3-3　Beyond 5G ネットワークのための先端光ファイバ無線技術
3-3　Advanced Radio-over-fiber Technologies for Beyond 5G Networks

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無線通信におけるサブテラヘルツ（THz）周波数帯は、利用できるバンド幅が非常に広いため、Beyond 5G の大容量無線通信ネットワーク構築のために重要な周波数帯であり、既にいくつかの検討がサブ THz 周波数帯において行われている。しかしながら解決しなければならない課題は多く、様々な新しい解決法が継続して模索されている。特に実用化の上では簡便なサブ THz 周波数帯信号生成方法の確立や、空気中での損失が大きいことや遮蔽物による伝達の阻害などの課題を解決する必要がある。本稿ではこれらの問題を解決する手段の一つとして光ファイバ無線技術（radio-over-fiber: RoF）によるサブ THz 信号の伝送に関する研究を紹介する。最初に D バンド（110–170 GHz）と 300 GHz 帯における光ファイバ通信と無線通信をシームレスに接続するための RoF 技術について紹介する。ここでは光領域における自己ヘテロダイン法を用いることにより、サブ THz 周波数帯の信号生成と、光信号を無線信号に変換する技術を確立した。これらの方法により、送信機の簡素化と共に生成信号の位相ノイズ低減を実現している。後半では RoF システムにおけるサブ THz シグナルのトランスペアレントなリレーやルーティングについて紹介する。原理実証としてカスケード接続した RoF アクセスリンクを構成し、100 GHz 帯信号の生成、伝送、受信を確認し、29 Gb/s のダウンリンクデータ伝送を実現した。これらの成果は提案した RoF システムの高いポテンシャルを示しており、Beyond 5G ネットワークにおけるサブ THz 帯利用を促進できるものと考えられる。

Radio in the sub-terahertz (sub-THz) band is promising in terms of facilitating extreme communications in Beyond 5G networks owing to its huge available bandwidth. Several studies have attempted to advance sub-THz communications. However, significant challenges remain, and new solutions are being sought constantly. The generation and transmission of sub-THz signals over fiber links using electronic technology are challenging. Furthermore, the bottlenecks of extremely high free-space and weak penetration have rendered the transmission of sub-THz signals over obstacles difficult. This paper presents our research efforts on radio-over-fiber (RoF) systems to overcome these disadvantages and facilitate radio communications in the sub-THz band. First, this study demonstrates seamless fiber–wireless systems in the D-band (110–170 GHz) and 300-GHz band employing the optical self-heterodyne method for the generation and up-conversion of optical signals to radio signals. The use of the optical self-heterodyne method with a single optical modulator significantly simplifies the transmitter and reduces the frequency offset and phase noise of the generated signals. Second, a transparent relay and routing of sub-THz signals is presented using a broadband RoF system. A proof-of-concept demonstration of the generation, transmission, and reception of radio signals in the 100-GHz band over a cascaded access system is provided and a transmission capacity of approximately 29 Gb/s is achieved in the downlink direction. The results confirm the potential of the proposed systems, and this study can serve as a reference for the deployment of sub-THz communications in Beyond 5G networks.

1 Introduction

In Beyond 5G networks, radio communications in high-frequency bands, such as the millimeter-wave band and sub-terahertz (sub-THz) wave band, are crucial for high data rate and low latency services [1]. In such cases, photonic technologies are vital for facilitating radio communications. Photonic technology transports radio signals between different locations and functions as a co-design and co-optimization of radio signals. Seamless fiber–wireless systems in high-frequency bands are considered cost-effective and flexible mobile transports for ultra-dense small cells wherein the use of fiber cables is not feasible or expensive [2]. Such systems also aid in the generation and transmission of radio access signals. In these applications, photonic technology can generate and transmit signals from a central station (CS) to antenna sites. Further, at the antenna site, the signal can be upconverted to radio signals in high-frequency bands using a high-speed optical-to-electrical converter. Thus, using these systems, radio waveforms can be transported over fiber links, and radio-wave signals can be generated using simple media converters at the antenna sites. Consequently, the cost, power consumption, and complexity of antenna sites are significantly reduced. However, the signal quality and complexity of receivers are highly dependent on the generation and transmission of radio signals. This study introduces the optical heterodyne and optical self-heterodyne methods for the generation of radio signals in the high-frequency band. The latter method, which uses optical modulation technology, is promising for the realization of simple seamless systems. Moreover, the frequency offset and phase noise of the generated radio signals are relatively small, which simplifies the signal demodulation at the receivers [3]. Subsequently, seamless fiber–wireless systems in the D-band (110–170 GHz) and 300-GHz band are introduced using the optical self-heterodyne method. More than 80 Gb/s orthogonal frequency-division multiplexing (OFDM) signals were successfully transmitted over the system in both the D and 300-GHz bands. The proposed systems can provide a simple yet high-capacity solution for future mobile transport and radio access applications in Beyond 5G networks.

Radio communications in high-frequency bands encounter significant challenges owing to their large free-space and penetration loss [4]. This renders the transmission of signals between outdoors and indoors and in areas with obstacles, such as public open spaces, difficult. Communication to and from indoor environments is vital owing to the generation of more than 80% of the mobile traffic. To overcome these disadvantages, transparent relaying, routing, and distribution of radio signals are crucial; however, these functions cannot be realized using electronic technologies [5]. Here, photonic technologies are crucial for the realization of unprecedented communication features. An analog radio-over-fiber (RoF) system can transparently relay, distribute, and route radio signals between locations to avoid penetration loss. This study proposes a dual-hop access network using a broadband RoF system to facilitate transparent relay and routing of radio signals in the sub-THz band. Further, proof-of-concept demonstrations of the transmission of 100-GHz radio signals over a cascaded system in the downlink direction are provided using newly fabricated low-loss optical modulators. The relay system is completely transparent to the sub-THz signals, thereby allowing the use of the same receivers for both indoors and outdoors. We successfully transmitted an OFDM signal of approximately 29 Gb/s over a converged system cascading two RoF links and two wireless links in the 100-GHz band. In addition, the perspectives and applicability of the proposed system for future radio communications are discussed. The proposed system can facilitate the deployment of sub-THz communications in Beyond 5G networks. The remainder of this paper is organized as follows. Section **2** presents the operating principle and system demonstration of the seamless fiber–wireless systems in the D and 300-GHz bands. Thereafter, Section **3** presents a description of a dual-hop radio access network using the signal transparent relay and routing. Further, a system demonstration of transparent relay and routing of radio signals in the 100-GHz band is provided. Finally, the conclusions are presented in Section **4**.

2 Seamless Fiber–wireless System

2.1 Operation principle

A schematic of a seamless fiber–wireless system using photonic technology is illustrated in Fig. 1(a). In this method, two optical signals at wavelengths of λ_1 and λ_2 are input to a high-speed optical-to-electrical (O/E) converter. The beat note between the two optical signals facilitates the generation of a radio signal with a frequency identical to the frequency difference between the two optical signals, that is, $f = |c/\lambda_1 - c/\lambda_2|$. By changing the wavelength of the optical signal(s), radio signals at different frequencies, including those in the millimeter- and THz-wave bands, can

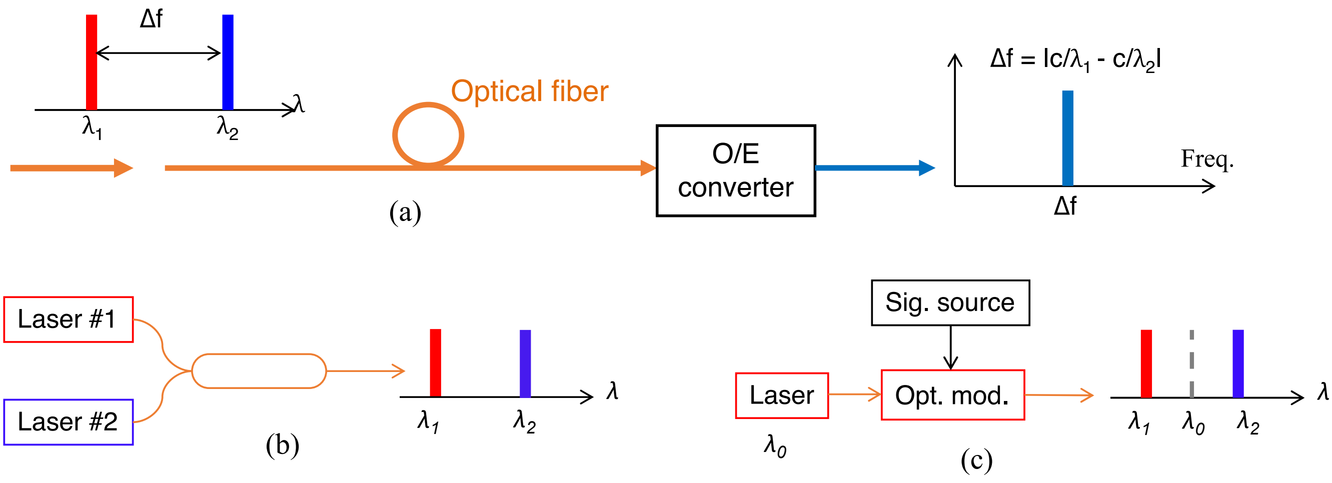

Fig. 1 (a) Principle of seamless fiber–wireless system; (b) optical heterodyne method; and (c) optical self-heterodyne method.

be generated. Furthermore, the modulation of the optical signal(s) using data facilitates the generation of modulated radio signals. This method provides a simple yet flexible solution for the generation of radio signals in the high-frequency band. The signals can be transmitted over fiber links before converting them to radio signals. This enables a seamless convergence of the wired and wireless systems for signal generation and transmission. Moreover, using this method, the antenna sites can be significantly simplified to include only an O/E converter and radio frontend. However, the stable generation of radio signals with low frequency fluctuation and low phase noise is a critical factor in these systems. Figures 1(b) and (c) show two different methods for the generation of radio signals using photonic technology [3]. The optical heterodyne method shown in Fig. 1(b) uses two different free-running lasers to generate two optical signals. This method offers the advantage of ultrawide frequency tunability for the generation of radio signals in different frequency bands. However, the frequency instability of the generated radio signals is significantly high, resulting in large frequency fluctuations and phase noise of the generated radio signals. To resolve this problem, a phase lock between the two lasers should be implemented; however, this increases the system complexity. The optical self-heterodyne method, shown in Fig. 1(c), utilizes a single laser source to generate two optical signals. In this method, high-order harmonic sidebands can be generated by feeding a strong continuous-wave radio frequency signal to an optical modulator. Consequently, at the output of the modulator, two signal modes can be selected for the generation of radio signals. The two generated optical signals are phase- and frequency-correlated. This facilitates the generation of highly stable radio signals with low frequency offset and phase noise. These features are essential to realize a simple and energy efficiency seamless system owing to the simplicity of signal demodulation at the receivers. This study employed this method to demonstrate a seamless system in the D and 300-GHz bands.

2.2 Seamless system in D-band

Radio communications in the D-band are promising

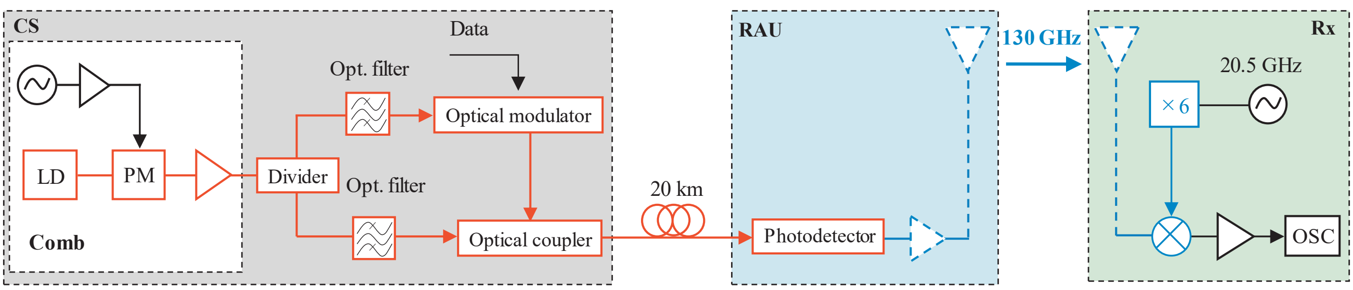

Fig. 2 Experimental setup for seamless fiber–wireless system in D band. CS: central station; LD: laser diode; PM: phase modulator; RAU: remote antenna unit; Rx: receiver; OSC: oscilloscope.

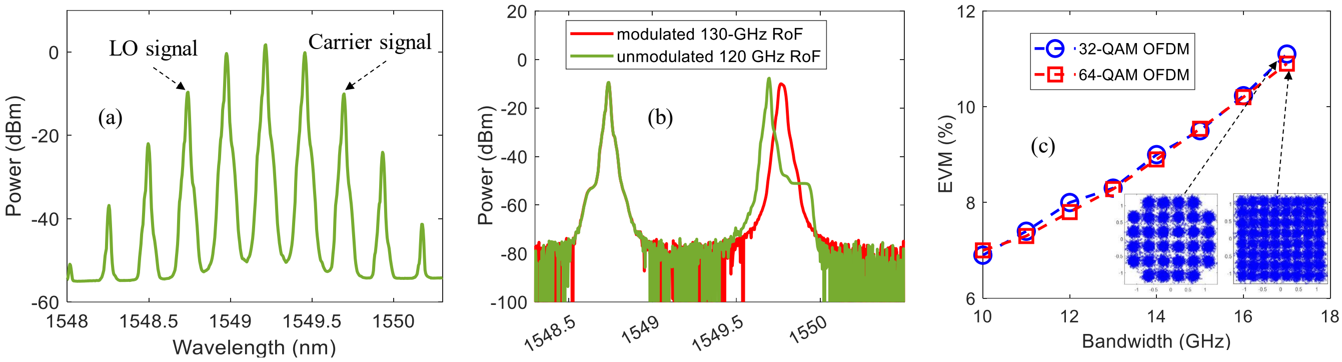

Fig. 3　Experimental results of seamless system in D-band: (a) generated comb signal; (b) spectra of RoF signals; (c) OFDM signal performance.

for access networks and mobile transport in Beyond 5G networks owing to their large available bandwidth and technological maturity. Figure 2 shows the experimental setup for signal generation and transmission over a fiber–wireless system in the D-band using a simple optical self-heterodyne method. To generate optical sidebands with a high signal-to-noise ratio, a broadband optical modulator with low half-wave voltage is important. This study employed a newly fabricated thin-film lithium niobate phase modulator for signal generation. The modulator was fabricated by fabrication of Mach–Zehnder interferometer waveguides through titanium diffusion on x-cut thin-film lithium niobate in the low dielectric constant layer [6]. Using the fabricated modulator, a simple optical frequency comb was generated by feeding a continuous-wave signal at 30 GHz to the modulator, as shown in Fig. 3(a). The generated signal was amplified using an erbium-doped fiber amplifier (EDFA) and divided into two branches using a 3-dB optical divider. Two comb modes with a frequency difference of 120 GHz were selected using optical filters. The first comb mode was modulated using a real-valued intermediate frequency signal at 10 GHz, and the other was unmodulated. The bias voltage applied to the modulator was controlled to generate a single-sideband suppressed-carrier signal. The modulated signal was amplified, filtered, and recombined with the unmodulated signal using a 3-dB optical coupler. The optical spectra of the unmodulated and modulated RoF signals with frequency differences of 120 and 130 GHz are shown in Fig. 3 (b). The combined signal was transmitted to a remote antenna unit (RAU) using a 20-km single-mode fiber (SMF). At the RAU, the signal was amplified using another EDFA and input to a uni-traveling-carrier photodiode (UTC-PD) for up-conversion to a sub-THz signal at 130 GHz. Further, an optical variable attenuator was inserted to adjust the incident optical power of the UTC-PD. Although the generated sub-THz signal can be amplified and emitted into free space using an antenna, in the experiment, for simplicity, the generated signal was downconverted to a lower frequency band using a subharmonic mixer without transmission in free space. Thereafter, the downconverted signal was amplified, sent to a real-time oscilloscope, and demodulated offline.

We transmitted OFDM signals over the system and evaluated the obtained performance using the error vector magnitude (EVM) parameter. An OFDM signal at 10 GHz comprising 2048 subcarriers, 20% of which were inactive at the band edges, was generated using an arbitrary waveform generator. A basic digital signal processing (DSP) algorithm using only one-tap equalization was used to demodulate the OFDM signal. The performance of the 32-QAM and 64-QAM OFDM signals for different signal bandwidths is shown in Fig. 3(c). The required EVM value for the 32-QAM signal to satisfy the 7% forward error correction (FEC) overhead bit error rate of 3.8×10^{-3} was 12.1% [7]. As evident from the figure, a 32-QAM signal with a bandwidth of up to 17 GHz was successfully transmitted over the system, achieving an EVM of 11.1%. For the 64-QAM signal, the required EVM value considering a 20% FEC overhead was 11.2%. Satisfactory performance was also confirmed for a 64-QAM signal with a bandwidth of 17 GHz, achieving a line rate of 81.6 Gb/s. The proposed system provides a simple yet high-capacity solution for future seamless access in Beyond 5G networks.

2.3　Seamless system in 300-GHz band

A seamless fiber–wireless system in the higher frequency bands can also be realized using the optical self-heterodyne method. However, owing to the high-frequency requirement of radio signals, higher-order harmonic sidebands should be generated from the optical modulator.

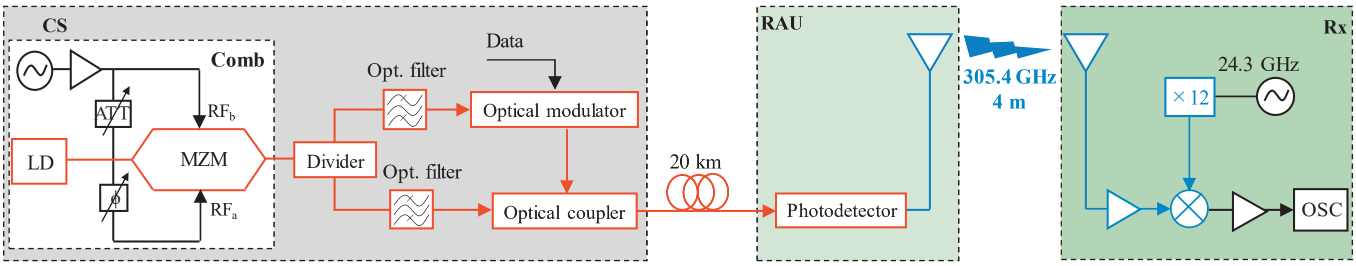

Fig. 4　Experimental setup for seamless fiber–wireless system in 300-GHz band. CS: central station; LD: laser diode; MZM: Mach-Zehnder modulator; RAU: remote antenna unit; Rx: receiver; OSC: oscilloscope.

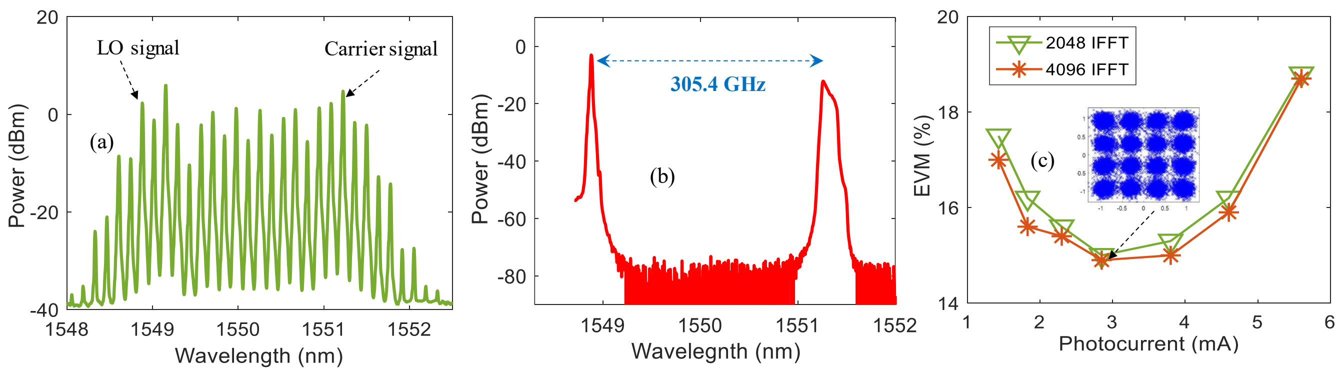

Fig. 5　Experimental results of seamless system in 300-GHz band: (a) generated comb signal; (b) spectrum of RoF signal; (c) OFDM signal performance.

Consequently, it is difficult to use a single optical phase modulator for optical comb generation, which is the case of the D-band system. To generate high-order sidebands, cascaded or paralleled modulators using signal synchronization can be employed. However, this comb generator and the signal control are relatively complicated. This study employed a simple method for the generation of a stable comb signal. The experimental setup is shown in Fig. 4, including the CS, RAU, and receiver (Rx). An optical frequency comb signal was generated at the CS. The comb generator comprised a laser diode (LD) and a LiNbO3 dual-drive Mach-Zehnder modulator [8]. A lightwave signal was generated from the LD and fed to the modulator through a polarization controller to maximize the modulation efficiency. Further, a sinusoidal radio frequency (RF) signal at 17.2 GHz was generated from an electrical synthesizer, amplified using a microwave amplifier, divided into two using a hybrid coupler, and fed to the electrodes of the modulator. The intensity of the RF-a signal injected into one of the electrodes was slightly attenuated using an attenuator. The phase difference between the RF-a and RF-b signals was aligned to zero using a mechanically tunable delay line, as shown in the figure. A flat comb signal can be generated by driving the modulator under the optimal conditions derived in [9]. Notably, our system did not require a fully flat comb because only two comb lines were selected for signal generation. Thus, the optimal driving conditions for the modulator were not necessarily satisfied. The generated comb signal with the spectrum shown in Fig. 5(a) was divided into two parts using a 3-dB optical divider. Consequently, two comb lines with a frequency separation of 292.4 GHz were selected using optical filters. The first comb line was modulated using an intermediate frequency OFDM signal at 13 GHz, and the other comb line was kept unmodulated for signal upconversion at the RAU. The bias voltage applied to the optical modulator was controlled to generate only the upper modulation sideband. Subsequently, the modulated signal was amplified and recombined with the unmodulated sideband. The frequency separation between the modulated and unmodulated sidebands was 305.4 GHz (= 292.4 + 13 GHz), as shown in Fig. 5(b). The combined signal was transmitted to the RAU using a 20-km SMF. Then, at the RAU, the signal was amplified and input to a UTC-PD to convert it to a radio signal at 305.4 GHz. The generated signal was emitted into free space using a 48.5-dBi lens antenna. After transmission over approximately 4 m in free space, the signal was received using another lens antenna at the Rx. Subsequently, the signal was amplified and downconverted to 13.8 GHz using a subharmonic mixer. Finally, the signal was amplified, sent to a real-time oscilloscope, and demodulated offline.

We transmitted OFDM signals and evaluated their performance using the EVM parameter [10]. OFDM signal generation and demodulation is realized based on a classical DSP method, which is identical to that used in the D-band system. The transmitted OFDM signals had a bandwidth of 22.5 GHz at 13 GHz. The numbers of subcarriers were 2,048 and 4,096, of which 10% of the subcarriers at the band edges were inactive. All subcarriers were modulated using the same 16 QAM level. The EVM requirement for the 16-QAM signal to satisfy the 7% FEC overhead limit was 17.16 %. Figure 5(c) shows the EVM performance of the OFDM signals for different photocurrents of the UTC-PD at the RAU. An OFDM signal with a line rate greater than 80 Gb/s was successfully transmitted, achieving an EVM of 14.9%. The optimal signal performance was obtained at a photocurrent of approximately 3 mA. Decrease in the photocurrent to below 3 mA resulted in performance degradation owing to an insufficient signal-to-noise ratio. Further, increase in the photocurrent to beyond 3 mA also resulted in performance degradation. This could be attributed to distortions at the receiver, particularly at the amplifier and subharmonic mixer, owing to the short distance of the radio link. Consequently, the distance of the radio link can be further extended by increasing the transmission power of the radio signal and/or using a sub-THz amplifier at the transmitter.

In the demonstrated systems, a basic DSP was used to demodulate the signals at the receiver owing to the high frequency stability and low phase noise of the generated radio signals. This is crucial for practical applications when sub-THz receivers are located at end users or antenna sites; thus, simplicity and lower power consumption are of critical importance. Furthermore, the system is applicable to large-scale multiple-input multiple-output (MIMO) signal transmission. Wavelength-division multiplexing (WDM) RoF systems are indispensable for the transmission of large-scale MIMO radio signals in high-frequency bands. However, owing to the interference and crosstalk between MIMO signals, channel estimation and synchronization at the receiver in case of large frequency fluctuations of the signals becomes difficult. In such a case, highly stable RoF systems with low-frequency fluctuations are vital for MIMO signal transmission. In [11], a 3×3 MIMO fiber–wireless system in the W-band was demonstrated using the optical self-heterodyne method and a combination of WDM and polarization-division multiplexing. A similar demonstration in the higher frequency bands, such as the D and 300-GHz bands, can also be realized using the fiber–wireless systems presented in this section.

3　RoF System for Sub-THz Radio Signal Relay

A dual-hop access network using a transparent relay and routing of sub-THz signals by RoF systems is shown in Fig. 6 [5]. This system facilitates the receival of sub-THz signals and their direct conversion to optical signals at relay nodes (RNs). RNs can be installed on the rooftops or windows of buildings to easily receive radio signals. Further, lightwave signals from WDM lasers can be input to sub-THz-to-optical (T/O) converters for signal modulation. The same sub-THz signals can be modulated into different optical signals at different wavelengths. Wavelength routers can distribute modulated optical signals to different access points (APs) where specific wavelengths can be assigned. At the APs, modulated optical signals are converted back to sub-THz signals using optical-to-THz (O/T) converters. In addition, APs can be flexibly placed to maximize the communication capacity, coverage, and energy efficiency. The key element in the proposed system is the relay RoF links, which are expected to transport broadband radio signals. This system can enable transparent relay and routing of sub-THz signals to different indoor locations without any signal waveform and frequency

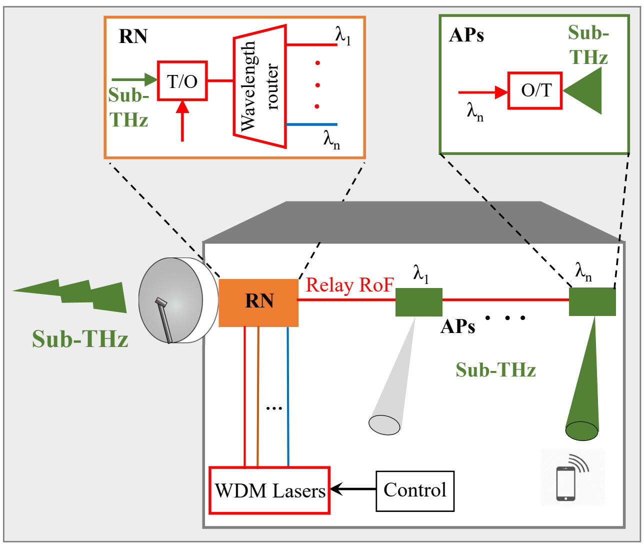

Fig. 6　Schematic of sub-THz signal transparent relay and routing using RoF system.

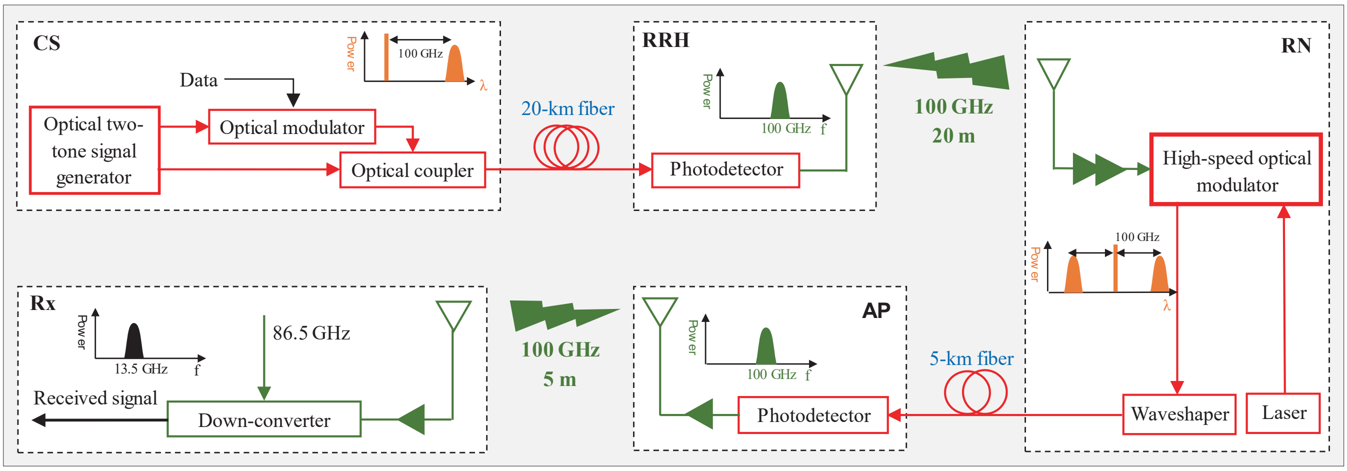

Fig. 7 Experimental setup for transparent relay and transmission of sub-THz signal in downlink direction. CS: central station; RRH: remote radio head; RN: relay node; AP: access point; Rx: receiver.

conversions. Thus, RN and APs can be significantly simplified. Moreover, based on the demand, the emission of THz signals from APs can also be turned on and off at appropriate intervals to save energy and reduce interference. Thus, this system can effectively overcome the high penetration loss of radio signals in the sub-THz band. Further, it can distribute sub-THz signals in areas with barriers, walls, and obstacles, such as offices, factories, and shopping malls. In this section, we present proof-of-concept demonstrations of the transparent relay and routing of sub-THz signals in the 100-GHz band over the cascaded access system using newly fabricated broadband optical modulators. The key design challenges and perspectives of broadband RoF systems and their applicability for future sub-THz communications are discussed. The results confirm the potential of the proposed system, thus rendering it a promising solution for facilitating the deployment of sub-THz communications in Beyond 5G networks.

Figure 7 shows a schematic of the proposed system in the downlink direction. The system includes five main parts: CS, RRH, RN, AP, and Rx. At the CS, a coherent two-tone optical signal with a frequency difference of 92 GHz was generated using an integrated parallel optical modulator. Consequently, the two optical signals were separated using an arrayed waveguide grating. The upper sideband was modulated by an intermediate frequency signal at 8 GHz using an optical in-phase quadrature-phase modulator. Subsequently, a single-sideband suppressed-carrier signal, including only the upper modulation sideband, was generated by controlling the bias voltage applied to the modulator. The signal was amplified, filtered, and recombined with the unmodulated sideband to form a 100-GHz RoF signal. The RoF signal from the CS was transmitted to the RRH using a 20-km SMF and was up-converted to a sub-THz radio signal centered at 100 GHz using a UTC-PD. The generated radio signal was then emitted into free space using a Cassegrain antenna with a gain of 42 dBi. The signal was transmitted over approximately 20 m in free space from the RRH and received using a 35-dBi antenna at the RN. It was amplified using a cascade of a low-noise amplifier and a power amplifier and was converted to an optical signal using a newly fabricated broadband optical modulator. Both the intensity and phase modulator can be used for signal conversion. The use of optical phase modulators without bias control can significantly simplify the system as well as the operation and management at the RN. Further, it prevents the system from performance degradation owing to bias drift. However, the phase-modulated optical signal should be converted to an intensity-modulated signal to enable direct detection at the APs. In the demonstration, a newly fabricated optical phase modulator was utilized [12], and the conversion of the phase-modulated optical signal to an intensity-modulated signal was performed via the rotation of the optical carrier signal by 90° using a WaveShaper. In addition, the optical carrier-to-sideband ratio was optimized to generate an optimal radio signal. The modulated optical signal was transmitted from the RN to the AP over a 5-km SMF. Consequently, the signal was input into another UTC-PD to convert it back to a sub-THz signal at 100 GHz. The input optical power to the UTC-PD was adjusted using an optical attenuator. Consequently, the radio signal transmitted from the AP was adjusted. The generated radio signal was amplified using a power ampli-

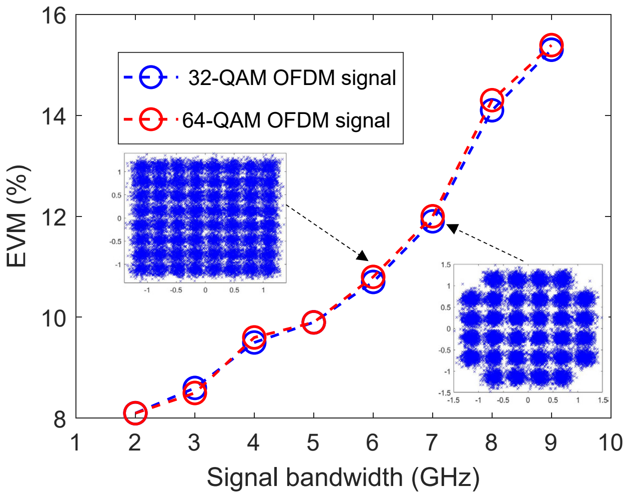

Fig. 8 Performance of OFDM signals after transmission over the relay system.

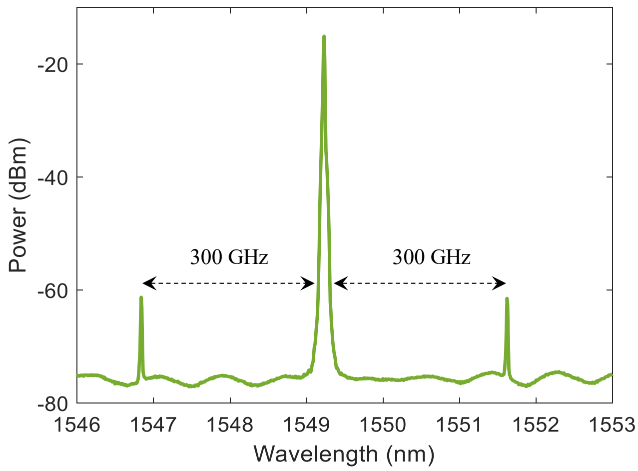

Fig. 9 Optical spectrum of 300-GHz modulated optical signal using a low-loss optical modulator.

fier and transmitted to the Rx using a 23-dBi horn antenna. The signal was then transmitted over approximately 5 m in fee space and received using another 23-dBi horn antenna at the Rx. Subsequently, the signal was amplified using a low-noise amplifier and down-converted to 13.5 GHz using a subharmonic mixer. Finally, the signal was amplified, sent to a real-time oscilloscope, and demodulated.

We transmitted an OFDM signal over the system and evaluated its performance using the EVM parameter [12]. In the experiment, an OFDM signal comprising 2,048 subcarriers, of which 20% at the band edges were inactive, was generated using an arbitrary waveform generator. The DSP for signal generation and demodulation is identical to the demonstrations presented in the previous section. The performance of the OFDM signal with different signal bandwidths is shown in Fig. 8. In this measurement, the carrier-to-sideband ratio was set at the optimal value of 12 dB using WaveShaper. Herein, satisfactory performance was confirmed for 7-GHz 32-QAM and 6-GHz 64-QAM signals, achieving a line rate of approximately 29 Gb/s.

In a sub-THz signal relay system, the optical modulator is the key component that facilitates the direct conversion of sub-THz signals to optical signals. Typically, commercially available optical modulators used in traditional optical communications have an operation frequency of less than 100 GHz. This renders their use in sub-THz signal relaying difficult. For RoF relay systems, conversion gain is an important parameter; it is proportional to the optical loss and inversely proportional to the half-wave voltage of the modulator [13]. Thus, designing a low half-wave voltage and low-loss optical modulator in the high-frequency band is crucial to achieve high link gain for radio signal transmission. These features can be realized using thin-layer structure modulators [14], as exhibited by those used in the system demonstration. Through the optimization of the radio frequency connectivity to the modulators for high-frequency radio signals, a direct conversion of sub-THz signals in the 300-GHz band to optical signals could be realized [5]. Figure 9 shows an example of the optical spectrum of the modulated signal at the modulator output. Further, recently, high-speed optical modulators with an operation frequency of up to 500 GHz were demonstrated using an electro-optic-polymer-based plasmonic modulator [15] and a thin-film LN modulator [16]. These developments reveal the possibility of converting high-frequency sub-THz signals to optical signals. Consequently, the transparent relay and routing of sub-THz signals are rendered feasible, even in high-frequency bands.

4 Conclusion

This study discussed advanced RoF technologies to facilitate sub-THz communications in Beyond 5G networks. First, seamless fiber–wireless systems in the D and 300-GHz bands were proposed and demonstrated using a simple optical self-heterodyne method. Thereafter, as a proof-of-concept demonstration, OFDM signals were transmitted over the systems to achieve transmission capacities greater than 80 Gb/s. The simplicity of signal generation and demodulation renders the proposed system a promising solution to facilitate the deployment of ultra-dense small cells in high-frequency bands. Further, a new network architecture was introduced for radio communication in the sub-

THz bands using a dual-hop access network. The sub-THz signals were transparently relayed between outdoor and indoor networks using a broadband RoF system. As a proof-of-concept demonstration, a 100-GHz radio signal transmission was performed over two cascaded access systems using a broadband RoF link. The system was realized using newly fabricated broadband optical modulators to facilitate the direct conversion of sub-THz signals to optical signals. We successfully transmitted an OFDM signal with a line rate of approximately 29 Gb/s over cascaded systems in the 100-GHz band. The obtained results confirm the potential of the proposed systems. Thus, this study can serve as a reference for the deployment of radio access networks in the sub-THz bands in Beyond 5G networks.

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