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# Tunable Yb-doped fiber laser with a Mach-Zenhder Interferometer

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**Abstract** A ring-shaped all fiber tunable Yb-doped fiber laser with tuning range over 20 nm is demonstrated by using a fiber Mach-Zenhder interferometer as an intra-cavity filter which is constructed with two 3-dB optical couplers. The method for fabricating the fiber Mach-Zenhder interferometer is detailed. The fiber laser has a moderate milli-Watt level output power over the whole tuning range from 1050 to 1071 nm, a side-band suppression ratio greater than 45 dB, and a bandwidth less than 0.1 nm.

Key words tunable fiber laser; ring-shaped fiber laser; ytterbium doped fiber; Mach-Zenhder Interferometer

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Continuous wave (CW) and pulsed high-power fiber lasers have been progressing greatly in the recent years[1~2]. Among all the high-power fiber lasers, the Yb-doped fiber lasers are especially important mainly for their high power level and high efficiency. These fiber lasers can be adopted as the fundamental pumping source of the secondary laser light to achieve harmonic generation or parametric conversion. This is mainly taken into consideration of the high beam quality associated with the fiber laser. Fiber lasers can realize a reasonable wide tunability, for example, about 100 nm for the Er-doped fiber laser, but are limited to this[3]. Compared with fiber lasers, optical parametric oscillator (OPO) is a kind of tunable laser which can offer much wider tunability in the infrared region[4]. Normally, the tuning wavelength of the OPO can be realized by adjusting the phase matching angle of the nonlinear crystal included or the grating period of some periodically domain reversed nonlinear optical crystal such as PPLN and PPMgLN[4]. The output of OPO can be tuned swiftly with the pumping wavelength if the pump laser is widely tunable, which can be either a solid-state laser or a fiber laser. Thus, an OPO pumped by a master-oscillator power amplifier (MOPA) structured tunable Yb-fiber laser will have a swift wide tunability[5].

Referring to the previous works tuning wavelength of the erbium-doped fiber laser can be realized in many ways, including the usage of a fiber Fabry-Perot (FFP) tunable filter[6], a widely tunable fiber Bragg grating[7], and a multilayer thin-film interference bandpass filter[8]. These grating or filters used in erbium-doped fiber laser systems are commercially available and are generally cost effective. For example, FFP tunable filters working at 1550 nm band can have a free spectral range (FSR) over 100 nm and thus make an Er-doped fiber laser easily cover a wide tuning range[9].

Compared with the method mentioned above, the tuning approach for a Yb-doped fiber laser working at 1-μm band is difficult to be implemented due to the limitation of intro-cavity filters near 1-μm wavelength region. The FFP filter working at 1-μm is much more expensive than that working at 1.5 μm, and also suffers from a narrow tuning range. Although an external cavity wavelength tunable Yb-doped fiber laser was reported which used an acousto-optic filter as a tunable filter[10], it involved bulk optical components and was too complicated for usage. In addition, a Yb-fiber laser constructed with tunable FBGs has shown a good performance covering a wide tunable range of 45 nm[11]. However, its long-term sustainability needs further testing as the high strain applied to the FBG may possibly injure the FBG itself.

In this paper, we present our recent work on

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the development of a continuously tunable Yb-fiber laser, which is constructed by using a Mach-Zenhder interferometer as an intra-cavity filter. The Mach-Zehnder interferometer served as the tuning element to decide the oscillating wavelength of the laser. This all-fiber laser was comprised of only pieces of ordinary optical components and could thus be easily constructed. It provides the possibility of developing a compact cost effective diode-laser pumped tunable fiber laser with high tuning rate, medium power, and narrow linewidth near 1 μm. Such a laser can serve as the seed source of the high power Yb-fiber amplifier with a wide tunability. It would be suitable for all-fiber $Q$-switched ring laser systems which are attractive laser sources for ranging, altimetry and lidar[12]. The fiber laser has a moderate milli-Watt level output power over the whole tuning range from 1050 to 1071 nm, a sideband suppression ratio greater than 45 dB, and a bandwidth less than 0.1 nm. It can thus serve as a compact seed source of a MOPA structured cladding pumped high power Yb-doped fiber amplifiers to achieve a wide tunability.

The structure of the ring-shaped tunable fiber laser is schematically depicted in Fig. 1. The laser resonator was comprised of a piece of Yb-doped fiber with length of 1 m and a Mach-Zehnder interferometer which was simply constructed by using two 3-dB optical couplers with central wavelength at 1064 nm. The Yb-doped fiber acting as the gain medium had an absorption coefficient of about 45 dB/m at 976 nm with core and cladding diameters of 4 and 125 μm, respectively. A fiber pigtailed laser diode (LD) working at 976 nm with the maximum output power of 100 mW was spliced to the ring cavity as the pumping source via a 980/1060 nm wavelength division multiplexing (WDM) coupler. An optical isolator was incorporated in the ring cavity to ensure the laser a unidirectional traveling wave operation. A fiber polarization controller was also included in the cavity to compensate for the residual birefringence of the resonator elements. The laser emission output was extracted from a 10:90 output coupler with central wavelength at 1064 nm. The laser output spectrum was monitored and measured by using an optical spectrum analyzer (OSA, AQ6317C from Ando).

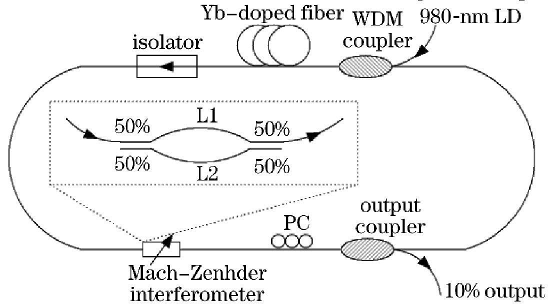


Fig. 1 Schematic diagram of the ring shaped Yb-doped fiber laser with the Mach-Zehnder interferometer

The inclusion of the fiber Mach-Zehnder interferometer in the ring-shaped fiber laser was essential to realize stable wide tunability. The characteristics of a fiber Mach-Zehnder interferometer in a ring-shaped fiber laser was once investigated when it was adopted to generate mulit-wavelength laser output in an Er-doped fiber laser[10]. In general, the path-lengths of the two interferometer arms are not equal, as shown in Fig. 1. The phase difference of the light beams passing through the two arms of the Mach-Zehnder interferometer is given by[13]

$$\varphi = \beta_0 (L_1 - L_2) = \beta_0 \Delta L, \qquad (1)$$

where $\beta_0$ is the propagation constant of the light in an optical fiber, $\Delta L = (L_1 - L_2)$ is the path difference between the two arms of the interferometer. For a 3-dB coupler as adopted in our experiment, the light is assumed to be split equally into two arms at fiber input port and to recombine at the output end of the interferometer. Hence, if we ignore the coupling loss, the transmission of the interferometer can be simply written as

$$T = (1 - \cos \varphi)/2. \qquad (2)$$

As $\varphi$ is associated with $\Delta L$, it can be concluded that the transmission spectrum of a fiber Mach-Zehnder interferometer constructed by two 3-dB couplers is characterized by a series of equally spaced transmission peaks in the frequency domain and determined by $\Delta L$. The wavelength spacing $\Delta\lambda$, between the adjacent transmittance peaks is given by

$$\Delta\lambda = \lambda^2 / n\Delta L, \qquad (3)$$

where $n$ is the effective refractive index of the laser mode and $\lambda$ is the laser wavelength in free space. The separation between adjacent transmittance peaks defines the tuning range of the interferometer. When the interferometer is configured into a ring-shaped fiber laser, the laser output wavelength coincides with the transmittance peak location. By presetting the path-length differences of interferometer arms, the laser wavelength tuning can be realized by slightly stretching the short arm to decrease the path difference $\Delta L$ between the two interferometer arms. Under a certain path-length difference between the two interferometer arms, it is ensured that the laser oscillates stably at a specific wavelength.

In order to maximize the fiber laser tuning range, it is important to specify the characteristics of the Mach-Zehnder interferometer as it is the key optical component in this laser system which defines the laser tuning range and laser frequency stability over time. The Mach-Zehnder interferometer was applied in the following way. One arm of the interferometer (about 10 cm) was deliberately made longer than the other and was cleaved into two pieces, which were then aligned using a fusion splicer (ERICSSON FSU 975) but kept not spliced. The Yb-doped fiber fluorescence spectrum under a launching pump power of 30 mW was measured by the OSA. The Yb-doped fiber has a wide fluorescence spectrum ranging from 1030 to 1130 nm with a peak at 1063 nm. Then fluorescence signal from the Yb-doped fiber was arranged to pass through the fiber interferometer and measured using the OSA, as shown in Fig.2. From the separation wavelength value, $\Delta\lambda$, of the spectral peak transmittances, we could estimate the path difference, $\Delta L_0$, according to Eq.(3). If the estimated tuning range, $\Delta\lambda$, is narrower than the expected one due to large $\Delta L_0$, an excess path-length difference should be cut off by means of fiber cleaving technique mentioned in Ref.[14]. Repeat the process until the obtained $\Delta\lambda$ satisfies the application requirement and then splice two fiber ends of the arm to finish the construction of the Mach-Zehnder interferometer. The laser tuning was realized by applying strain to the short arm of Mach-Zehnder interferometer. In the present case reported, the path difference, $\Delta L_0$, was about 36 $\mu$m. And the achieved tuning range in our experiment was about 21 nm from 1050.3 to 1071.5 nm, as illustrated in Fig.3. Such a tuning range was consistent with the measured peak transmittance response of the interferometer as shown in Fig.2(b).

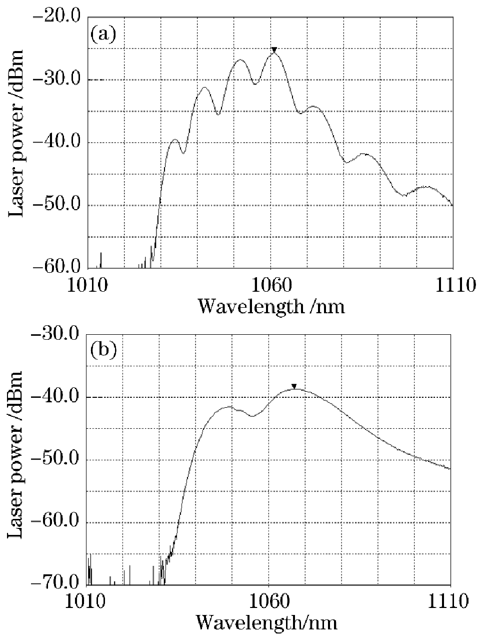


Fig.2 Fluorescence spectrum of the Yb-doped fiber after passing through the Mach-Zehnder interferometer with different paths. (a) $\Delta\lambda$ =~ 10 nm; (b) $\Delta\lambda$ = ~20 nm

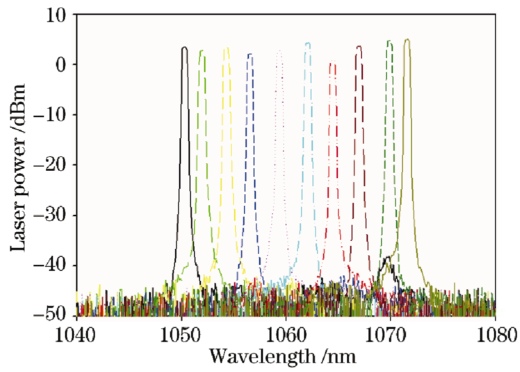


Fig.3 Output of the tunable Yb-fiber laser over the wavelength range from 1050 to 1071 nm

The laser output characteristics were investigated under the pumped power of 75 mW at 980 nm. The bandwidth of the laser was measured to be 0.07 nm as shown in Fig.4. It could be found that the signal-to-noise-ratio (SNR) was greater than 45 dB. The laser output power was about 2.5 mW and the laser slope efficiency was calculated to be about 3.3%, a value which can significantly be improved in the future by increasing the output ratio of the output coupler and optimize the fiber length and pump power.

As the laser cavity was not isolated from the laboratory environmental disturbance in the experiment, phenomenon of some mode hopping was ob-

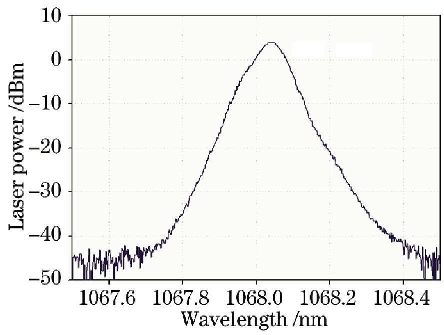


Fig.4 Spectrum of the fiber laser output at wvelength of 1068 nm

served during experiment. The stability of laser operation could be improved by placing the Mach-Zehnder interferometer into a mechanical oscillation damped base to eliminate the acoustic and mechanical vibration. Further extending of the tuning range to $\Delta\lambda$ of 80 nm is possible by reducing the $\Delta L$ to 10 $\mu$m level, but the environment noise that affects the stable operation of the fiber laser must be further eliminated. A nano-fiber Mach-Zehnder interferometer recently reported offered the possibility of a wider laser tuning range and the ability of stable laser operation due to its minor path-length difference between two interferometer arms and its immunity to acoustic noise[15].

In summary, a novel continuously tunable ring-shaped Yb-doped fiber laser working around 1064 nm was developed and a tuning wavelength range as large as 20 nm was realized. The tunable fiber laser used a fiber Mach-Zehnder interferometer as the tuning element, which can be specified to laser operation at certain wavelengths easily. The working principle of this tunable fiber laser was analyzed and the method of obtaining wide tunability by modifying the path difference of a fiber Mach-Zehnder interferometer was detailed. Tuning range of the laser wavelength from 1050.3 to 1071.5 nm was experimentally demonstrated and can be further extended by reducing the path-length difference of the interferometer arms and mitigating the environment noise disturbance. The laser had a power output greater than 2 mW over all the tuning range while the side band suppression ratio was greater than 45 dB and the bandwidth of the laser output was less than 0.1 nm.

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