Spacing-adjustable and wavelength-tunable multiwavelength fibre laser with nonlinear Brillouin gain and birefringence fibre loop mirror*

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This paper demonstrates a room-temperature multiwavelength fibre laser with spacing-adjustability and wavelength-tunability. The nonlinear gain of self-excited stimulated Brillouin scattering can suppress mode competition induced by homogeneous broadening of Erbium-doped fibre. With the use of a birefringence fibre loop filter, the wavelength spacing can be adjusted by changing the length of the used birefringence fibre, and the lasing wavelengths can be finely tuned through modifying the filtering profile of the birefringence filter. Multiwavelength output with spectral spacing as small as 0.076 nm and a wavelength number of more than 80 has been successfully produced.

Keywords: multiwavelength fibre laser, stimulated Brillouin scattering, birefringence fibre loop mirror

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1. Introduction

Multiwavelength fibre lasers have attracted considerable interest due to their simple configuration and comprehensive applications in the fields of optical communication,[1] optical fibre sensing,[2] optical component testing,[3] and microwave photonics.[4] In order to achieve room-temperature multiwavelength emission from the fibre laser, many different techniques have been developed to alleviate mode competition caused by the homogeneous broadening gain fibres. For example, frequency-shifted feedback provided through phase modulation in the laser cavity can prevent the single mode operation of the fibre laser,[5] four-wave mixing[6,7] and wavelength-dependent loss induced by nonlinear polarization rotation effect[8] inside the laser can stabilize multiwavelength operation, a semiconductor optical amplifier is incorporated to make use of their inhomogeneous gain characteristics,[9] and nonlinear gain of cascaded stimulated Brillouin scattering[10] or stimulated Raman scattering[11] combines linear gain of Erbium-doped fibre to form a hybrid gain fibre laser. Because the threshold of stimulated Brillouin scattering (SBS) in fibres is rather low, it is convenient to construct a multiwavelength Brillouin/Erbium fibre laser with cascaded SBS.[12]

The hybrid multiwavelength Brillouin/Erbium fibre laser was first proposed by Cowle and Stepanov.[12] Through an externally injecting Brillouin pump and cascading feedback, the multiwavelength output with wavelength spacing determined by the Brillouin frequency shift can be generated. However, in these cases the Brillouin pump must be required, which increases complexity of the laser configuration. Moreover, the mode spacing of the multiwavelength source is fixed at around 9–12 GHz in the 1550-nm region for most fibres, although the exact frequency shift depends on the material and structure of the used fibre.[13,14] Also, the number of generated Brillouin lines is limited, and the power is greatly uneven between each Brillouin wavelength. A new concept of self-starting multiwavelength Brillouin/Erbium fibre

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laser without a Brillouin pump has been proposed and demonstrated, which is achieved simply by incorporating a long single-mode fibre (SMF) into the fibre laser cavity.[15] In the experiment, more than one hundred Brillouin wavelengths with relatively uniform amplitude are generated by using such a simple scheme. However, the wavelength spacing is still unalterable, which corresponds to Brillouin frequency shift of the SMF.

In this paper, spacing-adjustable and wavelength-tunable multiwavelength fibre laser with nonlinear Brillouin gain and birefringence fibre loop filter has been demonstrated by using a simple cavity configuration. The nonlinear Brillouin gain can suppress the mode competition inside the homogenous broadening gain medium of Erbium-doped fibre. With a Sagnac loop consisting of a section of polarization-maintaining fibre (PMF) as the comb filter for selecting lasing wavelength, the wavelength spacing can be adjusted by changing the length of PMF, and the lasing wavelength can be finely tuned through modifying the filtering profile.

2. Experimental setup and operation principle

Figure 1 presents the experimental setup of our multiwavelength fibre laser with nonlinear Brillouin gain and a birefringence fibre loop filter. The laser is very simple, and only consists of three parts: an Erbium-doped fibre amplifier (EDFA), a length of SMF and a birefringence fibre loop mirror. The high-birefringence fibre Sagnac loop mirror is composed of a 3-dB coupler, a section of PMF and two polarization controllers (PCs). The port 3 of an optical circulator (OC) is connected to the port 1 through the EDFA which provides the linear gain. The nonlinear gain of SBS is generated in the 4-km long SMF. The laser output is directly from the spare port of the 3-dB coupler, and measured by using an optical spectrum analyser (OSA) with a spectral resolution of 0.01 nm.

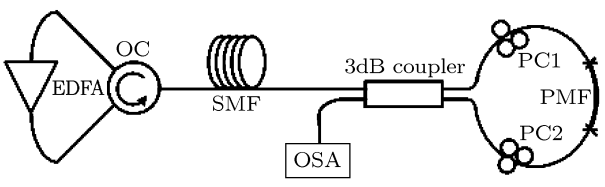


Fig. 1. Experimental setup of our multiwavelength fibre laser with nonlinear Brillouin gain and a birefringence fibre loop filter.

The birefringent Sagnac loop mirror serves as a selective element to determine the output wavelengths. The optical reflection of the birefringent Sagnac loop mirror is a periodic function of wavelength and the comb spacing is given by $\Delta\lambda = \lambda^2/(\Delta nL)$,[16] where Δn and L are the birefringence and the length of the polarization-maintaining fibre, respectively. Those wavelengths lain at the reflection peaks of the birefringent Sagnac loop filter are re-directed to the 4-km SMF, and oscillate in the laser cavity. The total gain experienced by these oscillating wavelengths combines the linear gain from EDF and the nonlinear gain from SMF, thus exhibits an inhomogeneous broadening mechanism. Therefore, the multiwavelength comb can be generated when the Brillouin gain is high enough. By changing the length of the used PMF inside the Sagnac loop mirror, the comb spacing of the birefringent Sagnac loop mirror can be adjusted, and multiwavelength output with adjustable wavelength-spacing can be obtained from the EDF laser. On the other hand, through adjusting the two PCs inside the Sagnac loop mirror, the reflection profile of the Sagnac loop mirror can be tuned. Thus the corresponding wavelength of the multiwavelength output can be tuned correspondingly. In this approach, the birefringent loop filter is used to determine the lasing wavelengths including wavelength value and wavelength spacing, while the multiwavelength operation is supported by SBS in the 4-km single mode fibre.

3. Results and discussion

In the experiment, a short segment of PMF with a length of 16 cm is firstly incorporated into the Sagnac loop mirror. When the 980-nm pump of the EDFA is turned on and its power is set at 160 mW, the multiwavelength output can be obtained under the arbitrary polarisation states of two PCs. The typical multiwavelength output with short PMF has been previously reported.[17] Within one wide reflection band of the Sagnac loop mirror, there are several tens, even more than one hundred Brillouin lines with mode spacing corresponding to Brillouin frequency shift ($\sim$ 0.088 nm). The mechanism has been contributed to the case that the narrowed main oscillating mode serves as the Brillouin pump and generates cascaded SBS bidirectionally within the reflection band of the Sagnac loop mirror.

Next, we investigated if the multiwavelength comb can still be generated, when the length of the

used PMF increases. Different PMF lengths of 7.9, 15.8, 70.2, and 79 m are used inside the Sagnac loop mirror, which produce comb spacings of 0.8, 0.4, 0.09, and 0.08 nm, respectively. Then, we have obtained multiwavelength combs with wavelength spacing corresponding to comb spacing of the birefringent loop filter, other than Brillouin frequency shift. The optical spectra of the multiwavelength output are shown in Fig. 2. The numbers of wavelengths are 9, 22, 84, and 86, respectively. It is noted that the output extinction ratio in each of the cases is more than 20 dB, which is larger than that in the case with short PMF. This is due to that the current multiwavelength combs are the results of wavelength filtering assisted with SBS, while the former is the SBS in one reflection band. To understand the role of SBS in the multiwavelength EDF laser, the 4-km SMF is removed from the setup with 15.8-m PMF. An unstable multiwavelength output is obtained and the competition between the multiple wavelengths is very strong, as shown in Fig. 3(a).

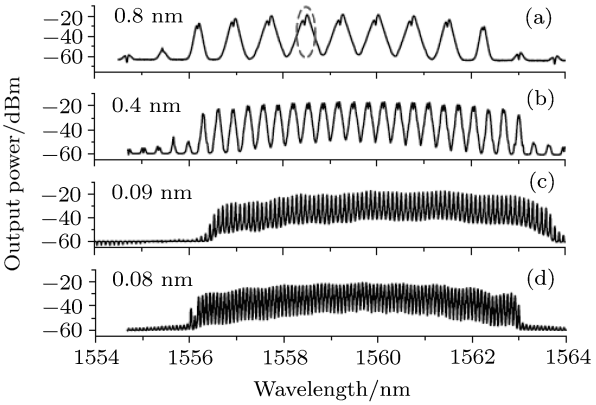


Fig. 2. Optical spectra obtained with different comb spacings of the Sagnac loop filter: (a) 0 8 nm; (b) 0.4 nm; (c) 0.09 nm; (d) 0.08 nm.

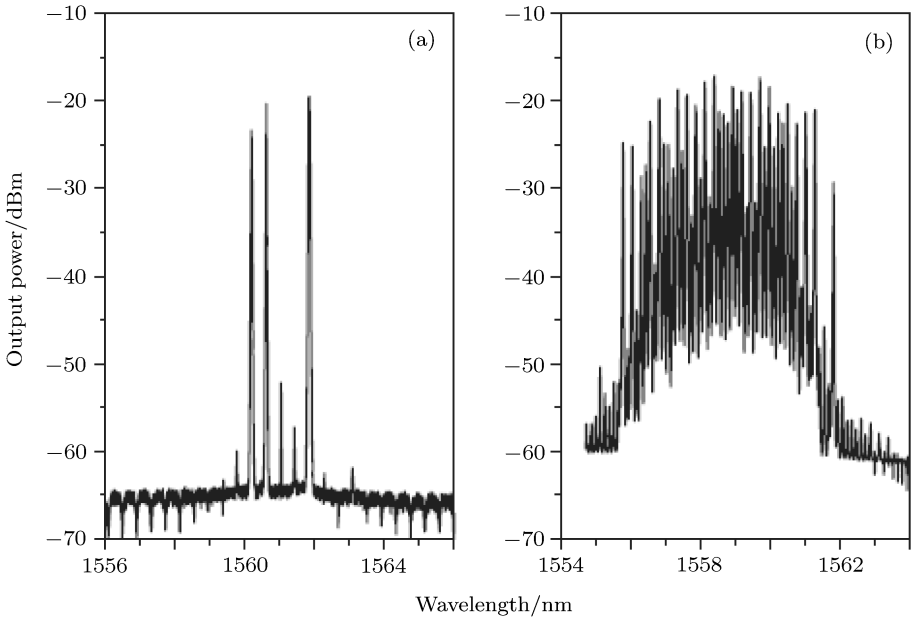


Fig. 3. (a) Output spectrum without SMF, while the used PMF is 15.8 m. (b) Output spectrum with 100-m PMF.

It is indicated that the nonlinear gain of SBS in the SMF can suppress the mode competition, and results in multiwavelength generation. Further evidence is that, within the lasing linewidth of multiwavelength comb with relative large wavelength spacing (Figs. 2(a) and 2(b)), fine spectral components with a spacing of 0.088 nm can be observed. A zoom-in view of an individual component of Fig. 2(a) surrounded by a dashed ellipse is shown in Fig. 4, which clearly shows the 0.088-nm component generated by SBS. Further increasing the PMF length, we can also obtain the multiwavelength comb with smaller wavelength spacing. But there exists a limit, which may be decided by Brillouin gain bandwidth. In our experiment, the minimum spacing that can be obtained is 0.076 nm. As a negative example, figure 3(b) shows the output spectrum with 100-m PMF, which has an unstable multiwavelength.

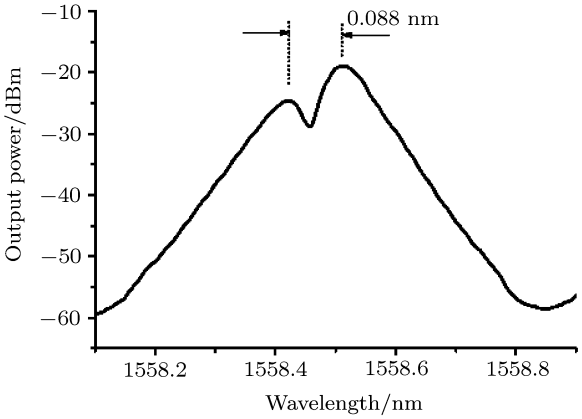


Fig. 4. The zoom-in of an individual component of multiwavelength spectrum with wavelength spacing of 0.8 nm in Fig. 2(a).

Then, to demonstrate tunability of the multiwavelength comb, we adjust the PCs to modify the reflection profile. These wavelengths can be finely tuned in the free spectrum range of the birefringence fibre loop filter, which is the inherent characteristic of the birefringence fibre filter.[18] Figure 5 shows the multiwavelength spectra with wavelength spacing of 0.09 nm under two different polarization states. Figure 6 is the zoom-in of the portion surrounded by a dashed rectangle in Fig. 5. Line 2 relative to line 1 of Fig. 6 has 0.045-nm shift towards right.

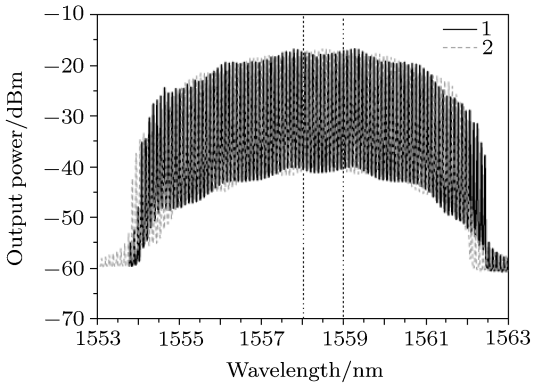


Fig. 5. Multiwavelength combs with wavelength spacing of 0.09 nm under two different polarisation states.

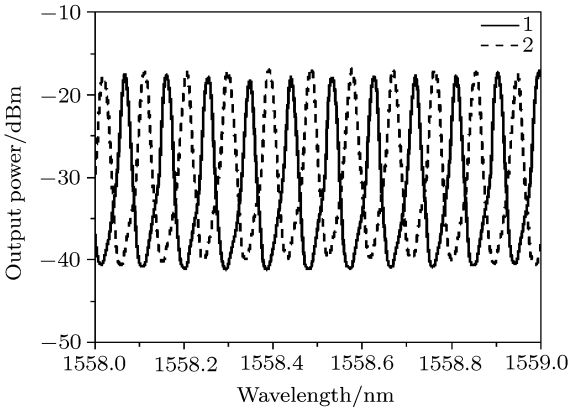


Fig. 6. The zoom-in of the portion surrounded by dashed rectangle in Fig. 5.

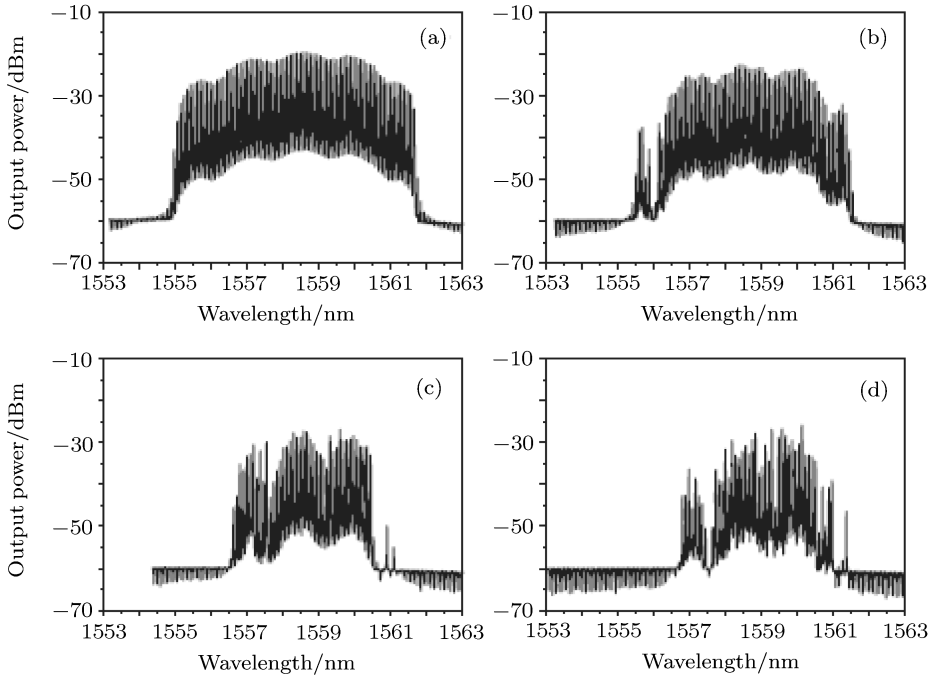


Fig. 7. Output spectra under different powers of 980-nm pump.

Additionally, we have checked the effect of the pump power on the multiwavelength generation. After the multiwavelength comb with wavelength-spacing of 0.09 nm generates at pump power of 160 mW (See Fig. 5 (line 1)), the polarization is kept unchanged, and the pump power decreases step by step. Figure 7 presents the results under the pump power 120, 80, 40, and 20 mW. With the decrease of the pump power the multiwavelength spectra become more and more uneven and unstable. The output spectrum under 40-mW pump power has almost separated into several bands. This is owing to the weakening of the SBS under low pump power.

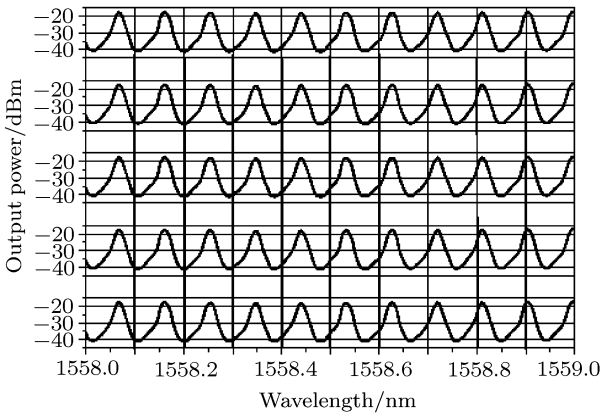


Fig. 8. Five repeatedly scanned spectra of the sampled wavelength band in the dashed box in Fig. 5 (line 1).

To verify the operation stability of the multiwavelength fibre laser source with wavelength spacing other than Brillouin frequency shift, we repeatedly scanned the multiwavelength lasing spectra with 0.09-nm spacing in half-hour spans with five-minute spacing, while keeping the polarization state of the PCs fixed. The results shown in Fig. 8, indicate that the wavelength-adjustable multiwavelength fibre laser source can operate stably on long time scale if no external perturbation is applied to the laser system.

4. Conclusion

We have demonstrated a room-temperature multiwavelength fibre laser with both spacing-adjustability and wavelength-tunability. The nonlinear gain of self-excited SBS can suppress mode competition induced by homogeneous broadening of EDF. With the use of a birefringence fibre loop filter, the wavelength spacing can be adjusted by changing the length of the birefringence fibre, and the lasing wavelength can be finely tuned through modifying the filtering profile of the birefringence filter. Multiwavelength output with spectral spacing as small as 0.076 nm and a wavelength number of more than 80 has been successfully produced.

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