High efficiency broad bandwidth erbium-doped superfluorescent fiber source

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A practical two-stage double-pass structure using high concentration erbium-doped fiber and 1480-nm pump laser diode is suggested for a high power and broad bandwidth erbium-doped superfluorcscent fiber source. A considerable increase in output power and bandwidth extension is achieved by adding an unpumped fiber and a broadband fiber mirror to make the most of wasted backward amplified spontaneous emission as both pump and input light source simultaneously. Superfluorcscent fiber source with nearly 80-nm bandwidth and 28.6-mW output power is obtained experimentally.

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Broadband optical sources with short coherence length, low spectral ripples and high spectral intensity have been a topic of continuing research because of their wide range of applications, from gyro sensors and component testing sources to sliced spectrum sources for lower-cost access networks[1,2]. In particular, fluorescent sources using amplified spontaneous emission (ASE) from an erbium-doped fiber (EDF) have been considered to be one of the optimum candidates of choice, owing to their broad spectral range, high output power, and low splicing loss[3]. Still, research on the EDF broadband source has been restricted mostly to the conventional wavelength range 1525 – 1565 nm (C-band), where most optical communication devices and conventional EDF amplifiers operate. However, the recent demand for immediate expansion of the fiber optic communication window has led to the development of long-wavelength-band (1565 – 1605 nm) amplifiers, which in turn call for the development of high power broad bandwidth sources operating at both conventional and long wavelength range[4-6]. In our previous work, we have introduced a novel one-stage structure that can generate 80nm flat bandwidth ASE source by simply balancing the C-band and L-band ASE spectrum. However, the configuration seems a little complicated because it needs two-pump sources[7].

In this letter, we present a simple method to extend the bandwidth and to enhance the pump efficiency of the EDF superfluorcscent fiber source (SFS) by full use of the wasted backward amplified spontaneous emission. Experimental results show the bandwidth has obviously extended and the output power is high with the proposed scheme. Using 1480-nm pump laser diode (LD) and high concentration EDF simultaneously help to obtain high pumping efficiency and output power.

Figure 1 illustrates the suggested two-stage double-pass configuration of SFS. It is simply composed of two sections of EDF, a 1480-nm pump LD, a fiber mirror and an isolator. The EDF used in our experiment is a standard EDF manufactured by Lucent Technologies, which is high concentration EDF with peak absorption of 27 – 33 dB/m at 1530 nm, mode field radius of 5.2 μm, cutoff wavelength of 1100 – 1400 nm, and numerical aperture of 0.25. The fiber mirror is simply manufactured by a 3-dB broadband couple. The isolator is used to avoid lasing. The output spectra are measured by an optical spectra analyzer (ANDO6317B).

The behavior of erbium-doped SFS is determined by the interaction between the population densities of the various energy levels and the optical signals. To analyze the evolution of the ASE spectrum with the variation of design parameters, the spectrum is divided into several regions and computed in each region. The propagation equations for the ASE and pump waves are[1]

$$\frac{\mathrm{d}P_s^{\pm}(z,\nu_s,i)}{\mathrm{d}z} = \pm[\gamma_s(z,\nu_s,i)P_s^{\pm}(z,\nu_s,i) + \gamma_{es}(z,\nu_s,i)2h\nu_{s,i}\left(\frac{\Delta\nu_h}{n}\right)], \tag{1}$$

$$\frac{\mathrm{d}P_p(z,\nu_p)}{\mathrm{d}z} = -\gamma_p(z,\nu_p)P_p(z,\nu_p), \tag{2}$$

where

$$\gamma_s(z,\nu_s,i) = \frac{A_0}{A_s}[\sigma_e(\nu_s,i)N_u(z) - \sigma_a(\nu_s,i)N_l(z)], \tag{3}$$

$$\gamma_{es}(z,\nu_s,i) = \frac{A_0}{A_s}[\sigma_e(\nu_s,i)N_u(z)], \tag{4}$$

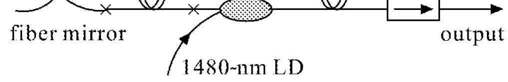

Fig. 1. Experimental configuration of the high efficiency broad bandwidth erbium-doped SFS.

for 1480-nm pumping

$$\gamma_p(z,\nu_p) = \frac{A_0}{A_s}[\sigma_{pa}(\nu_p)N_l(z) - \sigma_{pe}(\nu_p)N_u(z)]. \qquad (5)$$

The population densities of the various energy levers (N_u, N_l) can be derived from rate equations and the parameters in Eqs. (1)−(5) are defined referring to Ref. [1].

As the above equations, the characteristics of an SFS are determined by many parameters, which can be divided into three categories: material parameters (Er^{3+} concentration, codopant concentration, absorption and emission spectral cross section, etc.), waveguide parameters (numerical aperture, cut off wavelength, overlapping of optical field and fiber core areas, etc.), and working parameters (pump wavelength, pump power, EDF length, mirror reflectance, etc.). According to different boundary conditions, one can successfully simulate the characters of various SFS configuration by above equations.

In the experiment, the length of EDF I and EDF II selection is based on the following consideration. The total EDF length should be selected that the ASE spectrum can move to L-band and the length of EDF I be selected that the forward ASE is restricted to C-band. High concentration EDF enables relatively shorter fiber required for L-band ASE spectrum as compared with conventional concentration EDF. For LRL EDF, the simulations show that 20-m fiber has made the ASE spectrum move to L-band, and about 5-m fiber is suitable for generating forward C-band ASE spectrum. We happen to have 19-m fiber, therefore, the lengths of EDF I and EDF II are selected to be 4 and 15 m, respectively.

Figure 2 shows the output ASE spectrum of the proposed fiber source with the pump power of 110 mW. In this case, the SFS power is measured to be 28.6 mW, and its spectrum covers over C-band and L-band from 1525 to 1600 nm. We attribute the output power increase and the bandwidth extension to reuse of the backward ASE as a 1550-nm band pumping source for the unpumped EDF II, then generating photons in the 1600-nm band and seeding the amplifier stage EDF I.

To confirm the function of the unpumped EDF II and fiber mirror, we measured the output ASE spectra in the cases that the fiber source is cut at point A and B, respectively. The results are shown in Fig. 3. Figure 3(b) shows that the output ASE spectrum has an enhancement in L-band with adding an unpumped EDF II as compared to the conventional forward pump source (shown in Fig. 3(a)). Figure 3(c) shows that the output ASE spectrum has a larger enhancement in L-band with a fiber mirror. In this case, the bidirectional 1600-nm band photons of the unpumped EDF II are seeded to the amplifier stage EDF I. The ASE spectrum output from point A is measured, as illustrated in Fig. 4. The result shows that the forward 1600-nm band photons are considerable. Therefore, using a broadband fiber mirror and the forward 1600-nm band photons, the L-band ASE can be increased more.

The dependence of mean wavelength upon pump power to reflect the corresponding pump power efficiency are characterized also, and the results are shown in Figs. 5 and 6. From Fig. 5, we find that the mean wavelength has little or no dependence on pump power when the pump power is around 65 mW. Beyond this power, the

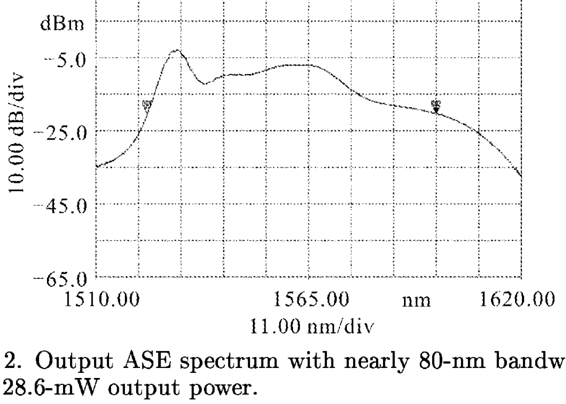

Fig. 2. Output ASE spectrum with nearly 80-nm bandwidth and 28.6-mW output power.

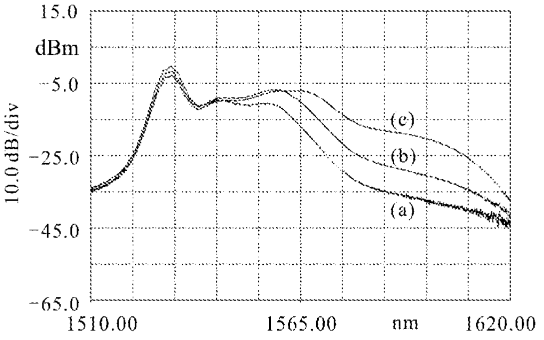

Fig. 3. Output ASE spectra. (a) Cut at point B; (b) cut at point A; (c) with a fiber mirror.

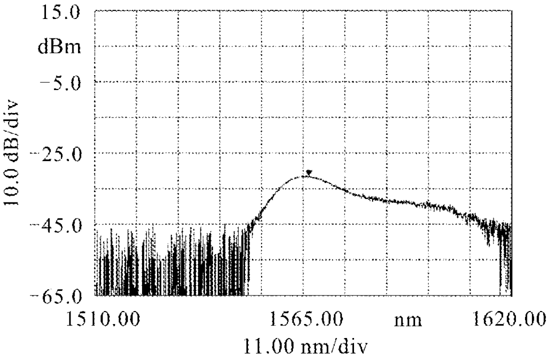

Fig. 4. Backward ASE spectrum measured at point A.

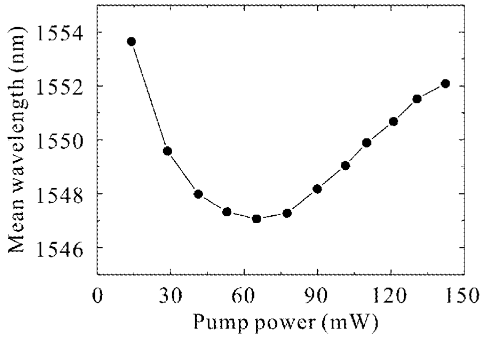

Fig. 5. Mean wavelength versus pump power.

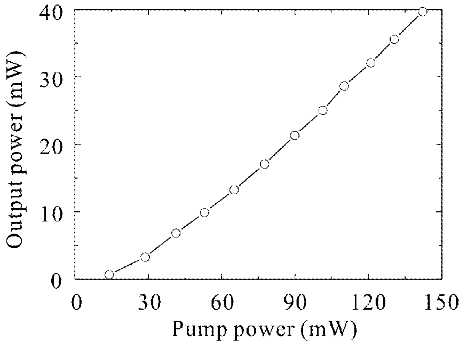

Fig. 6. Output power versus pump power.

mean wavelength shifts to longer wavelength as pump power increases, the pump power independent mean wavelength operation with $\partial\lambda/\partial P = 0$ is unable to exist for large pump power of this fiber source. Figure 6 shows that the source has an important advantage of high pump efficiency and low threshold. It attributes to using 1480-nm pump laser and high concentration EDF simultaneously.

In summary, we have presented and investigated a simple two-stage erbium-doped SFS with 80-nm bandwidth and 28.6-mW output power. A considerable increase in bandwidth and output power is achieved by full using all directions of the ASE with adding an unpumped EDF and a broadband fiber mirror. The most important advantage of the source is of high pump efficiency by use of 1480-nm pump laser and high concentration EDF simultaneously. It is believable that more flatter superfluorcscent fiber source may be obtained by further optimum the length of EDF I and EDF II.

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