High OSNR and simple configuration dual-wavelength fiber laser with wide tunability in S+C+L band

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A simple configuration dual-wavelength fiber laser, by combining the first-order Brillouin laser and the residual pump laser, is proposed and experimentally demonstrated. A 1 km long single-mode fiber is used as the stimulated Brillouin scattering gain medium pumped by a narrow linewidth tunable laser source (TLS). Through simply adjusting the TLS output power, power-equalized dual-wavelength lasing can be achieved with a high optical signal to noise ratio (OSNR) of >80 dB. With the good tunability of the TLS, the dual-wavelength fiber laser has a tunable range of ~130 nm, and simultaneously the beat frequency of the two lasing wavelengths can be tuned from 10.1875 to 11.0815 GHz with the tunable range of 0.8940 GHz. The high stability of the dual-wavelength operation is experimentally verified by the measured beat frequency fluctuation of ≤6 MHz in 1 h and power fluctuation of ≤0.03 dB in 2 h. The temporal characteristics of the fiber laser are also investigated experimentally. The fiber laser will find good applications in fiber sensing and microwave photonics areas.

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Dual-wavelength fiber lasers have been broadly investigated and have presented wide application potentials in fiber optic communication, fiber sensing, material processing, optical instrument testing, microwave generation, and terahertz radiation[1–9]. Many methods have been proposed to achieve dual-wavelength lasing in rare-earth-doped fiber laser systems, such as erbium-doped/thulium-doped fiber lasers, and most of them used two narrowband filters or a compact dual-channel filter in the laser cavity, such as cascaded fiber Bragg gratings (FBGs)[10], superimposed FBGs-based filter[5,7,11], fiber Fabry–Pérot filter[12], chirped Moiré FBG filter[13], dual-channel phase-shifted FBG filter[14], arrayed waveguide grating filter[15], in-fiber Mach–Zehnder interferometer filter[8,16], Sagnac loop mirror filter[17], birefringent FBG filter[18], all-fiber Lyot filter[19], etc. However, these narrowband filters are generally complicated and environmentally sensitive. It is generally difficult to obtain stable dual-wavelength lasing due to the strong wavelength competition presented in the homogeneous rare-earth-doped fiber gain medium. What is more, widely tunable operation is impossible based on the aforementioned schemes. The stimulated Brillouin scattering (SBS) in optical fibers has been broadly used to obtain dual-wavelength/multi-wavelength fiber lasers[20–24], avoiding the need of those filters. The strong first-order (1st) Stokes light with a frequency ~11 GHz shifted from the pump frequency can be obtained when the injected pump power exceeds the SBS threshold. The Brillouin fiber lasers possess the advantages of low cost, simple structure, narrow linewidth, and low phase noise. The SBS mechanism also enables widely tunable operation if only a pump laser source with wide tunability is used.

In this Letter, we demonstrate a low-cost dual-wavelength fiber laser with an extremely simple configuration. Using a narrow linewidth tunable laser source (TLS) as a pump, the dual-wavelength lasing is formed by combining the 1st Brillouin laser, using a 1 km long single-mode fiber (SMF) as a Brillouin gain medium, and the residual pump laser. The fiber laser output is with high stability, high optical signal to noise ratio (OSNR), and wide tunability.

Figure 1 shows the proposed dual-wavelength fiber laser configuration, which is simply composed of a 1 km long SMF (YOFC) as the SBS gain medium, a Yenista TUNICS-T100S-HP narrow linewidth (100 kHz) TLS with a tunable range from 1500 to 1630 nm as an SBS

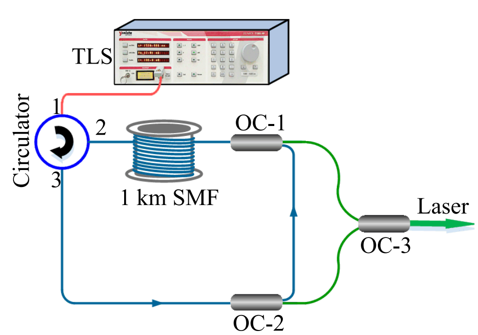

Fig. 1. Experimental setup of the proposed fiber laser.

pump, a three-port optical circulator, two 70:30 optical couplers (OCs, OC-1 and OC-2), and a 50:50 OC (OC-3). The TLS pump light is injected into the SMF gain medium through the circulator from port 1 to port 2, and the 1st Stokes light is excited when the pump power is beyond the SBS threshold of the used SMF. Then, the 1st Stokes light propagates counterclockwise through the circulator from port 2 to port 3 and goes back into the SMF again through OC-2 and OC-1. The 1st Stokes light is amplified by the SBS gain again, and a resonant loop cavity is formed for Brillouin laser generation. Note that the use of the circulator is also to make sure that only the 1st Stokes light is excited in the cavity, since the second-order Stokes light propagating clockwise is blocked. Using OC-2 and OC-1, 70% light is maintained in the laser cavity, and the 30% laser is extracted through OC-2. In order to get dual-wavelength operation, the 30% residual pump light is output by OC-1 and is combined with the Brillouin laser by OC-3. By carefully adjusting the TLS output power, a power-equalized dual-wavelength laser can be obtained. Here, the coupling ratio of 70:30 is selected for OC-1 and OC-2 in order to maintain relatively high energy Stocks light inside the laser cavity for achieving low threshold and high OSNR on the one hand and to output enough residual pump power for achieving power-equalized dual-wavelength lasers through the 50:50 OC-3 on the other hand, whereas the coupling ratios can be further optimized. The backward Brillouin frequency shift (BFS) ν_B is determined by the equation[24]

$$\nu_B = 2n_p v_A/\lambda_p, \tag{1}$$

where n_p and v_A are the effective mode index of pump and acoustic velocity of the SMF, respectively, and λ_p is the pump laser wavelength. From Eq. (1), we can know that the 1st Brillouin laser can possess almost the same tunable range with that of the TLS, only if the output power of the TLS can reach the SBS threshold of the used SMF during the tuning process. Meanwhile, we can infer that, with the tuning of the pump laser wavelength, both of the lasing two wavelengths and the corresponding spacing between them can be tuned simultaneously. Theoretically, the tunable ability and spectrum stability are not influenced by the ratios of the used OCs.

The experiments were carried out in a laboratory environment, and no temperature control and no vibration isolation were applied to the laser system. By adjusting the TLS wavelength and output power to 1550 nm and 9.93 mW, respectively, the typical optical spectrum was measured by a Yokogawa AQ6370D optical spectrum analyzer (OSA) with a resolution of 0.02 nm, as shown in Fig. 2. As can be seen, the OSNR is as high as >80 dB, the lasing wavelengths are 1550.030 and 1550.118 nm with a spacing of 0.088 nm, and a well equalized output power of two wavelengths is achieved. The high OSNR performance of the dual-wavelength operation mainly benefits from the simple laser configuration and the excellent pump TLS with a side mode suppression ratio of >90 dB. The spectrum stability was also verified by measuring the OSA repeated scans 17 times in ~90 min experiment time, as shown in the inset, indicating a high stable dual-wavelength operation situation.

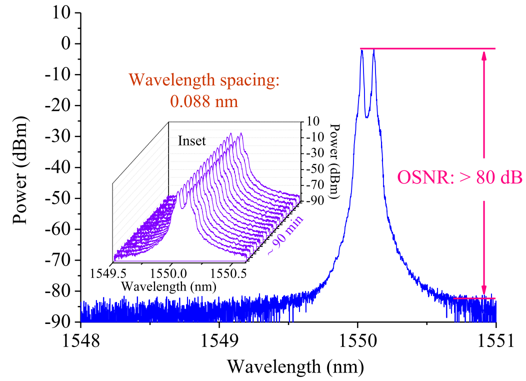

Fig. 2. Output laser spectrum at a pump wavelength of 1550 nm; inset shows 17 times OSA repeated scans in ~90 min measurement time.

The tunability of the proposed fiber laser is demonstrated, as shown in Figs. 3 and 4 for dual-wavelength lasing and corresponding frequency-spacing between two wavelengths, respectively. As can be seen in Fig. 3(a), by tuning the pump wavelength, the dual-wavelength operation is with as wide as ~130 nm tunable range (from

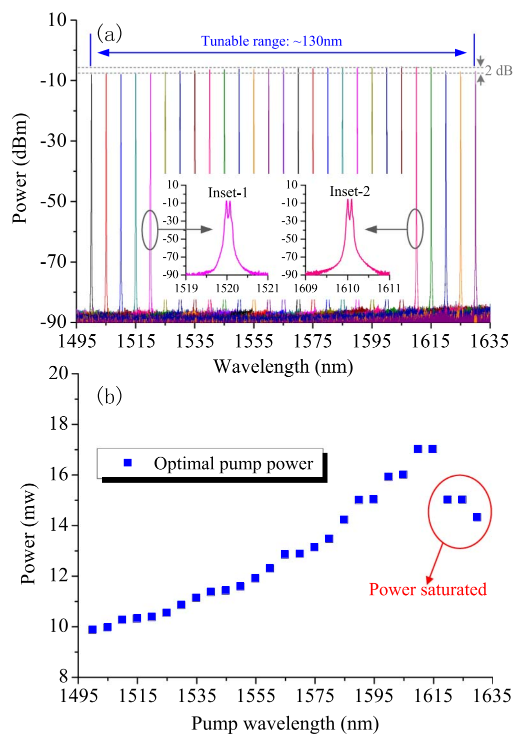

Fig. 3. (Color online) (a) Wide tunability of dual-wavelength operation with power-equalized output; Inset-1 and Inset-2 show the zoomed in laser spectra under the pump wavelengths of 1520 and 1610 nm, respectively. (b) Corresponding optimal pump power for power-equalized output of dual-wavelength lasing.

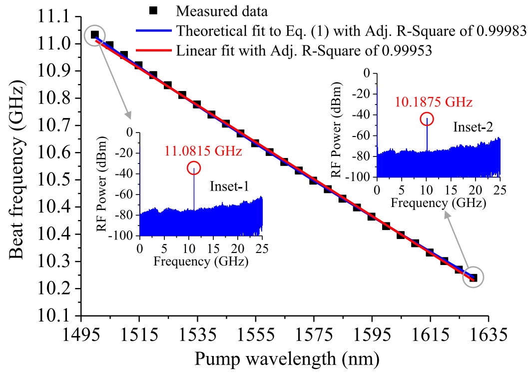

Fig. 4. (Color online) Beat frequency of dual-wavelength operation changing along with the pump wavelength; Inset-1 and inset-2 show the RF beating spectra at the pump wavelengths of 1500 and 1630 nm, respectively.

1500.020 and 1500.101 nm to 1630.028 and 1630.115 nm), almost covering the whole S+C+L band. The dual-wavelength fiber laser has the similar wide tunable range with that of the used TLS pump, consistent with the theoretical analysis. Inset-1 and inset-2 of Fig. 3(a) show the zoomed in dual-wavelength lasing spectra when the pump wavelengths are tuned to 1520 and 1610 nm, respectively. Note that, in order to get the equalized power for two lasing wavelengths after every tuning, we need to adjust the TLS power appropriately. Figure 3(b) shows the optimal pump powers at different pump wavelengths, displaying an increased trend except in the last three data points, due to the power saturation of the TLS at the corresponding lasing wavelengths. Actually, one can easily obtain power-equalized output for two lasers at any pump wavelength by inserting one variable optical attenuator into each input optical path of OC-3, however, which will increase the cost and complexity of the laser system. Figure 3(a) also displays that the total power fluctuation is less than 2 dB during the whole tuning operation. The frequency-spacing between two lasing wavelengths can be obtained by measuring the beat frequency of the laser output, using the self-homodyne method with an 18 GHz photodiode (PD) and a Keysight N9010A radio frequency (RF) electrical spectrum analyzer (ESA). Figure 4 shows the measured beat frequency as a function of the pump wavelength increasing from 1500 to 1630 nm. According to Eq. (1), the BFS ν_B is inversely proportional to the pump laser wavelength λ_p. So, we have theoretically fitted the measured data to Eq. (1) with an adjusted (Adj.) R-square (goodness of fit) of 0.99983, and the fitted parameters are $n_p = 1.45$, and $v_A = 5.728$ km/s, respectively. Meanwhile, we also linear-fitted the experimental data using the least squares method with an Adj. R-square of 0.99953. The theoretical fit curve and the linear fit line are almost overlapping, as can be seen in Fig. 4, indicating that the beat frequency has a good linear relationship with the pump wavelength and can be continuously tuned from 10.1875 to 11.0815 GHz with the frequency tunable range of 0.8940 GHz, which proves the fiber laser could be a good photonic generation source for tunable microwave signals.

The stability of the beat frequency at every tuned pump wavelength was studied by measuring the fluctuation in 1 h running time. To avoid redundancy for similar operation characteristics, as an illustration, only the results of the dual-wavelength lasing at 1550.030 and 1550.118 nm are shown in Fig. 5(a) measured at 2 min intervals. As can be seen, the beat frequency fluctuation is as low as ≤6 MHz, benefiting from the beating mechanism of the pump and the 1st Brillouin laser. We also studied the beat-frequency-induced temporal fluctuation of the dual-wavelength fiber laser over a time window of 50 μs, using the 18 GHz PD and a 200 MHz digital oscilloscope, and also as an example, the results at the same lasing wavelengths are only shown here. One strong intensity fluctuation result was captured, as seen in Fig. 5(b), with a period of ~5 μs, which is consistent with the time of one Brillouin laser roundtrip in the cavity. That indicates the temporal fluctuation was induced by the beating of the resonator modes, meaning that the Brillouin laser could not always operate in a stable single-mode state. It should be noted that a higher speed oscilloscope (>18 GHz) may reveal more detailed temporal fluctuation information but, unfortunately, that cannot be achieved based on the current experimental condition.

Finally, we investigated the output power stability of the dual-wavelength fiber laser by measuring the total output power using a power meter in ~120 min experimental time when the pump wavelength and power were fixed at 1550 nm and 9.93 mW, respectively, as shown in Fig. 5(a). The fluctuation of the output power was less than 0.03 dB, indicating an excellent long-term stability of dual-wavelength operation. Meanwhile, we also measured the Brillouin laser's temporally dynamical characteristics in a 50 μs time window, using the 18 GHz PD

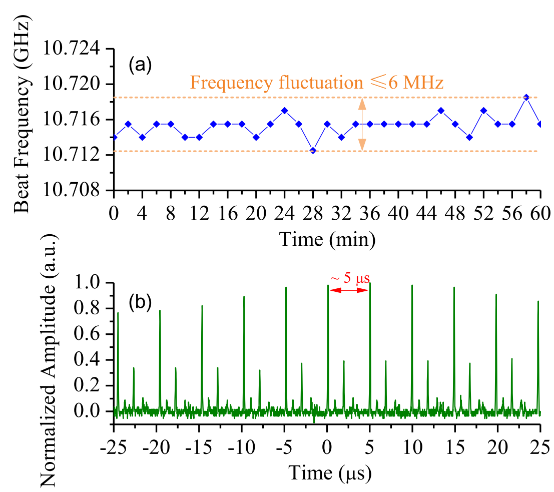

Fig. 5. For dual-wavelength operation, (a) the beat frequency long-term stability in 1 h measurement time and (b) the beat-frequency-induced temporal fluctuation in 50 μs measurement time.

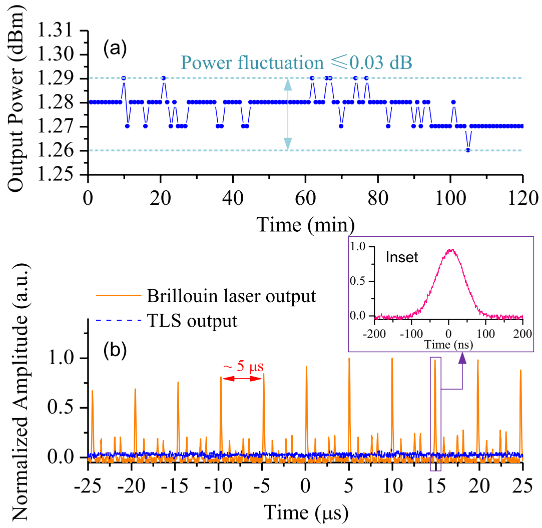

Fig. 6. (Color online) (a) Long-term stability of the total output power of dual-wavelength operation; (b) temporal fluctuations of the Brillouin laser and the TLS output, respectively.

and the 200 MHz oscilloscope, after cutting off the up input optical path of OC-3. One result with strong fluctuation was captured, as shown in Fig. 6(b), and plotted by the solid line, which is with a period of ~5 μs, similar with the result obtained in Fig. 5(b). For comparison, the temporal amplitude distribution with an extremely low fluctuation of the narrow linewidth TLS output was also measured, as plotted by the dashed line. That indicates, for some low temporal fluctuation needed applications, the Brillouin laser should be improved to guarantee stable single-mode operation. The inset shows the details of a fluctuation peak in a time window of 400 ns, and the relatively smooth curve indicates that the speed of the used oscilloscope is not enough for getting high frequency temporal fluctuations. The stability of the fiber laser could be improved further by using good vibration isolation and temperature control techniques.

In conclusion, we experimentally demonstrate a simple and low-cost dual-wavelength fiber laser with high OSNR, wide tunability, and high power stability. The dual-wavelength lasing is achieved through simply combining the 1st Brillouin laser and the residual pump laser. By adjusting the pump power, the power-equalized output for two wavelengths can be easily obtained. By means of the good tunability of the pump source, the dual-wavelength lasing output has a widely tunable range of ~130 nm, and the laser's beat frequency, corresponding to the frequency-spacing between two wavelengths, has a tunable range of 0.8940 GHz. With these good performances, the proposed dual-wavelength fiber laser will find applications in fiber optical sensing and tunable microwave signal generation.

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