Tunable dual-wavelength passively mode-locked Yb-doped fiber laser using SESAM

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In this linear-cavity passively mode-locked laser based on semiconductor saturable absorber mirror, an Yb-doped fiber is shared by two branch cavities as gain medium. These two cavities can respectively output single-wavelength pulse with the wavelength tuning range of 1 009.7–1 057.6 nm and 1 011.6–1 052.6 nm by adjusting volume Bragg grating. When two cavities output pulses together, the dual-wavelength pulses with the maximum and minimum wavelength separation of 34.8 and 2.4 nm, respectively, are achieved by net gain equalization method to suppress mode competition at room temperature. The maximum pulse energies of dual-wavelength pulses are 0.47 and 0.33 nJ separately; their repetition rates are 11.39 and 11.41 MHz.

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The dual-wavelength ultrashort pulse source has been widely applied in coherent pulse synthesis, optical pump-probe measurement, and coherent anti-stokes Raman scattering spectroscopy[1−3]. Nowadays, the dual-wavelength passively mode-locked fiber lasers have became research focus due to high beam quality, good heat dissipation performance, high conversion efficiency, and compact structure[4−6].

In recent years, various techniques have been proposed to establish the dual-wavelength passively mode-locked fiber laser. Hsiang *et al.* combined two polarization additive pulse mode-locked fiber lasers that shared one section of the cavities, to obtain a 1.03-μm pulse train and a 1.56-μm soliton bunch with 87- and 67-pJ pulse energy, respectively[7]. Liu *et al.* achieved a twin-pulse group with 248- and 296-ps duration at 2.5-MHz repetition rate by the Yb-doped fiber (YDF) laser based on nonlinear polarization evolution (NPE) and a long-period fiber grating bandpass filter[8]. Zhao *et al.* demonstrated a soliton ring fiber laser based on the single-wall carbon nanotube saturable absorber to realize the dual-wavelength pulses at 1 532 and 1 557 nm[9]. However, the dual wavelengths could not be tuned in the above experiments. Luo *et al.* presented a dual-wavelength NPE Bi-doped fiber laser with the wavelength separation between 2.38 and 20.45 nm by the filtering effect caused by polarizer and birefringence[10]. But the two wavelengths could not be tuned separately.

In this letter, an YDF is shared as gain medium by two branch cavities in this linear-cavity passively mode-locked fiber laser based on semiconductor saturable absorber mirror (SESAM). The same volume Bragg grating (VBG) acts not only as the cavity mirror but also as the wavelength tuning device. These two cavities can respectively output single-wavelength pulse with the wavelength tuning range of 1 009.7–1 057.6 nm and 1 011.6–1 052.6 nm by the spectra separation and mode selection effect of VBG. By adjusting the VBG along the clockwise direction, the pulse wavelength is tuned to longer wavelength; conversely, it becomes shorter. When two cavities output pulses together, the simultaneous dual-wavelength pulses with the maximum and minimum wavelength separation of 34.8 and 2.4 nm are achieved by net gain equalization method to suppress mode competition at room temperature. The maximum pulse energies of dual-wavelength pulses are 0.47 and 0.33 nJ respectively; and their repetition rates are 11.39 and 11.41 MHz severally.

Figure 1 shows the schematic diagram. The working central wavelength of all components is 1 035 nm. The application of all-fiber 3-dB polarization beam splitter (PBS) generates two branch laser cavities. The length of polarization maintaining PM-Yb-doped fiber (YDF) is 80 cm with the model number of Nufern PM-YSF-HI. The VBGs with reflection bandwidth less than 0.5 nm serve not only as the cavity mirror but also as the wavelength continues tuning device in two laser cavities separately. Port1 and port2 are used to measure the parameters of the pulses from cavity1 and cavity2, respectively, at dual-wavelength pulses operation.

In order to suppress mode competition caused by homogeneously broadened YDF and realize simultaneous dual-wavelength pulses with λ_1 and λ_2 at room temperature, we utilize the net gain equalization method, which makes each wavelength's loss equal gain by adjusting the loss of corresponding wavelength. Equation (1) should be satisfied to achieve dual wavelengths:

$$g_{\lambda i} \times L = G_{\rm th}(\lambda_i) = \delta_{\lambda i}, \quad i = 1, 2 \qquad (1)$$

where $g_{\lambda i}$ is gain coefficient of λ_i; L is YDF length; $G_{\rm th}(\lambda_i)$ is threshold single-pass gain; $\delta_{\lambda i}$ is the single-pass loss.

In Fig. 1, the same YDF is shared as gain medium in the two laser branch cavities. The cavity1 generates the pulse with wavelength of λ_1; the cavity2 generates the pulse with wavelength of λ_2. When neither λ_1 nor λ_2 is strong light, through adjusting VBGs, the threshold gain values of cavity1 and cavity2 are different. And the two VBGs are continuously adjusted until the actual gain values of λ_1 and λ_2 respectively equal the threshold gain of

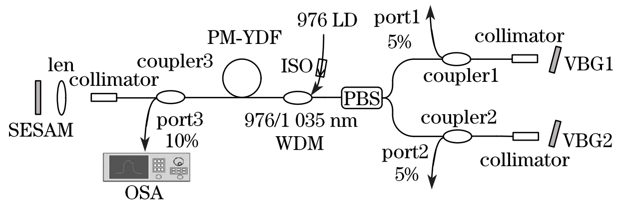

Fig. 1. Schematic diagram.

corresponding branch cavity. This can suppress the mode competition in the YDF to a certain extent; thereby simultaneous dual-wavelength pulses are achieved.

It is much easier to operate in Q-switched mode-locked state for the fiber laser with SESAM, which results in the unstable pulse power and pulse energy. As pump power increases, the laser successively undergoes the continuous ware (CW) laser, Q-switched mode-locked and continuous passively mode-locked state. In the picosecond laser, Eq. (2) should be met to inhibit self-Q-switching[11]:

$$E_{\mathrm{p}}^2 > E_{\mathrm{sat,L}}E_{\mathrm{sat,A}}\Delta R = (F_{\mathrm{sat,L}}A_{\mathrm{eff,L}})(F_{\mathrm{sat,A}}A_{\mathrm{eff,A}})\Delta R, \tag{2}$$

$$E_{\mathrm{p}} = P_{\mathrm{intra}}/f, \tag{3}$$

$$F_{\mathrm{sat,L}} = h\nu_{\mathrm{L}}/m\sigma_{\mathrm{L}}, \tag{4}$$

where E_{p} is the single pulse energy; P_{intra} is the average power; f is the repetition frequency; $E_{\mathrm{sat,L}}$ and $E_{\mathrm{sat,A}}$ are the saturation energies of YDF and SESAM, respectively; ΔR is the SESAM modulation depth; $F_{\mathrm{sat,L}}$ and $F_{\mathrm{sat,A}}$ are the saturation flux of YDF and SESAM; m is the times of pulse through YDF when it completes one round trip in the laser cavity (m=2); σ_L is the stimulated emission cross section of YDF; $A_{\mathrm{eff,L}}$ and $A_{\mathrm{eff,A}}$ are the effective spot areas of cavity mode in YDF and SESAM, respectively.

$E_{\mathrm{p,c}}$ is defined as the critical single pulse energy:

$$\begin{aligned} E_{\mathrm{p,c}} &\equiv (E_{\mathrm{sat,L}}E_{\mathrm{sat,A}}\Delta R)^{1/2} \\ &= [(F_{\mathrm{sat,L}}A_{\mathrm{eff,L}})(F_{\mathrm{sat,A}}A_{\mathrm{eff,A}})\Delta R]^{1/2}. \end{aligned} \tag{5}$$

$E_{\mathrm{p,c}}$ is the minimum pulse energy for stable continuous passively mode-locked state. When $E_{\mathrm{p}} > E_{\mathrm{p,c}}$, stable continuous mode-locked pulse is achieved; when $E_{\mathrm{p}} < E_{\mathrm{p,c}}$, Q-switched mode-locked pulse is obtained. Consequently, the SESAM with proper ΔR and small $F_{\mathrm{sat,A}}$ should be used in this experiment.

Because YDF and standard single-mode fiber are normal dispersion fibers, this fiber laser belongs to all-normal dispersion (ANDi) passively mode-locked laser without any anomalous dispersion compensation. The interaction of normal group velocity dispersion and self-phase modulation forms wide duration pulse, such that the peak power decreases and the nonlinear characteristics can be controlled, by which the pulse avoids being split, and the high single pulse energy is obtained.

The respective continuous tuning for each central wavelength of the dual-wavelength pulses[12] is achieved by the spectrum separation and wavelength selection effect of the corresponding VBG. The parallel beam from the collimator is reflected and dispersed by VBG. By adjusting the angle of VBG, the normal first order spectra (the spectral order m=1) returns to the laser cavity. Consequently, the diffraction wavelength λ_0 of VBG is dominated by

$$2\Lambda n_{\mathrm{o}}\cos\theta_{\mathrm{r}} = \lambda_0, \tag{6}$$

$$\sin\theta_{\mathrm{i}} = n_{\mathrm{o}}\sin\theta_{\mathrm{r}}, \tag{7}$$

where Λ is the period of refractive index for VBG; n_{o} is the average refractive index of VBG; θ_{r} is the angle between the input laser and z axis (refractive angle); θ_{i} is the incident angle. By adjusting VBG to change θ_{i}, the output wavelength can be tuned continuously. The adjustment direction of VBG determines whether the pulse wavelength is tuned to longer or shorter wavelength.

Figure 2 shows the relative reflectivity of the SESAM[13]. With only laser branch cavity1 oscillation, passively mode-locked single-wavelength pulse is observed at the fundamental frequency repetition rate of 11.39 MHz; the central wavelength can be tuned from 1 009.7 to 1 057.6 nm by adjusting VBG1. With only cavity2 oscillation, the single-wavelength pulse is realized at 11.41 MHz with the tuning range of 1 011.6–1 052.6 nm by VBG2. When the central wavelengths of the puls are same, the average output power from cavity1 is higher than that from cavity2 under the same pump power. It is because that loss in cavity1 is smaller than that of cavity2. When the VBG is adjusted along clockwise, the wavelength is tuned to longer wavelength; when along anticlockwise, it becomes shorter.

When the two branch cavities are allowed to oscillate simultaneously, the corresponding VBG in the laser cavity with stronger oscillation under the single-wavelength pulse operation state must be adjusted to add certain loss into this cavity. After fine-tuning the angle of this VBG, the net gain equalization is realized; and the simultaneous dual-wavelength passively mode-locked pulse output. The spot diameter on SESAM is about 75 μm. The maximum average output power measured on the common output port3 is 9.1 mW with the wavelength pair of (1 030 and 1 040 nm) at 310-mW pump power. And the maximum pulse energies are 0.47 and 0.33 nJ, respectively.

Figure 3 shows the dual-wavelength fundamental frequency passively mode-locked pulses. In Fig. 3(a), the blue line represents the pulse at 1 033.8 nm with 11.39-MHz repetition rate and 0.34-nm spectra bandwidth

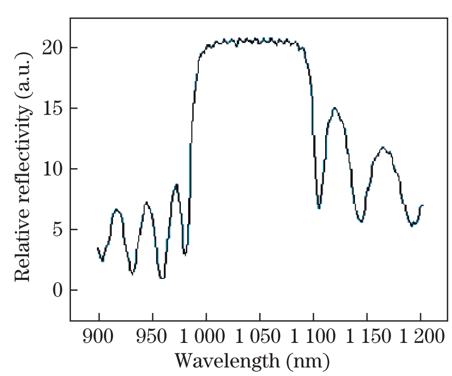

Fig. 2. Relative reflectivity of SESAM.

from branch cavity1, and the black one stands for the pulse at 1 028.9 nm with 11.41 MHz repetition rate and 0.44 nm spectra bandwidth from cavity2. The reflection bandwidth of VBG is narrow (<0.5 nm), therefore the spectra bandwidth of pulse is narrow. According to the formula of $\Delta\nu \cdot \Delta \mathrm{t} = 0.315$, the Fourier transform limit pulse duration from the cavity1 should be 3.30 ps with the hypothesis of output pulse being hyperbolic secant; and the duration from cavity2 should be 2.53 ps. However, the actual pulse durations are wider than 3.30 and 2.53 ps.

Figures 4(a–c) shows λ_2 is continuously tuned from 1 027.2 to 1 055.1 nm by adjusting VBG2, when λ_1 is fixed at 1 020.3 nm. And when λ_2 is fixed at 1 055.1 nm, λ_1 is tuned from 1 020.3 to 1 038.5 nm by adjusting VBG1, as shown in Figs. 4(c–e).

The minimum and maximum wavelength separation are 2.4 and 34.8 nm, as shown in Figs. 5 and 4(c). Dual-wavelength pulses with larger wavelength separation are relatively stable at room temperature. With small wavelength separation, the stability degrades, because the suppression to each other is stronger by mode competition, such that the balance between dual wavelengths can be easily broken by external disturbance. Moreover, if one of the two wavelengths or the pump power is changed, the VBGs should be adjusted in real time to ensure the net gain equalization and dual-wavelength pulses.

In conclusion, a tunable linear-cavity passively mode-locked YDF laser based on SESAM, which uses the same one VBG not only as cavity mirror but also as wavelength tuning device. This fiber laser is constructed with

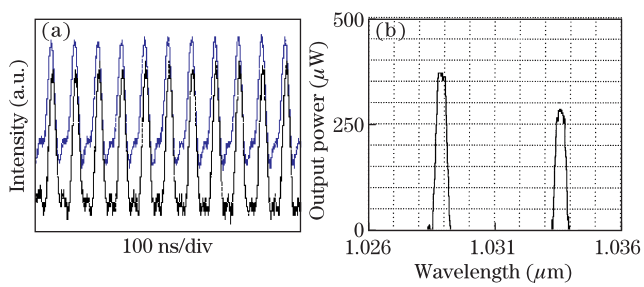

Fig. 3. Passively mode-locked pulse. (a) Pulse waveform; (b) spectra bandwidth.

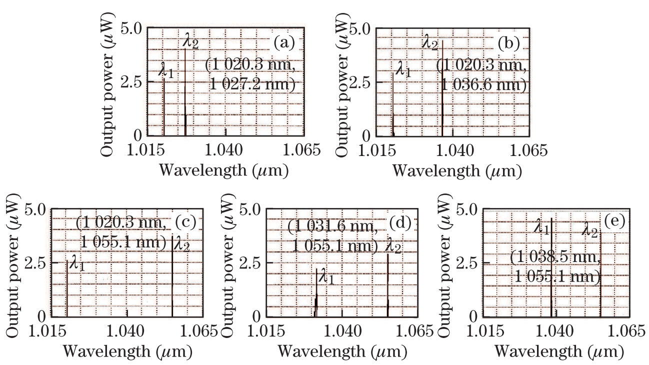

Fig. 4. The spectrum with wavelength tuning. (a)–(c) λ_1 is tuned; (c)–(e) λ_2 is tuned.

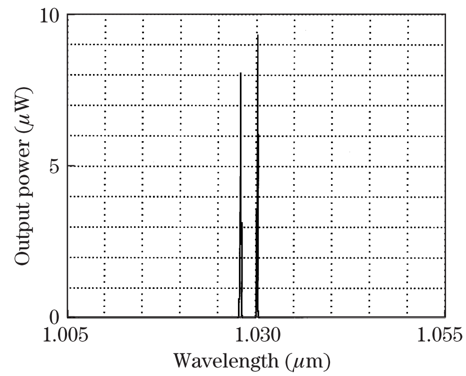

Fig. 5. Spectrogram of minimum wavelength separation.

an YDF and two branch cavities. These two cavities can respectively output single-wavelength pulse with the wavelength tuning range of 1 009.7–1 057.6 nm and 1 011.6–1 052.6 nm by adjusting VBG. By adjusting the VBG along the clockwise direction, the pulse wavelength is tuned to longer wavelength, and vise versa. Furthermore, simultaneous dual-wavelength pulses with the maximum pulse energies of 0.47 and 0.33 nJ are obtained by using the net gain equalization method at room temperature. The respective repetition rates are 11.39 and 11.41 MHz with the maximum and minimum wavelength separation of 34.8 and 2.4 nm. This fiber laser can be employed in coherent pulse synthesis, optical pump-probe measurement, and coherent anti-stokes Raman scattering spectroscopy after further improvement.

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