Direct Opto-Electronic Synthesis of mW-Level Millimeter-Wave Signals Using an Optical Frequency Comb Generator and a Uni-Traveling-Carrier Photodiode

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***Abstract*: —The first experimental demonstration of direct opto-electronic synthesis of mW-level millimeter-wave signals using an optical frequency comb generator is reported. We obtained signals from 10 to 60 GHz with a maximum power of +3 dBm at 60 GHz using a uni-traveling-carrier photodiode.**

I. INTRODUCTION

Optical frequency comb generators (OFCG) [1] are candidates for dense WDM optical synthesis and as sources for millimeter-wave fiber-fed wireless systems. The amplified fiber loop OFCG can offer a wide comb span with adjustable, exact comb line spacing. Generation of more than 100 lines over a 1.8-THz bandwidth in the 1.55-μm band has been reported [2]. An optical injection locking scheme can be used to select two lines from the comb with spacing up to this bandwidth, which enables millimeter-wave signal generation with a photodiode [3, 4]. These techniques have, however, suffered from lack of availability of high-power, high-speed photodiodes.

A key technology in our demonstration is a uni-traveling-carrier photodiode (UTC-PD) that can respond up to 310 GHz [5-7]. In the UTC-PD, the light is absorbed in the p-region so that only fast electrons act as carriers but the generated holes remain in the p-region as majority carriers. As a result, its response is very fast. In addition, the UTC-PD accepts extremely large optical power. Combining injection locked comb-line selection and UTC-PD technologies, we report the first experiments on multi-octave tunable, high-power direct opto-electronic millimeter-wave generation using an OFCG. Unlike conventional millimeter-wave sources, the UTC-PD can generate frequencies over a span of many octaves limited only by its upper cut-off frequency. The maximum power we obtained at 60 GHz was 3 dBm. Furthermore, the response was quite flat (±1.3 dB) within a span from 10 to 60 GHz.

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II. PRINCIPLE

The configuration for millimeter-wave generation is shown in Fig. 1. It has a cascaded structure of an OFCG, two injection locked lasers as wavelength filters, an Erbium-doped fiber amplifier (EDFA), and a UTC-PD. The OFCG emits a comb with arbitrary line spacing equal to the microwave reference frequency, f_{REF}, driving the phase modulator in the amplified fiber loop. From more than 100 lines, each injection locked laser selects only one line. The two laser outputs of frequency difference equal to the required millimeter-wave output are combined and amplified optically. These amplified laser outputs are incident on the UTC-PD and converted to the required millimeter-wave signal of a frequency of $n \cdot f_{REF}$ (n: integer). Since this system amplifies the laser signals optically, it enables high-power millimeter-wave generation without needing an expensive broadband millimeter-wave amplifier. A current maximum frequency limit for the detectors we used is reported to be beyond 300 GHz [7].

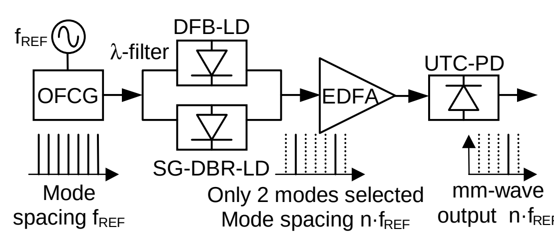

Fig. 1. Configuration for millimeter-wave generation.

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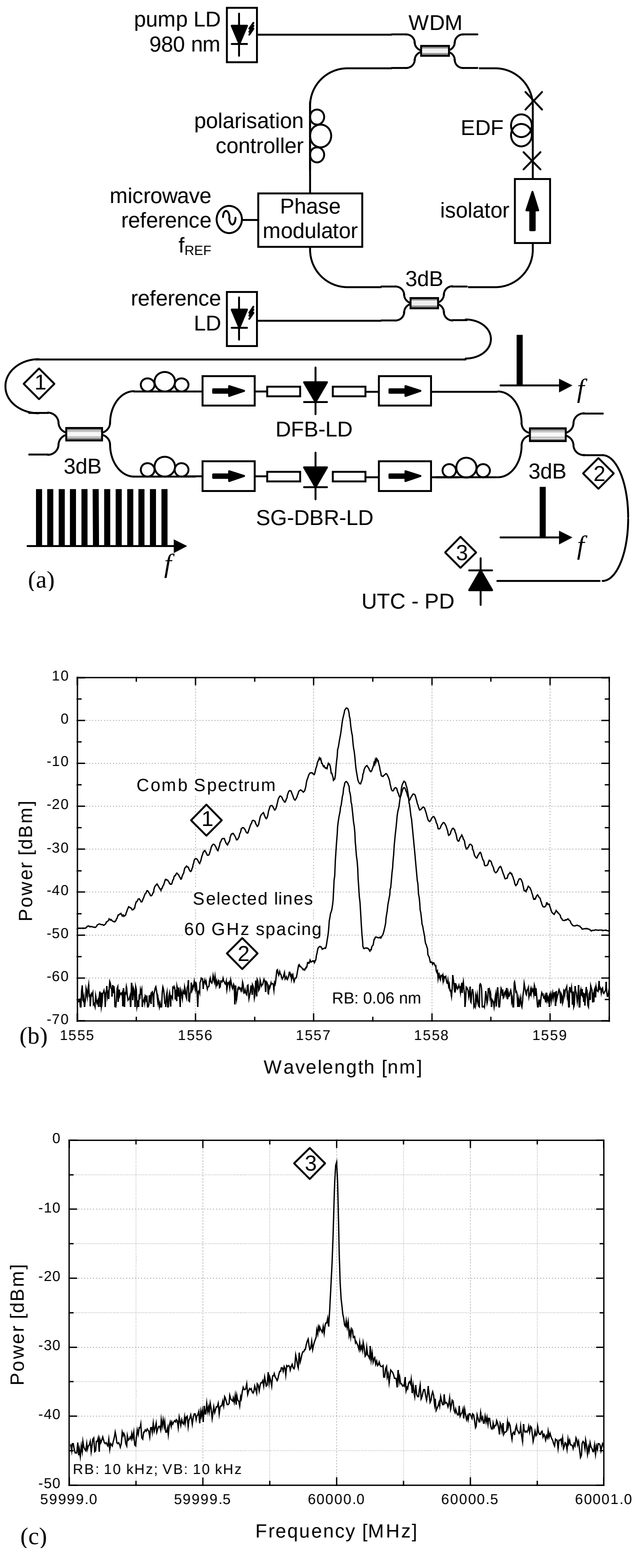

Fig. 2. (a) Experimental setup. (b) Typical spectra from the OFCG and two DBR-LDs. (c) Spectrum example of the generated millimeter wave signal.

III. EXPERIMENTS

Experiments were carried out using the arrangement shown in Fig. 2(a). A tunable laser was employed as a reference laser with wavelength 1555.9 nm. A 10-GHz reference signal was applied to the phase modulator and the OFCG generated more than 40 lines with 10-GHz spacing. The observed span was about 400 GHz. The lasers could be locked to any line in the OFCG output by adjusting their current and temperature. We used a conventional DFB-LD and a Marconi Caswell sampled-grating DBR-LD (SG-DBR-LD). The latter provides a very wide tuning range (>60 nm) for multi-octave millimeter-wave generation applications. Typical spectra from the OFCG and combined laser outputs are shown in Fig. 2(b). The beat frequency is six times the comb spacing, 60 GHz, in this case.

The UTC-PD employed has an edge-coupling interface [8]. Important characteristics are as follows: a junction area of 4.5x10 μm, a responsivity of 0.4 A/W and a 3-dB bandwidth of >60 GHz at a bias voltage of –4 V. A lensed-fiber was employed to couple the OFCG output to the UTC-PD, where the excess loss at the interface was –3 dB. A three-pad probe was used to collect the millimeter-wave power generated by the UTC-PD chip. Although the probe has 0.83-dB loss at 60 GHz, this is small and is not corrected for in this paper. The millimeter-wave power and phase noise were measured using an Agilent 8565EC spectrum analyzer for frequencies up to 50 GHz and using an Agilent 11974U preselected mixer and the same analyzer at 60 GHz.

Signals in the range 10 to 60 GHz were generated using this system. A typical synthesized spectrum is shown in Fig. 2(c), where the millimeter-wave frequency is 60 GHz. The optical power input to the UTC-PD and the DC

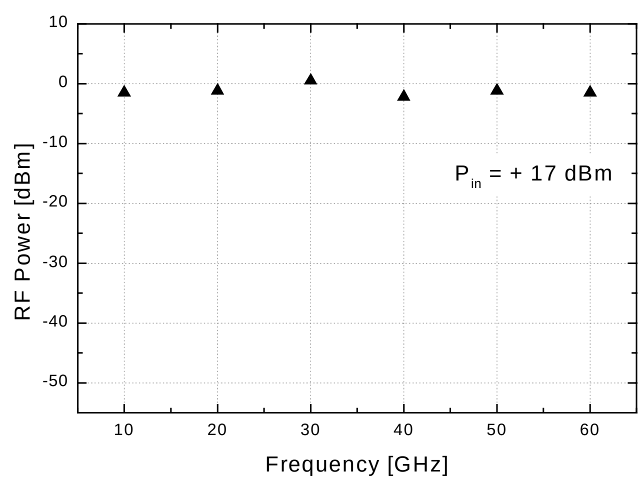

Fig. 3. RF output power dependence on the frequency.

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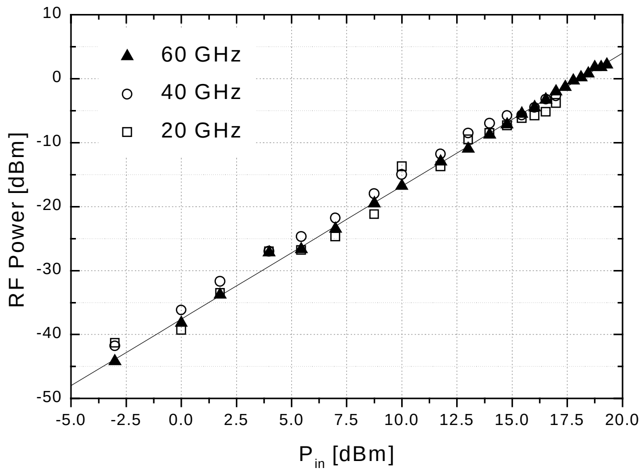

Fig. 4. RF output power dependence on the light power from OFCG.

photocurrent were +17 dBm and 10 mA, respectively. Figure 3 shows the frequency response at the UTC-PD output. The response is flat within ±1.3 dB up to 60 GHz, which proves a >60 GHz 3-dB bandwidth for the UTC-PD. We measured the RF output power dependence on the input light power, as shown in Fig. 4. For 20, 40, and 60 GHz, it is shown to be linear within the experimental range. Measurements were also carried out at 10, 30, and 50 GHz but they are not shown here because they displayed very similar results making figure cluttered. The highest power obtained at 60 GHz was +3 dBm, when the input was 19 dBm, the power limit of our EDFA. Because the UTC-PD does not show saturation, we could expect higher power to be obtainable with a higher-power EDFA.

Phase noise performance is of great interest for wireless applications. Using this generation system, single side band (SSB) phase noise was measured over a 10-to-60-GHz range. The noise spectrum at 60 GHz is shown in Fig. 5. SSB phase noise was measured as –67 dBc/Hz at 100-kHz offset. That measured between 10 and 50 GHz has an average of -71 dBc/Hz and a variation of ±3.5 dBc/Hz. Since the multiplied reference frequency phase noise varied from -100 dBc/Hz at 10 GHz to –84.4 dBc/Hz at 60 GHz, the measured phase noise floor is likely to be due to reference laser frequency fluctuations. This noise source could be reduced by including fiber loop length tracking in the OFCG [1].

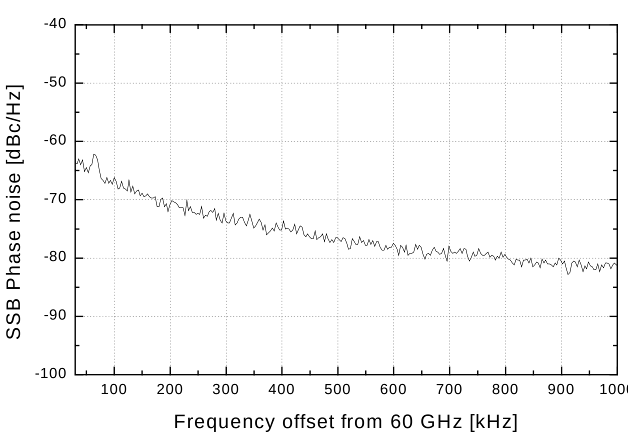

Fig. 5. Phase noise spectrum near the generated millimeter wave carrier.

IV. Summary

We have shown that the combination of the optical frequency comb generator and the uni-traveling-carrier photodiode produces a high-power, multi-octave tunable millimeter-wave signal. The maximum power obtained was +3 dBm at a carrier frequency of 60 GHz, which was limited by the EDFA output power. This approach can play an important role in millimeter-wave signal generation for emerging fiber-fed wireless applications since the upper frequency limit is set mainly by the photodiode bandwidth.

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