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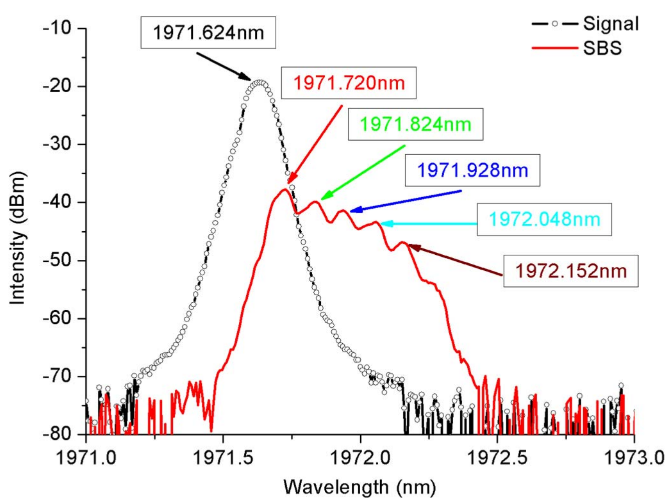
Xiong Wang
Pu Zhou
Xiaolin Wang
Hu Xiao
Lei Si



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Multiwavelength Brillouin-Thulium Fiber Laser

Xiong Wang, Pu Zhou, Xiaolin Wang, Hu Xiao, and Lei Si

College of Optoelectronic Science and Engineering, National University of Defense Technology, Changsha 410073, China

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Abstract: We demonstrate the first multiwavelength Brillouin-thulium fiber laser (BTFL) with wavelengths near 1.97 μm. The multiwavelength fiber laser was realized based on stimulated Brillouin scattering and nonlinear polarization rotation effects. The laser can generate five Brillouin wavelengths with spacing of about 0.105 nm, which is identical with the wavelength spacing of adjacent Brillouin Stokes lines. The peak power fluctuations of the multiwavelength BTFL were less than 0.5 dB, and the wavelength shifts were less than 0.01 nm in 20 min.

Index Terms: Multiwavelength fiber laser, Brillouin-thulium fiber laser, infrared lasers, nonlinear polarization rotation.

1. Introduction

Telecommunication employing 2 μm lasers have attracted more and more attention in recent years [1]–[4], since Tm-doped fiber has almost 400 nm (1700 nm–2100 nm) emission band, which is much wider than that of Er-doped fiber. Furthermore, hollow core photonic band-gap fiber is predicted to have the minimum loss near 2 μm band, thus telecommunication near 2 μm can provide a prosperous method to solve the difficulty on capacity limit at 1.5 μm telecommunication [4]. Multiwavelength fiber laser is the core component in wavelength division multiplexing (WDM) system and is indispensable in the telecommunication network based on 2 μm laser in the near future. In addition, multiwavelength Tm-doped fiber laser (TDFL) around 2 μm also has prospective applications in remote sensing, spectroscopy and medicine, etc. So the multiwavelength TDFL near 2 μm is in great demand and should be well investigated.

The multiwavelength fiber laser around 1.5 μm has been widely studied and there are many typical methods to generate multiwavelength lasing, such as liquid nitrogen cooling [5], [6], multiple-grating [7]–[9], tunable filter comb [10]–[13], spatial mode beating filter [14], [15], nonlinear loop mirror [16], [17], four-wave mixing (FWM) [18], [19], nonlinear polarization rotation (NPR) [20], [21] and stimulated Brillouin scattering (SBS) [22]–[25]. Multiwavelength TDFL near 2 μm has also been studied in very recent years. In 2013, Zhao *et al.* [26] reported switchable multiwavelength Tm-doped fiber ring lasers, Peng *et al.* demonstrated a switchable dual-wavelength TDFL at 1.94 μm [27] and a 42-wavelength TDFL near 1.97 μm based on nonlinear amplifier loop mirror [28]. We previously demonstrated a tunable, multiwavelength TDFL based on NPR and FWM effect this year [29].

SBS is an important nonlinear effect in fiber laser generated by the interaction between the incident light and the acoustic waves. The Stokes light's frequency has a down shift compared with

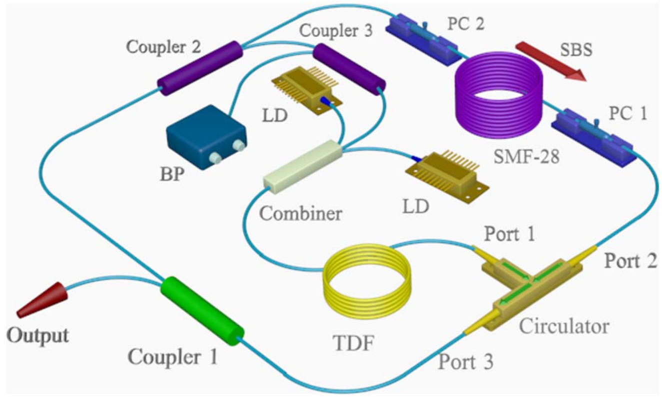

Fig. 1. Setup of the multiwavelength Brillouin Tm-doped fiber laser. BP: Brillouin pump; LD: laser diode; TDF: Tm-doped fiber; PC: polarization controller.

that of the original light, and the existing Stokes light can generate the next Stokes light when the threshold is surpassed. Hence, multi-Stokes light can be obtained to form a multiwavelength Brillouin fiber laser, where the channel spacings between the adjacent Stokes lines are nearly uniform and are suitable for dense WDM application and telecommunicaion. Up to now, there has been no report on multiwavelength TDFL based on SBS effect as far as we know.

In this paper, we demonstrate the first multiwavelength Brillouin-thulium fiber laser (BTFL) based on SBS and NPR effects. A typical inverse S-shaped fiber configuration was employed to generate multi-Stokes light in the cavity. NPR was employed to control the polarization states of the Stokes light as well as the signal laser. A piece of 450 m SMF-28 fiber was used as the nonlinear gain medium. Five Stokes lines were obtained and the channel spacing was about 0.105 nm, the peak power fluctuations of all the wavelengths were less than 0.5 dB and wavelength shifts were less than 0.01 nm in 20 minutes.

2. Experimental Details

Fig. 1 shows the experimental setup of the multiwavelength BTFL. The Brillouin pump (BP) laser was a single frequency fiber laser based on ultra-short cavity with linewidth of less than 100 kHz and central wavelength of 1.971 μm [30], the output power was amplified to about 200 mW. A $(2+1) \times 1$ signal-pump combiner was used to combine the BP power and 793 nm laser diode (LD) power together and launch them into the double cladding Tm-doped fiber. The 7 m long Tm-doped fiber had core diameter of 10 μm and cladding diameter of 125 μm, and the peak absorption was about 3 dB/m at 793 nm. The amplified signal laser (BP laser) was launched into a circulator for 2 μm, and the transmitted maximum signal power at port 2 was 3.2 W. When the BP laser was launched into the 450 m long SMF-28 fiber and the power exceeded the SBS threshold, the 1st Stokes light was generated and propagated in the clockwise direction. The circulator ensured the unidirectional operation of the Stokes light, and the 10% port of a 10/90 coupler (Coupler 1) at 2 μm served as the output port. The remaining Stokes light passed through a 40/60 2×2 coupler (Coupler 2) and 60% of the laser propagated along the clockwise direction and passed through the SMF-28 fiber to form a unidirectional ring oscillation mode. When the cavity gain surpassed the cavity loss, stable Brillouin lasing was obtained. The 40% port of coupler 2 was fusion spliced with one port of a 50/50 coupler (Coupler 3), thus the BP and the 1st Stokes light were launched into the Tm-doped fiber amplifier together. The 1st Stokes light was amplified and launched into the SMF-28 fiber, and the 2nd Stokes light may be generated and propagated in clockwise direction when the 1st Stokes light's power exceeded the SBS threshold. In the same way, the 2nd Stokes light can oscillate and excite the next order Stokes light. Thus multi-Stokes light was generated as long as the cavity gain exceeded the loss. The components in the laser cavity were all fiberized and fusion spliced together, which enhanced the stability and practicality of the multiwavelength BTFL.

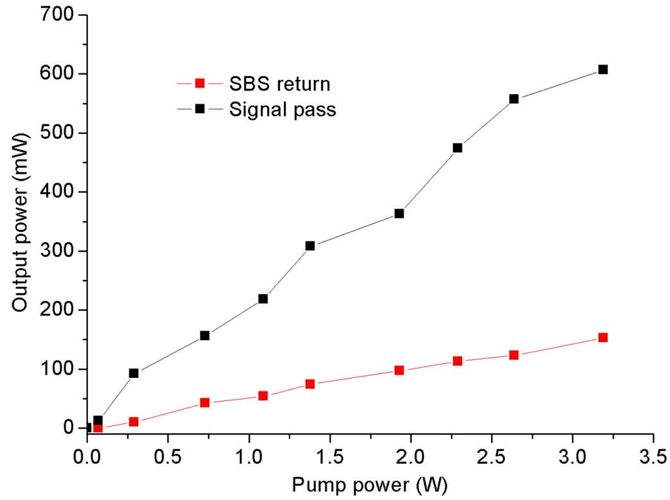

Fig. 2. Output power of multi-Stokes light and passed remainder BP (signal) power at different launched BP power.

Two polarization controllers (PCs) were placed at both ends of the SMF-28 fiber to control the polarization states of the BP and Stokes light, which can also play an important role in offering the intracavity filtering effects [31], [32].

3. Results

The output power of the multiwavelength BTFL was measured in the output port of coupler 1, as shown in Fig. 2. The remaining BP power was also measured at the spare 40% port of Coupler 2 (which is not depicted in Fig. 1), and the actual remaining BP power is calculated. One can find out that the sum of the remaining BP power and the Stokes light's power is much lower than the launched BP power. Actually, the background loss of SMF-28 fiber near 2 μm is rather high (tested to be about 22.2 dB/km for 1.971 μm), thus part of the BP power was depleted by the fiber loss and cavity loss, and part of it was used to generated the nonlinear Stokes light. The maximum output power of the multiwavelength BTFL has reached about 153 mW.

The threshold of the fiber laser was about 400 mW–600 mW, which was primarily caused by the relatively high SBS threshold at 2 μm band. The threshold of SBS in silica fiber can be estimated using (see [33])

$$P_{\text{th}}^{\text{SBS}} \approx \frac{21 A_{eff} K}{L_{eff} g_B} \tag{1}$$

where A_{eff} is the effective mode area, K is the polarization factor, L_{eff} is the effective fiber length, g_B is the peak Brillouin gain. L_{eff} can be calculated through Formula (2):

$$L_{eff} = (1 - \exp(-\alpha \times L))/\alpha \tag{2}$$

where L is the fiber length of nonlinear fiber, α is the attenuation constant in silica fiber for 2 μm laser. In our experiment, A_{eff} is about 78.5 μm^2, suppose that K is 2 for complete polarization scrambling of the pump laser, α is tested to be about 0.0051 m^{-1}, L is 450 m, g_B is 2.89×10^{-11} m/W. Then the SBS threshold of the fiber laser can be estimated to be about 650 mW, which is not favorable for multi-Stokes light generation. Hence, we employed the PCs to control the polarization states of the BP laser as well as the Stokes light. On the one hand, the PCs make the oscillation modes in the cavity be linearly polarized in a certain extent and reduce the SBS threshold. On the other hand, the PCs control the polarization states of the oscillation modes and suppress the polarization modes competition in the cavity.

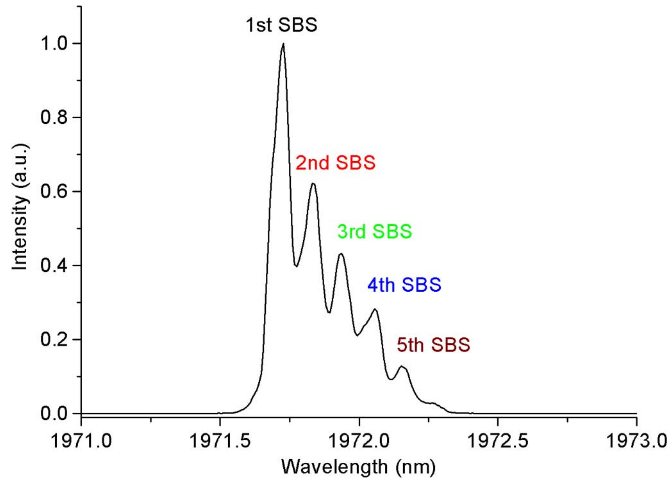

Fig. 3. Multi-Stokes lines spectrum in linear scale.

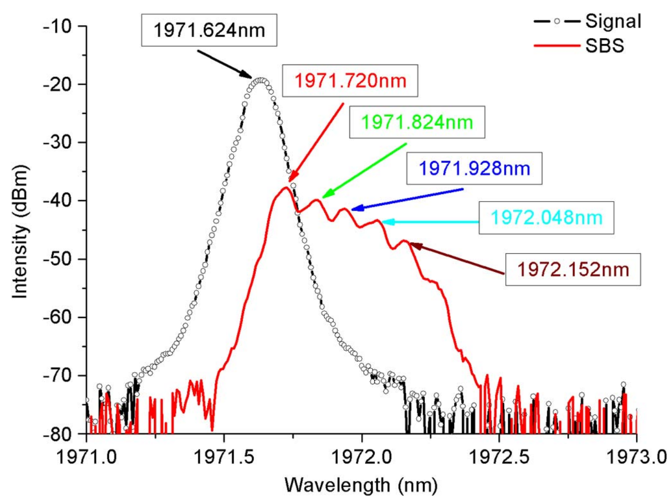

Fig. 4. Spectra of the signal laser (BP) and the multi-Stokes lines.

The wavelength shift of SBS Stokes light at 1.971 μm can be calculated by (see [33])

$$\Delta\lambda = \frac{\lambda_P^2}{c}\Delta\upsilon_B = \frac{\lambda_P^2}{c}\times\frac{2n_P\upsilon_A}{\lambda_P} = \frac{2n_P\upsilon_A\lambda_P}{c} \tag{3}$$

where λ_P is the BP wavelength ($\sim$1.971 μm), c is the speed of light, $\Delta\upsilon_B$ is the Brillouin frequency down shift, n_P is the refractive index ($\sim$1.45), υ_A is the speed of acoustic waves ($\sim$5.96 km/s). Hence, the SBS wavelength shift can be estimated to be about 0.11 nm.

The output spectrum of the multiwavelength BTFL was monitored by an optical spectrum analyzer (OSA) with resolution of 0.05 nm. The resolution was not really enough to measure the Stokes lines at 1.971 μm, since the wavelength shift in silica fiber is about 0.11 nm as estimated previously. Five Stokes lines were obtained when the pump power was 3.2 W and the PCs positions were adjusted, as depicted in Fig. 3. The detected amplified spontaneous emission (ASE) between the adjacent Stokes lines is relatively high, which may be mainly attributed to the limited resolution of the OSA in experiment.

However, the five Stokes lines can still be recognized and validated clearly, as Fig. 4 shows. The BP laser's central wavelength located at about 1971.624 nm (the last two digits were somewhat

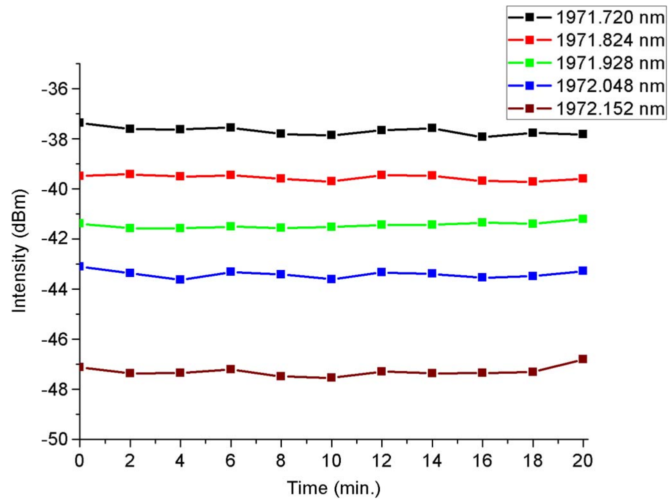

Fig. 5. Peak power fluctuations of the multiwavelength Brillouin TDFL.

estimated due to the limited resolution of OSA, although the wavelength were read out directly from the measured data). Comparing spectra of the signal laser and Stokes lines, we can find out that no signal lasing is observed in the output spectrum, so the BP laser is effectively suppressed in the cavity. The five Stokes lines, located near 1971.72 nm, 1971.82 nm, 1971.93 nm, 1972.05 nm, and 1972.15 nm, show the nearly uniform wavelength spacing of about 0.105 nm, which is in good conformity with the calculated wavelength shift at 1.971 μm. In this multiwavelength BTFL, high SBS threshold near 2 μm results in the limited number of Stokes lines. To increase the number of wavelengths, one can either scale up the pump power to increase the gain in cavity for higher order Stokes light, or reducing the SBS threshold through methods such as employing linearly polarized pump laser and increasing the effective nonlinear fiber length.

The stability of the multiwavelength BTFL was measured in 20 minutes, and the peak power fluctuations are depicted in Fig. 5. The results show that this multiwavelength fiber laser is operating with good stability, and the maximum peak power fluctuation is less than 0.5 dB. Meanwhile, the maximum Stokes lines' wavelength shift is less than 0.01 nm. However, we observed a slight red shift of the Stokes wavelengths as the time goes by, which we think is mainly due to the temperature rising of the nonlinear fiber. Hence, proper temperature control is also needed when this kind of multiwavelength BTFL is applied in practical circumstances.

4. Conclusion

We demonstrate a multiwavelength BTFL near 1.97 μm based on SBS and NPR effects. Five Stokes lines with channel spacing of about 0.105 nm have been obtained. The peak power fluctuations and wavelength shifts are less than 0.5 dB and 0.01 nm in 20 minutes, respectively. The number of wavelengths can be improved by increasing the BP power or reducing the SBS threshold employing linearly polarized laser or increasing the effective nonlinear fiber length. Temperature control could be used to further enhance the stabilities of the peak power and wavelength. This compact and robust fiber configuration can provide stable multiwavelength laser source for 2 μm telecommunication as well as applications such as remote sensing and medicine.

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