A widely tunable fiber ring laser with closed loop control based on high-precision stepper motor*

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A tunable single-longitudinal mode erbium-doped fiber ring laser based on stepper motor and closed loop control is proposed and demonstrated. The system consists of an erbium-doped fiber (EDF), a tunable fiber Bragg grating (FBG) filter and a wavelength detector. The characteristics of output laser, such as output power, power stability and 3-dB linewidth, are investigated in the operation range of 1 531—1 569 nm. The repeated experimental results of the fiber laser show that the 3-dB linewidth is less than 17 ps, the side-mode suppression ratio (*SMSR*) is up to 60 dB, the output power is up to 1.37 dBm, and the power variation is less than 0.61 dB.

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The tunable fiber ring laser have attracted much research interest in optical fiber communication system and fiber sensors[1-3] because of their potential advantage, such as tunable wavelength, high output power and high efficiency of energy transformation. The tunable optical filter [4,5] is a kind of most important devices for tuning the output longitudinal mode of the fiber laser, and the Fabry-Perot (FP) filter[6,7], dielectric thin-film (DTF) interference filter[8], acousto-optic tunable filter (AOTF)[9,10] and optical fiber grating filter[11,12] are commonly used as tunable optical filters. Compared with other approaches, such as magnetically tunable fiber Bragg gratings[13] and mechanically tunable fiber Bragg gratings[14], the laser based on stepper motor and closed loop control has better power stability and wavelength stability. A wavelength-tunable (1 522—1 573 nm) laser with side-mode suppression ratio (*SMSR*) of 68 dB was reported[15], but its wavelength shift is less than 2 pm in 75 min.

The output wavelength and power of the fiber lasers are usually affected by the surrounding environment and the jitter of pump current, so the fiber laser based on closed loop control[16,17] was proposed to minimize the error between the control and output process induced by any known and unknown interferences. Coherent beam combination of fiber laser was presented in Ref.[16]. The amplified laser beam from the seed laser was split into four beams and coupled to four phase modulators, and the laser power was coupled out using a collimator which provided partial laser power for feedback inside the photodetector. The fringe contrast of far-field intensity pattern was improved by more than 85% from 8% in open loop, and the residual phase error is less than $\lambda/20$ when the phase control system was in the closed loop.

Here we demonstrate an electronically wavelength-tunable and single-frequency erbium-doped fiber ring laser with closed loop control. The system is achieved by tuning the reflective wavelength of the optical fiber Bragg grating (FBG). The characteristics of output laser, such as the output power, 3-dB linewidth and power stability, are investigated in the operation range of 1 531—1 569 nm. The experimental results show that the output power is up to 1.37 dBm, the 3-dB linewidth is less than 17 ps, and the power variation is less than 0.61 dB. So the proposed fiber laser can be used as special light source in the system of distributed optical fiber sensors to realize long-distance coherent detection because of its narrow linewidth and high tuning stability.

The schematic diagram of the proposed wavelength-tunable and single frequency fiber laser with ring cavity is shown in Fig.1. The system mainly consists of the optical subsystem and main control subsystem. The optical subsystem is composed of the fiber laser with ring cavity, the tunable FBG filter and the wavelength detector.

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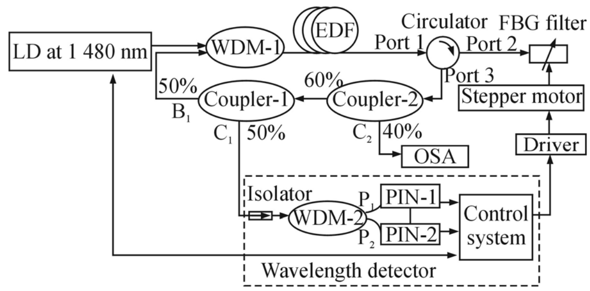

Fig.1 Schematic diagram of the tunable fiber ring laser based on stepper motor and closed loop control

The fiber laser with ring cavity comprises a 1 480 nm laser diode (LD) at 1 480 nm produced by JDS Uniphase Corporation, a 1 480/1 550 nm wavelength diversion multiplexer (WDM-1), an FBG-based FP filter as an original wavelength selector, a 50:50 coupler-1, a 60:40 coupler-2 and an optical circulator used as a cavity reflector to enable the FBG-based FP filter serving as a transmission filter. The erbium-doped fiber (EDF) with length of 6 m, numerical aperture of 0.23 and diameter of 125 μm is supplied by Yangtze Optical Fiber and Cable Company Ltd. Its absorption coefficient at 1 530 nm can reach 22 dB/m, which is much higher than that of ordinary EDF (about 3 dB/m). This high absorption means high gain, which is beneficial to the increase of output power.

The tunable FBG filter comprises an FBG and its package structure, a one-dimensional moving table, the connector, the stepper motor with 256 subdivisions and its driver circuit. The linear tuning range of the FBG is 38 nm (1 531—1 569 nm), and its reflectivity is maintained at the value higher than 70% even when the FBG filter is tuned to the maximum bandwidth in the range. The laser power is coupled out using the combination of 50:50 coupler-1 and 60:40 coupler-2, which provides 40% of laser power (C_2 port of coupler-2) for the output to the optical spectrum analyzer (OSA), 30% of laser power (60%×50%, B_1 port of coupler-1) for feedback inside the cavity, and another 30% of laser power (60%×50%, C_1 port of coupler-1) for wavelength detection in the main control subsystem to activate the closed loop control system for stabilizing the output wavelength .

The center wavelength of FBG is shifted by means of mechanical axial strain in our system configuration. The step motor is designed specially to realize 256 subdivisions, and each step angle is 1.8°/256≈0.007° considering the less compression axially of the fiber grating. The current flows into electric motors which drive the connector, and the connector brings external mechanical strain to the FBG which causes the wavelength variation. The output laser spectrum with wavelength tuning from 1 549.32 nm to 1 546.28 nm is realized by using 5 000 drive pulses in our experiments.

In the running stage, an EDF with length of 6 m is pumped by the 1 480 nm LD, Er^{3+} in the EDF is pumped to the atomic state $^4I_{13/2}$ firstly and then is radiated to the ground state $^4I_{15/2}$ in the form of non-coherent radiation, so the optical spectrum in the range of 1 530 nm—1 570 nm is produced. In addition, only the mode reflected by the optical filter can have a lasing emission, and the laser frequency can be adjusted by varying the center frequency of the optical filters. The laser power is coupled by using the combination of 60:40 coupler-2 and 50:50 coupler-1. 30% of laser power is provided for feedback inside the cavity to generate the amplified laser output (C_2 port of coupler-2) when the pump power is much higher than the threshold power of the fiber laser, which means system gain is higher than system loss.

The wavelength detector comprises an isolator, WDM-2, PIN-1 and PIN-2 detectors, and the control module which can receive and analyze the photoelectric conversion signal.

The coupling degree of fused-tapered WDM is defined as the ratio of the power output from one optical port P_1 or P_2 to the total power output from two optical ports P_1 and P_2 as shown in Fig.1, and it is related to the condition of waveguide in the tapered region. The coupling degree of WDM is a sine function of wavelength λ, which can be expressed as[18,19]

$$\gamma(\lambda)=\gamma_0\left\{1+\sin\left[\frac{2\pi}{\Delta\lambda}(\lambda-\lambda_k)\right]\right\}=\frac{P_2}{P_1+P_2}, \tag{1}$$

where $\Delta\lambda$ is the coupling period, $2\pi/\Delta\lambda$ is phase parameter, and λ_k is the reference wavelength.

The laser wavelength λ can calculated according to the coupling degree of WDM-2 $\gamma(\lambda)$ which is firstly get by the main control system through the photoelectric conversion signals of PIN-1 and PIN-2, and then compensation and correction are done repeatedly by accurately tuning the step motor with 256 subdivisions for obtaining the output wavelength approaching the input wavelength to stabilize the output wavelength.

The reflective spectrum of the fiber laser is shown in Fig.2. The central wavelength is at 1 558.80 nm, the *SMSR* is up to 60 dB, the peak power is 1.37 dBm, and 3-dB bandwidth is 17 ps. The reflective wavelength of FBG shifts when an axial strain is applied at the FBG by the stepper motor, and then the output laser wavelength changes. In order to give a clear display of the tuning process, a wavelength spacing of 2 nm is selected for recording, and the output spectra are shown in Fig.3. The initial wavelength is 1 531.12 nm, the final one is 1 569.14 nm, and the whole tunable range covers about 38 nm in C band. The maximum and minimum output power values are 1.38 dBm and 1.13 dBm at the wavelength of 1 556 nm and 1 538 nm, respectively, as shown in Fig.3. The low power variation benefits from the closed loop control and the gain flatness of the tunable FBG which is higher than 30 dB. The narrow linewidth and single-longitudinal mode fiber laser leads to high coherence, long coherence distance, low transmission dispersion and long transmission distance. The linewidth of fiber laser is one-hundred-thousandth of that of commercial source, which helps to minimize the space of channels and increase the number of channels.

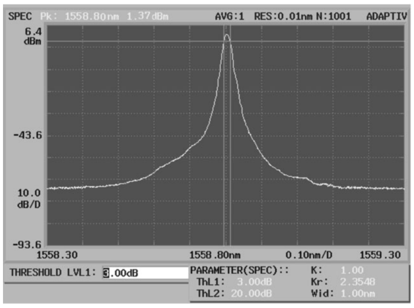

Fig.2 The optical spectrum of tunable fiber ring laser at wavelength of 1 558.80 nm

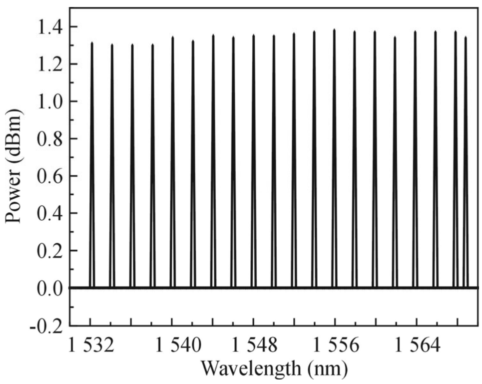

Fig.3 Output spectra of the tunable fiber ring laser with the wavelength tuning from 1 532 nm to 1 569 nm

Fig.4 shows the output power of the laser with the wavelength tuning from 1 531 nm to 1 569 nm. The output power fluctuates slightly between 1.38 dBm and 1.13 dBm which can be used in system of optical soliton communication and space communication to realize long-distance and error-free communication. The power stability of fiber laser at 1 558.8 nm is investigated as shown in Fig.5. The laser is observed every 5 min for 2 h in the laboratory. When the pump power remains unchanged without respect to the temperature variation, the peak and dip power values are 1.67 dBm and 1.06 dBm, respectively, and the power fluctuation is less than 0.61 dB. The repeated testing results show that the fiber laser also has high power stability at wavelength 1 560.01 nm when the pump power is changed from 3.2 dBm to 15.3 dBm.

The reflective wavelength of the FBG shifts when an axial strain is applied at the FBG by the stepper motor driven by laser pulse. Fig.6 shows the EDF laser output wavelength dependence on the driven pulse number *N*. In order to give a clear display of the tuning process, the results are recorded with a pulse number spacing of 500 as shown in Fig.6. The laser wavelength is tuned from 1 569.14 nm to 1 531.12 nm when the driven pulse number of stepper motor increases from 0 to 27 500, and the whole tunable wavelength range covers about 38 nm. The results shown in Fig.6 are tested in two days. It can be seen from Fig.6 that the output laser wavelengths in twice experiments do not coincide completely, especially with the pulse number ranging from 11 000 to 15 000. This might be caused by the mini-transmutation of the one-dimensional moving table affected by the reversed stress or the transverse strain applied by the stress. So the desired output wavelength can be decided by the pulse number when the wavelength tolerance is high and tunable wavelength range is small.

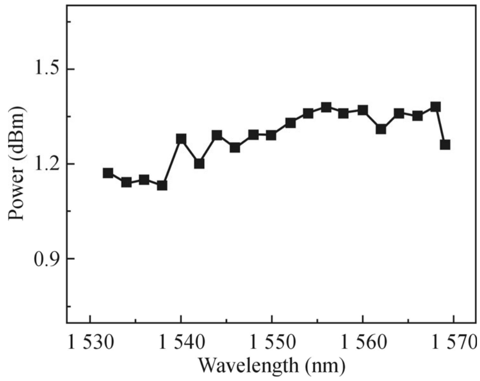

Fig.4 Variation of the output power with wavelength tuning from 1 530 nm to 1 569 nm

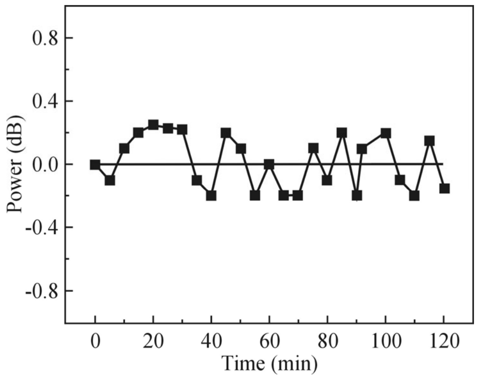

Fig.5 Variation of the laser power at wavelength of 1 558.8 nm in 2 h

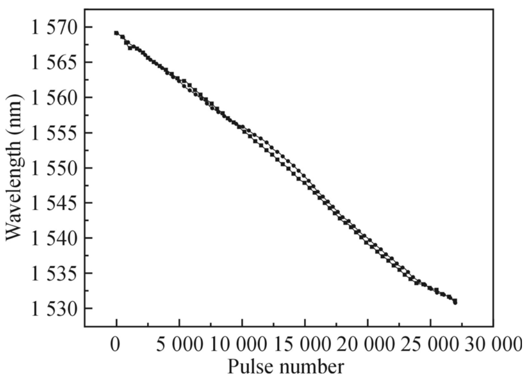

Fig.6 The output wavelength dependence on the driven pulse number of stepper motor for twice experiments in two days

In summary, a tunable narrow-linewidth erbium-doped ring laser using tunable FBG controlled by the 256 stepper motor is proposed and demonstrated. An approximately continuous tunable lasing output can be obtained, and the wavelength tunable range covers 38 nm from 1 531.12 nm to 1 569.14 nm. The repeated testing results show that the 3-dB linewidth is less than 17 ps, the output power is 1.37 dBm, and the power variation is 0.61 dB. The narrow linewidth fiber laser benefits coherence detection over long distance in distributed optical fiber sensor system.

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