Ultra-wideband Frequency Hopping Millimeter-Wave Generator Based on Optical Injection Locking

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***Abstract*—A frequency hopping millimeter wave generator, based on optical injection locking, is proposed operating in the 80-105 GHz range, having 6 channels and a total hopping bandwidth of 25 GHz.**

Keywords—semiconductor laser; optical injection locking; frequency hopping

I. INTRODUCTION

Recently, millimeter-wave (MMW), especially frequency band above 100 GHz, have drawn tremendous attention to meet the explosive growth of the demand for higher wireless capacity, driven by the applications of 6G mobile communication, satellite communications, radar for automated driving[1]. However, the security and reliability of MMW technology remains a major concern for MMW communications. Frequency hopping (FH) technology has been widely used in microwave band applications, such as local area network (LAN) and Bluetooth. Instead of communicating with a fixed-frequency carrier, frequency-hopped carriers controlled by pseudo-random sequence codes are used, which provides great covert and anti-interference capabilities. In the MMW band, the vast bandwidth makes it well-suited for implementing FH-MMW communications.

The FH bandwidth is a key performance indicator of FH technology. Nevertheless, bandwidth of traditional radio frequency devices are limited by the so-called “electronic bottleneck”, making it increasingly challenging to meet the demands of ultra-wideband frequency hopping millimeter-wave communication. Fortunately, photonics offers a promising solution with its large bandwidth advantage for the development of FH generators. Various photonic FH generators have been successfully demonstrated, including frequency-tunable optoelectronic oscillators[2], period-one (P1) dynamics of optically injected semiconductor lasers[3], and bias controlling of Mach-Zehnder modulations[4], indicating high performance of FH speed and operating bandwidth. However, there are almost no reports on frequency hopping generators in the MMW band above 100 GHz and the number of frequency channels of the reported FH generators is very limited, mostly 2 channels in particular.

In this paper, we propose a FH-MMW generator based on optical injection locking (OIL), which utilizes the narrow-band frequency selective filtering characteristics of semiconductor lasers under the condition of an optical frequency comb (OFC) injection to dynamically control each frequency point in the optical domain. Thanks to the phase locking effect of the OIL technique, stable and reliable millimeter wave signals can be generated by beating the frequency hopping optical signal with the reference light. The experiment demonstrates that it can operate at 80-105 GHz, with a 5 GHz hopping interval of 6 channels and a total hopping bandwidth of 25 GHz.

II. PRINCIPLE

The FH signal generator is consisted of a frequency set and a frequency selection module [5]. The frequency set contains all frequency points of the FH signal, and the frequency selection module is controlled by a series of pseudo-random FH sequences for frequency switching. To enhance the anti-interference and security capabilities of FH systems, the frequency set must have a large number of frequency points that are evenly distributed throughout the working bandwidth to prevent harmonic interference that deteriorate the signal quality. Optical frequency comb (OFC) is consisted of frequency components with uniform intervals and coherent phase stability. By using OFC as the frequency set, coherence can be preserved when switching among different channels, and steady MMW signals are obtained after beating with coherent reference light. In addition, the FH output needs to select a specific frequency point according to the frequency hopping sequence. The adjustable range, tuning speed and spectral resolution of the conventional filter are difficult to meet the application requirements of the FH signal generator. Therefore, a semiconductor laser based on the OIL technique is used as the frequency selection module. When an external optical signal is injected into a semiconductor laser, it exhibits nonlinear dynamical effects, such as injection locking, period oscillations, chaos, etc. [6]. For injection locking, the output frequency and phase of the laser are consistent with the external injection signal, which improves the stability and accuracy of the frequency.

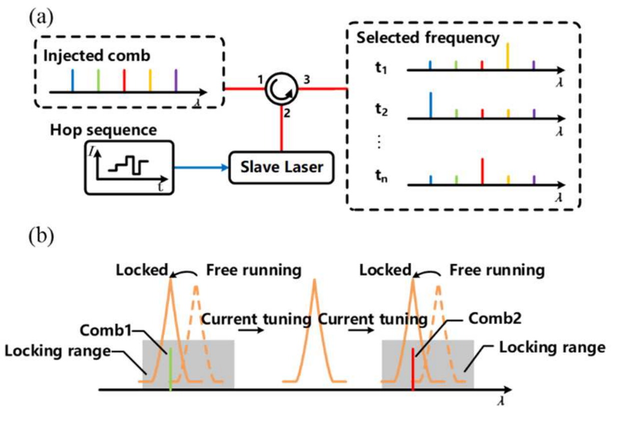

Fig. 1. (a) Dynamic switching principle of optical injection frequency; (b) Output of the DFB laser when the injection locking state is switched between adjacent optical comb line

Fig. 1 shows the principle of generating FH signals by optical injection locking of a semiconductor laser. When the OFC generated by the master laser is injected into the free-running semiconductor laser (slave laser), if one of the comb lines (i.e., a specific frequency point of the FH frequency set) is located in the locking range of the slave laser (the gray area in the Fig. 1(b)), it can be selected due to the narrow-band filtering amplification characteristics of the injection locking effects. Other frequency components in the OFC are suppressed due to mechanisms such as mode competition. The frequency of the free-running semiconductor laser can be controlled by the injection current and temperature. Since the adjustment speed of temperature control is a long time process, and it is easier to control the current than the temperature. In order to achieve fast tuning time and stability for the frequency hopping system, we consider controlling the wavelength of the semiconductor laser by adjusting the injection current. When the injection current changes, if the locked comb line is out of the locked range of the slave laser, the slave laser will first recover to its own free-running frequency. Then, when the other comb line is within the locked range of the slave laser, the slave laser will follow the frequency to complete the frequency switching. By changing the control current of the slave laser according to the frequency hopping sequence, the frequency range of the injection locking can be changed, and the dynamic switching between the frequency points of the FH frequency set can be realized.

III. Experimental

The experimental setup of the proposed FH-MMW generator is shown in Fig. 2. A narrow linewidth fiber laser with frequency f_o is split into two paths and then modulated by dual-drive Mach-Zehnder modulators (DD-MZM). OFC signals are generated in the upper path as the injection light, while coherent reference signals are obtained in the lower path for MMW generation by optical beating. The OFC is input through the optical circulator port 1 and injected into a distributed feedback (DFB) laser as a slave laser through port 2. By applying different level signals to change the injection current of the slave laser, the switching between different comb lines is performed to obtain the generation of optical domain FH signals. The output of the laser is output via port 3. Then, it is mixed with the coherent reference optical signals by a photodetector (PD), which generates a MMW signal with the frequency difference of the two optical signals.

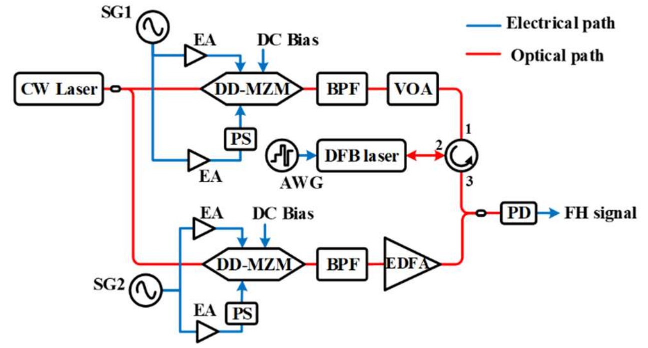

Fig. 2. Schematic of the experimental setup of the proposed FH-MMW generator. CW: Continuous Wave, EA: Electrical Amplifier, DC: Direct Current, PS: Phase Shifter, DD-MZM: Dual-drive Mach-Zehnder modulator, EDFA: Erbium Doped Fiber Amplifier, FH: Frequency Hopping, BPF: Optical bandpass filter, PD: Photodetector, SG: Signal Generation, AWG: Arbitrary waveform generator

The frequency of the RF drive signal of the lower path is $f_{m1} = 5$ GHz and the amplifier saturation power is 21 dBm. An electrical phase shifter is used in one arm of the DD-MZM to maintain the phase synchronization of the RF signals of the upper and lower arms. By adjusting the bias voltage of the DD-MZM to meet the flat spectral conditions, an OFC with a frequency of $f_o + nf_{m1}$ ($n = 0, \pm1, \pm2, \pm3, \cdots$) can be generated. In the experiment, the optical bandpass filter (OBPF) selects the OFC and filters out 7 comb lines from the -1st to the -7th order modulation sideband., covering a bandwidth of 35 GHz, and its comb spacing is 5 GHz. We selected six frequency points from n = -1 to -6 as the hopping frequency set. The frequency of the RF drive signal of the lower path is $f_{m2} = 25$ GHz. and the +3rd order sideband of the modulated optical signal is selected as the coherent reference light. Fig. 3 shows the optical spectrum of the output.

The hopping speed of the FH-MMW generator is mainly determined by the tuning time of the DFB laser. In the experiment, the DFB laser frequency tuning exhibited a linear region with a relatively fast speed (Fig. 4(a)), followed by a nonlinear region. With reference to a specialized acceleration pulse, known as the “turbo pulse,” used in [7] to enhance the thermal switching time of Mach-Zehnder switches, we made some modifications to the design of the level signal to utilize this linear region. Specifically, we insert a special pulse (positive or negative, duration of about 62 μs) during level switching, shown in Fig. 4(b). Without turbo pulse, the DFB laser takes 470 μs to tune the 5 GHz frequency by current control. This means that the hopping speed of the FH-MMW

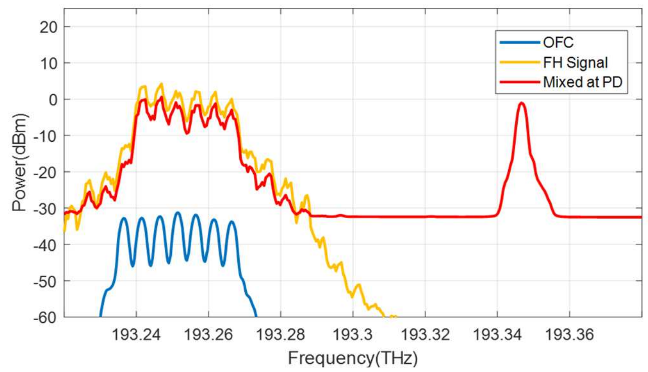

Fig. 3. Optical spectrum of the output of the upper DD-MZM and the DFB laser

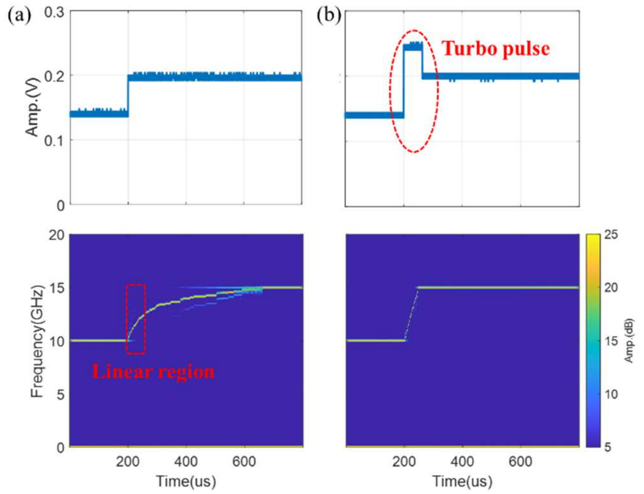

Fig. 4. Tuning time of the DFB laser (a) without turbo pulse (b) with turbo pulse

generator is 470 μs. When the turbo pulse is used, the hopping speed can be increased to 62 μs.

The FH optical signal is selected by the slave laser to lock and amplify the comb lines as the frequency points. The level signal controlling the slave laser applies the turbo pulse and performs dynamic frequency selection. After photodetection, an 80-105 GHz FH-MMW signal is obtained, with 6 hopping channels and a total hopping bandwidth of 25 GHz. The spectrum of the FH-MMW signal is shown in Fig. 5(a). In order to avoid the influence of the instantaneous frequency caused by the tuning of the DFB laser, we set the sampling time to 10 seconds, and sampled 20 times for power averaging. It should be noted that the amplitudes of different channels are

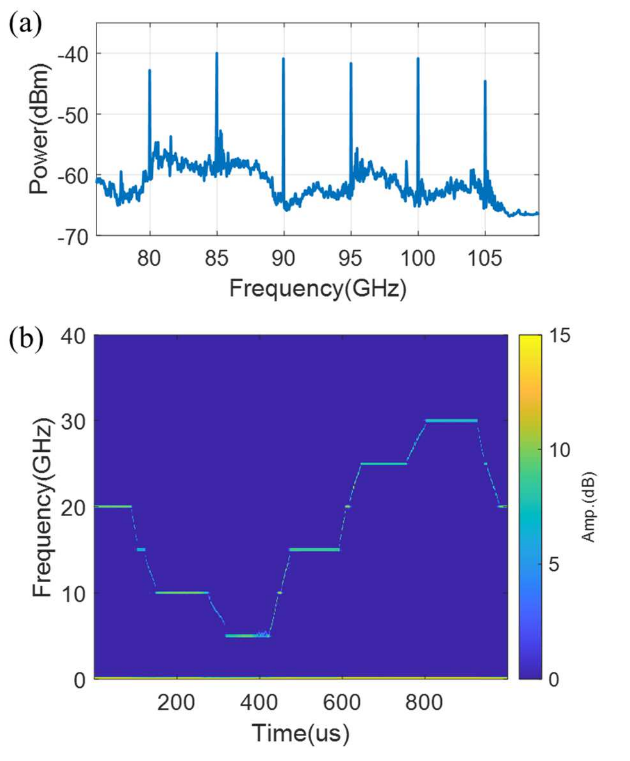

Fig. 5. (a) Measured frequency spectrum of the 80-105 GHz FH-MMW signal; (b)Time-frequency diagram of the down-converted FH signal

uneven, which may be due to the different side mode suppression ratios at each frequency point and the frequency instability during the tuning process of the DFB laser. Incorporating a feedback loop to achieve more stable injection locking effects can mitigate this phenomenon. Because of the limited bandwidth of PD, the power at 105 GHz is significantly lower than other frequencies.

According to the FH sequence {4,2,1,3,5,6}, the FH-MMW signal instantaneous frequency changes should be {95,85,80,90,100,105} GHz. To perform time-frequency analysis, we down-convert the FH-MMW signal to 5-30 GHz. A period of the FH signal is shown in Fig. 5(b), where the pre-set FH sequence determines which frequency points to output. The corresponding down-converted FH signal instantaneous frequency changes should be {20,10,5,15,25,30} GHz. What should be noted is that due to the limited sampling depth of the oscilloscope, we reduced the dwell time of each frequency point to measure the hopping speed more easily, which can be extended in practice. The hopping speed of each frequency point is measured to be 62 μs.

IV. Conclusion

In conclusion, we present a frequency hopping millimeter wave generator based on optical injection locking, which utilizes the narrow-band frequency selective filtering properties of semiconductor lasers under the condition of multi-frequency optical signal injection. The ultra-wideband frequency set is obtained by electro-optic modulation of the optical signal by DD-MZM. Frequency hopping is realized by current control of the semiconductor laser. The generator is capable of operating in the 80-105 GHz range, with 6 channels and a total hopping bandwidth of 25 GHz. The proposed FH-MMW generator holds potential for application in the next generation of millimeter-wave communication systems or radar detection and imaging with improved anti-interference performance.

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