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Citation: Chin. Phys. B . 2018, 27(3): 030703. **doi:** 10.1088/1674-1056/27/3/030703

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Demonstration of multi-Watt all-fiber superfluorescent source operating near 980 nm*

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(Received 29 September 2017; published online 11 February 2018)

The superfluorescent Yb-doped fiber source operating near 980 nm is studied. The design requirement is theoretically discussed aiming to suppress the amplified spontaneous emission around 1030 nm in the 980-nm superfluorescent fiber source. Based on the theoretical study, a multi-Watt, all-fiber, bi-directional, pumped, superfluorescent source operating near 980 nm is designed and experimentally demonstrated for the first time, to the best of our knowledge. The recorded 8.38-W combined output power is obtained with a 3-dB bandwidth about 3.5 nm. The power scaling of the 980-nm superfluorescent fiber source is limited by the parasitic laser oscillation.

Keywords: superfluorescence fiber source, amplified spontaneous emission, ytterbium-doped fiber

PACS: 07.60.Vg, 42.81.–I, 42.55.Wd **DOI:** 10.1088/1674-1056/27/3/030703

1. Introduction

Superfluorescent Yb-doped fiber source (SYFS) is a sort of broadband source realized by the amplified spontaneous emission (ASE) in the Yb-doped fiber (YDF).[1,2] It has attracted much attention because of its advantages of compactness, robustness, low coherence, high thermal stability, high efficiency, etc. Recently, rapid progress has been made on the power scaling of SYFS. The hundred-Watt single-stage SYFS and kilo-Watt master oscillator power amplification (MOPA) SYFS have been demonstrated.[3–8]

However, the current studies on the high-power SYFS are mainly focused on the band around 1030 nm to 1090 nm.[3–8] The study on the high-power SYFS operating near 980 nm (also called the 980-nm SYFS), which is considered as a promising alternative pump source of the rear-earth-doped fiber sources, is very limited. More difficult than the case of the SYFS around 1030 nm to 1090 nm (belonging to the quasi-four-level or four-level transmission system), the 980-nm SYFS does not only require a higher pump threshold, but also suffers from the gain competition with the ASE around 1030 nm (i.e., the 1030-nm ASE) because of its three-level transmission nature.[9] The realization of 980-nm SYFS is also harder than that of the 980-nm fiber laser. The reason is that the wavelength-selection devices such as the fiber Bragg gratings (FBG), cavity mirror, or seed source used in the 980-nm fiber laser play an important role in the suppression of the 1030-nm ASE,[10–16] but these devices cannot be used in the 980-nm SYFS, which makes it more difficult to suppress the 1030-nm ASE in the 980-nm SYFS. Besides, the parasitic laser oscillation induced by the optical feedback will bring another limitation to the power scaling of the 980-nm SYFS. Nowadays, how to realize a high-power all-fiber 980-nm SYFS is not so clear, and pertinent reports are very few, too.

In this paper, the basic requirement for suppressing the 1030-nm ASE in the 980-nm SYFS is theoretically discussed. Then, an 8-W all-fiber 980-nm SYFS with the bi-directional pumping scheme is experimentally demonstrated for the first time, to the best of our knowledge. A recorded 8.38-W combined output power is obtained within the 980-nm band, and the slope efficiency is about 11.7%. The spectrum spans from 974 nm to 982 nm with the 3-dB bandwidth around 3.5 nm. The power scaling of the 980-nm SYFS is mainly limited by the parasitic laser oscillation.

2. Theoretical analysis

As was mentioned above, the suppression of the 1030-nm ASE is of great importance for the 980-nm SYFS. Because of the lack of the wavelength-selection devices for the 1030-nm ASE suppression, the design of active fiber becomes the unique way for suppressing the 1030-nm ASE in the 980-nm SYFS. Former studies have revealed that the core-to-cladding ratio of the active fiber is important for the 1030-nm ASE suppression, and the larger the core-to-cladding ratio is, the better the 1030-nm ASE will be suppressed.[9,17] Reference [9] also gave a simple formula for estimating the relationship between the 980-nm and 1030-nm gains. With the values of ab-

*Project supported by the National Natural Science Foundation of China (Grant No. 61405249).
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sorption and emission cross sections given in Ref. [18] (i.e., $\sigma_a^{1030} = 4.9 \times 10^{-26}$, $\sigma_e^{1030} = 6.51 \times 10^{-25}$, $\sigma_a^{978} = 2.3 \times 10^{-24}$, $\sigma_e^{978} = 2.55 \times 10^{-24}$, $\sigma_a^{915} = 5.29 \times 10^{-25}$, $\sigma_e^{915} = 1.96 \times 10^{-26}$), the relationship between the 980-nm and 1030-nm gains can be given as

$$G_{1030} = 0.26 G_{980} + 1.06 \frac{\alpha_p}{\gamma}, \tag{1}$$

where G_λ is the gain of the ASE around wavelength λ-nm. Here, the gain of the 980-nm ASE is approximately estimated with the wavelength of 978 nm which is about the central wavelength of the 980-nm ASE. The gain of the 1030-nm ASE is estimated with the wavelength of 1030 nm. $\gamma = \Psi_p^d / \Psi_s^d$ (because of the slow variation of the modal field with wavelength, we can have $\Psi_{980}^d = \Psi_{1030}^d = \Psi_s^d$, where Ψ_λ^d is the normalized modal intensity averaged over the doped area at the wavelength of λ). Because the signal light is guided by the core and the pump light is guided by the inner cladding, γ is approximately equal to the core-to-cladding area ratio (A_{core}/A_{clad}) of the active fiber. From Eq. (1), it can be found that the increment of the 980-nm gain is faster than that of the 1030-nm gain. It means that the 980-nm gain should be larger than the 1030-nm gain as long as the 980-nm gain is large enough. By assuming that $G_{980} \geq G_{1030}$, we obtain

$$G_{980} \geq 1.43 \times \frac{\alpha_p}{\gamma} = G_{th}. \tag{2}$$

If the 980-nm gain is larger than the threshold G_{th}, it will be larger than the 1030-nm gain, and the 980-nm will be dominant in the gain competition with the 1030-nm ASE. Obviously, the smaller the threshold is, the more easily can the 980-nm gain be beyond the 1030-nm gain. Therefore, the decrement of the value (α_p/γ) is beneficial to the 1030-nm ASE suppression. In spite of this, it should be noted that in order to realize good enough absorption of pump light, the α_p should not be too small. Therefore, a large enough γ (i.e, a large enough core-to-cladding ratio) becomes very important for the 1030-nm ASE suppression in the 980-nm SYFS.

In a practical design, we hope that the gain suppression of the 1030-nm ASE can be as large as possible to ensure the gain dominance of the 980-nm ASE. To realize the Γ-dB 1030-nm gain suppression (defined as $(G_{980} - G_{1030})$), the 980-nm gain should satisfy

$$G_{980} = 1.43 \times \frac{\alpha_p}{\gamma} + 1.36\Gamma. \tag{3}$$

Figure 1 gives the plots of G_{980} and (α_p/γ) corresponding to various values of gain suppression. It can be found that a smaller value of (α_p/γ) is needed to obtain a larger 1030-nm gain suppression with a certain 980-nm gain. It also means that the 980-nm SYFS can be realized as long as the γ and α_p can be well designed.

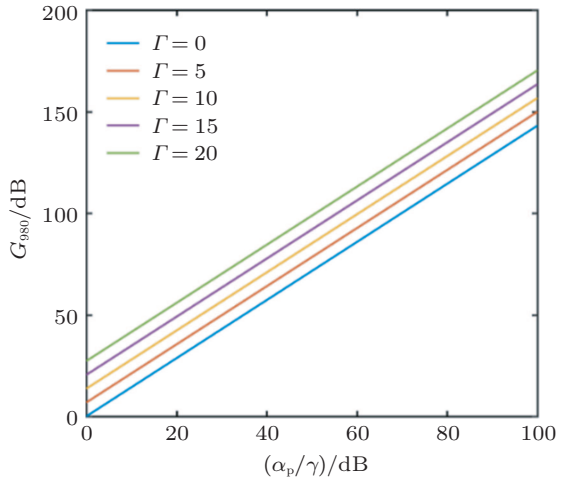


Fig. 1. (color online) Plots of G_{980} and (α_p/γ) corresponding to various values of gain suppression Γ.

3. Experimental demonstration

Based on the above theoretical analysis, we make an experimental demonstration of the 980-nm SFYS. The schematic diagram of the 980-nm SYFS is shown in Fig. 2. In our experiment, the distributed side-coupled cladding-pumping (DSCCP) YDF is used as the active fiber. This fiber is also known as the GTWave fiber,[19–21] multi clad fiber,[22] or multi-element first cladding fiber.[23] Here, it is named as the DSCCP fiber because of its unique propagation process of pump light.[4,5,24] The cross section of the DSCCP YDF is given in the inset of Fig. 2. The DSCCP YDF consists of a pump fiber and a signal fiber. Cladding 1 is the inner cladding of the signal fiber, and cladding 4 acts as both the cladding of the pump fiber and the outer-cladding of the signal fiber. Core 2 is the core of the pump fiber, while core 3 is the Yb-doped core of the signal fiber. Core 2 and cladding 1 are optically contacted but physically separated from each other. The pump light is input into core 2, and when it propagates along core 2, it is coupled gradually into cladding 1 in the manner of the evanescent wave. The pump light coupled into cladding 1 will pump the Yb-ion doped core 3 where the ASE will be induced. Because of the usage of the DSCCP fiber, the bi-directional pump scheme can be easily realized, which is beneficial to the amplification of 980-nm light.[14]

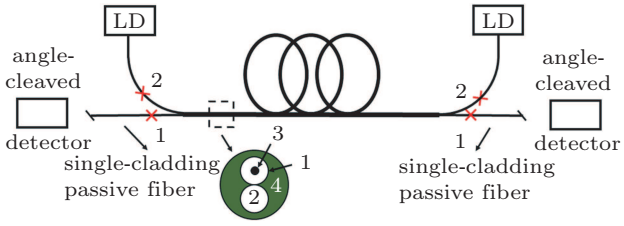


Fig. 2. (color online) Schematic diagram of the all-fiber 980-nm SYFS. The inset gives the cross section of the DSCCP fiber.

In our experiment, the diameter and numerical aperture (NA) of the Yb-doped core (i.e., core 3) are 60 μm and 0.1, re-

spectively, and both the pump core (i.e., core 2) and cladding 1 possess 125 μm diameter and 0.46 NA. Assume that the ASE optical field is uniform in the active core, the core-to-cladding area ratio of the active fiber should be about 0.115 (note that the pump core should also be taken into account for calculating the inner-cladding area).[24] Then, in order to obtain Watt-order output 980-nm ASE power, the 980-nm gain should be larger than 70 dB because of the small power of the spontaneous emission (which provides the seed light of the ASE). It means that the 1030-nm ASE should be suppressed with the 70-dB 980-nm gain in order to realize the output of 980-nm ASE. Therefore, the 980-nm gain threshold $G_{\rm th}$ given in Eq. (2) should be smaller than 49 dB with the purpose to get the gain suppression of the 1030-nm ASE, which means that the pump absorption should be smaller than 5.6 dB. Considering that the pump absorption of the DSCCP YDF is estimated to be about 12 dB/m, the length of the DSCCP fiber should be smaller than 47 cm. Thus, in our experiment, we use a 39-cm DSCCP YDF to suppress the 1030-nm ASE, which means that the 1030-nm gain suppression should be more than 8.6 dB with the 70-dB 980-nm gain (see Eq. (3)).

Besides, in our experiment, the single-cladding 60/125-μm passive fiber is spliced to each port of signal fiber in order to filter out the residual pump light (see Fig. 2). Both the output ports of the passive fibers are 8° angle-cleaved to suppress their optical feedback, which is important for suppressing the parasitic laser oscillation. In our experiment, the bi-directional pumping scheme is used. Two 915-nm diode lasers (LDs) are utilized as the pump sources.

The output powers are shown in Fig. 3. Figure 3(a) gives the output powers of the 980-nm ASE. It can be found that the backward output power is almost the same as the forward one, which can be expected because of the symmetry of the bi-directional pumping scheme. It can also be seen that these output powers increase monotonously with the pump power, and with the 134.7-W pump power, the forward and backward output powers are 5.5 W and 5.3 W, respectively, corresponding to a combined output power of 10.8 W. The combined slope efficiency is about 11.7%, and the threshold of the 980-nm SYFS is about 40 W.

Figure 3(b) gives the output powers of the 1030-nm ASE. It can be found that the output power of the 1030-nm ASE reaches its maximum (about 1 W) at the 85.36-W pump power, and then decreases to some extent with further increase of the pump power. Such a result is reasonable because the increment of the 980-nm gain is faster than that of the 1030-nm gain with the increase of the pump power (see Eq. (1)). When the pump power is large enough, the 980-nm ASE will be dominant in the gain competition with the 1030-nm ASE, and then the 1030-nm ASE will be suppressed and its output power will be decreased. By comparing Fig. 3(b) with Fig. 3(a), it can be found that the percentage of 1030-nm ASE in the output power decreases from 81.8% to 6.7% with the increase of the pump power.

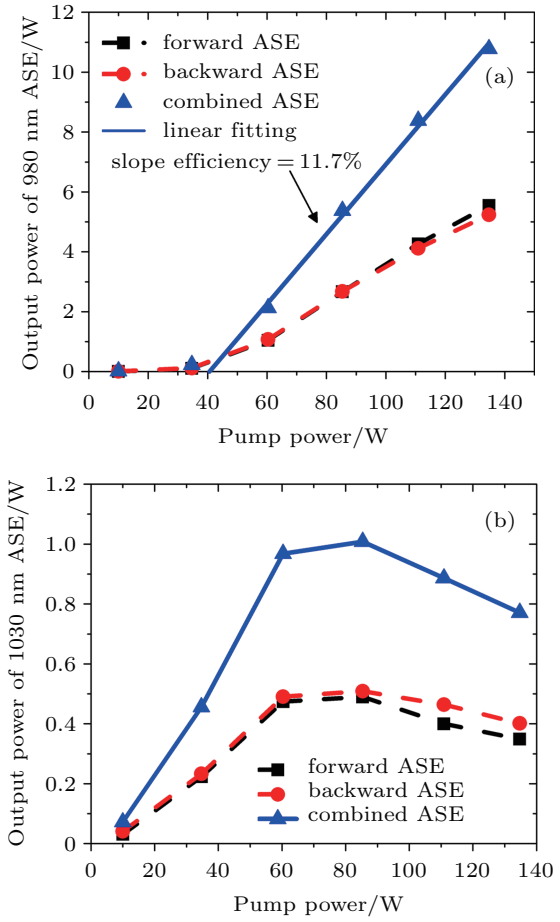


Fig. 3. (color online) The output powers of the (a) 980-nm and (b) 1030-nm ASE versus the pump power

Figure 4(a) gives the output ASE spectra with various pump powers, which shows that the peak suppression of 1030-nm ASE increases from 10.6 dB at 60.35 W pump power to 18.3 dB at 134.7 W pump power. Figure 4(b) gives the zoom-in of the 980-nm ASE spectra. It can be seen that the 980-nm ASE spans from 974 nm to 982 nm with central wavelength at about 977.3 nm, and its 3-dB bandwidth is about 3.5 nm. In spite of this, the fluctuation can be observed in the spectrum when the pump power reaches 134.7 W, which means that the parasitic laser oscillation should be present. Figure 4(b) shows that the smooth ASE spectrum can be obtained only when the pump power is lower than 110.9 W (corresponding to the 8.38-W combined output power of the 980-nm ASE). Thus, it can be concluded that the maximum output power of the 980-nm SYFS is 8.38 W which is limited by the parasitic laser oscillator. Such a limitation can be released by further reducing the optical feedback of the two output ports, which can be realized by the optimization of angle-cleaving of the output ports.

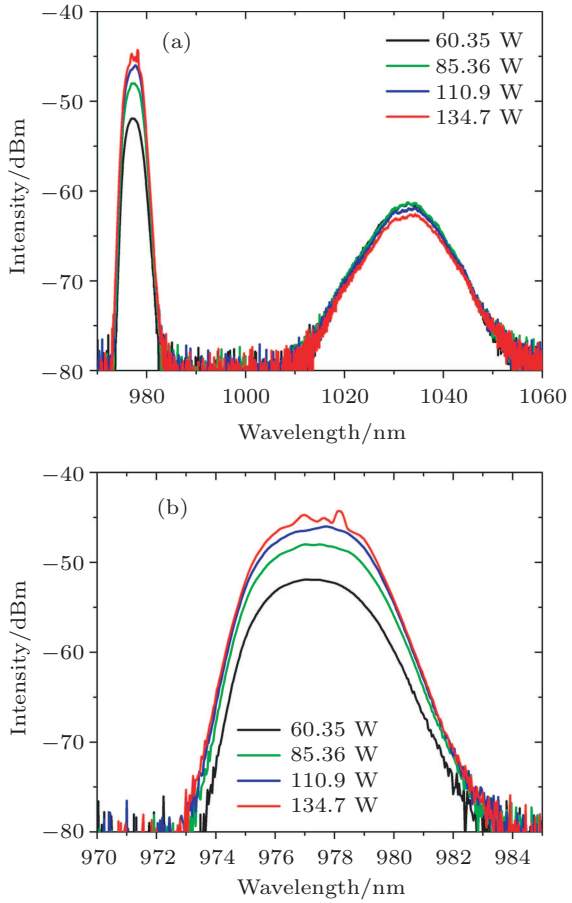


Fig. 4. (color online) (a) Output ASE spectra and (b) zoom-in spectra of the 980-nm ASE with various pump powers.

4. Conclusion

The 980-nm SYFS is theoretically and experimentally studied. By theoretical study, the design requirement of the active fiber is given for the suppression of the 1030-nm ASE in the 980-nm SYFS. Based on that, an 8-W, all-fiber, bi-directional, pumped 980-nm SYFS is demonstrated with the DSCCP YDF for the first time, to the best of our knowledge. The combined output power of the 980-nm ASE reaches 8.38 W, which is limited by the parasitic laser oscillation. The pertinent slope efficiency is around 11.7%. Such a low slope efficiency is mainly due to the insufficient absorption of the pump light. The 3-dB bandwidth of the 980-nm SYFS is about 3.5 nm with the central wavelength around 977.3 nm. By studying the output spectrum, it is demonstrated that more than 18-dB peak suppression of the 1030-nm ASE can be realized in the 980-nm SYSF. Higher 980-nm ASE output power can be expected by optimizing the angle-cleaving of the output ports. It is believed that the pertinent study will provide a significant guidance for studying and designing the 980-nm fiber sources.

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