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Widely tunable linear-cavity multiwavelength fiber laser with distributed Brillouin scattering

M. Ajiya[1], **M. H. Al-Mansoori**[2], **and M. A. Mahdi**[3*]

[1]*Department of Electrical Engineering, Faculty of Technology, Bayero University, PMB 3011, Kano, Nigeria*
[2]*Faculty of Engineering, Sohar University, P.O Box 44, Sohar P.C. 311, Oman.*
[3]*Wireless and Photonics Networks Research Center, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.*
[*]*Corresponding author: mdadzir@eng.upm.edu.my*

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We demonstrate a multiple wavelength Brillouin/erbium fiber laser in a linear cavity configuration. The laser cavity is made up of a fiber loop mirror on one end of the resonator and a virtual mirror generated from the distributed stimulated Brillouin scattering effect on the other end. Due to the weak reflectivity provided by the virtual mirror, self-lasing cavity modes are completely suppressed from the laser cavity. At Brillouin pump and 1480-nm pump powers of 2 and 130 mW, respectively, 11 channels of the demonstrated laser with an average total power of 7.13 dBm can freely be tuned over a span of 37-nm wavelength from 1530 to 1567 nm.

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Fiber lasers are of great importance in optical communications due to their advantages, notably compatibility with other optical devices and low threshold value. An efficient fiber laser that exhibits a threshold value of 3.6 mW by utilizing the principles of Brillouin scattering has been demonstrated[1]. Fiber lasers also offer the unique advantage of producing multiple frequencies from a single frequency coherent light source, thus an attractive candidate for the dense wavelength division multiplexing systems[2]. Technologies demonstrated for multiwavelength generation include multiwavelength Raman fiber laser (MWRFL)[3], multiwavelength erbium doped fiber laser (MWEDFL)[4], multiwavelength Brillouin/erbium fiber laser (MWBEFL)[5], multiple wavelengths generation using phase modulation in optical fibers[6], and multiwavelength fiber ring laser based on a chirped Moiré fiber grating that possesses excellent comb-like filtering characteristics[7]. MWBEFL and MWRFL have the advantage of maintaining a narrow channel spacing of about 10 GHz. MWBEFL also has the advantage of better optical signal-to-noise ratio (OSNR)[8]. However, a major drawback of MWBEFL is the limited wavelength tunability owing to the self-lasing cavity modes. Schemes employed to overcome this limitation include spectrum filtering[9], double-pass Brillouin pump (BP) amplification technique[10], and recently the use of variable optical attenuator to control the cavity mode oscillations[11]. Although the previous schemes were able to improve the tunability in MWBEFL, the self-lasing cavity modes cannot completely be suppressed from the laser cavity. We revealed the concept of virtual reflectivity in a ring cavity MWBEFL that remedies the tuning range limitation of MWBEFL, but the structure provides only four output channels[12].

In this letter, we demonstrate the concept of a virtual mirror in a linear cavity-configured MWBEFL. The laser not only demonstrates the complete absence of self-lasing cavity modes in the resonator, and thus can be widely and freely tuned, but also provides a higher number of output channels (11) compared with our previous work[12] at the same BP power of 2 mW and a 1480-nm laser diode (LD) pump power (PP) of 130 mW. The generated channels can broadly be tuned over a span of 37 nm from 1530 to 1567 nm, with an average channel power of 7.13 dBm. In this approach, the generated Brillouin Stokes (BS) line, which acts as the subsequent higher order BP signal, experiences double-pass amplification due to the positioning of the erbium-doped fiber amplifier EDFA in the resonator. In this way, the BS signal accumulates more energy, thus increasing the efficiency of the Brillouin gain in the optical fiber.

Figure 1 depicts the configuration of the proposed laser. The linear cavity was formed between a fiber loop mirror on one end and a virtual mirror on the other end of the laser cavity. The elements of the resonator are 3 dB optical couplers C1 and C2, an optical circulator (CIR), an EDFA gain block, a coil of dispersion compensating fiber (DCF), and an optical isolator. C1 and C2 are placed in the fiber loop section of the resonator. The BP signal, which is provided by an external tunable laser source, was injected into the laser cavity through C1. The output of the laser systems was connected to an optical spectrum analyzer (OSA) through C2. The optical circulator was utilized to form the fiber loop mirror. The EDFA gain block consists of 8-m-long erbium-doped fiber (EDF), a 1480/1550-nm wavelength selective coupler (WSC), and a 1480-nm LD pump with a maximum power of 130 mW used primarily for the excitation of the erbium ions in the EDF. The WSC was employed to multiplex the oscillating signals and the 1480-nm laser pump signal. An 11-km-long DCF was employed to serve as the Brillouin gain medium, whereas the optical isolator was used to guard against any back reflection from the transmitted BP signal at the other end of the DCF. The injected BP signal will be forced into the EDF gain block by the optical circulator, where it experiences pre-amplification before being guided into the DCF. When the power of the BP signal overcomes the threshold conditions in the DCF, stimulated Brillouin scattering (SBS) is initiated. This effect results in the creation of the first-order BS signal that propagates in the opposite direction to the propagation direction of the BP signal. The first-order BS signal experiences double-pass amplification before it is directed into the DCF. With sufficient power, this first-order BS signal acts as the BP to create the second-order BS signal. In the same way, the second-order BS signal induces the creation of the third-order BS signal. The process is incessant until the next higher-order BS signal cannot overcome the Brillouin threshold condition in the DCF. In a conservative linear cavity MWBEFL, the oscillating modes are reflected back into the laser cavity at their own wavelength by a physical reflector. In this research work, no physical reflector was employed at one end of the laser cavity in reflecting the oscillating modes, but the effect of SBS was used as a virtual mirror that ensures the oscillating modes to be reflected back into the laser cavity by their lower-order BS signals, and thus the reflectivity is determined by the Brillouin gain in the DCF. The resolution of the OSA was set to 0.015 nm for all observations and measurements in the experiment.

We investigated the tunability of the laser system by fixing the BP power and 1480-nm PP at their maximum values of 2 and 130 mW, respectively. We then tuned the laser over the entire C-band, from 1530 to 1570 nm with a step of 4 nm. We found that 11 generated channels with a total average power of 7.13 dBm could broadly be tuned over 37 nm. At a BP wavelength of 1570 nm, the number of channels dropped to 10 due to the reduction of the erbium gain, as depicted in Fig. 2, which also shows the total output power of the generated channels over a wavelength span of 40 nm. The tunability in MWBEFL is limited largely due to the intrinsically generated cavity modes in the laser cavity caused by the homogeneous effect in the EDF[9]. The obtained results indicate that our proposed structure exhibits superior performance to the 14.5-nm tunable range, where the highest channel has a peak power of −25 dBm[9], and the recently reported 23-nm tuning range, where the first Stokes signal of the 11 channels has a power of about −24 dBm[11].

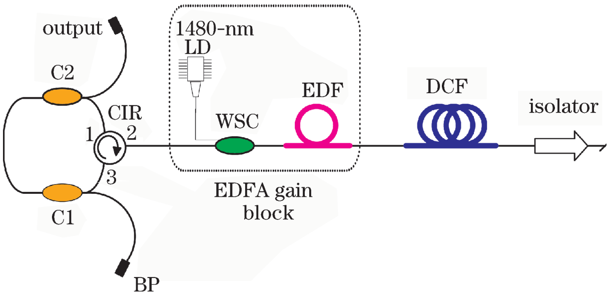

Fig. 1. Experimental setup of the proposed MWBEFL.

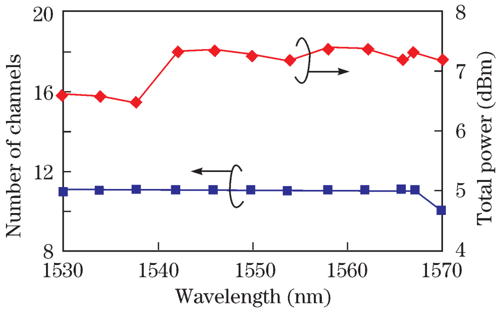

Fig. 2. Wavelength tunability of the laser and total channel power against the BP wavelength at a BP power of 2 mW and PP of 130 mW.

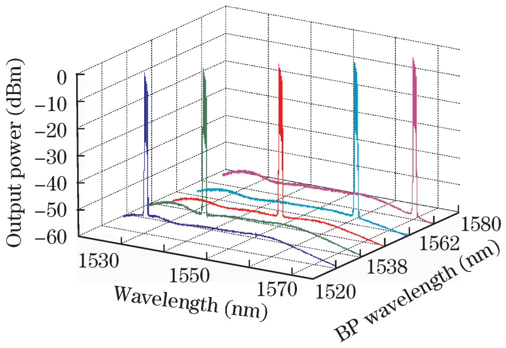

Fig. 3. Output spectra of the MWBEFL at a BP power of 2 mW and PP of 130 mW showing the generated channels at selected wavelengths of 1530, 1538, 1550, 1562, and 1570 nm.

The wide wavelength tunability is attributed to the fact that the weak reflectivity offered by the virtual mirror is much lower compared with the effect of SBS. This means that the SBS has selected its bandwidth reflection based on the injected BP wavelength. The source of reflection in the DCF section is due to the Rayleigh scattering[12]. We then investigated the total power of the generated output channels against the BP wavelength over the entire tuning range as shown in Fig. 2, where the channel's total power at a BP wavelength higher than 1542 nm to the end of the tuning range stands above 7 dBm. The fact that the power did not drop at a BP wavelength of 1566 nm, which is the outer bandwidth of the erbium gain, signifies that there is no gain peaking due to the lasing conditions. We found such lasers to demonstrate very good stability. In our previously reported work[12], the lasing lines, except the highest Stokes line, have an average power fluctuation of 0.42 dB with a wavelength shift of only 0.002 nm after a 60-min observation period. The highest order Stokes line has an average power fluctuation of 1.85 dB due to its inability to reach its saturation level caused by the diminishing effect of the Brillouin gain.

The output spectra of the tunable laser system at the selected wavelengths of 1530, 1538, 1550, 1562, and 1570 nm are shown in Fig. 3. These wavelengths are selected to show that the MWBEFL is devoid of any self-lasing cavity modes within the laser cavity for any BP wavelength within the selected tuning range. The corresponding magnified view of the spectrum at a BP wavelength of 1530, 1550, 1567, and 1570 nm is depicted in Fig. 4. Referring to Fig. 4, the output consists of 11 channels up to 1567 nm BP wavelength and 10 channels at 1570-nm BP wavelength. The first channel resulted from the BP, whereas the other subsequent channels resulted from the SBS effect in the DCF. In this work, we define channels as the cascaded Stokes signals where the peak power difference between the neighboring Stokes signals is not more than 10 dB with each Stokes signal having an OSNR

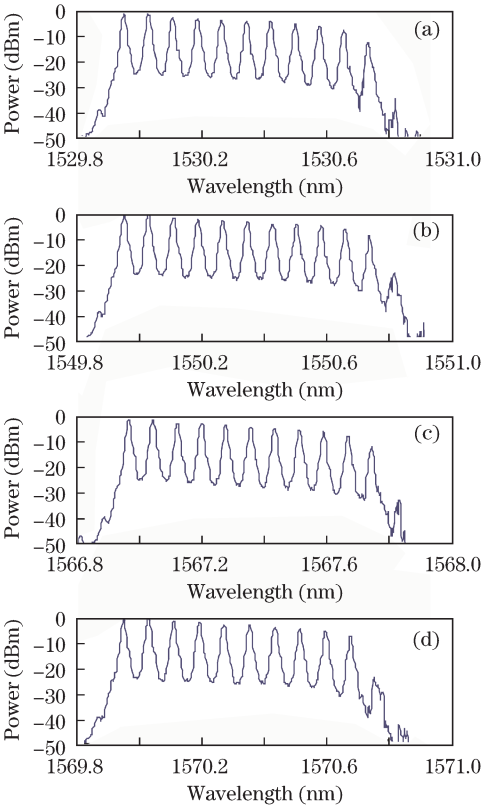

Fig. 4. Magnified view of the output channels at the BP wavelengths of (a) 1530, (b) 1550, (c) 1567, and (d) 1570 nm.

above 15 dB. Throughout the 40-nm tuning range, the first 10 channels have an individual power level above −10 dBm. Moreover, comparing the channel's peak power to the highest noise floor level, good OSNR above 20 dB was maintained by all the channels throughout the 40-nm tuning range. The results presented in Fig. 4 were obtained without having either spectral or cavity manipulation devices and confirmed a better performance than where the channels have the highest peak power of −25 and −23 dBm as reported in Refs. [9,11], respectively.

We have successfully demonstrated MWBEFL in a new linear cavity configuration made up of a fiber loop mirror on one end and a virtual mirror on the other. The laser system indicates the complete absence of self-lasing modes within the active gain region of the EDFA. The virtual mirror utilizes wavelength selective reflectivity generated from the distributed Brillouin scattering effect in the DCF. Due to the weak reflectivity condition, the self-lasing modes are completely suppressed from the laser cavity, thereby producing a wide wavelength tunable range. A total of 11 channels with an average total power of 7.13 dBm are freely tuned over a span of 37 nm from 1530 to 1567 nm at a BP power of 2 mW and PP of 130 mW.

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