EPJ Web of Conferences **48**, 00022 (2013)
DOI: 10.1051/epjconf/20134800022

Multiple wavelength generation using a compacted hybrid Raman / Bi-EDF amplifier

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Abstract. A multiple wavelength laser source is generated by a Brillouin seed signal and a compacted hybrid Raman / bismuth-based erbium doped fiber amplifier (Bi-EDFA) in a linear cavity. The gain media of the Raman/Bi-EDFA is only a 2.15 m Bi-EDF pumped bi-directionally by two laser diodes (LDs). In comparison to all of the conventional multiple wavelength sources generated via using the same Bi-EDF and LDs, the proposed multiple wavelength source has much more number of lines due to using Raman and EDF amplification.

1 Introduction

Multiple wavelength fiber laser sources with constant wavelength spacing are of great interest for some applications such as dense wavelength division multiplexing (DWDM) communication systems and optical sensing. These multiple wavelength lasers have been generated by various approaches such as immersion of EDF in liquid nitrogen and twin core EDF lasers [1], amplified spontaneous emission slicing [2], introducing four-wave mixing [3], and the usage of ultra-narrow bandpass filter as dual-phase-shift fiber gratings with ultra-narrow transmission bands [4].

Moreover, a group of multiple wavelength laser sources can be prepared from Brillouin Stokes as a seed signal. In this approach, narrow bandwidth of Brillouin gain is used to generate multiple wavelength Brillouin fiber lasers [5-7]. In order to increase gain and number of Brillouin Stokes lines, it is customary to use a hybrid-gain configuration. This idea is evident in multiple wavelength Brillouin erbium fiber lasers (MBEFLs) [8,9]. In addition, a Bi-EDF with larger emission cross section and broader emission bandwidth is usually used to generate Bi-EDFA having wider operational wavelength region extended especially in the L band region (1565– 1625 nm) [10,11]. Bi-EDF ability to disperse erbium ions has allowed erbium ion doping of more than 1000 ppm without significant concentration quenching effect. This property results in the realization of compact EDFA [12]. Thus, MBEFLs are also demonstrated using a hybrid Brillouin / erbium-doped fiber amplifier with a Bi-EDF in both a ring and linear cavity configurations [13,14]. Due to using gain twice per a round trip in a linear cavity, a larger number of Stokes and anti-Stokes are achieved compared to that resulted in using the ring configuration. The idea of hybrid-gain configuration is also extended in using simultaneously both of the nonlinear Brillouin and Raman gains [15,16]. Since Raman amplification has wider gain bandwidth compared to EDF amplification, the larger number of lines can be generated in this method. This approach is only limited by the available Raman and Brillouin pump sources and optical components. In fact, the Raman interaction is a third-order optical nonlinear process which can turn an optical fiber into Raman amplifier. Incident light (pump wave) scattered by molecules is downshifted in frequency to generate Raman Stokes wave (probe). If pump depletion is neglected, the pump power, Pp, varies due to damping along the fiber length. Then, the Stokes power at the end of fiber, $P_s(L)$, is given by [17]:

$$P_s(L) = P_s(0)\ \ \exp[(g_R P_p L_{eff} / bA_{eff}) - \alpha_s L] \tag{1}$$

where $P_S(0)$ and $P_S(L)$ are the Stokes power at entering and exiting of the fiber of length L, respectively, and P_P is the injected Raman pump power. The factor b denotes the relative polarizations of pump and Stokes waves and polarization properties of the fiber. In a fiber which does not maintain polarization, b=2, as assumed in our case, whereas, b=1, in a polarization maintaining fiber with the same pump and Stokes polarization states. The cross-sectional area of the light beams, A_{eff}, is equal to the core area of the fiber if the pump and probe wavelengths are slightly longer than the cutoff wavelength of the fiber. In conventional step-index fibers, $A_{eff} = \pi\ w^2/4$, where w is the mode field diameter (MFD) of the fiber at a given wavelength. g_R is the Raman gain coefficient, and L_{eff} is the effective length of the fiber given by $L_{eff} = (1-\exp(-\alpha_p L))/\alpha_p$ where α_p and α_s are the attenuation coefficients of the fiber at the pump and Stokes frequency, respectively. In the case $\alpha_p L \ll 1, L_{eff} \approx L$ whereas $L_{eff} \approx 1/\alpha_p$ for $\alpha_p L \gg 1$. The Raman threshold power P_{th} is defined as the pump power for which the Stokes wave at the fiber end is already as large as the pump wave. Assuming $\alpha_S = \alpha_P$ and a Lorentzian shape for the

Raman-gain spectrum, the threshold power is given approximately by

$$\frac{g_R P_{th} L_{eff}}{A_{eff}} \approx 16 \tag{2}$$

The numerical factor 16 must be replaced with 20 for the backward Raman pumping. The threshold power is calculated about 800 mW for a long SMF ($\alpha_p L >> 1$) with, A_{eff} =70 μm^2, and $L_{eff} \approx$ 20 km. Since the threshold power is much higher than the practical powers in optical communication systems, this process in which the Stokes wave builds up from noise appears typically harmless in these systems. However, if two optical waves whose wavelength separation falls within the Raman gain curve are co-injected into Raman-active medium, the longer wavelength wave (probe) experiences Raman gain and grows at the expense of the shorter wavelength wave (pump). The effect of Raman amplification can appear at much lower power in such systems [18-20]. Thus, Raman amplification can be detrimental in a wavelength division multiplex system due to this effect called Raman-induced crosstalk. By choosing a criterion for the critical pump power, P_C, at which amplification of probe by pump is less than 1 percent or 20-dB crosstalk, it results $P_S(L) = 1.01 P_S(0)$. This follows [21]:

$$\frac{g_R P_c L_{eff}}{A_{eff}} \approx 0.01 \tag{3}$$

Then, the number of 16 in Eq. (2) should be decreased to 0.01 so that $P_c \approx P_{th}/1600$ for the same fiber. The critical power for the SMF is about 1 mW. The maximum Raman amplification occurs at the maximal Raman gain which is about at the frequency separation 500 cm^{-1} corresponding to wavelength separation more than 100 nm at 1500 nm in fused silica ($\Delta\lambda = \lambda_p^2 \Delta f(\mathrm{cm}^{-1})$), where λ_P is the pump wavelength). Therefore, the separation wavelength between channels must be more than the maximal Raman gain in wavelength division multiplex systems. In these systems, the shortest-wavelength channel is most depleted as it can pump many channels simultaneously as long as the wavelength difference is within the bandwidth of the Raman gain [22].

Recently, among all non-silica fibers with large nonlinearities, fibers based on bismuth oxide (Bi_2O_3) have attracted considerable attention in recent years for applications related to nonlinear fiber optics [23-27].

In this paper, a Bi-EDF is used not only as EDFA gain medium but as the Raman gain one to demonstrate a multiple wavelength source by using Brillouin Stokes as a seed signal in a linear cavity.

2 Experimental setup

Figure 1 shows the proposed linear cavity configuration for the multiple wavelength generation. A standard 25 km long single mode fiber (SMF) with the mode field diameter of 9 μm is used as the Brillouin gain medium. The SMF has the cut-off and the zero dispersion wavelengths at 1161 nm and 1315 nm, respectively. A bismuth-based erbium doped fiber (Bi-EDF) of approximately 2.15 m in length is used as the gain media of the both Raman and Bi-EDF amplification. The Bi-EDF has the erbium concentration of 3250 ppm, the cutoff wavelength of 1440 nm, and the pump absorption rate of approximately 85 dB/m at 1466 nm. Through two wavelength division multiplexing couplers (WDMs), the Bi-EDF is pumped bi-directionally by using two laser diodes (LDs) with the operational wavelength region 1466-1473 nm at the maximum pump powers 120 mW. A signal from an external cavity tunable laser source (TLS) is used as the Brillouin pump (BP) with the linewidth of approximately 15 MHz and the maximum power of about 4.8 dBm. Two optical circulators OC1 and OC2, employed at the both ends of the linear cavity, act as reflectors as shown in figure 1. Besides, the couplers C1 and C2, incorporated between Port 3 and Port 1 of OC1 and OC2, are used to inject the BP and tap the output, respectively. The output is detected by the optical spectrum analyzer (OSA) with the resolution 0.015 nm.

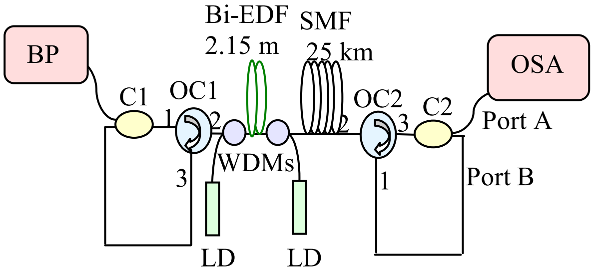

Fig. 1. The proposed linear cavity for multiple wavelength generation using the compacted hybrid Raman / Bi-EDF amplifier.

After BP is injected into the linear cavity via the 3-dB coupler C1 and OC1, it is amplified by Bi-EDFA and is routed into SMF to generate the first Brillouin Stokes signal if the BP power reaches the first Stokes threshold power. The first Brillouin Stokes propagating in the opposite direction of the BP signal is also amplified by Bi-EDFA and is re-circulated back into SMF via OC1 to act as the BP to generate the second Brillouin Stokes and then moves towards OC2 to complete a round-trip oscillation after reflecting from it. Similarly, when the first Brillouin Stokes power reaches the second Brillouin Stokes threshold power, the second Stokes is generated. This Stokes also begins to oscillate in the cavity to generate higher order Brillouin Stokes in the same condition. The subsequently cascaded Brillouin Stokes can be generated as long as the Brillouin gain is equal or larger than the cavity loss. The generated multiple wavelength has a line spacing of approximately 0.089 nm which is equivalent to the Brillouin Stokes shift in the SMF. The output is tapped from the port A of the coupler C2, and is measured by using the OSA with a resolution of 0.015 nm. The coupling ratio of the port B of C2 is chosen 99% to produce the minimum round trip loss and to generate the highest number of lines.

3. Results and discussion

In MBEFL systems, the operating wavelength is determined by the free-running spectrum which is the net gain equivalent to the difference between the EDF gain and the cavity loss. When the BP power is off, the free-running wavelength region is obtained by the bi-directionally pumped Bi-EDF. As shown in figure 2, the resulted free running spectrum lies between 1570.29 nm and 1572.28 nm in using the two LDs as the Bi-EDFA pumps. The free running also exhibits the highest Bi-EDF lasing gain peak power of about -24 dBm at 1570.78 nm.

By emitting the BP with the wavelength within the free-running region which is also the lasing region in these systems, MBEFLs can be generated as long as the threshold condition is satisfied [12,13].

In this work, however, as depicted in figure 3, the maximum number of lines in the generated multiple wavelength is produced by using the BP with the peak power of about 3.5 dBm at the wavelength 1568.6 nm which is about 2 nm lower than the free-running region.

Each of LDs has the wavelength region 1466-1473 nm at the fixed pump power 120 mW.

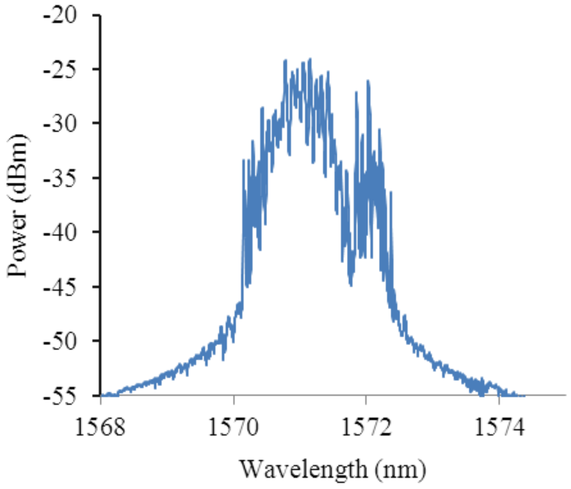

Fig. 2. Free running spectrum using the maximum Bi-EDFA pump power 120 mW.

At the port B ratio of 99%, more than 55 simultaneous lines are obtained, which is the highest number of lines with the line spacing of approximately 0.089 nm and the peak power above -30 dBm. The 3-dB bandwidth of each line is about 0.02 nm, limited by the OSA resolution of 0.015 nm.

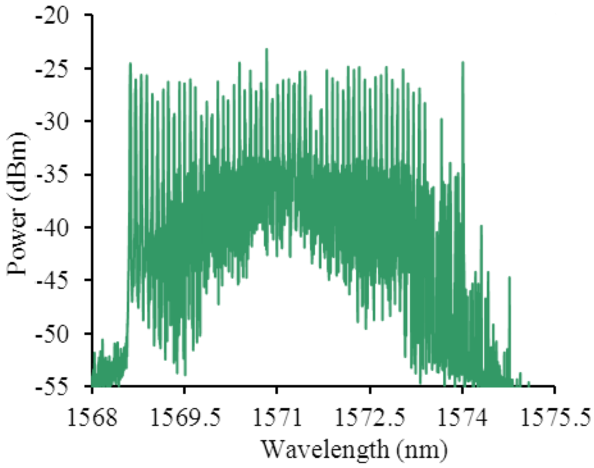

Fig. 3. The generated spectrum of over 55 Brillouin lasing wavelengths with the assistance of the compacted hybrid Raman / Bi-EDF amplifier.

Unlike common MBEFL systems, the used BP wavelength in this experiment is about 2 nm out of the free-running lasing region. The resulted number of lines is 22 more than that obtained in the conventional MBEFL linear cavity having the same components. This is due to the existence of Raman gain provided in Bi-EDF in addition to erbium gain in this wavelength region. The impact of the BP wavelength on the generated number of Stokes lines is depicted in figure 4. The BP wavelength is varied from 1567 nm to 1570 nm whereas LD pump powers are fixed at 120 mW. As shown in figure 4, the maximum number of lines is obtained at 1568.6 nm where the highest Raman gain exists in the bi-directionally pumped Bi-EDF. After this wavelength, Raman gain is reduced so that the number of lines is decreased to that obtained by the MBEFL systems.

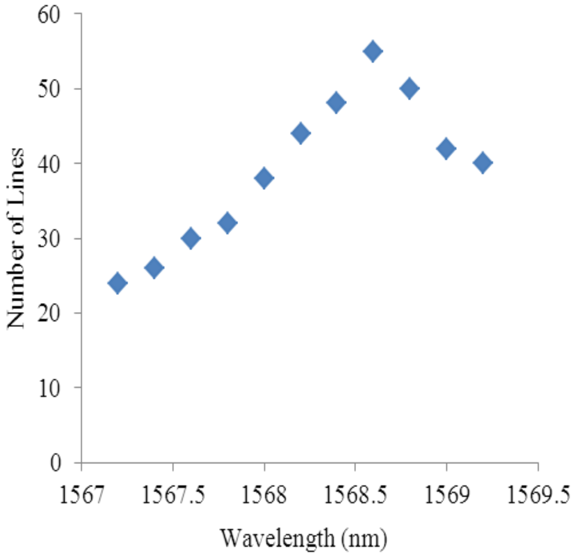

Fig. 4. Number of Brillouin Stokes lines resulted in the generated multiple wavelength spectrum using the proposed Raman / Bi-EDF amplifier at the different Brillouin pump wavelengths.

4 Conclusion

A multiple wavelength laser source is generated by using the proposed compacted hybrid Raman / Bismuth-based Erbium doped fiber amplifier (Bi-EDFA) in a linear cavity. The 2.15 m Bi-EDF in this hybrid Raman / Bi-EDFA is pumped bi-directionally by two laser diodes having the operational wavelength 1466-1473 nm at the fixed pump powers 120 mW. By injecting the Brillouin pump (BP) with the wavelength 1568.6 nm at the peak pump power of 3.5 dBm, the multiple wavelength laser source of about 55 number of Stokes lines is generated. This number of lines is more than that obtained in the MBEFL linear cavity having the same components but BP wavelength is in the EDFA free running wavelength region. This is due to the existence Raman gain in addition to erbium gain in the bi-directionally pumped Bi-EDF. This experiment also suggests that using a Bi-EDF instead of a conventional EDF in an EDFA, higher amplification can be obtained when the resulted Raman gain overlaps with the intense erbium gain prepared in this fiber.

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