IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 4, Number 1, February 2012

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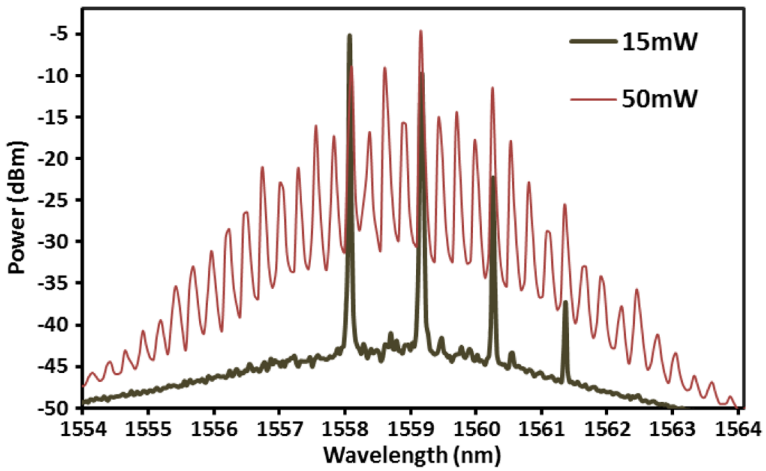

DOI: 10.1109/JPHOT.2011.2178400
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Spacing-Switchable Multiwavelength Fiber Laser Based on Nonlinear Polarization Rotation and Brillouin Scattering in Photonic Crystal Fiber

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DOI: 10.1109/JPHOT.2011.2178400
1943-0655/$26.00 ©2011 IEEE

Manuscript received November 6, 2011; revised November 25, 2011; accepted November 29, 2011. Date of publication December 7, 2011; date of current version December 23, 2011. This work was supported by the University of Malaya under the High Impact Research Grant Scheme (Grant D0000009-16001) and University of Malaya Research Grant (UMRG) (Grant RG108/11AET). Corresponding author: S. W. Harun (e-mail: swharun@um.edu.my).

Abstract: A new spacing-switchable multiwavelength erbium-doped fiber laser (EDFL) is demonstrated using switchable nonlinear polarization rotation (NPR) and stimulated Brillouin scattering (SBS) effects. The laser employs a 100-m-long photonic crystal fiber in conjunction with a four-port circulator in a figure-of-eight arrangement to provide the intensity-dependent transmission effect, as well as to discriminate the even-order and odd-order Brillouin Stokes to have a double-frequency Brillouin Stokes output. Without the Brillouin pump (BP), the laser operates in an NPR mode to produce at least 22 lasing wavelengths with a side mode suppression ratio of more than 10 dB and a wavelength spacing of 0.27 nm. In the Brillouin erbium fiber laser mode, at least 30 Brillouin lines with a spacing of 0.16 nm are obtained at BP power of 3 dBm and 980-nm pump power of 120 mW.

Index Terms: Erbium-doped fiber laser (EDFL), multiwavelength, nonlinear polarization rotation, stimulated Brillouin scattering (SBS).

1. Introduction

Multiwavelength lasers have attracted tremendous interest, owing to their potential applications in dense wavelength division multiplexing (DWDM) systems, as well as in optical sensors, spectroscopy, and optical instrument testing [1], [2]. Many techniques have been reported for multiwavelength generation in room temperature, which are mainly based on stimulated Brillouin scattering (SBS), spectral slicing, and semiconductor laser diode (SOA) type lasers [3]–[5]. Multiwavelength Brillouin erbium fiber lasers (BEFLs) have caught the interest of researchers due to its uncomplicated configuration and low threshold [2], [3]. The wavelength spacing of single-frequency BEFL of 0.08 nm is too narrow for DWDM system. Thus, double Brillouin frequency spacing fiber lasers seem to have a better potential for the DWDM system. Double Brillouin frequency spacing fiber laser has been reported utilizing EDFA, circulators, and kilometers long SMF in ring cavities [6], [7]. An erbium-doped fiber laser (EDFL) is a common option for generating a multiwavelength output. However, it is necessary to suppress the homogeneous broadening and the unstable mode

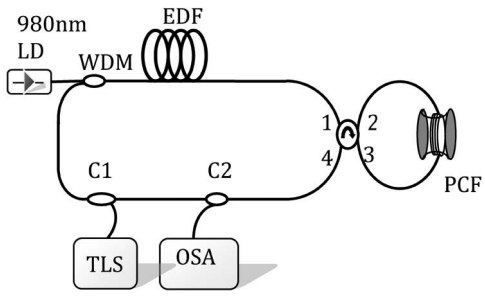

Fig. 1. Configuration of the proposed switchable multiwavelength EDFL.

competition of the erbium-doped fiber (EDF) to achieve a stable multiwavelength operation at room temperature [8]. To overcome this obstacle, various techniques have been proposed to realize room temperature multiwavelength fiber lasers [9], [10].

Nonlinear polarization rotation (NPR) is one of the techniques used to overcome the unstable mode competition and generate multiwavelength output in EDFL [11], [12]. NPR-based multiwavelength fiber laser can be realized using a simple structure as it does not need an external laser i.e., for Brillouin pump (BP) or pumps for FWM to create idler waves. NPR-induced intensity-dependent loss mechanism could suppress the mode competition, and hence generate multiwavelength laser. A birefringent fiber could introduce intensity-dependent state of polarization [13]. NPR can exist in birefringent fiber due to nonlinear birefringence induced phase shifting [14]. A typical index guiding PCF exhibits higher birefringence than a conventional fiber with at least 1 order of magnitude higher than that of the conventional fiber (the order of 10^{-4}) [15]. In addition, the multiwavelength generation could be further stabilized by the four wave mixing effect in the PCF.

Multiwavelength fiber lasers with a switchable channel spacing have been reported employing multiple polarization maintaining fiber in sagnac loop mirror [16], [17], inducing phase shift in FBG (fiber Bragg grating) [18] and discriminating odd and even order Brillouin Stokes [19]. In this paper, a new multiwavelength EDFL with a switchable channel spacing is demonstrated based on a hybrid SBS and an NPR mechanism in PCF. The channel spacing of the laser can be easily changed by switching on and off the BP laser. A circulator is incorporated in the laser cavity to play a dual-role of providing a unidirectional oscillation for NPR and selecting an element for double spacing BEFL.

2. Experimental Setup

Fig. 1 shows the experimental setup of the ring EDFL which is configured to implement the switching of NPR and SBS effects in the cavity. This switchable multiwavelength laser system consists of two 3-dB couplers, a four-port circulator, a tunable laser source (TLS), a wavelength selective coupler (WSC), an EDF, and a PCF. The PCF used has a length of 100 m with a nonlinear coefficient of about 11 W^{-1} km^{-1}, a zero-dispersion wavelength of around 1550 nm and an attenuation of 9 dB/km at 1550 nm region. The gain medium used is an 8 m long EDF with Er^{3+} concentration of 440 ppm. It is pumped by a 980-nm laser diode through a 980/1550 wavelength division multiplexer (WDM). A 3-dB coupler is used to extract a portion of the laser as an output to be fed into an optical spectrum analyzer (OSA) and another one is employed to couple the BP light from the TLS. A four-port circulator is used in the resonator to discriminate the even and odd-order Brillouin Stokes. In addition, the circulator provides a unidirectional operation for the NPR-based multiwavelength laser. The TLS used has a linewidth of 20 MHz, which is sufficient enough for SBS operation. A tunable laser is used as the BP so that its wavelength can be adjusted to be as close as possible to the free-running wavelength of the EDFL.

For the BEFL mode of operation, the coupling of the BP light to the laser system is achieved using of a 3-dB coupler. The Brillouin gain medium is provided by the PCF. The BP signal

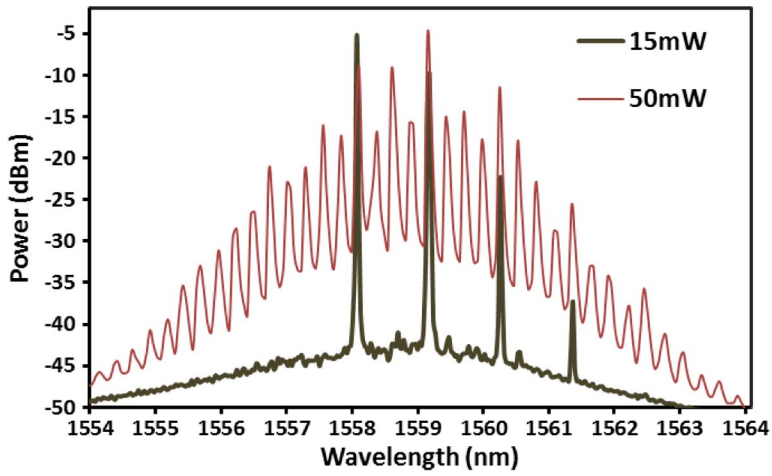

Fig. 2. Output spectrum of the proposed spacing switchable multiwavelength laser with NPR mode.

propagates in the EDF before entering the PCF. In this way, the BP accumulates more energy to increase the efficiency of the Brillouin gain in the PCF and subsequently generates a downshifted first-order Brillouin Stokes signal (S1) once the BP power exceeds its threshold. S1 travels in the opposite direction to BP toward port 2 and passes through port 3 toward the PCF to complete a round trip. S1 circulates in the cavity in counterclockwise direction and its amplification is provided by the BP. The second order Brillouin Stokes (S2) is generated when S1 (acting as pump for S2) reaches its threshold and later travels from port 3 toward port 4 in the same direction as the BP's travelling path. A portion of S2 will be amplified by the EDFA and higher order Stokes can be generated in a cascaded process, as long as the Stokes signal gain is higher than the cavity loss. Hence, the four-port circulator plays a role in discriminating the even-order and odd-order Brillouin Stokes to have a double-frequency Brillouin Stokes output at the 3-dB coupler.

The NPR mode of operation takes place when BP was not injected into the cavity. The circulator provides a unidirectional oscillation in the cavity. The isolator works together with the PCF to constitute an equivalent Lyot birefringence fiber filter with a periodic filtering spectrum [20]. In addition to the comb filter, an intensity-dependent transmission is also generated. This allows the transmissivity to degrade with the increase of intracavity light power, which can balance mode competition of homogenous broadening in the gain medium to get a room temperature multiwavelength generation.

3. Results and Discussion

Fig. 2 shows the multiwavelength oscillation without the BP. In the NPR mode, the multiwavelength laser exhibits wavelength spacing of 0.27 nm and 1.08 nm at pump power of 50 mW and 15 mW, respectively. Fifteen mW is the pump power threshold for the multiwavelength laser based on NPR, which is less than the value reported in [11], [12] and, to the best of our knowledge, is the lowest value of the NPR induced multiwavelength laser in fiber so far. This improvement is essentially due to much less insertion loss of the cavity from the absence of polarization controllers and an isolator which contributes to higher loss in the cavity. The multiwavelength generation is further stabilized by the four-wave mixing in PCF. As shown in Fig. 2, at least 22 lasing wavelengths are obtained with side mode suppression ratio of more than 10 dB and a wavelength spacing of 0.27 nm. The basic principle of NPR-based multiwavelength EDFL is intensity- and wavelength-dependent transmission of the laser cavity. The NPR can exist in PCF due to the presence of linear birefringence, which induces phase shifting and changes the polarization state from linear to elliptical [13], [14].

A four-port optical circulator is a key element, which works together with the PCF to generate intensity-dependent transmission. The PCF is a polarization maintaining type, whose function is to

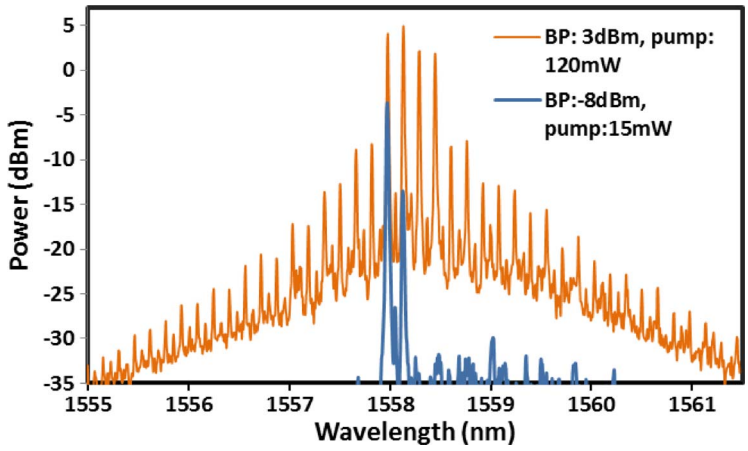

Fig. 3. Output spectrum of the switchable multiwavelength laser with BEFL mode at different BP and 980-nm pump powers.

increase the nonlinear effect and to form an in-line periodic birefringence fiber filter with the assistance of the optical circulator in the figure of eight cavity structure. The proposed laser operates with a negative feedback, where the cavity transmittivity decreases with the increase of the light power. That is, higher intensity input light experiences higher losses, and the combination functions as an intensity equalizer. This intensity-dependent loss can be used to suppress the mode competition resulting from the homogeneous gain broadening of EDF for stable room-temperature multiwavelength oscillations. The wavelength spacing is determined by the equation of $\Delta\lambda = \lambda^2/(\Delta nL)$, where Δn is the birefringence, and L is the length of the PCF. By including the estimated birefringence of the PCF of 5.8×10^{-5}, the operating wavelength of 1559 nm, and PCFs length of 100 m, the theoretical line spacing is calculated to be around 0.42 nm, which is close to the experimental value of 0.27 nm.

Fig. 3 shows the output spectrum of the multiwavelength laser with BEFL mode, which is obtained when the BP is on. The second-order BS line is clearly observed at the BP power of -8 dBm and at the 980 nm pump power of 15 mW with a spacing of 0.16 nm in wavelength. As the BP and the 980-nm pump power increase, the number and the power of the lines also increase as adequate pump power becomes available to amplify the higher order BS lines to reach their threshold for oscillation in the laser cavity. At the BP and 980-nm pump powers of 3 dBm and 120 mW, respectively, 30 double-frequency Brillouin lines are generated. Here, an improvement in the number of generated lines is observed in comparison with those reported by the previous reports [6], [7], owing to the use of PCF and EDFA in the cavity. The PCF enhances the four-wave mixing process, while the EDFA allows the BP to be preamplified before it enters the PCF. The proposed switchable fiber laser should be stable for different operating modes, but the range cannot be far from the free-running lasing wavelength of EDFL. The proposed laser has potential applications in future DWDM networks of specific functions and the design of tunable photonic microwave filters.

4. Conclusion

A spacing-switchable multiwavelength fiber laser system is demonstrated using a four-port circulator and 100-m-long PCF to allow the switching of NPR and SBS effects to occur in the cavity. Without the BP, the intensity-dependent transmission induced by the NPR effect is used for room-temperature multiwavelength generation. At least 20 lasing wavelengths are obtained with the SMSR of 10 dB and channel spacing of 0.27 nm at 980-nm pump power of 80 mW. In the BEFL mode, 31 lines with double Brillouin frequency spacing of 0.16 nm are obtained at the BP power of 3 dBm and 980-nm pump power of 120 mW.

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