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Multi-Wavelength Photonic Crystal Fiber Laser

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1. Introduction

The fiber lasers have some advantages compared to bulk-optics systems like compact size, high efficiency and high beam quality. The lasers in time-domain can be categorized into two groups "continuous wave fiber lasers" or "pulsed fiber lasers", and in wavelength domain as single wavelength or multi-wavelength. Such lasers were made as early as 1976 and have remained an active topic of study since then [2, 3]. Fiber lasers can be used to generate CW radiation as well as ultra-short optical pulses. The wavelength division multiplexing (WDM) techniques have shown to unlock the available fiber capacity and to increase the performances of broadband optical access networks. One of the essential components is the creation of new low-cost laser sources. Candidates for such applications are multi-wavelength fiber ring lasers as they have simple structure, are low cost, and have a multi-wavelength operation.

Recently, multi-wavelength lasers have caused considerable interests due to their potential applications such as WDM systems, fiber sensors and fiber-optics instrumentations. Requirements for multi-wavelength sources include; stable multi-wavelength operation, high signal to noise ratio and channel power flattening. Compared to a system that uses a number of discrete semiconductor diode laser [4], it is physically simpler to produce a multiple wavelength source using a single gain medium including a wavelength selective element. In order to define lasing wavelengths, wavelength selective comb filters have been included in the laser cavity. A multi-wavelength laser is highly desirable for the cost and size reduction, improvement of system integration and compatible with optical communication networks. For the past one decade or so, EDFs have been extensively studied and developed as a gain medium for the multi-wavelength laser.

In Erbium doped fiber laser (EDFL), the Erbium ions possess split Stark sublevels with multiple allowed transitions possibility of having oscillations at more than one wavelength. Therefore, the multi-transitions can be achieved in this fiber laser due to the depletion of Stark sub-levels which is selective and depends on the polarization of the wave. However, the outputs of the EDFLs are not stable at room temperature due to homogeneous broadening of lasing modes [5]. To increase the in-homogeneity one can cool Er^{+3} doped fiber at liquid nitrogen temperature [6, 7]. Generally, in order to produce the multi-wavelength, we have to employ intra-cavity filter in the EDFL cavity. In some works, a

polarization controller (PC) is used in the cavity to change both the number of lasing lines and spacing of the multi-wavelength laser [8, 9].

There are also other methods to get simultaneous multi-wavelength outputs such as multi-wavelength Raman lasers [10, 11], multi-wavelength generation using semiconductor optical amplifiers (SOA) [12] and multi-wavelength Brillouin fiber lasers (BFLs) [13,14]. Special fibers such as dispersion compensating fibers (DCFs) have been used to increase the Raman gain in multi-wavelength Raman fiber lasers where the output power are limited only by the available pump sources [15]. Furthermore, the BFL is easier to be generated due to the lower threshold pump power [16].

Of the various approaches, the interest on the multi-wavelength fiber laser is increasing due to the improvements in number of lasing lines and power flatness. Furthermore, the Brillouin Erbium fiber laser (BEFL) is easier to be generated due to the lower threshold pump power for achieving the stimulated fiber laser [17]. Recently, the hybrid of EDFAs and new compact optical fibers like PCFs as a gain medium have many applications for producing amplifiers and fiber lasers.

2. Photonic crystal fiber ring laser

Photonic crystal fibers (PCFs) have generated great interest over the past few years, growing from a research-oriented field to a commercially available technology. The PCFs were first developed by Philip Russell in 1998, and can be designed to possess enhanced properties over (normal) optical fibers. They can be divided into two fundamental classes, solid-core and hollow-core as shown in Figure 1.
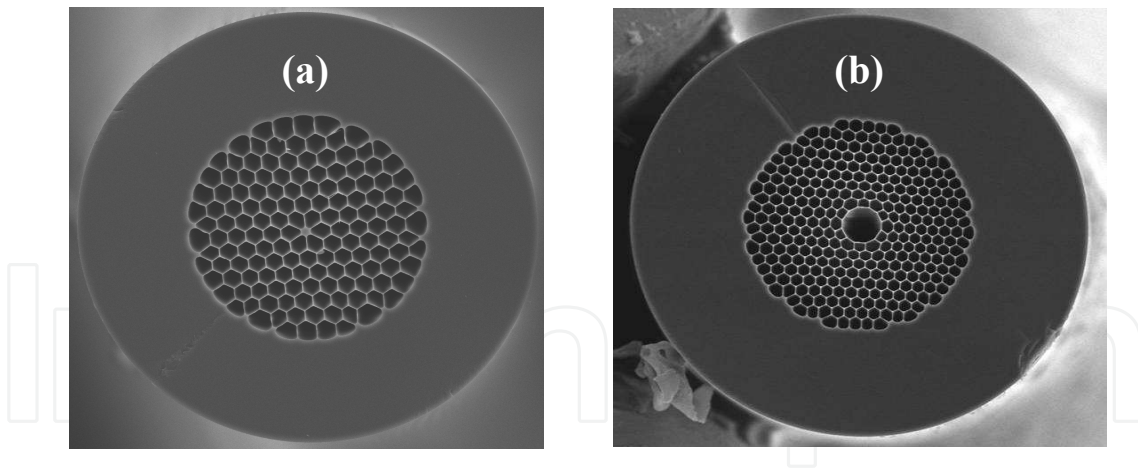

Fig. 1. Photonic Crystal Fibers Types, (a) Solid core PCF, (b) Hollow core PCF.

The solid core PCF is used in this report that is two dimensions (it has a periodic geometry in two directions and is homogeneous in the third) and we already introduced physical properties of that in table 1.

Figure 2 shows an electron micrograph of the cross section of this solid core PCF. Despite the hexagonal structure of the cladding, the mode field is very similar to that of the fundamental mode of a conventional fiber. The optical properties of PCFs rely on the specification of the size, shape and arrangement of the holes that surround a solid core to

form a cladding. These parameters can easily be tailored to increase fiber nonlinearity, which is difficult to achieve using conventional fibers.

Fiber Type	PCF	Bi-EDF
Length(m)	20	2.15
Numerical Aperture (NA)	0.2	0.2
Core(μm)	4.8	5.4
Cladding(μm)	125	125.7
Mode field diameter(μm)	4.2	6.12
Zero dispersion wavelength(nm)	1040	1513
Cut off wavelength (nm)	1000	1180
Effective area($\mu m)^2$	27.5	29.4
V-$_{number}$	1.94	2.18
Material	Pure silica	Bi_2o_3-Er doped
Insertion loss (dB)	~2@1.06μm ~1.5@1.55μm	0.82@1.55 μm 1.18@1.48 μm
Brillouin gain, g_B(m/W)	5×10^{-7}	3.8×10^{-7}
Chromatic dispersion @1550nm (ps/nm.Km)	~70	-120
Refractive index of core/cladding at 1.55 μm	1.46/1.45	2.03/2.02
Nonlinear coefficient, γ(w.km)$^{-1}$@1550nm	~33.8	~60

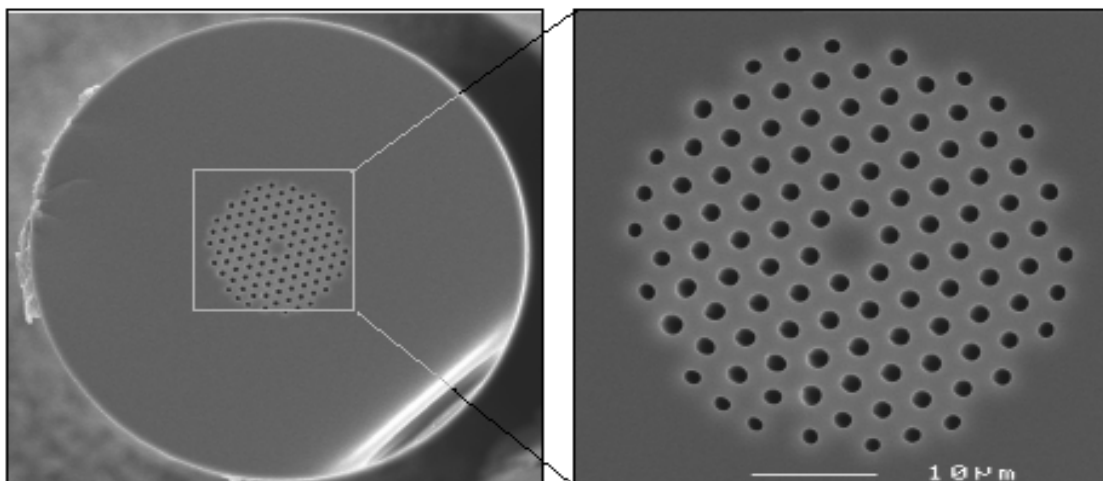Table 1. The physical parameters of PCF and Bi-EDF

Fig. 2. The Scanning Electron Micrograph (SEM) of the PCF cross section and an enlarged view of the central "holey" cladding.

The highly nonlinear PCFs have many applications such as wavelength conversion [18] and Brillouin fiber lasers (BFLs) [13]. So far, few reports have been published on the Brillouin effects in PCFs [18, 19, 20]. The stimulated Brillouin scattering (SBS) is a nonlinear effect that results from the interaction between intense pump light and acoustic waves in a fiber, thus

giving rise to backward propagating frequency shifted light [13]. In BFL applications, the required gain medium length can be substantially reduced using a holey fiber to replace the conventional SMF-28 Fiber of Corning Inc.[21]. However, most of the earlier works on PCF based BFLs are mainly on a single wavelength operation [21].

In this research, the fibre ring structure based on PCF can be used to make a very stable wavelength and narrow line-width laser. A conceptual structure of such a laser is very similar to a fibre ring resonator. In the ring configurations, a very short length of PCF (20 m) is added in the ring cavity BEFL in the proposed configurations to achieve a stable single and multi-wavelength laser generation.

3. Results and discussion

Figure 3 shows the experimental setup of the proposed PCF-based BEFL. The ring resonator consists of a circulator, a 20 m long PCF, a polarization controller (PC), two isolators and a bi-directionally pumped 215 cm long Bi-EDF. The PCF used is a polarization maintaining type with a cut-off wavelength of 1000 nm, zero dispersion wavelength of 1040 nm, nonlinear coefficient of 33.8 (W.km)$^{-1}$ at 1550 nm and a mode field diameter of 4.2 μm near zero dispersion wavelength. The Bi-EDF is pumped bi-directionally using two 1480 nm lasers. Optical isolators are used to block the Brillouin pump (BP) from oscillating in the cavity and also to ensure a unidirectional operation of the BFL. The PC is used to control the birefringence (breakage of a light ray into two different directions therefore creating two separate light rays) of the ring cavity, so that the power of the laser generated can be controlled. The experiment executed using 3 different types of couplers the 80/20, 90/10 and 95/5 and the output for BFL is tapped from the leg with the smaller coupler ratio before it is characterized using an optical spectrum analyzer (OSA).
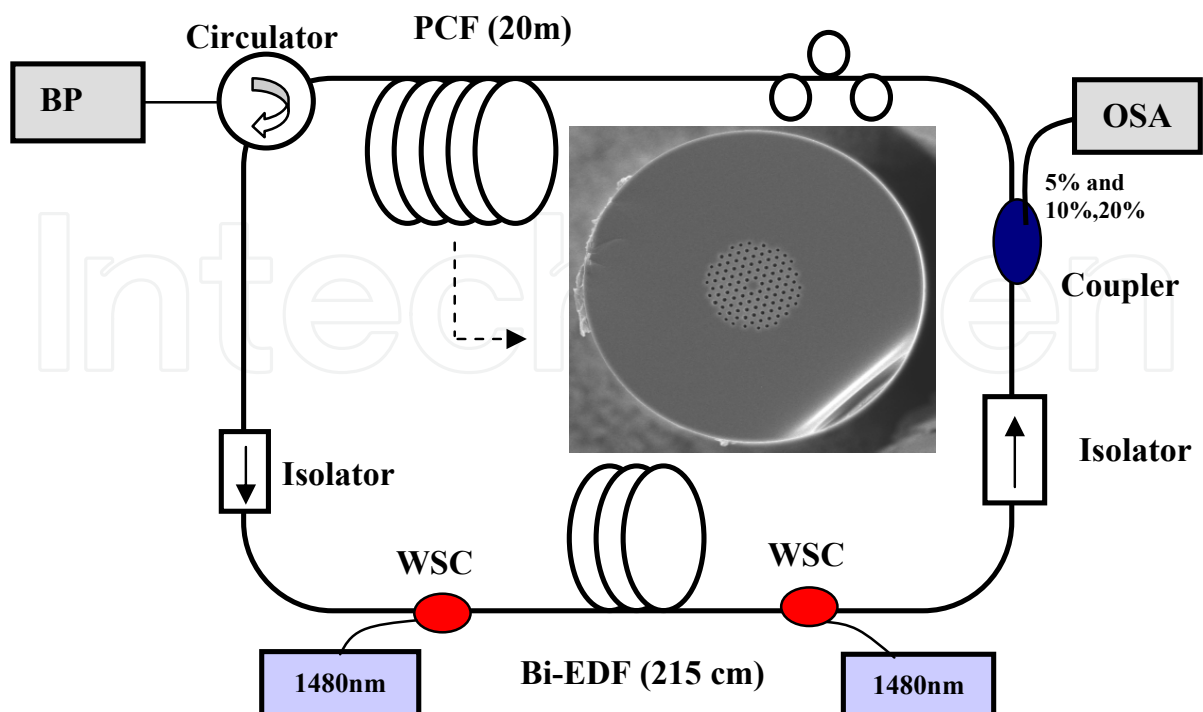

Fig. 3. Configuration of multi-wavelength BFL based PCF.

The BP is injected into the ring cavity and then PCF via the circulator to generate the backward propagating Stokes light at opposite direction. However, since the PCF length is not sufficient enough, the back-scattered light due to Rayleigh scattering is relatively higher than the Stokes light. Both back-scattered pump and the Stokes lights are amplified by the bi-directionally pumped Bi-EDF and it oscillates in the ring cavity to generate first Stokes in an anti-clockwise direction. This oscillation continues and when the intensity of the first Brillouin Stokes is higher than the threshold value for Brillouin gain, the second order SBS is generated in clockwise direction and this signal is blocked by the isolator in the cavity. However, the back-scattered light from second SBS will be amplified by the Bi-EDF. Hence, the nonlinear gain by both PCF and Bi-EDF only amplifies the Stokes light and thus the Stokes light is more dominant and laser is generated at the Stokes wavelength. The spacing between the BP and the BFL is obtained at approximately 10 GHz, which is equivalent to the Stokes shift in the single mode fiber (SMF).

The operating wavelength of the BFL is determined by the bi-directionally pumped Bi-EDF gain spectrum which covers the L-band region from 1560 nm to 1620 nm as well as the cavity loss. For comparison and the effect of different cavity resonators, three kinds of output couplers selected. Figure 4 shows the free running spectrum of the BEFL, which is obtained by turning off the BP for three different output coupler ratios; 80/20, 90/10 and 95/5. The output laser is taken from the leg with a lower portion. The peak wave generated at approximately 1574 nm with bandwidth of approximately 3 nm due to the difference between Bi-EDF's gain and cavity loss is the largest in this region. The chosen BFL operating wavelength must be within or close to the bandwidth of free running BFL. Therefore, the BP is set within 1574 nm region which is within the lasing bandwidth of the free running BFL. At the coupling ratio of 80/20, the free-running BFL exhibits the highest peak power of approximately -6 dBm with 20 dB bandwidth of approximately 1 nm. The cavity loss is the lowest with 80/20 coupler and therefore the peak power is the highest.
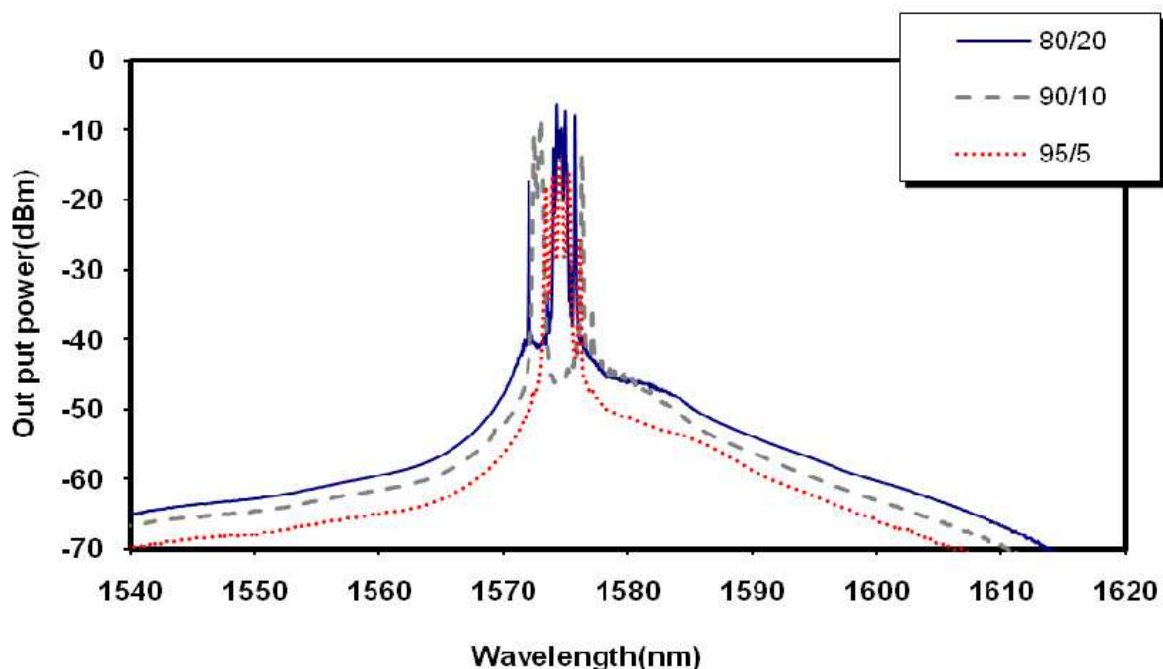

Fig. 4. Free-running spectrum of the BEFL using 80/20, 90/10 and 95/5 couplers.

Figures 5 (a), (b) and (c) show the output spectra of the BEFL at different output coupler ratios of 80/20, 90/10 and 95/5, respectively. The experiment was carried out for three different pump powers. Both the 1480 nm pumps are set at the same power and power of each pump is varied from 60 mW to 135 mW. The threshold of the BEFL is observed to be around 60 mW for all setups. At pump power below of 60 mW (threshold) the Erbium gain is very low and cannot sufficiently compensate for the loss inside the laser cavity and thus no Stokes are observed. When increasing the 1480 nm pump power the number of wavelength generated is increased and the anti-Stokes wave also surfaced, which attributed to the increment of the Erbium gain with the pump power. This situation provides sufficient signal for SBS as well as the four wave mixing (FWM) to generate Stokes and anti Stokes.

Besides that SBS, the Kerr effect or the quadratic electro-optic effect (QEO effect) was found in 1875 by John Kerr, a Scottish physicist. The Kerr effect describes a change in the refractive index of a material in response to an intense electric field. The index change is directly proportional to the square of the electric field instead of the magnitude of the field. In Kerr effect, the nonlinear phase shift induced by an intense and high power pump beam is used to change the transmission of a weak probe through a nonlinear medium [7] as such as PCF and Bi-EDF. Thus the change in the refractive index is proportional to the optical intensity and lead to nonlinear scattering and frequency shift.

However, the FWM is another nonlinear effect, which is due to the third-order electric susceptibility is called the optical Kerr effect. The FWM is a type of optical Kerr effect, and occurs when light of two or more different wavelengths is launched into a fiber. FWM is also a kind of optical parametric oscillation [22].

The FWMs in PCFs can occur at relatively low peak powers and over short propagation distances, and such processes can be possible in a much wider wavelength range (e.g. more than 120 nm). The FWM can be very efficient at the zero-dispersion wavelength. Besides the obvious advantage of shorter fiber requirement; the use of PCF would allow the operation of these nonlinear devices in the wavelength regime outside that of possible using conventional fibers. This is because, PCFs can have zero dispersion wavelength ranging from 550- 1550 nm.

In this experiment, more than 13 lines are obtained at the maximum 1480 nm pump power of 135 mW with wavelength spacing of approximately 0.08 nm for the BEFL configured with 95/5 output coupler as shown in Figure 5(c). Below of this input power, the number of lines decreased by 95/5 output couplers as such as Figures 5(a and b) which shows more restoratively in this kind coupler. However, the number of lines significantly reduced as the cavity loss increases. For instance, only two Stokes are observed with 80/20 coupler as shown in Figure 5(a). The side mode suppression ratio, which is defined as the power difference between the BFL's peak and the second highest peak (SMSR) are obtained at approximately 27.0 dB, 26.9 dB, 18.8 dB for 80/20, 90/10 and 95/5 couplers, respectively as shown in Figure 5. The multi-wavelength output of the BFL is observed to be stable at room temperature with only minor fluctuations observed coinciding with large temperature variances. The side modes are mainly due to anti Stokes and additional Stokes of the BFL, which arises due to FWM effect in the PCF.

The extremely FWM effect in PCF leads to the generation of a wave whose spectrum is the "mirror image" of the weak wave, in which the mirroring occurs about the pump
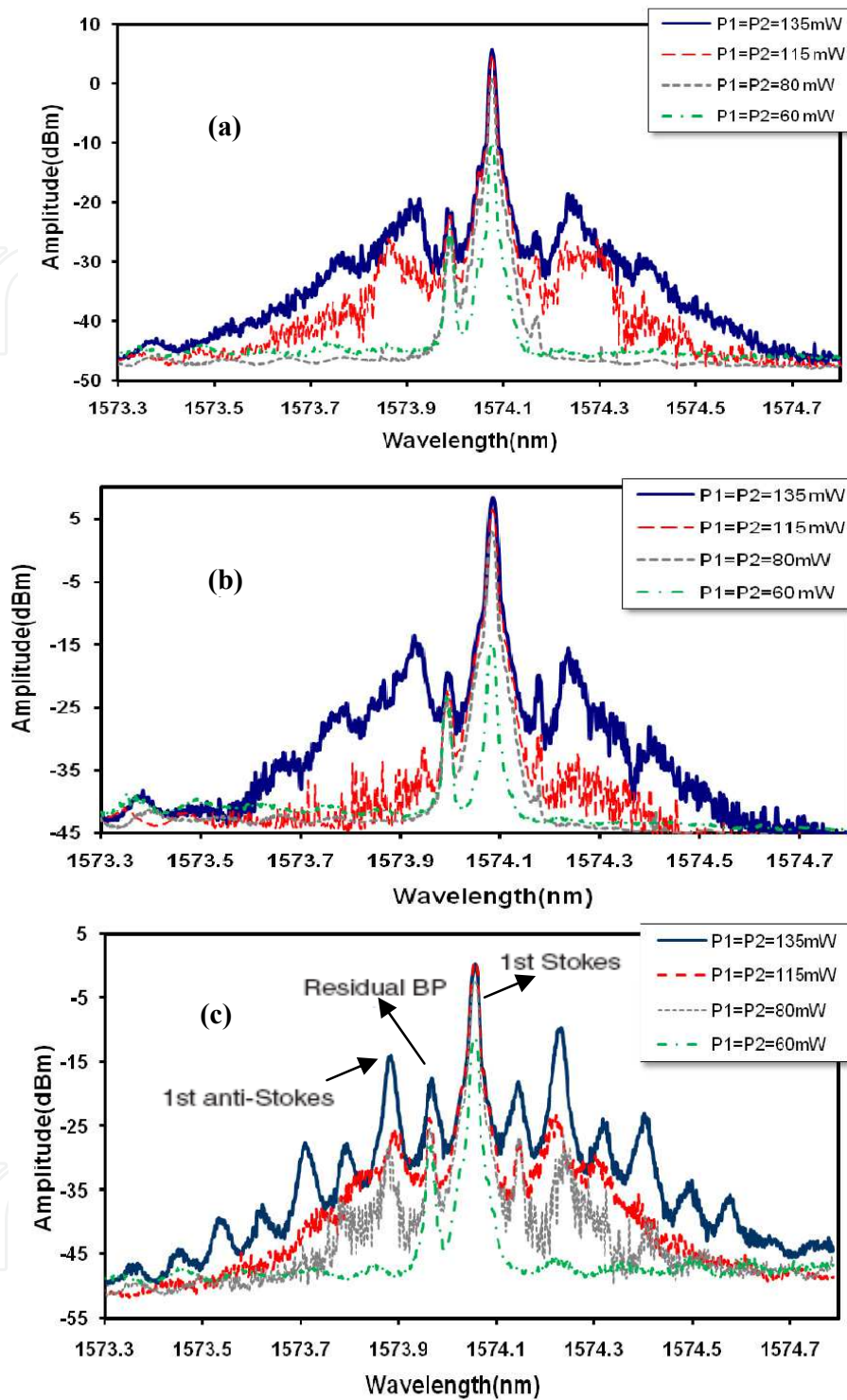
Fig. 5. The BFL output spectrum for (a) 80/20 coupler, (b) 90/10 coupler and (c) 95/5 coupler. Both pumps are at the same power for each output coupling ratio.

frequency. The representation of this image can be observed in Figures 5 where the multi-wavelength spectrum is more symmetry with the use of 95/5 output coupler.

Figure 6 shows the peak power of the first Stokes for different couplers against the input 1480 nm pump power of each pump (total pump power is double). The BP power and wavelength is fixed at 5 dBm and 1574 nm, respectively. The BEFL starts to lase at 1480 nm pump power of 60 mW which is the threshold power. Below this power, the Erbium gain is very low and cannot sufficiently compensate for the loss inside the laser cavity and thus no Stokes is observed. The output power saturates at 135 mW. As shown in the figure, the peak power is highest with 80/20 coupler and lowest with 95/5 coupler. Hence, we observed higher SMSR in Figure 5(a). Inset of Figure 6 shows the peak power of the first Stokes against the BP power at various output couplers. This figure shows that the threshold power of around 4~5dBm is required to generate the Stokes with the use of 95/5 output coupler. The threshold power reduces as smaller portion of light is allowed to oscillate in the ring cavity. For instance the threshold power is about 2 dBm with 80/20 output coupler.
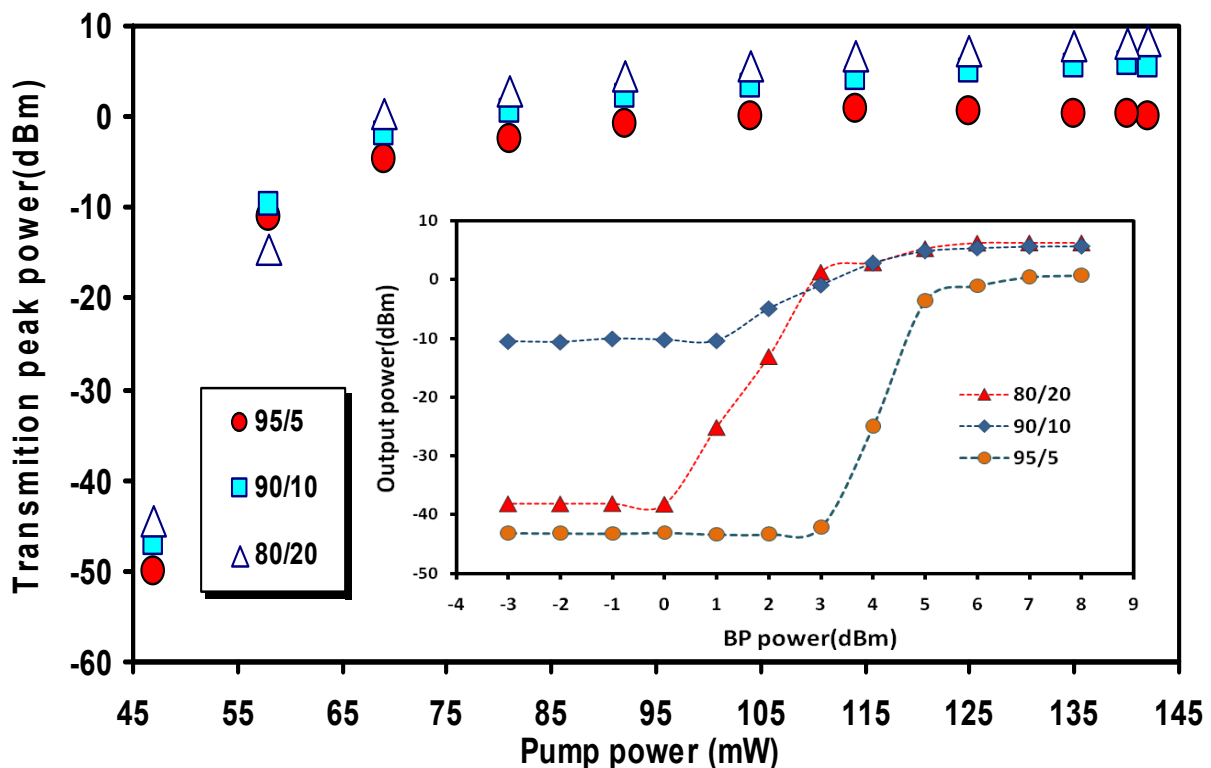

Fig. 6. Output peak power as a function of 1480 nm total pump powers. Inset shows the peak power against BP power.

In this area research, we also compared the results by another ring resonator based PCF. The second experimental setup for the proposed BFL is shown in Figure 7. The ring resonator is similar to figure 3 but consists of a forward pumped Bi-EDF and only 10 dB output coupler. The Bi-EDF is 49 cm in length and has a nonlinear coefficient of 60 $W^{-1}km^{-1}$ at 1550 nm, an erbium concentration of 3250 ppm and a cut-off wavelength of 1440 nm as well as a pump absorption rate of 83 dB/m at 1480 nm as the same of 215 cm long of Bi-EDF.
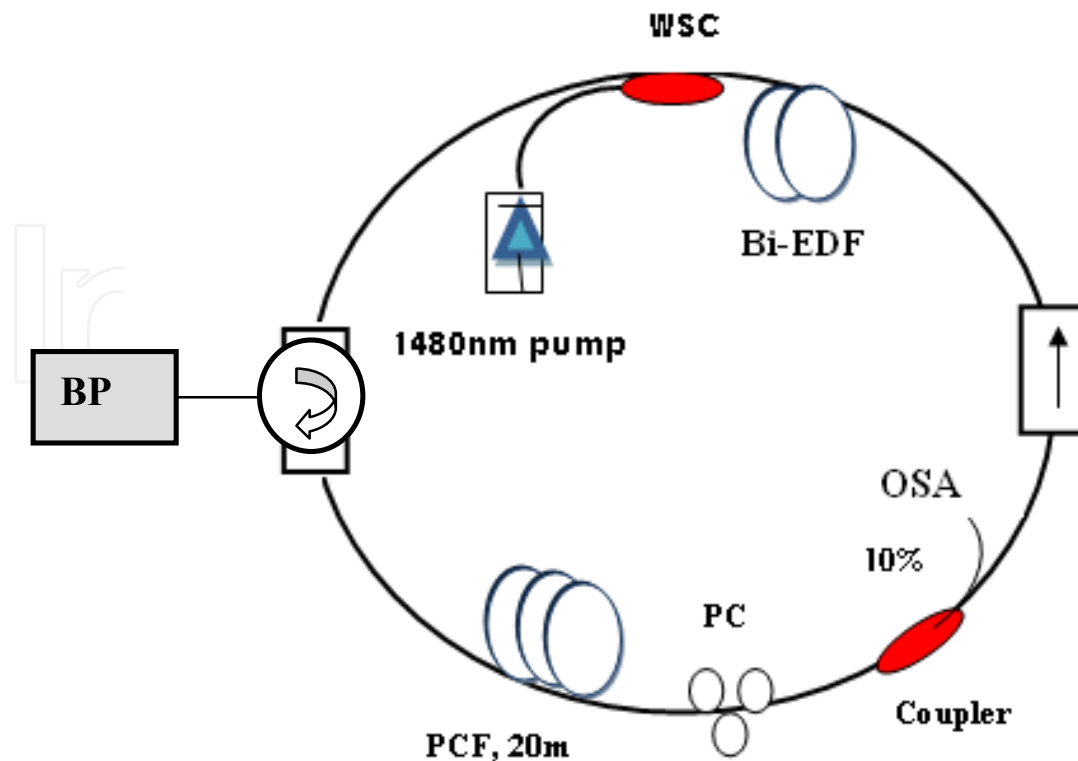
Fig. 7. Experimental setup for the proposed Bi-EDF and PCF based Brillouin fiber laser [23].

Without the BP, the larger spacing of 0.57 nm was obtained due to the incorporation of the PCF, which changes the cavity loss and dispersion parameter. The spacing is determined by the cavity length as well as the birefringence state in the cavity, which can be controlled by the PC.

The BP is injected into the ring cavity and a forward pumped Bi-EDF via the circulator to generate the backward propagating Brillouin Stokes and Rayleigh scattered light at Brillouin-shifted and BP wavelengths, respectively. The back-scattered light due to Rayleigh scattering, the reflections of the connectors and splices is relatively higher than the Brillouin Stokes light. Furthermore, the power, back scattered due to SBS, is frequency shifted to higher wavelength, because of the Doppler shift. The SBS will become significant effect, when high powers are used, because it is highly dependent on the intensity.

As we mentioned in Kerr effect, the change in the refractive index is proportional to the optical intensity and lead to nonlinear scattering and frequency shift.

However, both lights are amplified by the forward pumped Bi-EDF and oscillate in the ring cavity to generate a dual wavelength laser. The spacing between the BP and the BFL is obtained at 0.09 nm (~10 GHz) as shown in Figure 9.

The operating wavelength of this the Brillouin fiber laser set up is determined by the forward pumped Bi-EDF gain spectrum which covers the conventional band (C-band) region from 1525 to 1570 nm as well as the cavity loss. Therefore, the BP wavelength is optimized at 1559.00 nm, which is within the lasing bandwidth of the free-running erbium doped fiber laser (EDFL). The EDFL operates at around 1560 nm region due to the cavity
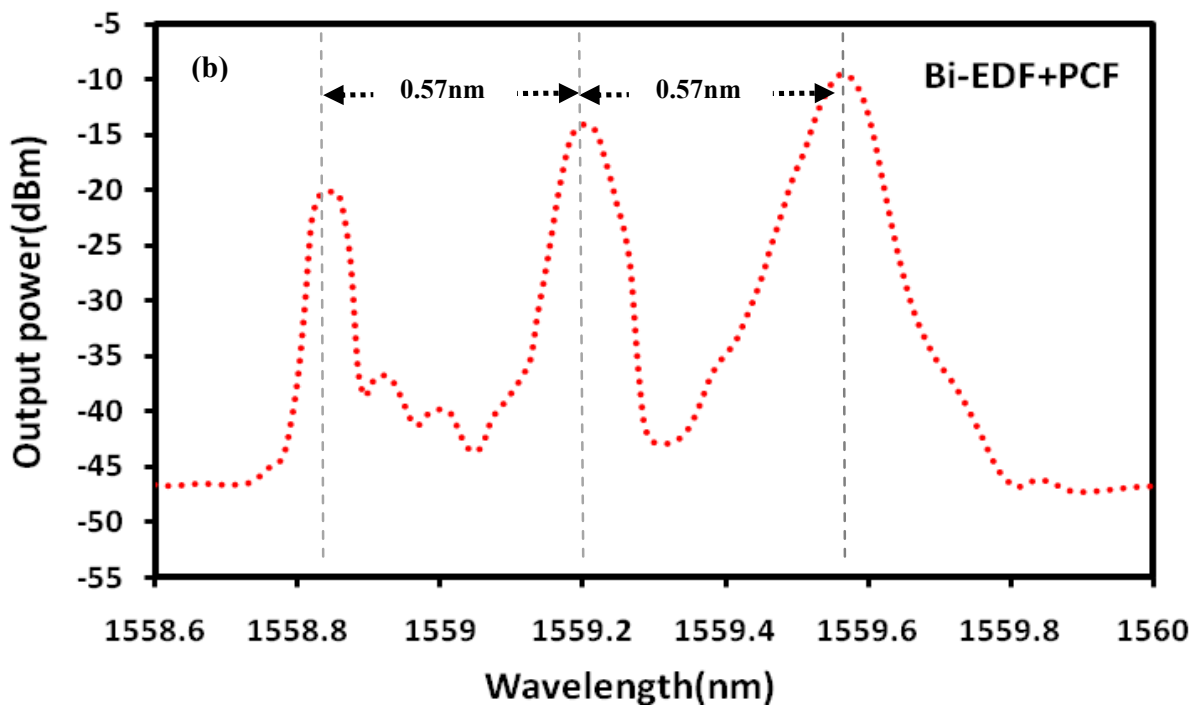
Fig. 8. Free-running spectrum of 49 cm of Bi-EDF and PCF.
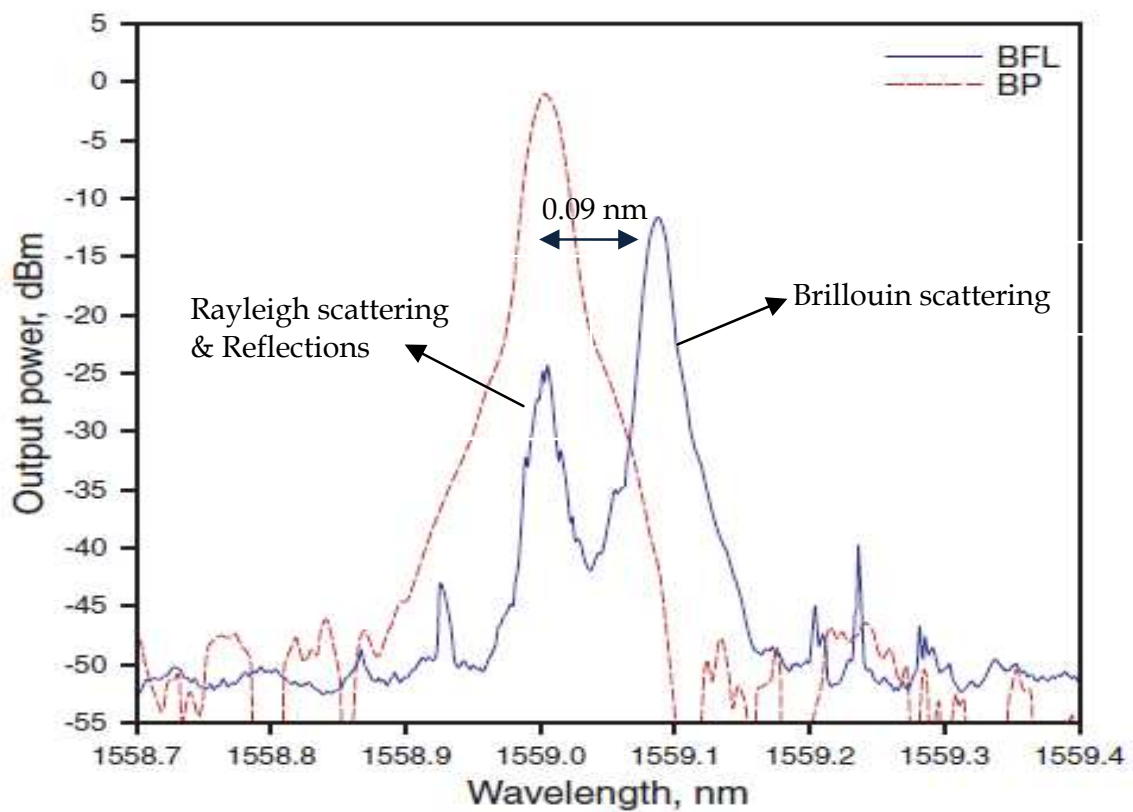

Fig. 9. Output spectrum of the proposed Bi-EDF and PCF based Brillouin fiber laser.

loss which is lower at the longer wavelength. Figure 9 compares the BP and output spectrum of the proposed BFL. The 1480 nm pump power is fixed at 150 mW. The BFL is achieved at 1559.09 nm with the peak power of approximately –12.3 dBm when the injected BP is set at 0 dBm. The 3 dB bandwidth of the BFL is measured to be approximately 0.02 nm limited by the OSA resolution. The SMSR is obtained at approximately 12 dB as shown in Figure 9. The anti-Stokes is also observed which arises due to FWM effect in the ring cavity.

However, the stimulated single wavelength BFL is obtained due to the SBS effect, which is more dominant especially in the PCF. The BFL output is observed to be stable at room temperature too.

4. Conclusion

In summary, new configurations of BFL are proposed and demonstrated using a PCF in conjunction with uni- and bi-directionally pumped Bi-EDF. By employing PCF ring configuration, more than 13 lines are obtained at the maximum 1480 nm pump power of 135 mW as shown in Figure 5(c). The wavelength spacing of setups is nearly between to 0.08-0.09 nm for the BEFL. The acceptable side mode suppression ratio (SMSR) are obtained in both configurations by 90/10 output coupler are approximately 26.9 dB and 12 dB, respectively. The side modes are mainly due to anti Stokes and additional Stokes of the BFL in the PCF. Despite of this, the 80/20 output coupler demonstrated the lowest cavity loss and the highest SBS in the peak power.

The BFL uses a ring cavity structure to generate Stokes and anti-Stokes via stimulated Brillouin scattering (SBS) and FWM processes. Hence, two nonlinear effects of SBS and FWM are extremely affective on ring fiber laser based PCF. The single- and multi-wavelength BFL are stable at room temperature with only minor fluctuations observed coinciding with large temperature variances and also is compact due to the use of only 20 m long of PCF and short long of Bi-EDF.

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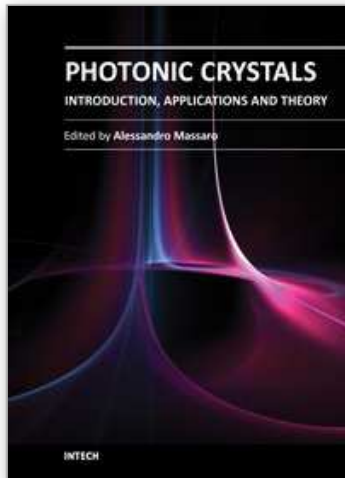
Photonic Crystals - Introduction, Applications and Theory

Edited by Dr. Alessandro Massaro

The first volume of the book concerns the introduction of photonic crystals and applications including design and modeling aspects. Photonic crystals are attractive optical materials for controlling and manipulating the flow of light. In particular, photonic crystals are of great interest for both fundamental and applied research, and the two dimensional ones are beginning to find commercial applications such as optical logic devices, micro electro-mechanical systems (MEMS), sensors. The first commercial products involving two-dimensionally periodic photonic crystals are already available in the form of photonic-crystal fibers, which use a microscale structure to confine light with radically different characteristics compared to conventional optical fiber for applications in nonlinear devices and guiding wavelengths. The goal of the first volume is to provide an overview about the listed issues.

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