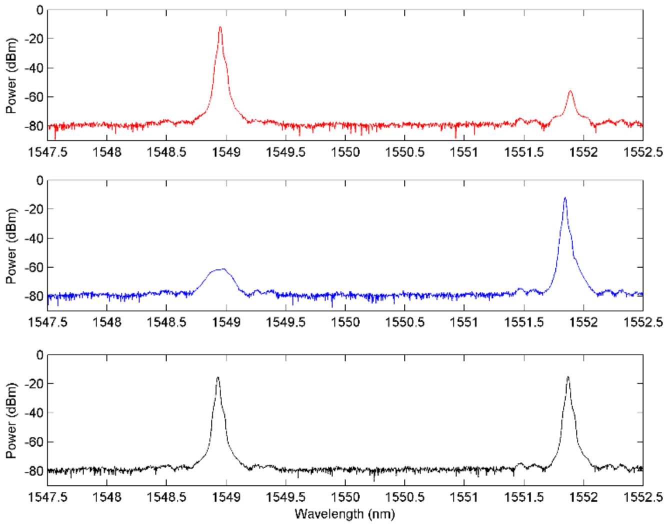

Figure 4 Laser output spectra for: single-wavelength lasing at ~1548.9 nm (red); single-wavelength lasing at ~1551.9 nm (blue); dual-wavelength lasing (black).The side mode suppression ration is more 42 dB for single-wavelength lasing at ~1548.9 nm and 46 dB at ~1551.9 nm.

The stability of proposed laser for dual-wavelength lasing is verified by monitoring the laser output with 2 minutes interval for half an hour, as shown in figure 5, where changes of lasing power and wavelength against time are plotted, we can see that both lasing wavelengths are stable with a power fluctuation less than 0.27 dB, and wavelength fluctuation less than 0.004 nm, showing good stability.

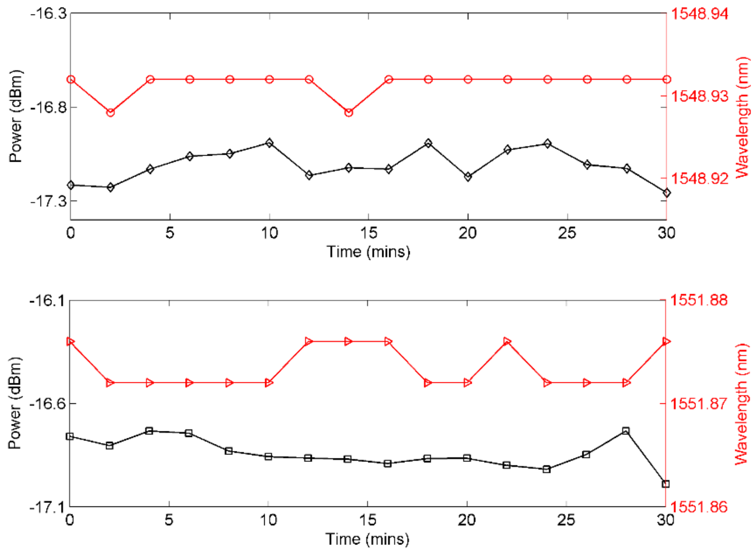

Figure 5 Output power and lasing wavelength fluctuation at: ~1548.9 nm (up) and ~1551.9 nm (down) measured with 2 minutes interval for half an hour.

The slope efficiency of the proposed laser is also characterized, laser output power as a function of pump power and the fitted line are plotted in figure 6. Figure 6(a) and figure 6(b) depict for single-wavelength operations, and figure 6(c) is for dual-wavelength operation. The slope efficiency and threshold power for single wavelength operation are 0.321% and 16.5 mw at ~1548.9 nm, and 0.284 % and 16.3 mw at ~1551.9. For dual-wavelength lasing, the slope efficiency and threshold power for each wavelength are 0.149 % and 17.4 mw at ~1548.9 nm, and 0.140 % and 16.3 mw at ~1551.9 nm. Note that the slope efficiency here is higher than the one in previous report based on tilted FBGs where longer EDF is used [12]. Differences between the slope efficiency and threshold power for the two lasing wavelengths may result from the difference in the feedback given by TC-FBG, as the reflectivity is not exactly the same at the two selected wavelengths. And the laser threshold power does not have much change when the laser is switched between single- and dual- wavelength operation, because the total cavity loss, which determines the laser threshold, is almost unchanged when the laser is switched. We see that the slope efficiency is much lower for dual-wavelength lasing compared with the one for single-wavelength lasing as the pump power is shared by two lasing lines. Considering there are several connectors and splices in the cavity, which inevitably induce some losses, and the EDF used here is only 2 meters long, we expect the slope efficiency to be low, and we believe by reducing the cavity losses and using a longer EDF, the slope efficiency can be increased.

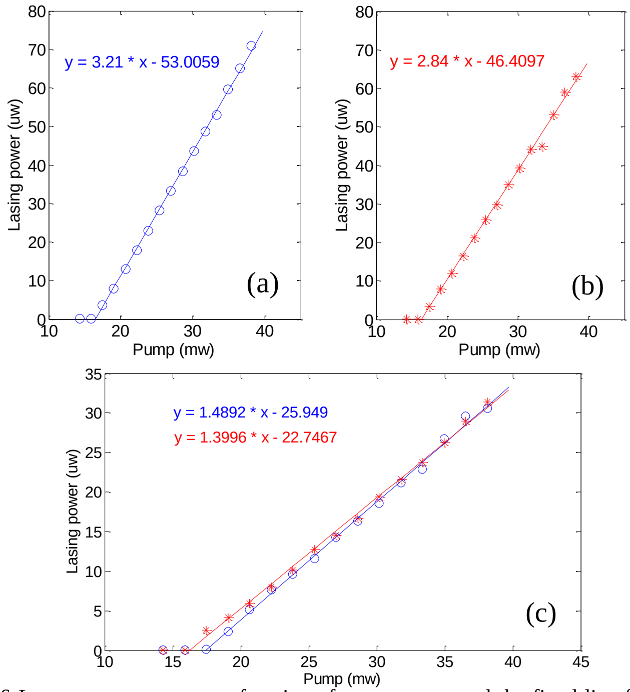

Figure 6 Laser output power as a function of pump power and the fitted line for: (a) single-wavelength at~1548.9 nm (b) single-wavelength at ~1551.9 nm(c) dual-wavelength at ~1548.9 nm (blue) and ~1551.9 nm (red)

3. Conclusion

In summary, we propose and demonstrate a switchable dual-wavelength erbium-doped fibre laser. Competition between the lasing wavelengths in erbium-doped fibre is suppressed by incorporating a two-channel fibre Bragg grating consisting of two highly localized sub-gratings fabricated by femtosecond laser in single mode fibre, which selects lasing wavelengths and balances cavity loss and gain of the two lasing wavelengths at the same time. The proposed laser can be switched between single- and dual- wavelength operation by simply adjusting the polarization controller. Stable dual-wavelength output at room temperature is verified by monitoring the laser output for half an hour with a 2 minutes interval, and power fluctuation is measured to be less than 0.27 dB, while wavelength fluctuation is less than 0.004 nm. As no photosensitivity is required for femtosecond laser inscription, TC-FBG can be written into gain fibre directly, making it promising candidate for more compact dual-wavelength fibre laser by inscribing two co-located phase shifted fibre Bragg gratings parallel in the fibre core, e. g. multiwavelength DFB lasers. Microscope view of the fabricated grating shows that there is still room in the fibre core to inscribe more sub-gratings, which will further improve its capacity.

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