# 110-m THz Wireless Transmission at 100 Gbit/s Using a Kramers-Kronig Schottky Barrier Diode Receiver

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**Abstract** We demonstrate wireless transmission of QPSK signals at a carrier frequency of 0.3 THz using a generalized Kramers-Kronig receiver with a Schottky barrier diode. We achieve a line rate of 100 Gbit/s over a transmission distance of 110 m.

## Introduction

The incessant increase of mobile data traffic [1] requires new approaches to high-speed wireless communications. High carrier frequencies near 0.3 THz are particularly promising due to the large available bandwidth and the small atmospheric loss [2]. Line rates of 100 Gbit/s and beyond [3]–[6] have already been demonstrated over distances of 2 cm up to 20 m, using complex modulation formats and coherent receivers (Rx) that include costly electronic mixers and electronic local oscillators (LO). The Rx complexity can be drastically reduced if mixer circuits are replaced by a single Schottky barrier diode (SBD) [7]. This approach has led to line rates of 50 Gbit/s transmitted over 50 m using simple intensity modulation (on-off keying) [7]. For advanced modulation formats, self-coherent systems can be used, exploiting a local oscillator (LO) tone that is transmitted along with the data signal [8]. These schemes have led to line rates up to 59 Gbit/s at a transmission distance of 5 cm [8]. To avoid signal-to-signal beat interference (SSBI) at the self-coherent Rx, the LO frequency can be separated from the data spectrum by more than the double-sided signal bandwidth, which comes at expense of a reduced spectral efficiency. This limitation has been overcome in optical communications by employing the Kramers-Kronig (KK) receiver, which allows to recover amplitude and phase of the data signal in the presence of SSBI [9]. It has been proposed to transfer this concept to THz communications [10]. However, experimental demonstrations so far relied on a digital emulation of a SBD, assuming an idealized quadratic characteristic [10].

In this paper, we demonstrate wireless THz transmission using a KK scheme with a real SBD at the receiver. Our experiments show that the assumption of an ideal quadratic characteristic is insufficient to describe the behaviour of the SBD. Based on this finding, we develop a generalized KK algorithm and account for the exponential-like characteristic of the device. The viability of the approach is confirmed by transmitting a 100-Gbit/s quadrature phase-shift keying (QPSK) signal over a distance of 110 m. To the best of our knowledge, this is the first hardware implementation of a KK receiver in a wireless link, leading to the highest line rate and at the same time the highest transmission distance achieved so far with an SBD as THz detector.

## Experimental setup

The experimental setup is depicted in Fig. 1(a). The THz signal is generated by down-conversion of optical signals using a high-speed uni-travelling-carrier photodiode (UTC - PD) [11] as a photomixer. For KK reception, the transmitted THz signal comprises a strong local oscillator (LO) tone right at the edge of the data signal spectrum. The optical QPSK signal is generated by modulating an optical carrier with frequency $f_0$ in an IQ-modulator that is operated by an arbitrary-waveform generator (AWG). This data signal is then superimposed by two unmodulated carriers at $f_0 - f_{LO}$ and $f_0 - f_{THz}$. The resulting optical spectrum is shown in the inset of Fig. 1(a). The frequency $f_{LO}$ is chosen to coincide with the low-frequency edge of the data spectrum. The carrier-to-signal power ratio (CSPR) is adjusted by varying the gain of the EDFA, see Fig. 1(a). Down-conversion in the UTC-PD then leads to a single-sideband THz data signal spectrum centered at a frequency $f_{THz}$ along with a LO line at its low-frequency edge. The converted THz signal is boosted by a 15-dB amplifier and radiated to free space using a horn antenna and a subsequent collimation lens.

After a transmission distance of 110 m, the THz signal is focused to the receiver with a second lens and a horn antenna. The THz transmission loss is partially compensated in a 24-dB low-noise amplifier. A SBD converts the THz signal to

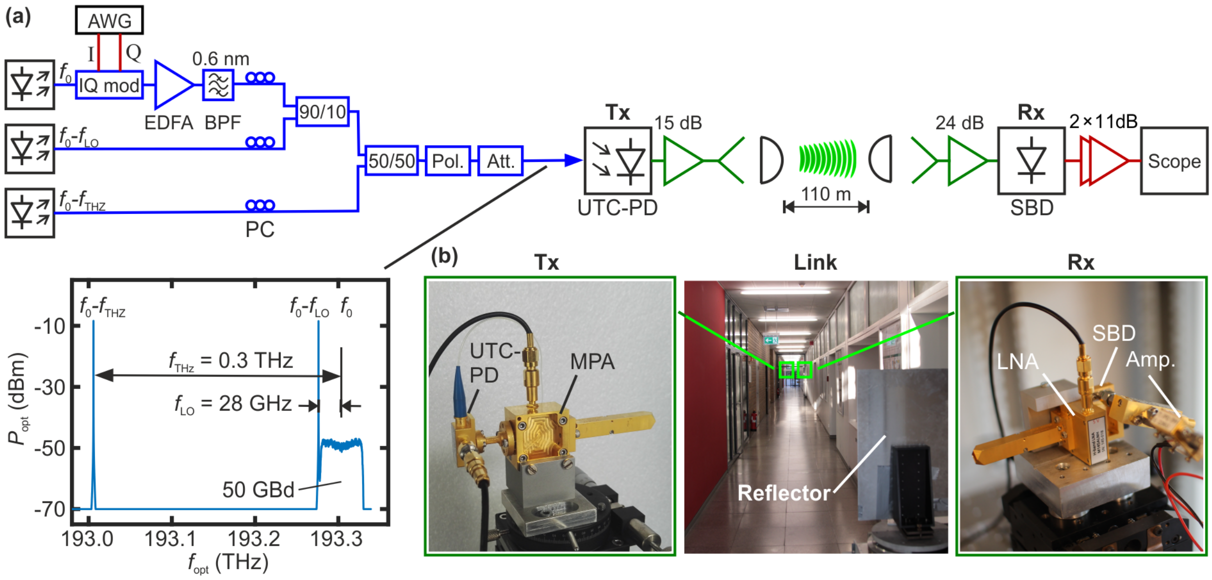


**Figure 1** Experimental setup. AWG: Arbitrary waveform generator. EDFA: Erbium-doped fiber amplifier. BPF: Optical bandpass filter. **(a)** The data signal is IQ-modulated on an optical carrier with frequency $f_0$ and converted to the THz domain by mixing with an unmodulated carrier $f_0 - f_{THz}$ in a high-speed uni-travelling carrier photodiode (UTC-PD). The inset shows the optical spectrum (RBW = 180 MHz) before the UTC-PD. The unmodulated carrier $f_0 - f_{LO}$ to the left of the data spectrum acts, after mixing with the optical carrier $f_0 - f_{THz}$, as a THz local oscillator (LO) at the Rx. A horn antenna/lens combination transmits and receives the THz signals over a distance of 110 m. After a 24 dB THz amplifier a Schottky barrier diode (SBD) receives the THz signal and converts it to an RF signal. A real-time oscilloscope captures the RF signal for off-line processing. **(b)** Image of the transmission link. A mid-way reflector doubles the transmission distance. Details of the Tx and Rx (focusing lenses not visible) are shown in the left and right image, respectively.

a single-sideband RF signal which is amplified by two concatenated 11-dB amplifiers and captured with a real-time oscilloscope.

Figure 1(b) shows photographs of the Tx, Rx and the transmission link. For doubling the distance of 55 m available in our building, a metal plate reflects the beam from the Tx back to the Rx, which is positioned side by side with the Tx. No Tx-Rx cross-talk can be observed.

In the digital domain, we reconstruct the complex-valued electric THz field represented by a complex voltage amplitude $u$. The measured SBD output current is $i = g(|u|)$. The usual assumption of a quadratic detector means $i \sim |u|^2$. A more realistic approximation of a SBD characteristic would be the exponential $i \sim \exp(\mathrm{a}\,|u|)$ with $\mathrm{a}$ being a constant. By applying the KK relation we find from the amplitude the associated phase $\varphi$

$$\varphi(t) = P\left\{\frac{1}{\pi t} * \ln\left[g^{-1}(i)\right]\right\}, \qquad (1)$$

where $*$ denotes the convolution operator, $g^{-1}$ is the inverse function of $g$, and $P\{\cdot\}$ stands for the Cauchy principal value. The amplifier following the SBD is AC coupled. Therefore the DC signal component is added digitally for proper KK processing. Because $\ln\left[g^{-1}(i)\right]$ is a nonlinear function, $i$ must be oversampled (in our case with 6 Sa/symbol) to prevent aliasing-induced errors. After signal reconstruction, we remove the DC offset, shift the QPSK signal to the baseband and down-sample to 2 Sa/symbol. The KK receiver DSP block is followed by a conventional single-carrier, single-polarization coherent DSP including timing recovery, digital equalization and carrier recovery.

## Experimental results

The experimental results are summarized in Fig. 2. We transmit QPSK symbols at a symbol rate of 50 GBd leading to a line rate of 100 Gbit/s. Figure 2(a) shows how the bit error ratio (BER) is influenced by the CSPR if the total optical power at the UTC-PD input is kept constant at 11.6 mW. Without KK processing (w/o KK) using conventional heterodyne reception, the BER decreases for a larger CSPR, because the signal-signal mixing term becomes less important. If the CSPR increases, the signal power decreases when keeping the total THz power constant, and the BER becomes larger at high CSPR. The optimum CSPR is in the order of 13.7 dB. Note that the CSPR is measured in the optical domain. The actually CSPR in the THz domain might be slightly different due to the frequency response of the UTC-PD and the amplifier afterwards.

With conventional KK processing and assuming $g(|u|) \sim |u|^2$ (quadratic KK), the BER does not improve in comparison to conventional hetero-

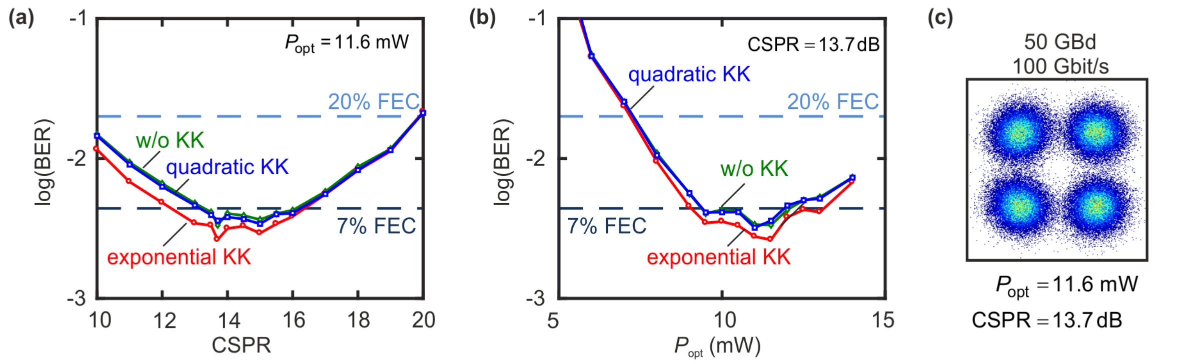


**Figure 2** Experimental results. **(a)** Bit error ratio (BER) as a function of the optical carrier-to-signal power ratio (CSPR) in front of the UTC-PD. The curve "w/o" KK" indicates a conventional heterodyne reception of the RF SBD output where signal-to-signal interference increases the BER. The curve marked "quadratic KK" stands for KK reception and assumes a quadratic dependence between THz field and the SBD current, while the label "exponential KK" assumes an exponential dependence. Obviously, a quadratic model is not an appropriate description of the SBD. **(b)** BER as a function of the optical power at the input $P_{opt}$ of the UTC-PD for the evaluation methods of Fig. 2(a). **(c)** Constellation diagram of the 100 Gbit/s QPSK signal. A BER below the 7 % FEC limit is achieved.

dyne reception. In contrast to that, if the more realistic characteristic $g(|u|) \sim \exp(\mathrm{a}|u|)$ (exponential KK) is chosen, the BER reduces for low CSPR values. We hence conclude that KK schemes are only effective if the characteristic of the nonlinear Rx element is properly described. We expect that with an even more realistic, precisely measured SBD nonlinear characteristic, the BER can be reduced further. This approach is subject to ongoing research.

Figure 2(b) shows the BER for different total optical input powers at the UTC-PD, leading to different total THz powers. The CSPR was kept constant at 13.7 dB while splitting the optical power equally between the line at $f_0$-$f_{THz}$ and the LO line at $f_0$-$f_{LO}$ together with the data signal. As expected, the BER initially decreases for larger optical powers. For very large optical powers, the BER increases due to amplifier saturation. Figure 2(c) shows the constellation diagram of a 50-GBd QPSK signal after a transmission distance of 110 m and exponential KK processing. The BER amounts to $2.6\times10^{-3}$ which is below the limit for an FEC with a 7 % overhead ($4.4\times10^{-3}$). To the best of our knowledge, this is the highest line rate demonstrated with an SBD receiver so far. Moreover, the transmission over 110 m corresponds to the largest distance so far demonstrated for a 100-Gbit/s wireless signal.

## Summary

We transmit a 100-Gbit/s QPSK signal at a carrier frequency of 0.3 THz over a distance of 110 m and receive it with a Schottky barrier diode (SBD). We employ a generalized Kramers-Kronig algorithm adapted for the exponential characteristic of the detector, achieving a BER below the 7% FEC limit. To the best of our knowledge, this is the first demonstration of a KK receiver hardware frontend in a wireless communication link leading to the highest line rate achieved so far with a SBD THz receiver.


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