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10 Gb/s optical carrier distributed network with W-band (0.1 THz) short-reach wireless communication system

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ABSTRACT

Millimeter-wave (mm-wave) operated in W-band (75 GHz–0.11 THz) is of particular interests, since this frequency band can carry signals at much higher data rates. We demonstrate a 10 Gb/s optical carrier-distributed network with the wireless communication system. The mm-wave signal at carrier frequency of 0.1 THz is generated by a high speed near-ballistic uni-traveling carrier photodiode (NBUTC-PD) based transmitter (Tx), which is optically excited by optical short pulses. The optical pulse source is produced from a self-developed photonic mm-wave waveform generator (PMWG), which allows spectral line-by-line pulse shaping. Hence these optical pulses have high tolerance to fiber chromatic dispersion. The W-band 10 Gb/s wireless data is transmitted and received via a pair of horn antennas. The received 10 Gb/s data is envelope-detected and then used to drive an optical modulator at the remote antenna unit (RAU) to produce the upstream signal sending back to the central office (CO). 20 km single mode fiber (SMF) error free transmission is achieved. Analysis about the optimum repetition rate of the optical pulse source and the transmission performance of the upstream signal are also performed and discussed.

1. Introduction

Nowadays, multimedia services such as video-conferencing, video-on-demand (VOD) and high-definition television (HDTV), etc., are becoming more and more popular. And people would like to access these multimedia services at anytime and anywhere. Hence wireless communications supporting higher and higher data rates, and operated at higher and higher frequency bands are required [1]. Wireless communications operated at V-band (60 GHz) has recently been deployed for the in-door wireless applications [2]. And the Wireless Gigabit Alliance (WiGig) has been formed for specifying the related wireless products and applications supporting >1 Gb/s short-reach wireless data rate transmission. Besides, millimeter-wave (mm-wave) operated in higher frequency W-band (75 GHz–0.11 THz) [3] is of particular interests, since it can carry signals at higher data rates. It is developed to support short-reach high bit rate transmission, providing secure and directional communication link. In many scenarios, the central office (CO) is quite far away from the antenna sites. Using copper cables to carry these high frequency mm-wave signals will produce high transmission loss and will be very costly. Hence, using radio-over-fiber (ROF) technology for carrying this mm-wave signal in optical domain to and from different antenna sites is attractive [4–6]. In addition, the architecture of the antenna sites (also called remote antenna unit (RAU)) can be very simple since the ROF technology allows the complicated electronic signal processing to be performed at the CO.

Here, we experimentally demonstrated a 10 Gb/s optical carrier distributed network with 0.1 THz short-reach wireless communication system. The 0.1 THz mm-wave signal was generated by a near-ballistic uni-traveling-carrier photodiode (NBUTC-PD) based transmitter (Tx) [7] optically excited by an optical short pulses. A self-developed photonic mm-wave waveform generator (PMWG) was used to produce high repetition rate and narrow optical pulses for the NBUTC-PD [8]. The wireless 10 Gb/s data at carrier frequency of 0.1 THz was transmitted and received via a pair of horn antennas. The received 10 Gb/s data was envelope-detected, amplified. Then it drove an optical modulator at the RAU to produce the upstream optical signal to the CO. 20 km standard single mode fiber (SMF) transmission was achieved without dispersion compensation. Numerical analysis about the optimum optical pulse repetition rate and the upstream optical signal performance were also given.

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2. Operation principle and experiment

Fig. 1 shows the experimental setup of the proposed 10 Gb/s optical carrier-distributed network with 0.1 THz short-reach wireless transmission system. There are three modules for the system: (i) the NBUTC-PD, (ii) the PMWG and (iii) the W-band receiver (Rx) with optical modulator for the upstream optical signal generation.

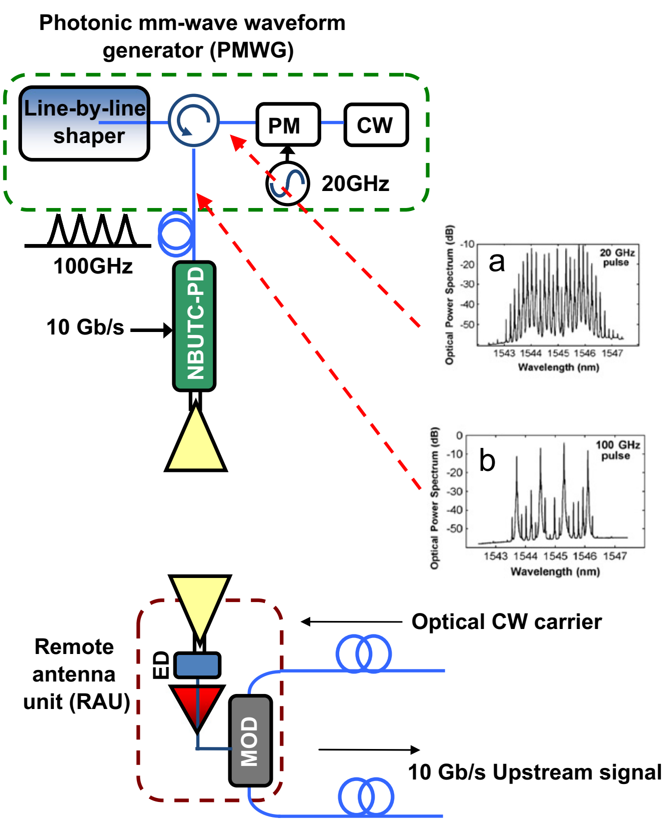

Fig. 1. Experimental setup including the NBUTC-PD, the photonic mm-wave waveform generator (PMWG) and the W-band receiver for the optical upstream signal generation.

Fig. 2(a) shows the top view photograph of the NBUTC-PD Tx with aluminum nitride (AlN) substrate. The Tx consisted of a flip-chip mounted NBUTC-PD with an active area of 100 μm^2, a fan-shaped broadband transition between the co-planar waveguide and coplanar slot-line, an intermediate-frequency (IF) input port, a W-band radio-frequency (RF) choke and a planar quasi-Yagi radiator. Molecular beam epitaxy (MBE) was used to grow the NBUTC-PD on a InP substrate. The quasi-Yagi radiator was designed so that it can be directly fed into a WR-10 waveguide. Hence the quasi-Yagi radiator can be inserted into the W-band horn antenna easily without the need of other RF adapter or connector. The NBUTC-PD was flip-chip bonded onto a 100 μm thick AlN for good thermal conductivity.

The UTC-PD is used because it provides the advantage of superior speed obtained by eliminating the slow transportation of holes in the absorption region [9]. However, in order to produce high output photocurrent, a high applied reverse-bias voltage is needed for the UTC-PD. This would result in a saturation of the electron drift velocity and limit the saturation current-bandwidth product of the conventional UTC-PD. Hence, the NBUTC-PD structure has been proposed and demonstrated; and this issue can be overcome by inserting an additional p-type charge layer into the collector layer of the conventional UTC-PD [7]. A significantly high bandwidth and high saturation current-bandwidth product performance (37 mA, 110 GHz, 4070 mA GHz) was obtained in our developed NBUTC-PD and it was used in the experiment.

Fig. 2(b) shows the measured emitted RF frequency under different dc biases, showing the NBUTC-PD can be operated at the W-band (> 100 GHz). We can also observe that high extinction ratio (~30 dB) W-band wireless signal can be emitted by the Tx by comparing the transmitted power and the noise floor. The Tx was directly modulated via the IF input port using electrical sinusoidal signals produced by a synthesizer in the modulation bandwidth study; and using 10 Gb/s non-return-to-zero (NRZ) signal produced by a bit-error-rate tester (BERT) in the transmission experiment.

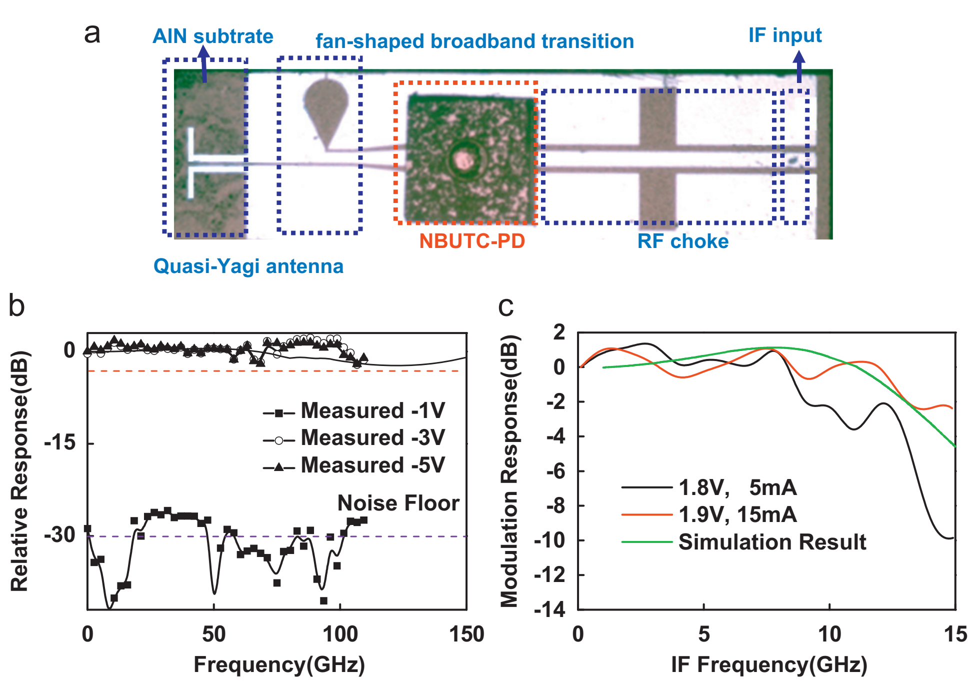

Fig. 2. (a) Top view photograph of the NBUTC-PD Tx, (b) measured emitted RF frequency under different dc biases, and (c) direct modulation response of the Tx.

Fig. 2(c) shows the direct modulation response of the Tx using different electrical input sinusoidal signal, showing the 3 dB electrical modulation bandwidth can be > 10 GHz, which is good enough for the 10 Gb/s NRZ signal transmission.

In our proposed system, optical short pulses are used for the excitation of the NBUTC-PD. This is because the optical short pulse can provide high modulation depth (> 100%) and hence higher output mm-wave power with a much smaller photocurrent applying to the NBUTC-PD [10]. Besides, by using the spectral line-by-line shaper, the narrow optical pulse width can be maintained when transmitting in 25 km SMF without any dispersion compensation [11]. In the experiment as shown in Fig. 1, a continuous-wave (CW) optical source (wavelength 1545 nm) was first modulated by a phase modulator (PM), which was electrically driven at 20 GHz sinusoidal signal with average power of +30 dBm. The PM was over-driven and multiple spectral comb lines (different Bessel sidebands) with 20 GHz frequency separation were generated at the PM output, as shown in inset of Fig. 1(a). These spectral comb lines were then launched into a line-by-line pulse shaper for independent phase/amplitude control, as shown in Fig. 3. Inside the line-by-line pulse shaper, a fiber pigtailed collimator and a lens were used to launch the optical comb lines onto a 1200 grooves/mm gold-coated grating. The polarizer maintained the launching polarization. These optical comb lines were diffracted and focused by a lens (focal length = 500 mm). A 2 × 640 pixel liquid crystal modulator (LCM, CRI SLM-640-D-NM) array, which was computer controlled, was used to separately control the amplitude and phase of individual comb lines. A retro-reflector reflected the modulated comb lines back to the input fiber. Then these modulated comb lines will be extracted by an optical circulator and then launched into the NBUTC-PD (Fig. 1).

Based on our simulation results in next section, > 50 GHz repetition rate optical pulses are required to generate upstream signal with Q > 18 dB. And the performance of the upstream signal will saturate at Q~21 dB when 100 GHz repetition rate optical pulses are used. Hence in the experiment, we generated four spectral comb lines with line-to-line separate of 100 GHz, as shown in inset of Fig. 1(b). As also shown in Fig. 1(b), the side-mode suppression ratio (SMSR) of the four dominant comb lines and the other suppressed comb lines was > 25 dB. These four comb lines at 100 GHz spacing produced the required 100 GHz repetition rate optical pulse train with full-width half-maximum (FWHM) pulse width of 2.5 ps.

The NBUTC-PD was directly modulated by the 10 Gb/s NRZ signal at the IF port and was optically excited by the 100 GHz optical short pulses (comb lines). It produced the frequency up-converted 10 Gb/s NRZ signal at W-band. The W-band mm-wave wireless signal was transmitted and received via a pair of W-band horn antennas. The received 10 Gb/s data was envelope-detected by a fast W-band power detector (Militech: DXP-10-RPFW0), amplified (JDSU: H301) and then drove an optical Mach-Zehnder modulator (MZM) (Avanex: IM10). An optical CW signal at wavelength of 1550 nm, average power of 0 dBm was launched into the MZM after propagating through 20 km of standard SMF. Then the CW signal was modulated by the MZM to produce the upstream NRZ signal sending back to the CO via another 20 km SMF.

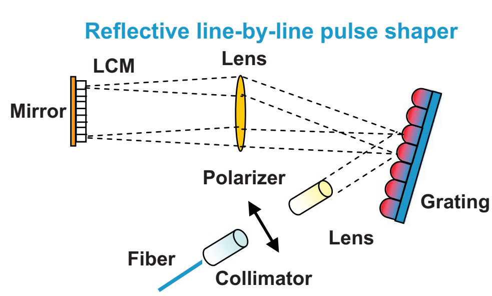

Fig. 3. Architecture of the line-by-line pulse shaper.

3. Results and discussion

First, we studied the emitted mm-wave output power of the NBUTC-PD Tx versus different numbers of comb lines under different reverse bias voltages. As shown in Fig. 4, the emitted mm-wave signal power can be enhanced by about 4 dB when using the optical short pulse excitation rather than using the conventional optical sinusoidal excitation (2 comb lines). This is because in the optical pulse excitation, the total power is obtained by adding up all the signal spectral comb lines during the beating in the PD, while the sinusoidal excitation only has two comb lines. We can also observe that when the number of comb lines is more than 4, the emitted power will become saturated. Hence we selected 4 comb lines in the experiment.

Then numerically analysis was performed about the repetition rate of optical pulse train for generating 10 Gb/s upstream optical signal. Commercial software VPI Transmission Maker V7.5 was used. The simulation setup was based on Fig. 1. Different repetition rates (from 10 GHz to 100 GHz) optical pulse train (FWHM = 2.5 ps) were coupled to the PD with the OE bandwidth obtained from the experiment. The signal was then emitted and received via a pair of W-band horn antennas (3-dB bandwidth from 75 to 110 GHz). In the simulation, 1550 nm CW optical signal was distributed to the Mach-Zehnder modulator (MZM) via 20 km SMF (dispersion parameter = 17 ps/nm/km). The wireless received signal was then amplified and envelope detected to produce the baseband 10 Gb/s NRZ signal, which then drove the MZM to produce the upstream signal. Finally, the upstream NRZ signal was received at the CO after traveling through another 20 km SMF.

Fig. 5(a) shows the simulated Q-values of the 10 Gb/s upstream NRZ signal at different repetition rates of optical pulse excitation (with 20+20 km SMF transmission). The Q-value was measured using the built-in function of the VPI Transmission Maker. According to the simulated results, when the repetition rate of the optical pulse train is low, the upstream signal is RZ-liked. And the quality of the upstream NRZ signal is highly dependent on the timing delay between the optical pulse and the applied electrical NRZ signal to the Tx. At the repetition rate of 10 GHz, the best performance of NRZ signal is observed when the optical pulse is positioned at the center of the NRZ signal. When the repetition rate is increased to > 30 GHz, the timing

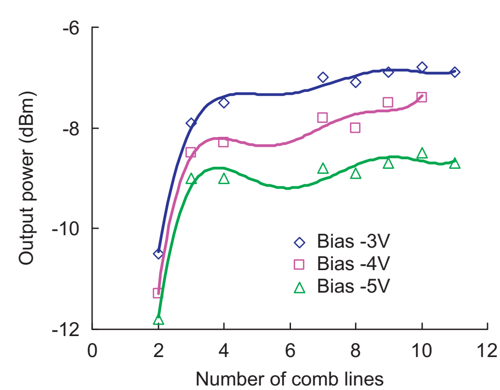

Fig. 4. Measured mm-wave output power of the NBUTC-PD Tx versus different numbers of comb lines under different reverse bias voltages.

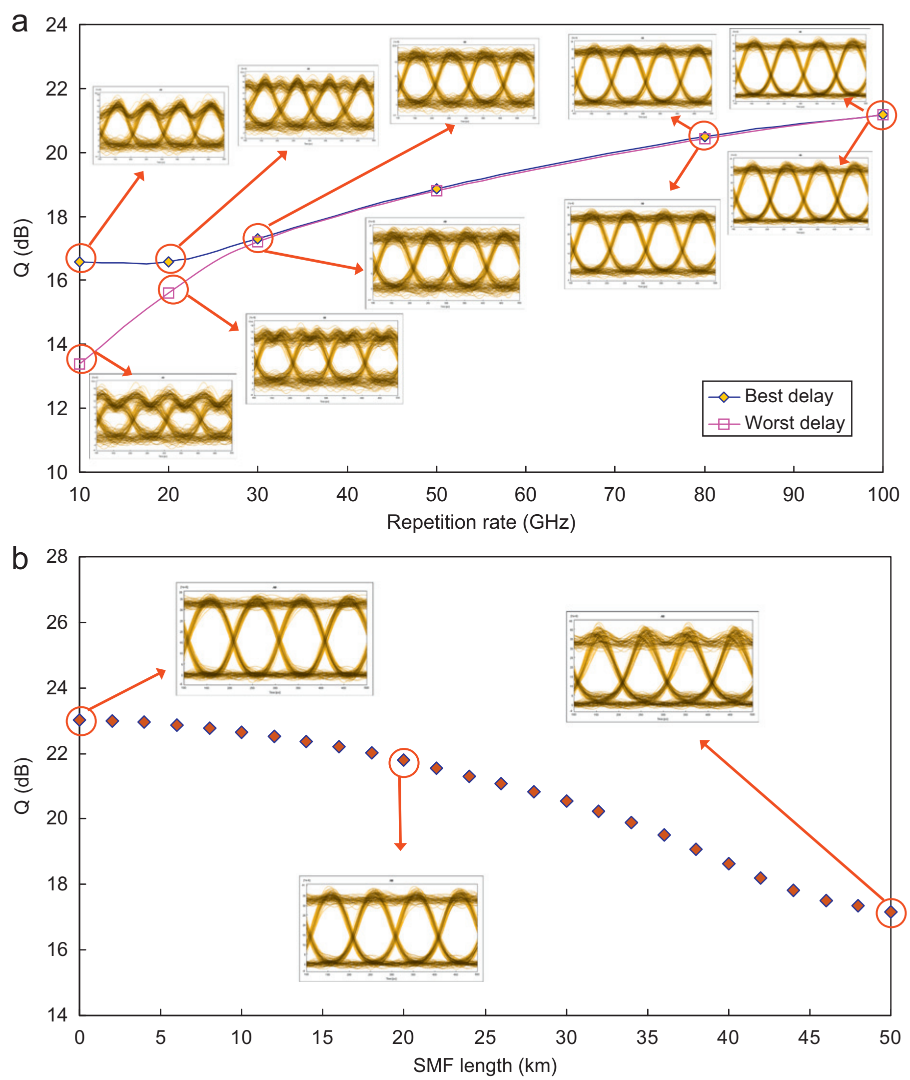

Fig. 5. (a) Simulated Q-values at different repetition rate optical pulses. (b) Simulated Q-values propagating through different lengths of SMF.

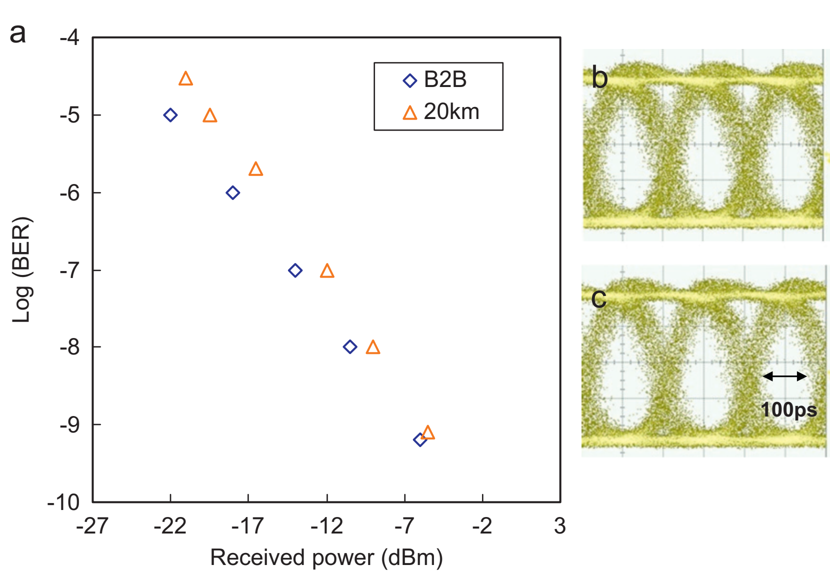

Fig. 6. (a) Experimental BER measurement of the upstream transmission of received 10 Gb/s W-band wireless-signal, with the corresponding 10 Gb/s NRZ eye-diagrams at (b) back-to-back and (c) after 20 km SMF transmission.

synchronization between optical pulse train and applied electrical NRZ is less important. When the repetition rate of the optical pulse train is >50 GHz, the Q of upstream NRZ signal can be >18 dB. And the performance of the upstream signal saturates at Q$\sim$21 dB when the repetition rate of the optical pulse train is 100 GHz. Hence 100 GHz optical pulses were generated by using the line-to-line pulse shaper in the experiment. We have also numerically analyzed that the increase in upstream signal when using high repetition rate optical pulses are due to the increase in average optical power coupling into the Tx. When the repetition rate increased from 10 GHz to 100 GHz, the average optical power increased from -9 dBm to -5 dBm. We also study the maximum transmission distance for the upstream NRZ signal. As shown in Fig. 5(b), the simulated Q of the upstream signal can be >16 dB even in 50 km SMF transmission without dispersion compensation. This shows that bit-error rate (BER) of 10^{-9} can be achieved. The BER of 10^{-9} is often considered as the minimum acceptable BER for telecommunication applications.

Then the experimental BER measurement was performed. Fig. 6(a) shows the experimental BER measurement of the upstream transmission of received 10 Gb/s W-band wireless-signal. The corresponding 10 Gb/s NRZ eye-diagrams at back-to-back and after 20 km SMF transmission are shown in Fig. 6(b) and (c) respectively. Negligible power penalty was observed when compared with the back-to-back (B2B). A good match in eye-shape (small amplitude overshoot in level "1" and flat level "0") between the simulation (Fig. 5) and experiment results can be observed.

4. Conclusion

We experimentally demonstrated a 10 Gb/s optical carrier-distributed network with wireless communication system. The mm-wave signal at carrier frequency of 0.1 THz was generated by a high speed NBUTC-PD based transmitter, which was optically excited by optical short pulses. The optical pulse source was produced from a self-developed PMWG, which allows spectral line-by-line pulse shaping. Hence these optical pulses had high tolerance to fiber chromatic dispersion. Besides, the emitted mm-wave signal power can be enhanced by about 4 dB when using the optical short pulse excitation rather than using the conventional optical sinusoidal excitation. The W-band 10 Gb/s wireless data was transmitted and received via a pair of horn antennas. The received 10 Gb/s data was envelope-detected and then used to drive an optical modulator to produce the upstream signal sending back to the CO. 20 km SMF error free transmission was achieved. Simulation shows that Q$>$18 dB upstream NRZ signal can be received when the repetition of the optical pulses >50 GHz. When the repetition rate is increased to >30 GHz, the timing synchronization between optical pulses and applied NRZ is less crucial.

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