Characteristics of stable L-band SFS using dual-forward synchronous pumping technique

Xiulin Wang (王秀琳)[1,3], Wencai Huang (黄文财)[2], Huiying Xu (许惠英)[2], and Zhiping Cai (蔡志平)[2*]

[1]*Department of Physics, Xiamen University, Xiamen 361005, China*
[2]*Department of Electronic Engineering, Xiamen University, Xiamen 361005, China*
[3]*Department of Physics, Jimei University, Xiamen 361021, China*
[*]*E-mail: zpcai@xmu.edu.cn*

Received December 2, 2008

We investigate the characteristics of the dual-forward synchronously pumped L-band erbium-doped superfluorescent fiber source (SFS). The effects of pump ratio and fiber length arrangements on the output characteristics of the L-band SFS in terms of mean wavelength, spectral linewidth, and output power are analyzed. It is shown that the optimized pump ratio and fiber length arrangements provide broadening spectral linewidth and enhanced pumping efficiency, while the synchronous pump ensures stable mean wavelength operation. A new single-forward pumping scheme with a section of unpumped fiber is proposed to achieve a mean wavelength stable L-band SFS with a broadening linewidth of 50.4 nm and a pumping efficiency of 33.5%.

OCIS codes: 060.2320, 060.2410, 140.6630.
doi: 10.3788/COL20090707.0568.

In the past decades, broadband superfluorescent fiber sources (SFSs) have been extensively studied owing to their various applications for dense wavelength division multiplexing (WDM) device characterization, spectrum-sliced sources, optical sensor systems, fiber optic gyroscopes (FOG), and optical coherence tomography[1−4]. In particular, SFSs based on erbium-doped fiber (EDF) amplified spontaneous emission (ASE) are considered to be good candidates for their simultaneous offering of broad spectral range, high output power, and excellent mean wavelength stability meeting the application requirements. As is well known, an SFS with stable mean wavelength and broad linewidth is desirable for FOG application in that the accuracy of rotation detection of FOG depends on the mean wavelength stability of its light source. Most reported mean wavelength stability in SFS was restricted to the conventional band (C-band, 1525−1565 nm)[5−8]. In recent years, more researches have focused on the long wavelength band (L-band, 1565−1605 nm) SFS to increase its output power and spectral linewidth to cater for the demand of band expansion of the fiber optic communication window[9−11]. There has been no research yet on designing a mean wavelength stable L-band SFS although it is very suitable in FOG application because of its potential larger linewidth, which achieves a higher signal to noise ratio (SNR) value. Recently, a synchronous pumping technique was used in a double-pass bi-directional configuration to achieve a mean wavelength stability L-band SFS[12,13]. And the mean wavelength stability L-band SFS with dual-backward pumped configuration has been reported[14]. One disadvantage of the synchronous pumping technique is that the mean wavelength stability becomes sensitive to the small variations in the power splitting ratio of the power splitter.

In this letter, the characteristics of the dual-forward synchronously pumped L-band SFS, including mean wavelength, spectral linewidth, and output power against the pump ratio and fiber length arrangements of the two-stage, are analyzed in detail. Furthermore, a new single-forward pumping scheme with a section of unpumped fiber is proposed to achieve a mean wavelength stability and linewidth broadening L-band SFS based on the analysis on the dual-forward synchronously pumped L-band SFS.

Figure 1 describes the proposed configuration of dual-forward pumped two-staged L-band SFS. The designed source consists of two conventional erbium-doped fibers (EDF1 and EDF2), two 980/1590-nm wavelength selective couplers (WDM1, WDM2), a 980-nm pump laser diode, a power splitter used to divide the pump power into two portions (P_1 and P_2), a fiber loop mirror (FLM) used to reflect the ASE light to form into a double-pass configuration, and an optical isolator (ISO) at the output port. We define the total length of EDF as $L=L_1+L_2$, where L_1 and L_2 refer to the first stage (EDF1) and second stage (EDF2) lengths, respectively. The fiber length ratio of the EDF1 length to the total length is defined as $R_L=L_1/(L_1+L_2)$. Similarly, the pump ratio is defined as the pump power of the first stage to the total pump power, that is, $R_p=P_1/(P_1+P_2)$. The EDF used here is Lucent Technologies heavily doped LRL fiber

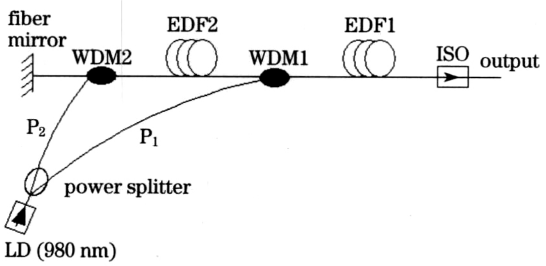

Fig. 1. Configuration of the dual-forward pumped two-staged L-band SFS.

(type number L12403) with a peak absorption of 27 to 33 dB/m at 1530 nm, mode field radius of 5.2 μm, cutoff wavelength from 1100 to 1400 nm, and numerical aperture of 0.25. From Fig. 1, we can see that the configuration is a conventional double-pass forward design with P_1=0, that is, R_p=0.

First, the commercial amplifier simulation package OASIX[15] is used to perform the simulations of the proposed configuration, as shown in Fig. 1, in order to gain insight into and to optimize its output properties. Previous simulations and experiments have indicated that the simulation results obtained from the software are quite accurate[7,11−14]. The mean wavelength and spectral linewidth of the ASE are computed respectively by[2]

$$\overline{\lambda} = \frac{\sum\limits_{i=1}^{n} p(\lambda_i) \cdot \lambda_i}{\sum\limits_{i=1}^{n} p(\lambda_i)}, \tag{1}$$

$$\Delta\lambda = \frac{\left[\sum_{i=1}^{n} \Delta\lambda_i \cdot P(\lambda_i)\right]^2}{\sum_{i=1}^{n} \Delta\lambda_i \cdot P(\lambda_i)^2}, \tag{2}$$

where λ_i is the wavelength of the ith ASE wave, $P(\lambda_i)$ is the power in the ith ASE wave of the emission spectrum, n is the number of discrete ASE wavelengths, and $\Delta\lambda_i$ is the spectral width represented by the ith ASE wave.

There is no doubt that the output ASE spectrum mainly depends on the used total fiber length. Therefore, the total EDF length L is initially optimized to obtain a flat L-band spectrum output. From Fig. 1, we can see that when P_1=0, the SFS design becomes a double-pass forward (DPF) configuration. Previous works on the DPF L-band SFS have pointed out that there is an optimal fiber length to obtain the flattest L-band spectrum output[9]. The effective FLM reflectivity is selected to be 90%. The output spectra of the L-band SFS at various EDF lengths are simulated. The simulated results indicate that for 160-mW pump power, the optimal fiber length to obtain the widest linewidth of the L-band SFS is approximate 19 m. The widest spectral linewidth means the lowest spectrum ripple and the flattest L-band spectrum. In the proposed dual-forward pumped L-band SFS configuration, we would like to set the same total EDF length to gain insight into its much better properties compared with the DPF configuration. Hence, the total EDF length is fixed at 19 m in the following simulations.

Then, for different given pump power allotments at a fixed 160-mW total pump power, the effects of the fiber length ratio R_L on the output characteristics of the L-band SFS are simulated. The calculated mean wavelength, linewidth, and output power of the L-band SFS with different R_L are given in Figs. 2(a)−(c), respectively. Figure 2(d) illustrates the available maximum output power with optimized fiber length ratio under different pump power allotments. Figures 2(a) and (b) show that: 1) when the proportion of the pump power for stage 1, P_1, is less than 120 mW (i.e., R_p <0.75), the mean wavelength and linewidth of the dual-forward pumped L-band SFS have little fluctuation at various fiber length ratios, and 2) by further increasing the proportion of P_1 to be larger than 120 mW (i.e., R_p >0.75), the large fluctuation of the mean wavelength and linewidth occurs at a specific fiber length ratio of around 0.1 to 0.3. The inset in Fig. 2(b) shows the available maximum linewidth by optimizing the fiber length ratio under different pump ratios. The maximum linewidth of about 78 nm can be achieved under a pump ratio of 0.94. From Figs. 2(c) and (d), we can find that the output power is mainly affected by the allotment of pump power. Figure 2(c) indicates that the optimization fiber length ratio for achieving the maximum output power has a little difference of 0.1 to 0.2 in different pump power allotments. Figure 2(d) shows that the available maximum output power initially increases with the proportion of P_1 and then decreases after it saturates. The pump power ratio of about 0.8 corresponds to the achieved maximum output power of about 58 mW. Compared with the conventional DPF scheme (R_p=0), the output power is improved about 70%, that is, from 34 to 58 mW.

Figure 3 illustrates the corresponding output spectra for the three typical pump powers in the following cases: (a) P_1=0 mW, P_2=160 mW; (b) P_1=130 mW, P_2=30 mW; and (c) P_1=160 mW, P_2=0 mW. The results show that the output spectra in the cases of (b) and (c) compared with the case (a), that is, the conventional DPF configuration, are both improved in terms

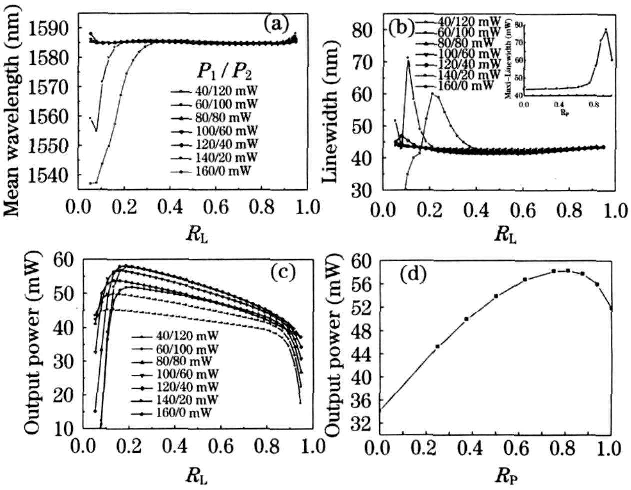

Fig. 2. (a) Mean wavelength, (b) linewidth with the inset of available maximum linewidth, (c) output power against R_L in the seven given pump power allotments, and (d) maximum output power calculated by optimizing the fiber length ratio in different pump ratios.

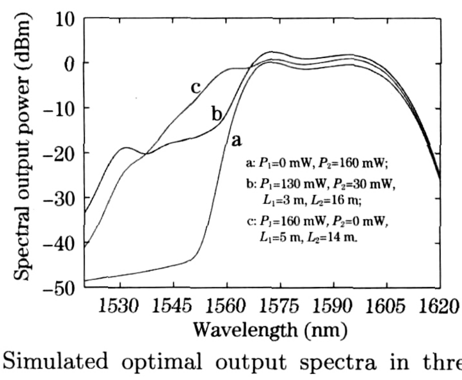

Fig. 3. Simulated optimal output spectra in three typical pump power cases.

of the linewidth and spectral intensity. Especially, there is a considerable broadening in the spectrum linewidth of about 10 nm when R_p=1. Compared with the conventional DPF configuration, the two-stage configuration can provide an L-band SFS with better characteristics in terms of the linewidth and spectral intensity.

The mean wavelength stability of the dual-forward pumped L-band SFS is also investigated. According to the above simulations, the fiber lengths of the two stages are selected at L_1=3 m, L_2=16 m, and L_1= 4 m, L_2=15 m in the following simulations. The mean wavelength against the total pump power is compared for DPF configuration and the suggested dual-forward pumped configuration in different pump power ratios as P_1:P_2=1:4, 1:2, 1:1, 2:1, 4:1, and 7:1, and P_2=0. The results are shown in Figs. 4(a) and (b) for the two fiber length arrangements, respectively. From the figure, we can see that in the case of DPF configuration and P_1:P_2=1:4, 1:2, the mean wavelength decreases monotonously with the pump power. However, the mean wavelength shows a different rule in the case of $P_1>P_2$, that is, it initially increases with pump power to a maximum value and then decreases gradually similarly to that in the DPF configuration when the pump power is large. In the case of P_2=0, the simulation shows that the mean wavelength increases monotonously with the pump power. Therefore, the reason for mean wavelength stability can be simply explained as follows: it can be seen clearly that the mean wavelength decreases monotonously with pump power when P_1=0, that is, the DPF configuration, while the mean wavelength increases monotonously with pump power when P_2=0. Hence, the pump power independent mean wavelength operation can be achieved with a suitable allotment of the pump power of P_1 and P_2. Figure 4(b) shows the mean wavelength characteristics of L_1=4 m, L_2=15 m, which are similar to the case of L_1=3 m, L_2=16 m. The difference between these two

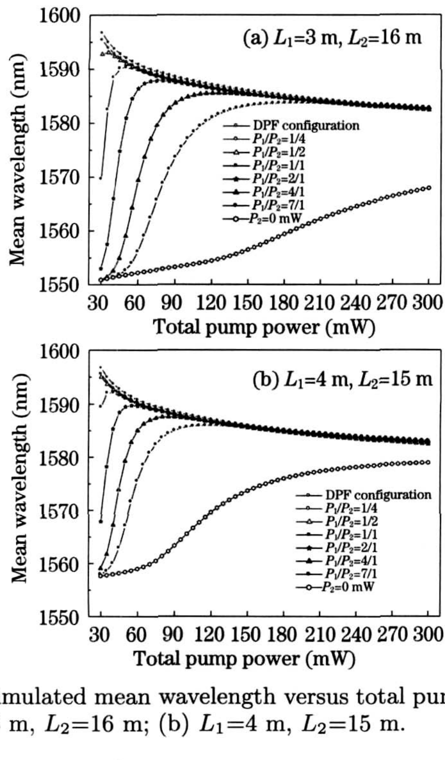

Fig. 4. Simulated mean wavelength versus total pump power. (a) L_1=3 m, L_2=16 m; (b) L_1=4 m, L_2=15 m.

fiber lengths arrangements is that the required pump power for a stable mean wavelength operation is smaller for L_1=4 m, L_2=15 m compared with that for L_1=3 m, L_2=16 m.

Furthermore, it should be noted that the total pump power to obtain a stable mean wavelength is different in the different pump ratios. Figure 5(a) illustrates the required pump power for stable mean wavelengths in different R_p, while Fig. 5(b) gives the corresponding available linewidth and pumping efficiency. We can see clearly from Fig. 5(a) that pump power independent mean wavelength operation cannot be always achieved by the proposed dual-forward pumping scheme. Too low or high pump ratios are not satisfactory for a stable SFS. The results show that a pump ratio between 0.5 and 0.95 is suitable to achieve a stable L-band SFS for this design. Figure 5(a) also indicates that the larger the value of R_p is, the higher the total pump power is needed to get the stable mean wavelength operation. Figure 5(b) directs us to select the optimization of R_p to obtain the best output characteristics of linewidth and pumping efficiency. The result of Fig. 5(b) shows that a higher pumping efficiency will be achieved with a larger value of R_p. For the case of L_1=3 m, L_2=16 m, the R_p of 0.8 corresponds to the stable L-band SFS with the widest linewidth of 46 nm and a pumping efficiency of 33.9% under a total pump power of 125 mW. However, the linewidth is increased monotonously with pump ratio for the case of L_1=4 m, L_2=15 m. The widest linewidth of 46.8 nm with a pumping efficiency of 36% is achieved under a total pump power of 200 mW with pump ratio of 0.95. In this point of view, the fiber lengths of the two stages of L_1=4 m, L_2=15 m are better in achieving a stable L-band SFS with larger linewidth and higher pumping efficiency than that of L_1= 3 m, L_2=16 m. Furthermore, as illustrated in Fig. 5(a), the pump power required for a stable mean wavelength operation is smaller for L_1=4 m, L_2=15 m compared with that of L_1=3 m, L_2= 16 m. Hence, properly increasing the fiber length ratio will decrease the required pump power of the stable mean wavelength operation. In this case, the pump power independent mean wavelength operation can be possibly achieved with pump ratio of 1.0, that is, the single-forward pumping scheme with a section of unpumped fiber. The characteristics of a stable SFS in terms of required pump power, pumping efficiency, and linewidth are simulated for three fiber lengths in the following cases: (i) L_1=4.5 m, L_2=14.5 m; (ii) L_1=5 m, L_2=14 m; and (iii) L_1=5.5 m, L_2=13.5 m. The results show that the stable single-forward pumped L-band SFS can be achieved for all the three fiber lengths cases. The case of (ii) is the optimal parameters to obtain a stable L-band SFS with the widest linewidth of 50.4 nm and a moderate conversion efficiency of 33.5%.

It should be noted that the major advantage of the single pumping scheme is that it is much simpler and has less strict requirements (e.g., the pump ratio requirement) in the structure parameters to achieve a mean wavelength stable L-band SFS. Furethermore, a meaningful comparison between the proposed single-forward pumped configuration and the conventional DPF configuration is as follows. With the same components and total fiber

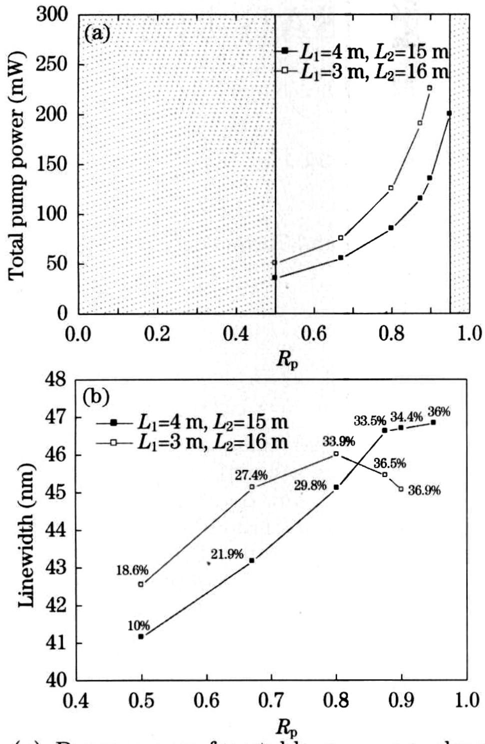

Fig. 5. (a) Pump power for stable mean wavelengths and (b) corresponding spectral linewidth and pumping efficiency against R_p.

length, a pump power independent mean wavelength operation with a broader bandwidth and higher conversion efficiency is realized by simply dividing a segment of the EDF arranged between the reflector and WDM coupler as the unpumped fiber. It is believed that the stable single-pumped L-band SFS is useful in FOG application, sliced WDM local-access networks, and the characteristic measurement for dense WDM components.

In conclusion, we investigate the characteristics of dual-forward synchronously pumped L-band SFS. Firstly, the pump ratio and fiber allotment of the two stages merely affect the output power when R_p is less than 0.75. This means that the mean wavelength and spectral linewidth of the output L-band SFS remain almost unchanged with the various fiber allotments of the two stages in different R_p when R_p is less than 0.75, while the larger output power can be obtained with higher R_p. However, the spectral linewidth is mainly affected by the fiber allotment when R_p is larger than 0.75. With the optimal fiber length allotment of the two stages, the spectral linewidth can be effectively broadened. Secondly, the L-band SFS with pump power independent mean wavelength operation can be achieved by using the dual-forward synchronous pump within large pump ratio ranges. The synchronous pump balances the mean wavelength variation caused by the pair of separate pump. Thirdly, the single-forward pumping scheme with a section of unpumped fiber is able to achieve a stable L-band SFS with a large linewidth by properly setting the fiber length arrangements. Simulation shows that a mean wavelength stable L-band SFS with a linewidth of 50.4 nm and a conversion efficiency of 33.5% can be achieved with the single-forward pumping scheme.

This work was supported by the Program for New Century Excellent Talents in Fujian Province University (No. X07204), the Scientific and Technical Project of Fujian Provincial Department of Education (No. JA08138), and the Key Scientific and Technical Innovation Project of Xiamen University (No. K70007).

References

1. J. S. Lee, Y. C. Chung, and D. J. DiGiovanni, IEEE Photon. Technol. Lett. **5,** 1458 (1993).
2. P. F. Wysocki, M. J. F. Digonnet, and B. Y. Kim, J. Lightwave Technol. **12,** 550 (1994).
3. M. E. Bray, R. T. Elliot, and K. P. Jones, in *Proceedings of OFC 2001* **3,** WI2-1 (2001).
4. G. Shi, Z. Ding, Y. Dai, X. Rao, and Y. Zhang, Chinese J. Lasers (in Chinese) **35,** 1429 (2008).
5. P. F. Wysocki, M. J. F. Digonnet, and B. Y. Kim, Opt. Lett. **16,** 961 (1991).
6. D. C. Hall and W. K. Burns, Electron. Lett. **30,** 653 (1994).
7. P. Z. Zatta and D. C. Hall, Electron. Lett. **38,** 406 (2002).
8. H. G. Park, M. Digonnet, and G. Kino, J. Lightwave Technol. **21,** 3427 (2003).
9. S. Hsu, T.-C. Liang, and Y.-K. Chen, Jpn. J. Appl. Phys. **41,** 3724 (2002).
10. S.-C. Tsai, T.-C. Tsai, P.-C. Law, and Y.-K. Chen, IEEE Photon. Technol. Lett. **15,** 197 (2003).
11. S.-P. Chen, Y.-G. Li, J.-P. Zhu, H. Wang, Y. Zhang, T.-W. Xu, R. Guo, and K.-C. Lu, Opt. Express **13,** 1531 (2005).
12. W. Huang, X. Wang, Z. Cai, H. Xu, and C. Ye, J. Opt. A: Pure Appl. Opt. **7,** 179 (2005).
13. W. Huang, X. Wang, B. Zheng, H. Xu, C. Ye, and Z. Cai, Opt. Express **15,** 9778 (2007).
14. X. Wang, W. Huang, X. Huang, C. Huang, H. Xu, and Z. Cai, Chinese J. Lasers (in Chinese) **36,** 647 (2009).
15. OASIX v3.0: Lucent Technologies erbium doped fiber devices simulation software.