W-Band Wireless Data Transmission by the Integration of a Near-Ballistic Unitraveling-Carrier Photodiode With a Horn Antenna Fed by a Quasi-Yagi Radiator

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***Abstract*—We demonstrate a novel W-band photonic transmitter mixer, which is composed of a planar quasi-Yagi radiator for feeding a WR-10 waveguide-based horn antenna and a near-ballistic unitraveling-carrier photodiode. The module demonstrates reasonable coupling loss in terms of the millimeter-wave (MMW) power launched from the integrated radiator into the WR-10 waveguide. With the bias-modulation technique and an optical MMW source, we can successfully achieve a wireless data transmission of 2.5-Gb/s quadrature phase shift keying at a carrier wave frequency of 102.5 GHz with a transmission distance of over 2.3 m.**

***Index Terms*—High-power photodiode, optoelectronic (OE) mixer, photonic transmitter, quasi-Yagi radiator.**

I. Introduction

The NEXT generation of wireless links for satisfying higher bandwidth requirements for gigabit wireless access applications may be constructed based on Radio-over-Fiber (RoF) communication systems [1], [2]. Such a system uses millimeter-wave (MMW) band signals as the carrier frequency, which allows us to obtain much broader transmission bandwidths. Low-loss fibers are used in RoF systems as a solution for the problem of high propagation loss not only in free space but also in electrical cables carrying MMW signals. High-speed and high-power photonic transmitters, which are composed of an antenna and a photodiode, serve as the key components to transduce the light to an electrical signal over the last mile of the RoF system [2]. Recently, a research group at NTT has demonstrated good 10 Gb/s line-of-sight on–off-keying (OOK) wireless linking, utilizing a unitraveling-carrier photodiode (UTC-PD)-based photonic transmitter [1], [2]. However, if the distance between the central office and base station is more than 100 km, chromatic-dispersion-induced intersymbol interference (ISI) becomes a serious problem [3]. Remote signal up-conversion techniques provide a promising solution for the aforementioned ISI problem [3]. A nonlinear detection scheme is one possible solution for the realization of such a technique [4]–[6]. In our previous work, we demonstrated a near-ballistic UTC-PD (NBUTC-PD)-based photonic transmitter mixer [7], [8] with wide modulation bandwidth and high operation current serving as the key component for nonlinear photodetection. The NBUTC-PD-based photonic transmitter mixer successfully achieved 1.25-Gb/s binary phase shift keying and 0.625-Gb/s quadrature phase shift keying (QPSK) with a bias-modulation technique [9]. However, the wireless transmission distance was short (~5 cm) and limited by the radiation pattern mismatch between the transmitting and receiving antennas. In this letter, we demonstrate a novel kind of W-band photonic transmitter mixer, which is composed of an NBUTC-PD and a compact planar quasi-Yagi radiator for feeding the WR-10 waveguide-based horn antenna. Using the demonstrated device, we achieve 2.5-Gb/s QPSK wireless data transmission with a nonlinear photodetection technique at 105 GHz and a transmission distance of over 2.3 m. In comparison to the demonstrated OOK data format and linear photodetection scheme discussed in the previous work [1], [2], higher spectral efficiency can be obtained with the demonstrated bias-modulation QPSK when used for wireless transmission, and it is more suitable for application to a long-reach optical-wireless network [3], [4].

II. Device Structure and Measurement Setup

Fig. 1(a) and (b) shows the top view of our novel photonic transmitter mixer and the measurement system setup for QPSK wireless data transmission. As can be seen in Fig. 1(a), the photonic transmitter mixer is composed of a diced NBUTC-PD with a 64-μm^2 active area, a planar quasi-Yagi antenna, a fan-shaped broadband transition between the coplanar waveguide (CPW) and the coplanar slot line, an intermediate-frequency (IF) signal input port, a W-band radio-frequency (RF) choke, and bond pads for flip-chip bonding process on a 100-μm-thick aluminum nitride (AlN) substrate for good thermal conductivity. Compared with the UTC-PD-based optoelectronic

Manuscript received August 10, 2009. First published October 6, 2009; current version published October 23, 2009. The review of this letter was arranged by Editor C. Jagadish.

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Digital Object Identifier 10.1109/LED.2009.2031602

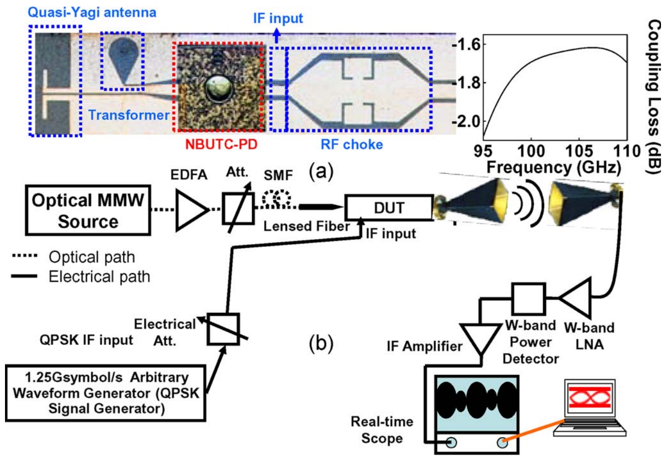

Fig. 1. (a) Top view of the demonstrated device and the simulated frequency response of the coupling loss. (b) Measurement system setup for QPSK wireless data transmission.

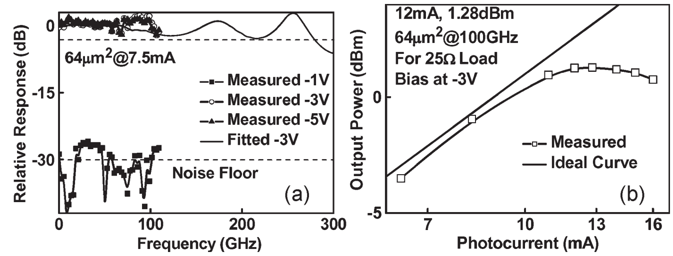

Fig. 2. (a) Measured and fitted O–E frequency responses of the NBUTC-PD. (b) Photogenerated MMW power versus photocurrent of NBUTC-PD

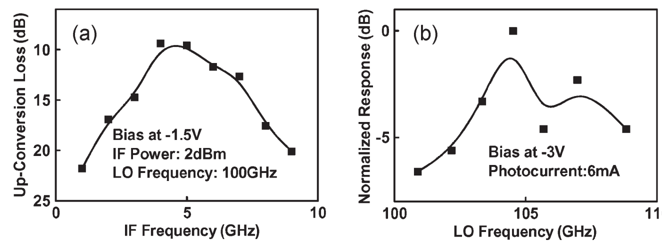

Fig. 3. (a) Frequency response of the up-conversion loss of our QPSK data transmission system measured under a fixed LO frequency (100 GHz) and different IF frequencies. (b) Measured O–E frequency response under different LO frequencies without IF injection.

(OE) mixer [5], [6], our NBUTC-PD-based OE mixer has an improved modulation bandwidth even under a higher operation current, due to the elimination of the forward bias operation [5], [6]. More details of these components can be found in our previous work [7]–[10]. The employed quasi-Yagi radiator discussed herein is comprised of a half-wavelength dipole element and a ground reflector. This makes it significantly more compact than the traditional tapered slot antenna used for rectangular waveguide feeding, which is normally several wavelengths in length. Furthermore, an antenna of this sort is relatively immune to the substrate modes. The MMW signal is delivered to the horn antenna via the WR-10 waveguide. The quasi-Yagi antenna, excluding the ground portion, is placed in the waveguide opening to excite the fundamental TE_{10} mode. Fig. 1(a) also shows the simulated coupling efficiency of the MMW power launched from the integrated radiator into the WR-10 waveguide. In our simulation, the radiator is assumed to be fed with a 50-Ω signal source. As can be seen, a small coupling loss (< -1.7 dB) can be achieved. As shown in Fig. 1, during the measurement, the electrical IF signal (1.25G symbol/s QPSK data with 2.5-GHz subcarrier frequency) generated by an arbitrary waveform generator is injected into the IF input port of device by the use of an on-wafer probe to modulate its bias point. The optical MMW local oscillator (LO) signal (100 GHz), which is provided by octupling the modulated optical frequency [9], [11], is injected into the device through a lensed fiber. The electrical QPSK signal is thus up-converted to the W-band, before being fed into the WR-10 waveguide-based horn antenna. The receiver end is composed of another 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) for detecting the envelope of the transmitted MMW power. The down-converted QPSK data signal is then further amplified, sampled, and demodulated by an IF amplifier, high-speed real-time scope, and offline signal processing [9], [11].

III. Measurement Results

Fig. 2(a) and (b) shows the optical-to-electrical (O–E) frequency response and power performance of the flip-chip bonded NBUTC-PD [12]. As can be seen in Fig. 2(a), the speed performance of the NBUTC-PD is greatly dependent on the bias voltage. Its 3-dB bandwidth far exceeds 110 GHz under a high (> 3 V) reverse bias voltage. By utilizing the device modeling technique [10], [12], we can further extract the O–E frequency response, which is indicated by the solid line in Fig. 2(a). The extracted 3-dB bandwidth can be as high as 280 GHz under -3-V bias. However, under -1-V bias, the bandwidth is extremely poor. Such significant bias-dependent speed performance indicates that our device can serve as a high-performance OE mixer under bias-modulation operation [7]–[12]. Fig. 3(b) shows the output photocurrent versus output MMW of the same NBUTC-PD at 100 GHz, which is flip-chip bonded onto AlN substrates with a metalized pattern of CPWs. As can be seen, under -3-V bias, the maximum saturation current is around 12 mA. A higher saturation current can be expected after inserting a flip-chip bonding pad below the p-contact metal of the NBUTC-PD [12]. We determine which operating frequency band has the flattest frequency response and is thus more suitable for data transmission by measuring the frequency response of our device. Fig. 3(a) shows the measured frequency response of up-conversion loss $(P_{\mathrm{LO}} - P_{\mathrm{RF}})$ when the optical LO frequency is fixed at 100 GHz and the injected IF signal is sweeping from 1 to 10 GHz, where the up-conversion loss is defined as difference between LO power (P_{LO}) and up-converted RF power (P_{RF}). As can be seen, there is a resonant peak with the lowest up-conversion loss (10 dB) at around 105 GHz with around ±1.5-GHz 3-dB bandwidth for data transmission. A lower up-conversion loss can be expected by increasing the injected IF power [8]; however, such approach does not significantly benefit the measured bit error rate (BER) for data transmission due to the distortion of bias-modulation eye pattern. A more detailed study of the optimized operation point of the device for data transmission will be published somewhere else. In order to confirm whether the system bandwidth is limited by the modulation speed of our NBUTC-PD

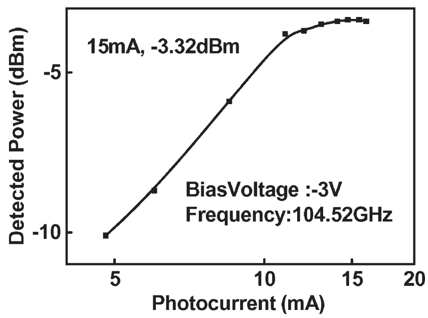

Fig. 4. Detected MMW power versus output photocurrent of our device

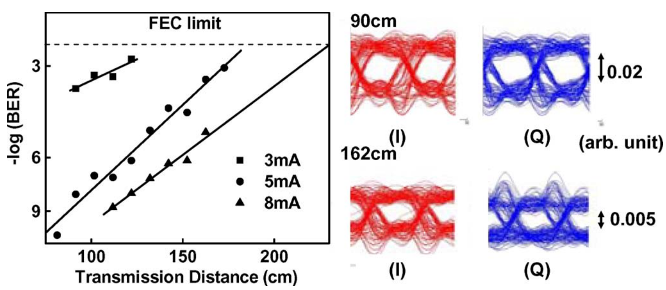

Fig. 5. $-\log(Bit\ Error\ Rate)$ versus transmission distance under different photocurrents during 1.25 billion symbols per second QPSK data transmission. Measured I and Q eye patterns under an 8-mA photocurrent at 90 and 162 cm are also specified.

or the frequency response of the integrated radiator with the PD, we also measure the frequency response by sweeping the optical LO frequency from 100 to 110 GHz without IF signal injection. As shown in Fig. 3(b), the measured response is also not flat, and the trace is similar to that shown in Fig. 3(a). We can thus conclude that the limited 3-dB bandwidth comes from the geometric structure of our passive–active integration and a well-designed layout or impedance-matching circuit with the desired bandwidth and operating center frequency is thus necessary to further improve the modulation bandwidth. Fig. 4 shows the radiated power performance of our transmitter module under a 50-Ω load and an optical modulation depth of 100%. During this experiment, the LO frequency is fixed at the resonant peak (105 GHz), as shown in Fig. 3. The radiated power is collected by another horn antenna of the same type, which is directly connected with a W-band power sensor (Agilent W-8486A) to record the collected power. The measured saturation current ($\sim$12 mA) of our transmitter mixer is the same as the saturation current of the PD, as shown in Fig. 2(b), and the maximum detected power is as high as -3.3 dBm. This number is much higher than that reported in our previous work (-17 dBm versus -3.3 dBm) [8] under a much lower operation current. By comparing the detected power and the ideal photogenerated RF power for a PD under a 50-Ω load, the total internal loss of our system, which includes coupling and free-space propagation loss, is around 7.6 dB. By excluding the -1-dB theoretical coupling loss between two horn antennas, the measured coupling loss between our device and WR-10 waveguide is estimated to be roughly around -6.6 dB, which can further be improved by considering the impedance-matching issue between the NBUTC-PD and antenna on the chip, as discussed before. Fig. 5 shows the $-\log(BER)$ versus transmission distance under different photocurrents during data transmission. The related eye patterns at 90 and 162 cm with 8-mA photocurrents are also given. As can be seen, clear eye opening can be observed even after 1.6-m transmission. By the use of the forward-error-correction (FEC) technique, with coding threshold at $BER = 3 \times 10^{-3}$ [13], the estimated maximum transmission distance with FEC coding is around 2.3 m under 8-mA photocurrent.

IV. Conclusion

In conclusion, we have devised a novel photonic transmitter mixer. This device can radiate the modulated MMW and then launch it into the WR-10 waveguide with a small coupling loss. We can achieve 2.5-Gb/s QPSK wireless transmission at 102.5 GHz under bias modulation and a distance of 2.3 m with this device.

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