A nonlinear optical loop mirror-based linear cavity switchable multi-wavelength erbium-doped fiber laser*

HUANG Ben (黄奔), MENG Hong-yun (蒙红云), WANG Hui-hao (王惠壕), WANG Qing-hao (王庆豪), ZHANG Xing (张星), YU Wei (余伟), TAN Chun-hua (谭春华), and HUANG Xu-guang (黄旭光)**

Guangdong Provincial Laboratory of Nanophotonic Functional Materials and Devices, School for Information and Optoelectronic Science and Engineering, South China Normal University, Guangzhou 510006, China

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A nonlinear optical loop mirror (NOLM)-based linear cavity switchable multi-wavelength erbium-doped fiber (EDF) laser is proposed and experimentally demonstrated. Due to the characteristics of the intensity-dependent transmissivity, the NOLM can effectively mitigate the mode competition of the homogenous broadening gain medium, so that the multi-wavelength lasing can be achieved at room temperature. By adjusting the states of the polarization controllers (PCs), the number of the lasing wavelengths in the proposed laser can be adjusted flexibly from 11 to 13 with a wavelength spacing of 0.4 nm around the wavelength of 1 530 nm.

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Multi-wavelength fiber laser has given rise to great research interest for its widespread applications in wavelength division multiplexing (WDM) transmission systems, optical sensors, optical measurement and so on. In particular, multi-wavelength erbium-doped fiber (EDF) lasers have attracted much attention in recent years due to the characteristics of low threshold, broad gain bandwidth and high power conversion efficiency. However, the major barrier for multi-wavelength EDF lasers to attain stable multi-wavelength lasing at room temperature is the fierce mode competition. One straight method is to cool the EDF in liquid nitrogen to alleviate the homogeneous gain broadening effect[1]. Obviously, this technique is not suitable for the practical applications. Hence, others methods have been proposed to alleviate the mode competition, such as adding a frequency shifter or a phase modulator in the oscillation cavity to avoid the single mode operation[2,3], inserting a semiconductor optical amplifier to introduce the inhomogeneous broadening gain[4], using nonlinear gain of cascaded stimulated Brillouin scattering or stimulated Raman scattering in the laser cavity to compose hybrid gain fiber laser[5-8], providing four-wave-mixing to even amplitude of simultaneous multi-wavelength oscillation[9,10] and utilizing nonlinear polarization rotation to induce intensity-dependent loss (IDL) for multi-wavelength oscillations[11,12]. But all these techniques inevitably add the excess complexity and the cost to the multi-wavelength lasers. In contrast, the nonlinear optical loop mirror (NOLM), which only consists of a polarization controller (PC), a segment of single-mode fiber (SMF) and an optical coupler, has the characteristics of simple constitution and costless components[13-15].

In this paper, we propose and experimentally investigate an NOLM-based linear cavity switchable multi-wavelength EDF laser. The NOLM can effectively provide the IDL, which can mitigate the mode competition in the gain media of EDF and result in the multi-wavelength output at room temperature. A polarization maintaining fiber (PMF)-based Sagnac interferometer, which includes a PC, a segment of PMF and a 3 dB optical coupler, serves as the comb filter. By adjusting the PCs in the NOLM and the Sagnac interferometer, 11 to 13 lasing wavelengths can be gained at room temperature, which is more than that in Refs.[11] and [16-18]. It is revealed that our linear system is more suitable for producing multi-wavelength lasing.

The proposed NOLM-based linear cavity switchable multi-wavelength EDF laser, as shown in Fig.1, consists of a pump optical source, a WDM coupler, a segment of EDF to offer the gain, an NOLM and a fiber Sagnac interferometer. The NOLM and the Sagnac interferometer make up the linear lasing cavity. The EDF with a length of 10 m plays a role of the gain medium. The Sagnac interferometer, which includes a segment of PMF, PC1 and a 3 dB optical coupler, severs as the output port as well. The NOLM, which consists of a 2.1 km-long conventional SMF, PC2 and a 3 dB optical coupler, acts as an amplitude equalizer. The PCs in the loops are used for polarization biasing. The output spectrum characteristics of the laser are monitored by an optical spectrum ana-

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** E-mail: hymeng@scnu.edu.cn

lyzer (OSA) with a resolution of 0.02 nm.

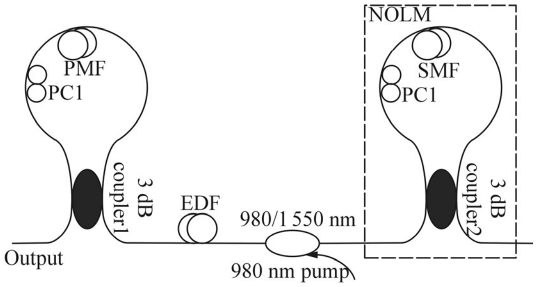

Fig.1 Schematic diagram of the proposed multi-wavelength laser

First of all, the transmission characteristics of the fiber Sagnac interferometer are investigated theoretically and experimentally. A phase difference between the fast and slow components of the light transmitting in the fiber Sagnac loop is caused by the birefringence of the PMF, which results in the interference between the two counter-propagating light waves. By adjusting the PC1 in the loop, the interference pattern can provide a multi-wavelength comb filter function. The wavelength interval of the comb filter is given by[19]

$$\Delta\lambda = \frac{\lambda^2}{\Delta nL}, \tag{1}$$

where Δn and L are the refractive index difference between the fast and the slow axes and the length of the PMF, respectively. According to Eq.(1), it is notable that the wavelength interval only depends on the PMF and is inversely proportional to the length and the refractive index difference of the PMF. For a further study, the measured reflection spectrum of the fiber Sagnac interferometer is shown in Fig.2, which is in accordance with our previous work[11]. The comb filter is achieved, and the wavelength interval is 0.4 nm. In this experiment, the length and the refractive index difference of the PMF used in the experiment are 10 m and 6.54×10^{-4}, respectively. Correspondingly, the wavelength interval of the comb filter is 0.4 nm in theory, which agrees with the experimental result.

The working principle of the NOLM is analyzed in detail as follows. The different nonlinear phase shifts will form when the light propagates in the NOLM due to the Kerr effect of the SMF. Further, the rotation of the polarization state can be accumulated in the SMF, and depends on the light intensity. As a result, the PC2 and the SMF form an intensity-dependent component. By adjusting the PC2, the two different states of saturable absorber (SA) and amplitude equalizer can be achieved due to the relation between the transmissivity and the intensity. In other words, the transmissivity of the NOLM can be varied with the input light power as the polarization state of the PC2 changes. Therefore, the NOLM can operate as an SA to generate passive mode-locking pulse output when the PC2 is adjusted to be at the state where the transmissivity increases with the signal power increasing. On the contrary, the NOLM can work as an amplitude equalizer to mitigate the mode competition when the PC2 is adjusted to be at the state where the transmissivity decreases with the signal power increasing. Consequently, the multi-wavelength oscillations can be attained when the IDL induced by the NOLM matches with the mode competition in the cavity.

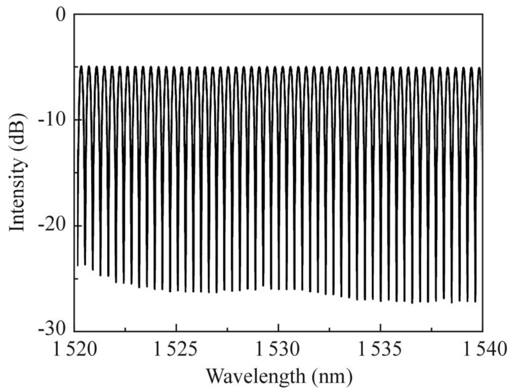

Fig.2 The measured reflection spectrum of the Sagnac interferometer

In the experiment, a 980 nm laser diodes (LD) and a 980/1 550 nm WDM coupler are used. The maximum output power of the 980 nm LD is 250 mW. At first, the output power of the LD is increased to 200 mW and fixed. Then the PC1 is rotated to the position and fixed, where the fiber Sagnac interferometer can get a comb output. By changing PC2, the multi-wavelength oscillation can be attained around 1 530 nm, as shown in Fig.3. As a result, a 13-line lasing is achieved with the bandwidth of 6.4 dB. The wavelength spacing and the side mode suppression ratio (SMSR) are 0.4 nm and 26 dB, respectively. By appropriately adjusting the PC2, the number of the lasing wavelengths is decreased, as shown in Fig.4. With the bandwidth of 4.9 dB, the 12-line lasing is gained, and the SMSR is 27 dB. With further carefully adjusting the PC2, the evenness of multi-wavelength lasing can be improved as shown in Fig.5. An 11-line lasing is achieved with the bandwidth of 3 dB, and the SMSR increases to 27.4 dB. The experimental results indicate that the fluctuation of the lasing wavelength power decreases, and the SMSR increases as the number of the lasing lines decreasing. As far as we know, this is the first time to report the NOLM-based linear cavity switchable multi-wavelength EDF laser. It is worth noting that an optimum length of the SMF in the NOLM should be selected to attain the multi-wavelength lasing. In the experiment, SMFs with different lengths of 1 km, 2.1 km, 5 km and 10 km are used in the NOLM, respectively. As a result, the best performance can be gained when the length of the SMF is 2.1 km. Compared with our previous work[11], the proposed laser has more lasing wavelengths with channel spacing of 0.4 nm and less cost, in which the expensive polarization-dependent isolator and optical circulator are not used.

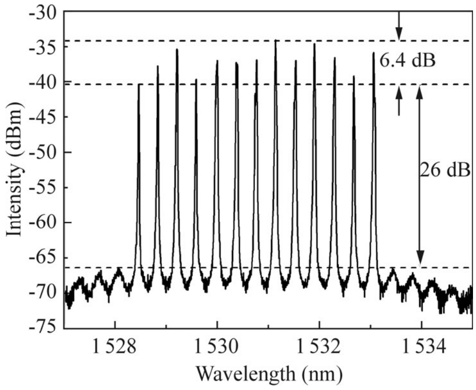

Fig.3 Output spectrum of the proposed laser in 13-line lasing operation

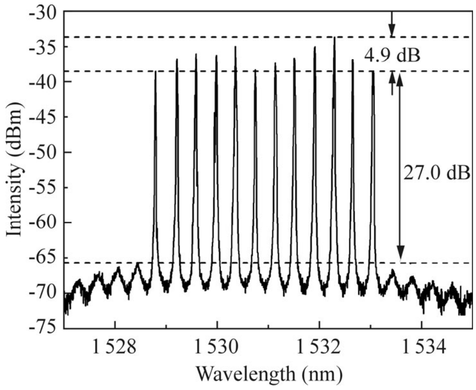

Fig.4 Output spectrum of the proposed laser in 12-line lasing operation

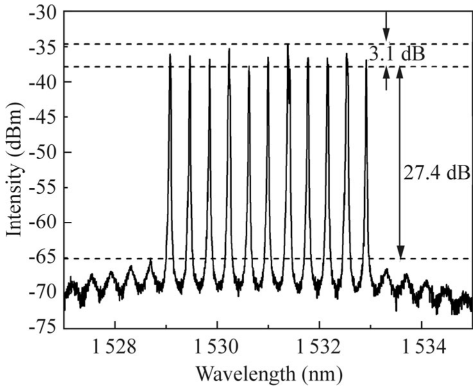

Fig.5 Output spectrum of the proposed laser in 11-line lasing operation

In order to confirm the stability of the proposed laser, we repeat the scanning of the power fluctuation and the wavelength drift of the channels of 1 532.93 nm, 1 530.63 nm and 1 528.70 nm in the 12-line laser state with interval of 3 min within 30 min, as shown in Fig.6. The results show that the maximum power fluctuation is smaller than 2.2 dB, and the wavelength shift is less than 0.08 nm. In our opinions, the power fluctuation is mainly caused by the stability of pump optical source's polarization state, the vibration of the experimental platform and the performance of the passive devices. Those factors can affect the polarization states of the fiber laser, so the power of lasing wavelengths and the stability of the proposed laser are affected. By using the high performance devices and the package, the stability of the proposed laser can be improved.

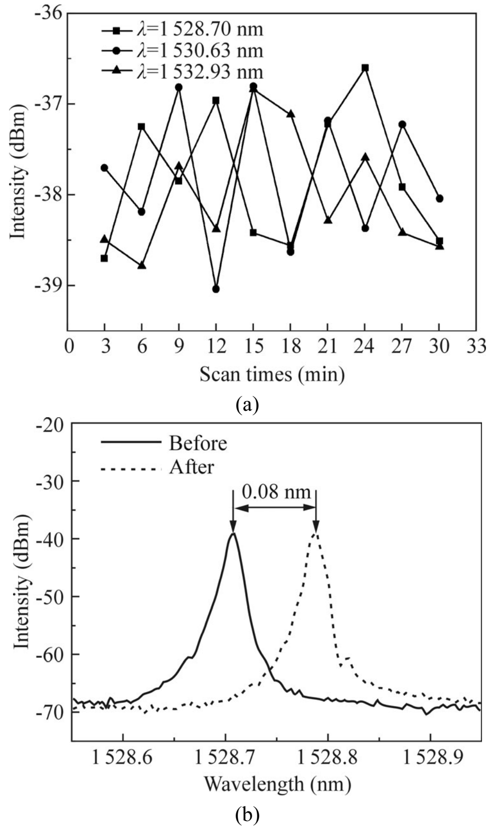

Fig.6 (a) Power variations and (b) wavelength drifts of three individual channels within 30 min

In conclusion, an NOLM-based linear cavity switvchable multi-wavelength EDF laser is proposed and demonstrated experimentally. By adjusting the PCs, the multi-wavelength lasing can be achieved, and the number of output wavelengths can be changed flexibly from 11 to 13. As a result, 11-line lasing operation with bandwidth of 3.1 dB and an SMSR of 27.4 dB is attained experimentally. The experiment results indicate that the proposed laser can stably operate at room temperature.

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