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Stable Pulse Generation from a Rational Harmonic Mode-Locked Fiber Ring Laser Using Carrier-Suppressed Return-To-Zero Modulation Format

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Abstract:

Using carrier-suppressed return-to-zero modulation format, we find stable pulse generation from a rational harmonic mode-locked fiber ring laser, the repetition rate of which is 20 GHz with the rational harmonic order of two.

1. Introduction

Optical time division multiplexing (OTDM) used for high speed optical communications needs an optical short pulse source with a high and stable repetition rate. Rational harmonic mode-locked fiber ring lasers can generate optical short pulses at a high repetition rate using a moderate modulation frequency [1]. However, the rational harmonic mode-locking has a problem of the pulse amplitude fluctuation, the origins of which are categorized into two classes. One is the fluctuation that forms a fixed pattern repeating in each modulation cycle. The other is the stochastic fluctuation, caused either by the change of the cavity length due to the temperature drift or by the competition between pairs of phase-locked modes. In particular, the patterned fluctuation is unique to rational harmonic mode locking, and should be suppressed using a special technique [2, 3].

We experimentally demonstrate the generation of a stable pulse train from a rational harmonic mode-locked laser using carrier suppressed return-to-zero (CS-RZ) format as a modulation waveform [4]. The most stable pulse is generated at the rational harmonic order of two achieving 20GHz repetition rate.

2. Pulse generation and modulation format

Let us consider a ring cavity with the cavity length of L. The fundamental frequency of the cavity, f_c, is given as

$$f_c = c/(L n_{\mathrm{eff}}), \tag{1}$$

where c is the velocity of light in vacuum, n_{eff} is the effective refractive index of the cavity. Harmonic mode-locking can be achieved if the modulation frequency f_m is an integer multiple of f_c, i.e.,

$$f_m = n\, f_c, \tag{2}$$

where n is an integer called harmonic order. This modulation frequency is equal to the pulse repetition rate. If we detune the modulation frequency by a fraction of f_c, i.e.,

$$f_m^{'} = (n + \tfrac{1}{p})\, f_c, \tag{3}$$

where p is an integer, then we can achieve rational harmonic mode-locking. The integer p is called rational harmonic order. This frequency detuning introduces time shift to pulses against the modulation waveform, and the self-consistency of the cavity field is achieved after p round-trips. In the laser output, we find p pulses within one modulation period, thus the repetition rate is

$$f_m^{''} = (pn + 1)\, f_c. \tag{4}$$

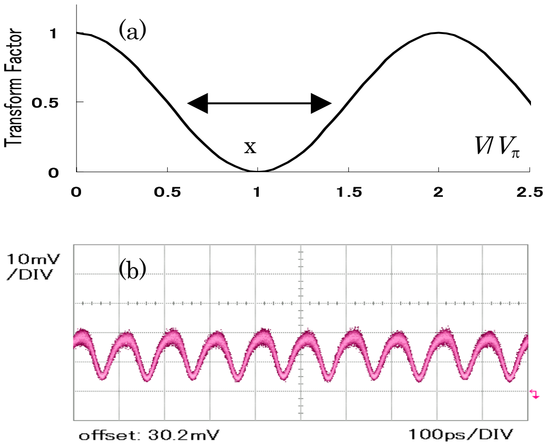


Figure 1: (a) Theoretical switching curve of a LN modulator, (b) CS-RZ waveform traced by oscilloscope.

Carrier suppressed return-to-zero (CS-RZ) is the signal format, in which the phase of adjacent symbols alternates between zero and pi. To obtain the CS-RZ format, we should bias the LN intensity modulator at the minimum transmission point (point x in Fig. 1 (a)), and keep the voltage swing within twice of V_π, the half wavelength voltage of the modulator. In Fig. 1 (b), we show an oscilloscope trace of the CS-RZ signal obtained from 10 GHz RF signal, where we use the same LN modulator as that used in the laser experiment described below.

3. Experimental set-up

The experimental set-up is shown in Fig. 2. The laser cavity in this system consists of an LN intensity modulator, the insertion loss of which is 2.7 dB (EO-space, 12.5 Gb/s, zero-chirp), a variable delay line, an amplifier, an optical band pass filter and a 10 % output coupler. The amplifier consists of a 20 m bi-directionally pumped erbium-doped fiber amplifier and a semiconductor optical amplifier (COVEGA, BOA567). All components are featured polarization maintaining. The laser output is split in two arms. One is directed to an optical spectrum analyzer, and the other is directed to a high speed photo-detector (bandwidth ≥ 50GHz)

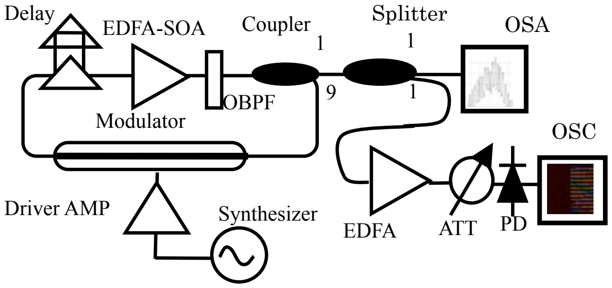
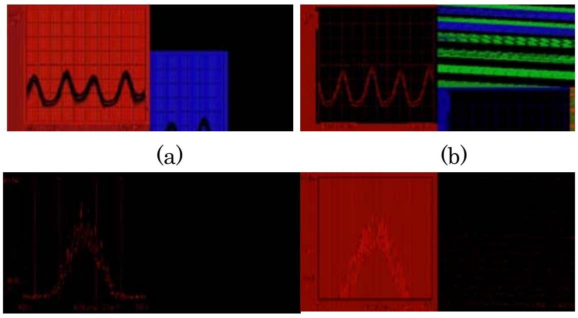


Figure 2: Experimental set-up. ATT: Attenuator, PD: Photo Detector, OBPF: Optical Band Pass Filter, EDFA: Erbium-Doped Fiber Amplifier, SOA: semiconductor optical amplifier, OSA: Optical spectrum analyzer, OSC: Oscilloscope.


(a) (b)

(c) (d)

Figure 3: Oscilloscope traces (a), (b) and optical spectrum (c), (d) at rational harmonic order of two. (a), (c): sinusoidally driven, (b), (d): CS-RZ driven.

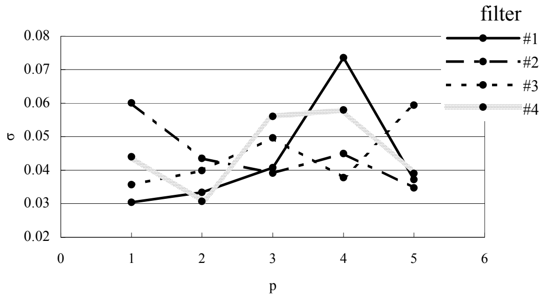


Figure 4: Stability of harmonic (p=1) and rational harmonic (p=2, 3, 4, 5) mode-locked lasers for various band pass filters.

connected to a sampling oscilloscope. An optical pre-amplifier (Furukawa, ErFA1215) is employed in the latter arm to obtain a clear view in the oscilloscope.

To achieve rational harmonic mode-locking, we manipulate the modulation frequency around 10 GHz with a step of 10 kHz. As an optical band pass filter, we tested four filters, #1: bandwidth (BW) 3nm (OPTQUEST, 0507C067), #2: BW 1nm (OPTQUEST, T030908A), #3: BW 1nm (OPTQUEST, T030115A), #4: BW 1nm (KOSHIN, IFOS-1565B-1-1-PY-FS).

The stability of the output pulses is evaluated from oscilloscope traces by measuring V_{std} and T_{std}, the standard deviation of the pulse peak voltage and that of the pulse leading edge time, respectively. We introduce a figure of stability σ defined as

$$\sigma = \sqrt{\left(V_{\mathrm{std}}/V_0\right)^2 + \left(T_{\mathrm{std}}/T_0\right)^2} \;, \qquad (5)$$

where V_0 is the average voltage, T_0 is the modulation period (=100ps). To obtain the statistics, oscilloscope traces are accumulated during 5 seconds.

4. Results

As a driving waveform of p=2 rational harmonic mode-locked laser, we compare an ordinary sinusoidal format and the CS-RZ format in terms of the quality of the pulse train. Oscilloscope traces and optical spectrum are shown in Fig. 3, where (a) and (b) are output waveform of the sinusoidally driven laser and that of the CS-RZ driven laser, respectively, and (c) and (d) are spectrum corresponding to (a) and (b), respectively. In these experiments we used the filter #4. The patterned fluctuation apparent in Fig. 3 (a) is relaxed in Fig. 3 (b). This tendency holds regardless of the type of the band pass filter. Whereas spectral peaks in Fig. 3(b) are spaced by 20 GHz, those in Fig. 3(d) are spaced by 10 GHz. This fact suggests the phase alternation in the output of the CS-RZ driven laser.

To examine stochastic fluctuation of the CS-RZ driven laser, we show in Fig. 4 the stability of the harmonic (p=1) and rational harmonic (p=2, 3, 4, 5) mode-locking for each band pass filter, where the stability figure σ is calculated using eq. (5). The smallest figures appear for p=1 with filter #1 and for p=2 with filter #4, where the figures are of the similar value. Thus, we can conclude that CS-RZ driven rational harmonic mode-locked lasers at harmonic order of two can show the similar stability as do ordinary harmonic mode-locked lasers.

5. Conclusion

We have experimentally demonstrated the generation of a stable pulse train in a rational harmonic mode-locked laser by using carrier suppressed return-to-zero (CS-RZ) format as a modulation waveform. Comparing the observed waveforms and spectrum, we have found the most stabilized pulse train for CS-RZ modulation format at rational harmonic order of two.

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