

Photonic crystal fiber-based multi-wavelength Brillouin fiber laser with dual-pass amplification configuration

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A simple technique for achieving a stable, room temperature and multi-wavelength lasing with narrow linewidth is demonstrated using Brillouin fiber laser (BFL) with a 100-m-long photonic crystal fiber (PCF) in conjunction with a dual-pass configuration. A broadband fiber Bragg grating (FBG) operating in the C-band region is incorporated at the end side of the setup to allow a dual-pass operation. The proposed BFL can operate at any wavelength depending on the Brillouin pump wavelength and the FBG's reflection region used. With a Brillouin pump (BP) of 15.7 dBm, approximately 7 Stokes and 4 anti-Stokes lines are obtained with a line spacing of 0.08 nm.

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Multi-wavelength fiber lasers have generated academic interest for two decades because of their potential applications in optical communications^[1], fiber sensors, and optical testing and measurements^[2]. In order to achieve a multi-wavelength lasing output, various techniques have been proposed and demonstrated, including erbium-doped fiber lasers based on a special twin core erbium-doped fiber (EDF) structure^[3], semiconductor optical amplifier (SOA)-based fiber laser with a comb filter^[4], and by using stimulated Brillouin scattering (SBS)^[5]. Among these, the SBS-based approach has many advantages, such as simple configuration, easy realization of tuneable wavelength, narrow linewidth, and no comb filter requiring. This approach is commonly considered as Brillouin fiber laser (BFL), which utilizes nonlinear gain in optical fibers.

Recently, the emergence of photonic crystal fibers (PCF) with high nonlinearity has enabled the SBS to occur more easily in a relatively shorter length of PCF (usually around 100 m) with low optical power^[6]. PCFs comprise a class of micro-structured fiber possessing a solid core surrounded by a cladding region, which is defined by a fine array of air holes that extend along the full fiber length. PCFs are typically made of a single material, usually pure silica, and guide light through a modified form of total internal reflection; this is because the volume average index in the core region of the fiber is greater than that of the surrounding micro-structured cladding. To date, PCF-based BFLs have been demonstrated using various configurations for both single wavelength and multi-wavelength operations^[7,8]. In this letter, a new configuration of a PCF-based BFL is proposed using a dual-pass approach. The proposed BFL uses a broadband fiber Bragg grating (FBG) operating in the C-band region as a reflector to allow dual-pass operation. This can improve the output powers of the cascading Stokes lines, thereby increasing the number of Stokes obtained. This type of BFL does not require a linear gain medium, such as EDF, to increase the effect. Therefore, it can operate at any wavelength depending on the Brillouin pump (BP) wavelength.

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The proposed BFL architecture for the generation of multi-wavelength Stokes lines is depicted in Fig. 1, with the inset showing the scanning electron micrograph (SEM) image of the PCF. It consists of a short piece of PCF, a 3-dB coupler, and a high-reflectivity broadband FBG at the cavity end; the PCF has a triangular core with an average diameter of 2.1 μm and cladding diameter of 128 μm . The average air hole diameter of the fiber is 0.8 μm with a 1.5- μm pitch. In the experiment, the PCF used was made from pure silica with 17.4 wt.-% of Ge-doped core region. The Ge-doped core functions to increase the nonlinear refractive index of the core, creating a smaller mode field diameter, which reduces confinement loss. This effect can reduce acoustic loss and avoid the broadening of the Brillouin spectrum linewidth. Here, the PCF was spliced to an intermediate fiber and then a single mode fiber (SMF) with a splice loss of 0.35 dB at each end.

The proposed BFL configuration consists of two main sectors: a ring cavity as a Brillouin gain block, which includes a piece of PCF and a 3-dB coupler, and a broadband FBG operating in the C-band region at the end of this linear structure to allow dual-pass Stokes lines oscillation in the ring resonator. The FBG has a 40-nm bandwidth centered at 1545 nm with a reflectivity of more than 99%. The BP is an external cavity tunable laser source (TLS) with a line-width of approximately 20 MHz,

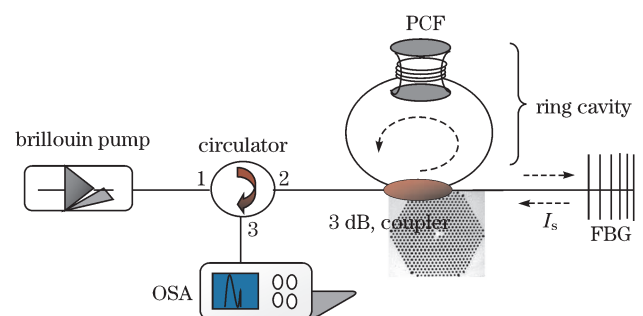


Fig. 1. Proposed multi-wavelength BFL architecture.

which is amplified by an EDF amplifier to provide sufficient power for this study. The BP is launched into the PCF through a 3-dB coupler via optical circulator to generate the first order Brillouin Stokes in a clockwise direction at a wavelength, which is downshifted by 0.08 nm from the BP wavelength. The Brillouin Stokes oscillates inside the ring resonator to generate the Brillouin laser. When the laser power exceeds the threshold, it creates the second order Stokes signal in the opposite direction; in turn, the second order Stokes signal creates the third order Stokes signal. The process continues until the next higher order Stokes signals power becomes too small to exceed the threshold, at which point the creation of subsequent Stokes order signal will diminish. The residual BP and even order Stokes lines propagating in the clockwise direction are reflected by the broadband FBG to doubly propagate inside the ring resonator in the opposite direction, thereby increasing the nonlinear gain in the resonator. In turn, this improves the multi-wavelength lasing process. The output of the BFL was characterized using an optical spectrum analyzer (OSA) with a resolution of 0.015 nm.

Figure 2 compares the output spectrum of the BFL in different configurations at the maximum BP power of 15.7 dBm or 37 mW. Firstly, the output of the BFL in the presence of the ring cavity but without FBG was studied. With this configuration, only the first Brillouin Stokes was achieved at a 1560-nm wavelength with a side mode suppression ratio (SMSR) of 26 dB. However, by incorporating the broadband FBG as in the proposed configuration of Fig. 1, seven Stokes waves and four anti-Stokes waves with nearly 13-dB signal-to-noise ratios (SNR) are obtained by 100-m PCF around the oscillated BP at 1559.98 nm, whereas we only achieved the first Stokes wave in the same configuration by incorporating 50-m PCF. This can be attributed to the fact that the 50-m-long PCF is not sufficient to create a multi-wavelength in this configuration. By incorporating the 100-m-long PCF, 4 anti-Stokes waves also arose due to four wave mixing (FWM) between co-propagating BP and BFL photons during the oscillation. The bi-directional operation of the laser also contributes to the anti-Stokes generation. The output spectrum of the BFL was also investigated in the absence of the ring cavity, in which

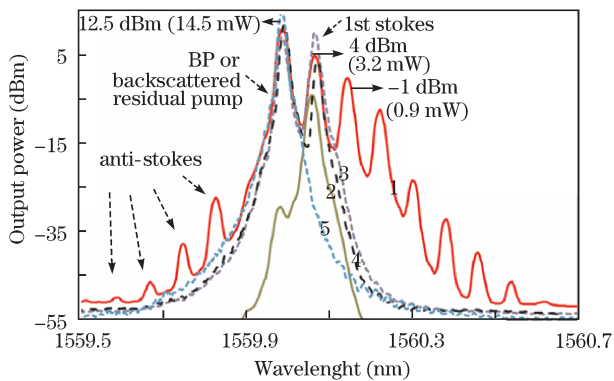


Fig. 2. Output spectra of the BFL with different configurations and PCF lengths. 1. with FBG & ring cavity, 100 m PCF; 2. with ring cavity & without FBG, 100 m PCF; 3. with FBG & without ring cavity, 100 m PCF; 4. with FBG & ring cavity, 50 m PCF; 5. BP.

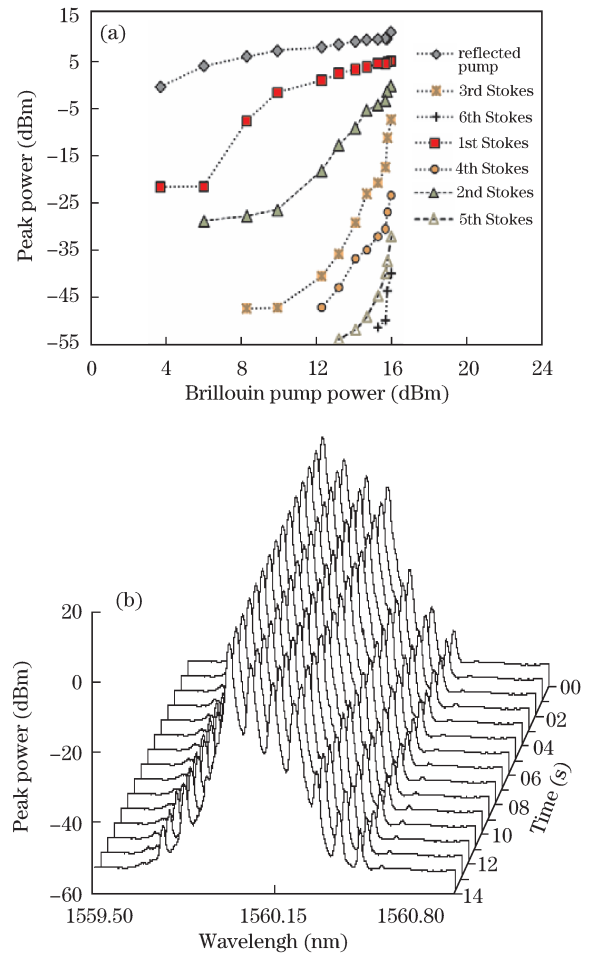


Fig. 3. (a) Residual BP and Stokes wave powers plotted against BP power; (b) the spectral evolutions of the proposed BFL against time, which is repeatedly scanned every 10 minutes.

the ring cavity was replaced by the PCF. In this BFL, only the first Stokes was observed with 2.5-dB SMSR. These results show that the presence of ring cavity and FBG is very important for multi-wavelength generation. The presence of FBG at the end side allows the BP and SBS light beams to propagate twice into the ring cavity section, enabling the cavity to create more Stokes lines. The Brillouin spectrum is also observed to be asymmetrical, whereby the earlier Stokes intensity is always higher than the subsequent Stokes. This can be attributed to energy loss during the generation of the subsequent Stokes. With FBG and a 100-m-long PCF, the first and second Stokes powers peaked at 4 and -1 dBm, corresponding to 3.2 and 0.9 mW, respectively.

Figure 3(a) shows the output Brillouin Stokes power and the transmitted residual BP power against the input signal BP power. The BP wavelength was set at around 1560 nm, while the BP power varied from 1.5–16 dBm. The number of generated Stokes and its power increases as the BP increases. This can be attributed to the increase of the nonlinear Brillouin gain as the BP power rises. This situation provides sufficient signal power for higher order Stokes signals to pump the PCF and maintain the cascading process of the Stokes into multiple Stokes. However, the power of each subsequent Stokes

line is typically lower than that of the previous one as each subsequent Stokes is generated through the energy of the previous Stokes, thus slightly reducing the power of the Stokes line. In addition, the Stokes lines begin to saturate as the BP power increases above the threshold power of the subsequent Stokes. For instance, the second Stokes line becomes saturated as the threshold for the third Stokes is reached. This is due to the power transfer from the second to the third Stokes, which occurs when the BP power is ~ 14.7 dBm. For the higher order Stokes, however, the threshold BP powers are obtained at almost the same level of 15.3 dBm. This is probably due to the FWM between the oscillating BP and Stokes signals, which improves the conversion efficiency by providing amplification for the higher Stokes generation. The output of the BFL is stable at room temperature with only minor fluctuations observed coinciding with large temperature variances as shown in Fig. 3(b).

In conclusion, we have experimentally demonstrated a stable, room temperature multi-wavelength lasing oscillation by utilizing SBS in a short PCF in conjunction with dual-pass configuration. Nearly 7 Brillouin Stokes lines with a constant spacing of 0.08 nm have been achieved with 15.7-dB BP power and a 100-m-long PCF. In addition, 4 anti-Stokes lines have also been obtained due to four wave mixing and bi-directional operations. Depending on the BP wavelength and FBG region used,

the proposed configuration can work at any wavelength. When the pump power exceeds the SBS threshold power, the previous Stokes line starts to saturate. This technique provides another simple approach to achieve stable, room temperature multi-wavelength lasing with narrow bandwidth.

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