Invited Paper

Recent advances in millimeter-wave photonic wireless links for very high data rate communication

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ABSTRACT

To provide integrated and high quality broadband services, higher carrier frequencies are required in wireless communications. Currently, there is a great deal of interests in wireless communications at sub-terahertz or terahertz frequencies, i.e., the millimeter-wave (MMW) or sub-millimeter-wave (sub-MMW). In this work, we will discuss our recent advances in millimeter-wave photonic wireless links for high data rate (10 – 20 Gb/s) communications. The concept of fiber-to-the-antenna (FTTA) system using radio-over-fiber (ROF) technologies will be given in the introduction. Then a design and the structure of the high speed MMW photonic transmitter, namely near-ballistic uni-traveling-carrier photodiode (NBUTC-PD), will be discussed in section 2. In section 3, the operation principle of photonic mm-wave waveform generator (PMWG), which is used to produce the optical pulse train for the photonic transmitter at the antenna-site will be illustrated. We then demonstrate the use of the NBUTC-PD and the PMWG for the downstream and upstream high data rate communications in the W-band.

Keywords: Millimeter-wave, fiber-to-the-antenna (FTTA), radio-over-fiber (ROF), terahertz (THz), uni-traveling-carrier photodiode (UTC-PD)

1. INTRODUCTION

Wireless connections to the end-users are becoming more and more important in future broadband access networks. In order to provide integrated broadband services, as well as high data rate and high quality connections, higher carrier frequencies are required. For example, Wireless LAN can provide 54 Mb/s data connection using the 2.4 GHz and 5 GHz carrier frequencies. Higher data rate solutions, such as WiMAX requires the carrier frequencies from 2-66 GHz [1]. Millimeter waves (mm-wave), the W-band (75 – 110 GHz) in particular [2], eshibits a much broader window with minimum transmission loss when compared with the 60 GHz frequency band. Hence it is more desirable for outdoor and higher data rate applications. However, high signal attenuation occurs for the transmission and distribution of these high frequency signals in the copper-cable-based wireless access networks. Because of this, fiber-to-the-antenna (FTTA) system has been proposed [1-5]. Fig. 1 shows a schematic comparing the conventional copper-cable-based wireless access network and the FTTA system. Due to the high propagation loss of high frequency electrical signal in the coaxial cable, the distance between the base station and antenna is usually limited to < 100 m. FTTA, on the other hand, can extend the radio-frequency (RF) signal distribution by using low loss and low cost optical fiber. In this system, the high frequency electrical RF signal will be transmitted in the optical domain by using the electrical-to-optical (EO) converter at the head-end. The generated optical radio-over-fiber (ROF) signal will then be distributed to different remote antenna units (RAUs). Inside the RAU, a high speed photodiode (PD) converts the optical signal back to electrical signal, which will then be transmitted wirelessly via the antenna.

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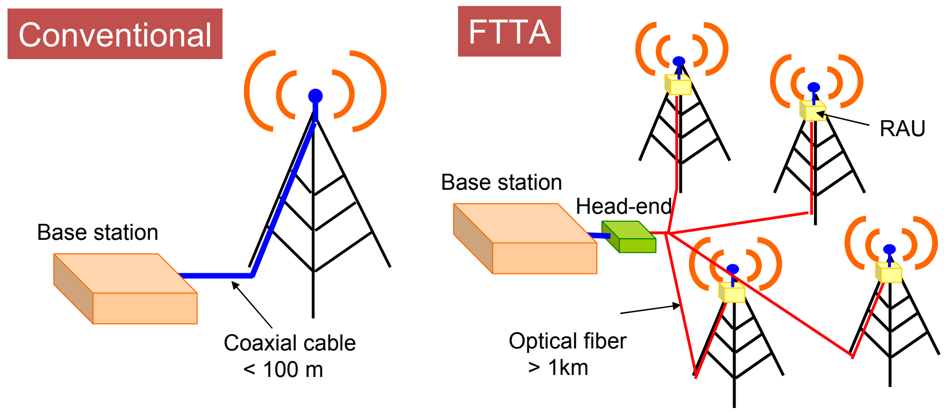

Figure 1. Schematics of the conventional wireless access network and the FTTA system. RAU: remote antenna unit.

The paper is organized as follow: the concept of FTTA system using ROF technologies will be given in the introduction. After this, the design and the structure of the high speed millimeter-wave photonic transmitter, namely near-ballistic uni-traveling-carrier photodiode (NBUTC-PD), will be discussed in section 2. In section 3, the operation principle of photonic mm-wave waveform generator (PMWG), which is used to produce the optical pulse train for the photonic transmitter at the RAU will be illustrated. The network demonstrations of using the NBUTC-PD and the PMWG for the downstream and upstream high data rate communications will be given in section 3 and section 4 respectively. Finally, a conclusion will be given in section 5.

2. DESIGN AND STRUCTURE OF PHOTONIC TRANSMITTER

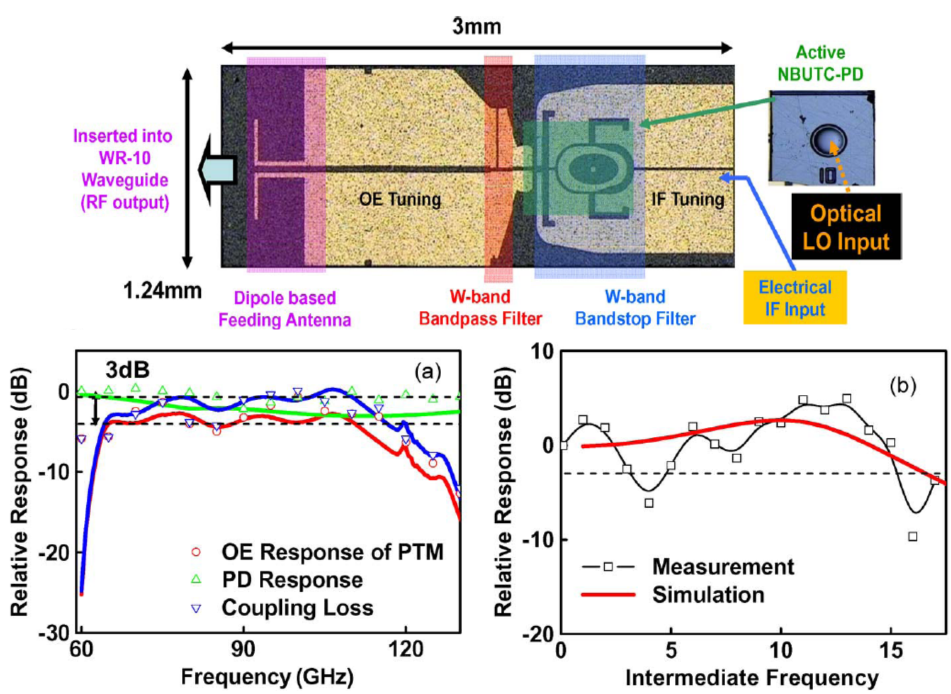

Figure 2. (a) Top view photograph of the NBUTC-PD transmitter, (a) OE response of our PTM module, the OE response of a NBUTC-PD chip with the same active area under a 50 Ω load, and the extracted coupling loss from the integrated NBUTC-PD to the WR-10 waveguide output port of the PTM. The simulation results of these three traces are also included as solid lines. (b) Measured and simulated IF modulation responses of our PTM under 15-mA photocurrent.

The photonic transmitter used in the RAU at the antenna site employed a near-ballistic uni-traveling-carrier photodiode (NBUTC-PD) developed by our group. Figure 2 shows the top-view of our NBUTC-PD-based photonic transmitter module (PTM). It is mainly composed of a flip-chip bonded NBUTC-PD with a 100 μm^2 active area, a bandpass filter (BPF), a band-stop filter (BSF), and a dipole-based feeding antenna (FA). The NBUTC-PD was grown by molecular beam epitaxy (MBE) on a semi-insulating InP substrate. The design of the quasi-Yagi radiator allows direct WR-10 waveguide feeding; hence the quasi-Yagi radiator can be easily inserted into the W-band horn antenna

Inset of Fig. 2(a) shows the measured and simulated optical-to-electrical (OE) responses of our PTM, the OE responses of the flip-chip bonded NBUTC-PD chip under a 50 Ω load, and the coupling loss of the planar dipole-based radiator to the WR-10 waveguide. Here, we used 0 dB as a reference of all frequency responses. It is defined as the output power from an ideal PD (infinite bandwidth), under an ideal sinusoidal optical source excitation (100% modulation depth), and with the same output photocurrent (4 mA) as used in the PTM and PD. From the measured results, the NBUTC-PD has a broad bandwidth to be operated at the W-band (> 100 GHz) [6]. An ultra-wide 3-dB bandwidth of 51 GHz (from 67–118 GHz) was achieved for both the coupling loss and the OE response. Besides, the measured OE responses agree well with the simulation results. The transmitter was directly modulated using the IF input port. Inset of Fig. 2(b) shows the IF modulation responses of our PTM operated at a photocurrent of 15-mA. In the measurements, the launched IF frequency was swept from 0.1 to 20 GHz, and the optical LO signal was fixed at 93 GHz. The result shows that the 3-dB electrical modulation bandwidth of the PTM can be > 15 GHz for data modulation.

3. DOWNSTREAM MMW DATA TRANSMISSION

Figure 3 shows the experimental setup for downstream MMW data transmission. The setup consists of three modules: (i) the PMWG, which is used to produce the optical pulse train; (ii) the NBUTD-PD based Tx for generating the W-band wireless signal (it has been discussed in section 2 above); and (iii) the W-band receiver (Rx) for bit-error-rate (BER) measurement.

The PMWG consists of a spectral line-by-line pulse shaper, which can tailor-make the properties and the repetition rate of the optical pulses launching into the NBUTC-PD. As discussed in our previous publication [7], using optical short pulses is more desirable than the conventional optical sinusoidal excitation for the NBUTC-PD. This is due to the fact that optical short pulse can provide higher modulation depth (> 100%) and hence higher mm-wave output power can be produced with a much smaller PD photocurrent [8]. Experimentally, we show that the mm-wave power produced in pulse excitation can be enhanced by > 7 dB. This can be qualitatively explained by noting the total power is obtained through the sum of beatings between every two comb lines in the frequency domain in the pulse source [7].

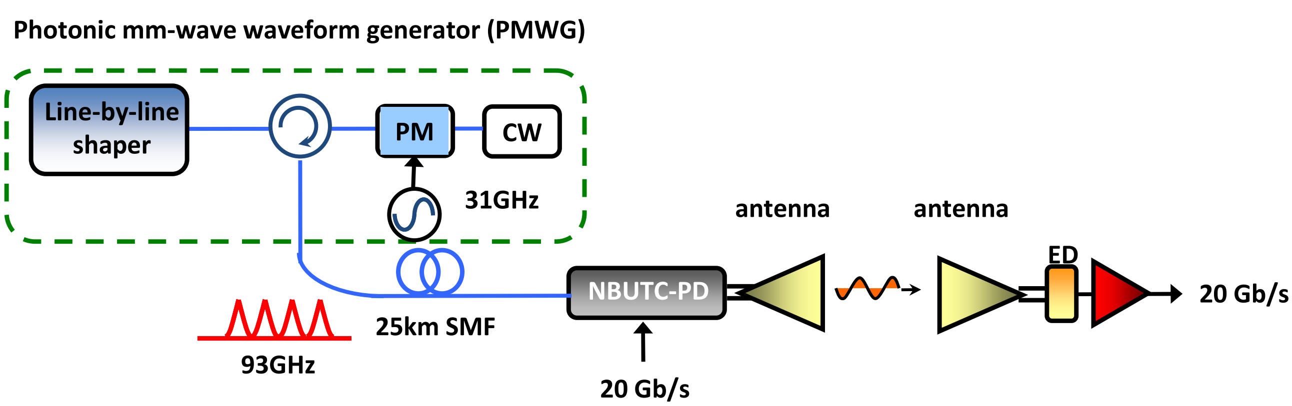

Figure 3. Experimental setup of downstream MMW signal transmission.

As shown in Fig. 3, a phase-modulated continuous-wave (CW) laser frequency comb is generated by launching a narrow-linewidth CW laser into of a low-Vπ $LiNbO_3$ phase modulator (PM). The PM was electrically driven by a 31 GHz sinusoidal signal from an ultra-low phase noise RF signal generator, having been amplified up to +33 dBm. The line-by-line shaper can also provide accurate dispersion pre-compensation for delivering short optical pulses to the NBUTC-PD at the RAU. Hence, it compensates the fiber chromatic dispersion in the 25 km single mode fiber (SMF)

ROF transmission [9]. No other dispersion compensation is necessary in the fiber link. In the experiment reported, 93 GHz repetition rate optical pulse train was used for the MMW generation. The frequency multiplication from 31 GHz to 93 GHz was done by applying periodic spectral phase values of {0, 2π/3, 2π/3, } onto the 31-GHz comb lines using the line-by-line shaper. Hence 93 GHz repetition short pulse train (1 ps) generated by the repetition-rate multiplication (RRM) technique has been achieved.

Afterwards, the optical pulse train was launched into the NBUTC-PD, which was directly modulated by a 20 Gb/s non-return-to-zero (NRZ) data for remote up-conversion [10]. The MMW signal carrying the 20 Gb/s data was emitted via a horn antenna. At the receiver end, it was composed of another W-band horn antenna and a fast power detector for detecting the envelope of received MMW power. The down-converted data was amplified by an IF amplifier, and then launched into an error-detector for the BER measurements. Figure 4(a) shows the BER measurement at 20 Gb/s (pseudorandom binary sequence (PRBS) of $2^{15} - 1$ against different wireless transmission distances measured under different optical excitation conditions, i.e., using 2 or 31 optical comb lines. The 31 optical comb lines were generated by using the RRM technique). The corresponding 20 Gb/s eye-diagrams are also giving in Fig. 4(b) and Fig. 4(c) respectively. We can observe that error-free (BER < 10^{-9}) 20 Gb/s operations are achieved for a 40 cm wireless and 25 km SMF transmission distances, when using the optical short pulses generated by RRM [10]. The BER improvement of using short pulse excitation when compared with the sinusoidal signal excitation (2 comb lines) can be qualitatively understood by noting that short pulses can improve the MMW output power performance.

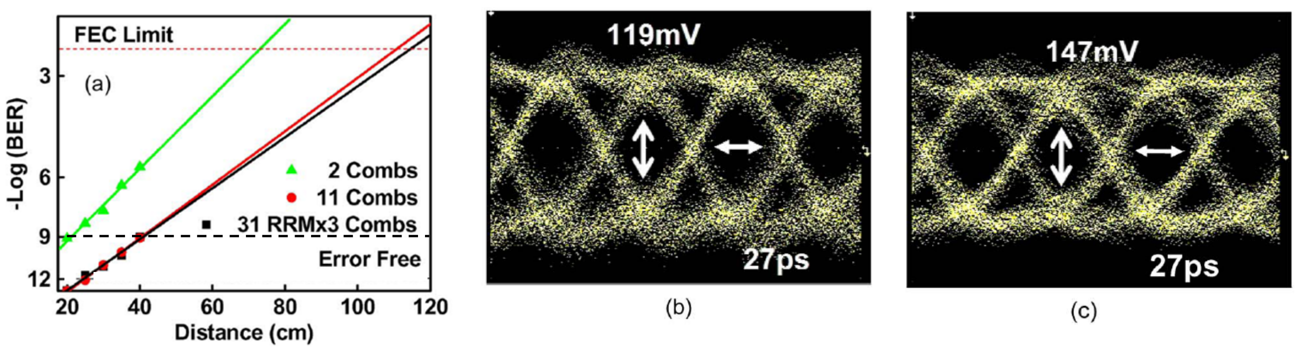

Figure 4. (a) BER measurements at 20 Gbit/s (PRBS: $2^{15} - 1$) against wireless transmission distances using different optical excitation schemes. Measured 20 Gb/s eye-diagrams using (b) two comb lines, and (c) 31 comb lines (generated by using the RRM technique).

4. UPSTREAM MMW DATA TRANSMISSION

In this section, we will discuss the transmission of upstream data. High data rate upstream signal transmission is also necessary for wireless access network, particularly for the on-site news reporters uploading high capacity of data and multi-media information back to the head-end office. An optical-carrier-distributed-network was proposed [11]. In this scheme, the optical CW carrier was sent from the head-end office to the RAU. The received electrical signal at the RAU will modulate the distributed CW carrier to produce the upstream signal. This carrier-distributed-optical-network can reduce the cost of the RAU since no laser is required at the cost-sensitive RAU. Besides, since the RAU is colorless (independent of the input laser wavelength), the same optical components can be used for all the RAUs.

Figure 5 shows the experiment setup. A narrow linewidth CW laser at the wavelength of 1545 nm was launched into a low V_{pi} PM, which was driven with a sinusoidal signal at 20 GHz an an average power of +30 dBm. By over-driving the PM, multiple Bessel sidebands (frequency comb lines) with line spacing of 20 GHz can be generated. The optical mode comb thus generated then was sent to a line-by-line pulse shaper for independent phase/amplitude control as described in section 3. Four comb-lines with line-to-line separate of 100 GHz were produced by the line-by-line shaper. This four comb-line at 100 GHz spacing produced optical short pulses with full-width half-maximum (FWHM) of 2.5 ps at a repetition rate of 100 GHz. The side-mode suppression ratio (SMSR) between every 100 GHz comb line was > 25 dB.

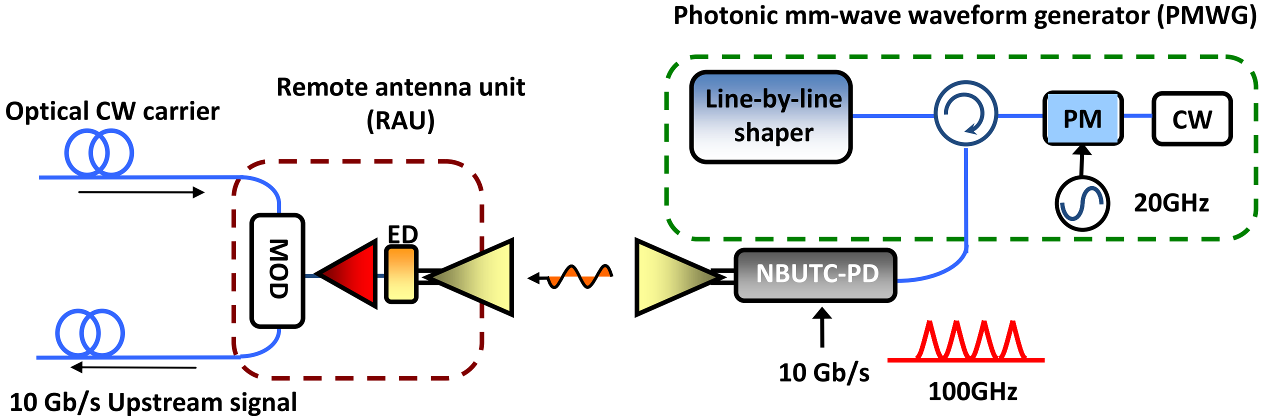

Figure 5. Experimental setup of upstream MMW signal transmission.

In the upstream transmission experiment, 10 Gb/s NRZ electrical data from a BER pattern generator was applied to the IF port of the NBUTC-PD-based photonic transmitter via an on-wafer probe. The 10 Gb/s NRZ electrical signal was RF up-converted to the W-band and then emitted via the horn antenna. Another W-band horn antenna was used at the Rx side. The received wireless signal was amplified by a W-band low-noise amplifier and envelope-detected by a fast W-band power detector. The antenna-to-antenna distance was kept at 20 cm. The envelope-detected signal then drove an optical modulator to generate the upstream signal. As shown in Fig. 5, the CW optical carrier (λ = 1550 nm) was distributed from the head-end office to the modulator via 20 km of SMF. At the modulator, the optical carrier was encoded by the 10 Gb/s NRZ signal, which was then sent back to the head-end office via another 20 km of SMF. Separate fiber paths for carrying the CW carrier and the upstream signal can avoid Rayleigh backscattering [12]. Figure 6 shows the experimental BER measurement of the upstream transmission of received 10-Gb/s W-band wireless-signal, with the corresponding 10 Gb/s NRZ eye-diagrams. ~ 4 dB power penalties were observed when compared with the back-to-back (B2B).

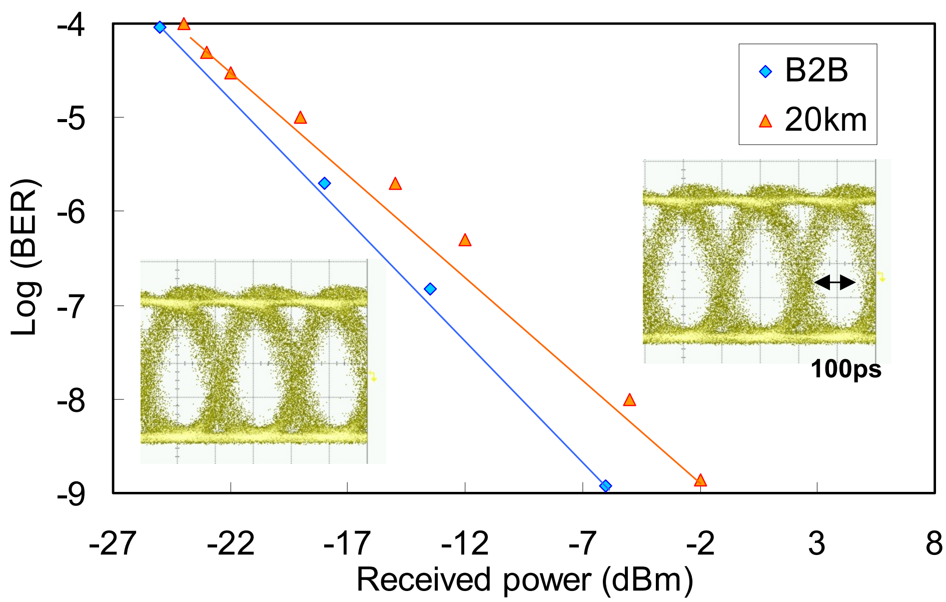

Figure 6. Experimental BER measurement of the upstream transmission of received 10-Gb/s W-band wireless-signal, with the corresponding 10 Gb/s NRZ eye-diagrams.

5. CONCLUSION

Wireless communications in the sub-terahertz region (MMW region) for very high data-rate and high capacity data communications have been actively pursued in the past few years [13]. In this work, we have discussed our recent advances in millimeter-wave photonic wireless links for high data rate (10 – 20 Gb/s) communications. It includes the design of a high speed MMW W-band (100 GHz) NBUTC-PD based photonic transmitter, the operation principle of PMWG for producing the optical pulse train to optically excite the photonic transmitter. The network demonstrations of using the NBUTC-PD and the PMWG for the downstream and upstream high data rate communications were also analyzed and discussed.

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