Photonics-based transceivers for THz communications and sensors

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***Abstract*— We present photonics-based continuous wave terahertz systems for applications in sensing and wireless communication. Both systems use waveguide integrated PIN photodiodes as THz sources. For sensing, non-contact layer thickness measurements with an accuracy higher than 0.5 µm were demonstrated. In wireless communication at 300 GHz carrier frequency, data rates of 160 Gbit/s were transmitted over a single channel.**

Keywords—terahertz, sensing, FMCW, wireless communications

I. Introduction

In the last decades, the terahertz frequency range of the electromagnetic spectrum has become an important research topic in both science and industry [1], [2]. The spectral range is commonly defined from 300 GHz, which is roughly the upper frequency of commercially available high frequency electronics, to 10 THz, which is the lowest frequency that can be generated with laser sources operating at room temperature [3]. Terahertz frequencies are particularly interesting for applications in (i) sensing, since dielectric materials like plastics, ceramics and paper are transparent [4], [5], (ii) spectroscopy, since a plurality of processes in physics, chemistry, material science, and biology occur on picosecond timescales [6], and (iii) wireless communications, since carrier frequencies > 0.3 THz promise to overcome the bandwidth limitation of existing wireless links [7]. In the last decade, photonic approaches to generate and detect THz waves accelerated the development of the technology from a purely scientific tool to a promising technique for real world applications [8]–[10]. Thereby, the exploitation of telecom technology was the driving force resulting in fiber coupled terahertz systems with high bandwidth and dynamic range [10], [11]. In this paper, we give an overview of applications of photonic terahertz systems and highlight the versatility of this approach for sensing and wireless communication.

II. Photonics-based THz sensing

For the last 30 years, the working horse of broadband terahertz sensing has been time-domain spectroscopy (TDS). In THz-TDS, a femtosecond laser pulse excites a biased photoconductor with carefully designed material properties, i.e. picosecond carrier lifetime, high carrier mobility and high breakdown fields. The overall idea of TDS is to translate the broad spectrum of a femtosecond pulse into a THz pulse via photoconductive switches. On the detector side, a time-delayed copy of the exciting laser pulse gates the conductivity of a photoconductive receiver with properties similar to the emitter. The incoming THz pulse is convolved with the impulse response of the receiver and therefore allows for amplitude and phase sensitive detection of the THz pulse [1]. The combination of femtosecond fiber-lasers emitting at a central wavelength of 1550 nm and photoconductive antennas sensitive to this radiation paved the way for compact and fully fiber-coupled THz spectrometer. The overall bandwidth of these systems can be as high as 6.5 THz with a peak dynamic range > 100 dB [12] while measurement rates ranging from several 10 Hz to a few kHz can be obtained [13]. Today, these systems are mainly used for broadband spectroscopy and non-contact layer thickness measurements on thin dielectric samples [2].

However, the main drawback of THz TDS systems is their complexity. They require expensive femtosecond pulsed laser sources and an optical delay based either on free-space optics and opto-mechanics [11], or cavity detuning[14], or the complex synchronization [15] of two femtosecond lasers [13], [16]. Consequently, all these approaches require complex electronic control schemes or make system assembly demanding. Hence, simpler approaches for generating and detecting broadband terahertz signals are required for sensing.

Photonics-based continuous-wave terahertz (cw THz) systems avoid both, moving parts and femtosecond lasers. In addition, cw THz systems are fully compatible with photonic and electronic integration technology, rendering it an extremely promising approach for simplified and miniaturized terahertz systems [9], [17], [18]. Photonics-based cw THz systems use photomixing in ultrafast semiconductors to convert the beat signal of two cw lasers into electromagnetic THz radiation [19]. For THz sensing, a homodyne configuration is commonly used, which employs the same optical beat signal on the emitter and the receiver, respectively (see Fig. 1) [20]. For a long time, the main limitation of cw THz systems seemed to be their acquisition rate of a few measurements per minute at best. In a recent publication, we demonstrated a THz system based on photonic frequency modulated continuous wave (FMCW) [10]. A schematic of the system architecture is shown in Fig. 1. In our method, we use a frequency-swept optical beat-

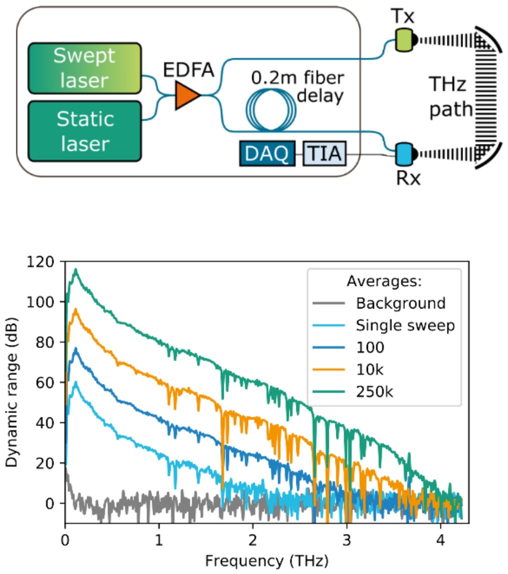

Fig. 1: (upper panel) Schematic of a frequency modulated FMCW terahertz system. (lower panel) Dynamic range of the FMCW THz system as a function of frequency and the number of averaged spectra. EDFA – Erbium doped fiber laser; Tx – transmitter; Rx – Reciever, TIA – transimpedance amplifier; DAQ – data acquisition unit..

signal to illuminate a waveguide integrated PIN photodiode, which acts as the THz emitter [21]. On the detector side, photomixing with an InGaAs based ultrafast photoconductor is used to downconvert the incoming THz wave to an intermediate frequency [20]. For the illumination of the receiver a time-delayed copy of the optical beat-signal that illuminated the emitter is used. Due to a path length imbalance, which is introduced by a 0.2 m long optical fiber in the receiver arm of the system, the receiver current is inherently phase-modulated without the need of an additional modulator. Owing to this technique, our broadband terahertz system features performance values (200 Hz measurement rate, or 4 THz bandwidth and 117 dB peak dynamic range with averaging, see Fig. 1) comparably to state-of-the-art terahertz-TDS systems, yet with significantly reduced complexity.

When this photonics-based system is employed for non-contact thickness measurements an accuracy better than 0.5 µm is achieved for dielectric single-layer samples and an accuracy better than 1.5 µm for multi-layer structures. A PET foil with a nominal thickness of 23 µm only, can still be resolved with high accuracy [10]. Note that the minimal thickness, which can be resolved in such a measurement, depends on the bandwidth of the signal used. Hence, the photonic approach with an instantaneous bandwidth of more than 2 THz is a prerequisite to address layer thickness measurements with THz systems.

Although the architecture of the photonics FMCW system presented in Fig. 1 is essentially simpler as compared to TDS, it still consists of discrete components, i.e. two packaged fiber coupled laser source an EDFA and a few meters of optical fiber. Therefore, the next step in the development of cost-efficient and handheld THz sensors, is the miniaturization and integration of the individual components on chip level. In order to achieve this photonic (hybrid) integration platforms based on InP [22], polymer [23], and silicon nitride can be combined. First results of this approach have already been published and are topic of ongoing research projects [9].

III. Photonics-Based Wireless Communication

The increasing demand for high-speed wireless data transmission, stimulated research on wireless data links with carrier frequencies in the sub-terahertz range [24]–[27]. Latest research mainly focused on carrier frequencies around 300 GHz, due to the atmospheric transmission window in this frequency range [8]. Additionally, frequencies up to 320 GHz have been standardized already by IEEE 802.15.3d [28]. For this application, photonic approaches have several advantages compared to all-electronic systems: the high bandwidth of photonic emitters and receivers can be exploited to cover several transmission channels with the same hardware. Photonics-based wireless networks offer direct connectivity to the existing fiber optical infrastructure, carrier waves with high stability and low phase noise can be generated, and spectrally efficient, complex modulation formats may be used [29]. In addition, photonic approaches allow for addressing carrier frequencies above 300 GHz without the need to develop fundamentally new hardware [30].

In a recent publication, we demonstrated a broadband PIN photodiode (PD), which was also employed as broadband emitter in our photonic FMCW spectrometer, as an emitter in wireless links with carrier frequencies around 300 GHz. We achieved a net data rate of 100 Gbit/s with QAM16 modulation, which was among the highest data rates reported at that time [25]. In order to improve the performance of our wireless link, we investigated the beam profile of our PIN-PD emitter in more detail. This is specifically important as the signal integrity in wireless links depends on the frequency dependent radiation pattern of the emitter. Hence, we investigated the radiation pattern of state-of-the-art PIN-PD emitters [31] and compared it to alternative antenna designs [32]. We found that a new antenna design reduced unwanted side lobes, which should avoid multi-path interference in a communication link [32].

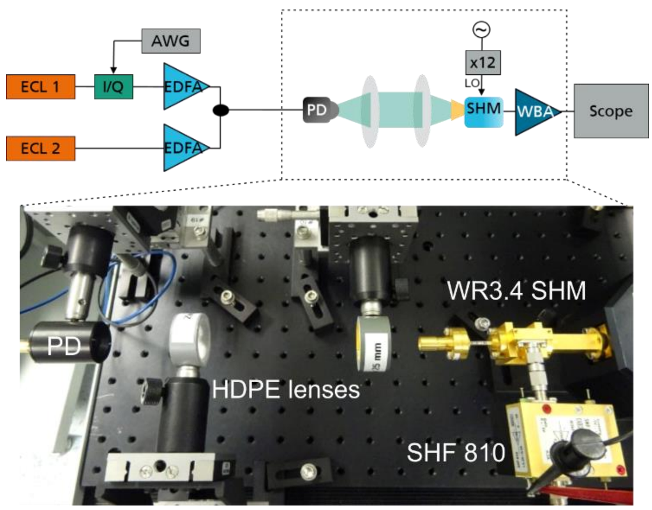

Fig. 2 (upper panel) schematic of the photonic based wireless communication link. (lower panel) photograph of the wireless link. ECL – external cavity laser, I/Q – IQ-modulator; AWG – arbitrary waveform generator; EDFA – erbium doped fiber amplifier; PD – photodiode emitter; SHM – sub harmonic mixer; LO – local oscillator; WBA – wide band amplifier (SHF810).

In this paper, we employ this novel fiber-coupled PIN-PD module as a THz emitter in a wireless communication link around 300 GHz. Fig. 2 shows a schematic (upper panel) and a photograph (lower panel) of our experimental wireless communication setup. Two free-running external cavity diode lasers (ECLs) emitting in the C-band were used for generating two optical carrier waves with a frequency spacing of 300 GHz. For coherent transmission, one of these tones was fed into an I/Q modulator, which was driven by a digital-to-analog converter (DAC) for in-phase and quadrature modulation. Afterwards, the modulated and unmodulated optical carrier waves were amplified by two erbium doped fiber amplifiers (EDFAs) and spatially overlapped. The resulting optical beat note was used to illuminate a fiber-coupled emitter with improved feeding point structure [32]. For broadband THz emission a 90° bow-tie antenna was attached to the diode. A hyper-hemispherical silicon lens with a diameter of 10 mm acted as a substrate lens to couple the terahertz radiation into free space. As the radiation pattern of the THz transmitter features an opening angle of ± 15° a pair of high-density polyethylene (HDPE) lenses was employed to reduce the free space loss. The modulated data was then transmitted over a distance of 0.5 m to the receiver. For coherent detection, we used a subharmonic mixer (SHM) based on a GaAs diode. The SHM down-converted the 300 GHz signal to an IF around 20 GHz by mixing with an electrical local oscillator (LO). The down-converted IF signal was amplified with an SHF810 and fed to a real-time oscilloscope (UXR Keysight, 70 GHz) that was connected to the I/Q analysis tool. To compensate the overall link distortion the measured signal was equalized.

In Fig. 3 the bit error ratio (BER) as a function of the photocurrent of the emitter is shown for different modulation formats QAM16 (a), QAM32 (b), and QAM64 (c). Symbol rates of 8 GBaud (black), 25 GBaud (red) and 32 GBaud (green) were used for each modulation format. In all measurements, we employed digital signal processing (DSP) and soft-decision (SD) forward-error correction (FEC) with 20 % overhead. Hence, the SD-FEC threshold is 2.2×10^{-2} such that all experiments depicted in Fig. 3 can be considered error-free after DSP. For all modulation formats, one observes that the BER depends strongly on the photocurrent of the PD. We expected a monotonic decrease of the BER for increasing photocurrents as the THz power emitted by the PD transmitter increases for higher photocurrents as long as the PD does not saturate. However, the BER curve is essentially non-monotonic. From 2 mA – 4 mA the BER decreases for all modulation formats and reaches a minimum between 4 mA – 6 mA. Note that this optimal value of the photocurrent increases for higher symbol rates and more complex modulation formats. If the photocurrent is further increased the BER starts to rise again. From THz power measurements on the PD, we can exclude that this increase is caused by saturation effects. Saturation starts with photocurrents around 9 mA. In contrast, we attribute this effect to THz reflections on the edges of the PD chip and on the silicon lens, respectively. Hence, an improved chip or module design should improve the BER even more.

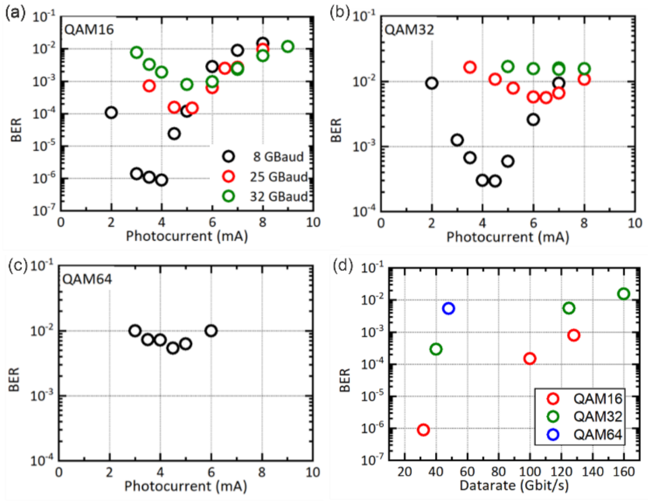

Fig. 3: Bit error ratio (BER) as a function of photocurrent in the PD emitter for QAM16 (a), QAM32 (b) and QAM64 (c) modulation. BER as a function of gross data rate (d) for the different modulation formats.

Fig. 3 (d) summarizes the BER as a function of the gross data rate. In these measurements, the transmitter was driven with the optimal photocurrent for the respective modulation format and symbol rate. Note that QAM64 modulation with 8 GBaud could be transmitted error-free, which corresponds to a gross data rate of 48 Gbit/s. This is the spectrally most efficient configuration. The highest data rate was achieved with QAM32 and a symbol rate of 32 GBaud, which corresponds to a record high gross data rate of 160 GBit/s. This highlights that photonics-based wireless links enable the transmission of extremely broadband signals over a single wireless channel by using high order modulation formats.

IV. Conclusion and Outlook

We have demonstrated the potential of photonics-based terahertz systems for applications in sensing and wireless communication. A broadband photonic FMCW system features a bandwidth of more than 4 THz with a peak dynamic range of 117 dB. This allows for non-contact thickness measurements on µm-thin dielectric layers with sub-micrometer accuracy. Hence, the high instantaneous bandwidth of a photonics-based terahertz systems, enables precise non-destructive testing. Further, we demonstrated that the same technology can be used for wireless communication links with carrier frequencies around 300 GHz. We employed a waveguide integrated PIN-PD, similar to the one used in the FMCW system, as THz emitter in a wireless link. We characterized the BER as the function of the driving parameters of the PD in order to identify the best operation point of the device. With the photonics-based wireless link we were able to transmit 160 Gbit/s over a single channel around 300 GHz. The modulation format was QAM32 and the symbol rate measured 32 GBaud. Again, the high instantaneous bandwidth of a photonics-based terahertz system enabled wireless links with extremely high data rates. However, both the FMCW sensing system as well as the photonics-based wireless links employed discrete photonic components such as lasers and modulators. In the future, it will be extremely promising to use photonic integration technologies in InP, polymer or silicon nitride, to miniaturize these systems in order to achieve compact and cost-efficient terahertz devices and systems.

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