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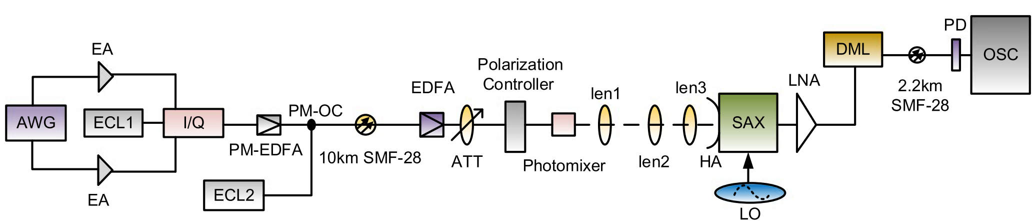

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Fiber-THz-Fiber Link for THz Signal Transmission

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Abstract: We propose and experimentally demonstrate vector signals seamless integration delivery over fiber-THz-fiber link. Up to 13 Gb/s quadrature-phase-shift-keying signals are transmitted over 10 km single mode fiber-28 (SMF-28), 3.8 m wireless link, and 2.2 km SMF-28 link. At the transmitter, we use a photonics-aided scheme to generate 450 GHz THz signal. While at the receiver side, we employ analog down-conversion by one electrical mixer, and then the down-converted signals are used to drive one directly modulated laser to realize electrical-to-optical conversion.

Index Terms: Terahertz-wave band, fiber-wireless-fiber integration system, quadrature-phase-shift-keying (QPSK), directly modulated laser, down-conversion, seamless integration.

1. Introduction

As we all know, widely deployed wireless communication networks are advancing in an unprecedented way, but the band (500 MHz $\sim$ 5 GHz) cannot meet our increasing needs to achieve a higher bit rate communication. Terahertz-wave band (300 GHz–10 THz) is worth exploiting because of its sufficient bandwidth [1]–[3], which can match the bandwidth of the optical fiber. Wireless communication using THz band provides the possibility to reach transmission rates comparable to those reached in wired local area networks [4]. What's more, it can help to solve the problems such as lack of frequency band and limitation of capacity [5]. However, researchers pay more attention to the application of the THz-band to indoor short-range wireless personal area networks (WPANs) [6], wireless local area networks (WLANs) or other areas because of the high atmospheric attenuation of the THz-band [1], [2].

After the disaster in Japan in March 2011, the government in Japan launched a project aimed at fiber and mm-wave wireless seamless communication system [6]. It is true that THz communication can be employed in some scenarios. For example in some island countries, lots of lakes and small hills lie between the main buildings or central offices, and it is inconvenient in deploying optical cables. What's more, some natural disasters, such as earthquakes and tsunamis, directly lead to the broken optical fiber communication devices and communication interruption [7], [8]. As a result,

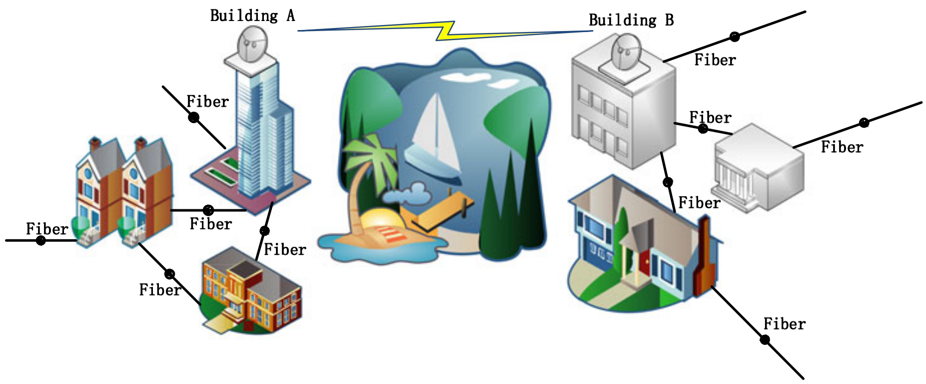

Fig. 1. Application scenarios of THz fiber-wireless-fiber integration system.

we need to develop a fiber-THz wireless-fiber system to solve the problem, which is helpful to establish a complete communication system to match the bandwidth of the optical fiber no matter what kind of environment. What's more, the advantages of large bandwidth of fiber communication and high mobility of wireless communication make the fiber-wireless-fiber seamless communication system a promising choice [9], [10]. Fig. 1 shows the situation. Here the central office or building A is far away from B. There are lakes or cliffs between A and B, which is hard to lay fiber cables. An excellent approach is to lay wireless communication between A and B, such as THz signal or mm-wave. Methods of generating mm-wave frequencies based on photonic techniques can not only overcome the bandwidth limitation of electrical components, but also effectively promote the seamless integration of fiber and wireless networks [11]. At THz transmitter side, we can employ photonics aided scheme to generate THz signals. At THz receiver side, we down-convert the signal to be a few or tens of GHz. Then this down-converted signals are used to drive the intensity modulator or directly modulated laser (DML) to realize electrical-to-optical conversion. This converted optical signals can be transmitted to long distance in optical fiber. Relative to intensity modulator such as Mach-Zehnder modulator or electrical absorption modulator, DML has a small size and simple architecture. Hence we employ it in our experimental demonstration.

A field-trial demonstration of integrated photonic 60 GHz wireless-over-fiber system for transmitting uncompressed high-definition video signals and existing WIFI services in campus fiber network at Georgia Tech was showed in [12], which showed the integrated systems are practical solutions. [13] showed a 20 Gbit/s wireless transmission at 220 GHz carrier frequency embedded into an optical fiber environment. At THz band, [2] realized a 24 Gbit/s transmission at 300 GHz for 50 cm wireless distance. [14] showed a 2.5 Gbit/s error-free transmission at 625 GHz. But less of them realized a fiber-wireless-fiber seamless integration system at THz band.

In this paper, we propose and experimentally demonstrate a fiber-THz-fiber seamless integration system using the DML with 10-GHz bandwidth to modulate signals because of its small size and simple architecture at 450 GHz enabled by the photonics-aided scheme at the THz band, which can transmit up to 13 Gb/s quadrature-phase-shift-keying (QPSK) signal. The signal can be transmitted over 10-km single mode fiber-28 (SMF-28) wireline link firstly, then through over 3.8-m free space THz wireless link and over another 2.2-km SMF-28 wireline link at last, with a bit-error ratio (BER) less than the hard-decision forward-error-correction (HD-FEC) threshold of 3.8×10^{-3}.

2. Experimental Setup

Fig. 2 shows the experimental setup for the fiber-wireless-fiber integration transmission system at THz-band. The frequency response of our mixer ranges from 330 $\sim$ 510 GHz. So we choose the middle frequency (450 GHz) in order to get a better response. In this system, we use the photonic remote heterodyning to generate 450 GHz THz-band signal. That is to say, the frequency spacing between two external cavity lasers (ECLs) is 450 GHz. The ECL1 is designed at 193.100 THz for

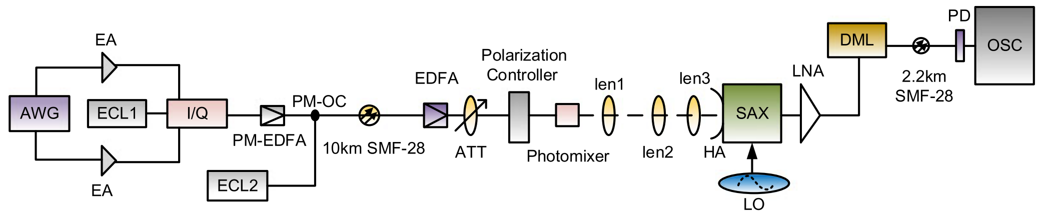

Fig. 2. Experimental setup for fiber-wireless-fiber integration transmission system at THz-band. (ECL: external cavity laser, the frequency spacing between ECL1 and 2 is 450 GHz. AWG: arbitrary waveform generator. EA: electrical amplifier. I/Q: I/Q modulator. PM-EDFA: polarization maintaining Erbium-doped fiber amplifier. PM-OC: polarization maintaining optical coupler. SMF-28: single mode fiber-28. ATT: attenuator. PD: photodiode, 15 GHz bandwidth. HA: horn antenna. SAX: signal analyzer extension module. LNA: low noise amplifier. LO: local oscillator. DML: directly modulated laser, 10 GHz bandwidth, output power at 41 mA:3.7 dBm).

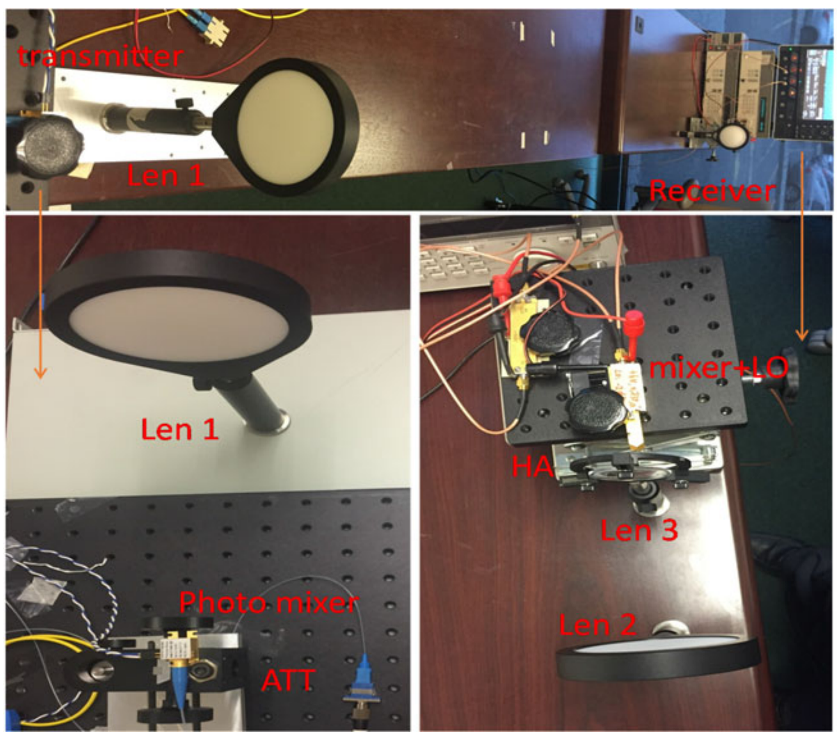

Fig. 3. Picture of the experimental setup for fiber-wireless-fiber integration transmission system at THz-band.

carrying the QPSK signal, while ECL2 is at 193.550 THz as an optical oscillator (LO). Fig. 3 gives the photos of the experimental system.

At the transmitter side, an ECL with linewidth less than 100 kHz is used as an optical source. The continuous-wavelength lightwave output from the ECL is modulated by QPSK signals, which is generated offline in Matlab and then loaded into an arbitrary waveform generator (AWG) with 12-GSa/s sampling rate and 3-dB bandwidth of 4 GHz. Before modulated onto the optical carrier, the output signals from DAC are boosted by an electrical amplifier (EA) to ~20 dBm to drive the I/Q modulator. The I/Q modulator is used to realize electrical-to-optical conversion, which has a 3-dB bandwidth of ~30 GHz. The modulated signal after I/Q modulator is injected into the first polarization maintaining Erbium-doped fiber amplifier (PM-EDFA), which is mainly used to compensate for the insertion and modulation loss of the I/Q modulator. Then one 3dB polarization maintaining optical coupler is employed to combine the QPSK optical signal and optical LO. After

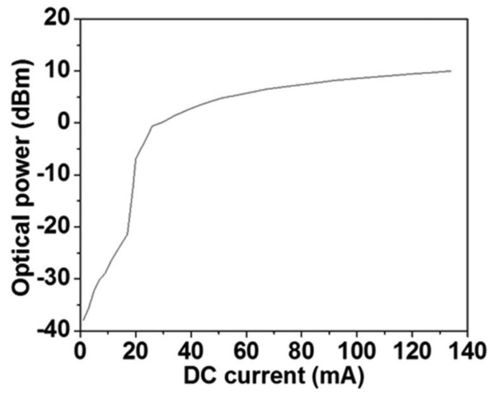

Fig. 4. Response characteristic of DML.

10-km SMF-28 transmission, another EDFA is used to boost optical power. Then an optical attenuator (ATT) is applied to adjust the received optical power for sensitivity measurement. The optical signals are detected by an NEL UTC-photomixer with an integrated antenna. Model number of the photomixer is IOD-PMAN-13001. It has an output power of −28 dBm at 450 GHz. This UTC-PD chip is monolithically integrated with a broadband antenna (Bow-tie). The chip was placed on a hyper-hemispherical Si lens. The THz wave was emitted through this Si lens. This procession allows for the optical signal to be converted into electrical THz signal. The pigtail fiber of the photomixer is polarization maintaining, so we need one polarization controller to control the polarization direction of the signal into the photomixer.

After the photomixer, three different types of lens are introduced to precisely focus the THz beam into a particular spot. Lens 1 and Lens 2 are Plano-Convex Teflon lens with a 10 cm diameter and a 20 cm focus length. Lens 3 is a Microtech Instrument with the model number of PTL-2-100BW, a diameter of 5 cm, and a focus length of 10 cm. Lens 1 is 20 cm away from the UTC-photo mixer. The distance between lens 1 and 2 is 3.4 m while lens 2 is 0.2 m apart from lens 3. The distance between lens 3 and the receiver is 0.2 cm. These lenses are used to maximizly accumulate the power of wireless signals [1], [15]. And the experimental results show 3.8 m is the longest distance in our experiment. Upon arriving at the horn antenna (HA) with 26 dBi gain, the signal passes through a SAX signal analyzer extension (SAX) module, which is manufactured by the VDI Company and has a WR2.2 waveguide input part. The SAX includes one THz mixer and one frequency multiplier with the 40 GHz maximum available intermediate-frequency (IF) bandwidth. Subsequently, the electrical down conversion process is conducted in the SAX with a 9.231 x 48 GHz radio-frequency (RF) source. The output signal from the SAX is located around 6.91 GHz followed by a low-noise amplifier (LNA) with 40 dB gain at 5 $\sim$ 17 GHz. Then the baseband signal is once again modulated by a DML with 10-GHz bandwidth. The commercially available 10-GHz bandwidth DML (NLK1551SSC) is biased at 50 mA, and the optical output power of the DML is 2.26 mW. The driving voltage amplitude is 1.75 V. We measured the performance of the output power of the DML as a function of the DC current. It is shown in Fig. 4. After 2.2 km standard SMF-28 with a total insertion loss of 1 dB, the received signal is detected by a photodiode with 15 GHz bandwidth. Due to the fiber dispersion, the double sideband modulated signals are heavily affected by the walk-off effect. So the signals can only be transmitted over 2.2 km after the DML. Finally, the signal is recorded by a real-time oscilloscope (OSC) which has a 3 dB bandwidth of 30 GHz and 80 GSa/s sample rate.

3. Experimental Results and Discussions

Fig. 5(a) shows the optical signal power before 10 km SMF-28 transmission. The frequency spacing between the two lasers is 450 GHz. Fig. 5(b) shows the optical power of 5 Gbaud QPSK signal after

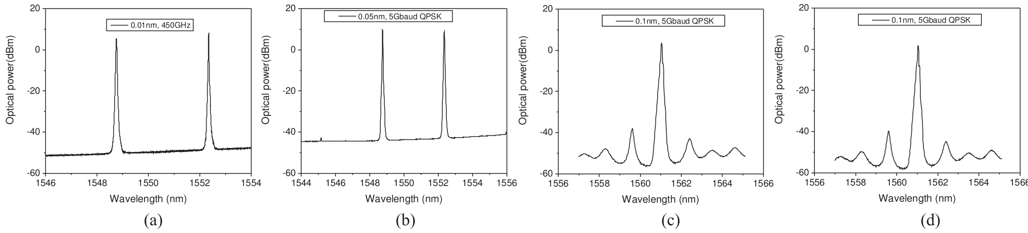

Fig. 5. Optical spectra: (a) before 10 km SMF-28 transmission, (b) after 10 km SMF-28 transmission, (c) before 2.2 km SMF-28 transmission, and (d) after 2.2 km SMF-28 transmission.

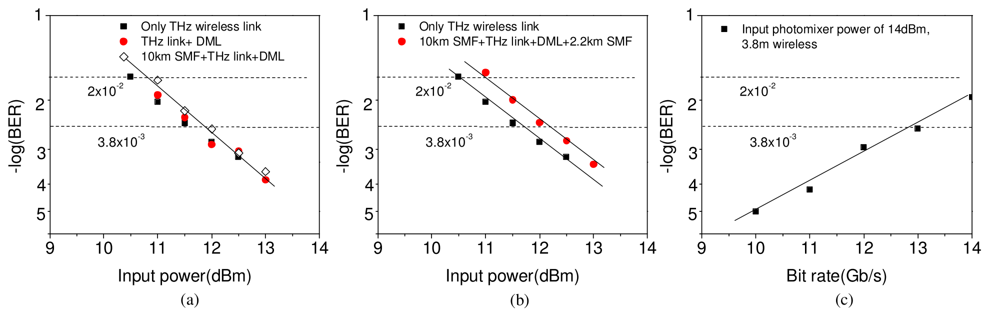

Fig. 6. The measured BER performances versus (a)-(b) input optical power over different links and (c) bit rate.

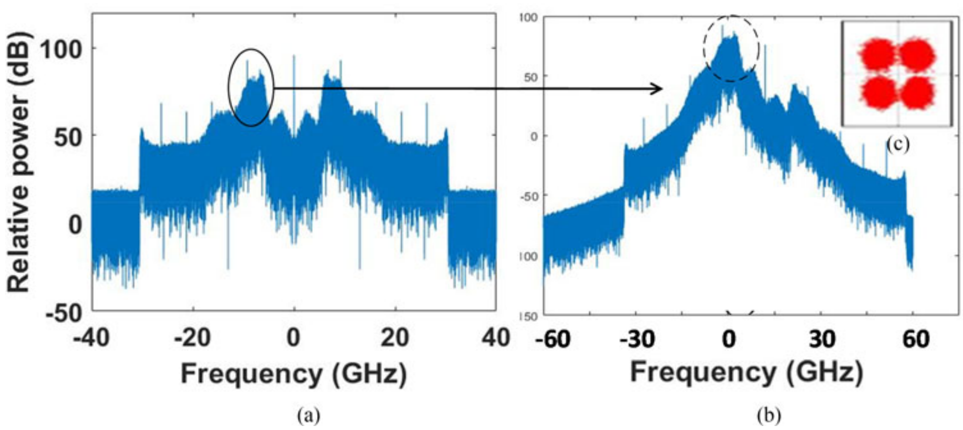

Fig. 7. (a) Complete spectrum after 2.2 km SMF, (b) signal spectrum, (c) constellation of offline DSP signals on condition of input power into photomixer is 13 dBm over the whole link (10 km SMF + 3.8 m wireless link + 2.2 km SMF).

10 km SMF-28 transmission. Fig. 5(c) shows the optical power of 5 Gbaud QPSK signal before 2.2 km SMF-28 transmission while Fig. 5(d) is after transmission. The side-mode suppression ratio of the DML is higher than 40 dB. Apparently, after transmission, the signal suffers from slight energy attenuation.

As is showed in Fig. 6(a), we compare the conditions of the only THz wireless link, THz link +DML, and 10 km SMF + THz link + DML with 5 Gbaud (10 Gbit/s) data. From Fig. 6(a), we can see that there is no obvious difference when with 10 km SMF transmission fiber or with additional DML. When input signal power into photomixer increases to 12 dBm, BER is below the HD-FEC threshold of 3.8×10^{-3}. But after 2.2 km SMF fiber is connected from the DML, there is 0.5 dB power penalty, which can be seen in Fig. 6(b). The main reason is the walk-off effect caused by the fiber dispersion in 2.2 km fiber. Also, the signal generated from DML has red-shift chirp. Fig. 6(c) gives the measured BER performance when we change the bit rate. Along with the growth of bit rate, the BER is increasing. Until the bit rate equals to 13 Gbit/s, BER begins to in excess of the FEC threshold of 3.8×10^{-3}. Higher bit rate signals need higher THz input power into the receiver or more signal to noise ratio (SNR) after the LNA at the receiver. We believe we can achieve higher transmission bit rates or better BER performance if we add a THz amplifier in the transmitter or receiver to boost the THz power. On the other hand, even if the SNR is higher enough, the small bandwidth of DML and other devices will limit the bit rate of the transmission signals. The electrical spectrum with the input power of 13 dBm into the photomixer is shown in Fig. 7(a). The received signals are first down-converted to baseband by frequency shifting in the digital domain. A fifth-order Bessel low-pass filter with 3 dB bandwidth of the baudrate is employed to select the left-side signal as shown in Fig. 7(b). The constellation of signals after the offline digital signal processing (DSP) is shown in Fig. 7(c).

4. Conclusion

For the first time, we propose and experimentally demonstrate seamless fiber-THz-fiber integration system at 450 GHz using DML to modulate the signals after THz wireless transmission. In other words, any short part of fiber can be placed by the THz wireless link seamlessly and solve the problem that mentioned above. Meanwhile, the system can combine the advantages of both THz and optical fiber, which means it is a better improvement in communication. In our experiment, the highest speed is up to 13 Gbit/s with BER smaller than 3.8×10^{-3}. The transmission distance is 10 km wireline fiber+3.8 m wireless distance+2.2 km wireline fiber. We believe the bit rate or transmission distance can be largely increased if a THz amplifier could be added to the transmitter or receiver side and the optical and electrical devices have a wide bandwidth.

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