Waveguide-integrated photoconductive THz receivers

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2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz) | 978-1-7281-9427-1/22/$31.00 ©2022 IEEE | DOI: 10.1109/IRMMW-THz50927.2022.9895580

***Abstract*—We present the first waveguide-integrated photoconductive antennas (PCA) for continuous-wave (cw) terahertz (THz) detection. The PCAs consisting of an InGaAs photoconductor mesa and a bow-tie antenna are equipped with an on-chip edge-coupled passive optical waveguide. Compared to state-of-the-art top-illuminated PCAs, the novel receivers show an improved frequency up to 2 THz and a total bandwidth of 4 THz. Moreover, these newly developed THz receivers open the door towards compact and low-cost fully integrated photonic THz systems that can be implemented in various industrial applications such as spectroscopy and communications.**

I. Introduction

PHOTONIC THz emitters and receivers are widely used in state-of-the-art THz-systems for various applications, such as spectroscopy and thickness measurements [1], [2]. Furthermore, THz devices based on photomixers continue to gain scientific attention for their potential in high-data rate wireless telecommunication [3]–[5]. For all the above-mentioned applications, compact and cost-efficient THz systems for out-of-lab use are of particular interest. A key factor to achieve this is the miniaturization, and ultimately the photonic integration of all system components. In this regard, cw THz systems operating in the C-band (1530 to 1565 nm) are very promising, since most components such as lasers and optical amplifiers are readily available in indium phosphide (InP) based photonic integrated chips (PICs). In order to be able to integrate THz emitters and receivers in PICs, waveguide-integrated devices are required. While most state-of-the-art photonic THz emitters already employ waveguide-coupled photodiodes as active elements[1], [6], photonic THz receivers are still based on vertically illuminated PCAs, which do not allow for photonic integration. Another advantage of waveguide integration is the possibility to improve the optical coupling of the optical excitation to the active element. In vertically illuminated PCAs, the absorption of the incoming light is hampered by the metallic contact electrodes placed on top of the photoconductor as well as the reflection at the interface between air and the photoconductor. In waveguide-integrated (WIN) PCAs, the evanescent coupling from a passive optical waveguide below the PCA to the absorber avoids these drawbacks. So far, waveguide integrated PCAs have only been demonstrated for pulsed THz emitters [7], [8]. These devices, however, were illuminated via grating couplers and showed a limited bandwidth of less than 2 THz.

In this work, we demonstrate the first PCAs for cw THz detection with an edge-coupled optical waveguide that guides the optical excitation to the photoconductive element. The devices show a performance surpassing the state-of-the-art top-illuminated PCA receivers based on the same photoconductive material, and show up to seven times the detected signal amplitude and a bandwidth of more than 4 THz. This is a significant step towards fully integrated cw THz systems.

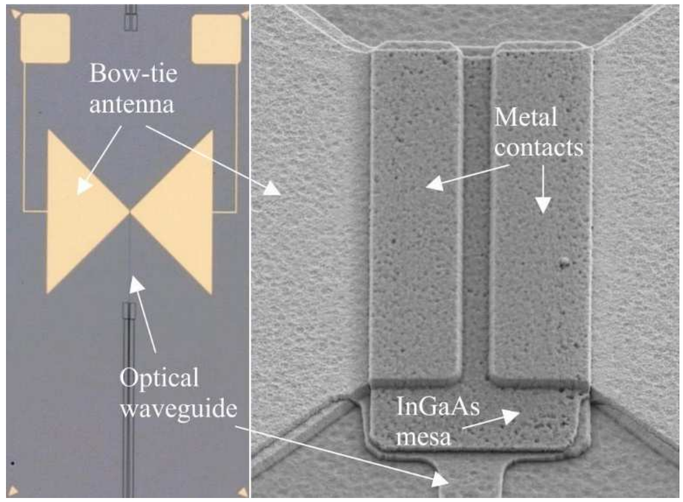

Fig. 1. Micrograph (left) and scanning electron micrograph (right) of the novel WIN PCAs.

II. Results

Our waveguide integrated PCAs consist of three main components. First, a passive optical waveguide, comprised of alternating layers of indium gallium arsenide phosphide (InGaAsP) and InP, guides the optical excitation from the chip edge towards the active element. Then, the light is evanescently coupled into a photoconductive mesa made of iron (Fe) doped indium gallium arsenide (InGaAs:Fe). Finally, a bowtie antenna captures the incoming electromagnetic THz-field and guides it to the photoconductor at its feeding point. We optimized the dimensions of the photoconductive mesa for maximum absorption through simulations with FIMMWave®. The highest absorption at 1550 nm of about 80%was predicted for a 7 µm wide and 18 µm long mesa with a thickness of 240 nm.

The PCAs were manufactured using two epitaxy steps: first, the optical waveguide stack was grown onto a semi-insulating InP:Fe waver by metalorganic vapor phase epitaxy. Second, the ultrafast InGaAs:Fe photoconductor was overgrown by gas-source molecular beam epitaxy. The metal antenna, mesa and waveguide structures were then patterned via photolithography. A micrograph and a scanning electron micrograph of the final device is shown in Fig. 1. In order to characterize the novel receivers we coupled the on-chip optical waveguide to a cleaved optical fiber after placing the chip on a hyper-hemispherical silicon lens. First, we measured the current-voltage (I-V) characteristics of the devices for voltages between -0.5 V and 0.5 V and optical input powers from 0 mW to

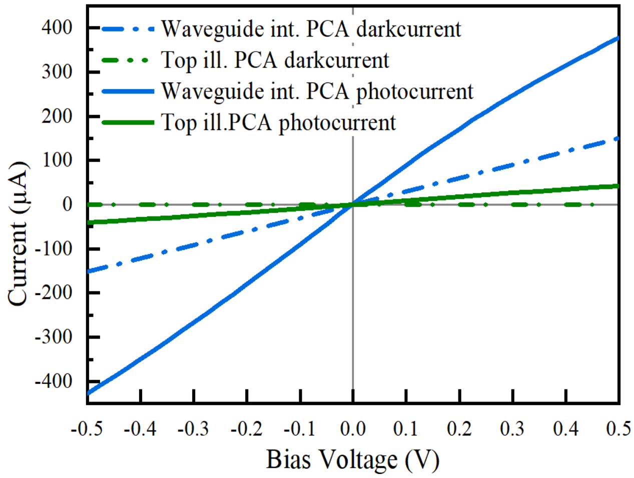

Fig. 2. I-V characteristics of the two receivers. The photocurrent was measured at an optical excitation with 30 mW.

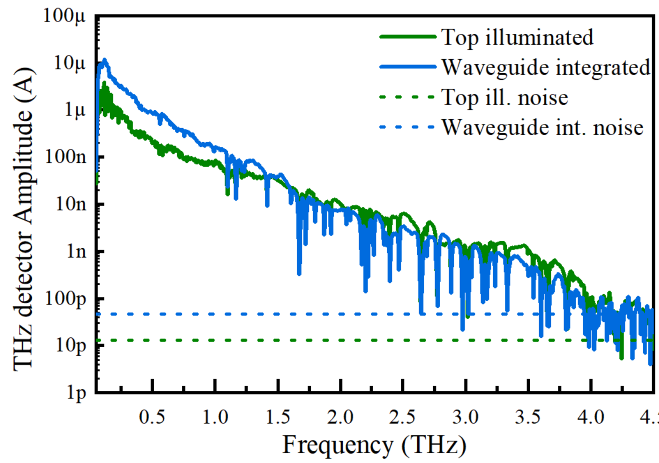

Fig. 3. Detected THz amplitude spectra measured with the novel WIN PCA (blue) and a state-of-the-art top-illuminated PCA (green) based on InGaAs:Fe. The same emitter was used for both measurements. Both receiver and emitter were excited with 30 mW optical power.

30 mW. The results shown in Fig. 2 indicate, that the waveguide-integrated PCAs exhibit both a significantly higher dark- and photocurrent compared to state-of-the-art top-illuminated receivers [9]. While the origin of the high dark current is yet unclear, we attribute the increased photoresponse to the improved coupling of the optical excitation into the photoconductor. We characterized the performance of our PCAs as THz receivers in coherent cw THz measurements using a state-of-the-art PIN diode as THz emitter [6]. The THz path consisted of two off-axis parabolic mirrors. The optical power on both emitter and receiver was set to 30 mW. The measured THz spectrum for WIN PCA (blue) is shown in Fig. 3 together with the spectrum detected by the state-of-the-art top-illuminated PCA receiver (green) [9]. The novel device shows superior performance particularly for frequencies below 2 THz where the detected THz amplitude is up to 7.3 times higher compared to the top-illuminated device. This correlates well with the I-V characteristics of the two devices since the photocurrent of the waveguide-integrated receiver is about 6.8 times as high as the photocurrent of the top-illuminated PCA, when corrected for the dark current. For higher frequencies, the waveguide integrated PCA shows slightly lower amplitudes, which could be caused by misalignment of the THz path in the on-chip measurement setup or inferior photoconductive material properties due to the epitaxial overgrowth step. Furthermore, the noise of the novel receiver is higher than for the conventional PCA. This stems from the higher conductance of the novel device as the noise of the receiver scales with the square root of the conductance. The I-V measurements of the waveguide-integrated receiver show a photoconductance about 10.5 times as high as that of the top-illuminated one suggesting a 3.2 times increased noise level. From the spectral measurements, we obtain a 3.6-fold higher noise level for the WIN PCA. The lower signal amplitude and higher noise level at frequencies >2 THz lead to a slightly decreased bandwidth of about 4 THz. An improved manufacturing process to reduce the dark current and consequently the noise level, however, could overcome this drawback.

In conclusion, we presented the first edge-coupled, waveguide-integrated photoconductive antennas for cw THz detection. The novel devices show up to seven times higher detected amplitudes compared to state-of-the-art top-illuminated PCA receivers. By improving the manufacturing process to reduce the dark current of the devices, we expect that both noise level and bandwidth can be improved further to match or even surpass the conventional devices. For photonic integrated THz systems, the presented WIN-receivers are a critical component as they allow flexible integration of a THz receiver with state-of-the-art performance in a photonic integrated circuit, for the first time.

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