Effective generation of optical quadruple frequency millimeter-wave based on fiber laser using injection rational harmonic mode-locked technique

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A method to generate the optical quadruple frequency millimeter-wave with high power efficiency is proposed and demonstrated based on the combination of the injection 2nd-order rational harmonic mode-locked fiber ring laser technique and the fiber grating notch filter. In this approach, the fiber Bragg grating notch filter is inserted into the laser cavity to prevent the undesired optical carrier, so that the pump power can be converted to 2nd-order harmonic wave more efficiently. In our experiment, the power efficiency of optical quadruple frequency millimeter-wave (40 GHz) generation is ten folds of that of our previous method based only on the rational harmonic mode-locked technique.

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Recently, optical generation of millimeter-wave (mm-wave) is of great interest for its potential applications in millimeter radio-over-fiber systems, radar and other military or commercial areas[1,2]. Several techniques have been proposed after intensively research over the past few years, including optical phase-locked loops[3], injection locked technique[4], external modulation of laser diode[5], rational harmonic mode-locked (RHML) technique[6], and so on. Among these techniques, RHML technique is attractive since the optical millimeter-wave with low-phase-noise can be achieved without the high-frequency micro/millimeter-wave source and modulator. For example, the fourth-order RHML technique is adopted to obtain 22.08-GHz millimeter-wave using 5.02-GHz microwave source[7]. However, high-order RHML technique needs the precise match between the frequency of driving source and the frequency interval of longitudinal modes in the fiber laser, which requires accurate control. In our previous work, an approach was proposed for generating the optical quadruple frequency millimeter-wave, where 2nd-order RHML technique was used and a fiber Bragg grating (FBG) notch filter at the output of fiber laser was adopted to prevent the optical carrier so that ±2nd-order harmonic waves with four times frequency interval were selected to generate millimeter-wave[8]. Although the method is simple and stable, the power efficiency is poor because the optical carrier in fiber laser is not utilized for the generation of mm-wave but filtered out by the FBG notch filter.

To improve the power efficiency, a novel method based on injection 2nd-order RHML is proposed and demonstrated in this letter. Different from previous 2nd-order RHML, the FBG notch filter is inserted into the cavity to prevent the optical carrier being amplified, and a light is injected into the fiber laser to provide the new optical carrier used for generating harmonic wave in the intensity modulator, so the pump power will not be consumed by the amplifying optical carrier. When the method is applied to generate 40-GHz optical millimeter-wave, according to the results, the power efficiency can be improved 10 folds of that of the previous 2nd-order RHML. Meanwhile, the harmonic noise and the phase noise of generated 40-GHz millimeter-wave is about 13 dB and −66 dBc/Hz@1 kHz, respectively.

Figure 1 shows the schematic diagram of an injection 2nd-order RHML fiber laser. Without the notch filter and the injection light, it is just the previous 2nd-order RHML fiber laser, which has been proposed in our previous work[1]. In the 2nd-order RHML fiber laser, by adjusting the cavity length to match the driving frequency and setting Mach-Zehnder modulator (MZM) at the maximum transmission point to suppress the odd-order harmonic wave further, the fiber laser can output optical carrier and ±2nd-order harmonic wave simultaneously with the frequency interval of double driving frequency. At the output port, a FBG notch filter is adopted to remove the optical carrier in order to achieve optical mm-wave with the quadruple frequency interval. However, the power of optical carrier is generally much higher than that of ±2nd-order harmonic wave. According to the data proposed in Ref. [8], the value is 7 dB, namely that only 28% of fiber laser

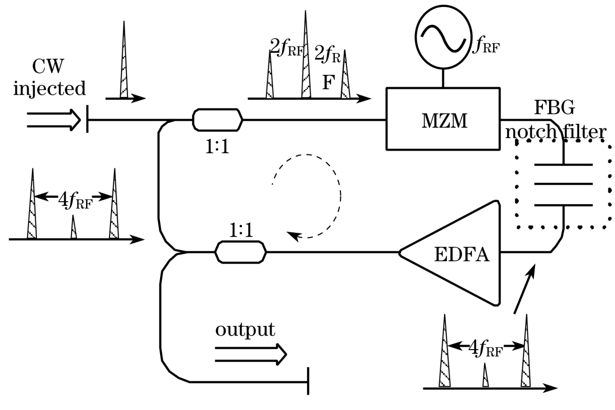

Fig. 1. Schematic diagram of injection 2nd-order RHML fiber laser.

output power is extracted for the generation of mm-wave.

To improve the power efficiency, the FBG notch filter is inserted into the cavity to prevent the optical carrier propagating into erbium doped amplifier (EDFA). In this case, the optical carrier will not consume inverse population of EDFA and only ±2nd-order harmonic wave are amplified. It can be expected that the power efficiency will be increased remarkably. However, if the optical carrier cannot propagate to the modulator either, the high-order harmonic wave will not be generated properly and cannot oscillate stably. So an external continuous wave (CW) light is injected into the laser cavity for providing the proper optical carrier to generate harmonic wave and ±2nd-order harmonic wave can oscillate stably in the fiber laser by controlling the wavelength and the power of injection light. This is the so-called injection mode-lock technique[9].

The proposed method based on the injection RHML technique is applied to generate 40-GHz millimeter-wave and the experimental setup is shown in Fig. 2. In the setup, the generation of harmonic wave is provided by a MZM (JDSU SN-389581F) with ~10 GHz radio frequency (RF) source (XKMVL100). The laser gain is provided by an EDFA with ~270-mW 980-nm pump power. A polarizer, a polarization controller (PC), and an isolator (ISO) are used to control the polarization and ensure unidirectional operation, respectively. A band-pass filter (BPF)(OTF-300) with the 3 dB-bandwidth of 0.6 nm is used to filter the undesired optical sidebands. The cavity length is adjusted through an optical variable delay line (VDL-001-35-60-NC-SS) with the tunable range and adjusting precision of ~10 cm and 0.01 cm, respectively. The FBG notch filter with the center wavelength of 1549.24 nm, reflection ratio of 98%, and 3-dB bandwidth of 0.1 nm is used to block the optical carrier. Meanwhile the output of the tunable external cavity laser (ECL) is injected into the fiber laser through a 1:1 coupler. Additionally, a variable optical attenuator (VOA) is inserted to control the power ratio of the injected light and the oscillating light in the cavity. The total loss of the passive cavity is about 22 dB. At the output port, the optical and electrical spectra are measured by an optical spectrum analyzer (OSA, ANDO AQ6317) and a photodetector together with an electrical spectrum analyzer (ESA).

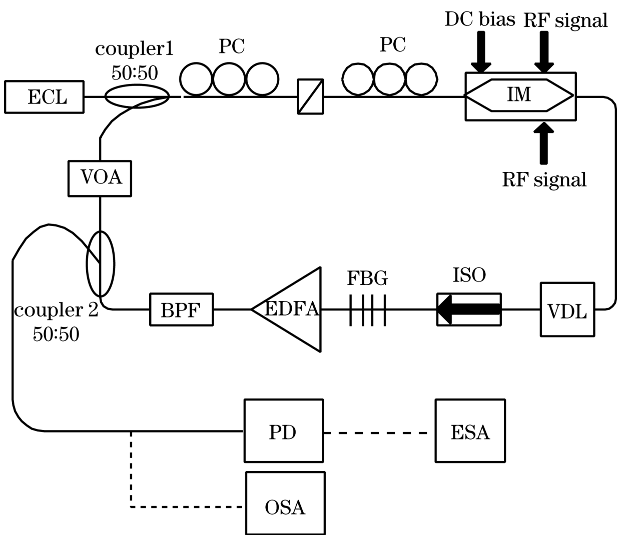

Fig. 2. Experimental setup for generation of millimeter-wave based on injection RHML technique.

In the experiment, the output wavelength of ECL was tuned at 1549.24 nm according to the center wavelength of FBG. In order to make the laser cavity operate at RHML mode, the MZM was first biased at the maximum transmission point to suppress the odd-order sidebands, and then the VDL was adjusted carefully to make the cavity length to match the driving frequency. Meanwhile, the VOA was also adjusted to control the power ratio between the oscillating light in the cavity and the inject light. Figure 3(a) shows the output optical spectrum when the attenuation of VOA is 6 dB. It can be found that three main sidebands at the frequency of 1549.24, 1549.08, and 1549.40 nm are much higher than the others. This proves that the fiber ring laser is operated at 2nd-order injection RHML mode. The wavelength interval of ±2nd-order harmonic wave is about 0.32 nm, which is corresponding to ~40-GHz millimeter-wave. However, the carrier is only 4 dB lower than ±2nd-order harmonic wave. The reason is that when the attenuation of VOA is 6 dB, the gain level of EDFA can just maintain the oscillation of ±2nd-order harmonic wave in cavity and the injected light power is much higher than that of the oscillating light power. To suppress the power of optical carrier, the attenuation of VOA is decreased further. When the attenuation is adjusted to 2 dB, the harmonic suppressing ratio can be improved to 12 dB and the result is shown in Fig. 3(b). If the attenuation is decreased much more, the injection mode lock cannot be achieved, as shown in Fig. 3(c). So there is an optimal value of VOA attenuation, which is related to the injection power and the passive cavity loss.

With the optimal value of VOA attenuation, the total power of output was up to 10.1 dBm (10.23 mW), which is 10 dB larger than that in our previous work with the same pump power[8]. Compared with the result of the 2nd-order RHML fiber laser proposed in our previous work, in which the output power is 5.6 dBm (~3.63 mW) and −0.08 dBm (27.5% of total power) is reserved after filtered by FBG, the power efficiency is improved 10 folds. Two reasons cause the improvement of power efficiency. One is that the FBG notch filter is laid into the fiber laser cavity to filter the optical carrier, which makes 4 folds improvement of power efficiency compared

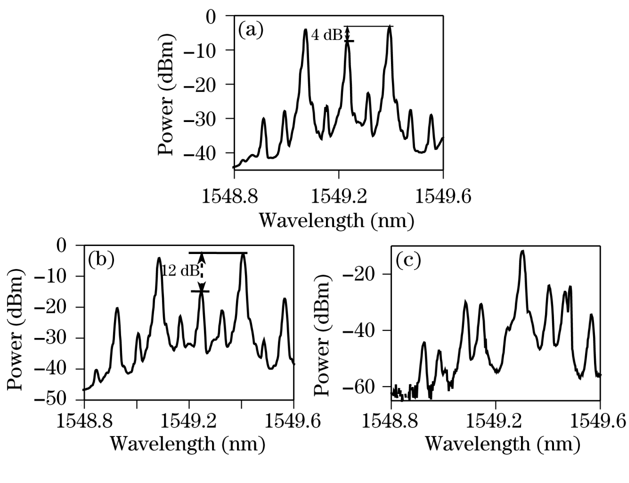

Fig. 3. Output optical spectrum at different attenuations.

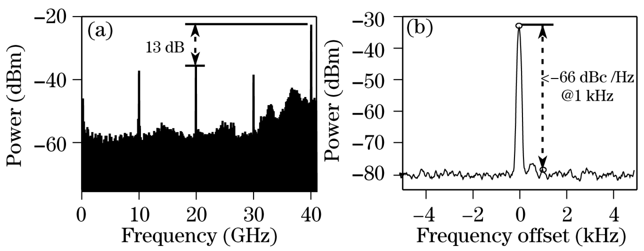

Fig. 4. Output of electrical spectrum.

with the result of filtering optical carrier outside of the cavity in our previous work. The other is the utilization of injection technique and the suppression of EDFA gain competition between the optical carrier and ±2nd-order harmonic wave. When the FBG notch filter is laid before EDFA, the optical carrier will be prevent from entering the EDFA and cannot consume a large portion of the EDFA pump power, so ±2nd-order harmonic wave will be amplified adequately. This causes 2−3 folds improvement of power efficiency.

Finally, the output lights were detected by using a 50-GHz-bandwidth photodetector (U^2T XPDV2120R), and then measured by an electric spectrum analyzer (Agilent E4446A). The results of the quadruple frequency mm-wave are shown in Fig. 4. The harmonic noise and the phase noise are 13 dB and < -66 dBc/Hz@1 kHz, respectively.

In conclusion, by employing 2nd-order injection rational harmonic mode-locked technique, we propose and demonstrate a novel method to generate a quadruple frequency mm-wave. Base on this method, 40-GHz millimeter-wave with the phase noise better than −66 dBc/Hz at 1 kHz offset is obtained through 10-GHz RF source and intensity MZM. The result reveals that with the same pump power of EDFA, the efficiency has a 10 folds increase compared with the method based on 2nd-order injection rational harmonic mode-locked technique.

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