Optical Fiber Technology 65 (2021) 102622

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte

Experimental investigations on upstream transmission performances in future-proof THz-band indoor network based on photonics

Sang-Rok Moon [a,*], Eon-Sang Kim [a], Minkyu Sung [a], Joonyoung Kim [b], Joon Ki Lee [a], Seung-Hyun Cho [a]

[a] *Optical Network Research Section, Electronics and Telecommunications Research Institute (ETRI), 218 Gajeong-ro, Yuseong-gu, Daejeon 34129, South Korea*

[b] *Department of Information and Communications Engineering, Sangmyung University, 31 Sangmyungdae-gil, Dongnam-gu, Cheonan-si 31066, South Korea*

A R T I C L E I N F O

Index Terms:
THz communication
Optical communication

A B S T R A C T

The upstream transmission performance was experimentally investigated to consider the practical deployment of a photonics-based terahertz (THz)-band indoor network. An experimental setup was established using several off-the-shelf THz and optical components, to evaluate the technical feasibility of the uplink. Two commercialized THz mixers were used to build the THz wireless link, and a cost-effective 10 GHz-class directly modulated distributed feedback-laser diode (DFB-LD) was employed as an optical modulator to configure the optical link for a THz-band indoor network. The power penalty by the bandwidth-limited optical components was approximately 4 dB at 10^{-4} bit error rate (BER) when the data rate of the uplink was fixed at 30 Gb/s. It is worth noting that the interplay between the frequency chirp of the directly modulated DFB-LD and chromatic dispersion in the optical fiber significantly affects the BER. Owing to this interplay, the measured BER is seriously degraded at 30 Gb/s from 1.38×10^{-5} (without transmission) to 9.27×10^{-5} (10 km transmission), which is located in the error-floor region, however it still satisfies within 7% forward error correction (FEC) threshold (3.8×10^{-3}). Subsequently, the BER curves over the wireless THz link were also measured. As a result, 30 Gb/s transmission over one m wireless and 10 km single-mode optical fiber distance was successfully demonstrated.

1. Introduction

With the evolution of wireless communication technology, the carrier frequency is continuously increasing because the traditional frequency band is gradually occupied, and the higher frequency has fundamental advantages in providing a higher data rate. In this context, the terahertz (THz) band (0.1–3 THz) has drawn considerable interest for next-generation mobile communication systems, such as 5G and 6G [1,2]. Signal generation in the THz-band had been considered in a 'technical gap', because the THz-band signal was difficult to handle by conventional electronics- and photonics-based devices. Fortunately, there have been several remarkable achievements that have enabled THz-band signal transmission. These technologies can be categorized into two groups: electronics-based and photonics-based approaches [3–7]. For electronic-based approaches, THz-band signals can be generated using high electron mobility transistors (HEMTs) [3], heterojunction bipolar transistors (HBTs) [4], and complementary metal-oxide semiconductors (CMOS) [5]. For the photonics-based approach, a uni-traveling carrier photodiode (UTC-PD) that uses beating components of two wavelength-separated optical signals can be used [6]. In addition, plasmonic detectors also showed potential as THz signal sources [7]. Although these technologies have their own advantages, photonics-based approaches using UTC-PD are one of the most widely used methods for high-speed (greater than100 Gb/s) transmission because of the accessibility of well-matured optical components with a wide and flat frequency response, and low propagation loss regardless of the operating frequency. Using UTC-PD, there have been several reports of greater than 100 Gb/s transmission [8–10].

One of the most promising applications of THz-band communication is the indoor network [11]. Because the THz-band signal has relatively high directivity and large free space path loss (FSPL), a short-range indoor network with low moving speed is a suitable system for THz-band communication. In addition, the property that the optical signal generator and photomixer can be separated by optical fiber with low propagation loss is beneficial for the practical deployment of THz-band indoor networks. There have been several demonstration results for

* Corresponding author.
E-mail address: srmoon@etri.re.kr (S.-R. Moon).

https://doi.org/10.1016/j.yofte.2021.102622
Received 19 February 2021; Received in revised form 18 June 2021; Accepted 19 June 2021
Available online 27 June 2021
1068-5200/

photonics-based THz-band indoor networks [12–15]. However, most results are focused on downstream transmission with a higher data rate above 100 Gb/s. Thus, it is necessary to investigate the feasibility and evaluate the performance of the upstream transmission in a THz-band indoor network.

In contrast with the downlink, the uplink requires a relatively lower data rate but requires higher cost-effectiveness. In this study, an uplink for a THz-band indoor network was established based on these considerations. A quadrature phase-shift keying (QPSK) modulation format was employed to double the data rate. For digital demodulation of the QPSK-modulated baseband signal, the baseband signal was frequency-shifted by a certain intermediate frequency (IF). Two commercially available THz mixers were used to build a THz band wireless link. For cost-effective realization, 10 GHz-class directly modulated distributed feedback laser diode (DFB-LD) was utilized as an optical source for configuring the optical fiber link. The chromatic dispersion effect in the uplink is quite different from that in the downlink. In the optical upstream transmission, the baseband signal spectrum is upshifted by the IF, whereas there is no spectral change in the conventional optical downstream transmission. Owing to the frequency upshift in the optical uplink, chromatic dispersion severely degrades the upstream transmission performance. In addition, in the uplink configuration, the performance degradation caused by the frequency chirp of the directly modulated DFB-LD should also be carefully considered. These two effects should be investigated to determine uplink feasibility.

In this study, the technical feasibility of upstream transmission was experimentally evaluated and the uplink transmission performance was investigated in a future-proof THz-band indoor network after the establishment of the uplink. In the wireless back-to-back configuration, bit error rate (BER) curves were measured to identify the power budget and verify the effect of the non-ideal system elements. In the optical transmission with the directly modulated DFB-LD, the interplay between the frequency chirp of directly modulated DFB-LD and chromatic dispersion affects the uplink transmission performance. Subsequently, the BER curves were measured as a function of the THz-band wireless transmission distance. As a result,

30 Gb/s transmission with 1 m THz-band wireless link and a 10 km single-mode optical fiber was successfully demonstrated using commercialized THz/optical components.

2. Experimental setup for upstream transmission

2.1. Photonic-based THz-band indoor network

Fig. 1 shows a conceptual diagram of a photonics-based THz-band indoor network. In the basement, an optical hub unit connected to the exterior network was placed. The optical hub unit is linked to the THz remote unit using an optical fiber. Conventionally, the optical transmission distance is a few kilometers. The THz remote unit communicates with the THz user equipment by a few meters of a THz-band wireless link. In the upstream path, the signal is transmitted from the THz user equipment to the optical hub unit through the THz remote unit. Thus, the uplink has a cascaded structure consisting of a THz-band wireless link and an optical fiber link. Based on this cascaded structure, an experimental setup was developed considering cost-effectiveness and simplicity.

2.2. Experimental setup

Fig. 2 shows the experimental setup used to evaluate the technical feasibility of the uplink in the THz-band indoor network.

Using arbitrary waveform generator (AWG), a frequency-shifted QPSK signal was generated based on a pseudo-random bit sequence (PRBS) with a $2^{15}-1$ pattern length. For bandwidth efficiency, a root-raised cosine filter was applied with 0.35 roll-off factor. In this experiment, the upstream data rates were 20, 25, and 30 Gb/s with IFs of 8, 9.75, and 11.5 GHz, respectively. Subsequently, the frequency of the modulated signal was up-converted by a local oscillator at the transmitter using a commercialized THz mixer (VDI SAX 3.4). The LO_{Tx} (frequency of the local oscillator at the transmitter) was set to 300 GHz (25 GHz $\times$ 12). The THz-band signal was transmitted with horn antennas with a 26 dBi gain. Two lenses with a focal length of 10 cm (Thorlabs TPX 100) were employed to compensate for the FSPL. Then, the transmitted signal over free space was down-converted using

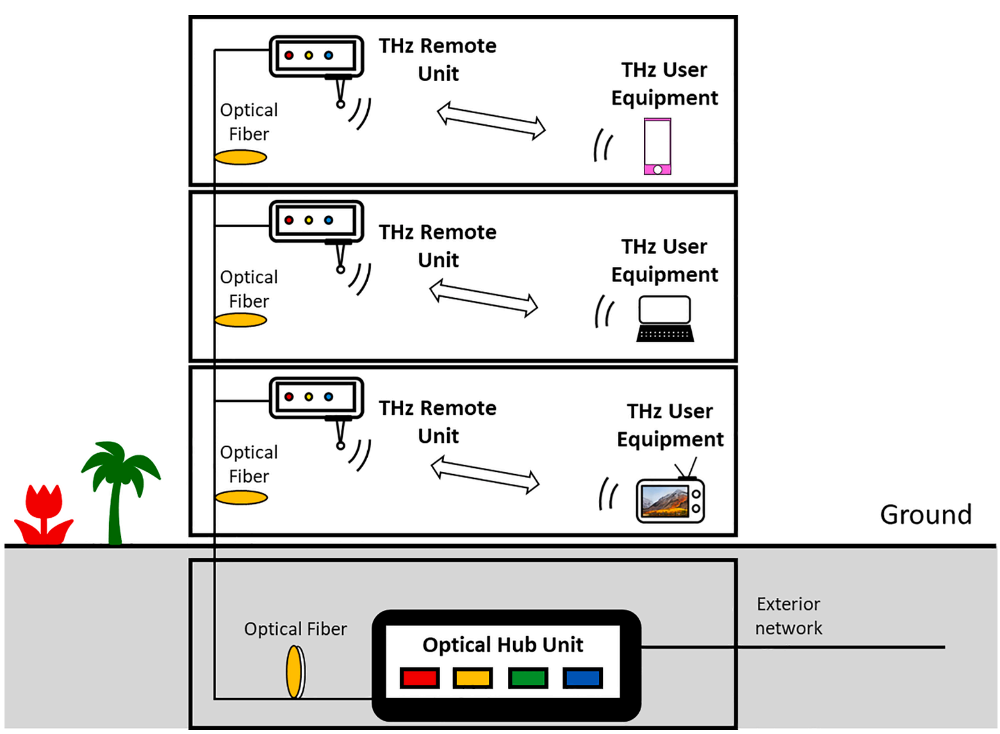

Fig. 1. Conceptual diagram of photonics-based THz-band indoor network.

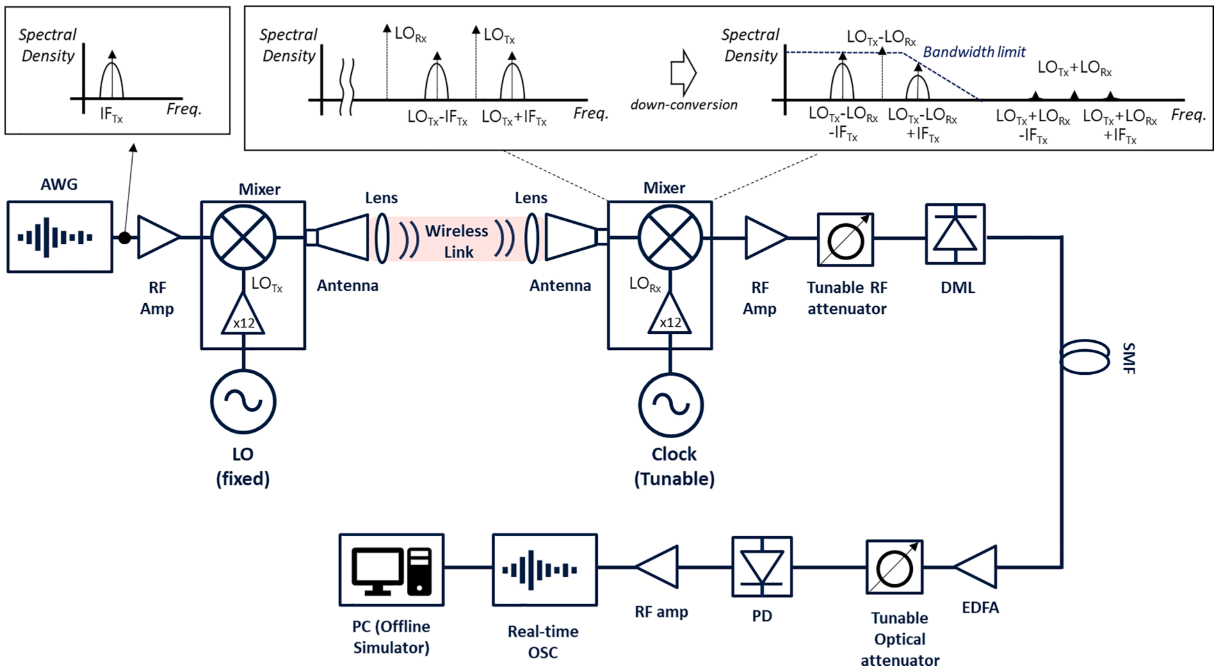

Fig. 2. Experiment setup for upstream transmission in THz-band indoor network. Inset shows signal spectra to show up/down conversion for THz-band transmission.

another off-the-shelf THz mixer (VDI SAX 3.4). The analog bandwidth of these two THz mixers was 40 GHz. The conversion loss for frequency up-conversion was 34 dB, and that for frequency down-conversion was 14 dB. As shown in the inset of Fig. 2, LO_{Rx} (i.e., frequency of the local oscillator at the receiver) was placed on the left side of the transmitted signal to generate IF. The IF at the receiver (IF_{Rx}) can then be expressed as LO_{Tx}-LO_{Rx}-IF_{Tx}. The higher frequency components (LO_{Tx}-LO_{Rx} + IF_{Tx}, LO_{Tx} + LO_{Rx}-IF_{Tx}, and LO_{Tx} + LO_{Rx} + IF_{Tx}) were filtered out by the bandwidth limitation of the system. It should be noted that the remaining frequency components in the out-of-band frequency are filtered again digitally after optical transmission. The IF_{Rx} can be controlled by adjusting LO_{Rx}. The LO_{Rx} is set to make IF_{Tx} and IF_{Rx} the same. Then, the signal is transmitted through the optical fiber link after the THz-band signal transmission.

In the optical fiber link, 10 GHz-class directly modulated DFB-LD was used as an optical source. The amplitude of the modulation signal was adjusted using an RF amplifier and a tunable RF attenuator to achieve an optimal optical modulation index (OMI) to obtain better optical transmission performance. The bandwidth of the RF amplifier and the tunable RF attenuator were 40 and 18 GHz, respectively. The directly modulated DFB-LD was operated at a bias current of 50 mA, and the output wavelength was fixed at 1550.53 nm. The output power of the directly modulated DFB-LD was set to + 5 dBm. The modulated light was transmitted over a single-mode optical fiber (SMF). An erbium-doped fiber amplifier (EDFA) and a tunable optical attenuator were also used for optical power adjustment. This was captured by a real-time oscilloscope with a 36 GHz analog bandwidth and 80 GS/s sampling rate after reception by the photodiode. The captured signal was transferred to a personal computer for offline digital signal processing (DSP).

The DSP operated as follows: First, the received signal was resampled to two samples/symbols. Then, it was digitally down-converted to the baseband, and the out-of-band frequency components were filtered out. After the filtering process, the frequency peaks generated by the LO leakage at THz mixers were smoothed by using the average values of the neighborhood frequency components. The baseband signal was first equalized using a constant modulus algorithm (CMA). The frequency offset was estimated and compensated by calculating the frequency peak of the fourth power of the CMA output signal. Then, it was equalized using a frequency-domain equalizer with a decision-directed least mean square algorithm [16]. The phase noise was also compensated in this equalizer. A total of 128 linear taps were used for equalization. In the BER calculation, approximately 10^6 bits were used. Thus, in the BER measurement, no error means that the BER is below 1×10^{-6}.

3. Experimental results

3.1. Back-to-back configuration

The BER curves were measured as a function of THz Tx power in a wireless back-to-back configuration (i.e., THz-band wireless distance and optical fiber distance were set to zero). The THz power was estimated using the input power and conversion loss of the THz mixer. Fig. 3 (a) shows the measured BER curves without an optical link. It should be noted that the maximum THz Tx power was carefully limited to –33 dBm to avoid damage to the THz mixer. As the data rate increased, the measured BERs gradually degraded. Although the THz transmission power was low, most BER values were obtained below 7% hard-decision forward error correction (FEC) threshold (3.8×10^{-3}, [17]). Fig. 3(b) shows the measured BER curves with an optical back-to-back link. The measured power penalties at 10^{-4} BER caused by the optical link were 2–4 dB. The power penalties increased with an increase in the data rate, which was because of the bandwidth limitation of the 10 GHz-class directly modulated DFB-LD. However, the 7% FEC threshold was still satisfied for most of the measured BERs, as shown in Fig. 3(b).

An elliptical constellation is observed, as shown in the inset of Fig. 3. This means that the remaining phase noise after phase noise compensation directly affects the uplink transmission performance. The phase noise originates from the multiplied LO frequency in the THz mixers. In the THz mixers, the input frequency was multiplied by 12 times. In this multiplication procedure, the phase noise in LO_{Tx} and LO_{Rx} was enhanced 144 times (square of 12). For further performance improvement, additional phase noise compensation algorithms (e.g., the Viterbi-Viterbi algorithm and blind-search algorithm) might be applied to mitigate the performance degradation.

3.2. Optical transmission

There are three factors that degrade optical transmission

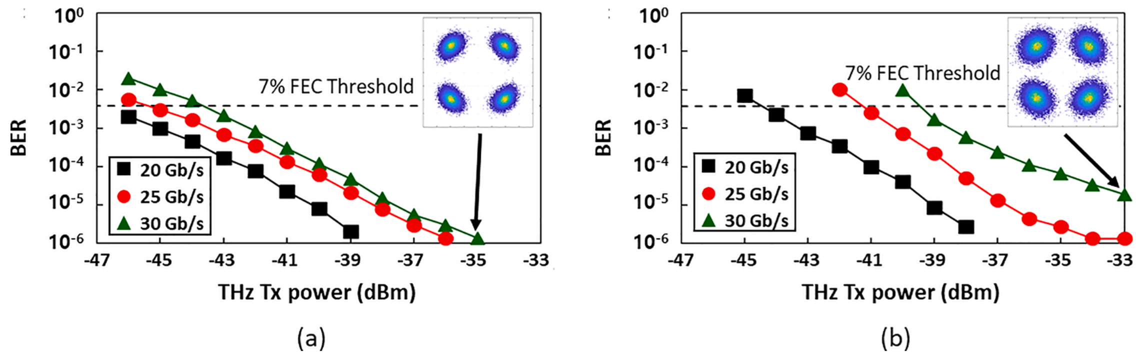

Fig. 3. Measured BER curve as a function of THz Tx power in wireless back-to-back configuration. (a) without optical fiber link, (b) with optical fiber link.

performance: attenuation, chromatic dispersion, and nonlinearity of the optical fiber. Because the optical transmission distance in an indoor network is very short, the effect of fiber attenuation is not significant. The effect of nonlinearity is also negligible because the fiber launch power is not sufficient to generate nonlinearity (in this experiment, +5 dBm). However, the effect of chromatic dispersion should be considered. Because phase information is recovered using IF, the pulse broadening by chromatic dispersion can be compensated by linear DSP algorithms. However, the effect of the interplay between the chromatic dispersion and the frequency chirp of directly modulated DFB-LD is quite complex, which results in high-order distortion [18]. This distortion cannot be compensated using a linear DSP; thus, the distortion components remain after the DSP procedure, which creates a power penalty. In addition, the above-mentioned interplay modifies the frequency response, which makes it more complex [19]. To confirm the effect of interplay, the received spectrum was measured at 20, 25, and 30 Gb/s with various optical transmission distances. Fig. 4 shows the received electrical spectrum at the output of the PD when the THz transmitting power was set to − 33 dBm and the optical received power was fixed at 0 dBm. In these figures, changes in the frequency response and second order distortions were observed. Despite the digital filtering of the out-of-band frequency components, the distortions at the in-band frequency affected the BER performance.

To investigate the impact of distortion components on the transmission performance, the BER curves were measured with various transmission distances. Fig. 5 shows the measured BER curves as a function of the received optical power at different optical transmission distances. As shown in the figures, the measured BER values for 30 Gb/s at error-floor were 1.38×10^{-5}, 3.53×10^{-5}, 9.23×10^{-5}, and 5.32×10^{-4} with transmission distance of 0, 5, 10, and 15 km, respectively. Although there were distortions because of the chirp-dispersion interplay, the measured BER values were still satisfied with the 7% FEC threshold. It should be noted that the power penalty caused by the chirp-dispersion interplay can be avoided by increasing the IF or compensated using advanced DSP techniques [20,21]. However, it should be considered that increasing the IF also increases the required bandwidth of the system, and the advanced DSP increases the complexity and latency.

3.3. THZ-band wireless transmission

To demonstrate THz-band wireless transmission, the BER was also measured as a function of the wireless transmission distance. Because the wireless link could be assumed as a point-to-point link, the dominant limitation factor was the FSPL. As mentioned in Section 2.2, two antennas and two lenses were used to compensate for the FSPL. Although the results in Fig. 5 show the possibility of 15 km optical transmission, the optical transmission distance was set to 10 km to reserve the BER margin for THz-band wireless transmission. The measured BER curves as a function of the wireless distance are shown in Fig. 6. In the BER measurements of the THz-band wireless link, the THz Tx power was fixed at –33 dBm, and the received optical power was set to + 2 dBm. As shown in this figure, measured BERs below the 7% FEC threshold were successfully obtained for 30 Gb/s with a wireless transmission distance of 1 m and optical transmission distance of 10 km.

4. Conclusions

In this study, the feasibility of upstream transmission for a THz-band indoor network was evaluated. To check the possibility of realization, an experimental setup with commercialized components was built considering cost-effectiveness. In the wireless back-to-back configuration, a BER below 10^{-6} for a data rate of 30 Gb/s was achieved. The power penalty induced by the optical component without optical transmission was 2–4 dB, which was mainly caused by the bandwidth limit of 10 GHz-class directly modulated DFB-LD. After optical transmission, distortion which originated from the interplay between the chirp characteristics of directly modulated DFB-LD and chromatic dispersion was observed. Because of this distortion, the error-floor at 30 Gb/s was degraded from 1.38×10^{-5} (without optical transmission) to 9.27×10^{-5} (10 km

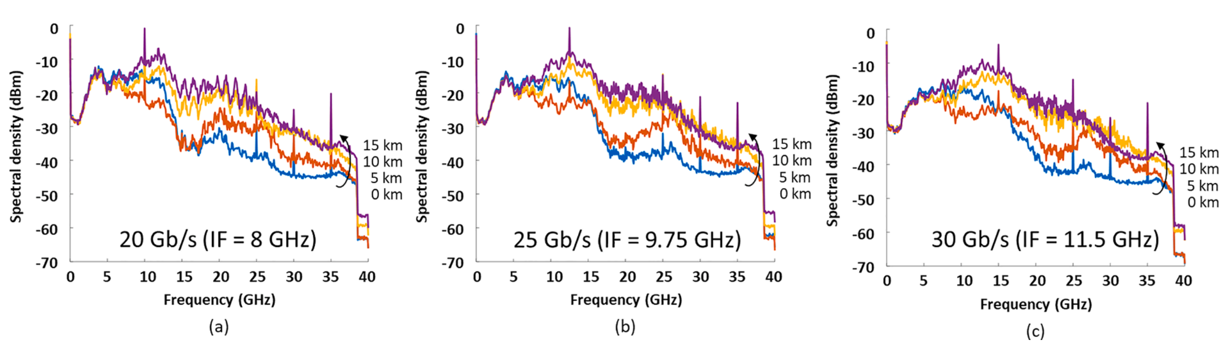

Fig. 4. Measured electrical spectra after optical transmission when THz power was –33 dBm and optical received power was 0 dBm. (a) 20 Gb/s, (b) 25 Gb/s, and (c) 30 Gb/s.

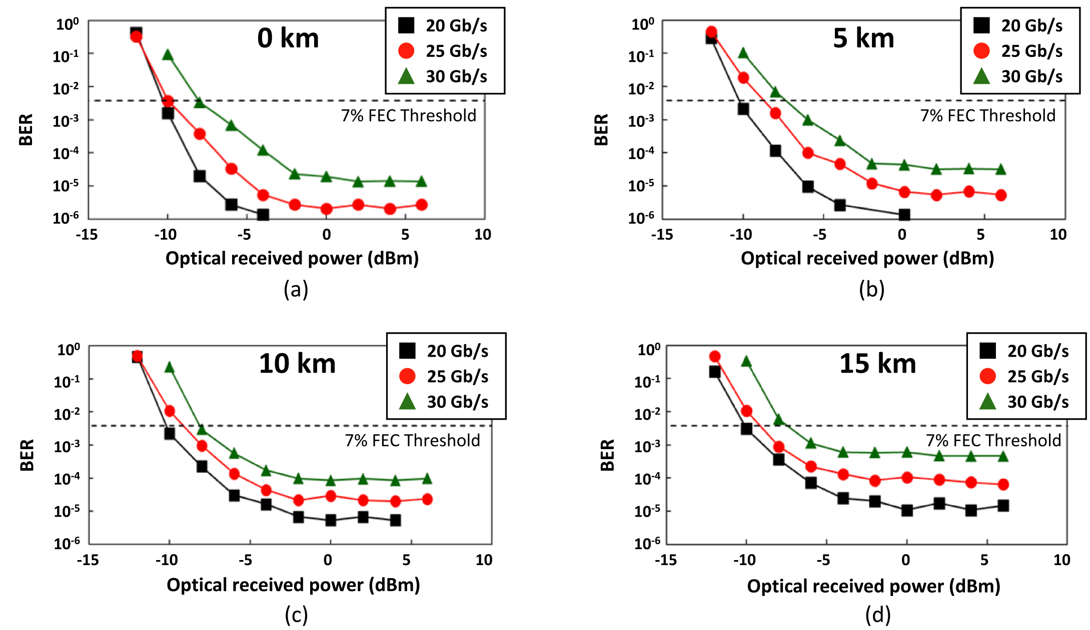

Fig. 5. Measured BER curves as a function of received optical power with optical transmission at –33 dBm THz power. (a) 0 km, (b) 5 km, (c) 10 km, and (d) 15 km.

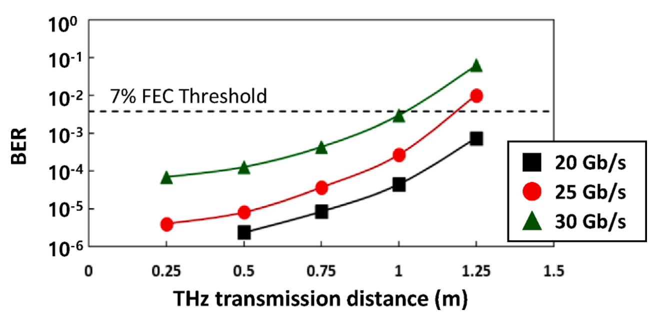

Fig. 6. Measured BER curves as a function of THz transmission distance at –33 dBm THz Tx power and 2 dBm optical Rx power with 10 km optical transmission.

transmission) and 5.32 × 10^{-4} (15 km transmission). In spite of this degradation, the measured BERs still satisfied the 7% FEC threshold (3.8 × 10^{-3}). Finally, the uplink transmission of a THz-band indoor network was demonstrated with a 30 Gb/s data rate over one m of wireless distance and 10 km of optical fiber.

5G standardization claims a 10 Gb/s peak uplink data rate for indoor networks [22]. If we expect that the required data rate might be doubled or more for the next generation indoor network, a demonstration with a 30 Gb/s data rate can be a meaningful milestone. As for the transmission distance, the 10 km optical fiber distance would be sufficient for the indoor network. However, the THz-band wireless transmission distance must be extended. Currently, the THz-band wireless transmission distance is mainly limited by the FSPL. Because high-power THz signal generators and THz-band amplifiers have been intensively developed, we expect that the proposed THz-band indoor network can be realized in the near future.

CRediT authorship contribution statement

Sang-Rok Moon: Conceptualization, Methodology, Software, Investigation, Writing - original draft, Writing - review & editing. **Eon-Sang Kim:** Validation, Formal analysis, Visualization. **Minkyu Sung:** Validation, Data curation. **Joonyoung Kim:** Methodology, Writing - review & editing. **Joon Ki Lee:** Resources, Supervision. **Seung-Hyun Cho:** Conceptualization, Resources, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Mr. Sung-min Cho and Prof. Ho-Jin Song (POSTECH, South Korea) for their advice on the construction of the experimental setup.

Funding

This work was supported by the Electronics and Telecommunications Research Institute (ETRI) grant funded by the Korean government. [21ZH1100, Study on 3D communication technology for hyper-connectivity].

References

[1] T. Nagatsuma, G. Ducournau, C.C. Renaud, Advances in terahertz communications accelerated by photonics, Nature Photon. 10 (2016) 371–379.

[2] H. Elayan, O. Amin, R. M. Shubair, and M. Alouini, "Terahertz communication: The opportunities of wireless technology beyond 5G," in 2018 International Conference on Advanced Communication Technologies and Networking (CommNet), Marrakech, 2018.

[3] H. Hamada, T. Fujimura, I. Abdo, K. Okada, H. Song, H. Sugiyama, H. Matsuzaki, and H. Nosaka, "300-GHz. 100-Gb/s InP-HEMT wireless transceiver using a 300-GHz fundamental mixer," in 2018 IEEE/MTT-S International Microwave Symposium - IMS, Philadelphia, PA, 2018, pp. 1480-1483.

[4] J. Grzyb, P. R. Vazquez, N. Sarmah, B. Heinemann, and U. R. Pfeiffer, "A 240 GHz high-speed transmission link with highly-integrated transmitter and receiver modules in SiGe HBT technology," in 42nd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), Cancun, 2017.

[5] K. Takano, S. Amakawa, K. Katayama, S. Hara, R. Dong, A. Kasamatus, I. Hosako, K. Mizuno, K. Takahashi, T. Yoshida, and M. Fujishima, "17.9 A 105gigabits per second 300GHz CMOS transmitter," in 2017 IEEE International Solid-State Circuits Conference (ISSCC), San Francisco, CA, 2017, pp. 308-309.

[6] H. Song, K. Ajito, Y. Muramoto, A. Wakatsuki, T. Nagatsuma, N. Kukutsu, Uni-travelling-carrier photodiode module generating 300 GHz power greater than 1mW, IEEE Microw. Wirel. Co. 22 (7) (2012) 363–365.

[7] T. Harter, S. Muehlbrandt, S. Ummethala, A. Schmid, S. Nellen, L. Hahn, W. Freude, C. Koos, Silicon-plasmonic integrated circuits for terahertz signal generation and coherent detection, Nature Photon. 12 (10) (2018) 625–633.

[8] S. Jia, X. Pang, O. Ozolins, X. Yu, H. Hu, J. Yu, P. Guan, F. D. Ros, S. Popov, Gunnar Jacobsen, Michael Galili, Toshio Morioka, Darko Zibar, and Leif K. Oxenløwe, "0.4 THz photonic-wireless link with 106 gigabits per second single channel bitrate," J. Lightwave Technol., vol. 36, no. 2, pp. 610-616, 2018.

[9] X. Li, J. Yu, L. Zhao, W. Zhou, K. Wang, M. Kong, G. Chang, Y. Zhang, X. Pan, and X. Xin, "132-Gb/s photonics-aided single-carrier wireless terahertz-wave signal transmission at 450GHz enabled by 64QAM modulation and probabilistic Shaping," in 2019 Optical Fiber Communication Conference (OFC), 2019, M4F.4.

[10] T. Harter, C. Fullner, J. N. Kemal, S. Ummethala, M. Brosi, E. Brundermann, W. Freude, S. Randel, and C. Koos, "110-m THz wireless transmission at 100 Gbit/s using a Kramers-Kronig Schottky barrier diode receiver," in 2018 European Conference on Optical Communication (ECOC), 2018, pp. 1-3.

[11] V. Petrov, J. Kokkoniemi, D. Moltchanov, J. Lehtomäki, Y. Koucheryavy, M. Juntti, Last meter indoor terahertz wireless access: Performance insights and implementation roadmap, IEEE Commun. Mag. 56 (6) (2018) 158–165.

[12] F. Rodrigues, R. Ferreira, C. Castro, R. Elschner, T. Merkle, C. Schubert, and A. Teixeira, "Hybrid fiber-optical/THz-wireless link transmission using low-cost IM/DD optics," 2020 in Optical Fiber Communication Conference (OFC), 2020, W2A.40.

[13] C. Wang, J. Yu, X. Li, P. Gou, W. Zhou, Fiber-THz-fiber link for THz signal transmission, IEEE Photonics J. 10 (2) (2018) 1–6.

[14] H. Shams, M.J. Fice, L. Gonzalez-Guerrero, C.C. Renaud, F. van Dijk, A.J. Seeds, Sub-THz wireless over fiber for frequency band 220–280 GHz, J. Lightwave Technol. 34 (20) (2016) 4786–4793.

[15] T. Kawanishi, THz and photonic seamless communications, J. Lightwave Technol. 37 (7) (2019) 1671–1679.

[16] M.S. Faruk, K. Kikuchi, Adaptive frequency-domain equalization in digital coherent optical receivers, Opt. Express 19 (13) (2011) 12789–12798.

[17] ITU, T Rec. G.975.1, "Forward error correction for high bit rate DWDM submarine system," 2004.

[18] E.E. Bergmann, C.Y. Kuo, S.Y. Huang, Dispersion-induced composite second-order distortion at 1.5 μm, IEEE Photon. Technol. Lett. 3 (1) (1991) 59–61.

[19] S.H. Bae, H. Kim, Y.C. Chung, Transmission of 51.56-Gb/s OOK signal using 1.55-μm directly modulated laser and duobinary electrical equalizer, Opt. Express 24 (20) (2016) 22555–22562.

[20] K. Zhang, Q. Zhuge, H. Xin, W. Hu, D.V. Plant, Performance comparison of DML, EML and MZM in dispersion-unmanaged short reach transmissions with digital signal processing, Opt. Express 26 (26) (2018) 34288–34304.

[21] B.G. Kim, S.H. Bae, H. Kim, Y.C. Chung, DSP-based CSO cancellation technique for RoF transmission system implemented by using directly modulated laser, Opt. Express 25 (11) (2017) 12152–12160.

[22] Rep., ITU-R M. 2410-0, "Minimum requirements related to technical performance for IMT-2020 radio interface, vols. 2410-0, 2017.