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Four-wave-mixing-assisted Brillouin fiber laser with double-Brillouin-frequency spacing

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ABSTRACT

The generation of multiwavelength Brillouin fiber laser assisted by four wave mixing has been demonstrated. A maximum of 18 channels of laser Stokes lines are generated at a Brillouin Pump (BP) of 190 mW (~22.5 dBm). The multiple peaks have a wavelength spacing of 0.176 nm (~20 GHz). A tunable optical bandpass filter is incorporated to the design to suppress up to 6 dB of the noise floor hump exhibited at the multiwavelength laser spectrum while limiting the laser peaks attenuation thereby providing a much cleaner and better OSNR.

1. Introduction

Multiwavelength fiber laser has drawn much attention into various applications such as sensor networks [1], microwave photonics processing, wavelength division multiplexing (WDM) light sources [2] and optical component testing. Bearing the traits of its low cost implementation and serving a high degree of immunity from effects of heat loading [3] as well as a stable narrow linewidth laser source [4], it soon became the centre of attention for researchers to investigate on a more channel, power efficient, usage versatile and flexible laser. Whilst various gain media such as erbium-doped fiber, Ytterbium-doped fiber, Bismuth-oxide-doped fiber and etc. are employed to designing fiber laser, nonlinear optical effects such as stimulated Brillouin scattering (SBS), stimulated Raman Scattering (SRS) [5] and Rayleigh scattering [6] have also been introduced to aid the performance of it. The design of Brillouin-erbium fiber laser (BEFL) on creating multiple lasing lines has been progressively reported for the past few years. Having the characteristic of stable operation in room temperature [4] and having multiple lasing lines, it soon became the attraction for optical signal processing applications [2,7,8]. The cons of them, however, are that the free running cavity modes constrain the wavelength tunability [9]. Besides, typical wavelength spacing of BEFL which is about 11 GHz will complicate the demultiplexing process at the near receiver end due to the narrow wavelength spacing [9].

Brillouin fiber laser (BFL), on the other hand, eliminates the free running cavity mode limitation as the erbium doped fiber amplifier (EDFA) does not sit within the cavity loop [10,11]. Yet the limitation of narrow wavelength spacing still could not be eliminated. In spite of BFL or BEFL designs, there were many attempts of generating a stable output laser comb with as many channels as possible via Brillouin scattering mechanism that operates at L, C and/or S band [15–18]. Shee et al. [9] have realized 20 GHz wavelength spacing of multiwavelength BEFL with 10 output channels and 9 nm tuning range is realized. It was done by incorporating a 4-port circulator into a 6.7 km SMF to expand the channel spacing. In its previous design [12], the Double-Brillouin-Frequency-Shift (DBFS) system serves to widen or expand the wavelength spacing which is 20 GHz rather than merely Brillouin wavelength shift of 10 GHz. It is then discovered that by tapping out signals from the opposite direction within the cavity loop, multiwavelength fiber laser assisted by multiple four-wave mixing (FWM) processes that intertwine each other [13,14] can be retrieved. Similar study has been reported employing 3-ports circulators and a 2.5 km SMF that outputs 19 lasing lines with 20 GHz wavelength spacing [19]. However, this finding exhibited a huge hump that would lead to poor OSNR. In present work, the OSNR of the multiwavelength laser is improved by suppressing the amplified spontaneous emission (ASE) noise floor of the EDFA.

2. Experimental setup

Fig. 1 shows the configuration of the Brillouin fiber laser by utilizing the nonlinear effect of FWM. It consists of a tunable laser source (TLS) modeled Santec WSL-100 with polarization extinction

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ratio of more than 20 dB/Hz and maximum output power of 13 dBm, a 1 W EDFA module from KEOPSYS, a tunable bandpass filter (TBF) with insertion loss of (1.5 dB), sideband suppression of (20 dB) and linewidth of (0.045 nm), an optical attenuator (OA), two optical couplers (OC), a 3-port circulator, a 6.5 km single mode fiber (SMF) that is used as Brillouin gain medium (BGM) and YOKOGAWA OSA AQ6373 with 0.02 nm resolution. The Brillouin pump (BP) from the TLS that has a linewidth of 5 MHz at wavelength of 1559.59 nm is amplified by an EDFA to provide the sufficient power for SBS to occur. The TBF is meant for suppressing ASE noise floor resulted from EDFA, hence producing a much cleaner OSNR. Output of TBF passes to an OA to control the laser power followed byOC1 that splits 5% of the power into optical spectrum analyzer (OSA2) for monitoring and 95% into the circulator port1.

The BP enters the circulator at port-1 comes out at port-2 and is launched into the 6.5 km SMF, which acts as BGM. At a relatively strong BP, given that it exceeds the Brillouin threshold, excites the first-order Brillouin Stokes signal (BS1) to propagate at the backwards direction. Then, BS1 enters OC2where 10% of the power monitors at OSA1 and the remaining 90% power re-enters BGM to complete the loos through the port-2 and -3 of the circulator. This is essentially the ring cavity. BS1 circulates within the cavity until BGM generates the sufficient energy to excite the second-order Stokes signal (BS2) that propagates at the forward direction.

FWM process does play a role in assisting and enhancing Brillouin effect to occur as discussed in [19,20]. To summarize the operating mechanism of the system, Fig. 2 illustrates a closer look on the backwards and forwards propagation of the signals. As BP enters the BGM, this power will be transferred to BS1. However, there will still be a remnant of Brillouin Pump (Re-BP) that forward propagates out of BGM. At the same time, a small amount of power will be transferred to the backwards direction of BP due to Rayleigh scattering (R-BP). This Rayleigh scattering also plays a crucial role to encourage FWM. The forward propagating BS2 as a result of the circulating BS1 within the ring cavity produces another Rayleigh scattered BS2 (R-BS2) in the backwards direction.

The three signals, R-BP, BS1 and R-BS2 that propagate at the backwards direction within the same fiber as illustrated in Fig. 2 experience FWM effect. These three signals will create idler frequency or wavelength at $f_{\text{idler}} = f_{\text{p1}} + f_{\text{p2}} - f_{\text{probe}}$ [14]. The two newly created signals from FWM effects are at 0.088 nm apart which coincides with the Brillouin wavelength. Thus, the FWM is indeed assisting SBS effect in the BFL system. The web of chain interaction between signals that circulating within the cavity further produce more idlers, provided that they have sufficient power. This can be explained when Cholan et al. [20] has demonstrated the performance of BEFL with and without the assistance of FWM. With the assistance of FWM, it does provide a much superior output. The generation of higher order Stokes signal stops when the circulating power within the loop can longer reach the higher Brillouin threshold of the SMF. Consequently, multiwavelength fiber laser can be observed at OSA1.

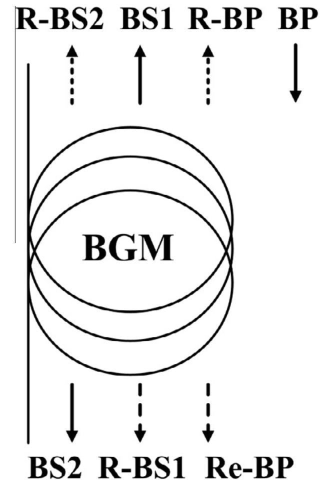

Fig. 2. Schematic for Brillouin Stokes signals propagation direction.

3. Experimental results and discussion

The multiwavelength output spectrum is first to be investigated in this work. Fig. 3 shows the multiwavelength output spectrum corresponding to the input BP spectrum. The backwards direction of the odd order Stokes signals show a relatively high OSNR as compared to the weakly Rayleigh scattered even order Stokes signals. Taking to an account of having more than 10 dB OSNR will only can be considered as one Stokes channel, the 19.9 dBm input BP is capable of producing 13 Stokes channels. The wavelength spacing of the Stokes signals are at 0.176 nm (~20 GHz) apart as shown in Fig. 3. This gives a huge benefit as double Brillouin frequency spacing configuration is easier to be demultiplxed as compared to the 0.088 nm-spaced (10 GHz) Brillouin Stokes output.

The ASE noise floor from the EDFA is suspected to be responsible for the high noise floor hump of the BFL output shown in Fig. 3. It is therefore worthwhile to investigate the noise floor phenomenon. In Fig. 1, the TBF (dotted line) is placed in and out from the system for comparison purpose. Fig. 4(a) and (b) shows the BFL spectrums evolution at different BP power stages. Fig. 4(a) has no TBF implemented in the system while the Fig. 4(b). Five different input peak powers are tested in this experiment which are 4.05, 41.11, 81.10, 130.92 and 179.06 mW. Observing the spectrums on both figures (with and without TBF cases), the noise floor suppression is not uniform at all input power. The noise floor suppression is at its minimal for BP input of 4.05 mW. At input power of 41.11 mW, the Stokes signals start to excite and rise. Comparing the spectrum of the same input power with its counterpart, the suppression is maximum at BP input range of 81.10 mW – 130.92 mW when the OSNR for the Stokes signals are considered at its optimal. However, when the BP power reached 179.06 mW,

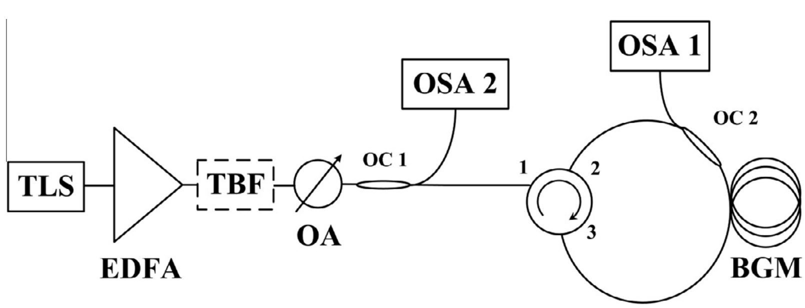

Fig. 1. Experimental setup for Brillouin fiber laser with double Brillouin frequency spacing.