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Distributed feedback multimode Brillouin–Raman random fiber laser in the S-band

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Abstract

A novel S-band multimode Brillouin–Raman random fiber laser based on distributed feedback of Rayleigh scattered light is demonstrated. It relies on a short length, 7.7 km long angle-cleaved dispersion compensating fiber in a mirror-less open cavity. Two 1425 nm laser diodes at a modest operating power amplify a Brillouin pump (BP) signal, which in turn generates a multi-wavelength laser output through the stimulated Brillouin scattering. Eleven Brillouin Stokes lines, spanning from 1515.15 to 1516.00 nm, were obtained at a Raman pump power of 361.66 mW. Out of these, five odd Brillouin Stokes lines were generated with a flat peak power of about 0 dBm.

1. Introduction

Random lasers constitute an emerging topic of intense current interest in photonics science [1–9]. Functionally a random laser relies on multiple scattering (due to the presence of a certain level of disorder) as in Anderson type localization of light [10, 11] that effectively results in long optical path lengths in a gain medium devoid of any resonator(s). In the case of a low density of scatterers, the required length of the medium would be relatively long. Turitsyn *et al* [1] have demonstrated random lasing through Raman gain and distributed feedback of Rayleigh scattered light in an 83 km long conventional single-mode fiber, which formed an open cavity. The mechanism exploited by them is radically different from conventional fiber lasers or traditional random lasers.

Various approaches have been proposed in the literature to achieve multi-wavelength fiber lasers (MWFLs), such as that demonstrated in [12, 13] on generating dual-wavelength and also multi-wavelength outputs based on Rayleigh scattering distributed feedback in conjunction with an array of fiber Bragg gratings (FBGs) in a linear configuration. In addition to these, other approaches that exploit the stimulated Brillouin scattering (SBS) seeded by Raman gain, which is known as a Brillouin–Raman fiber laser (BRFL) have also been reported in [14]. The prior art in research to generate multi-wavelength laser oscillation relied on either a linear cavity [15] or a ring cavity [16]. As compared to a ring cavity, the number of Brillouin Stokes lines generated in a linear cavity BRFL is relatively larger due to Rayleigh scattering, whose growth is effectively suppressed in the ring laser cavity [17]. The linear cavity geometry in the BRFL usually involves the use of a pair of optical circulators or mirrors at the ends of the cavity to reflect the Stokes lines back into the gain medium [17]. Park *et al* [18] investigated the threshold features of Brillouin Stoke combs generated in a distributed fiber Raman amplifier in the C-band or at longer wavelengths where the BRFL was realized with virtual mirrors. In most cases, the length of the fiber is very long—lengths of more than 50 km. Furthermore, these designs require high pump powers. In our proposed random fiber laser design, the operating wavelength is within the S-band region, which is of interest and to our knowledge has yet to be reported. The S-band MWFL is attractive because S-band amplifiers such as Raman fiber amplifiers (RFAs) are now well developed and are able to produce gain in any region within this band determined by the Raman pump (RP) wavelength [19].

In this paper, we demonstrate a mirror-less open cavity Brillouin–Raman fiber laser based on the distributed feedback of Rayleigh scattered light using a short length of dispersion compensating fiber (DCF), with a much lower Raman pump power. The 7.7 km long DCF has a mode effective area of 15 μm^2 and provides an efficient nonlinear gain medium, which is simultaneously pumped by Raman and Brillouin pumps from opposite ends. To ensure mirror-less open cavity operation, the DCF was angle-cleaved at ~8°. We believe the results of our measurements demonstrate the signature of a multimode random fiber laser in the S-band. At a Raman pump power of 361.66 mW, 11 Brillouin Stokes lines were generated, spanning over a 0.85 nm band from 1515.15 to 1516 nm. Thus, additionally, our results could be exploited as a multi-wavelength fiber laser (MWFL) with possible applications as a DWDM light source in the S-band region.

2. Experimental setup

Figure 1 shows the experimental setup for the open cavity S-band multi-wavelength Brillouin–Raman random fiber laser (BRRFL). A 7.7 km long DCF with a mode effective area of 15 μm^2 was used as the nonlinear gain medium to generate lasing output at multiple wavelengths. The DCF is spliced on either side to the common port of two 2 × 1 wavelength flattened couplers, designated as WFC1 and WFC2 and having a transmission range of 1420–1625 nm. Two laser diodes, which are designated as the Raman pumps (RPs) and both operating at a wavelength of 1425 nm were coupled to the DCF from its two ends as to generate the Raman gain in a bi-directional pumping configuration. The signal end of WFC1 (having a transmission range of 1460–1625 nm) is then spliced to Port 2 of a 2 × 2 a 3 dB fiber coupler, while the input Port 1 is cleaved at an angle of 8° to form the first end facet of the open fiber cavity, marked as END1. A tunable laser source (TLS) (Ando AQ8203) with a maximum output power of 12 dBm and a linewidth of 40 MHz was injected as the Brillouin pump (BP) into the cavity through Port 4 of the 3 dB coupler at 1515 nm. Port 3 of the same coupler is used to extract a portion of the signal oscillating in the laser cavity for analysis by an optical spectrum analyzer (OSA) (Yokogawa AQ6307B), which has a resolution of 0.02 nm. Similarly, the 1460–1625 nm port of WFC2 was also cleaved at an angle of 8°, which acts as the second facet of the fiber cavity, marked as END2. In this context, for comparison, experiments were also performed with flat-cleaved fiber ends.

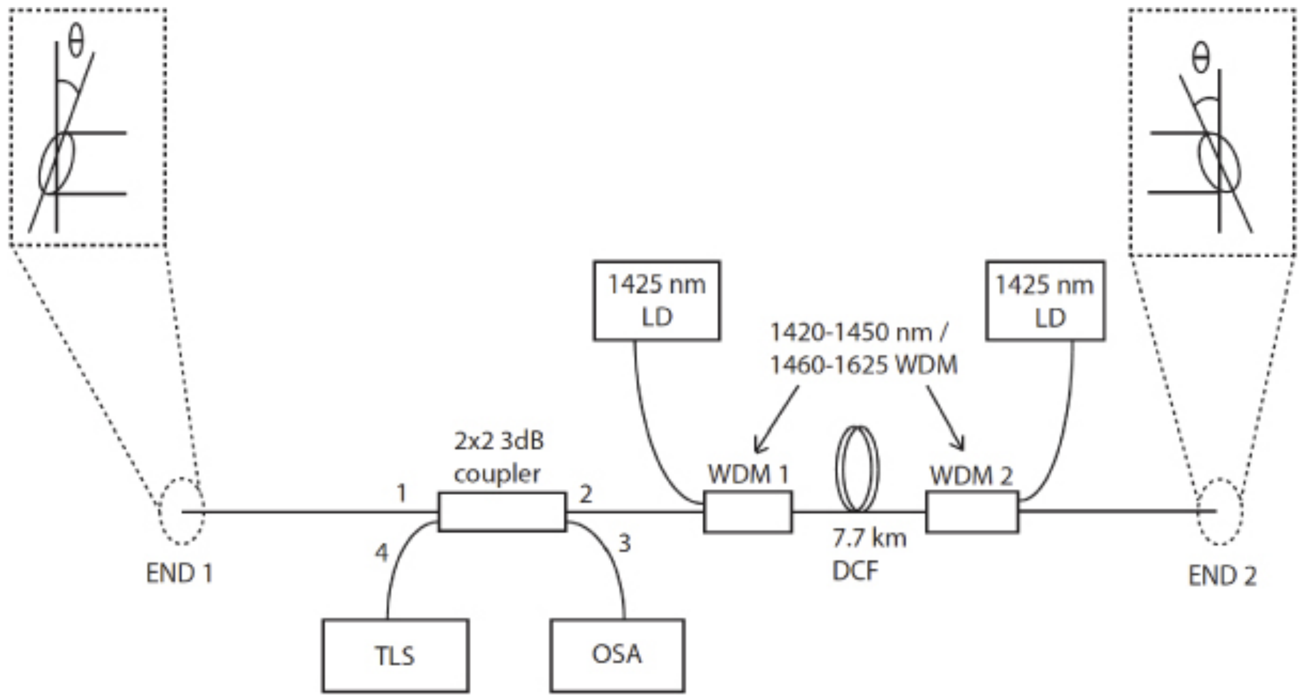

Figure 1. Experimental setup for the S-band multi-wavelength Brillouin–Raman distributed feedback random fiber laser; angle of the fiber cleave at both ENDs 1 and 2 are ~8°.

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The functional principle of our proposed BRRFL as a MWFL can be described as follows.

Due to larger refractive index contrast typical in a DCF, loss in a DCF is typically larger than in a conventional single-mode fiber. Accordingly, Rayleigh scattering (RS) losses in a DCF would be relatively stronger than in a SMF-28 type of conventional single-mode fiber because a larger index contrast requires a higher level of index modifiers as the dopants in fused silica. Thus in our view the same RS mechanism as in [1] is responsible for the distributed feedback leading to random lasing in our experiment. The BP signal from the TLS enters the DCF through the 3 dB fiber coupler followed by the WDM and gets amplified by the S-band Raman gain, which is being pumped by the two RPs. Once the BP signal exceeds the threshold power for SBS, the first Brillouin Stokes line is generated, which propagates in a direction opposite to the BP signal. When the first Brillouin Stokes line passes through the Raman gain medium, it gets amplified and generates the second Brillouin Stokes line in the same direction as the BP signal, with the condition that the power of the amplified first Brillouin Stokes line exceeds that of the threshold power for SBS. Similarly, the second Brillouin Stokes line would be amplified by the Raman gain medium and would act as the source for generating the third Brillouin Stokes line if it exceeds the Brillouin threshold power. This process continues until the generated Stokes line is incapable of generating further Stokes lines due to it being lower than the threshold value. The Stokes waves generated by the SBS process are down-shifted in frequency with respect to the frequency of the input signal [19].

3. Results and discussion

Figure 2 shows the output spectrum of the S-band BRRFL for different RP powers and a BP power of

9.4 dBm using (a) flat-cleaved fiber ends, with a 4% Fresnel reflection, and (b) angle-cleaved fiber ends. From both (a) and (b), it can be seen that the first Brillouin Stokes line is generated at a low threshold RP power of 0 mW. At a RP of 320.46 mW, multiple Brillouin Stokes line generation is observed in both the figures, which consists of seven Brillouin Stokes lines for the angle-cleaved fiber ends and four Brillouin Stokes lines for the flat-cleaved fiber ends.

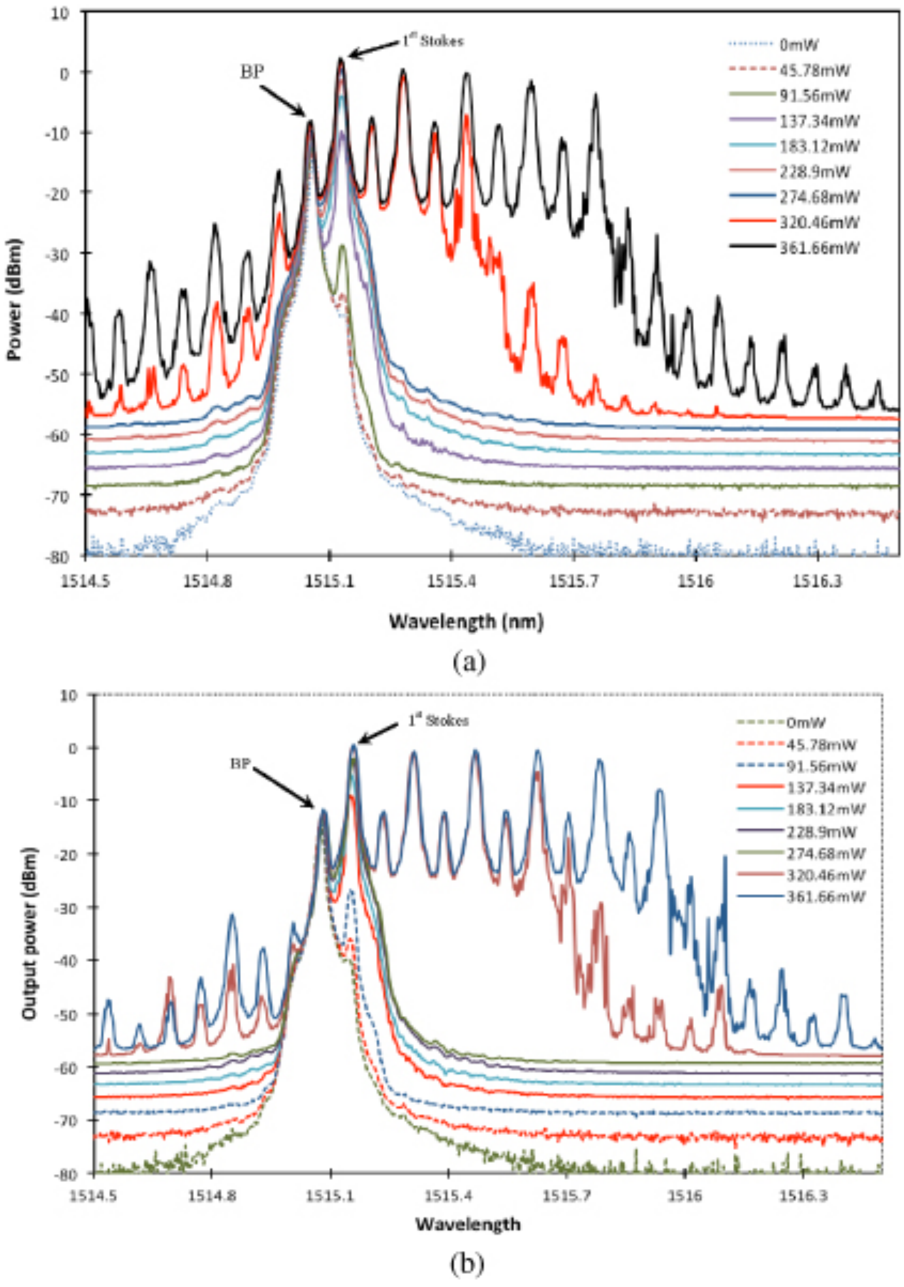

Figure 2. The output spectrum of the S-band BRRFL for different Raman pumping power using (a) flat-cleaved fiber ends, and (b) angle-cleaved fiber ends.

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The highest number of Brillouin Stokes lines generated is observed at the highest RP power of 361.66 mW, consisting of 11 Brillouin Stokes lines spanning from 1515.15 to 1516 nm within the output power range of 0 to −8 dBm, with five flat odd Brillouin Stokes lines at about 0 dBm for the proposed scheme with the angle-cleaved fiber ends. Whereas with the flat-cleaved fiber ends, nine Brillouin Stokes lines were generated at the same Raman pump power and falling within the same power range, which spans from 1515.15 to 1515.8 nm, with a number of five flat odd Brillouin Stokes lines at about 0 dBm. From figure 2, it can be seen that the odd Stokes lines experience the amplification twice as compared to the even Stokes lines. This is the reason that the peak power of the odd Stokes lines is higher than that of the even Stokes lines.

The output spectrum of the S-band distributed feedback BRRFL having angle-cleaved fiber ends for different BP powers is shown in figure 3. It can be seen from the figure that at a BP power of 0.4 dBm, the BP signal has exceeded the Brillouin threshold to generate the first Brillouin Stokes line.

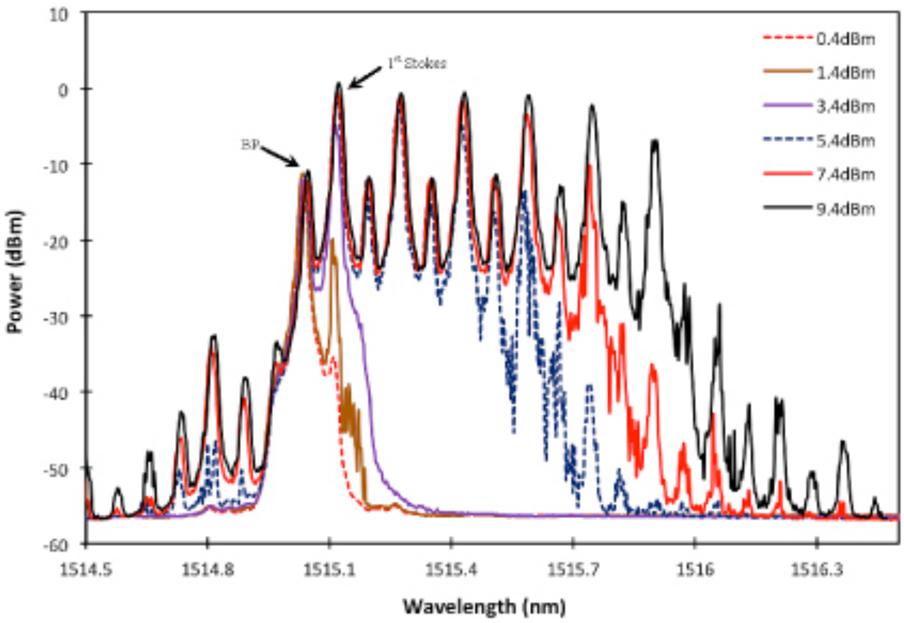

Figure 3. Output spectrum of the S-band distributed feedback BRRFL with angle-cleaved fiber ends at different BP powers.

Download figure (117 KB)

Further increases in the BP power will generate more Stokes lines, and this can be seen from the figure, whereby as the BP signal power is increased beyond 5.4 dBm, the number of the Brillouin Stokes lines generated also increases in tandem. The output power of the Brillouin Stokes lines is also observed to increase as the BP power is increased.

Figure 4 shows the number of Brillouin Stokes lines generated and the highest RP power and as the BP wavelength varies for cases of both flat and angle-cleaved fiber ends. From the figure, it can be seen that the number of Stokes lines generated for a BP wavelength of between 1490 and 1500 nm will result in only one Stokes line being generated for both cases. At a BP of 1505 nm however, the configuration with the flat-cleaved ends generates three Stokes lines, while the configuration with the angle-cleaved ends only generates one Stokes line. As the BP wavelength increases, the number of Stokes lines generated increases to nine Stokes lines for both cases, and a further increase of the BP wavelength above 1530 nm yields seven Stokes lines for the angle-cleaved configuration, and only six Stokes lines for the flat-cleaved configuration.

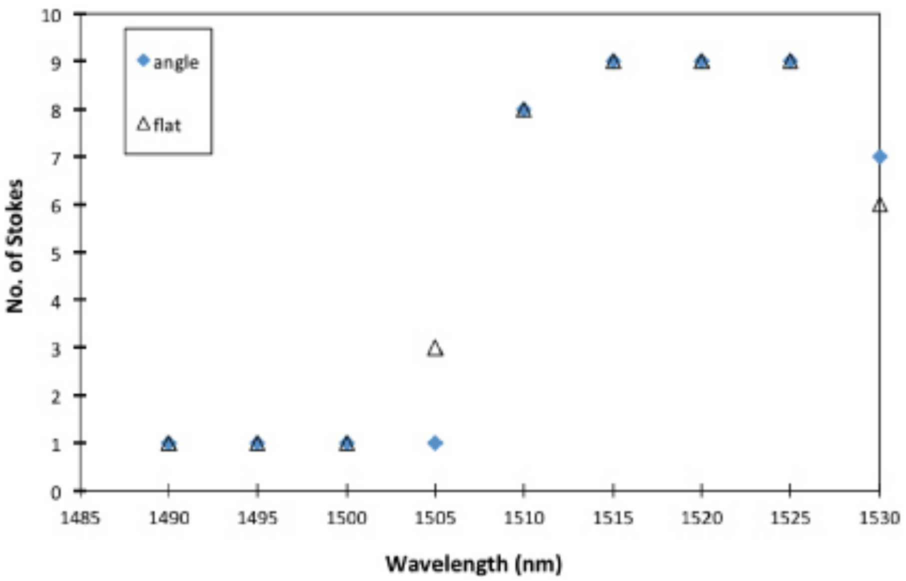

Figure 4. The number of Brillouin Stokes lines generated against different BP wavelength for flat and angle-cleaved fiber ends.

Download figure (54 KB)

This indicates that the proposed system, in particular the angle-cleaved configuration, can provide multimode laser behavior based on the random feedback laser mechanism. As in most cases, the output of random fiber lasers exhibits irregular stochastic behavior, especially around the low pump power or near threshold power region. From the above results, the output spectrum of the S-band BRRFL of this work has a distinct mode of oscillation, even at low RP powers.

The stability of the random laser output for the case of angled cleaves at both ends is shown in figure 5. The measurements are taken at 5 min intervals over a period of 60 min.

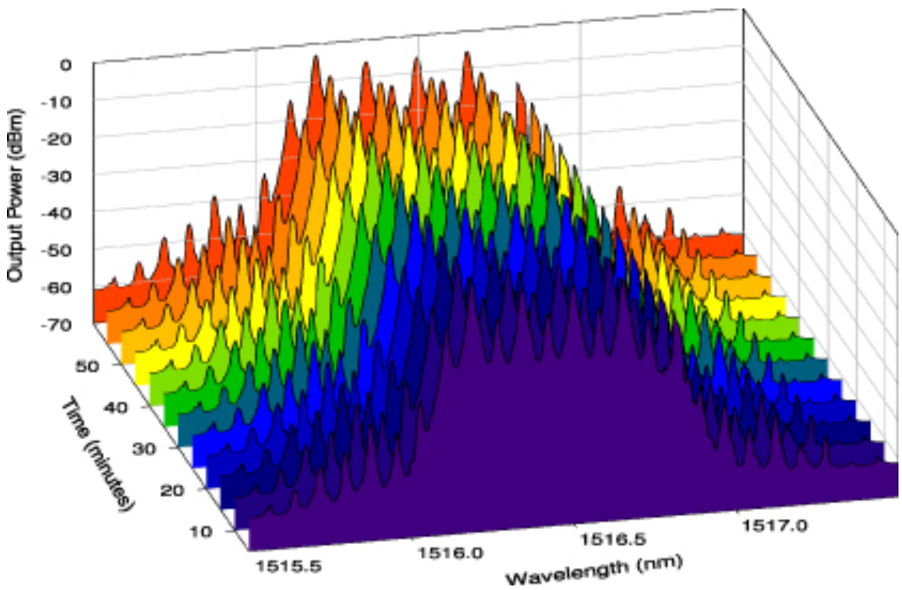

Figure 5. Stability measurement of random laser output with angled cleaved ends, taken for a period

of 60 min at intervals of 5 min.

Download figure (147 KB)

It can be inferred from figure 5 that the output is stable over time, with almost no observable fluctuations over the time period. This further establishes our proposition that the BRRFL in our experiment carries the signature of a random fiber laser with a stable output over time.

4. Conclusion

We have demonstrated a novel S-band multi-wavelength BRRFL in an open cavity that operates below 1520 nm, which has not been reported yet to the best of the authors' knowledge. It is based on a short length of DCF acting as the S-band Raman gain nonlinear medium, with a low RP power. We also prove that the BRRFL in this proposed scheme can be achieved based on the Rayleigh scattering effect in a mirror-less open cavity geometry, in which the fiber ends were angle-cleaved to prevent feedback. A BP signal is injected into the setup to generate Stokes lines via the SBS process. The performance of this proposed multimode BRRFL was studied under various Raman pump powers and also at different BP powers. The number of Brillouin Stokes lines generated under different BP wavelengths were analyzed and compared with the scheme employing flat-cleaved fiber ends.

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