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Wavelength tuning of 1/2-rational harmonically mode-locked pulses in a cavity-dispersive fiber laser

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We investigate electrical wavelength tuning of a cavity length dispersive fiber ring laser operated in the 1/2-rational harmonic mode-locking condition. By changing the modulator frequency around the optimum mode-locking frequency, a tuning range of 10.45 nm with a tuning rate of 0.067 nm/kHz is achieved. The repetition rate of the mode-locked pulses is twice the modulation frequency (~1 GHz) and the extinction ratio of the laser spectrum during the full tuning range is above 30 dB. Compared with the conventionally harmonic mode locking, the tuning range is about half reduced but the tuning rate has a same value. The variation of the modulation frequency and the length of the dispersion compensation fiber has a same effect on the wavelength tuning as in the case of conventionally harmonic mode-locking. © *1998 American Institute of Physics.*
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Tunable giga-hertz optical pulses are useful for wavelength-dependent instrumentation. The applications include the time-resolved spectroscopy, the remote sensing using absorption spectroscopy, and the measurement of optical components in wavelength division multiplexed systems. Mode-locked erbium-doped fiber lasers are good candidate as such sources. The generation of tunable picosecond pulses from such lasers by using spectral filters like Fabry–Perot etalons,[1] acousto-optic filters,[2] and fiber Blagg gratings[3] have been reported. Recently, Tamara and Nakazawa reported a conventionally harmonic mode-locked fiber laser self synchronized to an external clock by dispersion caused self tuning.[4] Unlike other schemes, no spectral selective components are required. The laser wavelength can be simply tuned by changing the rf driven frequency. Here we investigate the wavelength tuning of a 1/2-rational harmonically mode-locked fiber laser using the same dispersive tuning scheme. A tuning range of ~10 nm is realized at about 1 GHz electrical modulation frequency and providing a ~2 GHz optical pulse train.

The experimental setup is shown in Fig. 1, which is similar to the configuration of a conventional fiber ring laser except that there is no wavelength selective device besides a section of dispersion compensation fiber (DCF). The DCF has a positive dispersion coefficient of $D = -89.6$ ps/nm/km at 1.55 μm. It introduces a wavelength-dependent group velocity delay and equivalently a wavelength-dependent cavity length. Different round trip time will correspond to different operating wavelengths. By electrically changing the mode-locking frequency, one can thus tune the laser output wavelength.

In this work, the laser is operated in the state of rational harmonic mode-locking (RHML). In such a state, the driving frequency of the electrical modulation signal is not exactly equal to the cavity round trip frequency Δf or its integer multiples. It is detuned by $\pm\Delta f/n$ (n is an integer number) from the pth harmonic. As a result, the repetition rate of the mode-locked pulses is increased to $(np\pm1)\Delta f$ due to the interaction between the circulating pulses and the cavity loss modulation.[5] The advantages of this method include the repetition rate enhancement and a stable operation against the change of the modulator bias voltage.[6] However, the existence of higher pth harmonics in the case of $n\geqslant3$ results in an additional amplitude modulation of the mode-locked

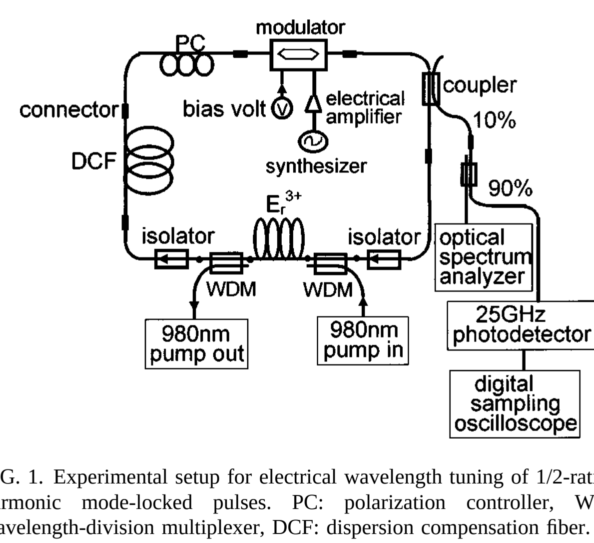

FIG. 1. Experimental setup for electrical wavelength tuning of 1/2-rational harmonic mode-locked pulses. PC: polarization controller, WDM: wavelength-division multiplexer, DCF: dispersion compensation fiber.

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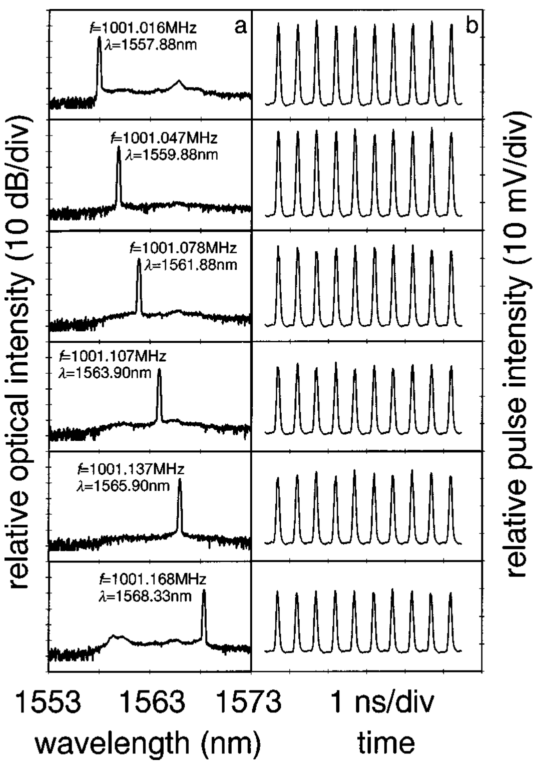

FIG. 2. Wavelength tuning of the mode-locked pulses at the 1/2 detuning from 1191th harmonic. (a) Optical spectrum, (b) corresponded pulse train.

pulses. Without employing further amplitude equalization schemes, it will be more practical to operate at $n=2$ as the case in our study.

The cavity gain is provided by a 10 m long erbium fiber with a doping concentration of 100 ppm and a pump with a maximum available power of 90 mW. A $LiNbO_3$ intensity modulator driven by an electrically amplified sinusoidal rf signal is used to provide active mode locking. Two isolators are used to prevent parasitic oscillations caused by intracavity reflections. The laser output is characterized by an optical spectrum analyzer (0.1 nm resolution) and a 25 GHz photodector connected to a 40 GHz sampling oscilloscope. When the laser is operated in cw, a longitudinal mode spacing of 0.84 MHz is observed by using a rf spectrum analyzer. Driven by around 23 dBm rf power at a suitable rf frequency, the laser is mode locked in the 1/2-RHML.

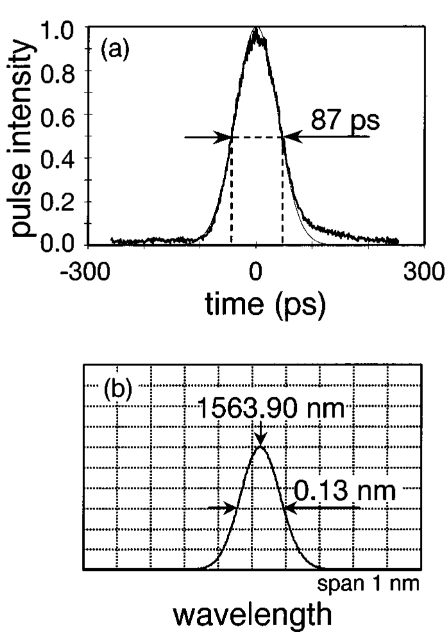

FIG. 3. Normalized wave form and its linear spectrum of the typical mode-locked pulses at optical wavelength 1563.90 nm and rf frequency 1001.107 MHz. The thin curve in (a) shows Gaussian wave form.

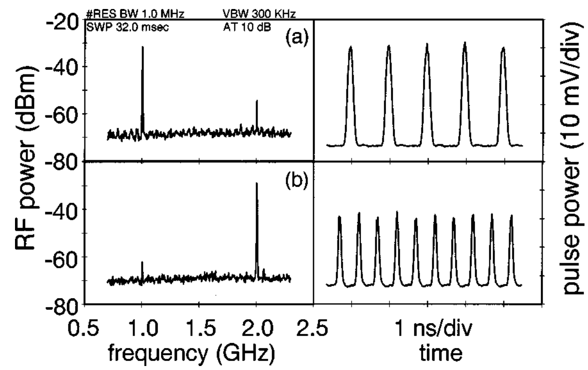

FIG. 4. Output performance comparison of the conventional harmonic and the 1/2-rational harmonic mode locking, where (a) is the rf spectrum of the 1191th harmonic mode locking (modulation frequency 1000.687 MHz) and (b) is that of the 1/2 detuning of the 1191th harmonic (modulation frequency 1001.107 MHz). Their corresponded mode-locked pulse trains are shown on the left.

Figure 2 shows the tuning and their corresponding pulse trains near 1/2 detuning of the 1191th harmonic, where 200 m Corning DCF is used. The tuning range is 10.45 nm (from 1557.88 to 1568.33 nm) corresponding to the modulation frequency F from 1001.016 to 1001.168 MHz. Within the tuning range, the extinction ratio of the output spectra is larger than 30 dB. Since there is no spectral filtering device placed in the ring, the mode-locked modes always have to compete with the cw modes which are inherently around the gain peak. As a result, the mode locking at other matched wavelengths is inevitably subject to be suppressed, especially at the edge of the gain band, and thus the tuning range is limited. Therefore, a relatively flattened cavity gain with a large bandwidth is desirous for getting a larger tuning range. This can be realized by adjusting the in-line polarization controller to depress the cw mode gain through some accumulated birefringence along the whole loop and the polarization-dependent transmission of the modulator. In the continuous tuning process the polarization controller is optimized and kept unchanged. Any other polarization settings

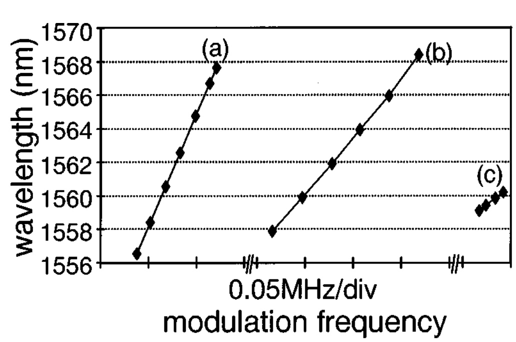

FIG. 5. Plot of the laser wavelength versus modulation frequency with 1/2 detuning at different harmonics, where (a) is from 500.288 to 500.371 MHz corresponding to the 1/2 detuning of the 595th harmonic, (b) is the case shown in Fig. 2, and (c) is from 1550.917 to 1550.942 MHz corresponding to the 1/2 detuning of the 1786th harmonic.

TABLE I. Comparison of the wavelength tuning for different fiber length.

Fiber length (m)	Tuning range (nm)	Tuning rate (nm/kHz)	Pulse width (ps)	Modulation frequency (MHz)
100	2.13 (1558.42–1560.55)	0.074	76	1002.775–1002.804 (29 kHz)
200	10.45 (1557.88–1568.33)	0.068	90±5	1001.016–1001.168 (152 kHz)
400	9.75 (1557.64–1567.39)	0.063	110±5	1000.225–1000.379 (154 kHz)

give different smaller tuning ranges. Simultaneous multi-wavelength mode locking which will limit the tuning range has appeared in conventionally harmonic mode locking (CHML).[4] However, this phenomenon is not observed in our 1/2-RHML.

Unlike CHML, the repetition rate (~2002 MHz) of the 1/2-RHML pulse train is twice the rf driven frequency as shown in Fig. 2(b). Within the tuning range, there is a variation of the pulse width (HWHM) from 86 and 95 ps, and of the average power from 263 and 352 μW, which corresponds to peak power variation from 1.5 to 2 mW. This variation is caused by the slight deviation of the cavity gain away from the gain peak. Figure 3(a) shows the typical shape of a normalized pulse, where $\lambda = 1563.90$ nm and $F = 1001.107$ MHz. The wave form fits well with a Gaussian shape (thin line) except the curve near the trailing edge, which may be caused by some imperfect mode-locked blue spectral components with slow speed. As shown in Fig. 3(b), spectral linewidth of the pulses is 0.13 nm (~16 GHz). The pulses can be compressed by passing them through a length of anomalous dispersion fiber. In our experiment, an 11.2 km long standard single mode fiber with a dispersion of $D = 17$ ps/nm/km can compress the pulse from 87 to 65 ps. The result shows that the 1/2-rational harmonically mode-locked pulse is partially chirped which is caused by the dispersive nature of the laser cavity.

Under exactly the same operation condition, the tuning range for the CHML (~ the 1191th harmonic) is about 20 nm (corresponding to modulation frequencies from 1000.557 to 1000.857 MHz).[7] Figure 4 illustrates the difference between the 1/2-RHML operation and the CHML operation, where the rf center frequencies of the mode-locked pulses are 1000.739 and 1001.107 MHz for the CHML and 1/2-RHML, respectively. In the 1/2-RHML case, the repetition rate is twice and the pulses suffer a modulation loss every other round trip, the output power and the tuning range is thus reduced to about half of that of the CHML case. It is worth while to note that the laser gives very stable mode locked pulses in both the cases, which can be seen clearly from their rf spectra.

Figure 5 shows the wavelength tuning curves of the 1/2-RHML at the modulation frequency around (a) 500 MHz, (b) 1000 MHz, and (c) 1550 MHz, respectively. The widths of the corresponding mode-locked pulses are (a) 130±5 ps, (b) 87±5 ps, and (c) 65±5 ps, respectively. The tuning curves are very linear and the measured tuning rates are 0.134±0.001, 0.067±0.001, and 0.042±0.001 nm/kHz, respectively. The results show that the tuning rate is not changed for both the cases at a same harmonic though the generation process of the 1/2-RHML is different from the CHML. Therefore, the tuning rate of the 1/2-RHML can also be expressed as $\delta\lambda/\delta F \cong -N/F_N^2 D L_{\mathrm{DCF}}$, where N is the harmonic order, L_{DCF} is the length of the DCF, and F_N is the modulation frequency corresponded to Nth harmonic. At a higher modulation frequency, the effective cavity gain is correspondingly reduced by the increase of the number of optical pulses in the cavity. Thus, the tuning range becomes smaller. This can be clearly seen from (c) where the tune range is only ~1 nm around the gain peak.

The wavelength tuning at different fiber (DCF) lengths is also studied. The results are shown in Table I. A longer fiber length generates a larger dispersion-induced pulse broadening and thus a longer mode-locked pulse. Similar to the CHML case, this tendency is clearly seen in the table. The variation of the tuning range with the fiber length is also similar to the CHML case.[7] There is an optimized DCF length. Shorter than that, the tuning range will be limited by the amount of the available dispersion provided by the DCF. Longer than that, the DCF will expand the optical pulses and make the modulator equivalently lossy. The result will be a reduction of both the gain curve and the tuning range.[7] Finally, it should be stressed that though the tuning range of the 1/2-RHML is only approximate half of that of the CHML, the extending of it to cover the whole gain band of the erbium fiber is still possible if increasing the pump power and/or using high doping active fiber.

In conclusion, the precise dispersion tuning of a 1/2-RHML fiber laser is demonstrated in a dispersion dependent laser cavity by changing modulation frequency. A tuning range of 10.45 nm with an extinction ratio of more than 30 dB around ~1001 MHz modulation frequency is realized. The mode-locked pulses are two times multiplied and the width is much narrower than that of the corresponding CHML. However, the tuning rates are same in both the operation states. The tuning performance under different modulation frequency and different length of DCF are also studied. The laser is stable and its wavelength can be easily and precisely tuned. Therefore, it is expected to be useful in many practical wavelength related applications.

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