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An ultra-wideband tunable multi-wavelength Brillouin fibre laser based on a semiconductor optical amplifier and dispersion compensating fibre in a linear cavity configuration

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Abstract. **A multi-wavelength Brillouin fibre laser (MBFL) with an ultra-wideband tuning range from 1420 nm to 1620 nm is demonstrated. The MBFL uses an ultra-wideband semiconductor optical amplifier (SOA) and a dispersion compensating fibre (DCF) as the linear gain medium and nonlinear gain medium, respectively. The proposed MBFL has a wide tuning range covering the short (S-), conventional (C-) and long (L-) bands with a wavelength spacing of 0.08 nm, making it highly suitable for DWDM system applications. The output power of the observed Brillouin Stokes ranges approximately from –5.94 dBm to –0.41 dBm for the S-band, from –4.34 dBm to 0.02 dBm for the C-band and from –2.19 dBm to 0.39 dBm for the L-band. The spacing between each adjacent wavelengths of all the three bands is about 0.08 nm, which is approximately 10.7 GHz for the frequency domain.**

Keywords: *Brillouin fibre laser, ultra-wideband semiconductor optical amplifier, linear cavity, lasing comb, Stokes lines.*

1. Introduction

One of the primary goals of continued research in optical communications systems is to increase the total transmission bit rate over long communication links in dense wavelength division multiplexing (DWDM) systems. Whilst the DWDM technology saves cost in terms of transmission infrastructure, multiple wavelength sources are still required to fully exploit the increased capacity of the DWDM-enabled system, and this can incur a significant cost (this would therefore negate any cost savings from the DWDM systems).

Multi-wavelength sources provide a viable cost-effective alternative over the use of multiple single-wavelength sources in DWDM systems, thus allowing the full capabilities of the DWDM system to be realised. Many linear and nonlinear methods can be employed to generate multiple wavelength sources from various gain media, including conventional erbium-doped fibre amplifiers (EDFAs), semiconductor optical amplifiers (SOAs) or via such nonlinear phenomenon as stimulated Brillouin scattering (SBS) [1–6]. The operational bandwidths of DWDM systems are determined by the operating regions of the optical amplifiers used in these systems. Conventional EDFAs are particularly effective at the C-band (from 1525 to 1565 nm) or the L-band (from 1570 to 1610 nm) and can also be extended to the S-band (from 1460 to 1520 nm) using depressed cladding erbium-doped fibres (DC-EDFs) [7, 8]. Small signal gain amplifiers in the form of SOAs also allow for amplification in all three bands. S-band amplification can also be realised using fluoride doped fibres [such as in thulium-doped fibre Amplifiers (TDFAs)] or by such nonlinear methods as Raman amplification [9, 10]. They can also be used for fabrication of multi-wavelength sources when combined with such techniques as the Sagnac loop mirror (SLM), Brillouin's effect and also tunable band-pass filters (TBFs) in a fibre laser configuration to generate a multi-wavelength output. SLM techniques typically make use of a polarisation maintaining fibre (PMF) of a particular length as a mirror in order to attain a multi-wavelength lasing comb [2, 5, 6], whilst the SBS effect can be used by inserting a high intensity source signal into a high-nonlinear fibre, thus generating Brillouin Stokes which are then amplified by a linear gain medium, for example, by a fibre amplifier [3, 4, 11]. The SBS technique is the most common method employed in developing multi-wavelength sources; however, it suffers from certain shortcomings in terms of generating a wide tuning range for the multi-wavelength output due to the homogeneous broadening effect experienced by the fibre amplifier. Many research works have shown that the tuning range of multi-wavelength fibre lasers developed with the SBS technique are limited to within a certain bandwidth of transmission [12–14].

To overcome this limitation, we propose a multi-wavelength Brillouin fibre laser (MBFL) with an ultra-wide tuning range. An SOA is used in the proposed MBFL as the linear gain medium to amplify the generated Brillouin Stokes from the nonlinear gain medium, because the inhomogeneous broadening characteristics of the SOA are well-known to be able to overcome the limitations of fibre-based optical amplifiers in terms of the range of wavelengths that can be amplified [1].

2. Experimental setup

Figure 1 shows the proposed setup for the ultra-wide band MBFL. The MBFL consists of a 7.7-km-long dispersion compensating fibre (DCF) that acts as a nonlinear gain medium. The DCF has a dispersion of -584 ps nm^{-1} and an insertion loss of approximately 6.66×10^{-3} dB m^{-1}. An ultra-wide bandwidth SOA is used as a linear gain medium to the MBFL system. A tunable laser source (TLS) acts as a Brillouin pump (BP). The BP enters the system through one of the 50% ports of 50:50 fused coupler. Upon entering the 50:50 coupler, the TLS signal then travels to the DCF, where it interacts with the nonlinear gain medium and generates a multi-wavelength out-

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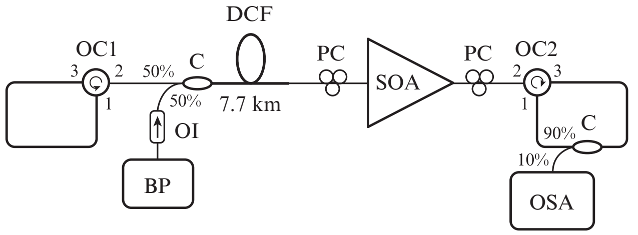

Figure 1. Experimental setup of the proposed MBFL: (BP) Brillouin pump; (OI) optical isolator; (OC) optical circulator; (DCF) dispersion compensating fibre; (PC) polarisation controller; (SOA) semiconductor optical amplifier; (C) coupler; (OSA) optical spectrum analyser.

put comb through the SBS process. The multi-wavelength output comb exits the DCF and enters the linear laser cavity [which is constructed using two optical circulators (OCs) with both ends connected to the BFL system designated as OC1 and OC2] as shown in Fig. 1. The OCs are configured to act as mirrors by connecting port 1 to port 3 whilst port 2 is connected to the input and output of the BFL system. The multi-wavelength signal is amplified by the SOA placed within the linear cavity. The SOA is manufactured by Alphion and has an operational amplification bandwidth of 1460 nm to 1620 nm, which is able to cover the S-, C- and L-band regions. A 90:10 fused coupler is placed between port 1 and port 3 of OC2 to extract a 10% portion of the signal for analysis by an optical spectrum analyser (OSA) with a resolution of 0.02 nm.

The SBS process is as follows: the BP signal is emitted by the TLS and travels into the linear cavity via the 50% port of the optical coupler. It then passes to the common port of the 50:50 fused coupler and continues onward to the DCF, where it will interact with the nonlinear gain medium to generate the first Brillouin Stokes. The electrostriction process that arises inside the nonlinear gain medium results in the production of phonon waves, which then contribute to the backscattered signal. This backscattered signal is corollary from the incidence of the BP with the phonon waves. The first Stokes from the backscattered signal will travel in the opposite direction of the BP towards OC1 and is then reflected back into the cavity where it enters the DCF and the interaction process repeats to generate the second Stokes. This process of oscillation continues, with each subsequent Stokes wavelength generated at a slightly lower power than the previous Stokes until the Stokes generates no longer the threshold power required for the SBS process to continue. The obtained multi-wavelength comb makes many passes through the SOA via the linear cavity configuration, and will be amplified to the point of lasing where it now becomes a multi-wavelength laser.

3. Results and discussions

Figure 2 shows the amplified spontaneous emission (ASE) spectrum of the ultra-wide band SOA at different injection currents. The observed ASE spectrum covers the region from 1400 nm to 1650 nm and can be used to gauge the gain pattern of the proposed MBFL.

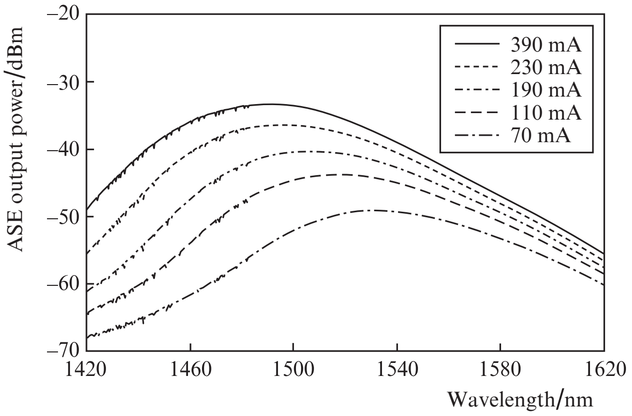

Figure 2. ASE output power spectrum of the SOA at different injection currents.

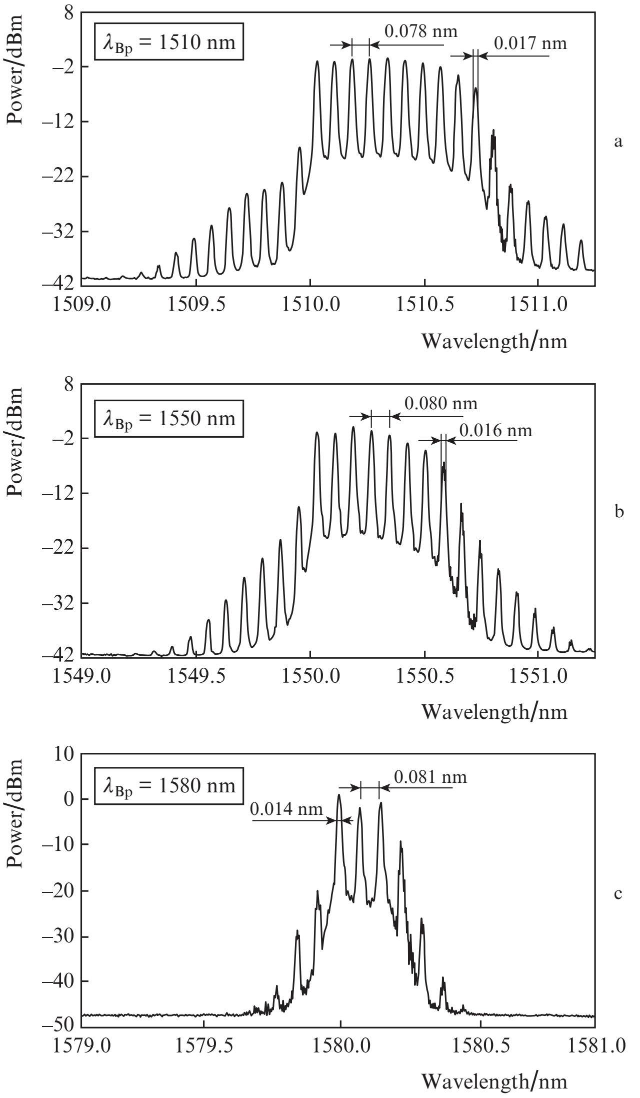

Figure 3. Lasing combs generated with a Brillouin pump wavelength of (a) 1510, (b) 1550, and (c) 1580 nm at 10.6 dBm.

It can be seen that the ASE output power generated by the SOA shifts towards the shorter wavelength region as the injection current is increased. This is attributed to the energy absorbed by the excited electrons from the lower energy level state to the higher energy level state, which is then de-excited and emitted as a photon with the same energy as the excited electron. The increase in the energy of the photon results in shorter wavelengths. Figure 3 shows multi-wavelength comb spectrum generated by BP wavelengths of 1510 nm, 1550 nm, and 1580 nm with a power of 10.6 dBm.

The injection current of the SOA is set to 390 mA as to provide the maximum linear amplification width (see Fig. 2). At a BP wavelength of 1510 nm, 10 Brillouin Stokes are generated. The peak powers of the lasing wavelengths in the S-band are observed to be in the range from –5.94 dBm to –0.41 dBm, with wavelength spacings of approximately 0.078 nm and a 3-dB linewidth of approximately 0.017 nm as obtained from the OSA. In the C-band, 8 Brillouin Stokes with peak powers of –4.34 dBm to 0.02 dBm and wavelength spacings of approximately 0.080 nm with a 3-dB linewidth of approximately 0.016 nm are observed. In the L-band, 3 Brillouin Stokes with peak powers ranging from –2.19 dBm to 0.39 dBm are obtained with wavelength spacings of approximately 0.081 nm between each consecutive Stokes line observed and a 3-dB linewidth of approximately 0.014 nm. The low number of Brillouin Stokes in Fig. 3c is attributed to the low ASE output power (and henceforth low gain) in that region (Fig. 2). One can see that the number of generated Brillouin Stokes is higher in the shorter wavelength region but reduces towards the longer wavelength region. This is attributed to the gain pattern of the ultra-wide band SOA, where the higher gain in the shorter wavelength region generates higher peak powers, and thus generates Stokes via the Brillouin effect. Essentially, this shows that the higher the gain, the higher the peak power achieved so as to overcome the threshold power and generate more Stokes via the Brillouin effect.

Further analysis of the output of the proposed MBFL shows that the generated multi-wavelength combs with the wavelengths shorter than the BP wavelengths (anti-Stokes) are caused by effect of four-wave mixing (FWM) as shown in the three cases. This is largely due to the high nonlinear properties of the SOA. The spacing between each adjacent wavelength is computed to be approximately 0.08 nm or approximately 10.7 GHz in the frequency domain. As a point to note, less anti-Stokes are generated using EDFAs as compared to the SOA. Figure 4 shows the number of lasing lines in the generated multi-wavelength comb at different BP wavelengths, and it can be inferred that the peak power of the lasing wavelengths from the generated multi-wavelength comb closely matches the ASE spectrum within the same wavelength range.

Since the ultra-wideband SOA used in this experiment covers a range of 1480 nm to 1610 nm, the Brillouin effect is also observed to be present within this wavelength region, as the SOA can provide the necessary amplification for the SBS process to continue. The total number of Stokes lines for each BP wavelength is plotted in Fig. 4. It can be inferred that the most Stokes lines are generated at a wavelength range from 1500 nm to 1520 nm, which is approximately 10 Stokes lines.

The MBFL system is tested at intervals of 10 min for a period of 70 min at room temperature to determine its stability and reliability. Actually, this system was left running for more than 10 h during the total duration of this experiment. The output of the system for different bands is presented in Fig. 5. It can be seen from Fig. 5 that the output of the MBFL is stable, with almost no fluctuations or variations in the output power. This ensures that the system is stable and can be used for various applications.

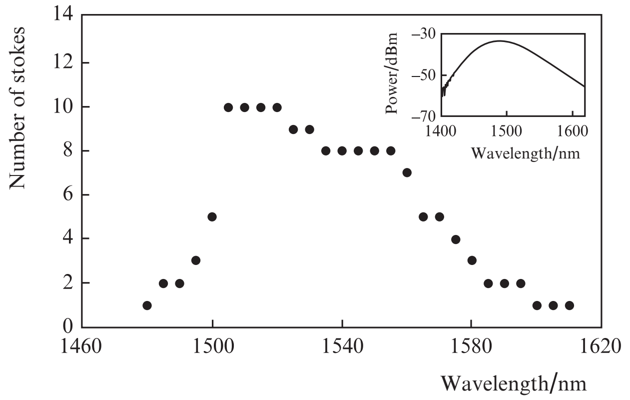

Figure 4. Total number of Stokes in the lasing comb, observed within 1480 nm and 1610 nm at a BP power of 10.6 dBm. The inset is the ASE spectrum of the ultra-wideband SOA with an injection current of 390 mA.

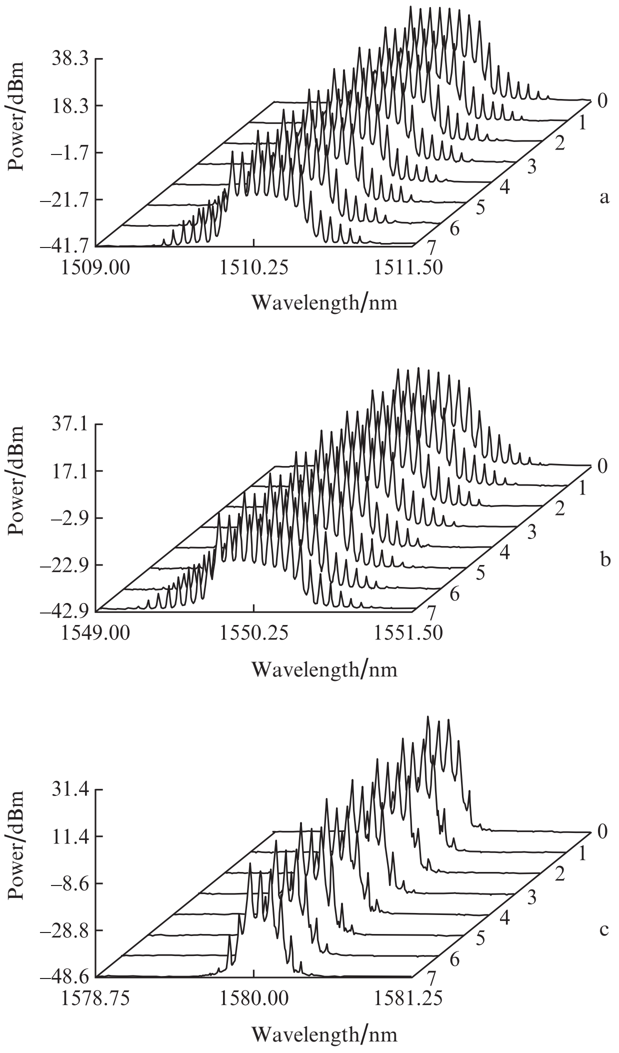

Figure 5. Spectra of the proposed MBLF at 10-min intervals over a testing period of 70 min for the (a) S-, (b) C- and (c) L-bands.

4. Conclusions

In this paper, we have proposed and demonstrated a novel MBFL with a wide tuning range from 1480 nm to 1620 nm that covers the S-, C- and L-bands for optical communications. A laser comb with 10 Brillouin Stokes has been achieved in the S-band, with a wavelength spacing of 0.078 nm and a

3-dB linewidth of 0.017 nm. The output powers from peak to peak vary from –5.94 dBm to –0.41 dBm. For the C-band region, 8 Stokes lines are generated with a wavelength spacing of 0.080 nm and 3-dB linewidth of 0.016 nm. The peak to peak output power varies between –4.34 dBm to 0.02 dBm. In the L-band region, 3 Stokes lines are observed which is due to the low ASE output power because of the gain distribution of the SOA. The wavelength spacing between these lines is approximately 0.081 nm with a 3-dB linewidth of 0.014 nm. The values of the output power are noted to be within the range of –2.19 dBm to 0.39 dBm. Continued running of the systems from 70 min to more than 10 h demonstrates the stability and reliability of the system, with power fluctuations of less than 2 dB.

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