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Coherent THz communication at 200 GHz using a frequency comb, UTC-PD and electronic detection

G. Ducournau, Y. Yoshimizu, S. Hisatake, F. Pavanello, E. Peytavit, M. Zaknoue, T. Nagatsuma and J.-F. Lampin

A coherent terahertz (THz) link at 200 GHz, with a variable data rate up to 11 Gbit/s, featuring a very high sensitivity at the receiver, is investigated. The system uses a quasi-optic untravelling carrier photodiode (UTC-PD) emitter and an electronic receiver. The coherent link relies on an optical frequency comb generator at the emission to produce an optical beat note with 200 GHz separation, phase-locked with the receiver. Bit error ratio testing has been carried out using an indoor link configuration, and error-free operation is obtained up to 10 Gbit/s with a received power $< 2 \mu\text{W}$.

Introduction: To serve new services such as video on mobile terminals, the demand for bandwidth is growing every year, and new ways for wireless data transmission are being investigated. Terahertz (THz) communications are thus very promising [1] as their open a huge space for new high data-rate services. THz communications have been intensively studied over the past few years and systems are now emerging based on photonic and/or electronic technologies. Among these different systems, coherent THz links pave the way for high performances in terms of data rate and sensitivity at receiver circuits. For example, using photonics at the emission, Nagatsuma *et al.* [2] have achieved real-time coherent 100 GHz up to 11 Gbit/s and Li *et al.* [3] reported 200 Gbit/s in the W-band using off-line demodulation and signal processing. Above the W-band, Koenig *et al.* [4] reported very recently up to 100 Gbit/s for a 20 m link at 237.5 GHz, also using the off-line detection. At the electronic side (both at emission and reception), Antes *et al.* [5] achieved 30 Gbit/s at 240 GHz, using off-line processing. Future real-time THz coherent communication systems will require a locking between the transmitter (Tx) and the receiver (Rx) to suppress any residual frequency drift between Tx and Rx, downconverted into random amplitude modulation at the receiving mixer. For this reason, off-line detection can be used to overcome the locking problem, in order to highlight the intrinsic characteristics of the THz link. At the photonic side, a very convenient way to create the dual-tone optical signal is to use optical frequency combs, where the combs remain locked on a microwave reference. One of the key issues to realise coherent communication by photonics-based THz generation is the phase locking. In the proposed system, the phases of two optical sidebands extracted with an arrayed waveguide grating (AWG) have been locked to the optical frequency comb.

Experimental setup: The data link is described in Fig. 1.

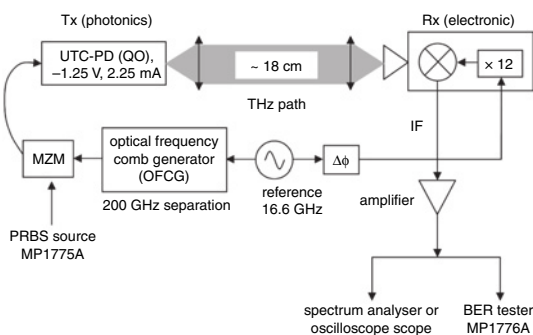


Fig. 1 Experimental setup of 200 GHz coherent data link

CW: continuous wave; $\Delta\phi$: fixed electrical phase shifter

Transmitter description: The system is first composed of the optical frequency comb generator (OFCG), described in Fig. 2. The phase of a single frequency continuous-wave (CW) laser is modulated with cascaded optical phase modulators to generate the OFC. The modulation frequency was 16.6 GHz. Dual-optical carriers with 200 GHz frequency separation are extracted with an AWG filter. The phases of the two optical carriers fluctuate independently due to temperature fluctuations and acoustic noise in the optical fibre cables between the AWG filter and the optical coupler. The coherence of the THz wave to be generated as a carrier for the wireless link is dependent on the stability of the phase

differences between the optical carriers. In our system, the phases of the two carriers are locked to that of the OFC to generate a coherent THz wave, the spectrum of which is given in Fig. 3. Details of the phase stabilisation system are described in [6, 7].

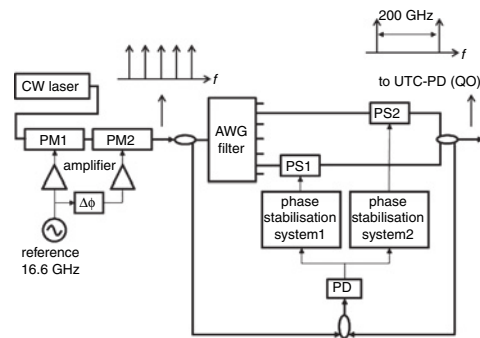


Fig. 2 OFCG details

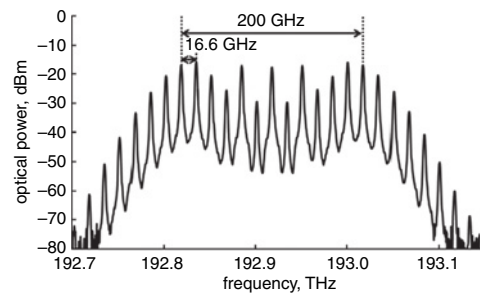


Fig. 3 Optical spectra obtained at OFCG output

The dual-optical signal is then modulated by a Mach-Zehnder amplitude modulator with a variable data rate up to 11 Gbit/s amplified with an erbium-doped fibre amplifier and feeds a quasi-optic untravelling carrier photodiode (UTC-PD) module, as shown in Fig. 4a. This UTC-PD has a 0.2 A/W responsivity, and is integrated with a log-periodic antenna. First, the quasi-optic UTC-PD module was power calibrated in free space using an Erickson PM4. Using a 1 mA photocurrent, the modulated THz signal emitted power was found to be around $3 \mu\text{W}$ (-25 dBm) at 200 GHz and $1.5 \mu\text{W}$ with a 0.7 mA photocurrent. The THz path was composed of two polymer lenses. This THz path was preliminarily tested using a quasi-optical vector network analyser (VNA), leading to THz losses of $\sim 3 \text{ dB}$ at 200 GHz frequency. However, it is worth mentioning that this value just estimates the losses as the first lens was fed by a waveguide horn antenna during the VNA experiment and was fed by the integrated silicon lens during the data transmission experiments.

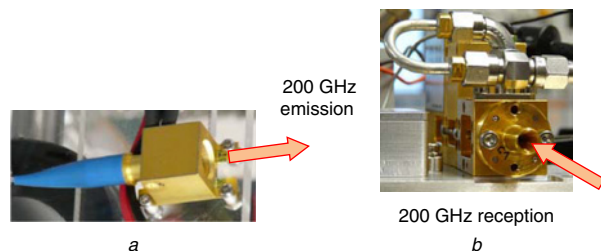


Fig. 4 Views of quasi-optic UTC-PD module and electronic receiver, working at 200 GHz

a Quasi-optic UTC-PD module

b Electronic receiver, working at 200 GHz

Receiver description: The receiver is first composed of a WR5.1 waveguide corrugated horn (Fig. 4b). The detected signal feeds a sub-harmonic mixer (SHM), pumped with a local oscillator at 100 GHz. This SHM exhibits 8 dB conversion losses at 200 GHz. The intermediate frequency (IF) signal is then amplified with a wideband amplifier (33 dB gain). When the optical beat note is controlled with the phase stabilisation system, the 200 GHz carrier is phase-locked to the

reference synthesiser. At the receiver side, the mixing produced is centred at DC as long as the carrier frequency remains in phase with the local oscillator. Under these conditions, the baseband data are recovered, and a limiting amplifier is used before eye diagrams display or bit error ratio (BER) measurements.

Results: In the experiment, the coherent operation was obtained using the same reference to feed the comb generator and the receiver circuits. This enables one to address easily the real-time capability of the THz link, without off-line data processing. Indeed, we succeed to realise true BER testing using the combination of the MP1775A tester (Anritsu) for pseudorandom binary sequence (PRBS) generation and the MP1776A (Anritsu) for BER measurement with 2^{15} -1 bit sequences, up to 11 Gbit/s. Up to 10 Gbit/s data rate, the slope of the BER curves is similar for the different tested data rates, as shown in Fig. 5. Moreover, an ~ 3 dB penalty was obtained when increasing the data rate from 5 to 10 Gbit/s. Indeed, an increase of the data rate by a factor of 2 while keeping the signal constant should decrease the signal-to-noise ratio by ~ 3 dB. The error-free operation (defined here for $\text{BER} < 10^{-11}$) is obtained at 5 Gbit/s for 0.7 mA in the UTC-PD, corresponding to a $1.5 \mu\text{W}$ power at the UTC-PD output. This should correspond to $\sim 0.75 \mu\text{W}$ (~ -30 dBm) received power. For 10 Gbit/s, the error-free operation was obtained with 1 mA photocurrent in the UTC-PD, corresponding to ~ -28 dBm received power.

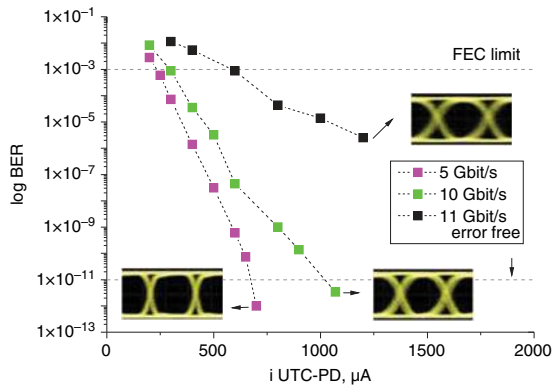


Fig. 5 BER characteristics, using 11 Gbit/s limiting amplifier
Inset: Eye diagrams for highest photocurrents tested

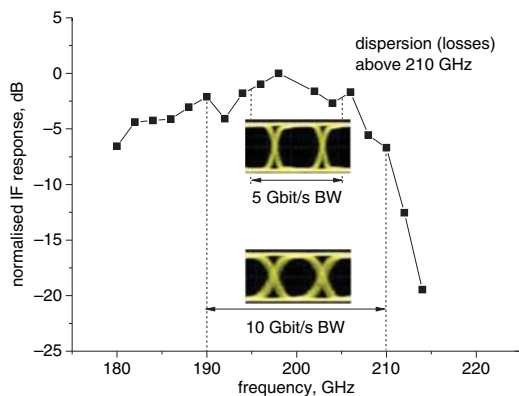


Fig. 6 Frequency response of heterodyne receiver including IF wideband amplifier

The BER curve obtained for the 11 Gbit/s data rate presented a reduced slope, and the achieved BER performance was limited to few 10^{-6} . We assume that this comes from the limited bandwidth available at the heterodyne receiver. To verify this assumption, a frequency response of the receiving mixer was carried out. In this experiment, the mixer was tested under waveguide conditions using a continuous-wave source coming from a VNA, and the frequency was tuned between 180 and 220 GHz. Fig. 6 presents the results. From this

curve, a 20 GHz bandwidth ± 10 GHz around the carrier frequency) enables an up to 10 Gbit/s error-free operation. For higher data rates, a very large amount of amplitude distortion affects the receiver, which is highlighted in Fig. 6 by an increase of the conversion losses (decreasing IF response). For that reason, the eye diagrams beyond 10 Gbit/s were degraded and the BER performance was limited. In our last experiment, an uncompressed high-definition television data stream (1.5 Gbit/s) was used to test the system with real applicative signals, and the stable operation (error-free video transmission) was obtained up to 0.6 mA photocurrent, corresponding to ~ 500 nW received power.

Conclusion: A coherent transmission system was demonstrated at 200 GHz, using a photonics-based emission, and featuring a very low power requirement at the reception. Error-free operation was obtained up to 10 Gbit/s data rates, with a limitation due to the receiver bandwidth, not by the comb or the UTC-PD transmitter. Next steps will concern high distance transmission using powerful photomixers at the emission. Moreover, in a future outdoor THz coherent scheme application, locking on the global positioning system (GPS) will lead to a common reference between Tx and Rx, avoiding the need for the common reference used here.

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One or more of the Figures in this Letter are available in colour online.

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