Quadruple-frequency millimeter-wave generation using second-order rational harmonic mode-locking technique

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A novel method for generating quadruple-frequency millimeter-wave (MMW) by using an actively mode-locked fiber ring laser is proposed and demonstrated. In this approach, the optical Mach-Zehnder intensity modulator (MZM) is biased to suppress the odd-order optical sidebands, the fiber laser operates in the second-order rational harmonic mode, and a fiber Bragg grating (FBG) notch filter is used to block the optical carrier. When the MZM is driven by a fixed radio-frequency (RF) source of 10 GHz, a stable MMW signal of 40 GHz with the phase noise better than −76 dBc/Hz at 1-kHz offset is generated.

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Recently, optical generation of millimeter-wave (MMW) has attracted considerable attentions for its potential applications such as millimeter radio-over-fiber (ROF) systems[1−4], radar, and other military and commercial applications. Several techniques have been proposed after intensive research over the past few years, including optical phase-locked loops[5], injection locking[6], external modulation of a laser diode[7,8], active mode-locking[9], rational harmonic mode-locking[10], and so on. For the phase-locked loops and injection locking techniques, very narrow linewidth (in kilohertz) lasers are required to suppress the high-frequency components of the phase noise[5,6]. External modulation technique is very attractive since very low phase noise can be achieved. By biasing the optical Mach-Zehnder intensity modulator (MZM) to suppress the even-order optical sidebands, a frequency-doubled MMW can be generated[7]. But in that approach, a high-frequency electrical source and a high-speed modulator are still required. In Ref. [8], a fiber Bragg grating (FBG) notch filter was introduced to external modulation technique. By biasing the MZM to suppress the odd-order optical sidebands and using the FBG to block the optical carrier, a quadruple-frequency MMW was achieved. However, this method requires high modulation depth to enhance the power of the second-order optical sidebands, which increases the requirement of the modulator. The active mode-locking technique as another MMW generation approach is usually employed to phase lock the longitudinal modes in the laser. It ensures that the beating signals generated by the longitudinal modes are stable and with low phase noise, but a high-frequency microwave source and a high-speed modulator are also required[9]. Recently, rational harmonic mode-locking technique has been demonstrated for MMW generation through a low-frequency microwave source and a low-speed modulator[10]. However, this method also requires high modulation depth to suppress lower order harmonics.

In this paper, we demonstrate a new approach for optical quadruple-frequency generation of MMW, which is based on the combination of the rational harmonic mode-locked technique and the nonlinear characteristics of MZM. The MZM in the actively mode-locked fiber ring laser is biased at the maximum transmission point to suppress the odd-order sidebands. Similar to Ref. [8], a FBG at the output of the laser is adopted to block the optical carrier so that two 2nd-order optical sidebands with four times frequency interval of the electrical modulating frequency are selected to generate MMW. To further suppress the odd-order sidebands, the fiber ring laser operates in the 2nd-order rational harmonic mode by tuning an optical variable delay line (VDL). Based on the above mechanism, experiments by using 10-GHz radio-frequency (RF) source and commercially available 10-GHz MZM with low modulation depth of ∼ 0.2 were carried out. According to the experimental results, the power of 2nd-order optical sidebands increased by ∼ 13 dB for 2nd-order rational harmonic mode operation compared with the actively mode-locked operation. Finally, by beating the two 2nd-order optical sidebands, a 40-GHz MMW with the phase noise better than −76 dBc/Hz at 1-kHz offset is achieved.

The experimental setup is shown in Fig. 1. An erbium-doped fiber amplifier (EDFA) with 16-m erbium-doped fiber (EDF) is used in the laser cavity as a gain medium.

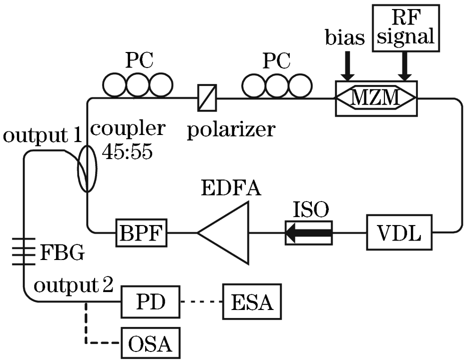

Fig. 1. Schematic diagram for optical generation of MMW signal. OSA: optical spectrum analyzer.

Two polarization controllers (PCs) and a polarizer are used to make sure that the polarization of the light in the cavity is equal to that in the MZM. An isolator (ISO) is incorporated to ensure a unidirectional operation of the ring laser. The bandpass filter (BPF) (OTF-300, Santec, Japan) with a 3-dB bandwidth of 0.6 nm is used to select the optical carrier wavelength. The tunable range and adjusting precision of optical VDL (VDL-001-35-60-NC-SS General Photonic, USA) are ~ 10 cm and 0.01 cm, respectively.

A ~10-GHz RF source (XKMVL100, Seekon Microwave, Chengdu) signal is applied to the MZM (JDSU SN-389581F, JDSU, USA) with the switching voltage V_π of ~ 5.3 V to achieve active mode locking. Usually, when the MZM is biased at ~ $V_\pi/2$ with low modulation depth, the intensity modulation frequency ω_{IM} is equal to the applied electric signal frequency ω_{E}, which is called linear modulation of MZM. If $\omega_{\mathrm{IM}} = N \cdot \omega_{\mathrm{E}}$ $(N = 2, 3, \cdots)$ is required, the MZM should be biased at maximum/minimum transmission point or high modulation depth (> 1) is applied as reported in Ref. [10], which is called nonlinear modulation. In our approach, the MZM is also biased at the maximum transmission point to suppress all the odd-order sidebands. But a rather lower modulation depth of ~ 0.2 is adopted so that the optical carrier and 2nd-order sidebands are obtained at the 45% port of the 45:55 coupler (output1 in Fig. 1). A FBG is set after ouput1 while the reflection ratio and 3-dB bandwidth are 98% and 0.1 nm, respectively. When adjusting the BPF to select the wavelength of the optical carrier equal to the central wavelength of the FBG, the optical carrier is blocked so that two 2nd-order optical sidebands with four times frequency interval of the electrical modulating frequency are selected. Then a beat signal can be generated in the photodetector (PD) and measured by the electrical spectrum analyzer (ESA).

By tuning the VDL, the fiber ring laser could operate in conventional active mode-locking or rational harmonic mode-locking. Theoretically, both cases can support even-order optical sidebands oscillating in fiber laser, so quadruple-frequency MMW is generated by the two kinds of mode-locking.

The cavity resonance frequency was 2.8 MHz which corresponded to the ring cavity length of ~ 72 m, and the modulating frequency was fixed at 9999.87 MHz. At first, the MZM was biased at the linear point of the transmission curve. By carefully tuning the VDL to make the modulating frequency equal to N times of the cavity resonance frequency[9,11], a conventional actively mode-locked fiber ring laser was established. The spectrum of the fiber laser at output1 was measured by the optical spectrum analyzer (OSA, AQ6317, ANDO, Japan), as shown in Fig. 2(a). It was observed that odd-order and even-order optical sidebands were both oscillating in the ring laser. Then the MZM was biased at its maximum transmission point to suppress the odd-order optical sidebands, and the spectrum of two 2nd-order optical sidebands plus the optical carrier was achieved, as shown in Fig. 2(b). However, as can be seen from Fig. 2(b), for the conventional actively mode-locked fiber ring laser, the power of the 2nd-order sidebands is quite small, which suggests that the intermedial odd-order sidebands is still strong enough so that the gain competition occurs between the odd-order sidebands and the second-order ones in the EDFA.

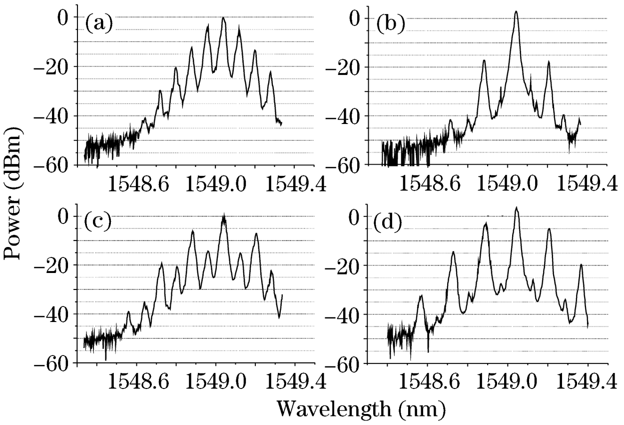

Fig. 2. Spectra at output1. (a) MZM biased at linear point of the transmission curve and (b) MZM biased at the maximum transmission point with conventional active mode-locking; (c) MZM biased at linear point of the transmission curve and (d) MZM biased at the maximum transmission point with 2nd-order rational harmonic mode-locking.

Then, the MZM was biased at the linear point of the transmission curve again. By further slightly tuning the VDL, the fiber ring laser operated in the 2nd-order rational harmonic mode[10,12]. Figure 2(c) shows the spectrum. In this case, the odd-order sidebands did not match the cavity resonance mode so these sidebands would be suppressed while the even-order sidebands kept oscillating. When the MZM was biased at maximum transmission point once again, the odd-order sidebands can be further suppressed, and the spectrum is shown in Fig. 2(d). Compared with Fig. 2(b), it can be observed that the power of second-order sidebands increased for ~ 13 dB. It indicates that in the 2nd-order rational harmonic mode, the odd-order sidebands are effectively suppressed so that their competitions against the even-order sidebands in the EDFA are almost negligible.

Based on the above results, 2nd-order rational harmonic mode-locking with the MZM biased at its maximum transmission point was adopted to generate the even-order sidebands. At the output of fiber ring laser, a FBG was used to block the optical carrier. The spectrum at output2 is shown in Fig. 3. It can be observed that 2nd-order sidebands with wavelength interval of 0.32 nm

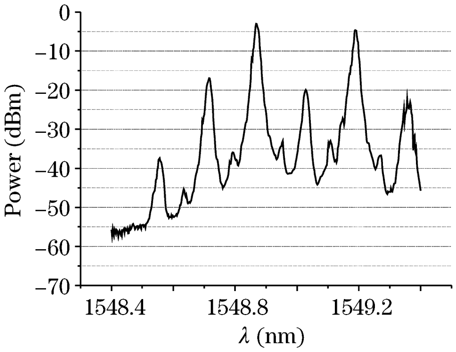

Fig. 3. Spectrum at output2 in the operation of 2nd-order rational harmonic mode-locking with the MZM biased at its maximum transmission point.

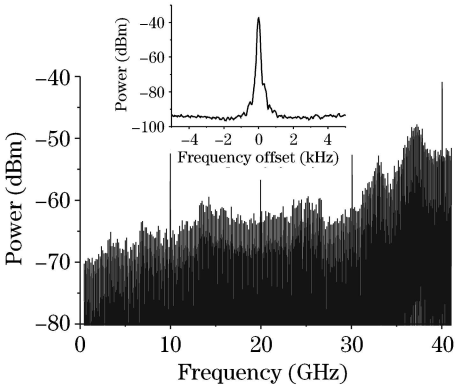

Fig. 4. Spectrum of the beat signal of the output after FBG. Inset is the zoomed-in view of the generated MMW at ∼ 40 GHz.

(∼ 40 GHz) are obtained and the power level is 15 dB stronger than that of other sidebands.

The output lights were detected by using a 50-GHz-bandwidth PD (U^2T XPDV2120R, U^2T, Germany), and then measured by an ESA (E4446A, Agilent, USA). The results of the beat signal are shown in Fig. 4. It can be seen that the quadruple frequency (40 GHz) is at least 12 dB higher than the harmonics at 10, 20, and 30 GHz, so the quadruple frequency modulation is successful.

The phase noise was measured by zoom in the spectrum around 40 GHz with 10-kHz span and 10-Hz resolution. As shown in the inset in Fig. 4, the measured phase noise is better than −76 dBc/Hz at 1-kHz offset, which is good enough for many applications.

In conclusion, we have proposed and demonstrated a simple method to generate a quadruple-frequency MMW signal with low phase noise. The method was based on the nonlinear characteristics of MZM and the rational harmonic mode-locking technique. A millimeter signal at 40 GHz with the phase noise better than −76 dBc/Hz at 1-kHz offset was obtained when the electrical source was fixed at ∼ 10 GHz. It was experimentally validated that the odd-order optical sidebands were further suppressed in the 2nd-order rational harmonic mode compared with the conventional active mode-locking mode when the MZM was biased at its maximum transmission point. This approach does not need a special tunable filter or a MZM with high modulation depth, which makes it easy to generate quadruple-frequency MMW signals.

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