Continuous-wave Terahertz System with 50 dB Dynamic Range at 1 THz Using a n-i-pn-i-p Superlattice Photomixer and an ErAs:InGaAs Photoconductor Operated at 1550 nm

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***Abstract*—We report on a 1550 nm continuous-wave THz system using a n-i-pn-i-p superlattice photomixer source and an ErAs:InGaAs photoconductive receiver with 51 dB dynamic range at 1 THz at 300 ms integration time.**

I. Introduction

THE increasing interest in Terahertz applications increases the demand for powerful THz systems and devices. For applications which require a large bandwidth, simple tunability and high frequency resolution, continuous-wave (CW) THz photomixing systems are an excellent choice. At the same time, already existing powerful telecom-wavelength technologies potentiates the interest on 1550 nm compatible THz devices, which are already applied for applications such as spectroscopy [1] or communication [2].

For CW, two telecom lasers, detuned by the desired THz frequency, are mixed in a photomixer that generates a current at the difference frequency of the two lasers which is then radiated by an antenna. At the photoconductive receiver, the incoming THz field, $E_{THz} = \mathrm{E}_0 \cos(\omega t + \phi)$, with the angular frequency ω and an acquired phase ϕ, biases a photoconductive gap that is illuminated with the same combined laser signal, $P_L(1 + \cos \omega t)$. The laser signal acts as a local oscillator. The photoconductor generates a DC photocurrent $I_D \sim E_0 P_0 \cos \phi$ which is proportional to the incoming THz electric field and can be read by post detection electronics. Tunability and resolution of the system are determined by the lasers. At 1550 nm, a standard DFB laser diode can be tuned by 1 THz linewidth on the MHz or even sub-MHz level.

In this work, a n-i-pn-i-p superlattice photomixer is used as transmitter. Typical p-i-n diodes working at frequencies (f_{THz}) above 100 GHz suffer from the trade-off between transit time roll-off, $\eta_{tr} \approx 1/(1 + (2\tau_{tr} f_{THz})^2$, and the RC roll-off, $\eta_{RC} \approx 1/(1 + (2\pi R_A C f_{THz})^2)$. While the first improves as transit time (τ_{tr}) reduces with shorter intrinsic layer lengths (l_i), the latter aggravates due to the increased capacitance ($C \sim l_i^{-1}$). The n-i-pn-i-p superlattice photomixer concept appears as a solution for this trade-off, by implementing a serial connection of p-i-n diodes. Each p-i-n diode is transit-time optimized by choosing a short intrinsic layer of length 200 nm. The RC roll-off is reduced by the serial connection of three diodes, reducing the capacitance by the number of stacked layers, three in this case [3], [4]. An np junction is formed between each period, where photogenerated carries accumulate at each side. This accumulation of carriers might result in a flat band situation. To avoid this undesired effect, it is necessary to introduce an efficient recombination element for electrons and holes. The recombination diode with negligible serial resistance is achieved by introducing 1.2-1.7 monolayers (ML) of semi-metallic ErAs between the n and p doped layers. More details can be found in [3]. At the same time, each of the individual periods makes use of ballistic enhancements [5]. The band structure of one period of a n-i-pn-i-p superlattice photomixer is shown in figure 1. With intrinsic layers of 200 nm, the obtained 3 dB transit time roll-off frequency is around 0.85±0.15 THz.

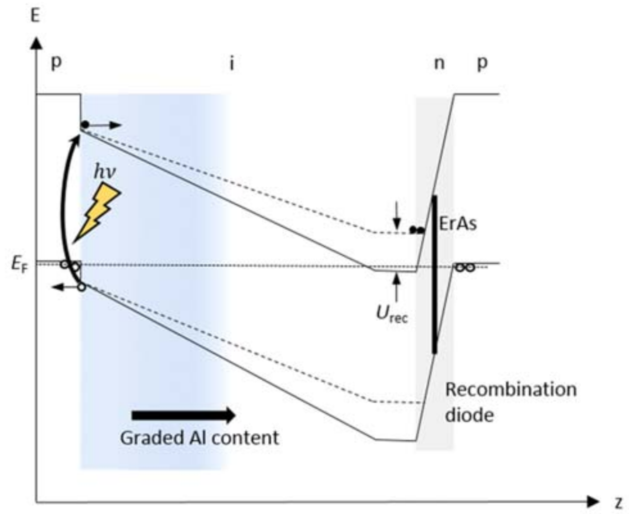

Fig. 1. Band diagram of one period of a n-i-pn-i-p superlattice photomixer. Conduction and valence bands are shown, with dashed lines representing the illuminatied case. E_F is the Fermi Energy and U_{rec} is the forward bias that appears at the recombination diodes due to the accumulation of charges, much smaller than the band gap voltage. The graded aluminum content of the intrinsic layer allows for absorption only in a small region near the p-contact, making the contribution of the slow and inefficient holes negligible.

An ErAs:InGaAs photoconductor serves as receiver. This type of device has already been used in a recent publication from our group [6] using photoconductors both as source and receiver. ErAs:InGaAs receivers allow for homodyne detection at room temperature with very low noise equivalent power (NEP). 0.8 monolayers (ML) of ErAs self-assemble to semi-metallic clusters within a superlattice of 10 nm InGaAs:p-doped 0.8 ML ErAs. This results in a short carrier lifetime required to optimize the life-time roll-off, $\eta_{LT} = (1 + (2\pi\tau_{rec} f)^2)^{-1}$ [3]. Further, the growth of the superlattice structure at the optimum InGaAs growth temperature ensures high carrier mobility.

II. RESULTS

The devices are driven using two DFB lasers from a commercial CW terahertz system from Toptica Photonics AG. While the receiver is driven by the combined laser signal from both lasers with a total power of 26 mW, the transmitter side is amplified using an erbium doped fiber amplifier (EDFA) up to a maximum laser power of 80 mW. We note that this power level is much lower than that used for the best results presented in ref. [4], however, 80 mW are still achieveable with standard telecom components whereas 190 mW that were used in ref. [4] required a high power EDFA. The photocurrent of the transmitter is 3.7 mA at a reverse bias of -1V. The photocurrent is considerably lower than that of waveguide-coupled p-i-n diodes at such power levels as we illuminate the device from the top with only about 15% absorption. During the THz measurement, we opted for modulation of the THz power by a sine-modulation of the n-i-pn-i-p bias from -2.0 to 1.2 V at about 12 kHz. Bias modulation is as a convenient solution, also finding applications in commercial systems. However, we note that this modulation technique does neither lead to a 100% modulation of the THz power nor to optimum operation conditions of the transmitter: firstly, the diode does not completely switch off at the maximum forward bias. Secondly, there is an optimum DC bias for ballistic transport around -1.8 V, leading to maximum THz power emission. The recorded dynamic range (DNR) is therefore lower than the DNR of the system under optimum operation conditions. The receiver is connected to a low noise transimpedance amplifier prior to lock-in detection.

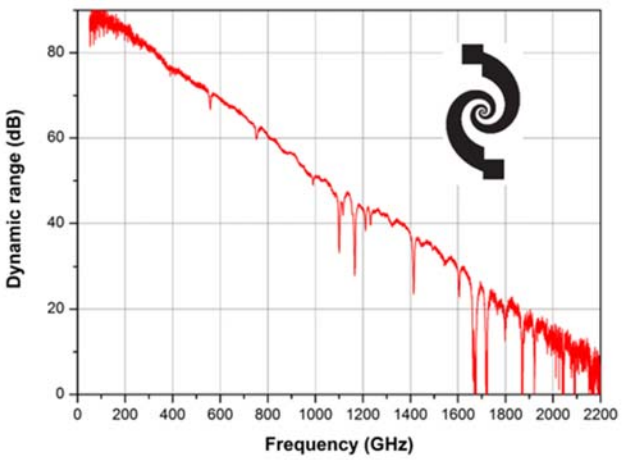

Fig. 2. THz spectrum of the system for integration time constant of 300 ms, Inset: sketch of the spiral antenna used for both emitter and receiver. The dynamic range is determined using the noise floor measured with 300 ms integration time, so that the data are comparable with those given in [6].

Both devices are attached to logarithmic periodic spiral antennas mounted on hyperhemispheric silicon lenses. The THz signal is collimated by a TPX lens and then focused on the receiver by a second TPX lens. With this configuration, we recorded the spectrum shown in Fig. 2, achieving a DNR of 51 dB at 1 THz and a peak DNR of 85 dB at 100 GHz at an integration time of 300 ms. The peak dynamic range is about 7 dB higher than the system reported in [6] using only photoconductors. At 1 THz, the DNR is almost the same. Above 1 THz, the setup using only photoconductors outperforms the system presented in this paper. As compared to a commercial p-i-n diode (Toptica Photonics/Fraunhofer Heinrich Hertz Institute) the presented system delivers about 13 dB lower dynamic range due to the lower THz power generated by the n-i-pn-i-p superlattice photomixer [7].

III. SUMMARY

We have demonstrated a CW terahertz system with >51 dB DNR at 1 THz at a source photocurrent of only 3.7 mA. Further improvement of the transmitter material, avoiding thermal constraints and increasing the efficiency of the light absorption, e.g. by a waveguide design, should allow for a fully ballistic p-i-n diode based source that outperforms current approaches.

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