Brillouin Fiber Laser using Nonlinear Birefringent Photonic Crystal Fiber

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ABSTRACT
A Brillouin fiber laser using a highly nonlinear birefringent photonic crystal fiber is reported. The core of the fiber was elliptical in shape. A single-longitudinal-mode high power fiber laser was used as a Brillouin pump and the laser produced multiwavelength output with a 0.04 nm separation. Adjusting the polarization controller plates made it possible to obtain a single wavelength laser. The effect of the small core birefringent photonic crystal fiber on the output of the laser was explored. The laser was stable and showed an intensity fluctuation of less than 0.2 dB. The output of the laser was monitored using an optical spectrum analyzer of resolution 0.01 nm.

Keywords
Fiber Laser, Brillouin Fiber laser, photonic crystal fiber, nonlinear optics, single-mode laser

1. INTRODUCTION
Stimulated Brillouin scattering (SBS) occurs when the optical power launched into the fiber exceeds a Brillouin threshold level. The Brillouin scattered light propagates in the backward direction with a frequency which is downshifted, due to the Doppler effect, by an amount of,

$$\nu_B = {2n\nu_A}/{\lambda_P}$$

where n is the refractive index, ν_A is the acoustic velocity and λ_P is the wavelength of the forward-propagating light. The SBS has a detrimental effect on devices based on highly nonlinear fiber because of the saturation effect of input power [1]. However, for a number of applications such as amplification, lasing, slow light generation, and sensing, SBS is very useful [2-7]. In general, a longer length of single-mode fiber (SMF) is required to develop devices using the SBS effect, due to its very low nonlinear coefficient. Recently, fibers with high nonlinear coefficients have been used to develop photonic devices with a greatly reduced length [2;8]. Nonlinear photonic crystal fiber (PCF) is very attractive for developing photonic devices for their unique optical properties. Recent investigations into SBS in highly birefringent photonic crystal fiber have found that the fiber is a good candidate for developing fiber lasers and sensors [9;10].

Multiwavelength fiber laser sources are very attractive for their applications in optical communications, photonic device characterizations, and sensing. Several techniques have been proposed and demonstrated to produce a multiwavelength fiber laser using an erbium-doped fiber as a gain medium [11-13]; SBS is one of these techniques [14-18].

In this letter, a dual-wavelength Brillouin fiber laser in a unidirectional ring cavity configuration using a highly nonlinear, polarization-maintaining photonic crystal fiber is demonstrated. An erbium/ytterbium co-doped high power fiber laser, designed and constructed in-house, was used as a pump. Further, the effects of the polarization-maintaining property of the PCF and modal (longitudinal) structure of the pump laser on the output of the Brillouin laser are experimentally investigated.

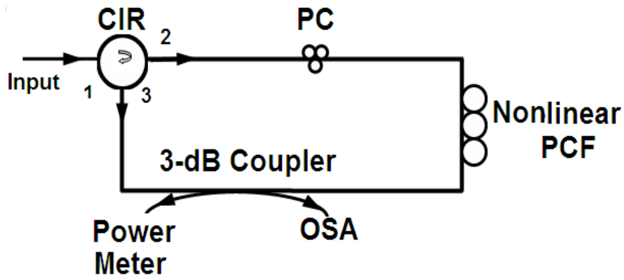


Figure 1: Experimental setup. CIR: Polarization insensitive optical circulator; PC: Polarization controller; OSA: Optical spectrum analyzer

2. EXPERIMENT
The schematic of the laser is shown in Figure 1. The ring resonator consists of a three-port polarization-independent circulator, a three-meter-long nonlinear elliptical core photonic crystal fiber, a polarization controller to control the polarization state of the light waves inside the cavity, and a 3-dB coupler to extract the output of the laser. The PCF has nonlinear coefficient of 0.12 m^{-1} W^{-1}, core dimension of 1.3×2.3 µm, birefringence of 2.2×10^{-3} at 1530 nm, attenuation of 84 dB/km at 1550 nm (which gives an effective length of 2.91 m), and a beat length of 0.7 mm. The Brillouin pump laser (input laser) could produce a single-longitudinal-mode laser with an output power of 450 mW. Figure 2 shows the modal structure of the pump laser obtained using a scanning Fabry-Perot spectrum analyzer (SFPSA, FSR=2 GHz) of resolution 6.7 MHz, which confirmed the single-longitudinal-mode oscillation of the laser. The pump laser was injected into the Brillouin laser cavity in the clockwise direction. The Brillouin wavelengths were generated in the anticlockwise direction and were extracted through a 3-dB coupler. The output of the laser was monitored using an optical spectrum analyzer (OSA) of resolution 0.01 nm. The output power from the forward propagating waves inside the cavity was monitored using the power meter.

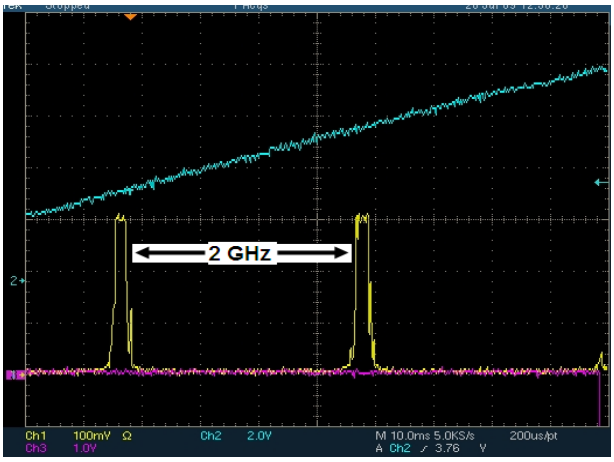


Figure 2: Modal structure, using a SFPSA and oscilloscope, of the input pump laser at 1565.96 nm with output power of ~ 450 mW

Figure 3 shows the output of the Brillouin laser obtained using 3 meters of nonlinear polarization-maintaining PCF with an input pump power of ~450 mW. The output of the laser shows multiple peaks. It was found that a small-core photonic crystal fiber produces multiple peaks in the SBS output spectrum due to highly multimode character of acoustic waves [9;10]. The separation between two consecutive peaks was 0.04 nm (~5 GHz). The intensities of the 2nd, 3rd and 4th peaks were more than 10 dB lower than the central Brillouin peak.

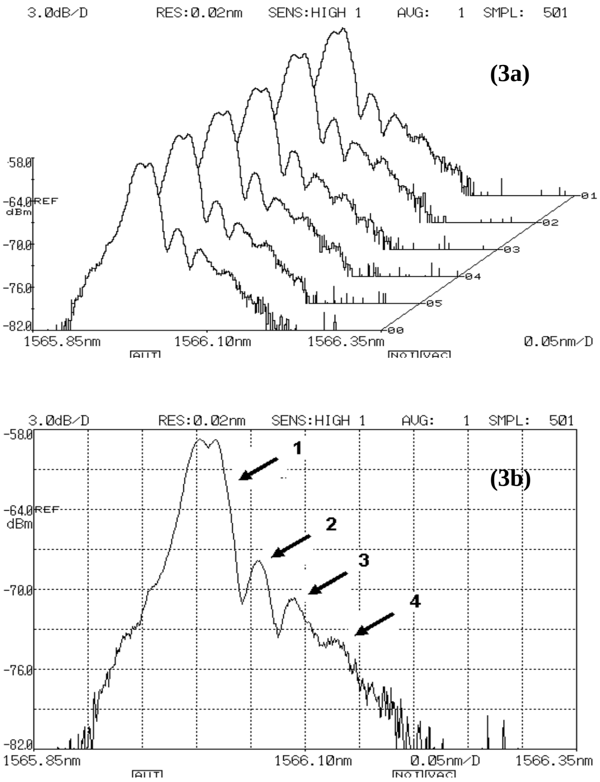
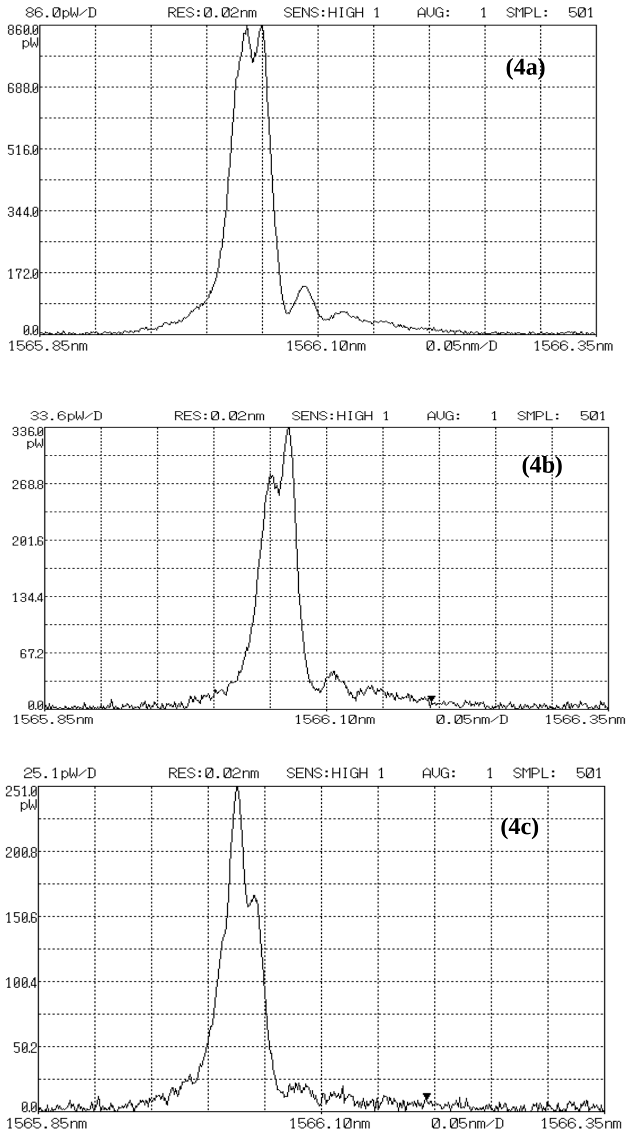


Figure 3: Output of the Brillouin fiber laser with 4 distinct peaks for an input pump power of 450 mW, (a) Multiple scan at 2 minutes interval; (b) single scan

Further, it is evident from Figure 3 that the central peak has two peaks; these two frequencies in the first order are due to the birefringent property of the PCF. Adjustment of the polarization controller plates produces a single peak or two peaks with equal intensities (Figure 4). The x and y components of the incident waves experienced different amounts of Brillouin frequency shift due to the difference in refractive indices ($n_x \neq n_y$). Thus, by adjusting the polarization controller plates, a particular polarization-mode could be excited. The higher order modes did not show any splitting due to their high threshold power [10].

The lasing lines were very stable, with an intensity fluctuation of less than 0.2 dB. The effective cavity length of the ring resonator was ~7 m, which corresponds to a longitudinal mode spacing of ~30 MHz. The threshold pump power of the laser was very high due to the high losses at the splices of PCF and SMF; the high splice losses also reduced the output power of the laser. To reduce these splice losses, a repeated arc discharge technique was used to splice the PCF and SMF. The multiple arc discharge increased the mode field diameter (controlled collapse of the air holes in the PCF reduced the effective refractive index contrast between core and cladding) of the PCF which matched with the mode field diameter of the SMF, and thus reduced the splice loss [19;20].



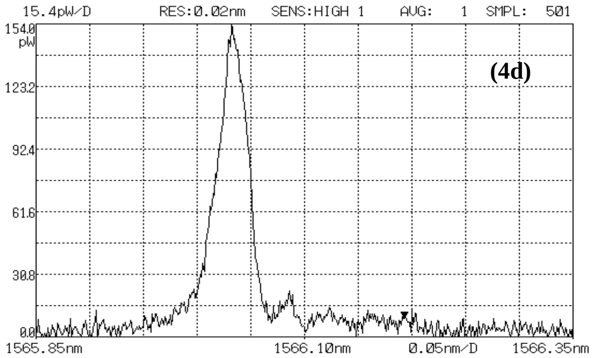


Figure 4a-4d: Output of the multiwavelength Brillouin fiber laser at different positions of the polarization controller plates

3. CONCLUSION

In conclusion, the authors have demonstrated a Brillouin fiber laser using highly nonlinear PCF. The laser could produce a multiwavelength output with a separation of 0.04 nm. The multiple peaks were due to the multimode property of the small-core PCF used in this experiment. Through adjustment of the polarization controller plates, the laser could be made to oscillate in single-wavelength or dual-wavelength regimes, where the separation between two lasing wavelengths depends on the birefringence property of the PCF. The high nonlinearity of the PCF reduced the length of the resonant cavity, which resulted in wider longitudinal mode spacing. The birefringent property of the PCF increased the stability of the laser.

4. ACKNOWLEDGEMENTS

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