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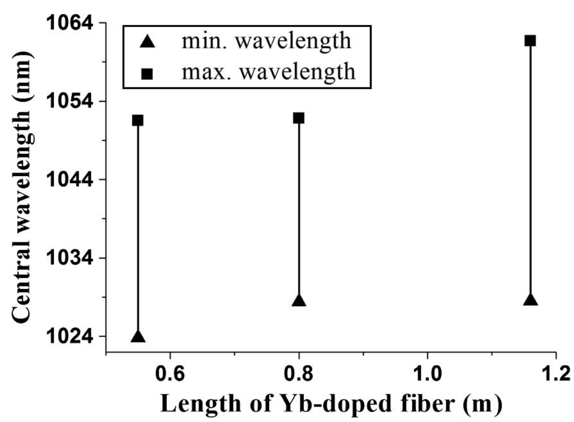

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Experimental Investigation of the Wavelength Tunability in All-Normal-Dispersion Ytterbium-Doped Mode-Locked Fiber Lasers

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Abstract: The wavelength tunability of all-normal-dispersion (ANDi) ytterbium (Yb)-doped mode-locked fiber laser is experimentally investigated, where the laser is mode-locked by nonlinear polarization rotation and the wavelength is adjusted by an intracavity tunable filter. The influences of pump power, gain fiber length, and cavity length (i.e., repetition rate) on the mode-locking wavelength and output spectrum are investigated. It is found that the tunable range of mode-locking wavelength depends on the length of the Yb-doped fiber, as well as the cavity loss, and is independent of the cavity length. Mode-locking in a longer wavelength regime can be obtained by increasing the gain fiber length, although the length depends on the cavity loss. Moreover, the effects of pump power, central wavelength, Yb-doped fiber length, and cavity length on other output parameters are discussed. The variation range of pump power to keep the mode-locking status is also analyzed. We find that the pump power range for keeping the mode-locking status decreases, and the typical output pulsewidth increases dramatically as the repetition rate decreases. Guidelines for designingANDi Yb-doped mode-locked fiber lasers are proposed.

Index Terms: Mode-locked fiber lasers, all-normal dispersion , Yb-doped fiber laser, tunable lasers.

1. Introduction

Ultrashort pulse lasers have attracted a lot of interests for their great potential applications in many fields, e.g., ultrafast optics, biology and medicine, and micromachining [1]. For lots of those applications, high energy and wavelength-tunable ultrashort pulse source is required. Passively mode-locked fiber laser is a stable and cost-effective technique to generate ultrashort pulse. However, the output pulse energy of traditional (soliton) fiber laser is limited by the nonlinear effects of fiber [2]. Recently, all-normal-dispersion (ANDi) ytterbium (Yb)-doped mode-locked fiber laser attracted great interests, for their simplified laser cavity without dispersion-compensation components and high output pulse energy [2], [3].

Wavelength tunability of laser pulse source is also strongly desired for many applications, e.g., optical measurement, medical treatment and biological metrology. In ANDi mode-locked fiber laser, an intra-cavity filter is generally required for the dissipative process, assisting to shape pulse and

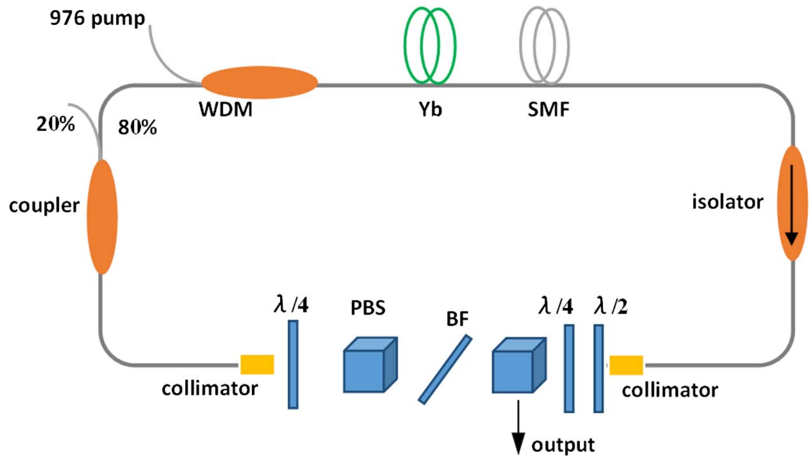

Fig. 1. Experimental setup. WDM: wavelength division multiplexer, $\lambda/2$: half-wave plate, $\lambda/4$: quarter-wave plate, PBS: polarization beam splitter, BF: birefringent plate, SMF: single-mode fiber (Nufern 1060-XP), Yb: Yb-doped fiber.

mode-lock [4]. Providing the filter is tunable, the mode-locking wavelength of laser can be adjusted conveniently. Due to the broad emission spectrum of Yb-doped fiber, widely tunable Yb-doped fiber sources could be obtained. Wavelength-tunable ANDi Yb-doped mode-locked fiber lasers have been proposed by L. Kong [5], M. Schultz [6] and C. Ouyang [7]. Tunable ranges of 1024–1070 nm, 1015–1050 nm, and 1032–1052 nm were obtained by use of tunable intra-cavity filters, i.e., birefringent filter, tilting interference filter, and hibi-fiber sagnac loop filter, respectively. Tunable ANDi laser with giant chirped pulse output was also obtained by long period fiber grating filter and the tunable spectral range was 1028–1039 nm [8]. The wavelength tunable range and bandwidth of above lasers are different. For some other applications, however, ultrashort pulse source with a specific wavelength is required. For instance, a 1060-nm seed source is desired for high-power ultrashort pulse amplification [9]. In order to design a desired tunable ANDi mode-locked fiber laser and control the output wavelength, it is necessary to investigate the behavior of wavelength tunability and other output parameters in ANDi Yb-doped mode-locked fiber laser systematically.

In this paper, the wavelength tunability of ANDi Yb-doped mode-locked fiber laser is experimentally investigated, and the influences of pump power, gain fiber length, and total cavity length (e.g., repetition rate) on the mode-locking wavelength and other output parameters are analyzed. Guidelines are given to help the design of ANDi fiber laser. For instance, though the mode-locking wavelength of Yb-doped fiber laser is normally around 1030–1040 nm, one can design an oscillator operating at 1060 nm according to these guidelines.

2. Experimental Setup and Results

In general, an ANDi Yb-doped mode-locked fiber laser consists of a pump source, Yb-doped fiber, filter, saturable absorber, etc. Our experimental setup is shown in Fig. 1. Two quarter-wave plates and one half-wave plate construct a polarization controller (PC). One polarization beam splitter (PBS) and the PC, in addition to some fiber, have the effect of nonlinear polarization rotation, which help to mode-lock the ANDi fiber laser. Meanwhile, two PBSs and a quartz birefringent plate (rotatable respect to its normal) serve as a wavelength-tunable filter. A fiber coupler, which is not necessary for mode-locking, is used here to monitor the laser conveniently.

First, we fix all the cavity components. The length of Yb-doped fiber (Nufern SM-YSF-HI, 250 dB/m absorption at 975 nm) is 1.16 m, the total cavity length is about 9 m, and the repetition rate is about 22 MHz. The dynamics of output parameter from the mode-locking laser versus the pump power is observed without tuning the filter, and a typical result is shown in Fig. 2. The central wavelength decreases as the pump power increases due to the reabsorption of Yb^{3+} ion, and the spectral bandwidth increases due to the increasing of self-phase modulation, which were also observed in

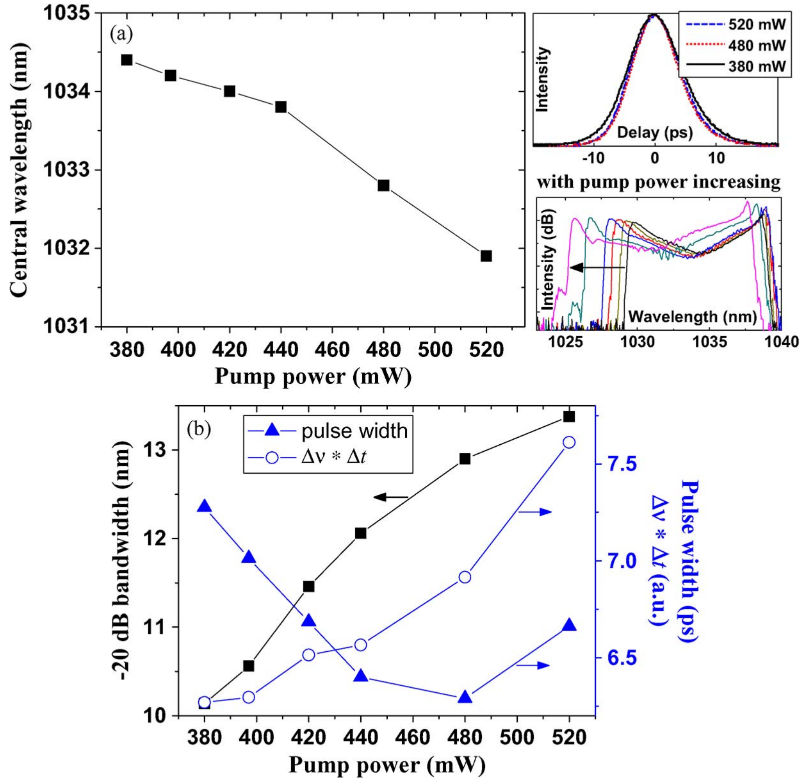

Fig. 2. (a) Central wavelength, (b) −20 dB bandwidth, FWHM duration, and time-bandwidth product of output versus pump power in ANDi Yb-doped fiber laser. The insets of (a) give the dynamics of output spectrum and autocorrelation traces with pump power increasing.

Ref. [10]. There is no obvious trend for the full width at half maximum (FWHM) duration of output pulse as pump power increases (in this specific case, the duration fluctuates in the range of 6.3–7.3 ps). However, the trend of time-bandwidth product is similar to that of spectral bandwidth, since the increment of bandwidth dominates the trend of the product.

There are limitations for pump power to get mode-locking. If the pump power is too small, mode-locking cannot be established. Whereas, with too large pump power, the status of mode-locking will be unstable and wave-break will occur, due to large nonlinear phase shift. Therefore, the shift of central wavelength will be limited by the range of pump power for holding the status of mode-locking. The pump power range will also be inspected in the followings.

Tuning the pump power only, the pump power range around a specific wavelength can be recorded. Fig. 3(a) shows the pump power range at some mode-locking wavelengths (the wavelength is tuned by filter). The minimum and maximum pump powers fluctuate for different central wavelength, but there is an overlap range of 440–520 mW, which can support mode-locking at any wavelength in the range of 1026–1064 nm. As shown in Fig. 3(b), the bandwidth and duration of output pulse do not show clear trends as the central wavelength increases. The fluctuations of output bandwidth and pulsewidth are relatively large (more than 50% in this specific case) for different central wavelength, even with the same pump power.

Secondly, the length of Yb-doped fiber is adjusted to investigate the effects of gain fiber length on the mode-locking wavelength and other output parameters. Gain fibers with length of 1.16, 0.80, and 0.55 m are used, respectively. In order to achieve all possible mode-locking wavelengths, the pump power and all plates are tuned carefully. For cavities with shorter Yb-doped fiber, stable mode-locking status around 1060 nm cannot achieved, no matter how to adjust the plates and pump power, as shown in Fig. 4. By increasing the gain fiber length, longer mode-locking wavelength can be obtained, of which the RF spectra (not show here) validates the stable output.

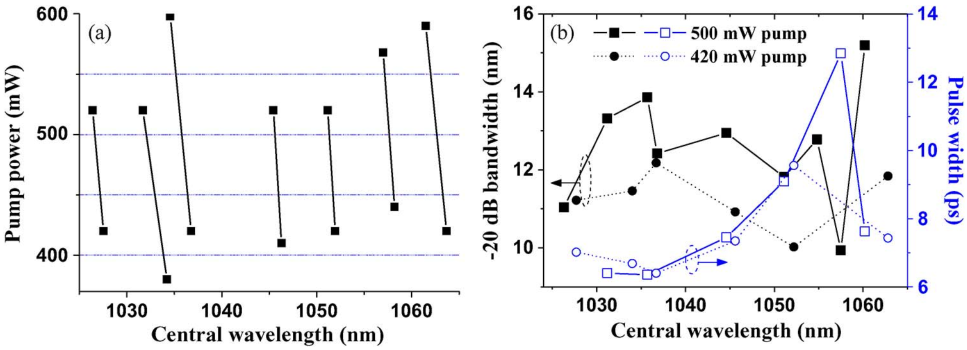

Fig. 3. (a) Pump power range for mode-locking at different wavelength. (b) −20 dB bandwidth and temporal duration of output versus central wavelength, keeping pump power at 500 (420) mW.

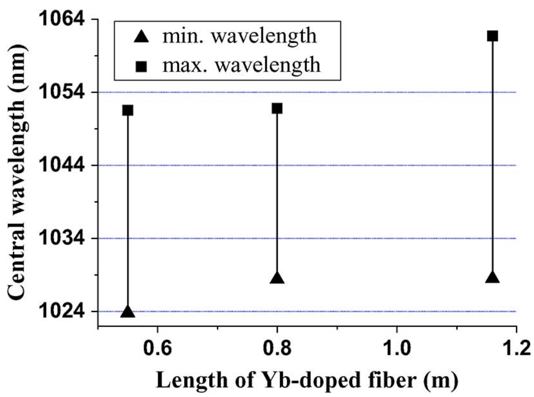

Fig. 4. Wavelength tunable range of ANDi mode-locked fiber lasers with different gain fiber length.

TABLE 1

Tunable ranges of wavelength and pump power and typical output parameters versus repetition rate

Repetition rate (MHz)	**11.01**	**16.64**	**22.02**
Wavelength tunable range (nm)	1024~1061	1028~1062	1026~1064
Pump power variation with keeping mode-locking (mW, typical)	30	90	130
-20 dB bandwidth of output spectrum with pump power about 400 mW (nm, typical)	12	13	11
FWHM duration of output pulse with central wavelength about 1035 nm (ps, typical)	20	12	7

Therefore, mode-locking at longer wavelength, which cannot be achieved in oscillator with shorter Yb-doped fiber, could be obtained by increasing the gain fiber. It will be discussed in Section 3 in detail.

Outputs at the same central wavelength have been compared for oscillators with different length of Yb-doped fiber. Keeping the pump power constant, the fluctuations of output bandwidth and pulsewidth are relatively small. In the specific case of Fig. 4, the output bandwidth varies only 10% and the pulsewidth varies about 20%.

Finally, the effect of cavity length (i.e., repetition rate, adjusted by changing the length of SMF directly following the gain fiber) on output is investigated. Lots of experiments are conducted and typical output parameters are given in Table 1. The length of Yb-doped fiber is kept as 1.16 m, and the repetition rate decreases from 22 to 11 MHz. It is observed that, in the cavity of higher repetition (i.e., shorter cavity length), mode-locking can be achieved more easily. As shown in Table 1, the pump power range for keeping mode-locking status decreases significantly for smaller repetition rate. This may due to the reason that for longer SMF, the nonlinear phase shift is larger. Hence, in longer cavity, the wave-break could occur even the pump power increases several tens milliwatt.

Though the repetition is different, the tunable range of mode-locking wavelength is almost the same (shown in Table 1). With the same pump power, the typical output bandwidth varies slightly. However, the typical pulsewidth increases significantly as the cavity length increases, resulting from the increment of accumulated group-velocity dispersion.

3. Discussion

From numerous experiment results, we observed the following rules for ANDi Yb-doped mode-locked fiber lasers:

1) For a fixed cavity configuration, increasing the pump power will decrease the central wavelength and increase the spectral bandwidth, and change the pulsewidth slightly; tuning the mode-locking wavelength will result in large fluctuations of spectral bandwidth and pulsewidth. Therefore, to maximize the output bandwidth (e.g., in order to minimize the duration of pulse compressed by subsequent dispersion-compensation devices) from a specific cavity, one can optimize the mode-locking wavelength and increase the pump power.
2) Adjusting the repetition rate and fixing the gain fiber, the wavelength-tunable range is almost the same. However, the pump power range for keeping mode-locking status decreases and the typical output pulsewidth increases dramatically as repetition rate decreases, because increasing the SMF length directly after the gain fiber will increase the nonlinear phase shift and the total amount of dispersion.
3) Mode-locking at longer wavelength can be obtained by increasing the length of Yb-doped fiber. Though the gain fiber length is different, the typical output bandwidth and pulsewidth vary slightly when operating at the same wavelength.

Followings are the explanations of the major observed rules, based on the physics of Yb-doped fiber laser. In Yb-doped continuous-wave fiber laser and amplifier, it has been pointed that, for a given Yb-doped fiber, the emission wavelength depends on the length of gain fiber, pump power, etc., due to the three-level nature of Yb-doped fiber [11], [12]. The emission wavelength will "redshift" when increasing the gain fiber length or decreasing the pump power, resulting from the ground-state reabsorption effect of Yb^{3+} ion [11]. For traditional (soliton) passively mode-locked Yb-doped fiber laser, it also found that, the wavelength-tunable range depends on the length of Yb-doped fiber [9], [13]. The three-level behavior of Yb-doped fiber has similar impact on the wavelength tunability in ANDi mode-locked fiber laser.

Recently, the effect of pump power on the output wavelength was observed in ANDi laser [10]. From the absorption spectrum of Yb^{3+} ion one can see that, for wavelength larger than 980 nm, the absorption at shorter wavelength is stronger than that at longer wavelength [12]. When decreasing the pump power, the reabsorption effect happens and the reduction of gain at shorter wavelength is larger, thus the output wavelength will "redshift". Meanwhile, since the signal gain decreases, the nonlinear phase shift of signal pulse will decrease, thus the spectral bandwidth becomes narrower with the decreasing of pump power. When fixing pump power and increasing the length of Yb-doped fiber, the reabsorption effect will also arise, and the variation of emission wavelength is similar to the case of fixing gain fiber length and decreasing pump power. We herein experimentally observed the influence of gain fiber length on the mode-locking wavelength, as shown in Fig. 4.

In order to further illustrate the effect of gain fiber length (L) on the amplification of three-level system, a sketch map of small-signal single-pass gain versus pump power (P) and L at a specific wavelength is given in Fig. 5. The figure is plotted according to the following facts. For a fixed pump power, there is an optimal length of gain fiber to maximize the gain due to the reabsorption effect of Yb-doped fiber; while for a fixed gain fiber length, the signal gain will saturate by increasing the pump power [12]. Typical curves of gain versus pump power or gain fiber length only are shown in the insets of Fig. 5. With a small pump power and long gain fiber length, the gain (in decibel) can be

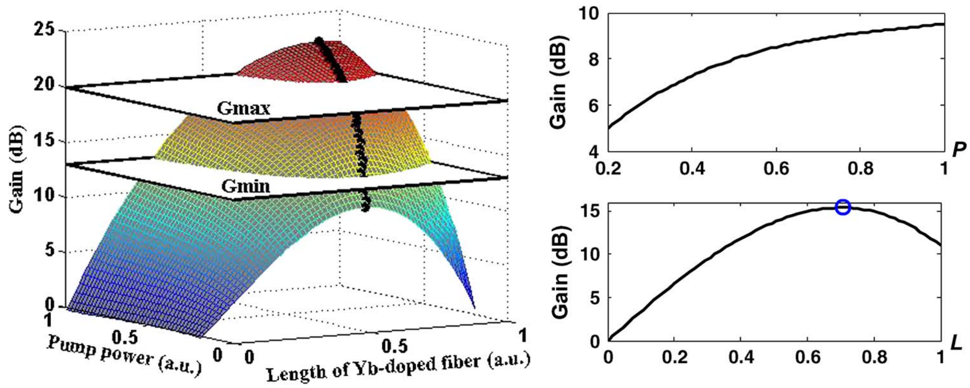

Fig. 5. Small-signal single-pass gain of Yb-doped fiber versus the pump power and gain fiber length. The insets show typical curves of gain versus pump power (P) or gain fiber length (L) only. Circle (**o**): maximum gain with fixed pump power.

less than zero, i.e., absorption is occurred. To support mode-locking and prevent wave-break, the gain should be limited in a range of $[G_{\min}, G_{\max}]$, as depicted in Fig. 5. Only for those (P, L) pairs, the corresponding gains of which are in the range of $[G_{\min}, G_{\max}]$, stable mode-locking could be possible. Fig. 5 also shows that, for a specific L, there are three classes of the range of pump power with which the mode-locking is possible, i.e., null, $[P_{\min}, +\infty]$ and $[P_{\min}, P_{\max}]$, where the corresponding gain of $P_{\min}$ and $P_{\max}$ are $G_{\min}$ and $G_{\max}$, respectively. Similarly, for a specific P, there are three classes of the range of L with which the mode-locking is possible, i.e., null, $[L_{\min1}, L_{\min2}]$ and $[L_{\min1}, L_{\max1}][L_{\max2}, L_{\min2}]$, where the corresponding gain of $L_{\min1/\min2}$ and $L_{\max1/\max2}$ are $G_{\min}$ and $G_{\max}$, respectively. The complete model of mode-locking is much more complicated, however, the rules drawn from the simple sketch map could hold in general.

It should be noted that, the emission wavelength also depends on the nature of Yb-doped fiber, the pump wavelength and the cavity configuration [11]. Specifically, the cavity loss affects the wavelength tunable range as well. In our setup the cavity loss is relatively large. In order to get mode-locking status, the single-pass gain of Yb-doped fiber should be large, thus the pump threshold must be relatively high [e.g., see Fig. 3(a)]. The higher the pump power is, the longer the gain fiber should be in order to benefit the reabsorption effect and get mode-locking at longer wavelength. Above description can also be illustrated by Fig. 5, where the values of $G_{\min}$ and $G_{\max}$ should be increased as the increasing of cavity loss. Therefore, to obtain mode-locking at long wavelength, the cavity loss, gain fiber length and pump power should be optimized, and the length of Yb-doped fiber depends on the cavity loss.

4. Conclusion

In conclusion, we have investigated the wavelength tunability of ANDi Yb-doped mode-locked fiber laser experimentally. The influences of pump power, gain fiber length, and cavity length on the mode-locking wavelength and other output parameters are investigated. It is found that, the wavelength tunability depends on the length of Yb-doped fiber, the cavity structure (e.g., the cavity loss), and the pump power, due to the reabsorption of Yb^{3+} ion. One can optimize those parameters to obtain the desired output wavelength. Basically, decreasing the pump could "redshift" the wavelength (and reduces the spectral bandwidth), and the amount of wavelength increment is limited by the pump power range for keeping mode-locking status. Increasing the gain fiber length also increases the output wavelength. If mode-locking at long wavelength is demanded, the gain fiber length depends on cavity loss. Besides, when increasing the cavity length only, the wavelength-tunable range changes little; however, the pump power range decreases and the typical output pulse duration increases significantly. The investigation and discussion in this paper would helpful for the design of ANDi Yb-doped mode-locked fiber laser.

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