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Switchable and spacing-tunable dual-wavelength erbium-doped fibre lasers*

Feng Xin-Huan(冯新焕)† Liu Yan-Ge(刘艳格), Sun Lei(孙 磊),
Yuan Shu-Zhong(袁树忠), Kai Gui-Yun(开桂云), and Dong Xiao-Yi(董孝义)

Institute of Modern Optics, Nankai University, Tianjin 300071, *China*

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Two switchable and spacing-tunable dual-wavelength linear cavity erbium-doped fibre lasers are demonstrated experimentally. One of them utilizes a Bragg grating in polarization-maintained PANDA fibre and the other uses a Bragg grating in standard single mode fibre for wavelength selection. Both exploit the birefringence characteristics of the FBG induced by transverse strain. The proposed lasers can be made to operate in stable dual-wavelength or switch between two wavelengths at room temperature just by simple adjustment of a polarization controller. Transverse strain loading on the FBG allows the wavelength spacing to be controlled.

Keywords: Erbium-doped fibre, fibre Bragg grating, fibre laser, dual-wavelength lasing, polarization-maintaining fibre
PACC: 4280S, 4281W, 4255N

1. Introduction

Fiber lasers are of great interest to applications in wavelength-division-multiplexed (WDM) fibre communication systems, fibre sensors, and optical instrument testing.[1−19] Among the fibre lasers, a switchable multiwavelength laser with tunable wavelength spacing would provide unique capabilities. Various techniques have been proposed to realize switchable multiwavelength oscillations in fibre lasers.[3−15] Fiber Bragg gratings (FBGs), on the other hand, are ideal wavelength selection components for fibre lasers due to the unique advantages of fibre compatibility, easy use and low cost. Different FBGs have been incorporated in the laser cavities to perform simple or more elaborated filtering functions including cascaded fibre Bragg grating,[3,4] a tree, in-line topology FBGs,[5] a long-period FBG in polarization- maintaining fibre,[6] an FBG written in a high birefringent fibre,[7,8] and a sampled FBG.[9] In some systems mentioned above, the wavelength separation is tunable, but they need different FBGs for wavelength selection and their spacing is somewhat large. Stable multiwavelength operation of EDFLs with tunable wavelength spacing has been achieved using a segmented all-PM fibre ring resonator,[15] a spacing-tunable multiwavelength comb filter,[16] second-order nonlinearity of $LiNbO_3$ waveguides,[17] and chirped FBGs.[18] However, either the schemes being somewhat complicated, or the requirement for the use of liquid nitrogen[16] makes it difficult to operate them at room temperature.

We ever reported a tunable dual wavelength fibre laser based on one Bragg grating. [19] In this paper, on the basis of the previous work, we report two schemes of linear cavity erbium-doped fibre lasers (EDFLs) that enable us to achieve switchable and spacing-tunable dual-wavelength oscillations. The polarization-maintaining (PM) PANDA fibre and the standard single mode fibre (SMF) both include an FBG. Both exploit the birefringence characteristics of the FBG induced by transverse strain. Feedback from the FBG results in the laser operating in two longitudinal modes that are separated in both wavelength and polarization,[20] so wavelength switching can be achieved only by simple adjustment of the PC

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†E-mail: xh_feng1974@sohu.com

and wavelength spacing can be tuned by variation in strain. Both lasers have the advantage over alternative techniques in that they are spectrally stable and have a simple configuration, better control of tunability, and low cost.

2. Experimental setup and principle

The configurations of the proposed lasers are the same except for the FBGs used, similar to the ever reported ones.[19] In one experiment, the FBG in SMF was used for wavelength selection. In another experiment, the FBG was changed to an FBG in PM PANDA fibre. The configuration is shown schematically in Fig.1. The linear cavity laser consists of a 980nm/1550nm WDM coupler, a Sagnac fibre loop (SFL), 15m-long EDF, a polarization controller (PC), and an FBG with a section of strain modulation. The SFL acts as a broadband reflector for signal. The EDF with a concentration of ~500ppm was pumped by a laser diode with an output of 80mW at 980nm through the WDM coupler. The PC was used to rotate the polarization state and allowed continuous adjustment of the birefringence within the cavity. The FBG was placed between two pieces of Perspex. Transverse strain was applied through a screw on the FBG along with another fibre of the same type with coating removed, to ensure the load was applied from an orthogonal direction. The spectral characteristic was measured using an ADVANTEST Q8383 optical spectrum analyzer with the resolution of 0.1nm.

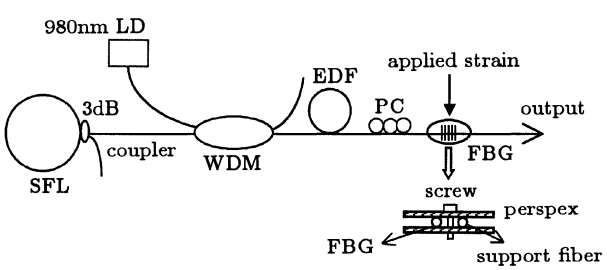


Fig.1. Schematic diagram of the proposed laser.

With no transverse strain applied, the Bragg reflection wavelength of an FBG is given by $\lambda = 2\Lambda n_{\text{eff}}$, where n_{eff} is the initial effective refractive index, λ is Bragg wavelength, and Λ is the period of the grating. With a transverse load applied, the refractive index of the FBG changes and becomes birefringent and two plane-polarized waves propagate, with the principal axes of polarization being parallel and perpendicular to the direction of the applied load. For simplicity, we assume the principal optical axes to be aligned with x, y, and z axes in Cartesian reference frame. The refractive index changes of the FBG are derived by use of the photoelasticity theory and are given by the formulae:[20]

for x polarization

$$(\Delta n_{\text{eff}})_x(x,y,z) = -\frac{1}{2}(n_{\text{eff}})^3[p_{11}\varepsilon_x + p_{12}(\varepsilon_y + \varepsilon_z)], \tag{1}$$

for y polarization

$$(\Delta n_{\text{eff}})_y(x,y,z) = -\frac{1}{2}(n_{\text{eff}})^3[p_{11}\varepsilon_y + p_{12}(\varepsilon_x + \varepsilon_z)], \tag{2}$$

where Δn_{eff} represents the effective refractive index difference between the two orthogonal states of polarization parallel and perpendicular to the direction of the applied load, p_{11}, p_{12} are the photoelastic coefficients of the undisturbed optical fibre; and ε_x, ε_y, ε_z are the strain components at the point $M(x, y, z)$ in the FBG in the x, y, and z directions, respectively.

By differentiating $\lambda = 2n_{\text{eff}}\Lambda$, we have

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta n_{\text{eff}}}{n_{\text{eff}}} + \frac{\Delta\Lambda}{\Lambda}, \tag{3}$$

where $\Delta\Lambda$ represents the changes in the period of the grating induced by the load.

Using the relationship $\varepsilon_z = \dfrac{\Delta L}{L} = \dfrac{\Delta\Lambda}{\Lambda}$, and substituting Eqs.(1) and (2) into Eq.(3), the Bragg reflection wavelength variation of the disturbed FBG is given as follows:

for x polarization

$$\Delta\lambda_x = \left\{\varepsilon_z - \frac{1}{2}(n_{\text{eff}})^2[p_{11}\varepsilon_x + p_{12}(\varepsilon_y + \varepsilon_z)]\right\}\lambda, \tag{4}$$

for y polarization

$$\Delta\lambda_y = \left\{\varepsilon_z - \frac{1}{2}(n_{\text{eff}})^2[p_{11}\varepsilon_y + p_{12}(\varepsilon_x + \varepsilon_z)]\right\}\lambda, \tag{5}$$

The wavelength spacing between the two wavelengths is as follows

$$\begin{aligned}\Delta\lambda =& \lambda_y - \lambda_x = \Delta\lambda_y - \Delta\lambda_x \\ =& \frac{1}{2}(n_{\text{eff}})^2(p_{12} - p_{11})(\varepsilon_y - \varepsilon_x)\lambda.\end{aligned} \tag{6}$$

For all-silica optical fibres we have p_{11}=0.121 and p_{12}=0.270,[20] and n_{eff}=1.46. We assume that the transverse strain is in the y direction and Fig.2 shows how the wavelength variation changes with the transverse strain. The dashed line, dashed dotted line, and the solid line represent the wavelength variations of

x polarization, y polarization, and the corresponding wavelength spacing calculated from Eqs.(4), (5), and (6), respectively. It can be seen from Eq.(6) and the figure that the wavelength spacing will change linearly with the strain and changes in the transverse strain can modify the wavelength spacing.

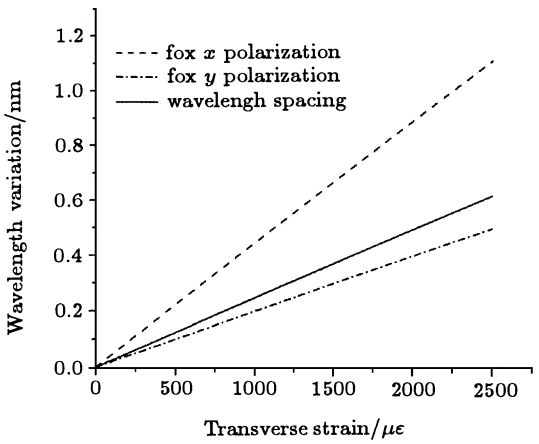


Fig.2. Computed Bragg reflection wavelength variation and wavelength spacing versus the applied strain.

As for a grating in PM fibre that has intrinsic birefringence, the influence of external perturbation on the refractive index is somewhat different. Applying the load in line with the fast axis reduces the birefringence of the fibre and causes the wavelength separation of the two modes to be decreased. On the other hand, the strain applied in line with the slow axis increases the index difference and a concomitant increase in wavelength spacing is produced. So, the change in wavelength spacing is related not only to the magnitude of the applied strain, but also to the direction in which the strain applied.

The switching operation principle of the laser is similar to that in Refs.[7] and [19] and can be described briefly as follows. The birefringence induced by the FBG is beneficial to the diversifying of the polarization states of different wavelengths in the EDF and the enhancing of the polarization hole burning (PHB). This PHB greatly increases the inhomogeneous gain broadening of EDF and accordingly reduces the wavelength competition. Then, it is possible to achieve stable dual-wavelength oscillations at room temperature. On the other hand, through adjusting the state of the polarization controller, the transmission characteristic of the FBG is changed. When the eigenaxes of one mode is more populated than that of the other mode, it will oscillate stably in that mode. Especially, when the eigenaxes of both modes are equally populated, the two modes can coexist with equal amplitudes. Thus mode selection is achieved in laser oscillation and the laser can be designed to operate in wavelength switching modes only by simple adjustment of the PC.

3. Results and discussions

In the first experiment, an FBG in standard SMF was used. The SMF used was hydrogen loaded for seven days in a vessel at a pressure of 120 bar. The FBG was subsequently fabricated by use of the phase mask method. Figure 3 shows the dual-wavelength operation of the proposed laser for various screwed angles. The wavelength spacing corresponding to the 0.4, 0.7, and 0.9rad screwed angles was 0.2nm, 0.38nm, and 0.5nm, respectively. The corresponding power outputs were about 1.58mW, 1.68mW, and 1.92mW, respectively. Note that the spectra shown in Fig.3(c) are the result of scans repeated 16 times. Amplitude variations of the two laser lines were less than 0.2dB and the stability of the dual-wavelength operation at room temperature was very good.

In another experiment, the FBG in SMF was changed to an FBG in PM fibre. The PM PANDA fibre used for the FBG fabrication was also hydrogen loaded for seven days in a vessel at a pressure of 120 bar and the FBG was subsequently fabricated by using the phase mask method. The PM fibre had a beat length of 3.1mm and corresponds to a wavelength separation of about 0.52nm in the orthogonally polarized modes of the reflection from the FBG. Two reflection peaks appeared at 1556.66nm and 1557.18nm respectively, leading to a wavelength separation of 0.52nm. Figure 4 shows the measured spectra from the second laser for various screwed angles and different directions in which the strain is applied. With no strain applied, the output spectrum of the laser is shown in Fig.4 (a). The corresponding wavelength spacing is 0.52nm and the power output is about 1.86mW. Figures 4(b) and (c) show the spectra when the strain was in line with the fast axis with a screwed angle being 0.7rad and with the slow axis with a screwed angle being 0.3rad, respectively. The corresponding spacing and power output were 0.2nm, 0.68nm and 1.6mW, 1.2mW, respectively.

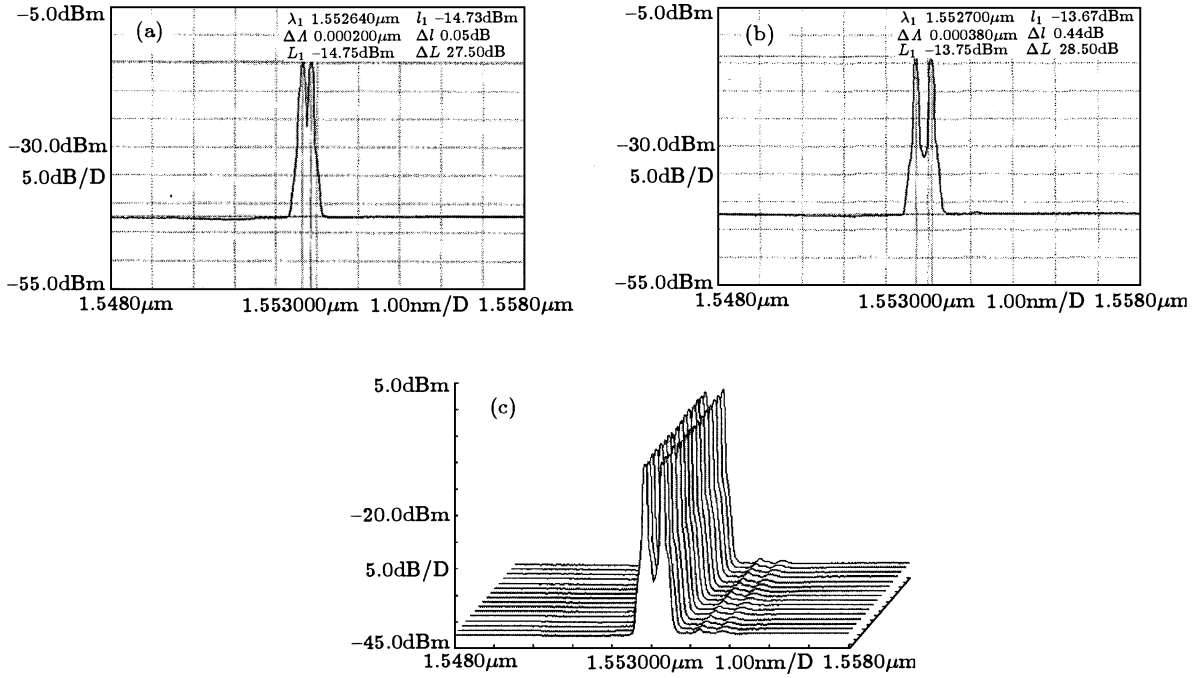


Fig.3. The measured spectra from the laser for various screwed angles: (a) 0.4rad, (b) 0.7rad, (c) 0.9rad.

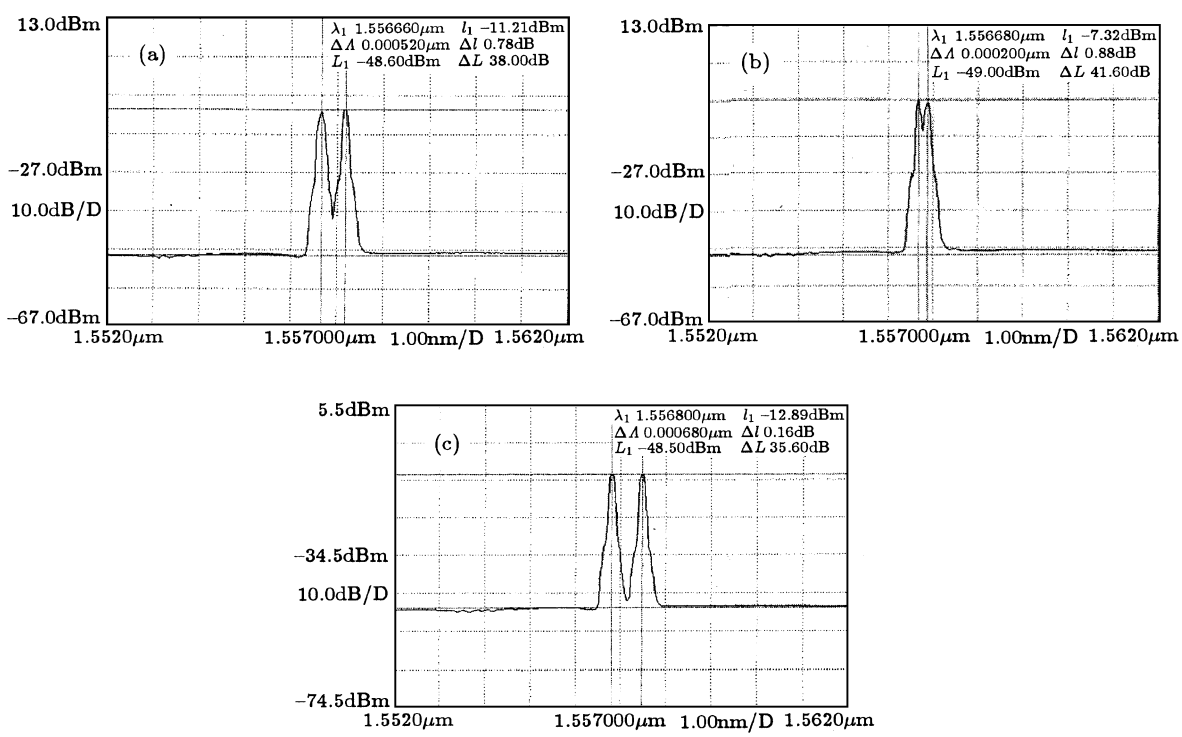


Fig.4. The measured spectra from the second laser for various screwed angles: (a) 0 rad, (b) 0.7rad, with the strain in line with the fast axis (c) 0.2rad with the strain in line with the slow axis.

Wavelength switching was also achieved by adjusting the state of the PC alone.Figure5 shows the output spectra as a function of the polarization state when the strain was in line with the slow axis with a screwed angle of 1.0rad. Figure 5(a) shows the operation at the wavelengths 1556.78nm and 1557.88nm, respectively, which leads to a wavelength spacing of 1.1nm. The corresponding power outputs were about 1.58mW and 1.75mW, respectively. The spectra under dual-wavelength operation of the laser are shown in Fig.5(b). As described above, each state can be obtained by adjusting the state of the PC.

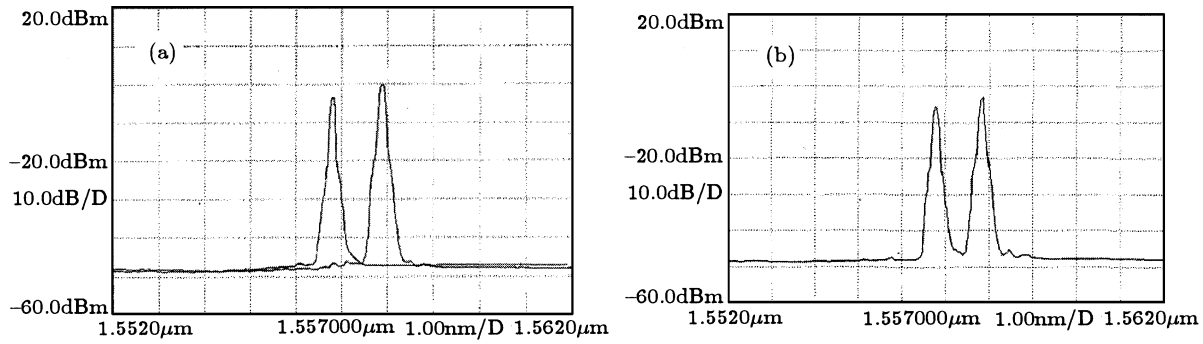


Fig.5. Typical output spectra of the laser operating in switching mode when the strain is in line with the slow axis with a screwed angle of 1.0 rad. (a) single-wavelength operation (1556.78nm, 1557.88nm), (b) dual-wavelength operation.

Figure 6 shows the dependence of the power output on wavelength spacing. It can be seen from the figure that when the strain applied on the grating is small, the variation of the output is also small, but when the strain becomes stronger, the variation in the output also becomes larger. This is mainly due to the decrease in corresponding transmission rate when the strain is strong. Considering the mechanical properties of the FBG, the largest wavelength spacing obtained in the experiment was respectively 0.5nm and 1.1nm for the first and the second lasers, respectively.

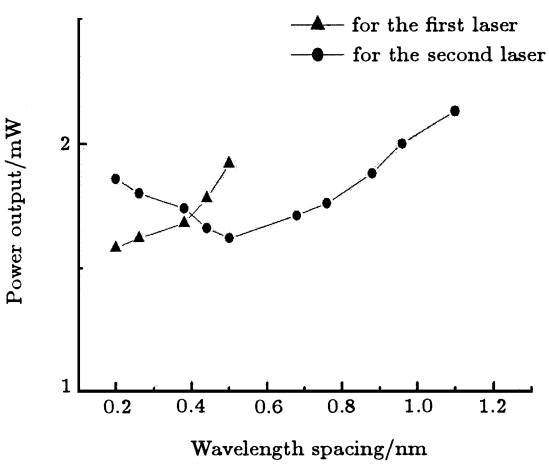


Fig.6. Dependence of power output on the wavelength spacing.

In both experiments, the dual-wavelength operation was very stable at room temperature and no significant drift in wavelength was detected. This is because the PHB greatly increased the inhomogeneous gain broadening of EDF and accordingly reduced the wavelength competition at room temperature. Bending and twisting the fibre led to the change in the output characteristic. But once the polarization controller setting is given and there is no perturbation, the output state is very stable and the FBG need not to be adjusted every time the laser is started up. Another point we have to note is that a change in the temperature of the laser will shift the two wavelengths simultaneously, but not affect the wavelength spacing.[20]

The two lasers demonstrated above have the same operation principle. Each has its own advantages and disadvantages. The second fibre laser has a wide wavelength spacing tunable range compared with the first one. In this paper, we obtain the 0.2–1.1nm tunable range for the second laser and the 0–0.5nm range for the first one. But for the first laser, we need not consider the direction in which the transverse strain is applied on the FBG. Furthermore, the fabrication of the FBG in SMF and the application in the laser are easier than the second one.

4. Conclusion

Two linear cavity EDFLs that enable us to achieve switchable and spacing-tunable dual-wavelength oscillations have been demonstrated. The standard SMF and PM PANDA fibres each included an FBG. Both exploit the birefringent characteristics of the FBG induced by transverse strain. The proposed lasers can be made to operate in stable dual-wavelength or switch between two wavelengths at room temperature, just by simple adjustment of a polarization controller. Transverse strain loading on the FBG allows the wavelength spacing to be controlled. Both lasers have the advantage over alternative techniques in that they are spectrally stable and have a simple configuration, better control of tunability, and low cost.

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