All-Photonic Heterodyne sub-THz Wireless Transmission at 80 GHz, 120 GHz and 160 GHz Carrier Frequencies

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***Abstract*— We experimentally demonstrate a heterodyne communication link using a p-i-n photodiode and a photoconductor coupled to THz antennas without bandwidth-limiting electronic components. As a proof-of-concept, a 100 Mbit/s BPSK stream is successfully transmitted at three different channels, spaced by 40 GHz, down-converting the wireless carrier to an intermediate frequency of 3.7 GHz. Optical frequency combs are employed for sub-THz generation and down-mixing to reduce the phase noise of the system.**

I. INTRODUCTION

THz communications based on photonics offer sufficient bandwidth and flexibility to reach the capacity demands of future wireless links [1]. However, current realizations of THz communication links still rely on components such as power amplifiers, horn antennas, and electronic receivers [1]. Although these devices are usually needed to overcome the restricted power budget at these frequency bands, they prevent photonics-based systems from exploiting the full potential of the THz range. The future of bidirectional ultra-high capacity THz communications is therefore linked to optoelectronic techniques at both ends of the communication link, potentially achieving modulation bandwidths of several gigahertz, tuning ranges for the wireless carrier above one hundred gigahertz as well as the flexibility to multiplex several channels in frequency.

Some recent works have demonstrated communication links using optoelectronic means for heterodyne down-conversion, making a significant step towards realizing full-photonic-based systems [2,3]. They employed waveguided amplifiers and horn antennas to increase the radiated power. However, an experimental demonstration of a system covering a wide range of the THz spectrum, without any restriction imposed by electronics, is still missing, mainly due to power limitations. Nevertheless, current THz optoelectronic technology already allows the implementation of short-range point-to-point links for a wide range of applications like wireless local area networks, data centers, and intra-device communications.

II. EXPERIMENTAL SETUP AND RESULTS

The proposed system is shown in Fig. 1, and it is based on a pair of continuous-wave (CW) THz photomixers that operate at telecom wavelengths. The transmitter is a p-i-n photodiode attached to a THz antenna, while the receiver is a photoconductive antenna [4]. The optical signals used for photomixing are extracted from two different optical frequency combs (OFCs). Therefore, the phase noise and frequency stability of the two resulting beat signals are adequate to transmit modulation formats carrying information in phase. Using free-running lasers would result in a considerably noisier output signal that cannot be demodulated or requires time-consuming data processing algorithms for equalization.

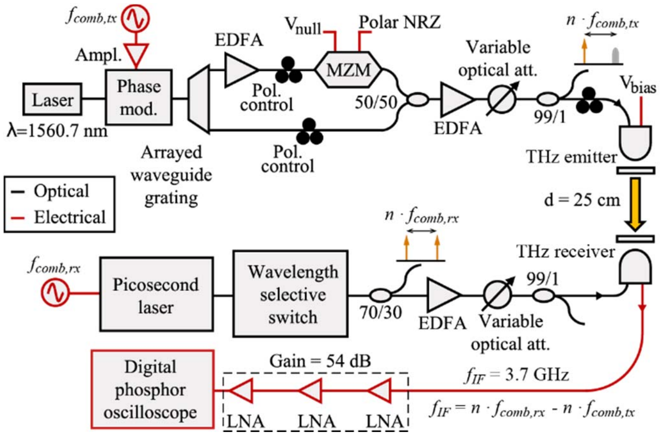

Fig. 1. Schematic of the experimental setup for an all-photonic heterodyne sub-THz wireless transmission.

On the transmitter side, the comb is generated with an optical phase modulator driven by a high-power oscillator with frequency $f_{comb,tx}$. This reference signal sets the repetition rate of the OFC within the range (30 – 40 GHz), restricted by the bandwidth of the driver amplifier. The two optical components needed for photomixing are filtered and separated by an optical demultiplexer. One of the tones is amplified and modulated with a Mach-Zehnder modulator (MZM) biased at the null point of its transmission function to reduce the power of the optical carrier and increase the modulation-to-noise relation. A 100 Mbit/s polar non-return-to-zero (NRZ) signal serves as a modulation waveform, producing an optical binary phase-shift keying (BPSK) signal at the output of the modulator. The second tone stays unmodulated, and a polarization controller changes its polarization to optimize the power conversion after photomixing. Then, the two components are coupled back with a 3-dB optical coupler. The frequency difference between these two signals determines the wireless carrier (f_c). Finally, an erbium-doped fiber amplifier (EDFA) sets the maximum optical power available for sub-THz generation to 30 mW (≈15 dBm). This is the optimum value according to the transmitter specifications. Finally, a variable optical attenuator (VOA) is added for bit error rate (BER) measurements.

On the receiver side, a mode-locked laser (MLL) provides a broadband OFC with a repetition rate, $f_{comb,rx}$, that can be fine-tuned around 40 GHz. In this case, a wavelength selective switch allows the filtering of the two intended components without using separate optical fibers. Again, an EDFA sets the power of the optical signal incident on the photoconductor to 30 mW. The beat frequency of the receiver system defines the local oscillator frequency of the heterodyne down-converter. After the wireless transmission over a distance of 25 cm, using a couple of Teflon lenses to collimate the radiation, the signal is down-converted. The intermediate frequency, f_{IF}, is

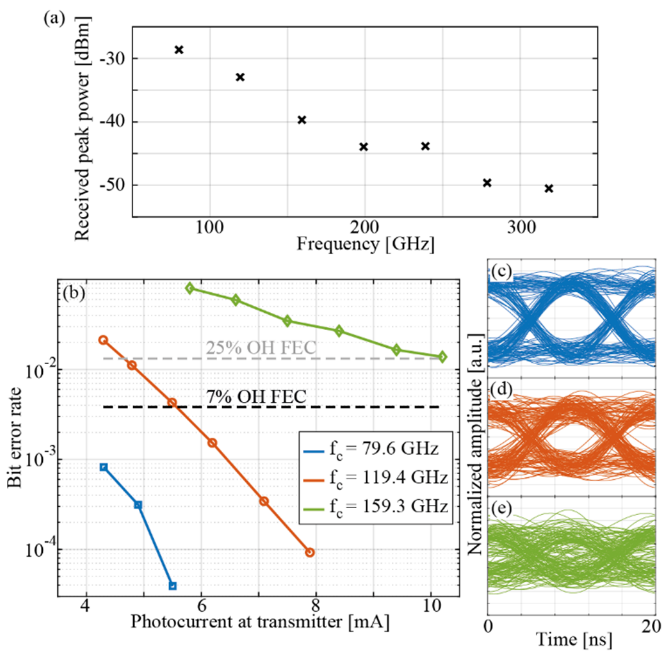

Fig. 2. Experiment results: (a) sub-THz spectrum, (b) bit error rate curves and eye diagrams when the photocurrent at the transmitter is 10.2 mA and the wireless carrier is (c) 79.6 GHz, (d) 119.4 GHz and (e) 159.3 GHz.

determined by the difference between the repetition rate between the two combs, so that $f_{IF} = n{\cdot}f_{comb,rx} - n{\cdot}f_{comb,tx}$, where n is an integer. An intermediate frequency of 3.7 GHz with a modulation bandwidth of around 200 MHz is chosen for this demonstration. These values are restricted by the electrostatic discharge protection circuit of the THz receiver. After down-conversion, three cascaded low noise amplifiers (LNAs) provide a total gain of 54 dB, and a digital phosphor oscilloscope (DPO) captures the signal for off-line processing.

First, a CW signal without modulation is transmitted and detected at seven wireless carriers from 80 GHz to 320 GHz in 40 GHz steps. The power of the detected intermediate frequency signal is plotted in Fig. 2(a). The shape of the curve agrees with the power profile of the THz transmitter and the free-space transmission loss. The power varies 22 dB from 80 GHz to 320 GHz. A power slightly below -50 dBm is measured in the last point, corresponding to a signal-to-noise ratio (SNR) of 22.2 dB. When the BPSK modulation was added, the SNR of the received signal was enough to demodulate the data in the first three cases: 80 GHz, 120 GHz, and 160 GHz. The off-line demodulation algorithm only incorporates digital filtering and a Costas Loop for carrier recovery, without additional equalization steps.

The measured BER as a function of the photocurrent in the transmitter is shown in Fig. 2(b). A BER value below 10^{-5} is obtained for the wireless carriers at 79.6 GHz and 119.4 GHz when the photocurrent in the transmitter is the maximum. The eye diagrams of these cases are included in Figs. 2(c)-(d). The BER magnitude increases for both frequency channels when the photocurrent decreases. In the case of 79.6 GHz, the curve stays below the limit imposed by forward error correction (FEC) techniques with 7% of overhead (OH) over the entire measurement range. The 119.4 GHz line is below the same limit when the photocurrent is more than 6 mA. The signal degradation with frequency is even more obvious for f_c = 159.3 GHz. The calculated BER for the maximum photocurrent is on the limit of FEC techniques with 25 % OH. This effect is also observable in the eye diagram in Fig. 2(c), which is almost completely closed.

The link performance is mainly determined by the received SNR. This fact suggests that the BER curves presented in Fig. 2(a) may be prolonged to the right if more powerful signals are radiated, enabling higher frequency channels. While several research groups work towards more power efficient optoelectronic sources and detectors, a possible solution is to use array configurations to increase the effective antenna gain [5]. The presented work serves as a starting point to implement full-photonic based sub-THz communication links without bandwidth restrictions imposed by electronics. The use of phase-locked optical signals for photomixing guarantees the frequency stability and low phase noise of the intermediate frequency signal, facilitating the demodulation of complex modulation formats.

III. CONCLUSION

The presented work demonstrates a heterodyne sub-THz wireless link for transmission at frequencies between 80 GHz and 160 GHz with scalability prospects to higher THz frequencies. Optoelectronic devices driven by OFCs are used for sub-THz signal generation and heterodyne down-conversion to an intermediate frequency of 3.7 GHz. A BER below 10^{-5} is achieved for wireless carriers spaced by 40 GHz without meaningful changes in the physical setup. These results are a significant step towards highly tunable THz communications and a full exploitation of the THz range for ultra-broadband communications.

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