151.5-GHz Sub-THz Signal Reception and Downconversion Using All-Optical Technology

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Abstract: A direct reception of a sub-THz signal and its conversion to the microwave band is demonstrated using an all-optical receiver and photonic downconversion technology. An 80-Gb/s OFDM signal was transmitted over a converged fiber–sub-THz–fiber system at 151.5-GHz.

OCIS codes: (060.5625) Radio frequency photonics; (350.4010) Microwave

1. Introduction

Communication in the sub-THz band is considered a key technology for ultra-high data rates in 6G and beyond networks. Among the frequency range, the lower edge, such as the W and D bands, can be first used for 6G access and Xhaul applications owing to its technology maturity [1]. However, high free-space loss and weak penetration are still considered bottlenecks, especially for communications between indoor and outdoor. To overcome these challenges, sub-THz signals should be received and distributed indoors using a dedicated distribution network. For receiving sub-THz signals, most systems rely on electronics-based receivers [2, 3], which complicate antenna sites owing to the inclusion of local oscillator sources. A fully transparent radio–optical conversion using an all-optical receiver is a promising solution to simplify antenna sites [4-7]. In Ref. [4], the transparent relaying of sub-THz signals from outdoor to indoor was demonstrated using a broadband radio-over-fiber system. Nevertheless, the sub-THz signal was transmitted directly to end users and electronically downconverted, rendering the system unsuitable for mobile Xhaul networks and fixed wireless access applications. Refs. [5, 6] employed coherent detection for detecting and downconverting modulated optical signals to baseband, complicating the receiver and requiring robust digital signal processing (DSP) for signal demodulation. A system using an all-optical receiver and photonic downconversion is promising to simplify antenna sites and the receiver; however, the signal frequency was limited to 100 GHz in the previous work [7] owing to the bandwidth limitation of optical modulators.

In this study, we demonstrated the first transparent fiber–sub-THz–fiber system using an all-optical receiver and photonic downconversion technology. For direct conversion of sub-THz signals to optical signals, we employed a newly fabricated broadband optical modulator. To simultaneously detect and downconvert the sub-THz signals to the microwave band, photonic downconversion technology with a pure two-tone optical signal was used. A high-extinction ratio Mach–Zehnder modulator (MZM) using an active Y-branch was fabricated and used to generate a pure two-tone optical signal. Using the proposed technologies, we successfully transmitted a 16-QAM orthogonal frequency division multiplexing (OFDM) signal with a line rate of over 80 Gb/s over the system in the 151.5-GHz band. To the best of our knowledge, this is the first fiber–radio–fiber system using an all-optical receiver and direct photonic downconversion for sub-THz signals beyond 100 GHz, and the achieved data rate is the highest to date. The proposed system can facilitate the deployment of sub-THz communications in 6G and beyond networks.

2. System concept and experimental demonstration

Figure 1 presents the concept of the proposed system. The sub-THz signal was received and directly converted to the optical domain using a broadband optical modulator at the relay node (RN). A two-tone optical signal with a frequency separation of f_{LO} was generated at the receiver (Rx), and the lower sideband was transmitted to the RN for signal modulation. A double-sideband suppressed-carrier signal was generated and transmitted to the Rx, and the upper modulation sideband was selected using an optical filter. Subsequently, the filtered signal was combined with the upper sideband of the generated two-tone optical signal using an optical coupler. Finally, the combined signal was input to a low-speed photodiode for conversion to an electrical signal with frequency $f_{Mw}= f_{sub\text{-}THz} - f_{LO}$, where $f_{sub\text{-}THz}$ is

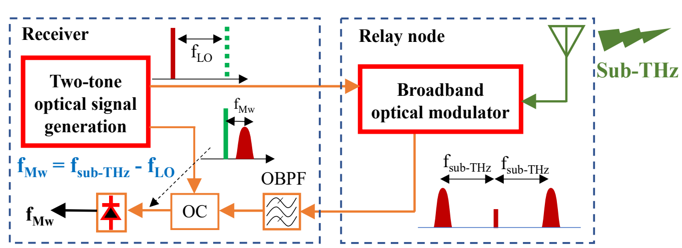


Fig. 1. Concept of sub-THz signal reception and detection using an all-optical receiver and photonic downconversion. LO: local oscillator; OC: optical coupler; OBPF: optical bandpass filter; Mw: microwave.

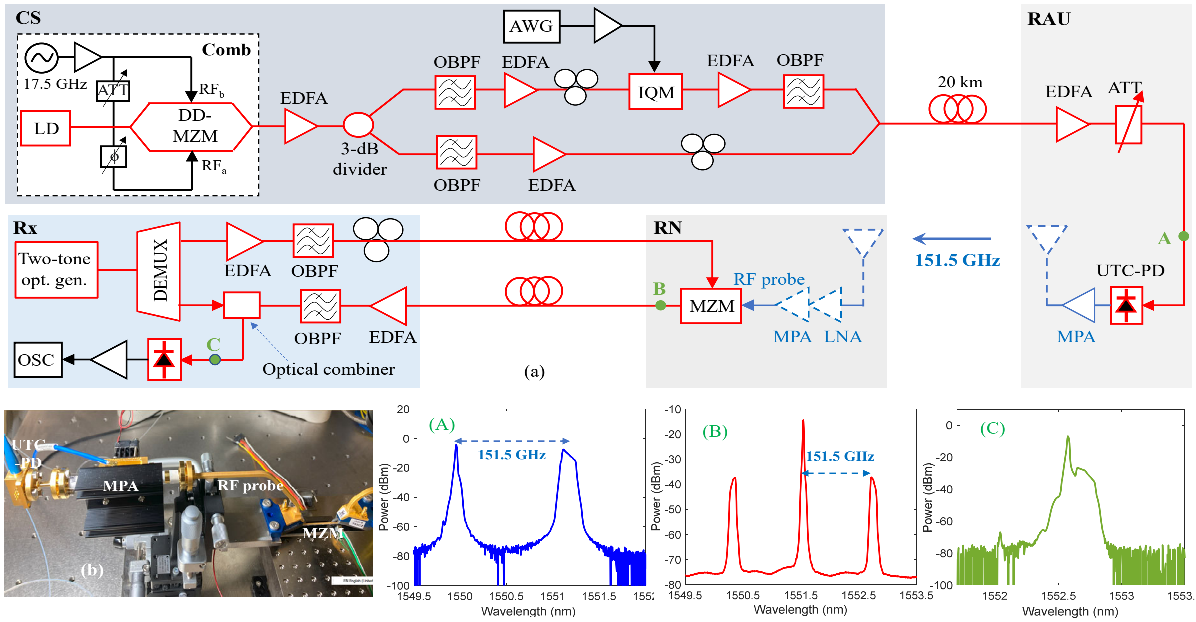


Fig. 2. (a) Experimental setup; (b) MZM setup.

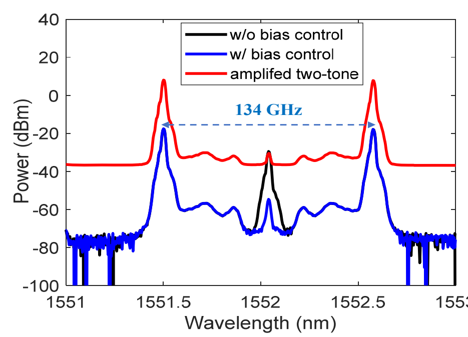
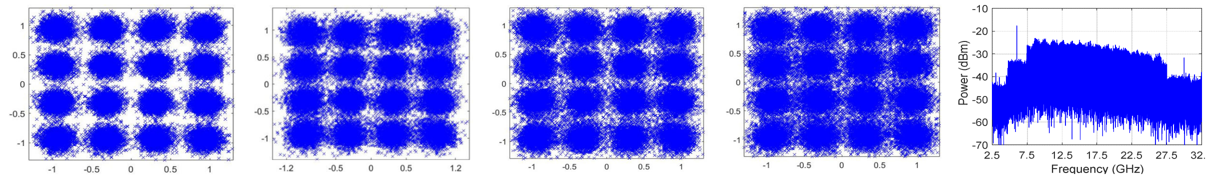


Fig. 3. Spectra of two-tone optical signal.

the frequency of the sub-THz signal and f_{LO} is the frequency separation of the two-tone optical signal. The experimental setup for the signal transmission over the proposed system is shown in Fig. 2, including the central station (CS), remote radio head (RAU), RN, and Rx. The CS generates and modulates the signal, whereas the Rx receives and demodulates the signal. The optical-to-radio conversion is performed at the RAU, whereas the RN converts the radio signal back to optical signal for transmission to the Rx. In this system, the RN comprises only an optical modulator and radio frontend, significantly simplifying the antenna site. At the CS, an optical frequency comb was generated using a dual-drive MZM [8]. An RF sinusoidal signal at 17.5 GHz was fed to the modulation electrodes, and two comb lines with a frequency separation of 140 GHz were selected using optical filters. The signals were amplified, and one of the comb lines was modulated by real-valued intermediate frequency OFDM signals at 11.5 GHz using an in-phase quadrature-phase optical modulator. The bias voltage applied to the modulator was controlled to generate only the upper modulation sideband. The modulated signal was amplified, recombined with the unmodulated comb line, and transmitted to the RAU using a 20-km single-mode fiber. At the RAU, the signal was amplified and input to a uni-traveling-carrier photodiode to convert it to a sub-THz signal centered at 151.5 GHz (=140 + 11.5 GHz). The generated sub-THz signal was amplified using a medium-power amplifier and could be emitted into free space for transmission. In the experiment, however, the signal was connected to the RN using a waveguide due to a lack of antennas in the operating frequency band. At the RN, the received signal was connected to a broadband MZM using RF probes. In this study, we employed a newly fabricated low-loss and high-slope-efficiency MZM using the x-cut thin-film lithium niobate [4]. The operating frequency of the broadband MZM could be increased to 330 GHz. To simplify the antenna site, the optical carrier signal for the sub-THz signal modulation was generated from the Rx and transmitted to the RN. In addition, photonic downconversion technology using a pure two-tone optical signal generation was employed to detect and downconvert the signal to the microwave band to simplify the receiver and DSP [7]. Using this method, a two-tone optical signal with a frequency separation of 134 GHz was generated by feeding a 67-GHz RF signal to a high-extinction-ratio single-drive MZM at the Rx. The modulator included an active Y-branch to control the optical balance between the interferometers by applying an electrical voltage to the active Y-branch to optimize the extinction ratio [9]. The optical spectra of the generated two-tone optical signal at the output of the modulator, with and without applying an optimal voltage to the Y-branch, are shown in Fig. 3. The extinction ratio of the modulator could be increased by approximately 26 dB by applying an optimal voltage to the Y-branch, and a pure two-tone optical signal could be generated. The generated signal was amplified, and the lower sideband was



53.5 Gb/s, EVM=12.9% 71.8 Gb/s, EVM=17.1% 75 Gb/s, EVM=17.8% 80 Gb/s, EVM=19.8% 80 Gb/s signal

Fig. 4. Examples of constellations and spectra of received OFDM signals.

amplified and transmitted to the RN for signal modulation. The bias voltage to the modulator was controlled to generate a double-sideband suppressed-carrier signal. The modulated signal was transmitted to the Rx and amplified, and only the upper modulation sideband was selected using an optical filter. Subsequently, the filtered signal was combined with the upper sideband of the generated two-tone optical signal. The frequency difference between the unmodulated and modulated sidebands was 17.5 GHz (=151.5 - 134 GHz). The combined signal was input into a 40-GHz photodiode for conversion to an electrical signal at 17.5 GHz. Finally, the signal was amplified, sent to a real-time oscilloscope, and demodulated. A photo of signal coupling to the MZM at the RN and optical spectra at different points are shown in Fig. 2.

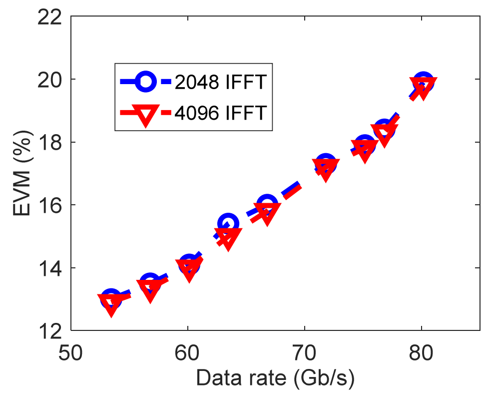


Fig. 5. Signal performance vs. data rate.

We transmitted an OFDM signal over the system and evaluated the performance using the error vector magnitude (EVM) metric. An OFDM signal at 11.5 GHz consisting of 2,048 and 4,096 subcarriers, of which 16.5% at the band edges were inactive, was generated using an M8196A arbitrary waveform generator. The required EVM values for the 16-QAM signal to satisfy the 7 and 20% FEC overhead limits are 17.16 and 22.09%, respectively [10]. Examples of constellations and spectra of the received OFDM signals for different data rates are shown in Fig. 4. A data rate of 71.8 Gb/s could be successfully transmitted with an EVM of 17.1%, satisfying the 7% FEC overhead limit. For the 80 Gb/s signal transmission, an EVM of 19.8% was achieved, satisfying the 20% FEC overhead limit. The signal performance for different data rates and numbers of subcarriers is shown in Fig. 5. In the experiment, the signal data rate was varied by changing the signal bandwidth around the center frequency at 11.5 GHz. The bandwidth of the transmitted signal was limited by several factors, including a 90º hybrid electrical coupler used for connecting the OFDM signal to the optical IQ modulator at the CS and an electrical bandpass filter at the Rx to suppress low harmonics. The signal bandwidth and thus data rate can be further increased using sufficiently high-bandwidth components. The signal performance was also limited by the non-flat frequency response of the system, as shown by the received spectra in Fig. 4. By employing a pre-emphasis algorithm and/or applying a power/bit loading technique, the signal performance and data rate can be improved. In the experiment, a basic DSP using classical algorithms and a single-tap equalization was used for signal demodulation owing to the ultra-high frequency stability and low phase noise of the generated signal using photonic downconversion technology. This significantly simplifies the receiver compared to using the coherent detection method [5, 6], rendering the proposed system promising for mobile access and Xhaul applications. The transmission of a sub-THz signal over free space between the RAU and RN was omitted in the experiment; however, a sub-THz link with a distance of 500 m or further can be included using a pair of 45-dBi antennas and cascaded amplifiers with a total gain of 40 dB at the RN.

3. Conclusion

We demonstrated a transparent fiber–sub-THz–fiber system in the 150-GHz band using all-optical receiver and photonic downconversion technology. The system employs a newly fabricated MZM modulator for direct conversion of a sub-THz signal to an optical signal and photonic downconversion method for simultaneously detecting and downconverting the signal to the microwave band, significantly simplifying the transceivers and improving the performance. We successfully transmitted 16-QAM OFDM with a line rate of 80 Gb/s over the system at 151.5 GHz. The system is promising for facilitating sub-THz communications in 6G and beyond networks.

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