

Wide and fast wavelength-tunable mode-locked fiber laser based on dispersion tuning

Shinji Yamashita and Masahiro Asano

Dept. of Electronics Engineering, University of Tokyo, Tokyo, Japan 113-8656
syama@sagnac.t.u-tokyo.ac.jp

Abstract: We demonstrate a wide and fast wavelength-tunable mode-locked fiber laser based on tuning the mode-locking frequency. The laser is in a sigma-laser configuration, and a wideband semiconductor optical amplifier (SOA) at 1.3 μm wavelength region is used as a gain medium. Mode locking is achieved by direct modulation of the injection current to the SOA, and a dispersion compensation fiber (DCF) is used to provide desired intracavity dispersion. By tuning the modulation frequency, a wide tuning range over 100 nm is achieved. Lasing wavelength is measured to be linearly in proportion to the RF frequency applied to the SOA. The sweep rate over the entire wavelength range (100 nm) can be raised to be as high as 200 kHz.

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1. Introduction

Wavelength-tunable lasers are versatile both in telecom and sensing applications. Many kinds of wavelength-tunable lasers, either laser diode (LD) based or fiber laser based, have been proposed so far. External cavity tunable LDs are commercially available [1], and erbium-doped fiber lasers have been demonstrated to have wide tuning bandwidth over 80nm [2]. These lasers, however, require tunable filters, such as rotatable diffraction grating [3],

polygonal mirror [4] or piezo-tunable Fabry-Perot filter [5]. So far, most of these filters have mechanically moving parts, which limits the tuning speed. In some applications, such as fiber Bragg grating (FBG) sensors [6] and optical coherence tomography (OCT) [7], fast tuning speed and wide tunable range are desired.

In this paper, we propose and demonstrate a novel wide and fast wavelength-tunable fiber laser. It is a mode-locked fiber laser in the pulsed operation, and it does not require tunable filters. It is based on the change of the modulation frequency and chromatic dispersion in the laser cavity. We realize the fast tuning over 100 nm at the sweep rate as high as 200 kHz by sweeping the modulation frequency and using a semiconductor optical amplifier (SOA) as a gain medium.

2. Principle

The free-spectral range (FSR) of the laser cavity F is expressed as

$$F = \frac{c}{nL}, \quad (1)$$

where L is the cavity length, n is the refractive index in the cavity, and c is the speed of light in the vacuum. When the cavity has chromatic dispersion, the FSR is a function of the light wavelength λ . Denoting the FSR at a wavelength λ as F , and ignoring higher order dispersion, the wavelength λ and the FSR F have a relation,

$$\lambda = -\frac{n_0}{cDF_0}(F - F_0) + \lambda_0 = -\frac{n_0^2 L}{c^2 D}(F - F_0) + \lambda_0, \quad (2)$$

where n is the refractive index at λ , and D is the dispersion parameter.

Active mode-locking is a technique to generate short pulse trains by applying a modulation to the laser cavity. For stable active mode locking, the modulation frequency f_m to the cavity has to match with an integer (N) times of the FSR ($=N \times F$), where N is the order of harmonic mode locking. That is, when we apply a modulation at f_m to the dispersive cavity, the laser favors to operate at the wavelength λ_m to meet the harmonic mode-locking condition, expressed as,

$$\lambda_m = -\frac{n_0^2 L}{c^2 ND}(f_m - f_{m0}) + \lambda_0 = -\frac{n_0}{cDf_{m0}}(f_m - f_{m0}) + \lambda_0, \quad (3)$$

where $f_{m0} = NF$. Thus the lasing wavelength can be tuned by changing the modulation frequency. This is sometimes called as dispersion tuning [8]. It is found from Eq. (3) that the wavelength shift is more sensitive to the change of modulation frequency when L is large, and N and D are small.

Wavelength tuning range $\Delta\lambda_m$ is primarily determined by lasing at the adjacent harmonic mode, $(N-1)$ -th or $(N+1)$ -th mode. It happens when the change of lasing frequency exceeds one FSR. From Eq. (3), $\Delta\lambda_m$ is expressed as,

$$\Delta\lambda_m = \frac{n_0 F_0}{cDf_{m0}} = \frac{n_0}{cDN}. \quad (4)$$

3. Experiment setup

The experimental setup of the proposed wavelength-tunable mode-locked fiber laser is shown in Fig. 1. The laser is in a sigma-laser configuration. An SOA (Covega BOA1017) having the 3 dB gain bandwidth of 70 nm is used as a gain medium in the laser cavity. Active mode-locking is realized by directly modulating the injection current to the SOA with the RF signal from a RF synthesizer. Direct modulation of the injection current instead of using an external

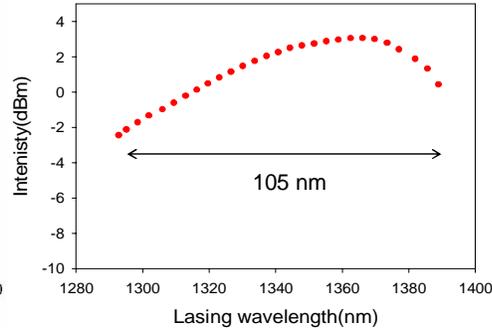
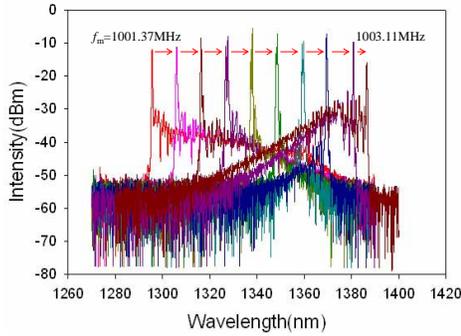


Fig. 2. Optical spectra of the proposed laser (DCF 20 m). Fig. 3 Output power as a function of lasing wavelength (DCF 20 m).

Table.1. Tuning characteristics.

DCF (m)	FSR (MHz)	Tuning sensitivity (nm/MHz)	Tuning range (nm)
20	3.73	53.8	105.0
35	2.36	49.3	68.9
50	1.76	45.6	44.6

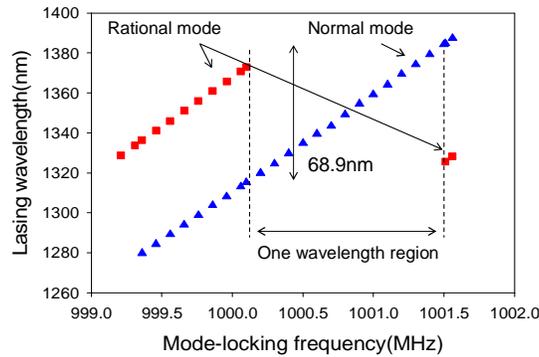


Fig. 4. Relation between mode-locking frequency and lasing wavelength (DCF 35 m).

In the rational mode-locking operation, at the mode-locking frequency F expressed as

$$F = \left(N + \frac{1}{m}\right)F_1, \quad (5)$$

a pulse train is generated at a repetition frequency of $m \times F$. Here, F_1 is a FSR of the cavity, and m is an integer number greater than one. Multiwavelength oscillation occurs at a frequency which satisfies both the normal mode-locking condition at one wavelength and the rational one at another wavelength. The rational mode-locking is more easily caused at lower harmonics of m , and we found that only 2nd harmonic rational mode-locking occur in the experiment. Figure 5 shows the optical spectra and mode-locked pulses when both mode-locking conditions are satisfied. Two wavelengths are lased and we find that repetition rates of the mode-locked pulses are different, one is 1 ns and the other is 500 ps.

Thus, we found that the tunable range of the mode-locking frequency is half of the FSR due to the rational mode-locking. We have to design the laser so that the FSR is more than twice of the desired tuning range.

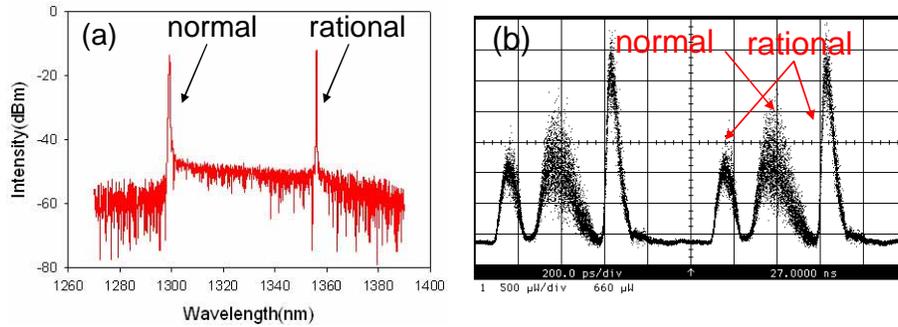


Fig. 5. Characteristic of rational mode-locking (a)Optical spectra, (b)Pulse waveform.

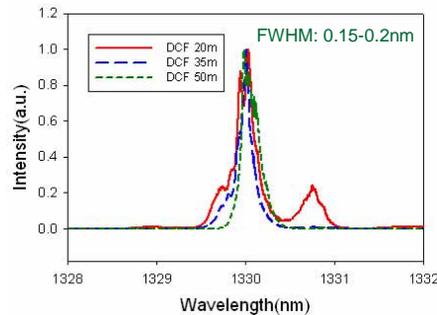


Fig. 6. Static optical spectra.

It is confirmed in both theory and experiment that the tuning range is wider with the shorter DCF. However, when the DCF is too short, an instantaneous spectral bandwidth of the lasing spectrum becomes broad due to a small dispersion. Equation (2) shows that decrease in dispersion in the cavity increases the tuning sensitivity, which means that the mode-locking is too weak to define a lasing wavelength. Figure 6 shows instantaneous lasing spectra at $\lambda = 1330$ nm with different lengths of DCF. The full-width half maximum (FWHM) of the lasing spectra are around 0.15-0.2nm for all cases, whereas the sideband is reduced and the spectral purity is enhanced as the DCF is longer.

4.2 Wavelength tuning rate

The lasing wavelength is swept by modulating the mode-locking frequency. A pattern of a RF modulation signal is shown in Fig. 7. A triangular waveform signal is applied as a modulation signal to sweep the lasing wavelength linearly. In the up-scan range where the frequency changes lower to higher, the lasing wavelength shifts toward longer wavelength, whereas in the down-scan range where the frequency higher to lower, the lasing wavelength shifts toward shorter wavelength. One period of a sweep corresponds to the area covered by a square in Fig. 7.

Figure 8 shows the results when the mode-locking frequency is modulated so as to cover the range where only one wavelength is lased when a 20 m-long DCF is inserted. Optical spectra (left) are measured using an optical spectrum analyzer at the peak-hold mode, and temporal waveforms are measured using an oscilloscope. The laser can be operated at a different sweep rate, 1 kHz, 50 kHz, 100 kHz, 200 kHz. The laser is periodically swept over 105 nm range at a sweep rate as high as 1 kHz. As the sweep rate increases, both spectrum and temporal waveform are almost unchanged until a sweep rate as high as 50 kHz, but the tuning range gradually decreases at higher sweep rate. Tuning range of about 100 nm is achieved at a sweep rate as high as 100 kHz. A decrease in the tuning range at a high sweep rate is due to a decrease in the number of pulse roundtrips. At an edge of the SOA gain profile, a pulse can not be formed during the roundtrips in the cavity at a high sweep rate. Figure 9

shows a result when 35 m-long DCF is inserted. Tuning range of about 70 nm is achieved at a sweep rate as high as 1 kHz. As the sweep rate increases, tuning range was also gradually decreased and the temporal waveform changed. The sweep rate at which the tuning range begins to decrease is lower than that with the 20 m-long DCF because the total cavity length is longer. A decrease in the tuning range at the high sweep rate is also due to a decrease in the number of pulse roundtrips.

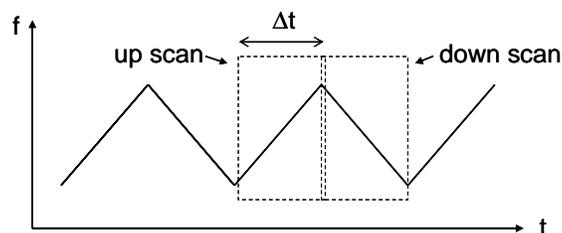


Fig. 7. RF modulation signal waveform.

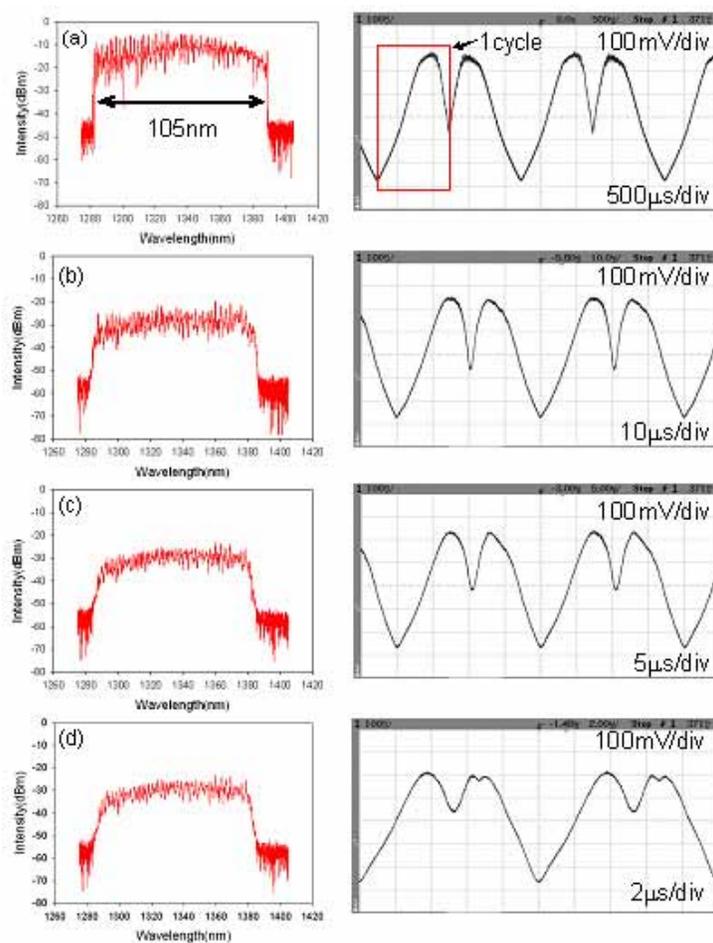


Fig. 8. Characteristics of the swept laser (DCF 20 m) (a) 1 kHz, (b) 50 kHz, (c) 100 kHz, (d) 200 kHz.

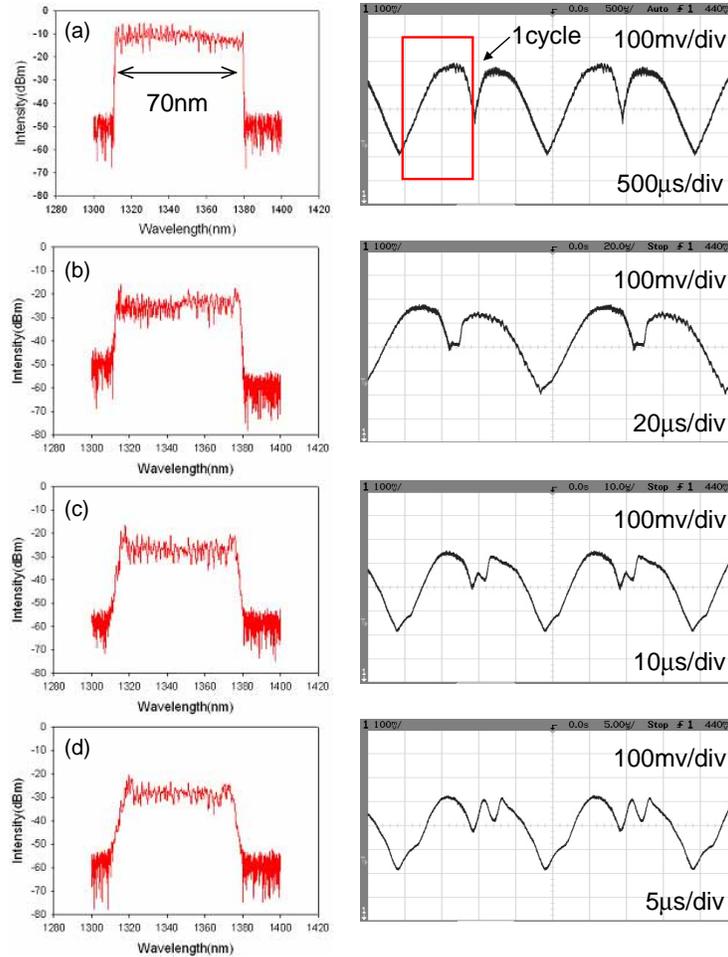


Fig. 9. Characteristics of the swept laser (DCF 35 m) (a)1 kHz, (b)20 kHz, (c)50 kHz, (d)100 kHz.

4.3 Tuning linearity

A lasing wavelength is in proportion to a mode-locking frequency as shown in section 4.2. A lasing wavelength can be swept linearly by applying the modulation waveform in which modulation frequency changes linearly. We measure a tuning linearity of the laser under the sweep operation. It is measured by using a fiber Fabry-Perot interferometer (FFPI). Experimental setup is shown in Fig. 10. By measuring a temporal response of each peak of a FFPI, we can measure a tuning linearity of the laser.

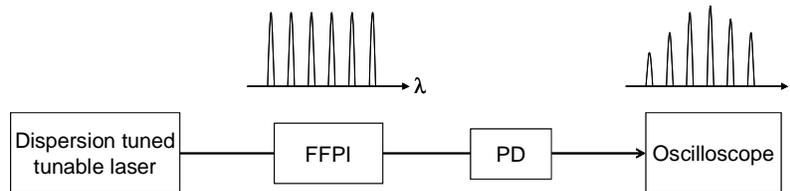


Fig. 10. Experimental setup for measuring a tuning linearity.

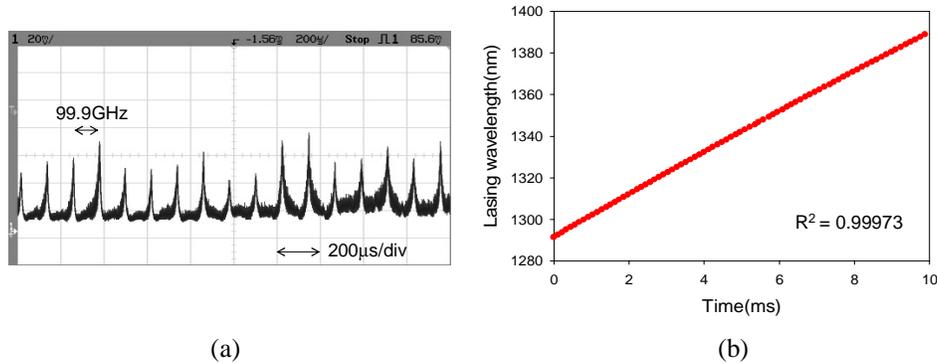


Fig. 11. Result of measuring a tuning linearity (a)Temporal waveform of the laser after FFPI, (b)Measured linearity.

A characteristic of the FFPI is as follows, FSR is 99.9 GHz, 3 dB bandwidth is 13.48 GHz, and finesse is 7.41. We measure a tuning linearity of the laser at a sweep rate of 100 Hz which is a resolution limit rate of the oscilloscope. Temporal waveform is shown in Fig. 11(a), and calculated linearity is shown in Fig. 11(b). Temporal waveform has a little noise because the bandwidth of the laser is not so narrow that each temporal peak contains a element of multiple spectral peaks of the FFPI. Each periodic temporal peak means each transmission peak of the FFPI. The laser can tune the lasing wavelength linearly under a sweep operation at a sweep rate of 100 Hz.

5. Summary

We demonstrated a wide and fast wavelength tunable mode-locked fiber laser using dispersion-tuning technique. By using an SOA as a gain medium and inserting a DCF for increasing a dispersion in the cavity, tuning range of over 100 nm was achieved. By modulating the mode-locking frequency, the laser could be swept over 100 nm at a sweep rate as high as 200 kHz. Although the tunable range of mode-locking frequency is limited due to the rational mode-locking, we confirmed that a wider tuning range is obtained by using a shorter DCF. However there is a trade-off between the tuning range and the instantaneous spectral bandwidth.

The sweep rate of our proposed dispersion-tuned mode-locked laser is limited only by the cavity length. It has a potential of faster sweep by using a dispersive element which can provide a higher dispersion with a short length. The proposed laser has a wide tuning range and a high sweep rate, and we expect that it is applicable as a light source for OCT, fiber sensors and so on.