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# 30 W all-fiber tunable, narrowband Yb-doped superfluorescent fiber source

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ABSTRACT

An all-fiber tunable, narrowband superfluorescent source is presented by using tunable seed source and two amplification stages. The output power reaches over 30 W with the tuning range of ∼35 nm (from ∼1045 to ∼1080 nm) and the slope efficiency in the final amplifier is about 67%. At the maximum output power, the full width at half maximum is about 0.7 nm and the signal-noise ratio reaches over 25 dB. More output power can be realized by simply adding pump source. To the best of our knowledge, it is the first time to use all-fiber configuration to realize the tunable output at 1 μm superfluorescent fiber source region.

## 1. Introduction

Superfluorescent fiber source (SFS) has been widely used in the fields of low coherence interferometry, navigational-grade fiber optic gyroscopes, and spectroscopy, due to its great advantages of high temporal stability, low coherence, and excellent beam quality [1–4]. What's more, high power Yb-doped superfluorescent fiber source can be used in spectral combination, laser cutting, or as an ideal pump for Raman lasers, which makes it potential to be an alternative way to realize high brightness light output [2,5]. There have been many investigations into the Yb-doped superfluorescent fiber source [3,6–11]. In 2007, Wang et al. reported 122 W output power with the overall range from 1035 nm to 1085 nm [6]. In 2015, Xu et al. generated 1.01 kW superfluorescent source with central wavelength of 1074.4 nm and full width at half maximum (FWHM) of 8.1 nm [7]. Superfluorescent source with 2.53 kW output power was demonstrated in 2016, and the central wavelength and FWHM were 1082.08 nm and 6.32 nm, respectively [9].

Compared with above-mentioned broadband SFS, the narrowband superfluorescent fiber source with tunable central wavelength is more charming and desirable in many applications, such as spectral beam combining and optical component testing [12,13]. In 2011, O. Schmidt et al. presented a narrowband superfluorescent source based on Yb-doped fiber with the output power of 697 W, the central wavelength of 1030 nm, and the FWHM of 12 pm [14]. Xu et al. used the all-fiber amplification stages to scale up the power of the seed source to 1.87 kW with central wavelength of 1080.7 nm and FWHM of 1.7 nm [2]. However, the tunable narrowband Yb-doped superfluorescent fiber source was only reported by Wang et al. in 2009 [12]. Besides, the source adopted space structure and the maximum output power was only 135 mW.

In this paper, we present an all-fiber tunable, narrowband Yb-doped superfluorescent fiber source employing tunable seed source and all-fiber amplification stages at 1 μm wavelength region. The source can be tuned from ∼1045 nm to ∼1080 nm and the FWHM is about 0.7 nm. All the output power of this source at different wavelengths are beyond 30 W and the signal-noise ratio reaches over 25 dB.

## 2. Experiment system

The narrowband, tunable SFS system contains three components: low power, all-fiber SFS seed which is narrowband and tunable, pre-amplifier stage and main-amplifier stage. The tunable narrowband superfluorescent seed source adopts backward signal and single-pass configuration as shown in Fig. 1. The seed source is pumped by a fiber-pigtailed wavelength-stabilized 975 nm laser diode (LD) with maximum output power of 25 W and core diameter of 105 μm. Through the pump fiber of a (2 + 1) × 1 signal-pump coupler, pump light is launched into the 9.0 m Yb-doped double-cladding fiber. The diameters of fiber core and inner cladding are 10 μm and 130 μm, respectively. The numerical apertures of core/inner cladding are 0.075/0.46. Its cladding absorption coefficient of the gain fiber near 975 nm pump wavelength is about 3.9 dB/m and 9.0 m long gain fiber is enough for the power extraction. The residual pump power and the reflectivity from fiber end facet could reduce the lasing threshold and affect the stability of source, thus the cladding pump laser stripper (CPS) is spliced and the forward output port is cleaved with 8 degree and angle-polished to achieve low feedback reflectivity. Besides, the output from the forward port is measured

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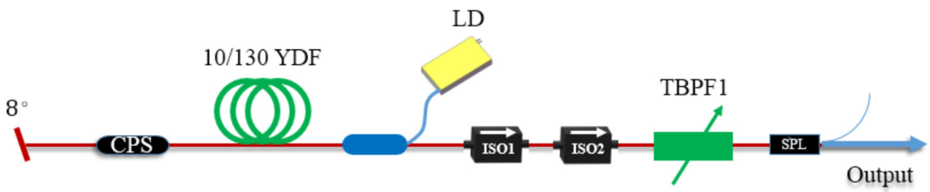


**Fig. 1.** Schematic of the narrowband tunable superfluorescent seed source.

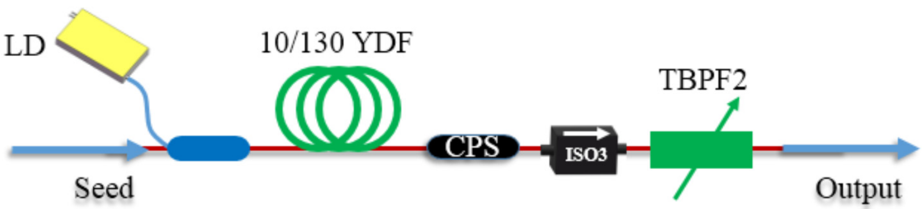


**Fig. 2.** Schematic of the pre-amplifier stage.

to monitor the operation state of the system. To prevent the backward signal entering into seed source and suppress effectively laser oscillation, the signal fiber of the coupler is spliced to two high power broadband isolators (ISO) with > 60 dB isolation. One tunable band-pass filter (TBPF1) with bandwidth of ~1 nm is connected with the output port of the ISO2 to filter the broadband seed spectra and generate narrowband tunable superfluorescent seed source. Before injecting the seed into pre-amplifier stage, one splitter (SPL) with splitting ratio of 99:1 is spliced to measure the output spectra and operation state of seed which is injected into the pre-amplifier stage.

As Fig. 2 shown, the output from seed source with narrow band is seeded into the pre-amplifier stage for power scaling. The same LD and gain fiber as employed in the seed source is adopted in the pre-amplifier stage. A (2 + 1) × 1 combiner is used to inject the pump light into the gain fiber with length of 10 m. After the pre-amplifier stage, one isolator with > 30 dB isolation is used to prevent the propagation of backward signal. Besides, one tunable band-pass filter (TBPF2) with same parameters as adopted in seed source is used to filter the possible noise which emerges in the pre-amplifier stage and ensure a certain signal-to-noise ratio, which can increase the performance of main-amplifier stage.

Fig. 3 shows the structure of main amplifier which consists of one commercial 976 nm multimode LD with maximum output power of 100 W, a (2 + 1) × 1 signal-pump combiner and a 5 m gain fiber. The gain fiber is as same as that adopted in the broadband seed source and pre-amplifier stage. To ensure the pump extraction and reduce the amplified spontaneous emission at other wavelength region, the length of gain fiber is selected to be 5 m. The remaining pump light in the cladding is dumped down by stripping cladding and coating with high refractive gel. One 0.5 m matched passive Ge-doped fiber is spliced with the gain fiber for power delivery. The output port of the passive fiber is angled with 8 degree to decrease feedback from fiber facet and suppress lasing. To relieve the effect of temperature on system, a water-cooled Al heat think with 16 °C is used to fix the gain fiber, pump laser and fusion joints.

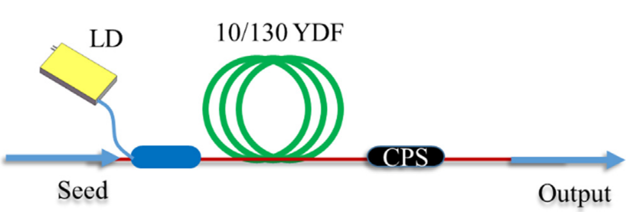


**Fig. 3.** Schematic of the main amplifier.

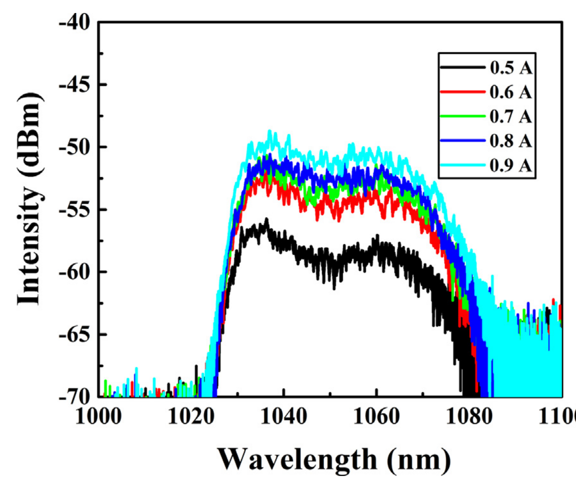


**Fig. 4.** Output spectra of broadband superfluorescent fiber source at different currents of pump source.

## 3. Experiment results and discussions

The output spectra of broadband superfluorescent seed source after ISO2 are measured by scattering light from the power meter and are shown with different currents of pump source in Fig. 4. The wavelength range covers from ~1025 nm to ~1090 nm and the intensity grows with the increase of current. When the current is 0.9 A, the output power after ISO2 reaches 1.237 W and the central wavelength, FWHM are 1039.24 nm and 14.79 nm, respectively. When the current of pump source is higher, parasitic lasing emerges. To get seed source with more stable operation state and higher output power, special optimization, such as immersion cell [15], should be added to reduce the reflectivity from fiber end facet.

In order to get seed source with narrow band and tunable central wavelength, a wavelength-tunable band-pass filter (TBPF1) is used to filter the broadband spectra and select a small part from that. Then, one central-wavelength-tunable narrowband seed source is formed and the output spectra after the TBPF1 are shown in Fig. 5. The whole intensity distribution is as same as that in Fig. 4 and the lowest power, maximum power are 209.8 μW at 1090.04 nm, 20.92 mW at 1039.31 nm, respectively. The wavelengths are tuned from 1028.32 nm to 1090.04 nm with FWHM of about 1.0 nm. During all wavelengths, the signal-noise ratio (SNR) are over 20 dB. The differences of SNR in different wavelengths are induced by the emission spectra of broadband superfluorescent source and the properties of filter.

The light from narrowband superfluorescent seed source is then seeded into the per-amplifier stage as shown in Fig. 2. Although the