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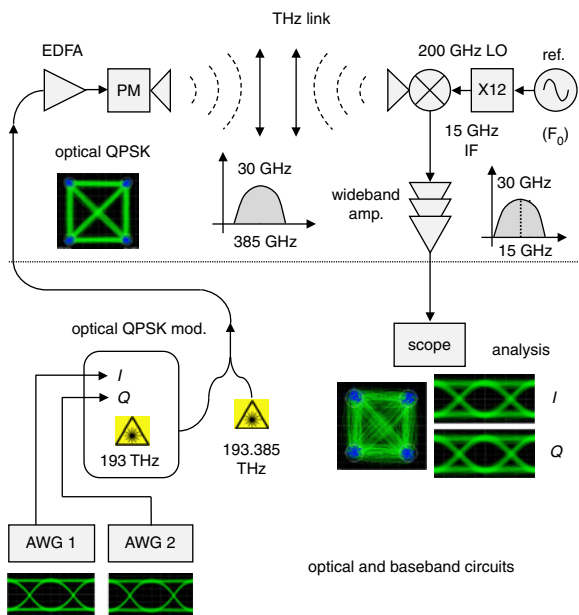
# 32 Gbit/s QPSK transmission at 385 GHz using coherent fibre-optic technologies and THz double heterodyne detection

G. Ducournau<sup>✉</sup>, K. Engenhardt, P. Szriftgiser, D. Bacquet, M. Zaknoue, R. Kassi, E. Lecomte and J.-F. Lampin

The first quadrature phase shift keying (QPSK) data link at 385 GHz, using a photonic-based terahertz (THz) emission and a double heterodyne THz detection, is reported. The QPSK signalling is investigated up to 16 Gbaud (32 Gbit/s) on a short range distance, with 20  $\mu$ W received power levels.

**Introduction:** Over the last five years, the continuously growing demand for data rates is pushing up the performance of terahertz (THz) devices and systems. Such technologies are strongly envisaged for communication applications [1]. Among the different systems already reported, the highest performances have been obtained using a combination of photonics at emission and electronic receivers [2]. As the THz bandwidth is large, the use of simple amplitude modulation schemes can easily lead to up to >40 Gbit/s data rates [3, 4]. However, such schemes are already challenged by higher spectral efficiency (bit/s/Hz) links using quadrature phase shift keying (QPSK) or PSK-8 modulation formats and also with a required compatibility of the THz links with other services [5]. In this Letter, we present the first THz link using QPSK signalling in the sub-millimetre range with data rates of several 10 Gbit/s. Such link, associated with the development of coherent data optic fibre links in metro networks, could be used as a direct converter of a guided optical QPSK into a THz radio, for very high data rate indoor applications.

**Description of THz link:** Fig. 1 shows a general overview of the experimental setup, showing the details of the photonic-based THz emitter, THz link and electronic receiver.

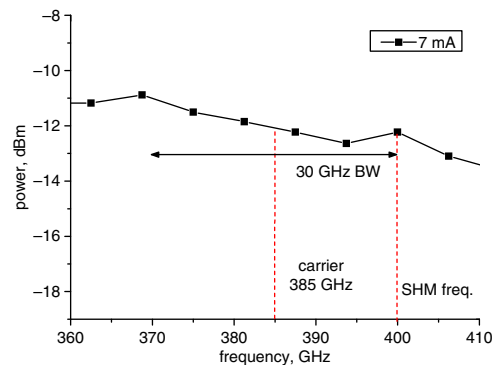


**Fig. 1** General overview of THz link  
PM is the photomixer

The system is first composed of a fibre-optic based Tx designed for QPSK signalling over wavelength division multiplexing optical carriers. One C-band channel (193 THz) was modulated in optical QPSK using a dual nested Mach-Zehnder configuration. Two arbitrary waveform generators (AWGs) were used to create two baseband non-return-to-zero data signals: the in-phase ( $I$ ) and quadrature-phase ( $Q$ ) signal. These signals were generated using a digital Gaussian filtering of 0.65 with the AWG to optimise the size of the spectrum.

Once the QPSK is created in the optical domain, a second continuous-wave (CW) optical tone is added, with a frequency separation of 385 GHz. These two optical signals are amplified using an erbium-doped fibre amplifier, and feed a uni-travelling-carrier photodiode,

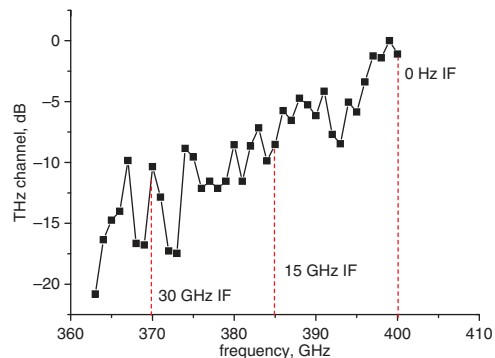
integrated in the waveguide. The DC response of the photomixer (PM) is 0.2 A/W, and the PM is operated within its linear regime as QPSK signalling is investigated rather than standard amplitude modulation schemes. Fig. 2 plots the output power capability of the PM for a 7 mA current, showing a carrier (385 GHz) power (without modulation) of  $-12$  dBm at the transmitter output. The used bandwidth is indicated in the graph, showing the effective used bandwidth ( $\sim 30$  GHz) during the experiment for the highest data rate tested.



**Fig. 2** Output power (measured in waveguide) of photomixer used in experiment

The THz signal is then collimated using a first 25 mm diameter polymer lens. After direct propagation over 0.4 m, a second lens focuses the radiation inside an electronic receiver composed of a sub-harmonic mixer, integrated in the WR2.2 (325–500 GHz) waveguide, driven at 200 GHz (mW level source) to operate at 400 GHz. Assuming the 385 GHz carrier frequency, this produces an intermediate frequency (IF) signal at microwave frequencies (15 GHz). A wideband amplifier is then used to amplify the signal before real-time oscilloscope detection. The total gain used at the Rx side, including the SHM losses and the ‘base band’ wideband amplifier gain, was 2 dB.

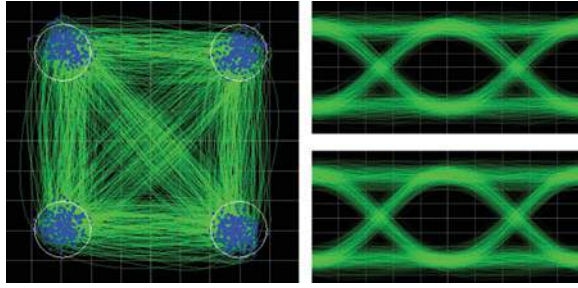
Fig. 3 shows the THz channel response, measured with a CW THz tone, adjusted from 360 to 400 GHz. The minimal losses found were around the IF minimum frequency due to SHM pumping (200 GHz). Around 10 dB differential losses are affecting the signal over the 30 GHz total modulation bandwidth (16 Gbaud filtered QPSK signal).



**Fig. 3** THz channel response around carrier frequency (SHM receiver is pumped at 200 GHz in order to operate at 400 GHz)

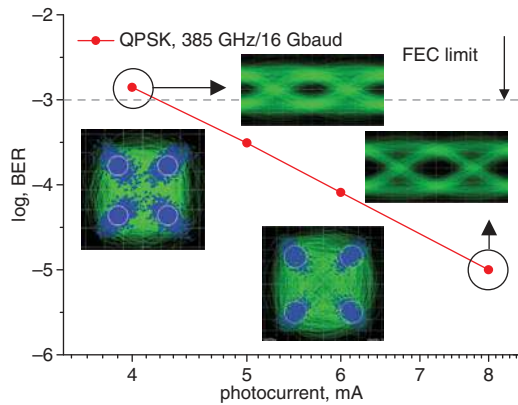
This IF signal is then measured using a real-time scope (33 GHz bandwidth), and real-time analysis (second heterodyne detection) is processed on the data to plot constellations, eye diagrams and bit error rate (BER) analysis using sufficient long time sequences. Different  $I$  and  $Q$  pseudo-random binary sequences lengths were used ( $2^7-1$  for  $I$  and  $2^9-1$  for  $Q$ ) to keep the arbitrary behaviour between  $I$  and  $Q$  tributary channels and ensure a proper signal recovery at the receiver.

The system was first operated using limited data symbol rates in order to optimise the modulation parameters and THz channel parameters. An example of constellation is given in Fig. 4 for a 2.5 Gbaud QPSK, with a 7.7 mA at the Tx. In that case,  $\sim 70$   $\mu$ W output power was used at the Tx side and around 20  $\mu$ W at the reception (input WR2.2 horn). This was obtained by measuring the losses of the quasi-optic link ( $S_{21}$ ) using a quasi-optic vector network analyser in the 325–500 GHz range.



**Fig. 4** 385 GHz QPSK link evaluation at 2.5 Gbaud (5 Gbit/s) using raised-cosine filter (0.9 normalised bandwidth) and 7.7 mA photocurrent in Tx (in that case, transmission is error free)

**Vectorial transmission:** After validation of the QPSK error-free operation at 2.5 Gbaud, the system has been driven up to 16 Gbaud symbol rate. The highest data symbol rate tested was 16 Gbaud (32 Gbit/s), and the associated results are displayed in Fig. 5. The detection was realised by analysing time sequences long enough, in respect to the BER performance, as given in Table 1. The BER performances obtained are measured using long time sequences, depending on the BER level. The BER values found are compatible with forward error correction (FEC) processes [6] for  $I > 5$  mA photocurrents.



**Fig. 5** BER curves measured for 16 Gbaud (32 Gbit/s) QPSK signal (0.65 Gaussian filtering)

Insets show the constellation diagrams (blue points: sampling points) and eye diagrams

**Table 1:** BER measurements, number of bits analysed and corresponding time lengths for 16 Gbaud (32 Gbit/s)

$I$ (mA)	BER	Number of bits analysed	Time length ( $\mu$ s)
4	$1.4 \times 10^{-3}$	101 888	3.18
5	$3.17 \times 10^{-4}$	324 768	10.1
6	$8.15 \times 10^{-5}$	503 072	15.7
8	$1 \times 10^{-5}$	1 006 144	31.4

**Analysis:** The clear QPSK constellations results (blue points correspond to decision point) confirm that the vectorial QPSK nature is conserved in the optical to THz conversion, as expected. At 32 Gbit/s, the detection gives a  $10^{-5}$  BER value for the highest tested current (8 mA), corresponding to a  $-11$  dBm THz power. Owing to the wideband amplifier and limited available total gain at the Rx (2 dB), some noise is affecting

the eye diagram. Further work will address the receiver optimisation on noise and total gain to reach point-to-point links over higher distances.

**Conclusion:** A 385 GHz vectorial wireless link has been presented, using a combination of photonic and electronic THz devices, associated with coherent optical QPSK emission. Up to QPSK/16 Gbaud data signalling has been investigated and 32 Gbit/s data rates compatible with standard FEC limits. With the huge developments of coherent optical networks [7], such architectures could be very interesting to deploy optical-to-THz radio bridges for future access networks and network convergence.

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

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