Optics Communications 492 (2021) 126969

Contents lists available at ScienceDirect

Optics Communications

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

Cost-effective photonics-based THz wireless delivery system using a directly modulated DFB-LD

Eon-sang Kim *, Sang-rok Moon, Minkyu Sung, Han Hyub Lee, Joon Ki Lee, Seung-hyun Cho

Optical Network Research Section, Electronics and Telecommunications Research Institute, 218 Gajeong-ro, Yuseong-gu, Daejeon, 34129, Republic of Korea

ARTICLE INFO

Keywords:
Terahertz communication
Optical communication
Directly modulated laser (DML)
Laser-to-filter detuning effect

ABSTRACT

We present a cost-effective photonics-based THz wireless delivery system using a directly modulated distributed feedback laser diode (DFB-LD). A DFB-LD with non-return to zero (NRZ) modulation up to 25 Gbps and a uni-traveling-carrier photodiode (UTC-PD) with a horn antenna is employed to transmit a THz wave into free space in the photonics-based THz signal transmitter. A Schottky barrier diode (SBD) with a horn antenna is used to directly detect the THz wave from free space at the THz signal receiver. To achieve the best bit error rate performance, we varied the optimal THz carrier frequency in a photonics-based THz wireless delivery system. After THz carrier frequency optimization, bit error rates were measured by varying THz link operating conditions, such as the data rate, photocurrent of UTC-PD, and wireless transmission distance. We successfully transmitted a 25 Gb/s NRZ signal over 1.6 and 2.2 m wireless transmission distances before and after managing the adiabatic chirp characteristic of directly modulated DFB-LD using the laser-to-filter detuning effect, respectively, while satisfying the 7% hard decision-forward error correction (HD-FEC) threshold (3.4×10^{-3}).

1. Introduction

Wireless data transmission bandwidth is required to respond to the increasing need of content and services with the evolution of wireless communication technology. Wireless transmission technology employing THz bands that completely exploit the bandwidth of several hundreds of GHz is attracting significant attention for services beyond 5G [1–4]. In particular, the frequency band around 300 GHz is an interesting window as a carrier frequency of THz wireless communication systems, owing to the relatively low atmospheric loss and unassigned frequency spectrum for commercial purposes [5,6]. Consequently, numerous studies have been conducted on THz signal transmission using a band near 300 GHz [7–10].

Recently, THz wireless transmission systems using photonics-based THz wave generation schemes have been the topic of studies worldwide [3,5,9,10]. Photonics-based THz wave generation methods offer several advantages compared to those of electronics-based THz wave generation. For example, nonlinear behavior of the multiplier chain and limitations of the modulation index in electronics-based components, including the sub-harmonic mixer, may be avoided [5].

In photonics-based THz wave generation, two optical sources with different wavelengths separated by the THz carrier frequency are injected into the photo-mixer (e.g., uni-traveling carrier photodiode, UTC-PD). Subsequently, the beating components of the two optical sources are converted to the THz wave with a carrier frequency corresponding to the wavelength difference by the principle of optical heterodyne mixing [9,10]. To date, numerous studies addressed an increase in the wireless transmission distance and the data throughput over 100 Gb/s in photonics-based THz signal transmission systems with an external optical modulator (e.g., Mach–Zehnder modulator) [11–14]. Using an external optical modulator to carry a significant amount of data information, THz signal transmissions with high-order modulation formats, such as quadrature amplitude modulation, have been reported. However, these complex modulation methods increase the overall implementation cost of the THz transmission system.

In contrast, using a non-return-to-zero on–off keying (NRZ-OOK) modulated optical transmitter with directly modulated LD, could lower the cost of the photonics-based THz transmission system and simplify the system architecture. Recently, a study on a widely tunable dual-wavelength DFB-LD for THz signal generation was also published in [15]. It is of high importance to use a direct detection scheme with a simple envelope detector, such as a Schottky barrier diode (SBD), in comparison with a coherent detection scheme utilizing a harmonic mixer with a local oscillator (LO) to realize a cost-effective THz communication system. The direct detection scheme has no impact on the degradation of transmission performance caused by the frequency drift and phase noise at the THz signal receiver. Otherwise, these parameters severely affect the transmission performance in the coherent detection scheme. Thus, it is practically significant to utilize the directly modulated LD at the photonics-based THz signal transmitter and the SBD at the THz signal receiver for cost-effectiveness.

* Corresponding author.
E-mail address: eskim@etri.re.kr (E.-s. Kim).

https://doi.org/10.1016/j.optcom.2021.126969
Received 19 October 2020; Received in revised form 27 February 2021; Accepted 22 March 2021
Available online 26 March 2021

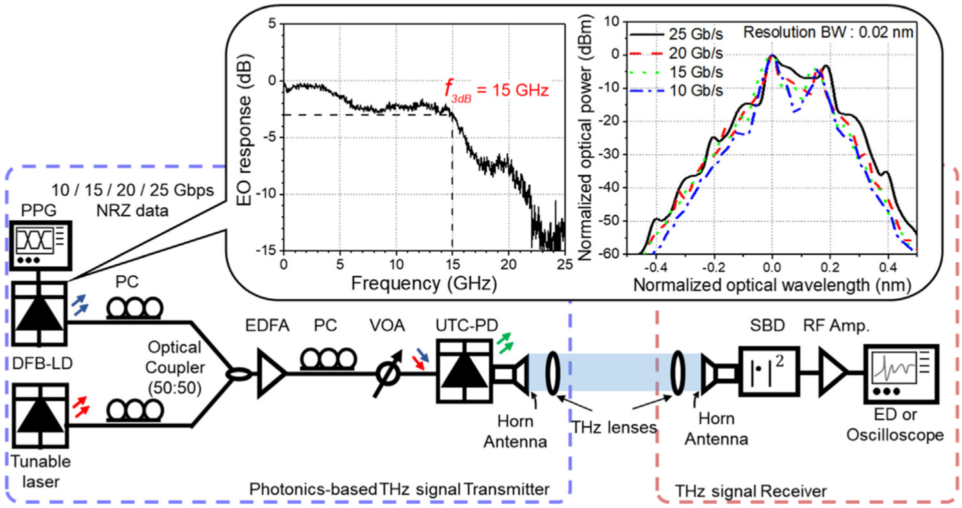

Fig. 1. Experimental setup for investigation of transmission performances of photonics-based THz wireless delivery system. (PPG: pulse pattern generator, DFB-LD: distributed feedback laser diode, PC: polarization controller, EDFA: erbium-doped fiber amplifier, VOA: variable optical attenuator, UTC-PD: uni-traveling carrier photodiode, SBD: Schottky barrier diode, RF Amp.: RF amplifier, ED: error detector)

For improving the transmission performance, we suggest to use the adiabatic-chirp management based on the laser-to-filter detuning effect, which is simple and highly effective scheme in direct detection-based THz communication system. The adiabatic-chirp management can be easily implemented by controlling a center wavelength and bandwidth of an optical filter at the output of directly modulated DFB-LD.

In this study, we achieve 25 Gb/s NRZ signal transmission over a wireless distance of 2.2 m below 7% HD-FEC threshold (3.4×10^{-3}) using a directly modulated DFB-LD as a modulator, the UTC-PD as a photomixer, and SBD as a detector. To obtain the best transmission performance and increase the wireless transmission distance, we manage the adiabatic chirp characteristics of DFB-LD using the laser-to-filter detuning effect.

2. Experimental setup and methods

We experimentally investigate the transmission performance of a photonics-based THz communication link with DFB-LD (Emcore 1742c) at the THz signal generator and the SBD (VDI WR3.4ZBD) at the THz signal receiver, as shown in Fig. 1. We employed a pulse pattern generator (Anritsu MU183020 A PPG) to generate the NRZ-OOK signal with a 2^{31}-1 pseudorandom binary sequence (PRBS). The NRZ signal was used to drive a butterfly packaged directly modulated DFB-LD with 15 GHz modulation bandwidth shown in the inset of Fig. 1. The center wavelength of the DFB-LD was fixed at 1550.13 nm, and the bias current was set to 65 mA, which generated +8.5 dBm of optical output power. The extinction ratio (ER) of the directly modulated DFB-LD was set to 5 dB, regardless of the data rate. To determine the optimum THz carrier frequency, we used a C-band wavelength-tunable laser with a linewidth of 100 kHz as an optical LO. Then, two optical sources were combined by a 50:50 optical coupler after polarization alignment. Because the UTC-PD was used as a photomixer for THz wave generation, the system required relatively high optical input power of at least +10 dBm. Thus, the optically coupled light was amplified by an Erbium-doped fiber amplifier (EDFA) and then injected into the UTC-PD. The maximum photocurrent of the UTC-PD was limited to 7 mA, which generated −13.5 dBm of THz output power to prevent damage to the UTC-PD. We employed the polarization maintaining variable optical attenuator (VOA) to reduce the fluctuation of the UTC-PD input power, which was sensitive to polarization change. The total length of the fibers used in this setup was within 100 m, assuming the THz wireless transmission system for indoor network. To establish the free-space wireless link between the THz signal transmitter and the THz signal receiver, two waveguide horn antennas with waveguide rectangular (WR) 3.4 specifications were used. A pair of THz lenses with a 38 mm diameter and 100 mm focal length were used to collimate the THz wave. At the THz signal receiver, we employed the SBD detector and the RF amplifier with 40 GHz bandwidth to detect THz signals. We also measured the bit error rates (BERs) and eye diagrams using an error detector (Anritsu 183040B ED) and a digital communication analyzer (Agilent 86109B DCA), respectively. To make sure that the THz beam to the horn antenna at the SBD detector was collimated and focused effectively, we monitored with the DCA that the eye opening of the received NRZ signals was maximized while manually aligning the two THz lenses.

3. Results and discussion

3.1. THz carrier frequency optimization

First, we examine the optimum THz carrier frequency of the THz wireless delivery system based on directly modulated DFB-LD when two waveguide horn antennas in the THz signal transmitter and receiver were placed at a distance of 20 mm from each other without the THz lenses (i.e. wireless back-to-back). In short-distance transmission of THz communication system, the measured BER varies periodically due to the standing wave generated by multiple reflection between the antennas [16]. We measured the minimum BERs as a function of the wavelength of the tunable laser output by adjusting the extra wireless distance from 0.1 mm to 1 mm when the wavelength of the DFB-LD was fixed at 1550.13 nm. Fig. 2shows the measured BER as a function of THz carrier frequency under a wireless back-to-back configuration when the photocurrent and the bias voltage of the UTC-PD were fixed at 7 mA and –1.1 V, respectively. To investigate the data-rate-dependent transmission characteristics, we also measured BERs at four different data rates of NRZ signals: 10 Gb/s (blue down-triangles), 15 Gb/s (green up-triangles), 20 Gb/s (red circles), and 25 Gb/s (black squares). Because we utilized THz components based on the WR3.4 specification in the experimental setup, the range of THz carrier frequency was limited to 220–330 GHz. The variations of the BER in this pass-band were determined by the frequency response of THz components such as UTC-PD, SBD, and WR3.4 horn antennas. For 25 Gb/s NRZ transmission, the frequency range to satisfy the 7% HD-FEC threshold ($3.4{\times}10^{-3}$) was 270–330 GHz. As shown in Fig. 2, we observed that the optimum THz carrier frequency was 295 GHz for all

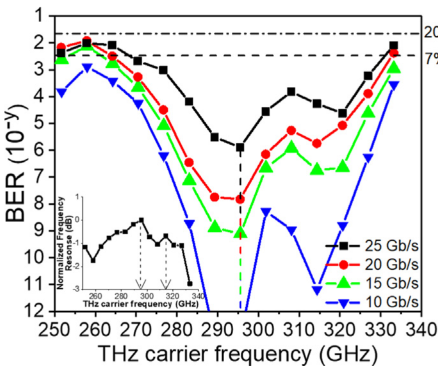

Fig. 2. BER performance as a function of THz carrier frequency with wireless back-to-back configuration.

data rates, indicating that the wavelength difference between the DFB-LD and the tunable laser was 2.36 nm. The second dips of the BER plots in the THz carrier frequency were in the range of 310–320 GHz. These frequency-dependent BER characteristics were caused by the frequency response of the UTC-PD, which is illustrated in the inset of Fig. 2. It is also experimentally observed that the BERs drastically decreased at the frequency range below 290 GHz and above 320 GHz within 3 dB sensitivity of UTC-PD. This is because the spectral width of directly modulated DFB-LD due to the spectrum broadening effect is too wide, which the frequency components of the optical signal on both sides are filtered. In comparison with a coherent detection scheme using a harmonic mixer with a LO, the NRZ modulation with a simple envelope detector, such as the SBD is inherently free from the phase noise of the DFB-LD. Thus, the frequency response of the UTC-PD and the spectral broadening effect by directly modulated DFB-LD mainly limited the transmission performance. Based on these results, the optimum THz carrier frequency was set to 295 GHz.

3.2. Performance of the wireless transmission

Fig. 3 shows the measured BER as a function of the UTC-PD photocurrent with the wireless back-to-back configuration (Fig. 3a) and over the free space transmission distance (Fig. 3b). Up to 15 Gb/s transmission, error-free transmission ($< 10^{-10}$) was achieved when the UTC-PD photocurrent was fixed at 7 mA, as shown in Fig. 3a. As the data rate increased, the BER performances were gradually degraded owing to the limitation of the modulation bandwidth of DFB-LD. We measured $1.3{\times}10^{-6}$ BER of when the data rate was increased up to 25 Gb/s. All measured BERs were below the 7% HD-FEC threshold when the photocurrent of the UTC-PD was increased up to 7 mA.

To investigate the performance of the wireless transmission, we further measured BERs by varying the wireless transmission distance with various data rates. We also fixed the photocurrent of 7 mA to the UTC-PD. Because the THz wireless link was assumed to be a point-to-point configuration, the dominant factor degrading the performance was the free-space path loss (FSPL). To compensate for the FSPL, we used a pair of THz lenses for collimating the THz beam radiated from the WR3.4 horn antenna at the THz signal transmitter. BER performance degradation was not observed, because the THz beam radiated to free-space was well-collimated through THz lenses up to 1 m of free space distance. However, as the wireless transmission distance increased beyond 1 m, the BERs were severely degraded by the impact of the FSPL. As shown in Fig. 3(b), a 1.6 m wireless transmission of 25 Gb/s NRZ signal could be achieved, which met the 7% HD-FEC requirement. For NRZ signal transmission below 20 Gb/s, the maximum wireless transmission distance was increased up to 2.2 m to meet the 20% SD-FEC ($2.2{\times}10^{-2}$) threshold. In our experimental setup, we were not able to increase the wireless transmission distance by more than 2.2 m because of the limited length of the alignment rail.

3.3. Chirp management using optical filtering

The characteristic of the frequency chirp in directly modulated DFB-LD is one of the dominant factors affecting the transmission performance. The frequency chirp causes optical spectral broadening, which limits the maximum transmission distance and degrades transmission performance. Consequently, transmission performance degradation is induced by the interaction between the frequency chirp and fiber dispersion in most optical communication systems with directly modulated light sources. The directly modulated DFB-LD with the NRZ signal format generally has an adiabatic chirp-dominant characteristic [17,18]. Thus, two peaks are observed in the optical spectrum, which depict "1" and "0" levels separated by $\Delta\nu$, as shown in the inset of Fig. 1. To improve the transmission performance of the adiabatic chirp-dominant DFB-LD, a simple method, such as spectral filtering in the optical domain, is widely used [19,20]. When the spectral components corresponding to the "0" level is filtered out, the optical power of "0" level is reduced, which results in the increase of effective ER. In addition, to change the ER of the directly modulated light, the spectral components associated with "1" level or "0" level are selectively removed by the optical band-pass filter. To improve the BER performance in a photonics-based THz transmission system with DFB-LD, we employed an optical band-pass filter at the output of directly modulated DFB-LD and filtered out the spectral components corresponding to the "0" level. In other words, we intentionally mis-aligned the center wavelength of the optical band-pass filter with it of the DFB-LD, meaning that the laser-to-filter detuning frequency would be increasing. Fig. 4(a) represents the passband of a flat-top-shaped optical filter (blue line)

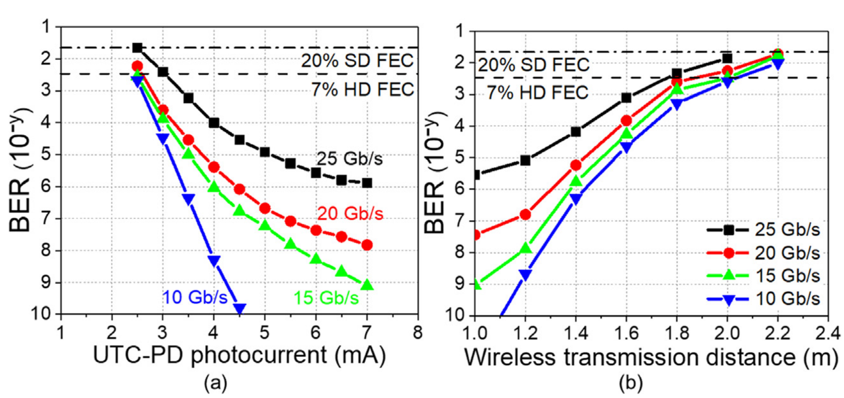

Fig. 3. BER performance as a function of (a) UTC-PD photocurrent with wireless back-to-back configuration and (b) wireless transmission distance when UTC-PD photocurrent is fixed at 7 mA.

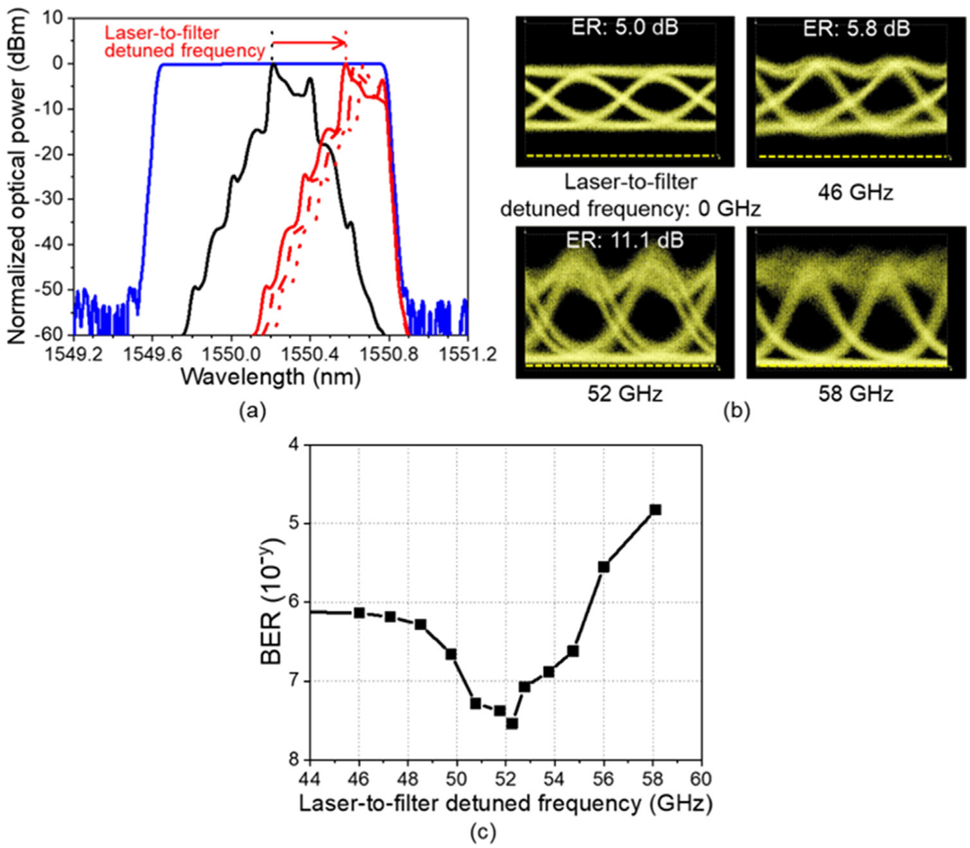

Fig. 4. (a) Filtered optical spectra of directly modulated DFB-LD with 25-Gb/s NRZ signal; (b) measured optical eye diagrams with marked ER for four detuned frequencies of 0 GHz, 46 GHz, 52 GHz, and 58 GHz; (c) measured BERs as a function of the laser-to-filtered detuned frequency.

and the measured spectrum of the directly modulated DFB-LD with 25 Gb/s NRZ-OOK signal (black line). The 3-dB bandwidth and the center wavelength of the flat-top-shaped optical filter were 145 GHz (1.16 nm) and 1550.13 nm, respectively (filter-edge roll-off factor was 1000 dB/nm). To increase the ER of the DFB-LD output, we changed the laser-to-filter detuned frequency, which indicates the difference in the center frequency between the DFB-LD and the flat-top-shaped filter, as shown in Fig. 4(a) (red lines). Fig. 4(b) shows the measured optical eye diagrams marked with enhanced ER as the laser-to-filter detuned frequency increased. This is because the effective optical power of the "0" level was lowered by filtering the spectral component corresponding to the "0" level. However, if the laser-to-filter detuned frequency is increased by more than 52 GHz, the spectral component associated with the "1" level was filtered out simultaneously, such that the noise component of "1" level was increased. Fig. 4(c) shows the measured BERs as a function of the laser-to-filter detuned frequency. As the laser-to-filter detuned frequency was increased up to 52 GHz, the BER performance improved slightly. However, when the laser-to-filter detuned frequency was increased above 52 GHz, significant BER degradations were observed due to the noise increase of "1" level, as mentioned above. In this experiment, we used a fiber within 100 m, assuming the THz wireless transmission system for indoor environment.

Fig. 5 shows the measured BERs by fixing the laser-to-filter detuned frequency at 52 GHz and changing the THz carrier frequency. The transmission performance improves slightly owing to the enhanced ER compared to the case where the optical bandpass filter was not used. The optimum THz carrier frequency was also 295 GHz, regardless of optical filtering, as shown in Fig. 5. This indicates that the optimum THz carrier frequency is dominantly determined by the frequency response of THz components, such as the UTC-PD, irrespective of the modulated optical source. The range of the THz carrier frequency

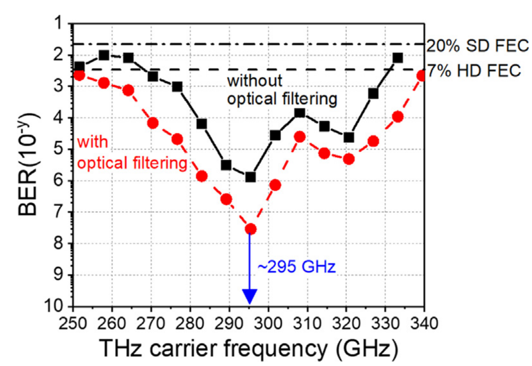

Fig. 5. Improved BER performance as a function of THz carrier frequency with an optical filter.

satisfying the 7% HD-FEC threshold was significantly broadened from 60 GHz (270–330 GHz) to 90 GHz (250–340 GHz) with the help of an optical band-pass filter.

Fig. 6 shows the improved BER performance using the optical filter as a function of the UTC-PD photocurrent with a wireless back-to-back configuration (Fig. 6a) and wireless transmission distance (Fig. 6b). The chirp management by optical filtering improved the BER performance by ~10^2 from 1.3 $\times 10^{-6}$ to 2.9 $\times 10^{-8}$ when the photocurrent of the UTC-PD was fixed at 7 mA. As shown in Fig. 3b, BER degradation was not observed when the wireless transmission distance was increased to 1 m owing to the well-collimated THz beam. However, when the wireless transmission distance increased above 1 m, BER performances were drastically degraded by the FSPL, as mentioned above. As shown

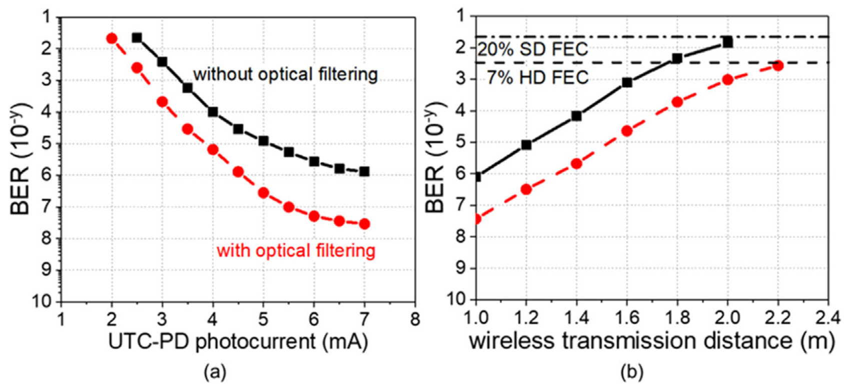

Fig. 6. Improved BER performance as a function of (a) UTC-PD photocurrent under wireless back-to-back configuration and (b) wireless transmission distance when the UTC-PD photocurrent is fixed at 7 mA.

in Fig. 6b, the transmission performances could be improved by increasing the wireless distance from 1.6 m (without the optical filter) to 2.2 m (with optical filter), which met the 7% HD-FEC threshold. This setup is expected to transmit beyond 2.2 m below the 20% SD-FEC threshold.

4. Summary

We experimentally demonstrated the NRZ-OOK signal transmission in a photonics-based THz wireless delivery system using a directly modulated DFB-LD. To realize a cost-effective THz wireless link, a DFB-LD was employed as a modulator, a UTC-PD as a photomixer, and an SBD as a detector. We measured the BERs to determine the optimum THz carrier frequency by changing the wavelength difference between the DFB-LD and the tunable laser as an LO for optical heterodyne mixing. To examine the basic transmission performances of the photonics-based THz wireless delivery system, BERs were also measured by varying the bit rate, the photocurrent of the UTC-PD, and the wireless transmission distance. We were able to transmit a 25 Gb/s NRZ signal over a 1.6 m wireless transmission distance below the 7% HD-FEC threshold. To increase the wireless transmission distance, the adiabatic-chirp management technique based on the laser-to-filter detuning effect was employed. To observe the improvement of the transmission performances, we measured BERs and eye diagrams as a function of the laser-to-filter detuned frequency. When the laser-to-filter detuned frequency was fixed at 52 GHz, a 2.2 m wireless transmission of 25 Gb/s NRZ signal was achieved below 3.4×10^{-3} BER based on a 7% HD-FEC threshold. We expect the wireless transmission distance to be increased up to 2.5 m when the BER threshold is lowered to the 20% SD-FEC requirement (2.2×10^{-2} BER). Given that the performance degradation due to FSPL is mitigated using digital signal processing and THz-band amplifiers, the maximum transmission distance will be further increased. We hope that this cost-effective THz wireless communication system based on DFB-LD will be established in the near future to manage large-capacity indoor wireless traffic.

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.

Acknowledgments

This work was supported by Electronics and Telecommunications Research Institute (ETRI), South Korea grant funded by the Korean government [21ZH1100, Study on 3D communication technology for hyper-connectivity]. The authors would like to thank Dr. Eui Su Lee, Dr. Il-Min Lee, and Dr. Kyung Hyun Park for their helpful discussions on technical issues in this paper.

References

[1] H.-J. Song, T. Nagatsuma, Present and future of terahertz communications, IEEE Trans. Terahertz Sci. Technol. 1 (1) (2011) 256–263.

[2] S. Lee, S. Hara, T. Yoshida, S. Amakawa, R. Dong, A. Kasamatsu, J. Sato, M. Fujishima, An 80-Gb/s 300-GHz-band single-chip CMOS transceiver, IEEE J. Solid-State Circuits 54 (12) (2019) 3577–3588.

[3] S. Jia, M.-C. Lo, L. Zhang, O. Ozolins, A. Udalcovs, D. Kong, X. Pang, X. Yu, S. Xiao, S. Popov, J. Chen, G. Carpintero, T. Morioka, H. Hu, L.K. Oxenløwe, Integrated Dual-DFB Laser for 408 GHz Carrier Generation Enabling 131 Gbit/s Wireless Transmission over 10.7 Meters, in: Optical Fiber Communication Conference 2019, Th1C.2 (2019).

[4] P. R.-Vazquez, J. Grzyb, B. Heinemann, U.R. Pfeiffer, Optimization and Performance Limits of a 64-QAM Wireless Communication Link at 220-260 GHz in a SiGe HBT Technology, in: IEEE Radio and Wireless Symposium, 2019.

[5] T. Nagatsuma, G. Ducournau, C.C. Renaud, Advances in terahertz communications accelerated by photonics, Nature Photon. 10 (6) (2016) 371–379.

[6] A.-A.A. Boulogeorgos, A. Alexiou, T. Merkle, C. Schubert, R. Elschner, A. Katsiotis, P. Stavrianos, D. Kritharidis, P.-K. Chartsias, J. Kokkoniemi, M. Juntti, J. Lehtomaki, A. Teixeira, F. Rodrigues, Terahertz technologies to deliver optical network quality of experience in wireless systems beyond 5G, IEEE Commun. Mag. 56 (6) (2018) 144–151.

[7] G. Chattopadhyay, Technology, capabilities, And performance of low power terahertz sources, IEEE Trans. Terahertz Sci. Technol. 1 (1) (2011) 33–53.

[8] M. Seo, M. Urteaga, A. Young, V. Jain, Z. Griffith, J. Hacker, P. Rowell, R. Pierson, M. Rodwell, 300 GHz fixed-frequency and voltage controlled fundamental oscillators in an InP HBT process, in: IEEE MTTS International Microwave Symposium digest, 2010, pp. 272–275.

[9] T. Ishibashi, N. Shimizu, S. Kodama, H. Ito, T. Nagatsuma, T. Furuta, Uni-traveling-carrier photodiodes, in ultrafast electronics and optoelectronics, in: M. Nuss, J. Bowers (Eds.), in: 13 of OSA Trends in Optics and Photonics Series, Optical Society of America, 1997, paper UC3.

[10] H.-J. 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.

[11] K. Liu, S. Jia, S. Wang, X. Pang, W. Li, S. Zheng, H. Chi, X. Jin, X. Zhang, X. Yu, 100 gbit/s THz photonic wireless transmission in the 350-GHz band with extended reach, IEEE Photon. Technol. Lett. 30 (11) (2018) 1064–1067.

[12] K. Takiguchi, Real-time wireless OFDM communication in THz-band using optical DFT processing, in: 2017 International Topical Meeting on Microwave Photonics (MWP), 2017, pp. 1–3.

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

[14] T. Harter, C. Fullner, J.N. Kemal, S. Ummethala, M. Brosi, E. Brundermann, W. Freude, S. Randel, 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), T3F.7, 2018.

[15] Q. Tang, Y. Liu, L. Zhang, X. La, S. Liang, L. Zhao, W. Wang, 25 gb/s directly modulated widely tunable 1.3 μm dual wavelength DFB laser for THz communication, IEEE Photonics Tech. Lett. 32 (7) (2020) 410–413.

[16] T. Nagatsuma, K. Oogimoto, Y. Inubushi, J. Hirokawa, Practical considerations of terahertz communications for short distance applications, Nano Commun. Netw. 10 (2016) 1–12.

[17] P.J. Corvini, T.L. Koch, Computer simulation of high bit rate optical fiber transmission using single frequency lasers, J. Lightwave Technol. LT-5 (1987) 1591–1595.

[18] J.C. Cartledge, G.S. Burley, The effect of laser chirping on lightwave system performance, J. Lightwave Technol. 7 (1989) 568–573.

[19] J. Downie, I. Tomkos, N. Antoniades, A. Boskovic, Effects of filter concatenation for directly modulated transmission lasers at 2.5 and 10 Gb/s, J. Lightwave. Technol. 20 (2) (2002) 218–228.

[20] W. Lee, S.H. Cho, M.Y. Park, J.H. Lee, C. Kim, G. Jeong, B.W. Kim, Frequency detuning effects in a loop-back WDM-pon employing gain-saturated RSOAs, IEEE Photonics Technol. Lett. 18 (13) (2006) 1436–1438.