Widely tunable/wavelength-swept SLM fiber laser with ultra-narrow linewidth and ultra-high *OSNR*[*]

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We propose and demonstrate a novel single-longitudinal-mode (SLM) erbium-doped fiber laser (EDFL) capable of operating at fixed-wavelength lasing mode with a tunable range more than 54 nm, an ultra-narrow linewidth of 473 Hz and an ultra-high optical signal-to-noise ratio (*OSNR*) more than 72 dB, or operating at wavelength-swept mode with tunable sweep rate of 10—200 Hz and a sweep range more than 50 nm. The excellent features mainly benefit from a triple-ring subring cavity constructed by three optical couplers nested one another and a fiber Fabry-Pérot tunable filter which can be driven by a constant voltage or a periodic sweep voltage for fixed or wavelength-swept operation, respectively. The proposed EDFL has potential applications in high-resolution spectroscopy and fiber optic sensing.

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Widely tunable erbium-doped fiber lasers (EDFLs) are preferred light sources for many applications, such as wavelength-division-multiplexed systems, fiber optic sensing, spectroscopy, and passive component characterization[1-3]. Recently, the wavelength-swept EDFL as a type of special tunable fiber laser has been studied extensively and experimentally applied in some quasi-distributed and distributed fiber sensing systems[4-6]. However, for ultra-high spatial resolution application requirement in those areas, the EDFLs are further needed to operate in single-longitudinal-mode (SLM) with narrow linewidth. To achieve stable SLM oscillating and wide wavelength-tuning or wavelength-sweeping simultaneously, a well-designed laser cavity structure and a high quality optical filter with wide tunable range, narrow pass-band and low insertion loss are necessary. The excellent SLM selection capability and ultra-broadband tuning realizability of the multiple-ring structured compound cavity have been demonstrated previously[7-11]. Several widely wavelength-tunable/swept optical filters have been reported, including equivalent all-fiber Lyot filter[12], stretching/compressing-based fiber Bragg grating (FBG) filter[9], two-tapers-based Mach-Zehnder interferometer filter[13,14], single-mode biconic fiber taper filter[15], rotating polygon mirror[16], galvo scanned mirror[17], acousto-optic tunable filter[18], and fiber Fabry-Pérot tunable filter (FFP-TF)[6,19]. Among them, the fiber pigtailed FFP-TF has been already commercialized, and it can be driven by a selectable constant voltage or a periodic scanning voltage for fixed or swept pass-band running with a wide tunable range. However, an SLM EDFL using a compound cavity combined with an FFP-TF for either tunable or wavelength-swept operation has not yet been reported.

In this paper, we propose and experimentally demonstrate a novel tunable and wavelength-swept SLM fiber laser with high output performance of stability, linewidth, tunable/swept range and optical signal to noise ratio (*OSNR*). These advantages mainly benefit from the use of a high quality triple-ring subring-cavity[11] (TR-SC) and an FFP-TF in the laser cavity.

Fig.1 shows the configuration of the proposed EDFL which is structured by a main-cavity and a TR-SC. A 7-m-long EDF, pumped by a 980 nm laser diode (LD) through a 980/1 550 nm wavelength division multiplexer (WDM), is utilized as the gain medium. An optical isolator ensures the unidirectional oscillation in the main cavity. A broad-band in-line polarizer with the combina-

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tion of two polarizers (PC-1 and PC-2) is used to introduce polarization-dependent loss to suppress the mode competition and mode-hop significantly. An FFP-TF (Micron Optics FFP-TF2) with a 3 dB pass-band of 0.164 nm and a finesse of 652 is employed as the original mode restricting element, which can be driven by a manually-selectable constant voltage or a periodic sweep voltage for wavelength fixed or swept operation. The TR-SC is constructed by three optical couplers (two 80:20 couplers, OC-1 and OC-2, and one 50:50 coupler, OC-3). OC-1 and OC-2 keep 80% energy reserved inside the subring cavity. Three couplers form three nested rings (ring-1, ring-2 and ring-3) with the lengths of 1.36 m, 0.90 m and 1.02 m, respectively, producing corresponding free spectrum ranges (*FSRs*) of 150 MHz, 230 MHz and 200 MHz, respectively. One 50:50 coupler (OC-4) is utilized to extract the laser for measurement. The FFP-TF2 is placed in front of the OC-4 to enable the maximal *OSNR*. The length of the main cavity is approximately 18.5 m, indicating that the longitudinal mode spacing is 11.0 MHz.

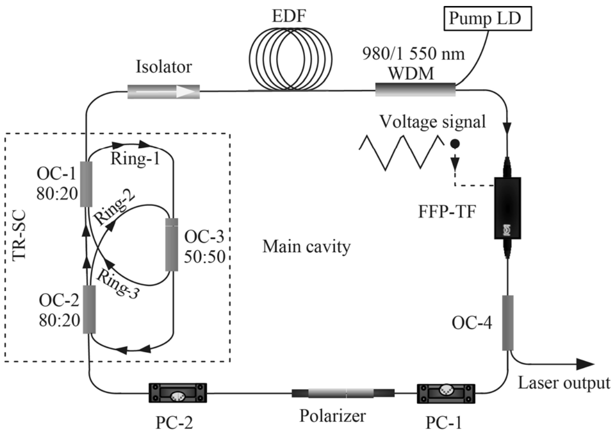

Fig.1 Experimental configuration of the proposed EDFL

Compared with the Type-1 and Type-2 ring cascaded secondary cavity[9] or Type-1 and Type-2 ring nested subring cavity[20], the TR-SC is lossless with the exception of the insertion loss of approximately 0.2 dB for each coupler only. The principle of SLM selection from the dense main cavity longitudinal modes using the TR-SC is explained as follows. On the one hand, according to the *FSRs* of three rings, the effective *FSR* of the TR-SC, calculated based on the Vernier effect[21], is approximately 13.8 GHz (~0.110 nm at 1 550 nm band), which is 0.67 times of the pass-band of FFP-TF2; On the other hand, according to the coupling ratio and insertion loss of 0.2 dB for each used coupler and ring-1 length of 1.36 m, the calculated 3 dB pass-band of the TR-SC can be approximately 11.4 MHz[20], which is slightly larger than the mode spacing of 11.0 MHz of the main cavity. On the basis of above effects, the TR-SC guarantees at least one and only one longitudinal mode located in the pass-band of the FFP-TF2, with all the time either in manual-tuning or wavelength-swept operation for the EDFL[9].

Keeping the pump power at 150 mW and the FFP-TF2 without being driven, we can obtain single wavelength operation with high stability and high *OSNR* by adjusting the PCs appropriately to control the light gain and loss in the cavity. The typical optical spectrum of the laser output is shown in Fig.2(a), measured by an optical spectrum analyzer (OSA, Yokogawa AQ6370C) with a resolution of 0.02 nm. The ultra-high *OSNR* of 72 dB is achieved, benefiting from the excellent laser resonant cavity configuration. Fig.2(b) shows the spectra of 10 times of repeated OSA scans with an interval of 20 min. The wavelength fluctuation and power fluctuation are less than 0.01 nm and 0.05 dB, respectively during the 3 h experimental time, indicating that the EDFL is lasing with high stability.

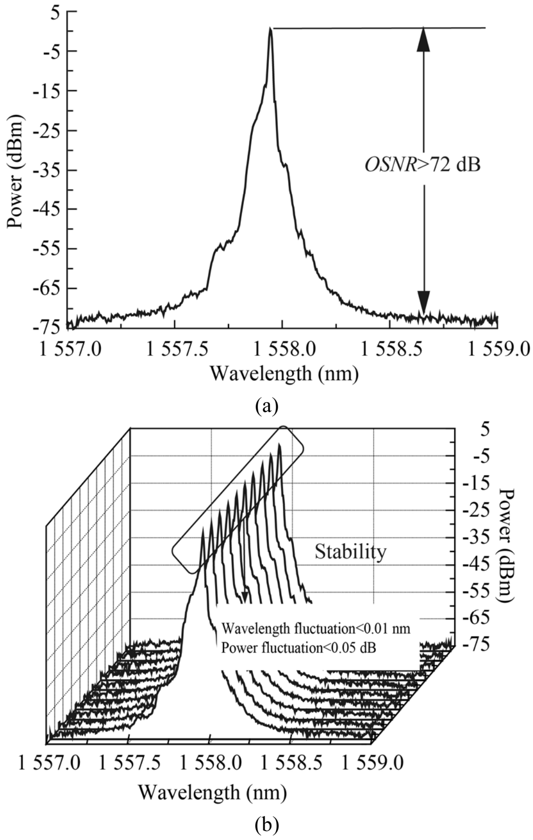

Fig.2 Optical spectra lasing at a fixed single wavelength: (a) Typical spectrum; (b) 10 times of repeated OSA scans with an interval of 20 min

The SLM operation and laser linewidth characteristics are investigated by the delayed self-heterodyne measurement system (DSHMS) composed of a 400 MHz photo-detector (PD), a Mach-Zehnder interferometer with a 200 MHz acoustic optical modulator and a 100-km-long SMF-28 fiber in two arms respectively, and a radio frequency (RF) electrical spectrum analyzer

(ESA, Keysight Technologies N9010A). Fig.3(a) proves that the EDFL is in stable SLM operation without mode-hop, because there is only one strong beating signal captured at 200 MHz, which is generated by the delayed laser and the frequency-shifted laser. To get the fine details of the laser linewidth, Fig.3(b) gives the beating signal measured in 199.90—200.10 MHz range with a higher ESA resolution. The measured data is fitted by the Lorentz line shape, and a 9.46 kHz for 20 dB bandwidth of the curve is obtained. That means the EDFL is with an ultra-narrow linewidth of 473 Hz calculated by the 1/20 of the 20 dB bandwidth[22].

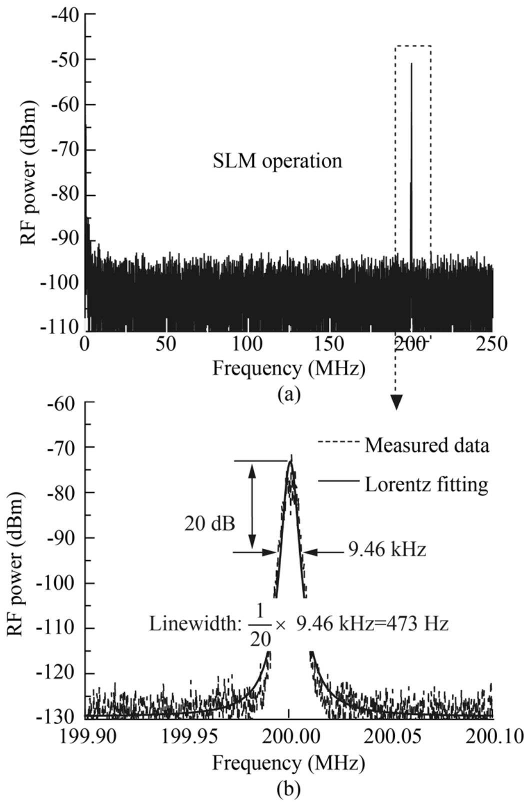

Fig.3 RF beating spectra measured by DSHMS: (a) In 0—250 MHz range with a 10 kHz resolution bandwidth; (b) In 199.90—200.10 MHz range with a 100 Hz resolution bandwidth

The broadband manual-tunability of the EDFL is achieved by applying different voltages on the FFP-TF2 to shift its pass-band, which is generated from a stabilized DC source. As shown in Fig.4, the lasing wavelength can be tuned over 54 nm from 1 572 nm to 1 518 nm, when the voltage is tuned from 11.5 V to 22.0 V. The corresponding tuning efficiency is approximately 5.1 nm/V. The tunable range of the EDFL has almost covered the whole amplified spontaneous emission spectrum of the used EDF. The laser linewidth is also measured simultaneously when the lasing wavelength is tuned, and it keeps at about 500 Hz across the entire tuning range.

Our EDFL can also operate in wavelength-swept mode when a swept voltage signal is applied on the FFP-TF2, as shown in Fig.5 and Fig.6. The swept voltage is generated by a self-designed driving circuit to provide triangular voltage with a tunable sweep rate from 10 Hz to 200 Hz. We adjust the offset voltage to 10 V and peak-to-peak voltage to 13 V, and generated four triangular swept voltages in turn with the speeds of 20 Hz, 50 Hz, 100 Hz and 200 Hz, respectively, as shown in Fig.5, to drive the FFP-TF2.

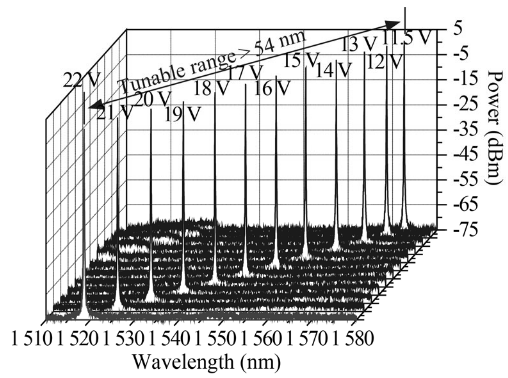

Fig.4 Wavelength manual-tunability of the EDFL when the voltage applied on the FFP-TF is tuned from 11.5 V to 22.0 V

Fig.6 shows the corresponding laser spectra at four sweep rates, when the OSA scans many times in a maximum-hold mode. No synchronization is implemented between the OSA scanning and the laser wavelength-sweeping. The wavelength sweep range is larger than 50 nm for all the four kinds of swept voltage signals. However, it slightly decreases with the increase of the sweep rate. It is also observed that the power of the maximum-hold spectrum decreases when the sweep rate increases due to the integral time of the maximum-hold function of the OSA. When the sweep speed is below the reciprocal of the integral time, the maximum is updated in each sweep period. That means the decrease of the laser peak power may not occur really when the voltage sweep rate is increased. In addition, we have also measured the RF noise spectrum over 0—400 MHz, as shown in Fig.7, using the self-homodyne system when the laser is sweeping at 100 Hz. There is no beating or high frequency RF component captured, indicating that the EDFL can maintain SLM operation even running in the sweep mode. Due to the lack of an efficient method to measure the dynamic linewidth of the swept laser, we could not investigate the linewidth properties during the EDFL operation in sweep mode. The characteristics of sweep range and speed of the EDFL could be further improved by using semiconductor optical amplifier as gain medium and using good swept-voltage-driving-sources with high speed and low noise.

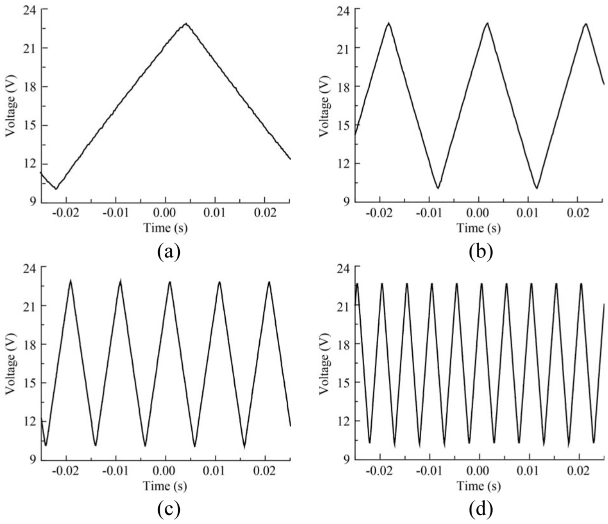

Fig.5 Different triangular swept voltage signals with the sweep rates of (a) 20 Hz, (b) 50 Hz, (c) 100 Hz and (d) 200 Hz, respectively

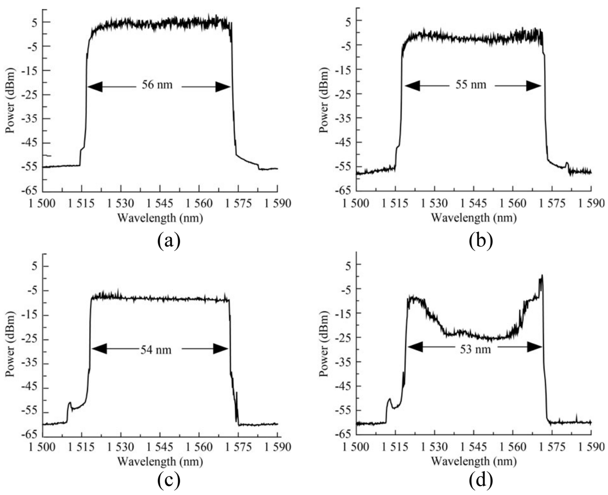

Fig.6 Typical laser spectra when swept voltages are applied on the FFP-TF2 with the sweep rates of (a) 20 Hz, (b) 50 Hz, (c) 100 Hz and (d) 200 Hz, respectively

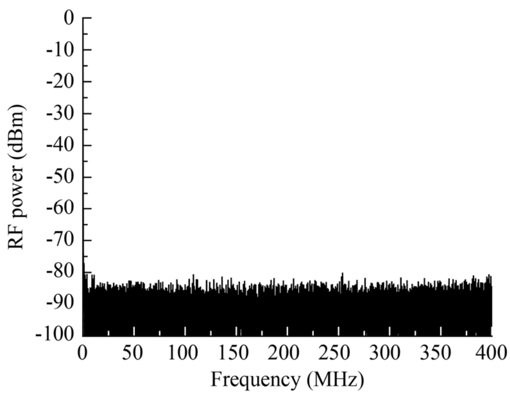

Fig.7 RF beating spectra measured by the self-homodyne system in swept mode with a triangular voltage sweeping at 100 Hz

In summary, we have proposed and demonstrated an SLM EDFL, which can operate either at fixed wavelength with wide tunable range or in widely wavelength-swept mode with a tunable sweep rate. Using a novel TR-SC with the combination of an FFP-TF to select SLM from dense main cavity longitudinal modes, the EDFL has good performance. In the fixed wavelength operation mode, the EDFL has a tunable range more than 54 nm, an ultra-narrow linewidth of 473 Hz, an ultra-high *OSNR* more than 72 dB, and the tuning efficiency is about 5.1 nm/V. In the wavelength-swept mode, the EDFL has a tunable sweep rate range of 10—200 Hz and a sweep range of more than 50 nm, and it can always operate in stable SLM. The excellent features enable the proposed EDFL to find wide applications in high-resolution spectroscopy and fiber optic sensing.

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