Photonic Impulse-Radio Wireless Link at W-Band Using a Near-Ballistic Uni-Traveling-Carrier Photodiode-Based Photonic Transmitter-Mixer

F.-M. Kuo, Yu-Tai Li, J.-W. Shi, Shao-Ning Wang, Nan-Wei Chen, and Ci-Ling Pan

***Abstract*—A W-band photonic transmitter-mixer, constructed by integrating a planar quasi-yagi radiator for feeding the WR-10 waveguide-based horn antenna and a near-ballistic uni-traveling-carrier photodiode, is used with a mode-locked fiber laser to obtain 2.5-Gb/s impulse-radio (IR) wireless data transmission at around a center frequency of 100 GHz. The bias-modulation technique provides less jitter and a longer maximum transmission distance compared with the technique of modulating the optical pulse train using an electrooptics modulator. Using the bias-modulation technique, we achieve a 2.5-Gb/s IR wireless data transmission.**

***Index Terms*—High-power photodiode, impulse radio (IR), millimeter-wave, photonic transmitter.**

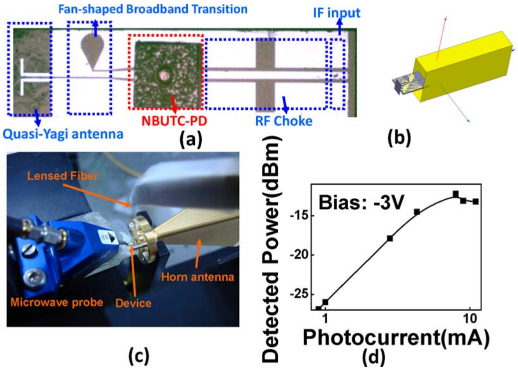

Fig. 1. (a) Top-view of the demonstrated device; (b) conceptual diagram for the WR-10 waveguide feed; (c) photograph of the device during measurement; (d) detected MMW average power versus average output photocurrent under optical pulse excitation.

I. INTRODUCTION

RECENTLY, the demand for low-transmission-power, high-bit rate, wireless local area networks (WLANs) in homes and offices has grown rapidly. Ultra-wideband (UWB) [1] or impulse-radio (IR) [2] technologies have been proposed to meet this need. However, the transmission distance of conventional UWB or IR technologies is limited due to the huge propagation loss of such short electrical pulses in air. This difficulty can be circumvented by combining photonic technology with the UWB and IR systems, where the signal is first distributed optically through a low-loss optical fiber, converted to electrical pulses, and then radiated to the user-end for the last-mile. Some photonic UWB communication links have already been demonstrated [3], [4] with a data rate as high as 1.5 Gb/s [4]. A photonic transmitter (PT) composed of a high-speed/power photodiode (PD) integrated with an broadband antenna [4], [5] serve as a key component in such systems. In our previous work, using a mode-locked fiber laser with a short optical pulse output and a high-performance photonic transmitter-mixer (PTM) [6], we were able to raise the operating frequency of an IR system to around 100 GHz for wireless data transmission. In this work, we study in detail the dynamic performance of such a system [6] and further increase the maximum 2.5-Gb/s wireless transmission distance by increasing the operation current of the PTM. We adopted the optical-to-electrical (O-E) three-port equivalent circuit model [8] during the design process of this new demonstrated device instead of using the electrical two-port model as in our previous PTM [7], which led to a great increase in its O-E bandwidth. The two different modulation schemes are measured. The bias-modulation technique [7], [9] provides a larger signal-to-noise (S/N) ratio and a longer maximum transmission distance than with the technique where the optical pulse train is modulated through the use of an electrooptics (E-O) modulator. Under an average output photocurrent of 8 mA, which corresponds to a charge of around 800fC per pulse, we successfully demonstrated a 2.5-Gb/s data rate and a 5-m maximum transmission distance.

II. DEVICE STRUCTURE

Fig. 1(a)–(d) shows the top-view of the novel PTM, a conceptual diagram of the WR-10 waveguide feed, a photograph of the device during measurement, and the averaged output photocurrent versus averaged coupling millimeter-wave (MMW) power fed into the WR-10 waveguide under a fixed -3-V bias voltage. As can be seen in Fig. 1(a), the PTM is composed of a diced near-ballistic uni-traveling-carrier photodiode (NBUTC-PD) with a 144-μm^2 active area, a planar quasi-yagi antenna, a

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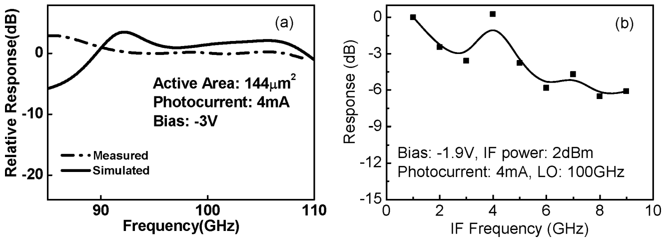

Fig. 2. (a) Measured and simulated O-E frequency responses of our photonic transmitter; (b) measured up-conversion O-E frequency response with LO frequency fixed at 100 GHz.

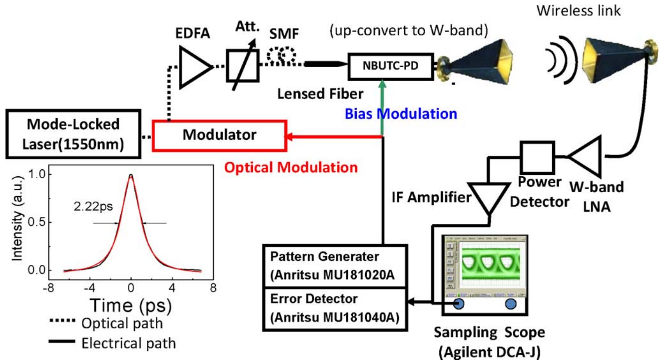

Fig. 3. Conceptual diagram of the IR communication system including EDFA, Att, SMF, and LNA represent erbium-doped fiber amplifier, optical attenuator, single-mode fiber, and low-noise amplifier.

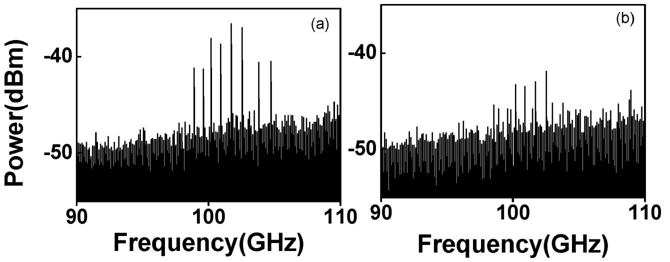

Fig. 4. (a) Measured MMW spectrum with bias modulation; and (b) optical modulation.

fan-shaped broadband transition between the coplanar waveguide (CPW) and the coplanar slot-line (CPS), an intermediate frequency (IF) signal input port, a W-band RF choke, and bond pads for flip-chip bonding onto a 100-μm-thick aluminum-nitride (AlN) substrate (for good thermal conductivity). The setup for device measurement can be seen in Fig. 1(c). An on-wafer probe is used to input the electrical signal and modulate the bias point of the device [7], [9]. The O-E 3-dB bandwidth of the flip-chip bonded NBUTC-PD is over 110 GHz with a maximum saturation current of around 30 mA under continuous-wave (CW) operation [8]. However, as shown in Fig. 1(d), under optical pulse excitation, the average saturation current is smaller, around 8 mA, compared with that obtained under CW operation.

This can be understood by noting that the peak optical power for the former is much higher than for the latter. As a result, the space-charge screening effect is more severe for the pulse case and reduces the average saturation current [10]. The optical pulse train, with a pulsewidth of around 2 ps, as shown in Fig. 3, and a frequency bandwidth well over 100 GHz, is injected into the device through the use of a lensed fiber. The up-converted 2.5-Gb/s data is then radiated through the horn antenna. Fig. 2(a) shows the simulated and measured O-E frequency response of our transmitter module when it is used for feeding the WR-10 waveguide connected to a millimeter-wave power sensor. For measurement, we sweep the frequency of the optical local-oscillator (LO) signal, which is generated by the two-laser heterodyne beating system, and the IF input port is left open.

As can be seen, the simulation and measurement results match well. Transmission is achieved over a wideband (88–110 GHz). This is an important issue for effectively radiating the short electrical pulse, which covers a wide range of frequency. The up-converted modulation bandwidth is also an important issue during the operation of this PTM [9]. Fig. 2(b) shows the up-converted frequency response of our PTM. For this measurement, the optical LO frequency is fixed at 100 GHz while we sweep the frequency of the injected IF signal. Excluding the dip at 3 GHz, the 3-dB bandwidth of the up-converted signal is around ±5 GHz. The nonflat frequency response can be attributed to interference between the injected and reflected IF signal, which can be minimized by further optimizing the geometric structure of the IF input port as shown in Fig. 1(a). In comparison to our previous reported PTM [7], there is a great improvement in the transmission band (3 versus 22 GHz) and modulation bandwidth (±1.5 versus ±5 GHz). This is because of the incorporation of a three-port equivalent-circuit model [8], which includes the O-E response of the PD, during the design process of the PTM.

III. MEASUREMENT SETUP AND RESULTS

Fig. 3 shows the measurement setup for data transmission. The optical pulse train (with a 10-GHz repetition rate) is provided by a commercial fiber mode-locked laser (Calmar Laser, PSL-10-2T). The inset shows the shape of the optical pulse after passing the erbium-doped fiber amplifier (EDFA), measured by an autocorrelator. Two different modulation schemes were adopted in our experiment: one the modulation of the injected optical pulse train through the use of an E-O modulator (optical modulation); and the other by directly modulating the bias point of the PTM [7], [9] (bias modulation). The test signal at 2.5 Gb/s with a pseudorandom binary sequence (PRBS) of $2^{15}-1$ is generated by a pattern generator and then fed either into the E-O modulator or IF input port of the PTM. The receiver end is composed of a W-band horn antenna, a W-band low-noise-amplifier (LNA), and a fast W-band power detector to detect the data envelope. The signal detected by the power detector is boosted by an IF LNA with a 3-dB bandwidth of around 1 GHz and a gain of 50 dB then fed into a high-speed sampling oscilloscope. Fig. 4(a) and (b) shows the MMW power spectrum received through the LNA using bias modulation and optical modulation, respectively. As can be seen, a significant power envelope exists around 100 GHz for both cases. The trace for the former, however, exhibits a much better S/N ratio than the latter. These results can be attributed to the larger extinction ratio of the bias-modulated signal than the optically modulated signal. The transfer-curve of our PTM under CW operation shows a

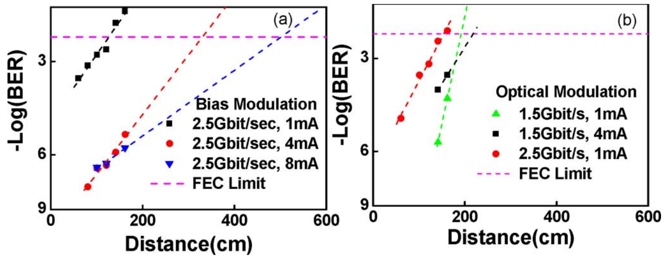

Fig. 5. (a) $-\text{Log}(\text{Bit Error Rate})$ versus transmission distance for 2.5-Gb/s data transmission under bias modulation and different output photocurrents; (b) $-\log(\text{Bit Error Rate})$ versus transmission distance for 1.5 or 2.5-Gb/s data transmission under optical modulation and different output photocurrents.

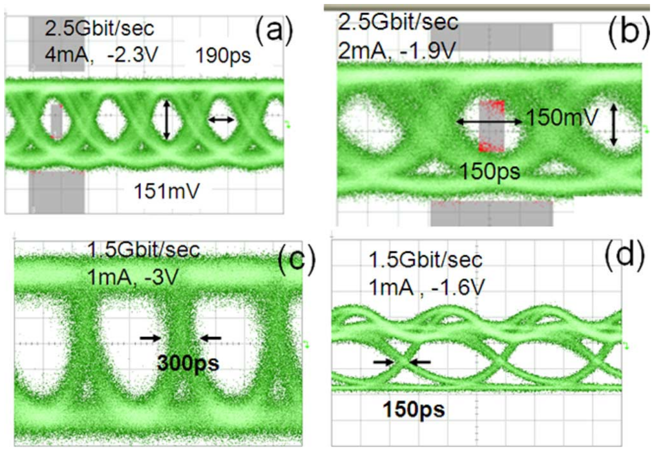

Fig. 6. Bias-modulation 2.5-Gb/s eye patterns measured under (a) 4 mA and (b) 2 mA. The measured (c) optical-modulation; and (d) bias-modulation eye patterns at the same 1.5-Gb/s data rate.

35-dB extinction ratio of MMW power at 100 GHz when the bias voltage swings from -1 to -2.2 V. The highest RF extinction ratio achieved with a commercial E-O modulator,[1] under a peak-to-peak driving voltage as large as 8 V, is just around 30 dB. Fig. 5(a) and (b) shows the measured bit-error-rate (BER) versus transmission distance for the bias modulation and optical modulation cases, respectively. Fig. 6(a) to (d) shows the 2.5- or 1.5-Gb/s eye diagrams measured under different output photocurrents, different reverse voltages, and a fixed transmission distance (20 cm). For bias modulation, the dc reverse bias voltage is optimized under different output photocurrents for the best eye pattern performance. As shown in Fig. 5(a), by increasing the operation current for the case of bias modulation, we can greatly increase the transmission distance. Under a high output average photocurrent (8 mA), the forward-error-correction [(FEC) BER $= 3.84 \times 10^{-3}$] [11] limited maximum transmission distance is around 5 m.

Such results may be attributed to the enhancement of high-speed performance and photogenerated MMW power of the NBUTC-PD under high-power operation [8] indicates the improved quality of the eye patterns during bias modulation. Fig. 6(a) and (b) clearly shows the wider eye width of the eye patterns measured at 4 mA compared with the 2.5-Gb/s eye patterns measured at 2 mA, (190 versus 150 ps). On the other hand, as shown in Fig. 5(b), increasing the output photocurrent during optical modulation does not significantly increase the maximum transmission distance. This can be attributed to the influence of noise, which always increases with the injected optical power. This has a much more significant limitation on transmission performance during optical modulation than bias modulation. Fig. 6(c) and (d) clearly shows such phenomenon. It can be clearly seen that measured 1.5-Gb/s eye patterns have much less jitter (150 versus 300 ps) than the optical modulation patterns with the same data rate. The more serious noise problem of optical modulation can be attributed to the fact that the optical pulse train occupies a broad optical bandwidth (1530–1560 nm) and suffers from significant amplified spontaneous emission (ASE) noise when it passes the EDFA. On the other hand, for bias modulation, the injected electrical data is fed directly into the PTM; smaller influence of ASE noise on data can thus be expected.

IV. CONCLUSION

A bias-modulation technique was used in a novel PTM. We demonstrated 2.5-Gb/s IR data transmission. Compared with optical modulation, bias-modulation exhibits less jitter and can achieve a longer transmission distance. This is obtained by increasing the injected optical pulse energy. A higher data rate (>2.5 Gb/s) can be expected by further reducing the system noise and increasing the bandwidth of IF LNA in the receiver end.

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