Photonic Generation of Microwave Signal Using a Rational Harmonic Mode-Locked Fiber Ring Laser

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***Abstract*—A novel method for microwave signal generation using a rational harmonic actively mode-locked fiber ring laser is proposed and demonstrated. The microwave signal is generated by beating the actively mode-locked longitudinal modes from the rational mode-locked fiber ring laser at a photodetector. The phases of the longitudinal modes are phased locked, which ensures a generated microwave signal with very low phase noise. In the proposed approach, the generated microwave signal has a frequency a few times higher than the microwave drive signal. Therefore, only a low-frequency reference source and a low-speed modulator are required. A rational harmonic actively mode-locked fiber ring laser is experimentally demonstrated. With a microwave drive signal at 5.52 GHz, a microwave signal with a frequency that is four times the frequency of the microwave drive signal at 22.08 GHz is generated. The generated microwave signal is very stable with a spectral width of less than 1 Hz.**

***Index Terms*—Fiber ring laser, microwave photonics, optical generation of microwave signal, radio over fiber, rational harmonic mode locking.**

I. Introduction

OPTICAL generation and distribution of millimeter-wave signals has many potential applications such as broad-band wireless access networks, radar, software-defined radio, and satellite communications, and has been intensively investigated over the past few years [1]–[8]. In general, the techniques to generate microwave signals in the optical domain can be divided into three categories, which are: 1) optical phase locking or injection locking of two laser diodes [1], [2] or the combination of the two [3]; 2) external modulation of a laser diode [4]–[6]; and 3) direct beating of dual-longitudinal or multilongitudinal modes of a laser at a photodetector (PD) [7], [8]. In the first category, two lasers are phase or injection locked to a microwave reference. The beating between the two phase-locked wavelengths can generate a millimeter-wave signal. Since the two wavelengths are phase locked, the beating signal will have low phase noise. In the second category, instead of using two laser sources, a single laser source is required. By modulating the laser output using an external modulator, a series of optical sidebands will be generated. To generate a microwave signal, only two sidebands are needed. Usually, an optical filter is used to select two optical sidebands. A system based on this method was demonstrated in [4]. A frequency-doubled electrical signal was optically generated by biasing the intensity modulator to suppress the even-order optical sidebands. A 36-GHz microwave signal was generated when the intensity modulator was driven by an 18-GHz microwave signal [4]. We have recently demonstrated a microwave generation system using an electrooptic phase modulator and a narrow-band fiber Bragg grating notch filter [6]. When the electrical drive signal is tuned from 18.8 to 25 GHz, two bands of millimeter-wave signals from 37.6 to 50 GHz and from 75.2 to 100 GHz with high quality were generated. In the third category, the output of a laser with dual-longitudinal or multilongitudinal modes is applied to a PD. For a dual-longitudinal-mode laser, the beating signal has a single frequency with signal quality depending on the property of the laser [7]. For a multilongitudinal-mode laser, the beating signal consists of a fundamental frequency, which is equal to the frequency spacing between two adjacent longitudinal modes, and many high-order harmonics. To ensure that those beating signals are stable and with low phase noise, mode-locking techniques are employed to phase lock the longitudinal modes. Both passive [9] and active [10] mode-locking techniques have been implemented. For microwave generation using passive mode locking, no reference source and high-speed modulator are required, which greatly simplifies the laser system and reduces the cost. However, the phase noise of the generated microwave signal is higher than that generated using an actively mode-locked laser [9]. In an actively mode-locked laser, however, to generate microwave signals at very high frequency, a high-frequency reference source and a high-speed modulator are required. To generate a microwave signal using a low-frequency reference source and a low-speed modulator, in this paper, we propose to use the rational harmonic mode-locking technique for microwave signal generation. Rational harmonic mode-locking technique has been investigated for optical communications systems to increase the repetition rate of an optical pulse train [11]. To the best of our knowledge, this is the first time that the rational mode-locking technique is proposed for microwave signal generation. To demonstrate the microwave generation capability, a rational harmonic actively mode-locked fiber ring laser is built. A major problem related to the rational harmonic mode-locking technique for microwave generation is the poor suppression of lower order harmonics. One solution to this problem is to use the nonlinear modulation technique. The nonlinear modulation technique was proposed to equalize the amplitude of a rational mode-locked pulse train [12]. For microwave signal generation, it is demonstrated that by biasing the intensity modulator in its nonlinear region, the lower order harmonics can be efficiently suppressed. In the experiment, a

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microwave signal at 22.08 GHz is generated when a microwave drive signal is tuned at 5.52 GHz. Lower order harmonics with amplitudes up to 24 dB lower than that of the generated microwave signal is achieved. The generated microwave signal is very stable with a spectral width less than 1 Hz.

II. Principle

A microwave signal can be generated by beating the longitudinal modes of a mode-locked laser. For a laser that is mode locked, the phases of the longitudinal modes are identical. Mathematically, the output of mode-locked laser can be expressed as

$$E(t) = \sum_{p=0}^{N} A_p \cos\left[2\pi(f_0 + p\cdot f_c)t + \theta_0\right] \tag{1}$$

where $E(t)$ is the electrical field of the laser output, N is the number of longitudinal modes in the laser, f_c is the frequency spacing between adjacent modes, and A_p and $f_0 + p\cdot f_c$ are the amplitude and frequency of the modes. The phases of the longitudinal modes are all locked to θ_0.

By applying the laser output to a PD, beating signals between the longitudinal modes will be generated. The photo-current generated from the PD can be expressed as

$$\begin{aligned} i &= RE^2(t) \\ &= R\left\{\sum_{p=0}^{N} A_p \cos[2\pi(f_0 + p\cdot f_c)t + \theta_0]\right\}^2 \\ &= R\sum_{p=0}^{N} A_p^2 \cos^2\left[2\pi(f_0 + p\cdot f_c)t + \theta_0\right] \\ &\quad + R\sum_{m<n} A_m A_n \Big\{\cos\left[2\pi(2f_0 + (m+n)f_c)t + 2\theta_0\right] \\ &\qquad + \cos\left[2\pi(n-m)f_c t\right]\Big\} \end{aligned} \tag{2}$$

where R is the responsivity of the PD. It can be seen from (2) that microwave signals at the frequencies of $k\cdot f_c (k = 1, 2, \ldots)$ are generated. Since the phases are locked, the beating between the longitudinal modes will cancel the phase terms, which ensures a generated microwave signal with low phase noise.

Mode locking can be achieved actively or passively. For passive mode locking, the frequency of the generated microwave signals is $k\cdot f_c (k = 1, 2, \ldots)$, where the cavity fundamental frequency f_c is determined by the optical length of the laser cavity. For a ring laser, we have

$$f_c = c/nL \tag{3}$$

where c is the light velocity in vacuum, n and L are, respectively, the refractive index and the length of the ring cavity.

For a fiber ring laser using erbium-doped fiber as gain medium, L is usually longer than 10 m to ensure a sufficient gain so that f_c can be less than 20 MHz. To generate a microwave signal that has a frequency at tens of gigahertz (say, 20 GHz), the cavity length must be smaller than 1 cm. This is not possible for a fiber ring laser. One solution to this problem is to use active harmonic mode locking. For active harmonic mode locking, the frequency of the generated microwave signals is equal to the frequency of the microwave drive signal applied to the modulator. This frequency can be tuned at Nf_c (N is an integer) so that mode locking at Nf_c and its multiples can be established. The key problem related to this approach is that the frequency of the generated microwave signal is limited directly by the speed of the intensity modulator. Currently commercially available intensity modulators can usually operate below 40 GHz. For many applications, such as the next-generation wireless access networks, the operating frequency can be in the 60-GHz band, the use of active mode locking to generate a high-frequency microwave signal will significantly increase the system cost, although a high-frequency microwave signal can be generated using an external modulation technique with a microwave drive signal having a frequency much lower than the generated microwave signal, and a low-speed external modulator [4]–[6]. However, the power of the generated microwave signal using external modulation technique is very low because of the low electrical-to-optical conversion efficiency at the external modulator. We propose to solve these problems by using a rational harmonic mode-locked laser. First, the microwave drive signal can have a frequency several times lower than the generated microwave signal, therefore, only a low-frequency reference source and a low-speed modulator are required. Second, the generated microwave signal is obtained by beating the laser output at a PD. The power can be much higher than using the external modulation technique.

The rational harmonic mode-locking technique has been investigated in recent years for communication systems to increase the repetition rate of optical pulse. Being different from conventional active harmonic mode locking, the modulating frequency f_m for a rational harmonic active mode-locked laser is slightly detuned from the exact harmonic of the laser cavity fundamental frequency f_c

$$f_m = (i + 1/j)f_c \tag{4}$$

where i is a positive integer and j can be either a positive or negative integer. It can be shown [11] that the repetition rate of the mode-locked pulse train is the lowest common multiple of the laser cavity resonance frequency and the microwave modulation frequency. The repetition rate is now

$$f_p = |j|f_m = (i|j| \pm 1)f_c. \tag{5}$$

Therefore, by beating the rational harmonic mode-locked laser output at a PD, the microwave signal that has a frequency that is $|j|$ times the microwave drive signal is generated.

III. Experiment

The schematic diagram of our experimental set up is shown in Fig. 1. An erbium-doped fiber amplifier (EDFA) is used in the laser cavity as a gain medium. An isolator (ISO) is incorporated to ensure a unidirectional operation of the ring laser. A JDS-Uniphase $LiNbO_3$ intensity modulator driven by a reference source is incorporated in the laser cavity to achieve active mode locking. A polarization controller (PC) is used to adjust the polarization state of the light into the $LiNbO_3$ intensity modulator. The mode-locked output is obtained from the 10% port

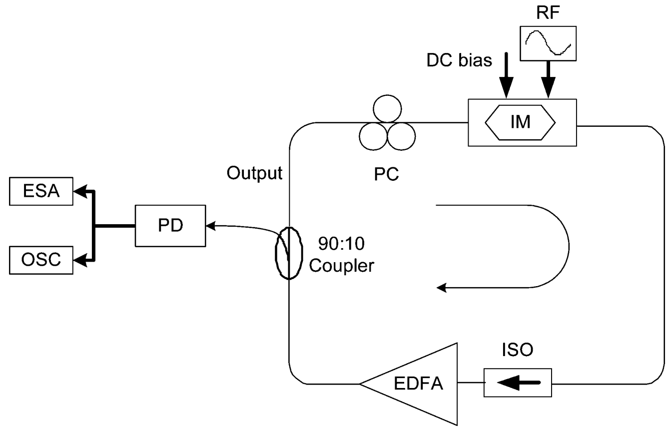

Fig. 1. Schematic diagram of the rational harmonic mode-locked fiber ring laser. PC: polarization controller, IM: intensity modulator, ISO: isolator, EDFA: erbium-doped fiber amplifier, PD: photodiode, ESA: electrical spectrum analyzer, OSC: oscilloscope.

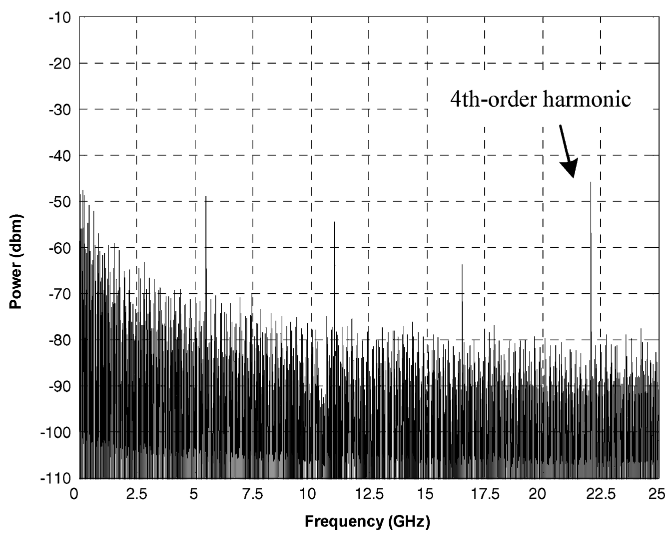

Fig. 2. Spectrum of the beat signal of a fourth-order rational harmonic mode-locked fiber ring laser.

of the 90 : 10 coupler, which is then sent to a 25-GHz PD. A beat signal is obtained at the output of the PD, which is displayed by an electrical spectrum analyzer and an oscilloscope.

In the experiment, the frequency of the microwave drive signal is set at 5.52 GHz. By slightly tuning the frequency of the microwave drive signal and adjusting the PC, rational harmonic mode locking is established. By applying the output to a PD, a microwave signal resulted from the beating between the mode-locked rational harmonics at 22.08 GHz is observed. The frequency of the generated microwave signal is four times higher than the frequency of the microwave drive signal. The spectrum of the beat signal is shown in Fig. 2.

As can be seen from Fig. 2, the amplitudes of the lower order harmonics are very high. By using a microwave bandpass filter centered at 22.08 GHz, the lower order harmonics can be removed. For many applications, however, the generated microwave signal is distributed over optical fiber to a base station. To simplify the base station design and to reduce its cost, it is desirable that the low-order harmonics can be eliminated in the optical domain. This can be implemented by using the nonlinear modulation technique. The principle of the nonlinear modulation technique for low-order harmonics suppression can be easily explained in the time domain. Assume that the laser is rational harmonic mode locked at the pth-order harmonic; the lower orders must be suppressed. In this situation, the laser output in the time domain is a pulse train with a repetition rate equal to the frequency of the pth-order harmonic. Fig. 3 shows a pulse train of a rational mode-locked laser with $p = 4$. If the low-order harmonics are not suppressed, then the lower order harmonics will contribute to the laser output. The effect is to make the pulse train with unequal amplitude. Fig. 3 shows a pulse train with unequal amplitude. For optical communications, the equalized pulse train is expected. A simple and efficient approach to equalize the amplitude of the pulse train, which is equivalent to suppressing the lower order harmonics, is to use nonlinear modulation.

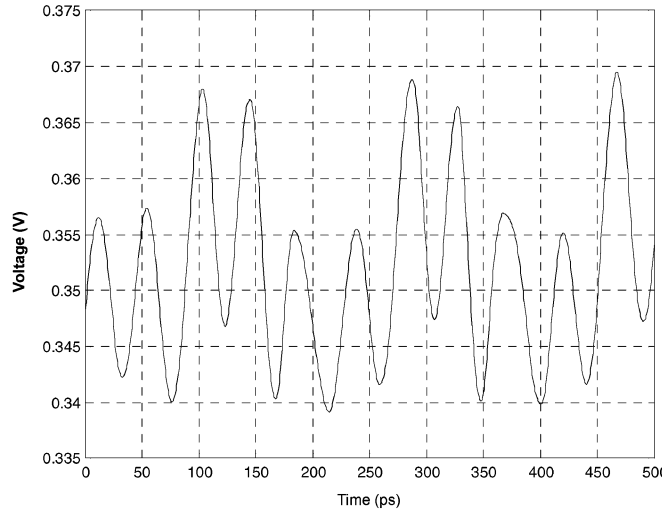

Fig. 3. Pulse train of the fourth-order rational harmonic mode-locked laser with unequal amplitude.

The analysis of the nonlinear modulation shows [12] that the transfer function of the modulator is

$$T(t) = (1-\alpha)\left\{1 + \sin\left[\pi\Big(b + M\cos\big(2\pi f_m t\big)\Big)\right]\right\} \quad (6)$$

where α is the insertion loss, b is the normalized bias point of the modulator, M is the normalized amplitude of the modulating signal, and f_m is the frequency of the microwave drive signal. This equation means that by choosing a different set of b and M, the transfer function of the modulator can have a different complex shape in one modulation cycle. If for a certain integer p, a suitable set of b and M is chosen so that there are p points in a modulation cycle having the same value of transmission, then the amplitudes of these p pulses must be the same. Thus, the amplitude of the pth-order harmonic pulses are equalized by the nonlinear modulation.

Fig. 4 shows the simulation results based on (6). The solid line is the transfer function of the modulator when $b = 1.5, M = 0.7$, and $f_m = 5$ GHz. The four stars indicate the four points with the same transmission on the transfer function curve. When the optical pulses pass the modulator at the time marked by these four points, the amplitude equalization for

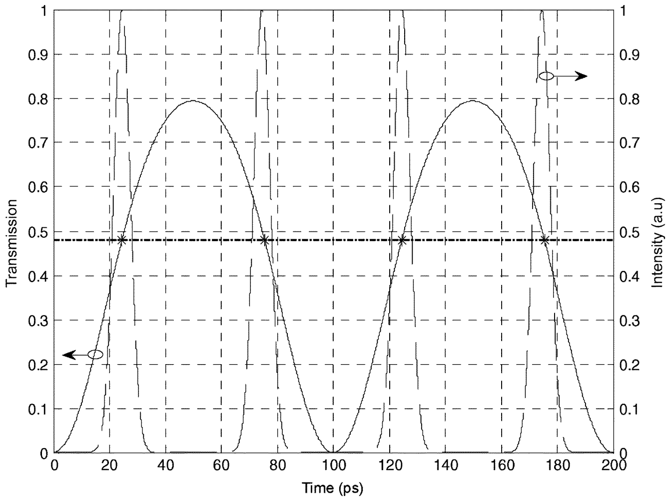

Fig. 4. Simulated transfer function of the modulator and the intensity of the pulse train for the fourth-order rational harmonic mode locking.

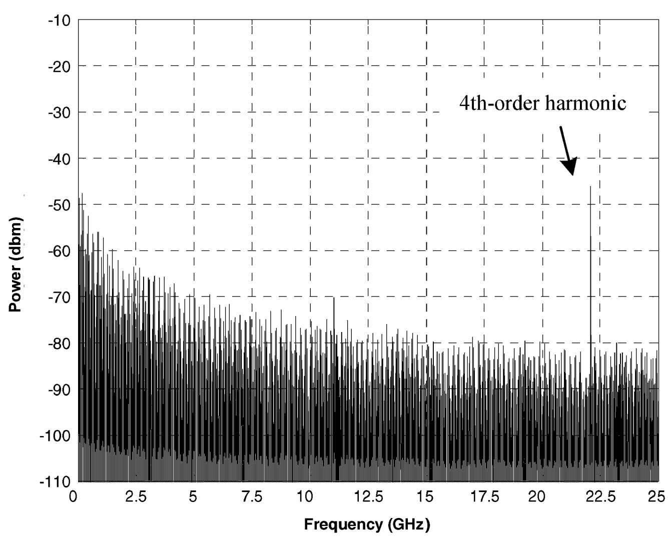

Fig. 5. Spectrum of the beat signal of the fourth-order rational harmonic mode-locked laser with suppressed lower harmonics by nonlinear modulation.

the fourth-order rational harmonic mode-locking is, therefore, realized. The dashed line shows the simulated intensity of the optical pulse train under this situation.

Based on above analysis, an experiment using nonlinear modulation to suppress lower order harmonics is performed. By carefully tuning the frequency of the modulating signal, a microwave signal at 22.08 GHz is generated. This frequency is the fourth-order harmonic of the frequency of the modulating signal, which is 5.52 GHz. The spectrum of the generated microwave signal is shown in Fig. 5.

Fig. 5 shows the beat signal measured by an electrical spectrum analyzer. It can be seen that the fourth-order harmonic frequency is 24 dB stronger than the fundamental and second-order harmonic frequencies. The third-order harmonic is totally suppressed, which is below the noise floor.

Since the generated microwave signal is resulted from the beating of the mode-locked longitudinal modes, the phase fluctuations between the longitudinal modes are completely cancelled. Fig. 6 gives a zoomed-in view of the spectrum of the generated microwave signal. As can be seen from Fig. 6, the generated microwave signal has very narrow spectral width. In the experiment, the linewidth reaches the resolution limit of the electrical spectrum analyzer, which is 1 Hz.

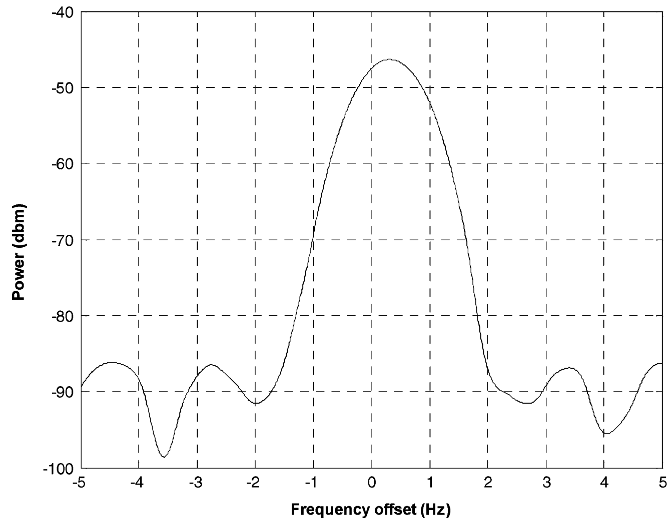

Fig. 6. Zoomed-in view of the spectrum of the generated microwave signal. Center frequency: 22.08137747 GHz.

IV. Conclusion

We have proposed and demonstrated a simple microwave photonic system to generate a microwave signal with low phase noise. The system was based on a rational harmonic mode-locked fiber ring laser in which the microwave drive frequency was slightly detuned from the exact harmonic of the laser cavity fundamental frequency to enable a rational harmonic mode locking. To suppress the lower order harmonics, the modulator was biased in its nonlinear region. A high-quality microwave signal at 22.08 GHz was obtained when a microwave drive signal at 5.52 GHz was applied to the intensity modulator. The significance of this approach is that by using a low-speed intensity modulator and a low-frequency reference source, a microwave signal that has a few times the frequency of the microwave drive signal with very low phase noise can be generated.

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