Enhancement of multiwavelength generation in the L-band by using a novel Brillouin-Erbium fiber laser with a passive EDF booster section

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Abstract: We demonstrate a novel scheme to generate multiple wavelengths in the L-band using a Brillouin-Erbium fiber laser. Our scheme utilizes extraneous amplified spontaneous emission in the C-band as a secondary pump source for a passive Erbium-doped fiber gain section along the cavity. The Brillouin gain medium is generated by the 6.7 km long of single mode fiber (SMF-28). We experimentally demonstrate that a total of 28 stable output channels with a spacing of 0.089 nm can be generated using our new scheme. This represents a 33% increase in the number of wavelengths generated compared with conventional schemes.

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References and links

1. Introduction

Multiwavelength laser sources are of great interest in many physics and engineering applications requiring optical sensing and high speed, high density signal transmission. Due to the increase in data volumes, the available bandwidth in conventional C-band is not adequate for present-day dense wavelength division multiplexed (DWDM) transmission systems. Therefore, engineers are trying to utilize the longer wavelength band (L-band) in the low-attenuation window [1].

Stimulated Brillouin scattering in optical fibers has been exploited as the key mechanism to create closely-spaced channels around 0.089 nm (~ 10 GHz) in Brillouin-Erbium fiber laser (BEFL) structures [2]. BEFL’s simultaneously utilize the inhomogeneous broadening characteristics resulting from the optical coupling of erbium gain medium with the narrow-band nonlinear stimulated Brillouin scattering gain in optical fiber. It is well-known that ring-cavity fiber laser structures utilizing above processes can generate a significant number of laser lines in the C-band [3-5]. However, for the L-band region, only five Stokes lines can be generated from such a ring-cavity laser structure [6]. Moreover, the generation of Brillouin Stokes lines in L-band is very much dependent on the design of the resonator. Recently, a linear-cavity BEFL structure of having higher number of Brillouin Stokes lines have been reported in [7]. The improvement of Brillouin Stokes lines generation in [7] is owing to the interaction of Brillouin pump (BP) and the Stokes lines twice as they propagate through the linear cavity medium after end-mirror reflections.

Due to the energy band distribution of Erbium ions, EDF amplifiers can provide higher efficiency in C-band compared with L-band. Therefore, active gain enhancement techniques tailored for EDF amplifiers operating in the L-band are essential for them to be useful in practice. It is widely known that the tail of the erbium gain band overlaps with the L-band and hence the emission and absorption coefficients tend to have lower values compared with corresponding values in the C-band, leading to an overall reduction in the amplifier gain. To circumvent these deficiencies in the L-band, recently, several novel gain enhancement techniques were reported in literature [8-11]. One of these techniques effectively re-use the unwanted broadband amplified spontaneous emission (ASE) as a pumping source for passive Erbium-doped fiber (EDF) section [10]. Using this technique, the transformation from C-band to L-band ASE source is realized [12]. Even though that this technique has already been adopted in ring-cavity BEFL, no experimental work has undertaken until now to investigate its impact on the number of Stokes lines in such a configuration [6].

In this paper, we propose and experimentally demonstrate the utilization of extraneous ASE into a passive EDF section to increase the number of Brillouin Stokes lines in the linear cavity of a BEFL. The main innovative step in our approach is the use of extraneous ASE as a secondary pump source for EDF to strengthen the signal strength of Brillouin Stokes lines in the cavity. Moreover, use of ASE as a secondary pump source increases the efficiency of the overall scheme.

2. Experimental set-up

We consider two different variants of BEFL configurations in this paper. Figure 1 shows the base linear-cavity common to both these configurations. Brillouin gain is provided by the single-mode fiber (SMF-28 type) with length of 6.7 km. In the lasing configuration, lasing feedback is provided by placing two mirrors (M1 & M2) at ends of the resonator cavity. The primary pump laser of 1480 nm is used to invert the Erbium ions from the ground state level to the upper energy level for the optical amplification. We use 1480 nm pumping because of...
the higher efficiency it provides compared with the 980 nm pumping scheme [13]. Pump light is multiplexed via a wavelength selective coupler (WSC) into a length of EDF.

For BEFL Configuration-A, the resonator cavity consists only a length of 12 m EDF coil as depicted in Fig. 1. The EDF has a doping density of 900 ppm of Er$^{3+}$-ions, an absorption coefficient of 19 dB/m at 1530 nm and a cut-off wavelength around 1420 nm. The EDF is optimally designed for the 1480 nm pumping scheme.

In order to study the impact of unused broadband ASE from the EDF, the passive EDF coil of 4.5 m length is placed in between M2 and WSC (between point X and Y) as depicted in Fig 1. This fiber laser structure is denoted as the BEFL Configuration-B. The generation of broadband ASE in the C-band region is strong at the entrance port of the 1480 nm pump light. The unused broadband ASE propagates from the 12 m long EDF coil in the opposite direction to the 1480 nm pump light propagation. Thus, this unused broadband ASE can be utilized as the secondary pump source for the L-band amplification in the 4.5 m long EDF as reported previously [8, 11]. The optical pumping mechanism is occurred owing to the effect of intra-Starks phonon interactions which absorbs short wavelength energies to be used for the longer wavelength amplification.

Fig. 1. Experimental setup of a linear cavity multiwavelength L-band Brillouin-Erbium comb fiber laser (BEFL Configuration-A). For the BEFL Configuration-B, the passive EDF of 4.5 m long is inserted between point X and Y.

In order to create Brillouin Stokes lines, the Brillouin pump must be injected through the 3-dB coupler into the SMF-28 fiber, which is down-shifted by 0.089 nm from the BP wavelength. Throughout the experiment, the BP power and wavelength are set at 1.1 mW and 1603.1 nm, respectively. The Brillouin Stokes line generation can be only realized when the BP power is above its threshold. This first-order Brillouin Stokes line propagates in the opposite direction of the BP, passes into the EDF and re-injected into the long SMF for double-pass amplification in each round trip. If the total gain generated is equal to the cavity loss, a laser oscillation is formed between M1 and M2. The higher-order Brillouin Stokes signals can be generated in both directions by the lower-order Brillouin Stokes signals that travel along SMF-28 fiber two times in a round. This cascading effect of Brillouin Stokes lines generation continues until the total gain in the laser cavity is less than the cavity loss. The output of the system is taken at the output port of the 3-dB coupler as shown in Fig. 1.

3. Results and discussions

Figure 2 illustrates the impact of 1480 nm pump power on the number of Brillouin Stokes lines for both BEFL configurations. In general, the number of output lines increase linearly with the 1480 nm pump powers until it reaches the maximum value of 24 and 28 in the BEFL Configuration-A and BEFL Configuration-B respectively. In addition to this, the number of output lines in the BEFL Configuration-A is higher than that of the BEFL Configuration-B for pump powers below 73 mW. For both BEFL configurations, there exists an optimum maximum number of output lines directly correlated with the pumping power level. For example, for a pump operating at the 1480 nm wavelength, the maximum number of output lines can be achieved for 73 mW and 86 mW for BEFL Configurations A & B, respectively.
Beyond these pump power values, the number of Stokes lines tends to decrease for both configurations. This is due to the appearance of cavity modes in which extract energy from the same amount of pump photons in the laser cavity.

Based on the experimental findings, the additional passive EDF has interrupted the lasing condition created in the conventional BEFL configuration. Referring to Fig. 2, the same number of Stokes lines is achieved when the pump power is set at 73 mW. The output spectra from the BEFL configurations are depicted in Fig. 3. It is clearly seen that the number of output lines is the same for both BEFL configurations. However, the total laser power of the BEFL Configuration-A is about 6.4 mW, higher than that of the BEFL Configuration-B. This is due to the fact that the cavity loss is lower in the BEFL Configuration-A than that of the BEFL Configuration-B. For pump powers of lower than 73 mW, the passive EDF coil acts as an additional lossy element, thus causing the number of Stokes lines to decrease compared with a conventional BEFL configuration. In this case, the primary pump power of 1480 nm is inadequate to produce substantial amount of backward C-band ASE for the L-band signal amplification. For pump powers of higher than 73 mW, the generation of backward C-band ASE is utilized as the secondary pump for the L-band signal amplification. Therefore, the number of Stokes lines is also increased. In this case, photons with higher energy (i.e. short wavelength) are absorbed and re-emitted with lower energy (i.e long wavelength), very much mimicking a quasi two-level laser system [14]. The quasi-two-level system is possible where a crystal or ligand field induces a Stark effect, which results in the splitting of the energy levels. The population distribution between sub-levels is attributed to the Boltzmann’s distribution that eventually makes it possible to consider each of them as single energy level [15]. Therefore, the L-band amplification can be realized due to sufficient interaction between these two manifolds in the passive EDF region.
The output spectrum from both BEFL configurations at 86 mW pump power is depicted in Fig. 4. For the BEFL Configuration-A, the self-lasing cavity modes start to appear in the wavelength range 1605-1607 nm. It is also possible to observe some distortions on the noise floor within the Brillouin Stokes lines group. This is due to the interference of self-lasing cavity modes with cavity Stokes lines sharing energy from the same pump source. On the other hand, the inclusion of passive EDF section provides additional gain to the Brillouin Stokes lines generated in the cavity. Due to the presence of high-intensity Brillouin-Stokes lines and the inhomogeneous characteristics of the nonlinear propagating medium, the effective gain seen by the self-lasing cavity modes are much less than what would have been predicted from a linear gain model [15]. This is a unique feature and one of the main advantageous of the proposed BEFL configuration compared with conventional setups. Detail numerical modeling and simulations confirming this experimental finding is beyond the scope of this paper and hence will be published elsewhere. Thus, seven more Brillouin Stokes lines are generated at the longer wavelength as shown in Fig. 4. Based on these findings, the efficiency of Brillouin Stokes lines generation in the L-band wavelength range is improved by adding a length of passive EDF coil. This efficiency improvement on the number of Brillouin Stokes lines generated is attributed to the utilization of backward C-band ASE as the secondary pump source for the passive EDF section, generating more photons in the L-band wavelength range through Starks effect of splitting energy levels into a few sub-bands.

Contrary to the above comments, the domination of Brillouin Stokes lines is reduced when the pump power is pushed beyond 86 mW. Under such high power conditions, owing to saturation effects in the nonlinear gain medium, the higher order Brillouin Stokes lines fail to successfully compete for gain with self-lasing cavity modes. This is a cascading effect where self-lasing cavity modes effectively consume all the available gain, and thus effectively suppressing the generation of higher-order Brillouin Stokes lines in the cavity.
4. Conclusion

We demonstrated a novel scheme that can considerably increase the number of Brillouin Stokes lines in the L-band. Our scheme used Brillouin-Erbium fiber laser with linear cavity as the resonator and used the undesired ASE in the C-band as a secondary pump source for a passive EDF section to enhance the Brillouin Stokes lines in the L-band. Our experimental results clearly showed that our new scheme is very effective in increasing the number of Brillouin Stokes lines in the resonator cavity. A total of 28 output lines with a spacing of 0.089 nm are achieved as compared to 21 output lines obtained from the conventional Brillouin-Erbium fiber laser configurations reported in the past. Furthermore, the proposed laser structure is also able to efficiently suppress the mode competition normally seen in conventional setups at high pump power values.

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