A W-Band Photonic Transmitter-Mixer Based on High-Power Near-Ballistic Uni-Traveling-Carrier Photodiodes for BPSK and QPSK Data Transmission Under Bias Modulation

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***Abstract*—In this study, we demonstrate wireless binary phase-shift keying (BPSK) and quadrature phase-shift keying (QPSK) data transmission at the W-band by use of bias modulation on photonic transmitters-mixers, which are composed of near-ballistic uni-traveling-carrier photodiodes and quasi-Yagi antennas without the integration of an Si-lens. By use of such a device and a novel optical millimeter-wave source with octupling optical frequency, we can successfully achieve 1.25-Gb/s BPSK and 0.625-Gb/s QPSK data-transmission at 105 GHz with 5-GHz intermediate-frequency signals.**

***Index Terms*—High-power photodiode, optoelectronic mixer, photodiode, photonic transmitter.**

I. INTRODUCTION

THE tremendous increase in the required volume of wireless data-transmission has stimulated attention on ways to use the millimeter-wave (MMW) bands above 60 GHz (V-band) or above 100 GHz (W-band) as the carrier frequency for the realization of systems with very high transmission data rates in excess of many gigabits-per-second [1], [2]. Unfortunately, there is a large propagation loss of the MMW signal in the $>$ W-band or V-band frequencies, whether in free space or in a coaxial cable. One promising solution to this problem is the radio-over-fiber (ROF) technique [1], [2], where the MMW signal is distributed through a lossless optical fiber and then radiated over the last-mile to the user-end. Recently, a research group at NTT reported excellent results for a 10-Gb/s wireless link at 120 GHz, achieved by using a uni-traveling-carrier photodiode (UTC-PD)-based photonic transmitter [1], [2]. In order to eliminate the serious fading and time-shifting effects induced by fiber chromatic dispersion of the data signal with the high-frequency local-oscillator (LO) signal at the V- or $>$ W-bands, two different optical wavelengths are usually adopted for the data and LO signals [3], [4] in the ROF system. An additional high-frequency MMW mixer or electrooptic (E-O) modulator is usually necessary at the base station to up-convert the data signal to the LO frequency and then radiate the up-converted signal to the user-end [3]. The idea of utilizing the nonlinearity of high-speed PDs [4], [5], such as UTC-PDs, to realize this up-conversion process is very attractive, because this could eliminate the necessity of the high-frequency electronic mixer or E-O modulator [5]. To use such a technique, it is necessary to swing the bias of UTC-PD to the forward bias regime in order to get a high extinction ratio of modulated MMW power. However, this approach limits its modulation bandwidth performance [5]. Furthermore, it is usually necessary to integrate an additional Si-lens with such a photonic transmitter to overcome the substrate-mode problem [2] of the antenna. The monolithic integration of uniplanar high-directivity Yagi–Uda antenna with UTC-PD to serve as the photonic emitter is another possible good solution, which eliminates the necessity of additional Si-lens [6]. In our previous work [7], [8], we demonstrated a photonic transmitter/mixer that operated at the W-band. The device consisted of a high-speed high-power near-ballistic uni-traveling-carrier photodiode (NBUTC-PD) [9] and a planar quasi-Yagi antenna [7], [8] on an aluminum–nitride (AlN) substrate. The device was insensitive to the aforementioned substrate modes and thus did not call for the integration of an additional Si-lens. By utilizing the strong bias-dependent nonlinearity of speed of NBUTC-PD under a reverse bias regime, our transmitter could also serve as a photonic mixer, generating high-power up-converted MMW signals with a wide modulation bandwidth [10]. In this current work, we demonstrate wireless data transmission at the W-band (105 GHz) using a novel optical MMW source with octupling optical frequency [11] and our device under a bias modulation of 1.25-Gb/s binary phase-shift keying (BPSK) and 0.625-Gb/s quadrature phase-shift keying (QPSK) data modulation format with a 5-GHz intermediate-frequency (IF) signal. As compared to the demonstrated on–off keying (OOK) data format and linear photodetection scheme in previous work [1], [2], the demonstrated QPSK with bias modulation on NBUTC-PD for wireless data transmission can have a higher spectral efficiency and more suitable for the application to the long-reach ($>$100 km) optical-wireless access network [3], [4].

II. DEVICE STRUCTURE AND MEASUREMENT SETUP

Fig. 1 shows a top view of the demonstrated device. The device consists of a diced NBUTC-PD chip with a 100 μm^2 active

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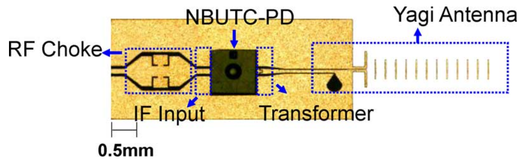

Fig. 1. Top-view of the demonstrated device;.

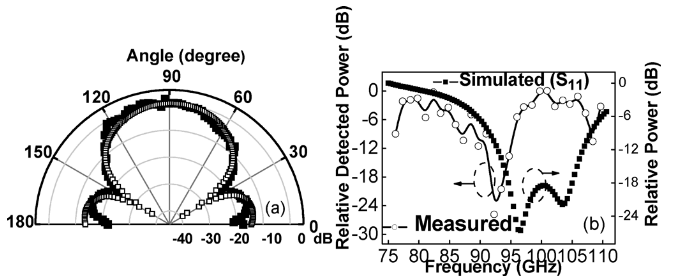

Fig. 2. (a) Measured (closed squares) and simulated (open squares) radiation patterns for the demonstrated device at the E-plane. (b) Simulated S_{11} parameter (close squares) and the detected power (open circles) spectrum.

area, which exhibits a 100-GHz optical-to-electrical bandwidth under a 25-Ω load resistance with a responsivity of 0.15 A/W [9] and a quasi-Yagi planar antenna chip. The whole module is formed on an AlN substrate, giving it good thermal conductivity for high-power operation. The antenna chip is comprised of a quasi-Yagi antenna [7], [8]. The fan-shaped broadband transition between the coplanar waveguide and the slotline acts as an impedance matching circuit. A flip-chip bonded active NBUTC-PD, an IF signal input port, a W-band radio-frequency (RF) choke, and bond pads for the dc bias are also included. Compared to our previous work [7], we have increased the number of directors and modified the geometric size of the antenna, which increases its directivity and bandwidth. The simulated gain and directivity of the quasi-Yagi antenna at around the center operating frequency (100 GHz) is 9.4 and 9.8 dB, respectively. During measurement, the optical LO signal is generated by the heterodyne-beating technique. The modulated optical signal is then focused on the microlens [9] on the backside of the diced NBUTC-PD by a lensed fiber. The LO signal with the up-converted RF signals are all radiated to free-space through the quasi-Yagi antenna to be detected by a standard horn antenna at the W-band (with a 24 dB gain), which is connected to a W-band mixer (Agilent 11970W) and a spectrum analyzer (Agilent E444BA).

III. MEASUREMENT RESULTS

The simulated and measured radiation patterns at the E-plane of the photonic transmitter are shown in Fig. 2(a). As can be seen, they are in excellent agreement. Fig. 2(b) shows the simulated S_{11} of the quasi-Yagi antenna without considering the integrated active device and the measured frequency response of the detected power of our transmitter as the LO frequency sweeps from 75 to 110 GHz. We can clearly see that a significant resonance of radiated power exists at around 100 GHz, which is consistent with the S_{11} of the quasi-Yagi antenna. Fig. 3(a) shows the detected up-converted RF power versus the injected electrical IF power under a fixed optical LO power (21 dBm) and an optimum bias point (−1.5 V) for mixer operation. The 1-dB compression points of the up-converted RF power (−32 dBm) and injected IF power (7.5 dBm) are both specified in Fig. 3.

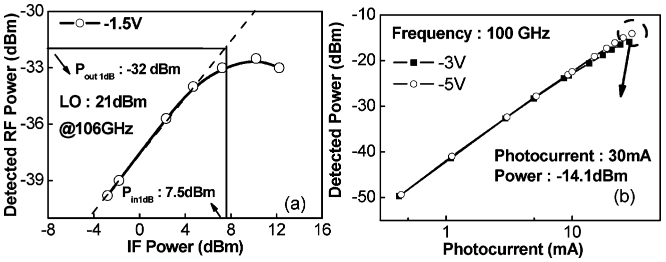

Fig. 3. (a) Up-converted RF power versus IF power under −1.5 V and 21 dBm optical LO power injection. (b) Maximum detected power versus photocurrent for an operating frequency fixed at 100 GHz under bias voltages of −3 and −5 V.

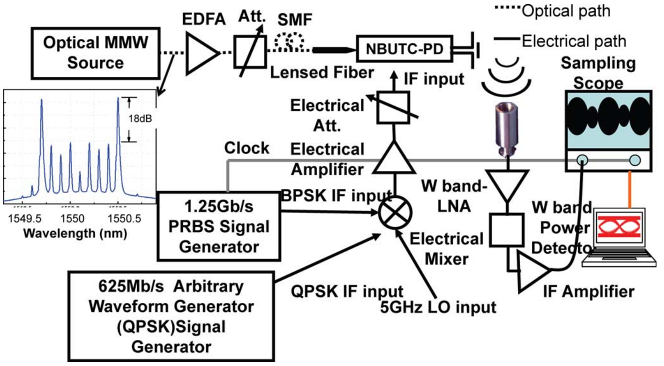

Fig. 4. System setup for BPSK or QPSK data transmission.

In addition to the up-converted RF power, the maximum radiated LO power under high reverse bias (over −2.5 V) is also an important factor for evaluating the performance of a photonic transmitter. Fig. 3(b) shows the detected MMW power of the device. We achieve a 100-μm^2 active area under optical signal injection with a 100% modulation depth, as a function of the photocurrent under bias voltages of −3 and −5 V. As indicated on the plot, the maximum detected power is −14 dBm, obtained when the photocurrent is around 30 mA. Fig. 4 shows the system setup for BPSK or QPSK data transmission. Compared to the traditional OOK data transmission process [1] using a photonic transmitter, the modulation format of the BPSK and QPSK techniques allows for higher spectral efficiency and is compatible with today's wireless communication systems. In order to realize the goal of free-space data transmission, we also develop a high-performance W-band optical photonic source [11]. The inset to Fig. 4 shows the output optical spectrum from this optical source. As can be seen, the optical harmonic distortion suppression ratio is 18 dB, and is limited by the bandwidth of our dual-parallel E-O modulator (i.e., 10 GHz) [11]. This source is much less noisy than the two-laser heterodyne-beating system, which was used for device characterization. During the experiment, the BPSK signal is a 1.25-Gb/s pseudorandom bit sequence $2^{31}-1$ signal. The 0.625-Gb/s QPSK signal is generated by an arbitrary waveform generator (AWG) at a data rate of 625 Mb/s. Both kinds of signal are up-converted with an analog IF signal at 5 GHz by the use of an electronic mixer. The mixed signal is then fed into the IF input port of the photonic emitter/mixer to modulate the bias point of the device. The injected IF power is around 2 dBm, which corresponds to around 0.8V$_{pp}$ (peak-to-peak) amplitude of driving voltage. The modulation

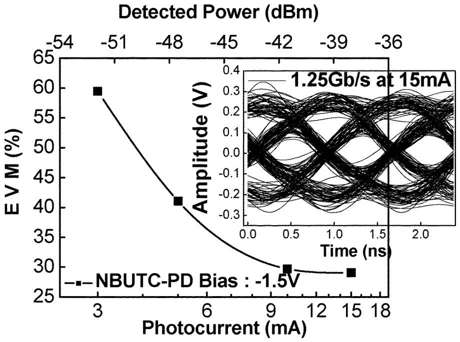

Fig. 5. Measured EVM versus received MMW power and output photocurrent. The inset shows the reconstructed BPSK eye-pattern at 1.25 Gb/s.

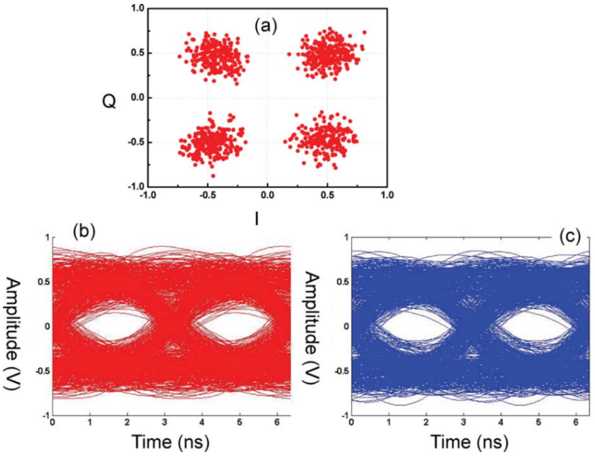

Fig. 6. (a) Constellation of the 0.625-Gb/s QPSK signal. Eye diagrams of the 0.625-Gb/s QPSK signal: (b) I; (c) Q.

frequency of the optical LO signal from the photonic source is 100 GHz. The 1.25-Gb/s BPSK or 0.625-Gb/s QPSK signal is thus up-converted to 105 GHz (LO: 100 GHz. IF: 5 GHz) and then radiated to the receiving end. The receiver end is composed of a W-band horn antenna, a W-band low-noise-amplifier (QuinStar: QLW-90a06030-P1), and a fast W-band power detector (Militech: DXP-10-RPFW0) to detect the envelope and phase of data signal at 5-GHz IF. The signal detected by the power detector is boosted by an IF amplifier and then fed into a high-speed real-time scope prior to performing off-line signal processing [8], [11]. The transmission distance is around 5 cm, which can further be increased by increasing the directivity of used antenna [1]. Fig. 5 shows the output photocurrent of transmitter or received MMW power versus the error vector magnitude (EVM) of the transmitted data. The EVM is defined as $\mathrm{EVM}[\%] = 100 \times [\sum_{i=1}^{N} |\overline{d_r} - d_i|^2/N]^{1/2}/|d_{\max}|$, where $\overline{d_r}$ and d_i are the received and ideal symbols, respectively, and $d_{\max}$ is the maximum symbol vector in the constellation. The inset shows the reconstructed BPSK eye-pattern with clear eye-opening at 1.25 Gb/s under a photocurrent of 15 mA. As can be seen, when the MMW power received MMW reaches −42 dBm and the output photocurrent reaches 10 mA, the measured EVM can be less than around 30%.

Fig. 6(a) shows the constellation of the received 0.625-Gb/s QPSK signal when the output photocurrent is 10 mA; while (b) and (c) show the digital signal processing reconstructed I and Q eye diagrams. The corresponding EVM is around 24.7%. According to the measured frequency response of our system (channel), we can expect a higher data transmission rate (>1.25 Gb/s) by increasing the bandwidth of the W-band power detector and the IF frequency (>5 GHz).

IV. CONCLUSION

In this study, we devise an NBUTC-PD based W-band photonic transmitter/mixer. This novel device can be used with an optical MMW source, to realize 1.25-Gb/s BPSK and 0.625-Gb/s QPSK wireless data transmission at 105 GHz under direct bias modulation.

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