Temperature Dependence of Spectral Properties of Yb-Doped Superfluorescent Fiber Source

Jinming Wu, Fengchang Li, Peng Wang, Hanwei Zhang, Hanshuo Wu, Xiaoming Xi, Chen Shi, Baolai Yang, Xiaolin Wang, Kai Han, and Jinbao Chen

***Abstract*—Fiber laser has been developed to the point where the average power scaling can reach several kilowatts readily for oscillators and more for amplifiers. In the meanwhile, the thermal effects inside the fiber laser also become prominent. Temperature rise of the fiber core caused by thermal effects has a conspicuous impact on laser performance. In this paper, the spectral properties of superfluorescent fiber sources at low temperature have been studied experimentally and theoretically. We observe a significant flattening of the arc top of the spectra and a broadening to the short-wave direction as the gain fiber temperature decreases from 25 °C to −95 °C. The corresponding 10 dB bandwidth and 20 dB bandwidth increased by 7.216 and 4.004 nm, respectively. The 10 dB center position and the 20 dB center position of the spectrum also move 6.1 nm and 4.2 nm towards short-wave direction, respectively. The absorption and emission cross-sections at different temperatures, calculated based on Lorenz fitting theory, are used to simulate the experimental phenomena, and the results are consistent with the experiment. Additionally, the small signal gain coefficient at low temperature is calculated to help explain the observed phenomena in the experiment.**

***Index Terms*—Superfluorescent fiber source, spectral property, temperature, fiber amplifier.**

I. Introduction

YB-DOPED fiber (YDF) laser has mature application in many fields such as medical, industrial processing, lasing cutting, science, sensing, and defense due to its excellent advantages such as convenient heat management, high conversion efficiency and good beam quality [1], [2], [3], [4]. However, it's still challenging for such devices to operate in abnormal temperature environment steadily, such as laser ignition, satellite communication, etc. In scenarios with abnormal temperature, the fiber laser will be severely limited in performance, or even unable to be used normally. The main reason here is the temperature susceptibility of laser diode (LD) and YDF. In detail, the output power and spectra of LDs vary with working temperature obviously, thus the condition of the pump light will change when the temperature of LD fluctuates. Such effects on LD are direct, legible and can be characterized realistically, while it doesn't for gain fiber. The effects brought by temperature variation for gain fiber are multidimensional and comprehensive [5]. According to the Boltzmann distribution, the laser ion activity is exponentially related to the temperature. Hence, temperature changes in the fiber will cause variations in the actual cross-sections, which has an impact on the conversion process of the pump light. The homogenization of the gain fiber would also be nibbled when the temperature deviates from the normal since the mechanical properties of the glass fiber would be harmed [5]. The damage of the fiber homogenization, indicating the stress, temperature and refractive index, etc. changed in the full fiber, would influence the evolution of the signal light transmission, including the fall of the efficiency and the degeneration of the beam quality due to the increased attenuation and the distortion of the modes field.

Experimental and theoretical works have been made to clear the effect of gain fiber temperature variation on the fiber laser. In the experiment field, the most explicit conclusion is that at different temperature, the lasing performance is wavelength dependent. In Ref. [6], a shift of spectral center wavelength from 1103 nm to 1120 nm is observed in a fiber laser with spatial configuration over the gain fiber temperature range from 2 °C to 90 °C. In [7], lasing with central wavelength of 1064, 1150 and 1180 nm are operated at 20 °C and above 100 °C. In high temperature condition, lasing at 1064 nm is suppressed while lasing at 1150 and 1180 nm is promoted. In 2006, Kurkov et al. [8] heated active fiber up to 70 °C to increase the absorption of the pump light from a fiber laser with the wavelength of 1070 nm, and suppress the spontaneous emission in the meantime, finally they achieved 3.2 W lasing output at 1160 nm with slope efficiency of 45%. In 2010, Vazquez-Zuniga et al. [9] found that the temperature changing from 10 to 100 °C of gain fiber resulted in a signal power drop of approximately 16% at 1060 nm and 5% at 1080 nm respectively, based on an ytterbium-doped fiber amplifier (YDFA). In 2013, researchers from Johannes Gutenberg University [10] placed gain fiber in liquid nitrogen, achieving a significant decrease of the reabsorption on 1015-nm signal light, and managed to amplify their 1015 nm seed laser to 10 W. In Ref. [11], a 1080-nm YDFA tandem pumped by a 1018 nm fiber laser have been studied at different temperatures.

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Jinming Wu and Fengchang Li are with the College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha 410073, China.

Peng Wang, Hanwei Zhang, Hanshuo Wu, Xiaoming Xi, Chen Shi, Baolai Yang, Xiaolin Wang, Kai Han, and Jinbao Chen are with the College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha 410073, China, also with the Nanhu Laser Laboratory, National University of Defense Technology, Changsha 410073, China, and also with the Hunan Provincial Key Laboratory of High Energy Laser Technology, National University of Defense Technology, Changsha 410073, China (e-mail: zhanghanwei100@163; kdchenjinbao@aliyun.com).

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The power conversion efficiency has been improved from 58.7% to 81.3% by heating the active fiber temperature from room temperature to 302 °C. The influence of temperature on the output spectra and power of Yb-doped superfluorescent fiber source (SFS) are investigated in Ref. [12], in which the central wavelength tuned from 1062.70 nm to 1067.31 nm is observed over the temperature of the gain fiber from 20 °C to 60 °C. The investigation results above demonstrated the promise of lasing at longer wavelength by means of heating the active fiber, owing to the temperature characteristic of the gain fiber. Regarding the theoretical research, the related report is relatively few. Ref. [5] presents a theoretical treatment of thermal effects for power scaling in double-clad silica fibers. The work points out that a large change in core temperature may result in significant change in the refractive index which could affect the waveguiding properties and eventually degrade the laser efficiency. Ref. [13] put forward a theoretical model of deriving the cross-sections of any temperature according to the cross-sections of room temperature, which is very helpful to stimulate the performance of fiber laser at different temperatures.

In this paper, the temperature dependence of spectral properties is experimentally and theoretically studied based on a SFS in the temperature range of 25 to −95 °C. Compared to the study of a specific wavelength of laser, our research is conducted based on a superfluorescent fiber source, the spectral range of which covers the most typical output spectra of Yb-doped fiber laser. With the SFS, we can explore the universal law of YDF laser at different temperature over the entire typical wavelength band. The mechanism of the temperature-dependence spectral properties is revealed from a perspective of small signal gain. It's worth to note that, compared to the previous work [12], we pay more attention to the characteristics of SFS at low temperature, and we cool down the active fiber to a greater extent, with a range of more than 100 °C. As a matter of fact, the research of fiber laser at low temperature is very lack for the inconvenience of facility, thus the previous research is mainly focused on the temperature range that higher than the normal temperature [9], [11], [12], [13]. Ref. [10], [14] cooled down the fiber via liquid nitrogen, which has a huge gap from normal temperature. In addition, we have established a more perfect theoretical model with cross-sections for arbitrary temperature and wavelength, by which the lasing performance of SFS can be studied under a wide temperature span and fine temperature gradient.

II. Experimental Setup and Results

To conduct experimental research, we built an SFS seed laser and amplifier. The schematic structure of SFS seed and its amplifier are shown in Fig. 1(a) and (b). The seed is mainly composed of a section of 15-m YDF, a backward multimode power combiner (MPC) and a LD with central wavelength of 976 nm, as shown in Fig. 1(a). The pump light of the LD is injected into the YDF from the MPC and produces forward and backward SFS. The backward output end is cut at an angle of 8° to reduce the backward feedback and increase the self-excitation threshold. The self-excitation is further inhibited by inserting two isolators (ISOs) between the seed and the amplifier stage.

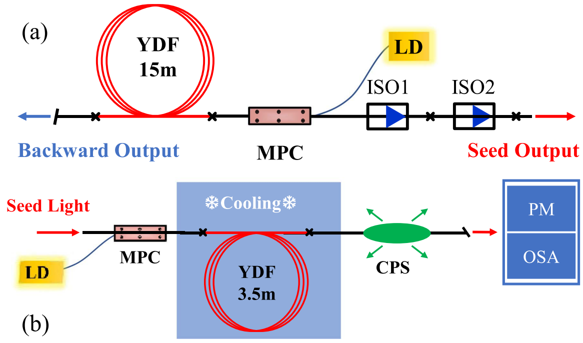

Fig. 1. Schematic structure of the SFS (a) seed and (b) amplifier.

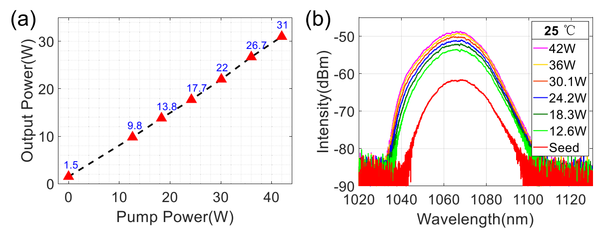

Fig. 2. (a) Variation of the SFS amplifier output power and (b) the spectrum with pump power.

As shown in Fig. 1(b), the seed light pours into the 3.5 m-long amplification stage YDF through the amplification stage MPC, and amplified by the pump light from another LD with central wavelength of 976 nm. The residual pump light is filtered out by a cladding power stripper (CPS). The output of the amplified SFS is collected by a power meter and its scattered light enters the optical spectrum analyzer (OSA) producing real-time spectral images. The core/cladding diameter of both seed and amplification YDF is 10/130 μm, and the absorption coefficient of them are 4.1 dB/m for 976 nm (seed YDF) and 1.6 dB/m for 915 nm (amplification YDF). The entire YDF of amplifier was placed inside the refrigerator and coiled in fiber slot on an aluminum plate. In such methods, the entire YDF of amplifier can be controlled at the same temperature.

With the refrigerator, the spectral characteristics of SFS at different temperatures can be experimentally studied. The evolution of the output power and spectra with the pump power were investigated at room temperature firstly. Fig. 2(a) shows that, the SFS seed with power of 1.5 W is attained when the pump power of the seed is 8 W. Subsequently, with the increase of the pump power of the amplification stage, the SFS is scaled linearly and reach its maximum power of 31 W, when the pump power of the amplifier is 42 W. Fig. 2(b) shows that in the process of the power scaling, the spectra width of the SFS broadened obviously.

With the conditions unchanged other than the temperature of the refrigerator, the evolution of the output power and spectra were further investigated when the temperature of the amplification stage YDF is −30 °C, −50 °C, −70 °C, −90 °C, −95 °C. The results are shown in the Fig. 3.

It should be noted that there is a hysteresis before the gain fiber reach the setting temperature of the refrigerator, so we monitor

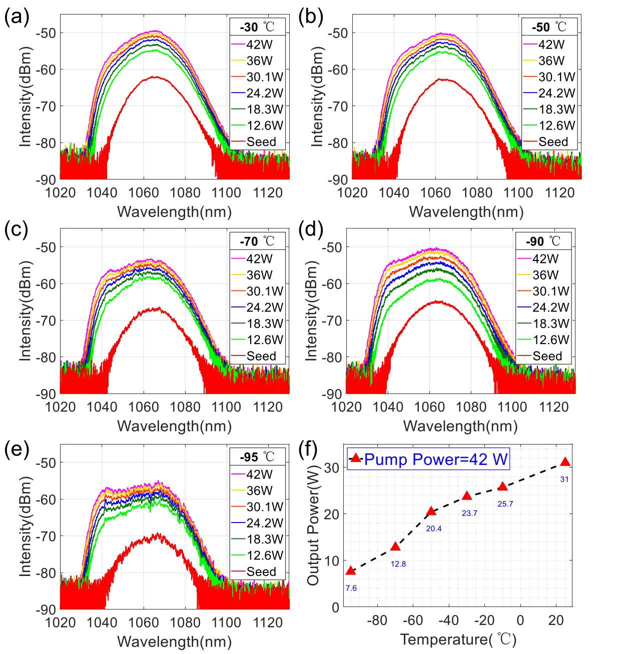

Fig. 3. Evolution of the spectra with the temperature of the amplification stage YDF at (a) −30 °C, (b) −50 °C, (c) −70 °C, (d) −90 °C, (e) −95 °C. (f) The output power of the amplifier at different temperature when the amplification stage pump power is 42 W.

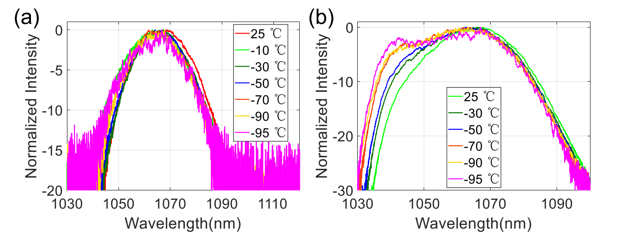

Fig. 4. (a) Normalized spectra of the SFS seed and (b) amplifier at different temperature. The pump power of the SFS seed and the amplification is 8 W and 42 W, respectively.

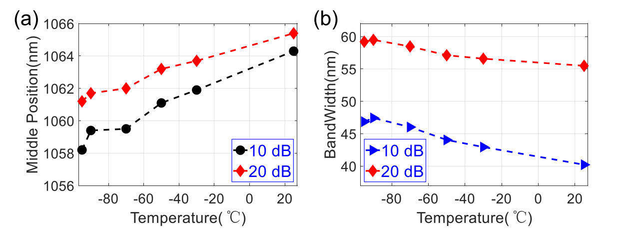

Fig. 5. Variation of the 10 dB and 20 dB (a) middle position and (b) bandwidth of the spectra with temperature.

the real-time temperature of the devices by several thermocouples. The operation of lasing is launched when the real-time temperature coincides the setting temperature. Fig. 3(a)–(e) show the entire process of the evolution of the SFS output spectra under different pump power with the downgrowth of temperature. At room temperature, the spectra are dome-shaped, shown in Fig. 2(b). The spectral lines are straightened between 1040 nm and 1070 nm, forming oblique lines, when it is −30 °C and −50 °C, as shown in Fig. 3(a) and (b). When it descends to −70 °C and −90 °C, the slope of the oblique lines between 1040 nm-1070 nm decreased obviously. Lastly, when the temperature is down to −95 °C, the previous dome-shaped spectra almost turn horizontal lines. Besides, when the temperature is lower, the smooth curve of the spectra at room temperature become echinate gradually. The output power also collapses gradually with the temperature falling down, as shown in Fig. 3(f). With the temperature dropping from −25 °C to −95 °C and the pump power unchanged at 42 W, the output power goes down from 31 W to 7.6 W, corresponding the optical efficiency goes down from 70% to below 20%. This phenomenon is very bad, and the main reason may be the leakage of cladding light, followed by the increased background loss in fiber at low temperature, especially at the fiber melting point. In Ref. [14], there is also a significant decrease in the efficiency of fiber laser at low temperature. This phenomenon is directly related to the fiber itself, mainly reflected in the technology of fiber manufacturing and the construction of the fiber laser. The pump light is mainly affected in this process, while the signal light in the fiber core is barely affected. Therefore, this paper will not discuss the efficiency of the laser for the time being, and will focus on analyzing the spectroscopy characteristic at different temperature.

To facilitate the comparison of the spectra at different temperature, the spectra of the SFS seed and amplifier are normalized. Fig. 4(a) shows the spectra of the SFS seed at different temperature, and the pump power of the seed is 8 W. Without the pump power of the amplification, the spectra of the seed blue shifted after the transmission of a section of more cryogenic YDF, which is different with the situation of normal temperature. While, when pump power of amplification is applied, the situation is different again. As shown in Fig. 4(b), the spectra broadened to the short-wave direction obviously, when the temperature drops from 25 °C to −95 °C, and the corresponding pump power is 42 W. Morphologically, the left boundary lines of the spectra are arranged from left to right with a high degree of separation, according to the order of temperature from low to high. The right boundary lines of the spectra remain nearly superposition, rather than shift in parallel like in Fig. 4(a).

Due to the wide range of spectra and the obvious noise of the spectral line at low temperature, it is more appropriate to characterize the spectra with 10 dB and 20 dB bandwidth. The peak position is also inappositely to represent the central wavelength, and is superseded by the middle position of the 10 dB and 20 dB band. The middle position of the 10 dB and 20 dB band of the SFS amplifier spectra in the Fig. 4(b) are shown in Fig. 5(a), and linear shift of 6.1 nm and 4.2 nm to the short-wave direction are found correspondingly. Fig. 5(b) displays the 10 dB and 20 dB bandwidth of the SFS amplifier spectra. The 10 dB and 20 dB bandwidth increase linearly as temperature drops to −90 °C. At −95 °C, the bandwidth goes down instead, due to the abnormal spectral behavior and curve shape. Excluding this temperature point, the 10 dB and 20 dB bandwidth increases by 17.9% and 7.2%. The widening of bandwidth mainly occurs in the band of 1030-1060 nm, and has little to do with the band of 1060 nm-1100 nm, as shown in Fig. 4(b). Similarly, the spectra of the seed intersect at 1060 nm, as shown in Fig. 4(a).

III. Simulation and Discussion

In general, signal light would redshift in the gain fiber if there is no pump power, which is caused by the reabsorption. Interestingly, in our experiment, when the fiber temperature decreases, the redshift becomes blueshift. Further, under low temperature conditions, after applying amplification stage pump light, the phenomenon becomes the expansion of the spectra to the short-wave direction. A good perspective to explain this is the small signal gain coefficient, which is based on the upper-level particle population distribution solved from the steady rate equations. There has been literature numerically model the behavior of Yb-doped fiber laser in different temperature condition via steady-state rate equations. The cross-sections under varied temperature are often obtained by experimental measurement [9], [14], [15] and numerical estimation [6], [11], [12]. In this paper, the temperature-dependent cross-sections are acquired by Lorentz fitting based on the precise measurement results at room temperature [13]. At any temperature *T*, the absorption coefficient $g_a(\nu,T)$ can be expressed as follows [13]:

$$g_a(\nu,T) = \sum_{x=a}^{d}\sum_{y=e}^{g} \frac{e^{-\frac{E_x}{k_b T}}}{\sum_{x=a}^{d} e^{-\frac{E_x}{k_b T}}} g_{xy}(\nu) \tag{1}$$

Where *a* - *d*, *e* - *g* are the Stark lower and upper levels, E_x is the energy level difference between levels *x* and *a* in the ground state when $x\in[a, d]$ and the energy level difference between levels *x* and *e* in the upper manifold when $x\in[e, g]$, and k_b is the Boltzmann Constant, 1.38065×10^{-23} J/K, g_{xy} is the absorption coefficient from Stark level *x* to *y*, and can be expressed as a Lorentz linetype function as follows:

$$g_{xy} = \frac{g_{xy}^0}{1 + \left(\frac{\nu - v_{xy}}{\Delta\nu_{xy}}\right)^2} \tag{2}$$

Equation (2) is a Lorentz linetype function, where g_{xy}^0, $\Delta\nu_{xy}$ represent the peak and half width at half maximum, respectively. By performing Lorentz decomposition of the absorption cross-section at room temperature, the specific values of g_{xy}^0, $\Delta\nu_{xy}$ can be obtained, thus obtaining g_{xy}. In (1), a temperature-dependent coefficient, which represents a probability characterized by the proportion of particles at different energy levels, is attached to g_{xy}, and from this we end up with absorption cross-sections at different temperature. The same applies to the acquisition of emission cross-sections.

In such methods, we can get the cross-sections at any temperature without repetitive measurements. The temperature-dependent absorption (Abs) and emission (Emis) cross-sections are attained as shown in Fig. 6(a) and (b). Considering the actual fiber core temperature will uprush when the laser is under operation, here we assume that the temperature range in the model is −60 °C to 60 °C, a little higher than that in the experiment. Combined with the traditional steady-state rate equations [12], [16], [17], the temperature-dependent spectroscopy characteristic of the SFS amplifier is modeled.

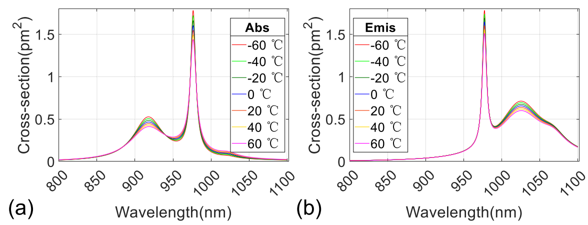

Fig. 6. Temperature-dependent (a) absorption cross-sections and (b) emission cross-sections ranging from −60 °C to 60 °C. Note that the cross-sections at 20 °C are obtained from experimental measurement, and the cross-sections at any other temperature are obatined from the theoritical calculation.

TABLE I
Parameters of SFS Amplification Stage in Simulation and Experiment

	Simulation	Experiment
Pump Wavelength (nm)	976	976
Pump Power (W)	42	42
Gain Fiber Length (m)	10	3.5
Abs coefficient of Gain fiber (dB/m)	4.8	4.8
R1	0	0
R2	0	0

Notes: R1--The reflectivity of the forward end of the fiber; R2--The reflectivity of the backward end of the fiber.

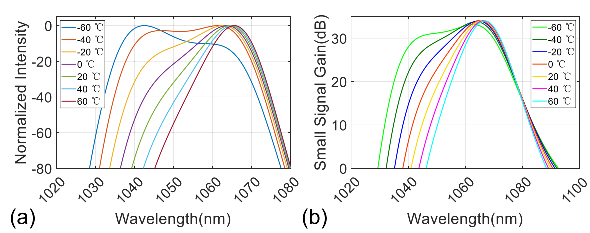

Fig. 7. (a) Modeled output spectra and (b) small signal gain coefficient of the amplifier at different temperature.

The parameters of SFS amplification stage in simulation and experiment are compared in Table I. The SFS amplifier output spectra at different temperature obtained by simulation have been normalized, as shown in Fig. 7(a). In Fig. 7(a), we can find obvious widening of spectra with the temperature lowering, consistent with the above experimental results in Fig. 4(b). In the simulation, longer gain fiber is required to acquire the consistent spectral change trend with experiment due to the disability of the current simulation method to consider the influence of temperature on the fiber laser in all aspects, mainly the properties of the fiber itself. Despite the difference, the simulation helps us demonstrate that the spectral characteristics are varied with temperature in a certain direction.

In order to explore the root cause of this law, we further calculate the small signal gain coefficient in fiber lasers to help understand the phenomena.

According to the above cross-sections, the small signal gain coefficient [16], [17], [18] of the signal light can be expressed as:

$$G(\lambda) = k_0 N \Gamma_s L \left[\sigma_a(\lambda) + \sigma_e(\lambda)\right] \left[n - \frac{\sigma_a(\lambda)}{\sigma_a(\lambda) + \sigma_e(\lambda)}\right] \quad (3)$$

Here, k_0 equals 4.343, N is the doping concentration of ytterbium ion, $\Gamma_s$represents the overlap between the signal optical mode field and the doping region, $\sigma_e$and $\sigma_a$denote the emission and absorption cross-section of Ytterbium ion, L is the gain fiber length, and n is the average inversion number of laser upper level in gain fiber.

The small signal gain coefficient at different temperature is shown in Fig. 7(b). The morphological changes of the output spectra are similar to those of the small-signal gain coefficient. This is because the shape change of the output spectrum is determined by the internal physical process of the laser, with the small signal gain coefficient being an important factor. In 1030 nm–1100 nm band, the lower the temperature, the weaker the absorption and the stronger the emission, as can be seen in Fig. 6(a) and (b). But an obvious difference is that the change around 1080 nm is very small, while the change around 1030 nm is more drastic. That is, low temperature increases the small signal gain near 1030 nm from two aspects of absorption and emission. Therefore, when the SFS passes through a cryogenic gain fiber, the spectrum shifts towards short-wave direction since the reabsorption near the 1030 nm is greatly weakened. In other words, at lower temperature, the output spectra suffered an overall efficiency reduction, but the short-wavelength reduction is less. When the pump light is applied, the small signal gain coefficient increases relatively in the short-wave direction, so the spectrum expands to the short-wave direction.

IV. Conclusion

In this paper, the influence of low temperature on the spectral characteristics of SFS seed and amplifier is studied experimentally. At low temperature, the spectra of SFS seed and amplifier are blue shifted. As for amplifier, the spectra expand to the short-wave direction, corresponding to that the center positions of 10 dB and 20 dB band move towards the short-wave direction by 6.1 nm and 4.2 nm, and the 10 dB and 20 dB bandwidth increase by 17.9% and 7.2%. The absorption and emission cross-sections at different temperature are theoretically calculated based on Lorenz fitting. The variation trend of absorption and emission cross-section with temperature is consistent with the previous research results, and we have successfully patterned the variation of SFS amplifier spectra with different temperature through these absorption and emission cross-sections. According to the change trend of small signal gain with temperature, we can conclude that low temperature will increase the gain of short-wavelength signal light, which is beneficial to improve the output efficiency of short-wavelength fiber laser. In our experiment, the boundary of the short-wavelength and long-wavelength is located around 1060 nm. The research results are helpful to improve the related theories of fiber laser and provide reference for the design of fiber laser.

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