Wavelength tunable and amplitude-equilibrium dual-wavelength lasing sources with dual-pass Raman/Brillouin amplification configuration

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Abstract: A simple technique for achieving wavelength tunable and amplitude-equilibrium dual-wavelength fiber laser source based on a dual-pass Raman/Brillouin amplification configuration is proposed and experimentally investigated. A stable room-temperature dual-wavelength lasing oscillations with average channel power of more than 1 mW and signal-to-noise ratio of more than 30 dB were obtained with only 250 mW Raman pump power. The dual-wavelength lasing oscillations with wavelength spacing of 0.076 nm were so stable that the maximum power fluctuations and wavelength shifts over more than 10 minutes of observation were less than 0.5 dB and 0.002 nm, respectively. The dual-wavelength lasing output can also be tuned in a range of ~35 nm from 1545.090 nm to 1580.078 nm with an amplitude-equilibrium of less than a peak power difference of 0.25 dB at the two wavelengths.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (290.5900) Scattering, Stimulated Brillouin; (290.5910) Scattering, Stimulated Raman.

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1. Introduction

All-fiber dual-wavelength fiber laser sources with narrow linewidth have attracted considerable interests in recent years because of their potential applications in microwave photonics systems, fiber-communication systems and fiber sensing systems. In order to achieve narrow linewidth and even single longitudinal mode dual-wavelength lasing output, various techniques have been proposed and demonstrated, including distributed-feedback (DFB) erbium-doped fiber (EDF) lasers based on special fiber grating structure designs [1-3], introducing ultra-narrow bandpass filter, such as dual-phase-shift fiber gratings with two ultra-narrow transmission bands, in laser cavity [4] and using stimulated Brillouin scattering [5-11]. Among them, the main challenges to achieve stable dual-wavelength lasing using the DFB EDF method and introducing ultra-narrow bandpass filter method in laser cavity are to suppress the unstable mode competition induced by the homogenous line broadening of the EDF and to realize the complicated design and fabrication of the fiber gratings with special structures and ultra-narrow transmission bands.

Stimulated Brillouin scattering is a representative nonlinear process in optical fiber that induces efficient power conversion from the input signal to the backward-propagating Stokes waves. Compared with the foregoing two methods, the approach based on stimulated Brillouin scattering to achieve dual- or multi-wavelength lasing has many advantages such as simple configuration, easy realization of tunable wavelength and no ultra-narrow filter requiring. This approach is commonly considered as hybrid Brillouin/erbium or Brillouin/Raman gain configuration which manipulates narrow bandwidth of Brillouin gain in optical fibers. Compared with the hybrid Brillouin/erbium fiber lasers [6-7], multi-wavelength Brillouin-Raman fiber lasers [8-11] have more remarkable advantages such as room-temperature stable operation and extremely broad workable wavelength band nearly without limitation as long as pump lasers at the corresponding wavelengths are available. Though several hundred Brillouin Stokes lines have been achieved based on blended effect of Raman amplification, Brillouin shift and Rayleigh scattering in a single-pass Raman amplification configuration [10, 11] and a linear laser cavity [8, 9], respectively, the stability of the multi-wavelength lasing outputs were unsatisfactory and unstable mode hopping was clearly observed from the given spectra in their experiments [8-11]. Moreover, their proposed configuration has somewhat complicated and the output power of the Brillouin stokes lines was less than -15 dBm with more than 300 mW Raman pump power.

In this paper, a new design for wavelength tunable and amplitude-equilibrium dual-wavelength Brillouin-Raman fiber laser source based on a simple dual-pass Raman/Brillouin amplification configuration is proposed and experimentally investigated. In our experiment, a laser diode at 1455 nm wavelength with a maximum output power 250 mW was used to pump a section of 1.5 km high nonlinear fiber (HNF) and a section of 1 km dispersion- compensating fiber (DCF) to generate Raman gain. A stable room-temperature dual-wavelength lasing oscillations with average channel power of more than 1 mW and signal-to-noise ratio of more than 30 dB were obtained. The dual-wavelength lasing oscillations with wavelength spacing of 0.076 nm were so stable that the maximum power fluctuations and wavelength shifts over more than 10 minutes of observation were less than 0.5 dB and 0.002 nm, respectively. The dual-wavelength lasing output can also be tuned in a range of ~35 nm from 1545.090 nm to 1580.078 nm with an amplitude-equilibrium of less than a peak power difference of 0.25 dB at the two wavelengths.

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2. Experimental setup

The configuration of the proposed laser for the generation of tunable and stable dual-wavelength lasing output based on Brillouin/Raman amplification is depicted in Fig. 1. The linear cavity of the laser source consists of a circulator, a polarization controller (PC), two WDM couplers, two sections of Raman/Brillouin gain fiber and a sagnac fiber loop mirror (SFLM) made up of a 5:5 fiber coupler. The Raman/Brillouin gain fiber, consisting of a section of DCF with a length of 1 km and a section of HNF with a length of 1.5 km, was Raman pumped by a laser diode (LD) with a maximum output power of about 250 mW at 1455 nm wavelength via the left 1455/1550 nm WDM coupler. The forward-pumped Raman amplification configuration with respect to the direction of the Brillouin pump (BP) was used in order to generate stronger stimulated Brillouin scattering. The residual pump power was exported by the right 1455/1550 nm WDM coupler. The nonlinear coefficient of the HNF is about 10.00 $(Wkm)^{-1}$ and the mode field diameter at 1550 nm is about 3.83 µm. The nonlinear coefficient and effective mode field area of the DCF is about 5.67 $(Wkm)^{-1}$ and 19 μm^2, respectively. The two ends of the DCF and the HNF were both spliced to the standard single mode fiber (SMF). The insertion losses of the section of HNF and the DCF after being spliced with SMF are about 3.699 dB and 1.828 dB at 1455 nm, 2.491 dB and 1.553 dB at 1550 nm, respectively. The SFLM acted as a perfect broadband reflection mirror with nearly 100% reflectivity for 1550-nm spectral region. The PC was used to rotate the polarization state and could achieve continuous adjustment of the polarization-dependence gain or loss within the cavities. An external-cavity tunable semiconductor laser with maximum output power of 10 dBm and linewidth of ~100 kHz was used as the BP and was injected into the gain fiber via the circulator. The BP signal after being double-pass Raman amplified, as well as the generated and amplified Brillouin Stokes lines, was exported from the port 3 of the circulator. Finally, an ANDO AQ6319 optical spectrum analyzer (OSA) with 0.01 nm resolution was used to do all the measurement.

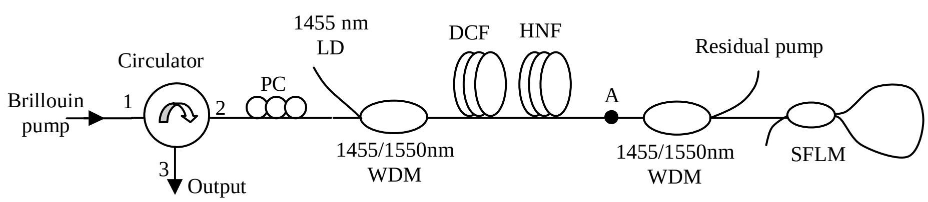

Fig. 1. Schematic diagram of the proposed dual-wavelength Brillouin/Raman fiber laser source: WDM, wavelength division multiplexer; PC, polarization controller; DCF, dispersion-compensating fiber; HNF, high nonlinear fiber; SFLM, Sagnac fiber loop mirror.

3. Experimental results and discussion

In the first experiment, the SFLM was not connected into the light route in order to investigate the characteristics and interactions of Raman amplification, Brillouin scattering and Rayleigh scattering in a single-pass forward-pump fiber Raman amplification configuration. The power of the 1455-nm LD was tuned to 250 mW and the BP wavelength was fixed to 1554.991 nm. The BP power was set to about 1.03 dBm. Figure 2 gives the spectrum (the left picture) of the input Brillouin pump signal and the spectrum (the right picture) measured at the point A after the input signal was single-pass Raman amplified with the configuration of Fig. 1 excluding the SFLM. The spectrum show the peak power after the signal being amplified is 6.04 dBm indicating a Raman net gain of ~5dB. It is noted that a new wavelength at 1555.068 nm with a frequency redshift of 0.076 nm were observed as a result of Rayleigh backscattering of the first-order Brillouin stokes generated from the BP in the gain fiber. The peak power of the new wavelength measured by the OSA is -13.56 dBm, which is lower with a value of 19.60 dB than the transmitted BP signal. Figure 3 shows the spectra measured at the port 3 of the circulator with and without Raman pump injection. Rayleigh backscattered (frequency unshifted) light,

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Brillouin-Stokes (frequency redshifted, +0.076 nm) and anti-Stokes (frequency blueshifted, -0.076 nm) of the BP lines were observed in the spectra as a result of spontaneous scattering in the DCF and the HNF. In contrast, the center Rayleigh component shows much higher power than the other two lines, as a result of the high Landau-Placzek ratio in the DCF and the HNF [11]. However, its lasing was very unstable and its peak power fluctuation was at least higher than 2 dB observed by the OSA. While the stability of the Brillouin-Stokes and anti-Stokes lines were very well and their power fluctuations were less than 0.1 dB observed by the OSA. With increasing Raman pump injection into the fiber, the powers of the three lines were all increased and the Brillouin-Stokes line grew much faster than the other two lines owing to its lower nonlinear threshold power. But the power of Brillouin-Stokes line is always lower than the center Rayleigh component no matter what the input BP and Raman pump powers were. In other words, the room-temperature stable and amplitude-equilibrium dual-wavelength lasing can not be achieved in the single-pass forward-pump Raman amplification configuration within the actual experimental condition.

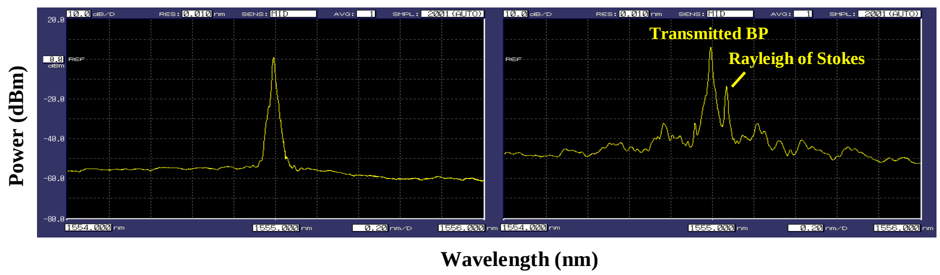

Fig. 2. The left picture is the spectrum of the input Brillouin pump signal; the right picture is the spectrum measured at point A of Fig. 1 with Raman pump power of ~250 mW.

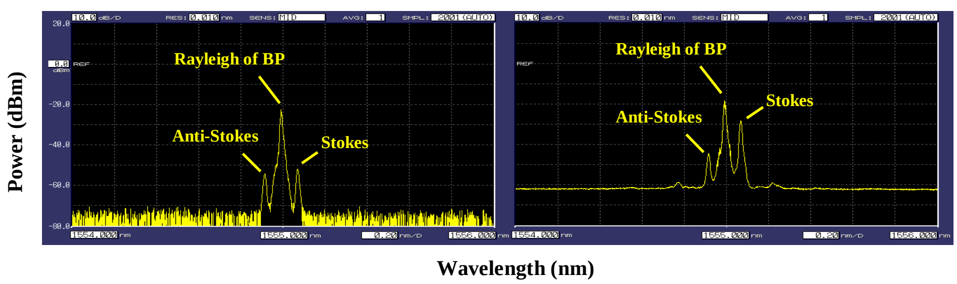

Fig. 3. The spectrum measured at port 3 of the circulator without the SFLM: the left picture is with the LD power off and the right picture is with the LD pump power of ~250 mW.

When the dual-pass configuration with the SFLM as shown as Fig. 1 was used, the BP signal, which was dual-pass Raman amplified with more gain saturation than the single-pass configuration, will generate much stronger power conversion from the input BP signal to Brillouin-Stokes lines. The BP signal with forward and backward propagation in the gain fiber with respect to the direction of the input Brillouin pump (BP) will generate backward and forward propagation Brillouin-Stokes and anti-Stokes lines. Due to the reflection of the SFLM, the Brillouin-Stokes and anti-Stokes in the two directions as well as their Rayleigh components after being Raman amplified were all exported at the port 3 of the circulator. Therefore, the output Brillouin-Stokes line has higher power because of the double-pass Raman/Brillouin amplification and saturates quickly to a level owing to its low nonlinear threshold power. Additionally, in our laser configuration, the pump LD is common semiconductor laser diode without removing polarization, due to the notable polarization-dependence characteristic of Raman gain, the amplitude of the output Brillouin-stokes line can be adjusted to lower than, equal to and even higher than that of the transmitted BP via rotating the polarization controller

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in the configuration. This is owing to the facts that different polarization state of the input BP will generate different Raman gain because of the polarization-dependence effect of Raman gain as well as different power conversion from the BP signal to Brillouin stokes. Higher Raman gain would induce more effective power conversion from the BP signal to Brillouin stokes lines as well as deeper Raman gain saturation. Therefore, the relative power level between the two wavelengths can be adjusted by rotating the PC. Figure 4 shows a typical amplitude-equilibrium dual-wavelength lasing output spectrum made up of the transmitted BP signal and the generated Brillouin-Stokes line with a frequency redshifted of 0.076 nm when the input BP wavelength and output power was set to 1555.01 nm and 6 dBm, respectively. Seen from the left spectrum, the output peak powers at the two wavelengths are 0.17 dBm and 0.25 dBm, respectively, with a power difference of 0.08 dB. Their 3 dB bandwidths are both less than 0.01nm and signal-to-noise ratios are both greater than 30 dB. The Raman net gain of the BP signal in the dual-pass configuration is about ~ -5.8 dB, indicating that the BP is deeply saturated and very efficient power conversion from the BP signal to the Stokes waves is induced. Figure 4 also shows the 10 times repeated scanning spectra of the two-wavelength lasing oscillations with a time interval of 1 minute, which indicates the stability of the laser is very well. The maximum peak wavelength shifts at the two wavelength were both less than 0.002 nm measured by the OSA. The maximum power fluctuations at the peak wavelength of 1555.01 nm and 1555.086 nm were 0.49 dB and 0.31 dB, that is, the output powers are so stable that the peak fluctuations are less than 0.5 dB. We think the power fluctuations mainly come from the fluctuation of the input BP signal, which has a measured value of ~0.19 dB, and a small quantity of Rayleigh components in the two lines which are unstable as shown as in the foregoing experimental results of Fig. 3. We believe that more stable dual-wavelength lasing output can be achieved if we try to improve the stability of the input BP and restrain or reduce the Rayleigh scattering.

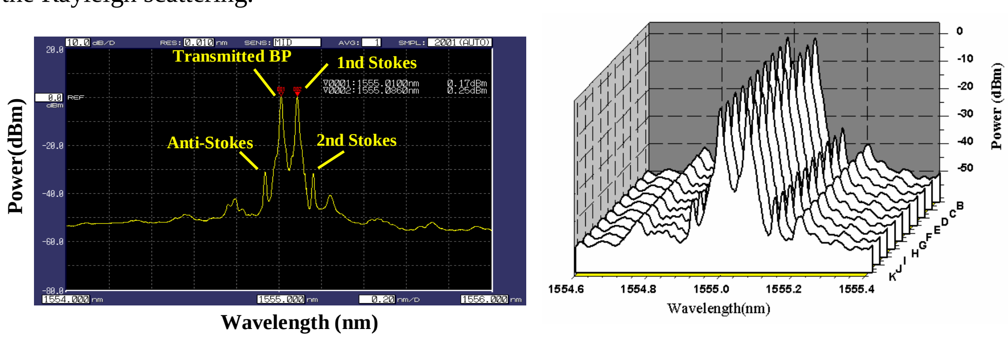

Fig. 4. Amplitude-equilibrium dual wavelength lasing output spectrum using the proposed double-pass Raman amplification configuration: the left is the single-time scanning spectrum and the right is the 10-time repeated scanning spectra with a time interval of 1 minute.

When the BP wavelength is changed, the wavelength of the Brillouin-stokes line is also changed correspondingly. Therefore, tunable dual-wavelength lasing output with a certain wavelength spacing of 0.076 nm can be achieved by adjusting the input BP wavelength. Experiment found that the wavelength tuning range and spectrum stability of the amplitude-equilibrium dual-wavelength lasing output could both be affected by the LD pump power and the input BP power. The higher the Raman pump power and the BP power were, the wider the wavelength tuning range was obtained and the better the spectrum stability was. Figure 5 shows the tunable dual-wavelength lasing spectra with different LD pump power and the same BP power (~6 dBm). When the LD pump power was 250 mW, amplitude-equilibrium dual-wavelength lasing outputs, with a power difference of less than 0.25 dB, could be obtained in a tunable wavelength range of ~35 nm from 1545.090 nm to 1580.078 nm. The maximum output peak powers at the two wavelengths are 0.96 dBm and 0.88 dBm, respectively, when the

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BP wavelength was tuned to 1560.010 nm, which is nearly located at the center wavelength of the Raman peak gain bandwidth. The output peak powers at the two wavelengths are reduced to (-0.01, -0.30) dBm and (-1.23, -1.37) dBm when the BP wavelength was tuned to 1545.090 nm and 1580.001 nm, respectively. While the LD power was decreased to 200 mW, the tunable wavelength range with amplitude-equilibrium output was also correspondingly reduced to ~20 nm from 1549.012 nm to 1569.082 nm. The output peak powers at the two wavelengths are (-0.69, -0.80) dBm, (0.24, 0.35) dBm and (-0.69, -0.93) dBm when the BP wavelength was tuned to 1549.012 nm, 1560.009 nm and 1569.005 nm, respectively. These results indicate the dual-wavelength lasing can have uniform peak power within the Raman peak gain bandwidth of the double-pass Raman amplification configuration. This is owing to the facts that more effective power conversion from the BP signal to Brillouin stokes lines is induced with deeper Raman gain saturation of the BP signal in the peak gain bandwidth and the generated Stokes line achieves its saturation level faster because of its higher gain when higher Raman pump power and higher input BP power were used in the double-pass amplification configuration.

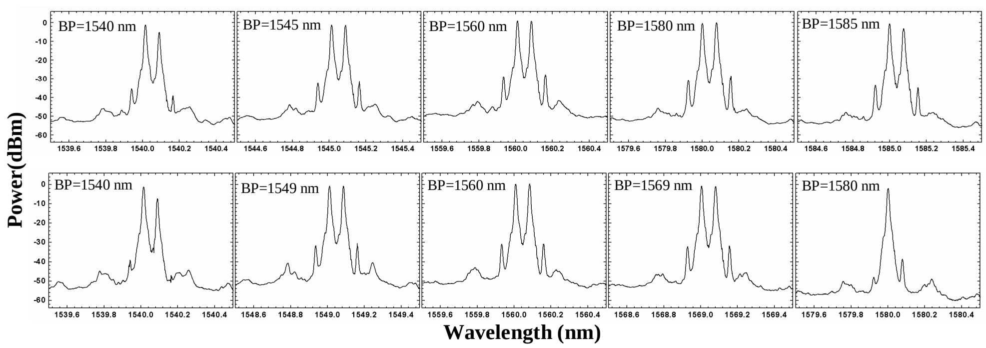

Fig. 5. Tunable dual-wavelength lasing output spectra with different Raman pump power and the same Brillouin pump power: the upper spectra are with 250 mW LD pump power and the below spectra are with 200 mW LD pump power.

4. Conclusion

In conclusion, we have demonstrated that wavelength-tunable and amplitude-equilibrium dual-wavelength lasing oscillations could be achieved by exploiting Brillouin scattering in a simple double-pass fiber Raman amplification configuration. A stable room-temperature dual-wavelength lasing oscillations with average channel power of more than 1 mW and signal-to-noise ratio of more than 30 dB were obtained only using a 1455-nm LD with a maximum output power of 250 mW acted as Raman pump. Dual-wavelength lasing oscillations obtained by this method were so stable that the maximum power fluctuation over an observation of more than 10 minutes was less than 0.5 dB for 0.076 nm wavelength spacing. The dual-wavelength lasing output could be tuned in a range of ~35 nm from 1545.090 nm to 1580.078 nm with an amplitude-equilibrium of less than a peak power difference of 0.25 dB at the two wavelengths. The wavelength tuning range could also be broadened via increasing the Raman gain bandwidth with multi-wavelength pump solution. We believe that this technique provides another simple approach to achieve room-temperature stable and wavelength tunable dual-wavelength lasing with narrow bandwidth.

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