ISSN 1054-660X, Laser Physics, 2010, Vol. 20, No. 3, pp. 720–725.

Switchable and Tuneable Multi-Wavelength Er-Doped Fibre Ring Laser Using Sagnac Filters[1]

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Received August 6, 2009; in final form, September 24, 2009; published online February 2, 2010

Abstract—We demonstrate experimentally a simple configuration to perform wavelength-tuning and multiwavelength operation in a fibre ring laser that is composed of an Erbium-doped fibre and includes a fibre-optic Sagnac interferometer as a spectral filter. We consider three different Sagnac filters including a 3 dB coupler, two wave retarders (WRs) and respectively 7 cm, 1 and 7 m of high birefringence fibre. The transmission spectrum of each filter is sinusoidal with a 70, 6, and 0.85 nm period, and its maxima can be shifted over one period by adjusting the angle of the retarders in the loop. By adjusting the WRs included in the filter and in the laser ring, tuneable single wavelength and several two- or three-wavelength lasing regimes were observed. In particular, fine adjustments of the WRs allow observing two- and three- wavelength operation with wavelength separations well below the homogeneous bandwidth of the gain medium. The stability of these modes of operation however strongly depends on environmental conditions at room temperature.

DOI: 10.1134/S1054660X1005004X

1. INTRODUCTION

Many applications, such as wavelength division multiplexing (WDM), fibre sensors and calibration of optical instruments require tuneable and multiwavelength laser sources. In this work we study experimentally a simple configuration to perform wavelength tuning and multiwavelength operation in a fibre ring laser including Sagnac filters.

As a possible source for WDM networks, multiwavelength lasers have been investigated extensively in recent years. Several methods have been proposed and demonstrated. For example, multiwavelength Erbium-doped fibre lasers have been demonstrated by using the periodic filtering effect of a birefringent fibre together with a polariser [1, 2], by inserting in the laser a comb filter [3] or a Fabry–Perot cavity [4], by using fibre Bragg gratings [5] or intracavity frequency shifting of the lasing modes [6]. In many cases, multiwavelength lasers involve cooling the fibre amplifier, which is required for stable multiwavelength operation when line spacing is of the order of 1 nm, because of the relatively broad homogeneous line width of the Erbium-doped fibre amplifier and subsequent gain competition between the lasing modes.

In this paper, we propose and experimentally demonstrate a tuneable single and multiwavelength erbium-doped fibre ring laser (EDFRL) by using birefringent Sagnac filters [7], which present several advantages. Besides its simple design, the Sagnac structure, in which the two beams propagate along the same path, is more robust to environmental changes than other interferometric schemes. One advantage of the device is its polarization independence [7], which makes it compatible with randomly polarized light from ordinary fibre transmission systems. The spectral filter function intrinsically extends over a wide bandwidth, whereas the bandwidth of one individual channel transmission window only depends on the loop birefringence, and can thus be made arbitrarily wide or narrow. Finally, the device, which consists only of a 50/50 coupler and a piece of fibre, is very cost-effective in comparison with other schemes requiring polarizers [1, 2], circulators [2], a laser diode [4], Bragg gratings [5] or other devices.

Several laser schemes were proposed including one or several Sagnac filters, sometimes in combination with other filtering devices [8–16]. Some schemes use a Sagnac filter for multiwavelength operation [8, 13]; while in other schemes the device allows tuneable single-wavelength operation [9, 10]. In [15], multiwavelength laser operation with a very small channel separation was demonstrated with a Sagnac filter including a polarization-maintaining photonic crystal fibre. In [11, 12], widely tuneable single-wavelength lasers were demonstrated by using two Sagnac filters in series. In [16], the use of a Sagnac filter in combination with eight fibre Bragg gratings allowed discrete wavelength tuning over 80 nm in a bismuth erbium-doped fibre

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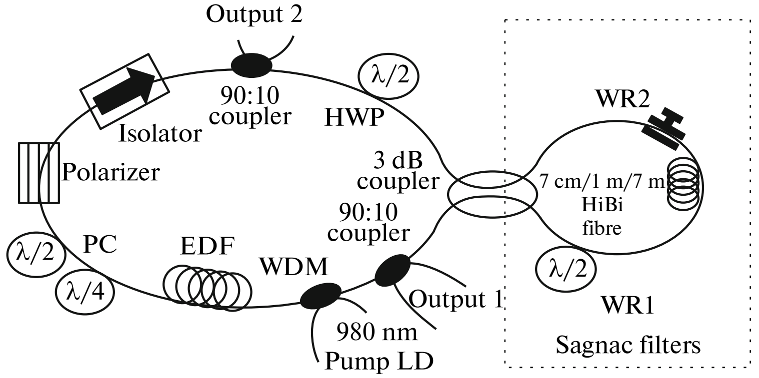

Fig. 1. Experimental configuration of the tuneable and switchable single- and multiwavelength EDFRL. EDF: erbium-doped fibre; LD: 980-nm laser diode; PC: polarization controller; HWP: half-wave plate.

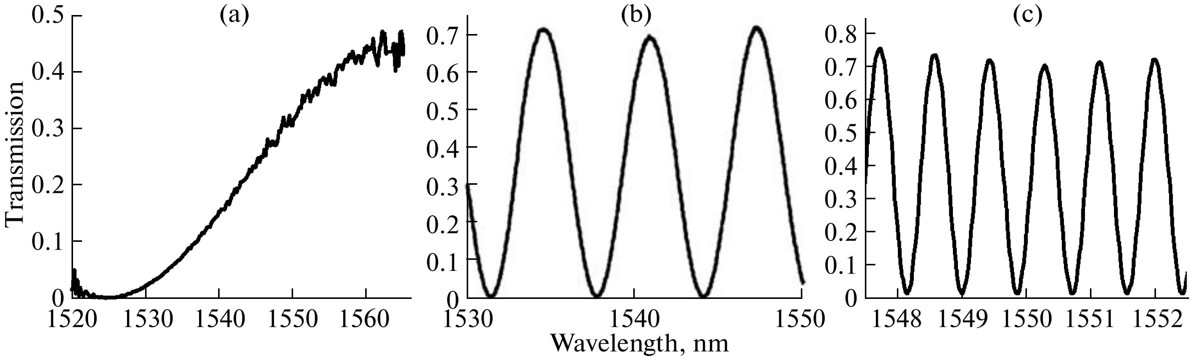

Fig. 2. Experimentally measured transmission of the Sagnac filters including (a) 7 cm, (b) 1 m, and (c) 7 m of HiBi fibre. Transmission spectra were measured using the amplified spontaneous emission of a 980-nm pumped erbium-doped fibre. The filter insertion loss in each case is attributed to splicing losses between high-birefringence and standard fibre in the loop.

laser. In [14], a switchable multiwavelength laser scheme was proposed, which used both a Sagnac interferometer and two fibre Bragg gratings as filtering elements, and allowed generation of two to three closely spaced wavelengths at room temperature. In most works however, multiwavelength and tuneable single-wavelength operations are not observed using the same scheme. In this Paper, we demonstrate experimentally both tuneable single-wavelength and switchable multiwavelength operations in an EDFRL including a Sagnac filter.

2. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The ring cavity includes 4 m of Erbium-doped fibre pumped by a 980 nm laser diode to generate light in the 1550 nm region. An isolator was inserted in the ring cavity to ensure unidirectional propagation of light. The Sagnac filter includes a 3 dB coupler, two wave retarders (WRs) and a segment of high-birefringence (HiBi) fibre. The WR1 is a half-WR, obtained by coiling the fibre over 6 turns with a properly chosen diameter. The WR2 is obtained by applying a mechanical pressure on a section of the fibre, which determines its phase shift. The orientation of the WR2 can also be adjusted. We used three different lengths of HiBi fibre in the experiments. In the first experiment we used 7 cm of HiBi fibre; we used 1 m in the second experiment and 7 m in the third experiment. The fibre beat length is <5 mm. The transmission spectrum is a nearly sinusoidal function of wavelength [7], whose period (or channel spacing) $\Delta\lambda = \lambda_{0c}L_B/L$, where λ_{0c} is the centra) wavelength, L_B is the beat length and L is the length of the HiBi fibre. The experimental values of the filter period are 70, 6.4, and 0.85 nm, respectively (Fig. 2), these values being reasonably close to those calculated using $\Delta\lambda = \lambda_{0c}L_B/L$ with $L_B = 5$ mm and $\lambda_{0c} =$ 1550 nm. The transmission maxima can be shifted over one period by adjusting the angle of WR1 and the angle and pressure of WR2 in the filter.

The ring cavity also includes a polariser and several WRs. The polariser, together with the birefringence of the ring is also responsible for a filtering effect [17, 18].

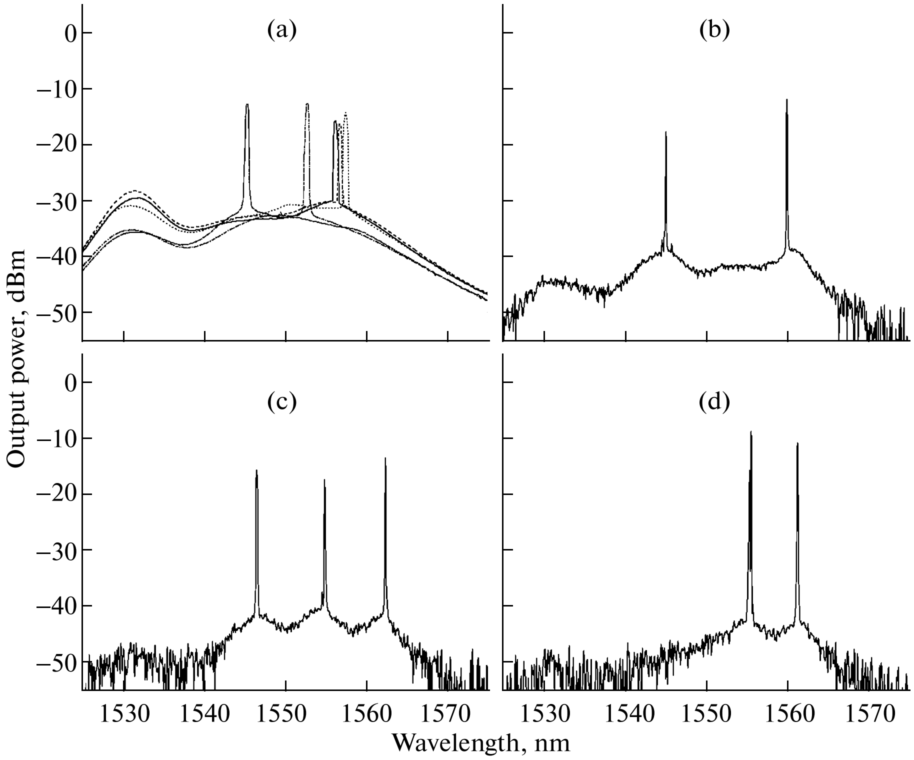

Fig. 3. Output spectra of laser including the 7-cm Sagnac filter; (a) Tuneable single-wavelength operation from 1545 to 1563 nm; (b) double-wavelength oscillation at 1545.1 and 1560.0 nm; (c) triple-wavelength oscillation at 1546.4, 1554.8, and 1562.3 nm; (d) double-wavelength oscillation at 1558.6 and 1563.9 nm.

As the fibre birefringence is small (no HiBi fibre was used in the ring section), this effect induces a slowly varying wavelength-dependent loss, which can be adjusted through the orientation of the WRs.

3. RESULTS AND DISCUSSION

In a first experiment, we used the Sagnac filter including the 7-cm HiBi fibre, and we found that the output spectrum characteristic of this filter has a period of ~70 nm (Fig. 2a). In this case, the filter bandwidth is comparable with gain bandwidth. The purpose of this poorly selective filter is to introduce an adjustable wavelength-dependent loss that will allow us to modify the oscillating wavelength(s). By adjusting the WRs in the filter, single wavelength and several multiwavelength lasing regimes were observed. In single-wavelength operation, the lasing wavelength can be continuously tuned from 1545 to 1563 nm by adjusting the WR1 retarder (Fig. 3a). The tuneable range is about 18 nm. For another adjustment of the retarders, lasing was observed simultaneously at two-wavelengths: 1545.1 and 1560.0 nm, presenting a 15 nm spacing (Fig. 3b). After another small adjustment of the retarders, lasing was observed simultaneously at three wavelengths at 1546.4, 1554.8, and 1562.3 nm presenting ~8 nm spacing (Fig. 3c). Further adjustment of the retarder also allows eliminating either of the first two lines, leading thus to two-wavelength lasing (Fig. 3d shows the spectrum when the two upper wavelengths are maintained). In each case however, the lasing wavelengths were quite instable, due to the poor wavelength selectivity of the filter.

It has to be noted that wavelength tuneability was also observed by adjusting the WRs inserted in the ring cavity, taking advantage of the filtering induced by the fibre birefringence and the polariser [17, 18]. As in the case of the Sagnac filter, the adjustment of the WRs orientation allows adjusting the transmission spectrum of the filter, and thus the oscillating wavelength(s).

In a second experiment, a 1-m section of HiBi fibre was used in the Sagnac filter, which produced a period of ~6.4 nm (Fig. 2b). In this case, several periods of the filter are included in the gain spectrum, defining several wavelength channels. The wavelength-dependent loss due to the fibre ring birefringence and polariser was used to select the channel(s). The WRs in the ring were adjusted to operate in the 1560 nm region. Figure 4a shows one lasing wavelength at 1562.3 nm. For single-wavelength operation, the lasing wavelength can be continuously tuned first from 1562.3 to 1564.6 nm by adjusting the retarders in the Sagnac filter (Fig. 4b). When we further rotated one of the retarders the lasing wavelength jumped to 1558.5 nm, in an adjacent spectral window of the Sagnac filter.

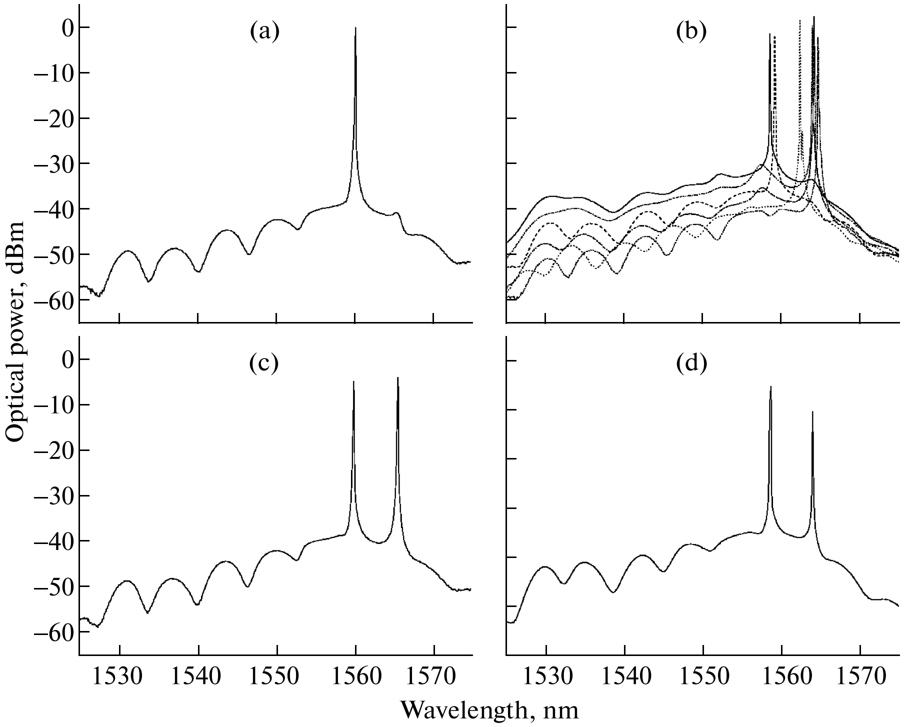

Fig. 4. Output spectra of laser including the 1-m Sagnac filter; (a) Single-wave length oscillation at 1562.3 nm; (b) Tuneable single wavelength operation from 1558.5 to 1559.1 nm and 1562.3 to 1564.6 nm; (c) double-wavelength oscillation at 1560.0 and 1565.6; (d) double-wavelength oscillation at 1558.6 and 1563.9 nm.

Wavelength could then be continuously tuned from 1558.5 to 1559.1 nm (Fig. 4b). For another adjustment of the retarders, lasing was observed simultaneously at two wavelengths at 1560.0 and 1565.6 nm presenting a 5.6 nm spacing, i.e., ~1 Sagnac period (Fig. 4c). For other adjustments, two-wavelength operation was also observed at 1558.6 and 1563.9 nm, presenting a 5.3 nm spacing (Fig. 4d). In this configuration however, three-wavelength lasing was not observed. For a given adjustment of the WRs, the lasing wavelengths were in this case much more stable than in previous configuration, thanks to the much narrower bandwidth of the Sagnac filter. The lasing linewidth was smaller than the resolution limit of the optical spectrum analyser (0.1 nm).

As a third experiment, a 7 m HiBi fibre was inserted in the Sagnac filter to generate a spectral period of approximately 0.85 nm (Fig. 2c). In single-wavelength operation, the lasing wavelength can be tuned by steps of 0.85 nm from 1560.65 to 1570.20 nm by adjusting the WRs in the ring (Fig. 5a). The tuneable range is about 10 nm. For another small adjustment of the retarder, lasing was observed simultaneously at two wavelengths, which could be continuously tuned over several nm. Figure 5b shows double-wavelength operation at 1559.1 and 1565.2 nm, presenting 6.1 nm spacing (~7 Sagnac filter periods), and at 1563.5 and 1570.5 nm, presenting 7.1 nm spacing (~8 Sagnac periods). We also were able to observe two-wavelength operation at 1565.15 and 1566.91 nm, presenting only 1.76 nm spacing (2 Sagnac periods) (Fig. 5c). It is noticeable that the double wavelength lasing was relatively stable, as it was maintained during ~5 min or more, considering the strong competition due to homogeneous broadening that takes place between so close wavelengths. When we rotated smoothly the retarder, we even observed three-wavelength operation at 1565.15, 1566.03, and 1566.91 presenting 0.88 nm spacing (one Sagnac period) (Fig. 5d). Three wavelength operation was maintained during 20 repeated scans of the spectrum analyser (~20 s) before disappearing. In this case however, the amplitude of the first line of lasing was quite instable. The former experiment was realized in the morning, and we repeated the experiment at a different time of the day to check if this multiple-wavelength operation appeared again. This operation was not observed, however. Instead, three-wavelength operation with a larger separation (several Sagnac periods) was observed. Our results thus show that closely spaced (separation <1 nm) multiple (two-three) wavelength operation is possible in an EDFRL at room temperature; however it requires a very fine equalization of the losses at each wavelength. The environmental perturbations (temperature changes, mechanical vibrations) are also expected to play a major role in the stability of the lasing lines; in particular, the device should be temperature-stabilized for long-term stable operation.

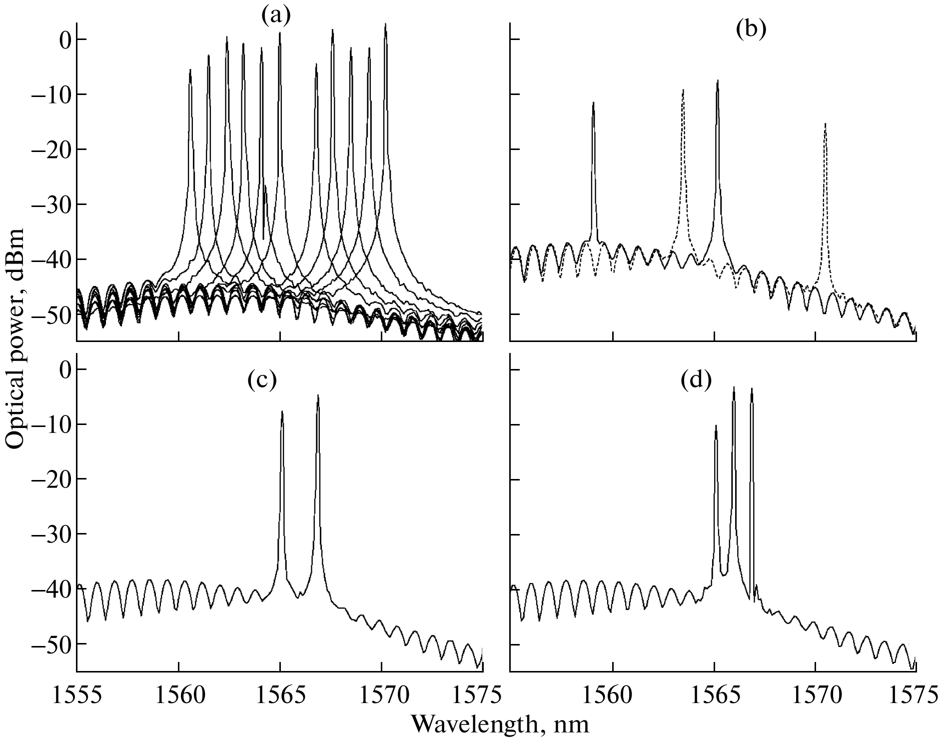

Fig. 5. Output spectra of laser including the 7-m Sagnac filter; (a) discretely tuneable single-wavelength operation from 1560.65 to 1570.20 nm; (b) double-wavelength operation at 1559.1 and 1565.2 nm and at 1563.6 and 1570.5 nm; (c) double-wavelength oscillation at 1565.15 and 1566.91 nm; (d) triple-wavelength oscillation at 1565.15, 1566.03, and 1566.91 nm.

4. CONCLUSIONS

We have studied wavelength tuneability and multiple wavelength operation of an EDFRL including a birefringent Sagnac filter. A Sagnac filter including a short segment of HiBi fibre introduces wavelength-dependent losses, which can be adjusted using WRs to obtain tuneable single-wavelength operation or multiple (two or three) wavelength operation. Adjustable wavelength-dependent losses are also present in the ring laser, which includes a polariser and small-birefringence fibre, as well as WRs for adjustment. The use of a Sagnac filter including a longer segment of HiBi fibre defines several narrow channels in the gain spectrum, and stabilizes the oscillating wavelength(s). Switching between discrete channels, as well as multiple-wavelength operation can be obtained by adjusting the wavelength-dependent losses through the WRs in the ring. Simultaneous lasing at two or three wavelengths separated by several nm is relatively easy to observe, and remains stable thanks to the inhomogeneously broadened gain medium. Tuneable two-wavelength operation over several nm was also demonstrated in one case. By a fine adjustment of the wavelength-dependent losses, we also obtained two- and three-wavelength lasing with 1.76 and 0.88 nm wavelength spacing, respectively, these values being much smaller than the homogeneous bandwidth of the gain medium at room temperature. Although our results demonstrate that simultaneous oscillation at two and three closely spaced wavelengths is possible in an EDFRL including a Sagnac filter at room temperature, they also show that stable long-term operation requires temperature stabilisation.

ACKNOWLEDGMENTS

A. González-García was supported by CONACyT grant 175808 and O. Pottiez supported by CONACyT grant 53990.

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