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The Evolution of Dual-Wavelength Dissipative Soliton in Yb-Doped Fiber Lasers

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Abstract

Dual-wavelength dissipation soliton (DS) in the all-normal-dispersion ytterbium-doped fiber laser (YDFL) is reported. Using a phase-shift long period fiber grating (PS-LPFG) as an all-fiber format spectral filter in the laser cavity, self-starting dual-wavelength pulses are obtained by nonlinear polarization evolution (NPE). The mode-locking mechanism of the ANDi cavity with different central wavelengths has analyzed. Experimental results show that the NPE together with the PS-LPFG play key roles in the generation of the dual-wavelength, meanwhile, a switchable dual-wavelength mode-locked fiber laser can achieve through change the polarization of the cavity.

Keywords: *all-normal-dispersion, fiber laser, mode-locked laser, switchable, multiwavelength.*

1. Introduction

Multi-wavelength fiber lasers have versatile applications including fiber optic sensing, instrumentation, optical signal processing and especially in the design of optical division multiplexing systems (WDM) [1-5].

Recently, all-normal-dispersion (ANDi) fiber lasers have attracted great interests because of their simple cavities and higher pulse energies than soliton or dispersion-managed soliton [6, 7]. However, most of the spectral filters, in the ANDi cavity used so far, are the bulk components such as interference filters or birefringent filters, which sacrifice the advantages of all-fiber format [6]. Özgören et al [8] reported a single wavelength all-fiber-format ANDi mode-locked femtosecond laser using a polarization mode fiber (PMF) as the Lyot filter. However, it did not have the capability of producing dual- or multi-wavelength mode locking because of the output wavelength was determined by the length of the PMF and splice angle. Zhang et al [9] reported a multi-wavelength dissipative soliton operation in an erbium-doped fiber laser based on semiconductor saturable absorber mirror (SESAM). Zhu et al [10] reported a switchable dual-wavelength and passively mode-locked ANDi Yb-doped fiber lasers by nonlinear polarization evolution (NPE) effect.

In this paper, using a phase-shifted long period fiber grating (PS-LPFG) as an all-fiber-format spectral filter in the laser cavity, a self-starting dual-wavelength and mode-locked laser is achieved based on nonlinear polarization evolution (NPE) effect. The positions of dual-wavelength are coincident very well with that of the passbands of the PS-LPFG. The mode-locking mechanism of the laser system is illustrated, which exactly analysis the evolutionary process of the dual-wavelength mode-locked Yb-doped fiber laser. The pulses width and pulses energy can change further by adjusting the polarization states of the waveplates in the cavity.

2. Experiment Setup

In our experiment, the PS-LPFG was fabricated using a CO_2 laser focused on a Corning HI 1060 single-mode fiber. The diameter of the focused laser spot was ~100μm, a π-phase shift was introduced at the center of the PS-LPFG. The pitch of the fabricated PS-LPFG was 318μm, and the number of grating period was 70.

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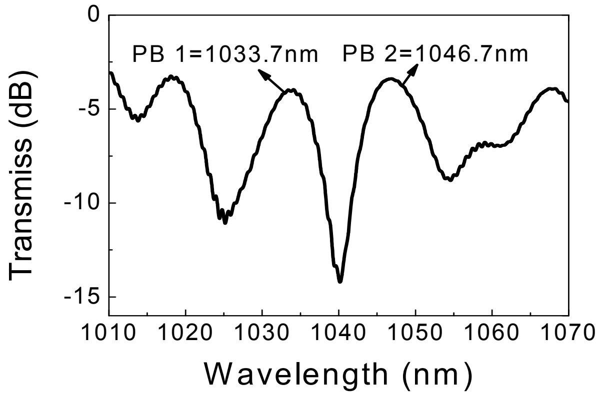

Figure 1. Shows the output spectrum of PS-LPFG measured by optical spectrum analyzer (OSA).

We can see that the two near-symmetrical passbands (PBs) measure at 1033.7nm for PB1 and 1046.7nm for PB2, respectively. The two passbands will serve as the spectral filter in the dual-wavelength mode-locked laser. The full width at half maximum (FWHM) of the two PBs was 7.8nm for PB 1 and 8.3nm for PB 2, respectively.

Figure 2 shows the configuration of the experimental setup of a dual wavelength and passively mode-locked Yb-doped fiber with a PS-LPFG as the spectral filter. The laser was building in a unidirectional cavity for self-starting operation. A 28 cm piece of Yb-doped gain fiber (612 dB/m absorption at 976 nm) was placed after 72.4 m of single-mode fiber (SMF). A 4.2 m segment of SMF placed after the gain fiber to increase the nonlinear phase shift accumulated by the expected modest pulse energy. The pump laser was a 976 nm grating-stabilized laser diode, which delivers up to 530 mW to the gain fiber through a wavelength-division multiplexer (WDM). Mode-locking operation was initiated and stabilized by nonlinear polarization evolution (NPE), which was implemented with quarter-wave plates (QWPs), a half-wave plate (HWP) and a polarizing beam splitter (PBS). The output of the laser was directly from the NPE rejection port.

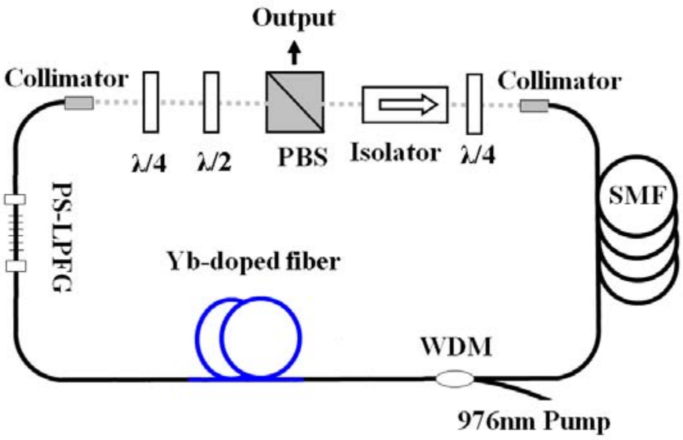

Figure 2. Configuration of an all normal dispersion passive mode-locked Yb-doped fiber cavity with a PS-LPFG as the spectral filter. $\lambda/4$, $\lambda/2$: quarter and half waveplates.

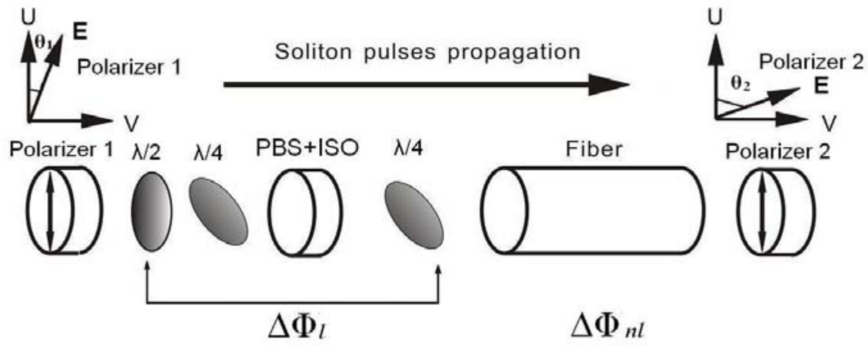

Figure 3. Illustration of the polarization states of the light in the mode-locked system. E: electric vector of the input signal, U and V: the two orthogonal birefringent axes of the optical fiber.

In order to explain the mechanism of the dual-wavelength laser in the ANDi system, firstly, we start to analyze the light transmission of the laser cavity as shown in Figure 3. θ_1 is the angle between the polarization direction of the input signal and the vertical birefringent axis U, and θ_2 is the angle between the polarization direction of the analyzer and the vertical birefringent axis U. Both θ_1 and θ_2 can be changed by adjusting the wave plates (quarter and half waveplates). The PBS and isolator play the roles of both the polarizer, transforming an arbitrarily polarized light into a linear one, and the analyzer, introducing an intensity dependent transmittance to obtain passive mode-locking acting as an artificial saturable absorber. The signal light is linear polarized after the PBS. Next, the λ/4 transforms the light to an elliptical polarization state. The polarization state of the light rotates as it propagates in the cavity due to different effects of the self-phase modulation (SPM), cross-phase modulation (XPM) and group velocity delay on two orthogonal polarized components. The angle of rotation is proportional to the light intensity. Therefore, the PBS can let only a certain polarization to pass through via adjusting the λ/4 and λ/2 wave plates in another end. The combination of waveplates (quarter and half waveplates), PBS, and isolator acts as a polarization-dependent loss for the wavelength choose. The waveplates acts as the polarization controls (PCs) in the laser system. The transmittivity T of the structure can expressed as:

$$T = \cos^2\theta_1\cos^2\theta_2 + \sin^2\theta_1\sin^2\theta_2 + \frac{1}{2}\sin 2\theta_1\sin 2\theta_2\cos(\Delta\phi_l + \Delta\phi_{nl}) \qquad (1)$$

Where

$$\Delta\phi_l = \frac{2\pi L}{\lambda}(n_y - n_x) \qquad (2)$$

$$\Delta\phi_{nl} = \frac{2\pi n_2 LP}{3A_{eff}\lambda}\cos 2\theta_1 \qquad (3)$$

$\Delta\phi_l$ is the linear phase shift resulting from modal birefringence, $\Delta\phi_{nl}$ is the nonlinear phase shift whose magnitude is the sum of the SPM and XPM contributions. n_x and n_y are the refractive indexes of the fast and slow axes of the optical fiber, respectively. L is the length of the laser cavity length. λ is the operating wavelength, n_2 is the nonlinear (Kerr) coefficient, P is the instantaneous peak power of input signal, and A_{eff} is the effective fiber core area. From Eq. (1) we can see that the system transmission depends on the linear phase shift due to modal birefringence, and the nonlinear phase shift introduced by the nonlinear effects of SPM and XPM. The peak transmission depends on θ1 and θ2. When, both of them are equal to 0 or π/2, the peak transmission can reach 100%, all the wavelength at this polarization can pass through the cavity; while one of them is π/2, the other being 0, it changes to 0, no light can work in this case. Angles θ_1 and θ_2 are the other different values, the transmittivity of the fiber loop manifests as a trigonometric function of the operating wavelength and the instantaneous peak power. Consequently, the polarization-dependent loss of this system can translate into wavelength- and intensity-dependent loss. As can be seen from Eq. (1) that the transmittivity oscillates with operating wavelength. By incorporating wave plates and a PBS into Yb-doped fiber ring laser, passive mode locking based on NPE can readily implement. The polarization state of the light rotates as it propagates in the laser cavity. Moreover, owing to birefringence chromatic dispersion, different wavelengths will emerge from the round trip with different polarization states. Since the round-trip cavity loss critically depends on the scalar product between the polarizations of the incident light and the analyzer, only those wavelengths for which the loss is low enough to match the available gain will be laser.

It should note that in our laser systems, the PS-LPFGs as the all-fiber filter in the cavity, the filter have played a very important role in the wavelength choice. Only the wavelength that can satisfy the polarization of NPE and during the passband of the PS-LPFG at the same time can be laser. Namely, the NPE like a wavelength sweeping, different wavelength can be laser by changed the cavity's polarization. Only the wavelength adjusting by the waveplats trapped in the band of PS-LPFG, the wavelength can be output. Therefore, by adjusting the waveplates, the switchable dual-wavelength of ANDi fiber laser can also be obtained though combination the NPE and PS-LPFG.

3. Results and Discussions

The NPE technique using for achieve the self-started mode-locking state of the fiber laser. The threshold of the mode-locked output was about 300mW. When the pump power is increasing above the threshold, the dual-wavelength mode-locked can be readily achieved by properly adjusting the waveplates.

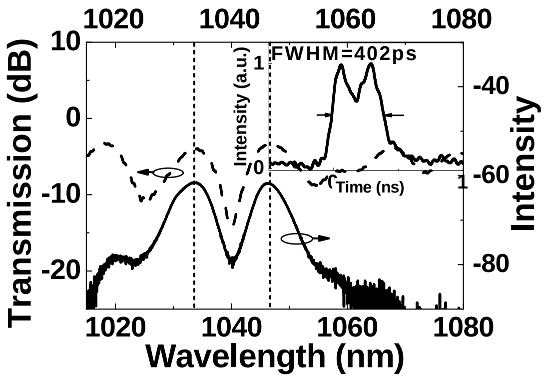

Figure 4. Spectrum of the mode-locked dual-wavelength laser and its comparison with the corresponding transmission spectrum of the PS-LPFG. Solid line: the spectrum of dual-wavelength laser output; dashed line: transmission spectrum of the PS-LPFG. Inset is the output pulse.

Figure 4 shows the spectrum of the mode-locked dual-wavelength laser output and its comparison with the corresponding transmission spectrum of the PS-LPFG. The pump power was 430mW. The dual-wavelength passively mode-locked output in the ANDi Yb-doped fiber lasers. It can be seen that the output wavelengths of the mode-locked pulses are coincident very well with that of the passbands of the PS-LPFG. The wavelengths of mode-locked dual-wavelength output were 1033.6nm and 1046.6nm, respectively, corresponding to 1033.7nm and 1046.7nm of the passbands of the PS-LPFG. The inset figure is the pulse shape of the mode-locked dual-wavelength output at an average power of 11.10mW with a repetition rate of 2.499MHz. The full width at half maximum (FWHM) of the pulse width is 402ps. It is show that there is a "dip" appearing in the middle of the pulse. This can explain that the two mode-locked wavelengths have different dispersions in the laser cavity, which will result in different time delay in the time domain. It should also be mentioned that it is not necessary to have dispersion management components to obtain the stable mode-locked outputs in the ANDi laser, because the spectral filter plays the key roles in pulse shaping and stabilizing mode locking by virtue of self-amplitude modulation in the cavity [6-7]. It can be found that the mode-locked dual-wavelength output is very stable and the PS-LPFG as the an all-fiber format spectral filter in the laser cavity is efficiency.

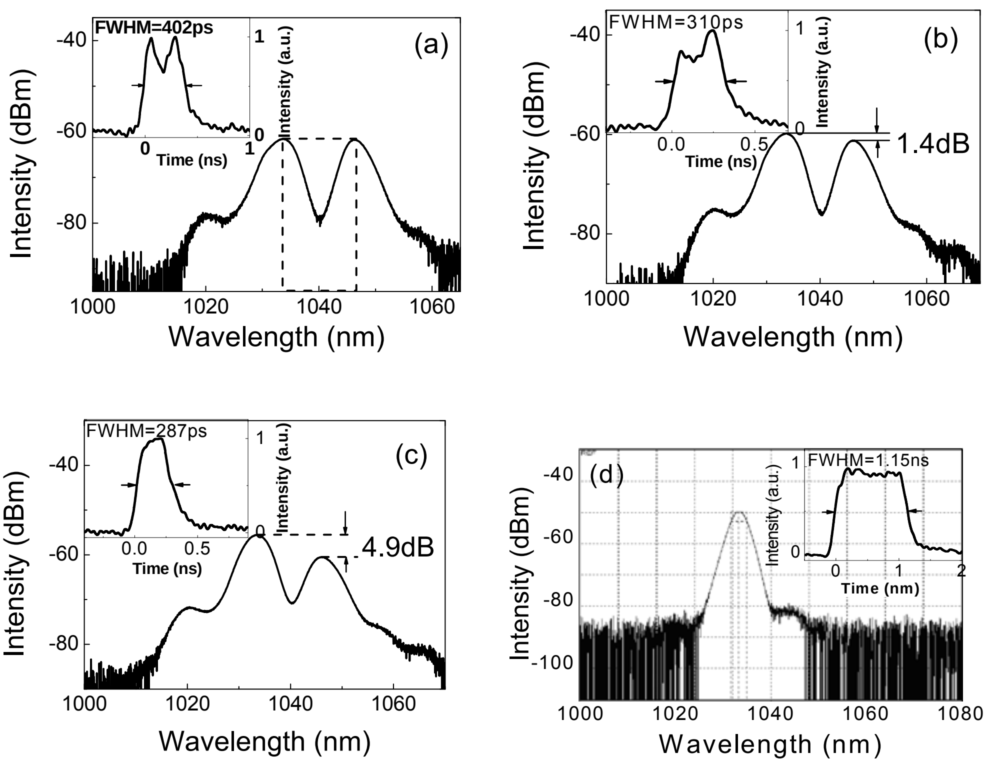

Figure 5. Evolution of the spectrum output of mode-locked laser operation in switching mode. Inset are the output pulses corresponding with the output spectra.

Figure 5 shows the evolution of the mode-locked output working in dual-wavelength and switchable mode with the pump power of 530mW. The wavelength switching can be achieved by adjusting the polarization components (e.g., quarter and half waveplates) as Figure 1 discussion. Figure 5(a) shows the wavelengths of mode-locked dual-wavelength output were 1033.6nm and 1046.6nm, respectively. The amplitude of the spectra peaks have the same intensity, corresponding to the output pulses with the same energy intensity. By slight change the polarization of the cavity, the polarization controls can introduce wavelength-dependent cavity loss, the spectra peaks of the dual-wavelength mode-locked are changed as shown in Figure 5(b). We can see that the amplitude of the left peak is 1.4dB higher than the right peak, corresponding to the output pulse energy intensity just reverse, namely, the amplitude of the right peak is higher than the left peak. Continually to change the polarization station of the cavity, the amplitude between the two spectrums is increasing as shown in Figure 5 (c). It should be noted that in the Figure 5(c) there only a single pulse output in the laser, the “dip” in the middle of the pulse disappeared, due to the spectrum amplitude intensity of the left is higher than the right one, which resulting in the pulse energy of the left peak is so small which can not be see in the pulse. Continually adjusting the polarization station of the cavity, the single wavelength mode-locked is achieved as shown in Figure 5 (d). It can be seen that full width at half maximum (FWHM) of the output spectral bandwidth is 3.25ns, and the corresponding pulse width is 1.15ns with the average output power about 42.3mW. From Figure 5 we can see that the NEP like as an intensity-dependent loss in the laser cavity, PS-LPFG as filter, the switchable dual-wavelength pulse can be generated by adjusting wave plates for control the wavelength-dependent loss.

4. Conclusion

In summary, a qualitative principle of dual- and switchable wavelength ANDi fiber laser has been analyzed. Using a PS-LPFG as an all-fiber format spectral filter in the laser cavity, self-starting stabilized dual-wavelength mode-locking operation is achieved by NPE effect. By adjusting the polarization components in the cavity, the pulses intensity and pulse width will be changed corresponding to the polarization station of the laser cavity. The switchable dual-wavelength mode-locked fiber laser can also be achieved by change the polarization of the cavity.

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