Multiple Brillouin Stokes Generation Utilizing a Linear Cavity Erbium-Doped Fiber Laser

Mohammed Haydar AL-Mansoori, Nor Kamariah Noordin, M. Iqbal Saripan, and Mohd Adzir Mahdi

Abstract: **This paper reports the design of a multiwavelength fiber laser source that utilizes a linear cavity of hybrid Brillouin/Erbium fiber laser (BEFL). The output power, threshold power and free running cavity modes were investigated against the pump powers. The structure exhibited low threshold operation of 4 mW at 2.3 mW injected Brillouin pump power. The optimization of Brillouin pump wavelength, power and Erbium gain led to a maximum possible number of channels generated. Simultaneous and stable operation of 21 channels with 10.88 GHz channels spacing were obtained from this architecture at 1 mW injected Brillouin pump power and 90 mW Erbium doped fiber pump power in the 1555 nm region.**

Index Terms: **Brillouin Stokes, Erbium, fiber lasers, multiwavelength laser source, optical communications, stimulated Brillouin scattering.**

I. INTRODUCTION

Dense wavelength division multiplexing (DWDM) is an attractive option for providing increased capacity in lightwave transmission systems and routing capability within optical networks. As the transmission capacity of optical communication systems is approaching a few Tb/s through wavelength division multiplexing (WDM) method in recent years, multi-wavelength generation technology becomes more important, considering that the complexity and the cost of the source will increase as the number of WDM channel increases. The wavelengths of DWDM channels are required to match a specified wavelength grid with a uniform spacing. Currently, these wavelengths are mainly generated by employing either multiple discrete distributed-feedback (DFB) lasers or monolithically integrated multiwavelength laser arrays. However, their output power and emission wavelength are susceptible to the variations of environmental temperature and injection current. Hence, an accurate control system is required to prevent wavelength errors and power fluctuations, and thus a DWDM transmitter becomes much more complicated and expensive. In order to achieve stable dense multiple wavelength laser sources, several approaches have been proposed [1], [2]. Erbium-doped fiber (EDF) was commonly used as a gain medium [2], [3], and others incorporated a semiconductor optical amplifier (SOA) into a laser cavity [4].

Recently multiwavelength Brillouin/Erbium fiber lasers (BEFL's) with several kinds of cavity configuration have been demonstrated as a densely (10 GHz) spaced robust multi-wavelength laser source operating at room temperature [5], [6]. A unique technique of integrating the nonlinear Brillouin gain and the linear Erbium gain in a ring cavity was proposed [5]. This hybrid technique led to the development of multi-wavelength BEFL by feeding back the Brillouin Stokes into the cavity via non-resonant direction [6], [7]. The enhanced version of the ring-cavity BEFL that incorporated an internal active feedback was demonstrated [8], [9]. In this case, a portion of the oscillating Brillouin Stokes was tapped and re-injected into the single mode fiber in the same direction of the Brillouin pump. In order to improve the Brillouin gain efficiency, another section of EDF coil was used in the re-injecting path to amplify the Brillouin Stokes.

Bidirectional generation of multi-wavelength Stokes was also investigated using a twin-cavity [10] and an intra-cavity distributed feedback laser [11]. High spectral broadening of the DFB mode, which accounts for the high lasing threshold ($\sim$70 mW) is observed. The exploitation of cascaded stimulated Brillouin scattering (SBS) process and the four wave mixing process to produce higher order multiple Stokes and anti-Stokes lines in scheme of a figure-of-eight BEFL's were investigated [12]. The first order Stokes line peak was observed at 13 mW EDF pump power. Operation scheme of BEFL that consists of two metal-coated fiber planar mirrors and a Sagnac reflector was demonstrated [13]. Threshold power of 17.1 mW was obtained to get the first order Stokes signal. However, all the previous research works were based on the ring-cavity laser system. Furthermore, the self-lasing cavity modes must be prevented in the laser cavity to stabilize the multiple Brillouin Stokes.

In this paper, a simple linear-cavity multi-wavelength BEFL is presented. The requirement of the internal active feedback was achieved by the bidirectional oscillation in the active medium thus eliminates an additional section of EDF as proposed in the ring cavity. Furthermore, the proposed design and it exhibited low threshold power for the Erbium gain pumped by a 980 nm laser diode. This was due to efficient utilization of the EDF and Brillouin gains; each Brillouin Stokes signal was amplified twice in the active medium and used to pump the next order Brillouin Stokes signals in both directions. A stable operation of 21-lasing channels with a spacing of 10.88 GHz was observed at 1555 nm.

II. EXPERIMENT

Experimental setup of a linear cavity hybrid BEFL is shown in Fig. 1. In this setup, the Fabry-Perot laser cavity was formed by using two optical circulators placed at both cavity ends to function as a mirror. Even though that the Fabry-Perot cavity can be formed by highly reflected metal-coated fiber ends or

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The authors are with the Department of Computer and Communication Systems Engineering, Faculty of Engineering, Universiti Putra Malaysia, email: adzir@ieee.org.

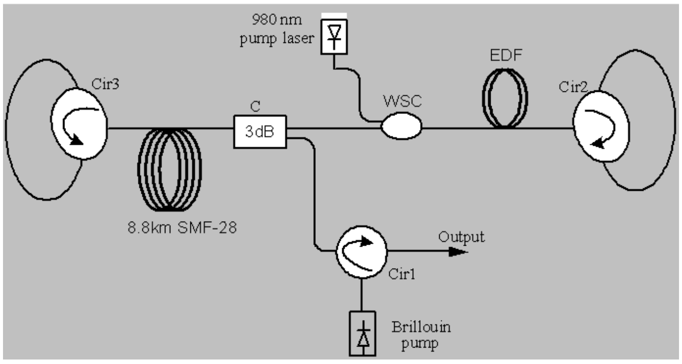

Fig. 1. Experimental setup of multiple-wavelength Brillouin/Erbium fiber laser in a linear cavity: C (coupler), WSC (wavelength selective coupler), and EDF (Erbium-doped fiber).

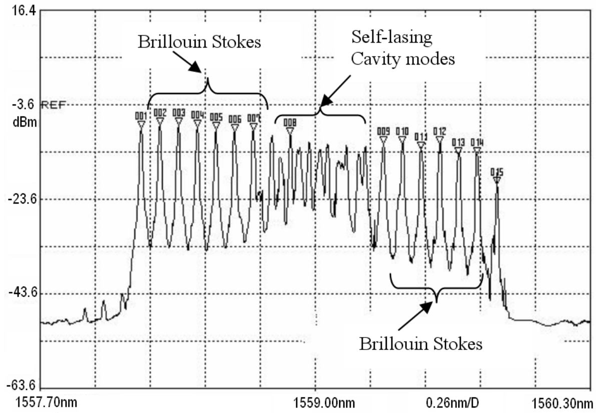

Fig. 2. The presence of the self-lasing cavity modes together with the Brillouin Stokes at small-injected Brillouin pump power.

their alternatives, we used the circulator to form the Fabry-Perot cavity because of the unavailability of the other reflecting devices during the experiment. A 980 nm pump laser of 90 mW maximum output power was used as the pump light for the EDF. The pump and signal lights were multiplexed via wavelength selective coupler (WSC). The length of EDF used in the experiment was 10 m. The cold cavity loss of 13.45 $\pm$ 0.05 dB from 1530 nm to 1570 nm wavelength was measured beforehand.

The Brillouin gain media was provided by the 8.8 km long of single mode fiber, SMF-28. The Brillouin pump (BP) was provided by an external cavity tunable laser with maximum power of 2.3 mW and 100 nm tuning range from 1520 nm to 1620 nm. The BP was coupled into the SMF-28 fiber using a 50/50 coupler (C) as shown in Fig. 1. With sufficient narrow linewidth BP power injected into the SMF at a wavelength close to the EDF peak gain, cascaded SBS was initiated by increasing the 980 nm pump power. When the total combined gain (EDF and Brillouin) is equal to the cavity loss, the system operates as a BEFL and a narrow bandwidth gain is generated at a frequency Stokes-shifted from the BP frequency by $V_B = 2nV_a/\lambda_p$, where n is the effective refractive index of the SMF, V_a is the acoustic velocity and λ_p is the BP wavelength. The narrow linewidth property of the Stokes was suitable to be applied as a BP to produce the next Stokes signal.

In the initial stage, the first generated Stokes signal propagated in the opposite direction of the pump signal and is passed into the EDF for effective amplification. The amplified Stokes signal traveled back into the SMF-28 fiber after gaining some energy in the EDF for the second time and reached at the third circulator (Cir3). The signal recycled back into the SMF-28 fiber through Cir3 and reached the 50/50 coupler for a complete one-trip pass. If the total gain of Brillouin and Erbium was equal to the cavity loss, a laser oscillation can be formed between the second circulator (Cir2) and Cir3. This oscillation continued and when the intensity of the first Brillouin Stokes was higher than the threshold value for Brillouin gain, the second Brillouin Stokes generated and oscillated in the cavity. This process continued and cascaded Brillouin Stokes can be generated as long as the total gain of the Brillouin and Erbium media was equal to the cavity loss. At the steady state condition, a stable laser was produced that consisted of the BP and its Stokes signals. The output of the linear cavity BEFL was taken at the output port of the first circulator (Cir1) and appeared at a Brillouin frequency shifted from that of an injected BP. It is worth to note that only a common EDF coil was used in this experiment to amplify the Stokes signal and support multiple wavelengths operation as compared to the utilization of two EDF coils in [8], [9]. Furthermore, only a single 980 nm pump laser was deployed instead of two units of pump laser as discussed in those reports.

III. RESULTS AND DISCUSSIONS

First, the observation of self-oscillation of the Erbium-doped fiber laser (EDFL) was performed. The amplified spontaneous emission super-luminescent centered on 1558 nm was obtained from the experimental configuration. When the BP injected into the laser cavity was small, the Brillouin gain was also small and not be able to suppress the competitions with the free-running modes which resulted unstable operation. Fig. 2 shows the appearance of cavity modes together with the Brillouin Stokes shifted signal at a small-injected BP power of 0.28 mW. The BP wavelength was set at 1558 nm and the 980 nm pump power was fixed at 90 mW. The resolution bandwidth of the optical spectrum analyzer (OSA) was set to 0.015 nm. However, the presence of EDFL cavity modes showed that the BP power was not enough to fully saturate the EDFL internal gain. Therefore, this caused instability on the Stokes signals and appropriate adjustments of pump power levels were taken to ensure that the BEFL operated without any EDFL cavity modes.

The threshold characteristic according to the 980 nm pump power was studied with a fixed BP power of 2.3 mW at 1555 nm. The 980 nm pump power was varied in order to obtain the threshold value when the first Stokes appeared in the laser cavity as depicted in Fig. 3. It can be seen that there was no significant observation of the Stokes appearance in Fig. 3(a) at 3 mW pump power of the 980 nm light. As the intensity of this pump light increased by 1 mW, the first Stokes emerged at 0.088 nm wavelength-shift from the BP wavelength as shown on Fig. 3(b). Even though the cavity loss was higher due to the double-pass trip, the fiber laser structure exhibited low threshold power of 4 mW to generate its first Stokes signal down-shifted by 10.88 GHz spacing as shown in the inset.

This value represented the lowest one that was ever reported

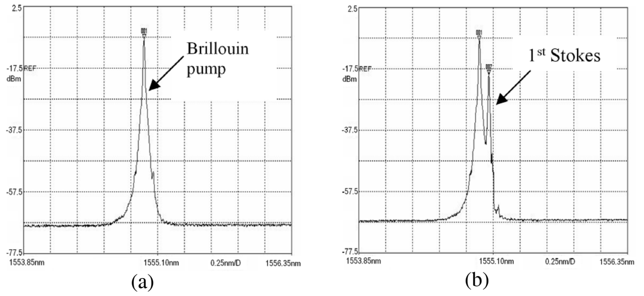

Fig. 3. Output spectrum of the first Brillouin Stokes for the BP wavelength at 1555 nm and the BP power was fixed at 2.3 mW; the 980 nm pump power was (a) 3 mW and (b) 4 mW.

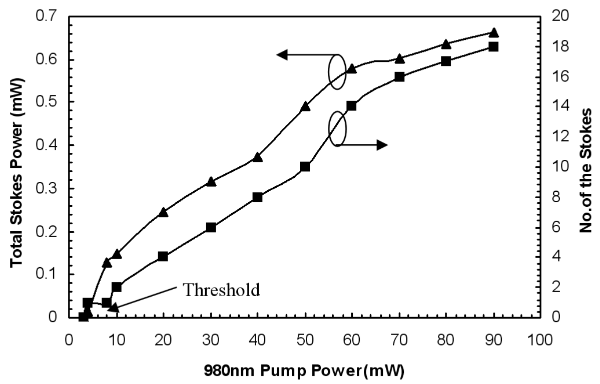

Fig. 4. Total Stokes power and number of the Stokes generated against 980 nm pump power at 1555 nm with 2.3 mW injected BP power.

so far in the development of multiple Stokes generation techniques. Although the cavity loss of the fiber laser was measured at 13.45 dB, the generation of Brillouin Stokes signals was still effective. The efficiency of the proposed laser system was determined by the linear cavity itself. Stokes signals were amplified twice in the EDF and at the same time, gained higher conversion efficiency in the 8.8 km SMF-28 fiber.

The relationship between the total Stokes powers, the number of Stokes and the 980 nm pump power is shown in Fig. 4. The 980 nm pump power was varied from its threshold power to 90 mW. The choice of BP wavelength was made based on the tuning range without any free-running cavity modes. As the 980 nm pump power increased, the total Stokes power and the number of the Stokes generated in the laser cavity increased in a linear relationship that was due to the increment of the Erbium gain. This situation led to sufficient signal power for higher order Stokes signal to pump the SMF and the process of multiple Stokes generation was successfully obtained.

To increase the signal capacity of the linear cavity multiwavelength BEFL system, it is important to optimize the cavity for high finesse. The optimization of 980 nm pump power, BP wavelength and BP power is very important to achieve the maximum number of Stokes signals. At a length of 8.8 km; SMF-28 the optimal condition to achieve the maximum number of Stokes signals was found when the 980 nm pump power was 90 mW and BP power was 1 mW at 1555 nm. Twenty-one laser lines were obtained in this condition as depicted in Fig. 5. The number of lines generated in the configuration reported above was

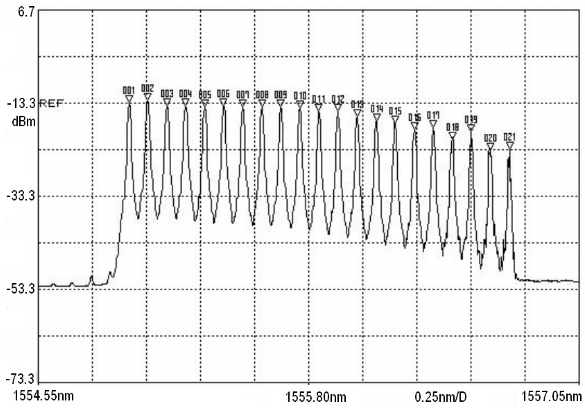

Fig. 5. Output spectrum of the BEFL at Brillouin pump of 1 mW and 980 nm pump power was set at 90 mW.

limited to 21 lines, because of the limited availability of 980 nm pump power. The number of lines can be generated higher if larger 980 nm pump powers were used in the experiment.

IV. CONCLUSIONS

We have successfully demonstrated a simple technique of generating stable multiwavelength laser source utilizing a linear cavity of hybrid BEFL. A low threshold of 4 mW was obtained at 1555 nm with 2.3 mW-launched BP, which led to the creation of the number of scattered Stokes signal with modest pump power. The optimization of BP wavelength, power and Erbium gain was very critical in order to achieve the maximum possible number of Stokes signal generated. Twenty-one stable output laser lines with 0.088 nm (10.88 GHz) spacing at 8.8 km SMF length were obtained. Higher Brillouin Stokes signal peak power can be obtained at a higher level of both EDF and BP powers.

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Mohammed Haydar AL-Mansoori was born in Dhamar, Yemen, on 1975. He received the B.Sc. degree with first class honors in Electronic and Communications Engineering from Al-Mosul University, Iraq in 1998. From 1998 to 1999, he worked with IBM Company, maintenance department, Sana'a branch. Since 1999 he has worked as Instructor at the department of Electronic and Communications Engineering, IBB University, Yemen. He received the M.Sc. degree from University Putra Malaysia in 2004. He is currently working as a lecturer at Faculty of Engineering and Technology, Multimedia University and he is working toward the Ph.D. degree at the department of Computer and Communication Systems Engineering, University Putra Malaysia. His current research interests include nonlinear optics, multiwavelength fiber lasers, and photonic crystal fiber laser.

Nor Kamariah Noordin received her B.Sc. in Electrical Engineering majoring in Telecommunications from University of Alabama, USA, in 1987. She became a tutor at the Department of Computer and Electronics Engineering, Universiti Putra Malaysia and pursue her Masters Degree at Universiti Teknologi Malaysia. She then became a lecturer in 1991 at the same department where she was later appointed as the head from year 2000 to 2002. She took a study-leave to pursue her doctorate degree at UPM in November 2002 and came back to serve the department in May 2006. She is currently the deputy dean (Academic, Student Affairs and Alumni) of the faculty. During her more than 15 years at the department she has been actively involved in teaching, research and administrative activities. She has supervised a number of undergraduate students as well as postgraduate students in the area of wireless communications, which led to receiving some national and UPM research awards. Her research work also led her to publish more than 50 papers in journals and in conferences.

M. Iqbal Saripan received the B.Eng. degree in electronic engineering from the Universiti Teknologi Malaysia in 2001 and the Ph.D. degree from the University of Surrey, Guildford, U.K., in 2006. Currently, he is a lecturer and head of Embedded and Artificial Intelligent Systems Engineering Research Group at the Department of Computer and Communication Systems Engineering, Faculty of Engineering, Universiti Putra Malaysia. His research interests are in the area of computer security, signal processing, image processing and embedded system. He is a member of the IEEE and IoP UK.

Mohd Adzir Mahdi received his B.Eng. degree from the Universiti Kebangsaan Malaysia, and M.Sc. and Ph.D. degrees from the Universiti Malaya in 1996, 1999 and 2002 respectively. He joined the Department of Computer and Communication Systems Engineering, Faculty of Engineering, Universiti Putra Malaysia on January 21, 2003 as an associate professor. He is now the Deputy Director of Knowledge Management Unit at Research Management Center and Research Fellow at the Photonics Transmission Cluster, TM Research & Development Sendirian Berhad. Prior to the current appointment, Adzir was the optical design engineer at IOA Corporation, Sunnyvale, USA. Since 1996, he has been involved in photonics research specializing in optical amplifiers and lasers. His notable research contributions in this area have earned him international recognition awards; IEEE LEOS Graduate-Student Fellowship, Australia-Malaysia Institute Research Fellowship and TWAS Affiliate Fellow. He has published more than 230 scientific papers in journals and conference proceedings. He is a senior member of the Institute of Electrical and Electronics Engineers (IEEE), a member of the Optical Society of America and International Association of Engineers. His research interest includes optical fiber amplifiers and lasers, optical fiber communications, and nonlinear optics.