Integrated Dual-DFB PIC for High-Purity THz Carrier Generation Enabling Ultrafast THz Wireless Communications

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Article

Keywords: Radio frequency photonics, THz photonics, THz wireless communication, integrated DFB laser.

Posted Date: April 8th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-325916/v1

Version of Record: A version of this preprint was published at Nature Communications on March 16th, 2022. See the published version at https://doi.org/10.1038/s41467-022-29049-2.

Abstract

With the explosive growth of global wireless data traffic, the Terahertz band (0.3–10 THz) is promising for ultrafast wireless communications, due to the enormous available bandwidth [1]. Photonic generation of THz carriers displays extremely large tunable range and modulation bandwidth, making it nearly ideal for THz communications. However, the current photonics-based THz carrier generators are based on discrete bulky components [2] with high cost and energy consumption, which hinder them from practical applications. Here, we present an injection-locked heterodyne source based on generic foundry-fabricated photonic integrated circuits (PIC) attached to a photo-mixing uni-travelling carrier photodiode (UTC-PD), generating high-purity THz carriers for high-speed and long-distance wireless communication. The generated THz carrier can span from 0 to 1.4 THz, determined by the tunable wavelength spacing between the two distributed feedback (DFB) modes within the range 0-10.7 nm. We show that a generated 0.4 THz carrier transmits a record-high single-channel net rate of 131 Gbit/s over 10.7 m of wireless distance with only – 24 dBm emitted THz power, by employing 16-QAM-OFDM modulation and a nonlinear equalization technique. To the best of our knowledge, this is the highest data rate for a single-channel THz wireless transmission and requires the lowest THz power/bitrate/distance. The scheme of the monolithic dual-DFB PIC based THz generation shows a great potential for fully integrated, cost-effective and energy-efficient THz transmitters.

Introduction

The global wireless data traffic today grows by around 50% per year [3], and existing wireless communication in traditional lower frequency bands is facing great challenges to meet the demand of this explosive growth. To support ultrafast wireless communications, higher frequency bands providing larger bandwidth need are explored. The terahertz range (THz, 0.3-10 THz) is promising to fill the data rate gap between fiber optic and wireless networks. The generation of THz carriers using photonic techniques is interesting because of the large tuning range and modulation bandwidth they offer, which enables the generation of high-quality THz signals capable of carrying 100 Gbit/s data rates and beyond [4].

Photonic integrated circuit (PIC) based THz synthesizers have the advantages of low weight, small footprint, and low power consumption. Moreover, facilitated by continuous development of semiconductor fabrication technologies, the open-access InP generic foundry photonic integration approach has allowed active and passive components to be monolithically integrated on the same substrate [5]. Therefore, combining two single-wavelength distributed feedback (DFB) lasers in parallel with a coupler, the open foundry platform has recently proven the potential for heterodyne THz generation at frequencies > 1.3 THz, with potentially significantly reduced cost. However, the tens-of-MHz laser linewidth and the lack of phase correlation between two free-running lasers lead to considerable instability of the heterodyne THz signals, which limits practical applications [6].

In terms of THz wireless communication reach, the 10-100 m range is recommended for indoor communications for carrier frequencies ranging from 350-910 GHz [2]. To exploit the THz frequency bands, extensive research has been conducted to achieve high data rate transmission at these frequencies alongside the efforts to reach longer distances. Fig. 1(a) summaries the experimentally demonstrated data rates and wireless reaches in the 350-910 GHz band [2, 7-15]. Using photonic schemes, high data rates can be achieved by frequency division multiplexing techniques often yielding data rates of 100 Gbit/s and above [8-12]. However, these multiplexing techniques increase the system cost and complexity. Single-channel wireless transmission with a data rate beyond 100 Gbit/s has recently been demonstrated over a very short distance [15]. Fig. 1(b) shows reported long-distance (>10 m) THz wireless transmission in different THz bands revealing the relation of data rate, distance and transmitter THz energy per bit per distance [14, 16, 17].

In this paper, we demonstrate the first single-channel THz photonic-wireless transmission achieving both high data rate and relevant reach, with >100 Gbit/s data rate and >10 m reach using a PIC-based THz transmitter. Monolithically integrated dual DFB lasers are injection-locked by a mode-locked laser (MLL) based optical frequency comb [18], therefore, the generated THz carrier is phase coherent and stable. The generated two continuous wave (CW) tones are separated by a wavelength division demultiplexer. One of the CW tones is data modulated with a high-speed signal, and then beats with the other unmodulated CW tone in a photo-mixing uni-travelling carrier photodiode (UTC-PD). Finally the modulated signal with a net rate of 131 Gbit/s on the 0.4 THz carrier is emitted through a THz antenna. After the 10.7 m wireless transmission, the THz signal is received by a THz receiver. To the best of our knowledge, this is the highest data rate for a single-channel THz wireless transmission and the largest bandwidth-distance product for the carrier frequencies above 350 GHz. In addition, compared with previous works, the lowest emitted THz power/bitrate/distance of 2.9×10^{-18} J/bit/m has been achieved, indicating the low noise of this THz carrier.

Results

Fully integrated on-chip THz transmitter for a THz FDM high-speed WLAN

The vision of a fully integrated on-chip photonic-wireless THz transmitter is shown in Fig. 2, where the THz frequency division multiplexed (FDM) high-speed wireless local area network (WLAN) is used as an exemplary application. The THz FDM high-speed WLAN system consists of a shared chip-based optical frequency comb and several integrated THz photonic-wireless transmitters. The frequency comb is distributed to each THz transmitter for injection locking dual-DFB lasers respectively. The THz transmitter consists of dual-DFB lasers, data modulator, and UTC-PD integrated THz antenna. The two free-running DFB lasers become phase coherent after injection locked to the frequency comb. One of the CW tones is modulated with a high-speed data signal and the other acts as a LO, and after the recombining they are launched into the UTC-PD for photomixing, and finally emitted as a THz signal through the THz antenna. By tuning the wavelengths of the DFB lasers in each THz transmitter, they can be injection locked to different tones of the frequency comb with different spacing and generate a different beating THz carrier to support THz FDM high-speed WLAN. Such a THz FDM high-speed WLAN will be desirable for indoor communications with high cybersecurity, since each user can have a distinct frequency channel.

Dual-DFB PIC injection-locked to OFCG for high-purity THz generation

As shown in Fig. 3(a), on the monolithically integrated dual-DFB PIC, the two tunable DFB lasers are coupled to the 3-dB multimode interference (MMI) coupler. The wavelength and intensity of each DFB tone are controlled with the thermal tuning current for integrated heater and injection current. The GSG transmission coplanar waveguide (CPW) supports RF current injection. After the MMI coupler, the superimposed optical dual-DFB emission is accessible via the spot-size converter (SSC) on the cleaved facet with anti-reflection (AR) coating. The on-chip PIN-PD allows for on-chip optical heterodyning generation up to 40 GHz that is far below the THz range. The operation frequency of PIN-PD and GSG are not within the THz range and thus not studied in this paper. The wavelength spacing between the two free-tuning DFB modes is variable within the range of 0-10.7 nm, corresponding to 0-1.4 THz, in the telecom C-band. To reduce the phase fluctuations between the two free-running tones, an off-the-shelf 9.951-GHz MLL-based OFCG is employed to injection-lock the two modes simultaneously to keep them correlated. The dual-DFB lasers are set to 1555.575 nm and 1558.975 nm, injection locked to two selected modes of the coherent OFC.

Fig. 3(a) also shows the overall experimental setup for characterizing the OFCG-locked dual-tone laser. Before sending the two coherent tones generated by the OFCG-locked dual-DFB PIC into the UTC-PD, an optical band-pass filter (OBPF), a polarization controller (PC), a polarizer, a polarization maintaining variable optical attenuator (VOA) are employed to control the polarization alignment and optical power of the input signal. At the output of the UTC-PD, the THz signal O/E-converted from the dual-tone laser emission with a frequency of 408 GHz is generated and emitted into a 10.7-m wireless link. A pair of THz lenses with 100-mm diameter and 200-mm focus length is used at the transmitter and receiver sides to collimate the THz beam. The 408-GHz THz carrier signal is then down-converted to the IF of 10 GHz with a SBD mixer, with the 12-time electrical tone being 398 GHz (corresponding to a fundamental rate about 33.17 GHz). The IF signal is collected with the ESA.

The typical behavior of the DFB laser is presented in Fig. 3(b), where the intensity and wavelength continuously increase as the injection current raises. The intensity and wavelength can also be tuned with the heater current. DFB-1 covers 1552-1556 nm and DFB-2 covers 1556-1560 nm. In the pure single-wavelength operation, the optical signal-to-noise ratio (OSNR) is around 60 dB. Fig. 3(c) shows the OFC spectra and the optically injection-locked two-tone emission collected at port 1 and port 3 of the optical circulator, respectively. From the OFC spectra, it can be seen that the OSNR of the tone of OFC is around 40-50 dB. When both lasers are aligned to the OFC and properly biased to have the 3.3-nm (408-GHz) wavelength separation, the OSNR of the two selected OFC tones increases to 50-60 dB. Therefore, the optical injection locking method can increase the OSNR of the tones by around 10 dB in respect to the original OFC. To enhance the side-mode-suppression ratio, the unwanted adjacent modes could be suppressed by using a sharp optical filter or a comb with wider spacing.

The IF electrical spectrum are shown in Fig. 3(d). The blue trace shows the down-converted beat-note when the two DFB lasers are free running. The red trace shows the down-converted beat-note when the lasers are properly biased and aligned to the OFC. The injection power of the master comb laser is 10 dBm, measured with an optical power meter at port-1 of the optical circulator. This locked beat-note shows a Hz-level 3-dB linewidth (see the inset) while the free-running beat-note shows a sub-GHz linewidth. In the free-running operation, the dual-DFB lasers are not correlated and thus generating a huge amount of phase perturbation, resulting in the large linewidth as well as the frequency drifting that is associated with the long-term frequency stability. The single sideband (SSB) phase noise power spectral density of the down-converted synthesized signal is measured experimentally for the dual-DFB lasers separated by 408 GHz (3.3 nm), as shown in Fig. 3(e). It demonstrates the effect of injection power level. In this range, a higher injection power level offers further phase noise reduction. The phase noise of the heterodyne signal is reduced to the level of less than -100 dBc/Hz at >1 MHz offset when the injection power is larger than 9 dBm.

Experimental demonstration of 131 Gbit/s THz wireless transmission over 10.7 m

At the transmitter, two continuous waves (CWs) at 1555.675-nm and 1558.975-nm are generated by the aforementioned dual-DFB laser chip, as shown in the inset of Fig. 4(a). For a phase-stabilized beat note, an off-the-shelf MLL, which emits a 9.951-GHz-spacing OFC, is used to injection-lock the two CW modes, making them correlated in terms of frequency and phase. In the experimental demonstration, the spacing between the two DFB lasers is also tuned to be 408 GHz in order to generate the carrier frequency. The overall experimental system setup is shown in Fig. 4. A de-multiplexer separates the two coherent tones generated in the dual-DFB laser chip with 408 GHz spacing. One tone is used as an optical local oscillator (LO) for heterodyne mixing in order to generate the THz wave. The other tone is used as modulation carrier and it is launched into the in-phase (I) and quadrature (Q) arms of an optical modulator (IQM).

A two-channel 64-GSa/s arbitrary waveform generator (AWG) is used to generate the IQ-OFDM signal. The length of the inverse fast Fourier transform (IFFT) and cyclic prefix (CP) of the IQ-OFDM signal are set to 1024 and 16, respectively, and the first subcarrier is set to null. The binary sequence used to generate the OFDM symbols is a random sequence generated from MATLAB software. The modulated 16-QAM-OFDM optical signals after the IQM are amplified by an erbium doped fiber amplifier (EDFA) followed by an OBPF. Here, a VOA is used to control the power of the optical signal before combining the optical LO, to keep the power ratio balanced between the optical LO and signal for the highest photo-mixing efficiency in the UTC-PD [19].

The baseband signal and the optical LO are polarization aligned, and then combined before launching into the broadband UTC-PD. A polarization maintaining (Pol. M) VOA is used to control the optical power launched into the UTC-PD. The optical spectrum of the combined signal and LO is shown in the inset of Fig. 4(b). At the output of the UTC-PD, a THz signal with carrier frequency centered at 408 GHz is generated and emitted into a 10.7-m line-of-sight (LOS) wireless link, as shown in Fig. 4(d). A pair of THz lenses with a 100-mm diameter and 200-mm focus length are used to collimate the THz beam. At the receiver, the THz signal is down-converted to an IF by employing a sub-harmonic Schottky mixer operating in the 0.3-0.5 THz band, driven by a 12-time (×12) frequency multiplied electrical LO. The electrical LO is tuned to be 32 GHz, resulting in a corresponding IF carrier frequency of 24 GHz. The IF signal is amplified by an RF amplifier with 45 GHz bandwidth and then converted to digital samples in a 160 GSa/s real time digital sampling oscilloscope (DSO) with 63 GHz analog bandwidth. The digital signals are processed and analyzed offline with a digital signal processing (DSP) routine.

The structure of the DSP routine is shown in Fig. 4(c). The channel equalization is composed of linear equalization (LE), phase noise compensation (PNC) and nonlinear equalization (NLE). First, the signal after the FFT module passes through the pilot based one-tap LE, which is used to compensate the system linear response and to reduce the system additive noise influence. After LE, the signal is equalized with a least-squares method-based PNC to reduce the impairment from phase noise. After the PNC, the Volterra series nonlinear model is used for estimating the nonlinear impairment, which considers the 2nd-order and the 3rd-order distortion terms (see details in **Methods** and **Supplementary information**).

The single-channel THz signal is evaluated after the 10.7-m wireless transmission. As shown in Fig. 5(a), the BER performance for four cases of different DSP modules combined (w/o equalization, LE, LE+PNC, LE+PNC+NLE) have been measured versus the optical power launched into the UTC-PD. For the case of nonlinear DSP (LE+PNC+NLE) employed, a BER below low-density parity-check convolutional codes (LDPC-CC) forward error correction (FEC) threshold (2.7 e-2, 20%-OH, the pre-FEC BER was calculated from the given Q factor in dB as $(1/2)\mathrm{erfc}(10^{5.7dB/20}/\sqrt{2})$) [20, 21] is successfully achieved. The 16-QAM-OFDM has a total bandwidth of 44.43 GHz, which corresponds to a gross bit rate of 157.46 Gbit/s (subtracting the pilot overhead) and a net rate of 131.21 Gbit/s after subtracting the FEC overhead. The capacity calculated by the generalized mutual information (GMI) [22] is also presented, and the capacity at 14 dBm optical power is 134.56 Gbit/s, which has ~2.5% variation with post-FEC capacity. The corresponding signal constellations captured at an optical power of 14 dBm with different DSP modules are shown in Fig. 5(b)-(e) respectively. The electrical spectra of the 44.43 GHz OFDM signal both before and after down conversion and filtering are shown in Fig. 5(f)-(g) respectively. The performance of the system here is limited by the SNR of the received signal, as shown in Fig. 5(g), a mean SNR of 13.45 dB is achieved.

Discussion

We have experimentally demonstrated a single-channel 131.21 Gbit/s net rate THz-band wireless transmission over 10.7-m distance, employing 16-QAM-OFDM modulation, nonlinear DSP flow, and OFC injection-locked heterodyne THz generator based on generic foundry fabricated PIC. Other components in the system such as modulator, de-multiplexer, circulator, VOA and optical filter also have integration solutions [23]. Therefore, the scheme of using a monolithic dual-DFB laser chip THz generation shows a great potential for fully integrated THz transmitters and further a cost-effective and energy-efficient THz FDM high-speed WLAN.

Method

Generic foundry approach for photonic integrated circuit

Open-access generic photonic integration technology enables building active and passive components on a single substrate, without the need of additional high-precision assembly. A broad variety of functionalities are feasible by using standard building blocks (BBs) including, but not limited to lasers, amplifiers, photo detectors, phase modulators, filters, wavelength multiplexers, power splitters, couplers and combiners. Mostly, they can be composed of a combination of waveguides of different widths and lengths. BBs are predefined to ease the design flow and can be called and parameterized according to process design kit (PDK) provided by foundry. The photonic integrated circuits (PICs) are manufactured within multi-project wafer (MPW) service whereby mask and wafer area are shared, and so is fabrication cost among multiple different users. The PIC used for the THz communication system was developed in such an MPW run, by Fraunhofer HHI, JePPIX (Joint European Platform for Photonic Integration of Components and Circuits).

Digital signal processing (DSP)

The DSP flow at the transmitter is similar to a conventional OFDM system, which is shown in the inset of Fig. 5. A mapping module is used to transform the parallel binary data in different subcarriers to QAM symbols. After mapping, the inverse fast Fourier transform (IFFT) module transforms the frequency domain symbols into time domain to realize the OFDM modulation. Then, cyclic prefix (CP) is inserted to reduce the influence of inter-symbol interference (ISI). To capture the OFDM data frame in the scope, we add a pseudo-noise (PN) sequence with length of 2^7-1 at the head of serial OFDM data for synchronization. At the receiver, the signal is first captured from the scope, then we use the autocorrelation of pseudo-noise (PN) sequence to find the frame head in the captured frame. After synchronization, the CP is first removed to mitigate the influence of multi-path interference induced ISI. Then, fast Fourier transform (FFT) module transforms the time domain symbols into frequency domain to realize the OFDM demodulation. After that, equalization is used to recover back the signal. The detailed derivations of the DSP routine and optimization of DSP parameters are described in the ***Supplementary information***.

Experiment

The experimental setup is shown in Fig. 4. The coherent OFCG is based on an off-the-shelf MLL with 9.951-GHz mode spacing. The optical power of the OFC injected into the dual-DFB chip is around 10 dBm. The gain of the EDFA in the path of optical LO after the de-multiplexer is tunable, to keep the power balance between optical LO and modulated signal. The coupled optical LO and modulated signal are launched into the UTC-PD, where the input power is up to 14 dBm controlled by a VOA. The THz output power of the UTC-PD with the conversion efficiency of 0.15 A/W is from -30 dBm to -20 dBm, depending on the optical input power. Then the Schottky mixer-based THz receiver with extremely high sensitivity down-converts the single-channel THz signal to IF. The IF output is fed into the DSO for analog-to-digital conversion. Finally, the digital signals are processed and analyzed offline.

Declarations

Supplementary Information. The details of photonic chip and digital signal processing (DSP) can be found in the Supplementary information.

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Author Contributions

S. J. and H. H. proposed the THz photonic-wireless transmission based on the monolithically integrated dual-DFB lasers chip injection locked by a coherent OFC. S. J. designed the overall experiment. M. L. developed the monolithically integrated dual-DFB lasers chip. L. Z. developed the OFDM-16-QAM modulation and DSP routine. S. J., M. L., L. Z., O. O., and A. U. carried out the experiment. D. K., X. P., L. K. O., and H. H. assisted in the discussion and interpretation of the results. S. J. wrote the draft of the manuscript. X. P., X. Y., S. X., S. P., J. C., G. C., T. M., L. K. O., and H. H. edited the manuscript. H.H. coordinated and supervised the experiment. All the authors discussed the results and reviewed the manuscript.

Funding Sources

This work was supported in part by the EU H2020 Marie Sklodowska-Curie grant agreement no. 713683 (COFUNDfellowsDTU), the EU H2020 Marie Skłodowska-Curie Grant agreement no. 642355 FiWiN5G and 713964 MULTIPLY, the Danish center of excellence CoE SPOC under Grant DNRF123, the Villum young investigator program grant of 2MAC and the Independent Research Fund Denmark under the grant of 9041-00395B, the Swedish Research Council (VR), the Swedish Foundation for Strategic Research (SSF), Göran Gustafsson Foundation, the Swedish ICT TNG, the EU H2020 MCSA-IF Project NEWMAN (#752826), VINNOVA funded SENDATE-EXTEND and SENDATE-FICUS, National Natural Science Foundation of China (61331010, 61722108, 61775137, 61671212, 61771424).

Notes

The authors declare no competing financial interest.

References

1. Federici, J. & Moeller, L. Review of terahertz and subterahertz wireless communications. *Appl. Phys.* **107**, 111101 (2010).

2. Nagatsuma, T., Ducournau, G. & Renaud, C. C. Advances in terahertz communications accelerated by photonics. *Nature Photon.* **10**, 371-379 (2016).
3. https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-738429.html.
4. Capmany, J. & Novak, D. Microwave photonics combines two worlds. *Nature Photon.* **1**, 319-330 (2007).
5. Smit, M. et al. An introduction to InP-based generic integration technology. *Sci. Technol*. **29**, 083001 (2014).
6. Lo, M., Zarzuelo, A., Guzman, R. & Carpintero, G. Monolithically integrated microwave frequency synthesizer on InP generic foundry platform. *Lightwave Technol*. **36**, 4626-4632 (2018).
7. Nagatsuma, T. THz communication systems. *In Optical Fiber Communication Conference (OFC 2017)*, Tu3B.1 (OSA, San Diego, 2017).
8. Jia, S., Yu, X., Hu, H., Yu, J., Guan, P., Ros, F. D., Galili, M., Morioka, T. & Oxenløwe, L. K. THz photonic wireless links with 16-QAM modulation in the 375-450 GHz band. *Express* **24**, 23777-23783 (2016).
9. Yu, X., Jia, S., Hu, H., Galili, M., Morioka, T., Jepsen, P. U. & Oxenløwe, L. K. 160 Gbit/s photonics wireless transmission in the 300-500 GHz band. *APL Photon*. **1**, 081301 (2016).
10. Pang, X., Jia, S., Ozolins, O., Yu, X., Hu, H., Marcon, L., Guan, P., Ros, F. D., Popov, S., Jacobsen, G., Galili, M., Morioka, T., Zibar, D. & Oxenløwe, L. K. 260 Gbit/s photonic-wireless link in the THz band. *In IEEE Photon. Conf. (IPC 2016)*, PD1-2 (IEEE, Hawaii, 2016).
11. Jia, S., Yu, X., Hu, H., Yu, J., Morioka, T., Jepsen, P. U. & Oxenløwe, L. K. 120 Gb/s multi-channel THz wireless transmission and THz receiver performance analysis," *IEEE Photon. Technol. Lett*. **29**, 310-313 (2017).
12. Li, X., Yu, J., Wang, K., Zhou, W. & Zhang, J. Photonics-aided 2 × 2 MIMO wireless terahertz-wave signal transmission system with optical polarization multiplexing. *Express* **25**, 33236-33242 (2017).
13. Jia, S., Lo, M., Zhang, L., Ozolins, O., Udalcovs, A., Kong, D., Pang, X., Yu, X., Xiao, S., Popov, S., Chen, J., Carpintero, G., Morioka, T., Hu, H. & Oxenløwe, L. K. Integrated dual-DFB laser for 408 GHz carrier generation enabling 131 Gbit/s wireless transmission over 10.7 meters. *In Optical Fiber Communication Conference (OFC 2019)*, Th1C.2 (OSA, San Diego, 2019).
14. Ma, J., Shrestha, R., Moeller, L. & Mittleman, D. M. Channel performance for indoor and outdoor terahertz wireless links. *APL Photon*. **3**, 051601 (2018).
15. Jia, S., Pang, X., Ozolins, O., Yu, X., Hu, H., Yu, J., Guan, P., Ros, F. D., Popov, S., Jacobsen, G., Galili, M., Morioka, T., Zibar, D. & Oxenløwe, L. K. 0.4 THz photonic-wireless link with 106 Gb/s single channel bitrate. *Lightw. Technol*. **36**, 610-616 (2018).
16. Nagatsuma, T., Oogimoto, K., Yasuda, Y., Fujita, Y., Inubushi, Y., Hisatake, S., Agoues, A. M. & Lopez, G. C. 300-GHz-band wireless transmission at 50 Gbit/s over 100 meters. *In 41st International Conference on Infrared, Millimeter, and Terahertz waves (IRMMW-THz 2016)*, 1-2 (IEEE Copenhagen 2016).

17. Harter, T., Füllner, C., Kemal, J. N., Ummethala, S., Brosi, M., Bründermann, E., Freude, W., Randel, S. & Christian Koos, C. 110-m THz wireless transmission at 100 Gbit/s using a Kramers-Kronig schottky barrier diode receiver. *In European Conference on Optical Communication (ECOC 2018)*, PDP 1-3 (IEEE, Rome, 2018).
18. Balakier, K., Fice, M. J., Dijk, F., Kervella, G., Carpintero, G., Seeds, A. J. & Renaud, C. C. Optical injection locking of monolithically integrated photonic source for generation of high purity signals above 100 GHz. *Express* **22**, 29404-29412 (2014).
19. Ishibashi, T., Muramoto, Y., Yoshimatsu, T. & Ito, H. Unitraveling-carrier photodiodes for terahertz applications. *IEEE J. Sel. Topics Quantum Electron*. **20**, 3804210 (2014).
20. Chang, D., Yu, F., Xiao, Z., Stojanovic, N., Hauske, F. N., Cai, Y., Xie, C., Li, L., Xu, X. & Xiong, Q. LDPC convolutional codes using layered decoding algorithm for high speed coherent optical transmission. *In Optical Fiber Communications Conference (OFC 2012)*, OW1H.4 (OSA, Los Angeles, 2012).
21. Agrell, E. & Secondini, M. Information-theoretic tools for optical communications engineers. *In IEEE Photonics Conference (IPC 2018)*, Invited Tutorial 1-5 (IEEE, Reston, VA, 2018).
22. Alvarado, A., Agrell, E., Lavery, D., Maher, R. & Bayvel, P. Replacing the soft-decision FEC limit paradigm in the design of optical communication systems. *Lightw. Technol*. **33**, 4338–4352 (2015).
23. Hu, H. et al. Single-source chip-based frequency comb enabling extreme parallel data transmission. *Nature Photon*. **12**, 469-473 (2018).

Figures

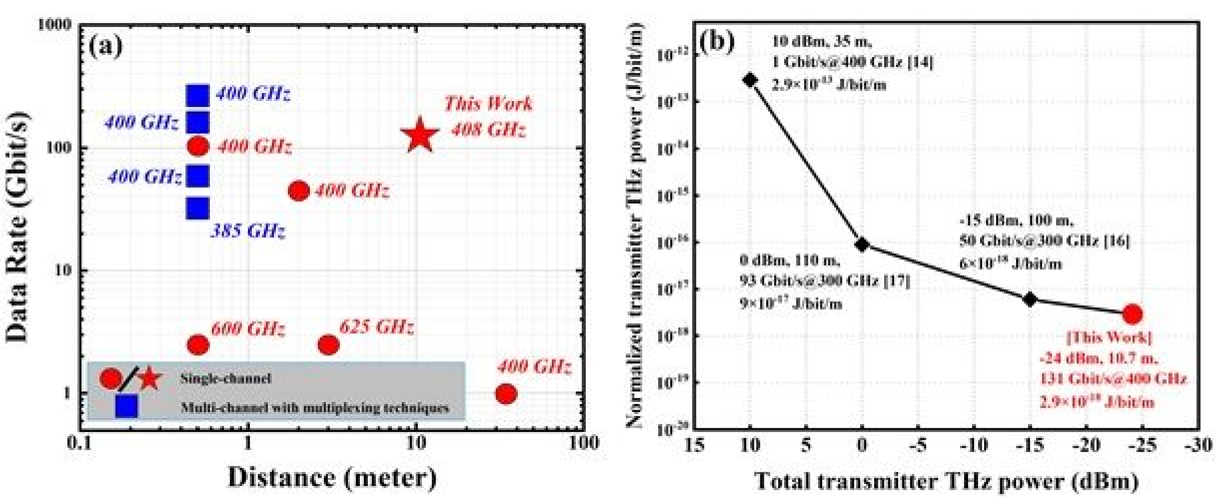

Figure 1

(a) State-of-the-art wireless bit rate vs. distance for frequencies above 350 GHz. (b) Comparison of normalized transmitter THz energy of the reported longest-reach demonstrations.

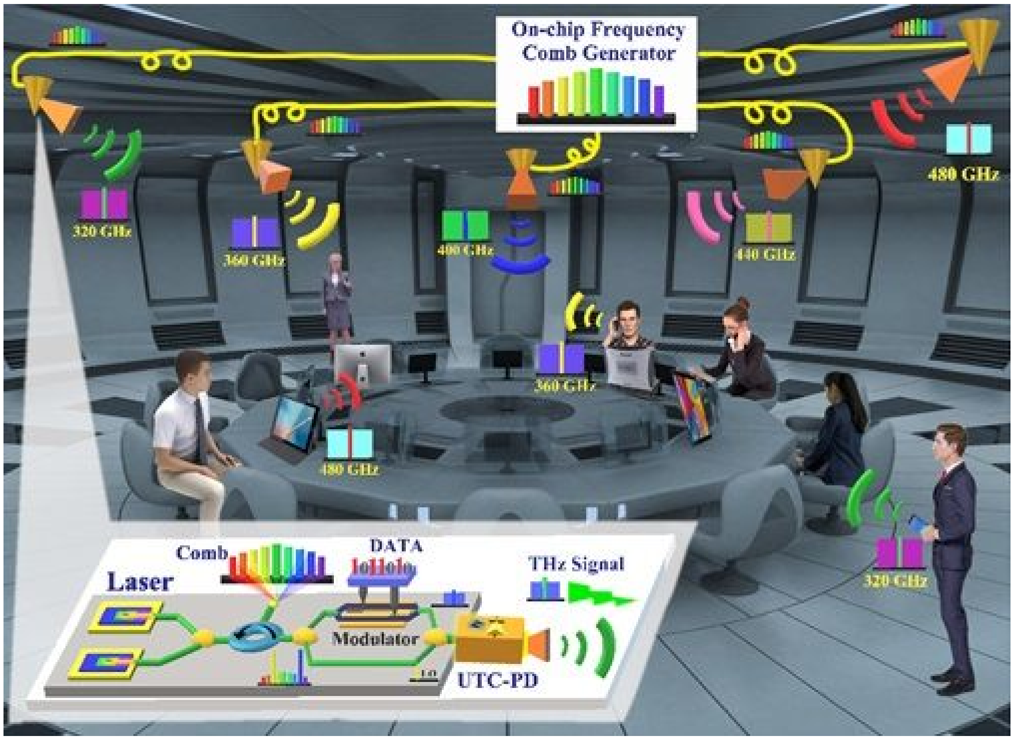

Figure 2

Vision of a THz frequency division multiplexed (FDM) high-speed wireless local area network (WLAN), which is based on fully integrated on-chip photonic-wireless THz transmitters injection locked by a frequency comb. The shared frequency comb is distributed to each integrated THz transmitter, consisting of dual-DFB lasers, data modulator, UTC-PD and THz antenna. LO: local oscillator; UTC-PD: uni-travelling carrier photodiode.

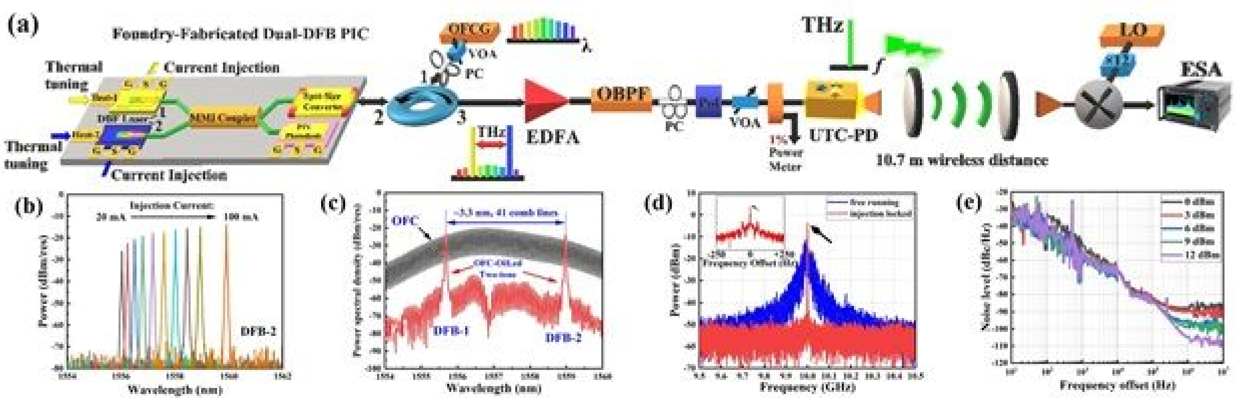

Figure 3

(a) Schematic of the experimental setup of THz carrier generation based on a master-slave optical injection-locking scheme. The OFCG as master injection-locks the two DFB lasers as slaves. VOA and PC control and optimize the injection strength and polarization state. The two-tone laser emission locked to the OFCG can be accessed at port 3 of the circulator. The wavelength and intensity of each DFB tone are controlled with the thermal tuning current for integrated heater and injection current. The OFCG-locked two-tone laser is amplified, band-pass filtered and optimized in polarization state prior to the UTC-PD. The two tones separated by 408 GHz are heterodyned on the UTC-PD and give rise to a 408-GHz wave. Propagating over 10.7 meters, the received 408-GHz is down-converted on the Schottky Barrier Diode (SBD) mixer with an electrical local oscillator. The collected IF signal is monitored on the ESA. (b) The DFB2 laser wavelength shifts from 1556 nm to 1560 nm and the intensity increases, as the injection current is varied from 20 mA to 100 mA. (c) DFB1 and DFB2 are set to 1555.375 nm and 1558.975 nm, respectively, and optically injection-locked to the MLL-based OFC. Within the 3.3 nm (408 GHz) wavelength separation 41 comb lines are covered whose comb spacing is 9.951 GHz. (d) The IF collected on the ESA. The blue trace shows the IF signal drifting around 10 GHz when the two DFB lasers are free running, not locked to the OFC. The red trace shows the IF signal at 10 GHz when both DFB lasers are optically injection-locked to the OFC. The locked tone is much narrower and 10 dB higher than the free-running tone. (e) The single sideband (SSB) phase noise versus different comb-injection powers. With a higher injection power, the SSB phase noise decreases, particularly in the region where the frequency offset from the carrier is greater than 100 kHz

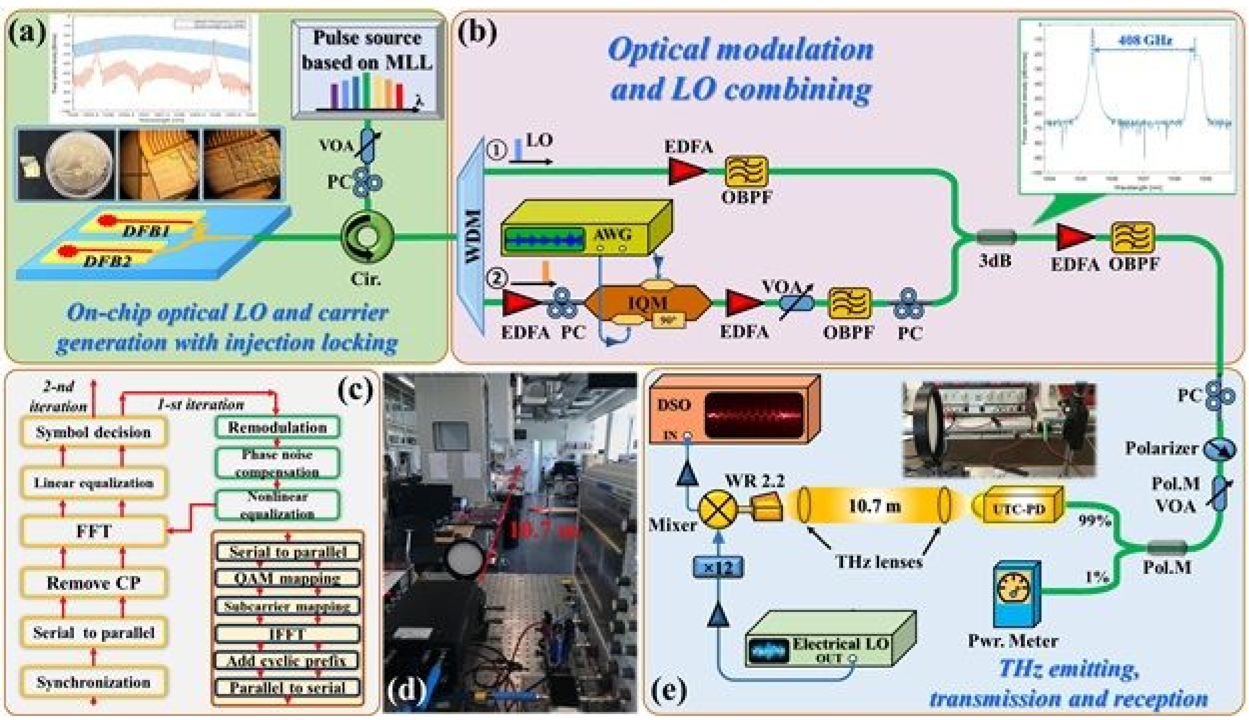

Figure 4

Experimental configuration of 131.21 Gbit/s single-channel photonic-wireless 16-QAM-OFDM transmission system over 10.7 m: (a) On-chip optical LO and carrier generation with injection locking. (b) Optical modulation and LO combining. (c) The structure of the DSP routine. (d) The picture of the actual THz link. (e) THz emitting, transmission and reception.

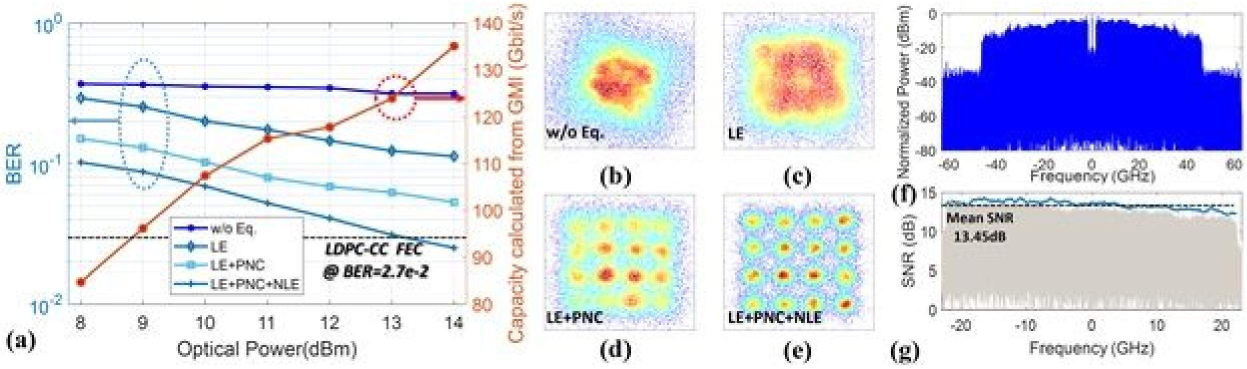

Figure 5

BER versus the optical power launched into the UTC-PD for 4 cases with different combinations of DSP modules. (b-e) Constellations for 4 cases with 14 dBm optical power and different combinations of DSP modules. (f) The electrical spectrum of the 16-QAM-OFDM signal before down conversion. (g) The SNR versus the frequency after down conversion.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformation.pdf