Graphene two terminal detector as THz mixer

A Sh Gazaliev\textsuperscript{1,2}, M V Moskotin\textsuperscript{3}, V V Belosevich\textsuperscript{1,4}, M G Rybin\textsuperscript{5}, I A Gayduchenko\textsuperscript{1,7} and G N Goltsman\textsuperscript{1,6}

\textsuperscript{1} Moscow Pedagogical State University, Moscow, 119435, Russia
\textsuperscript{2} NRC «Kurchatov Institute», Moscow, 123182, Russia
\textsuperscript{3} Moscow Institute of Physics and Technology (National Research University), Dolgoprudny, 141700, Russia
\textsuperscript{4} National Research University Higher School of Economics, Moscow, 101000, Russia
\textsuperscript{5} Prokhorov General Physics Institute, RAS, Moscow, 119991, Russia
\textsuperscript{6} NTI Center for Quantum Communications, National University of Science and Technology MISiS, Moscow 119049, Russia
\textsuperscript{7} Author to whom any correspondence should be addressed

igorandg@gmail.com

Abstract. The growing requirements for mobile communication networks (data transfer rates over 100 Gbps) makes it necessary to use carrier signal with a frequency of at least 100 GHz. This requires the development of cheap and broadband sub-terahertz (sub-THz) detectors. Here we report on our recent efforts toward the development of a heterodyne sub-THz detector based on a single layer graphene two-terminal device integrated with a bowtie antenna on a sapphire substrate. Our detector operates at frequency of 140 GHz, which corresponds to the maximum transmission of THz radiation in the Earth's atmosphere. The heterodyne detection is achieved by quasi-optical coupling of signals from two sub-THz radiation sources to the same detector. The measured frequency bandwidth is 5.8 GHz.

1. Introduction
The unprecedented increase in wireless data traffic makes it necessary to expand the carrier frequency range in order to increase the bandwidth of communication channels. One of the promising approaches for creating high-performance (over 100 Gb / s) wireless data transmission channels is the use of the terahertz frequency range (0.1-10 THz) \cite{1}. For the practical implementation of such systems, it is necessary to develop an element base based on fast, cheap and energy-efficient THz detectors and photo-mixers.

Due to the gapless band structure and high mobility, graphene is considered a promising material for creating ultrafast photodetectors in a wide spectral range: from visible to terahertz \cite{2}. A weak electron-phonon coupling together with a small specific heat capacity of graphene leads to strong heating of its electronic subsystem under the incident electromagnetic radiation and, as a result, to a thermo-emf signal \cite{3}. The second effect which leads to the appearance of photovoltage is the rectification of THz radiation at the graphene-metal interface (photovoltaic effect) \cite{4}. The photothermoelectric effect in graphene, as well as the photovoltaic effect, potentially leads to achieving high volt-watt sensitivity and speeding up to picoseconds even at room temperature \cite{2}. In this work, we demonstrate that an asymmetric two-terminal graphene device can act as an efficient mixer of sub-
THz radiation at a practically important frequency of 140 GHz, which corresponds to the maximum transmission of THz radiation in the Earth's atmosphere.

2. Measurements
Our devices are made in a two-terminal configuration, in which graphene synthesized by chemical vapor deposition is in contact with two electrodes made of metals with different work functions [4] (Figure 1). This geometry leads to non-uniform distribution of charge carrier concentration in the graphene channel due to contact doping. In such systems, photovoltage response occurs due to combination of photo-thermoelectric [5] and photovoltaic effects [4].

![Figure 1. Schematic representation of the experimental device: (a) - electric circuit diagram of the graphene detector, (b) – optical image of the graphene detector integrated with a bow-tie antenna.](image1)

The contact electrodes were made in the form of a bow-tie antenna to couple THz radiation to the sensing element using standard e-beam lithography technique (Figure 1). To reduce the parasitic capacitances limiting the performance of the device, we used sapphire substrates. The fabricated device was located in the center of the flat surface of hemispherical Si lens. The source and drain electrodes of the detector were connected to coplanar strip line to form intermediate frequency (IF) transmission line [6].

![Figure 2. Schematic representation of the experimental setup for measuring the bandwidth of detectors.](image2)
The measurement technique used in this study is based on the mixing of both local oscillator (LO) radiation and radio frequency (RF) radiation and described in ref. [6] (see figure 2). The setup includes two backward-wave oscillators (BWO), one as a fixed signal source. The second BWO was used as a tunable LO source which corresponds to an IF up to 13 GHz. The power of both BWOs was controlled by an RF thermistor power meter. Two signals from the specified sources are coupled to the Si lens on which graphene devices are located. The IF signal is amplified with a wideband amplifier that is connected to an FSV 9 kHz – 13.5 GHz Rohde & Schwarz spectrum analyzer. To provide photoresponse measurements under different bias conditions we connect the source meter through a bias tee.

3. Results
The heterodyne measurements for the IF band ranging from 0.1 – 13 GHz are presented in Figure 3. The measured IF gain data was fitted with function [7]:

$$ G = G_0 - 20 \log(1 + \omega^2 \tau^2) $$  

(1)

where $G_0$ is IF gain at low frequency, $\omega$ is the angular frequency and $\tau$ is the response time. The -3 dB bandwidth of the graphene-based mixer is 5.8 GHz that might be limited by bonding wires. The measurements under zero bias and constant bias demonstrate no significant changes in photoresponse value illustrating the non-bolometric origin of the photoresponse. To clarify the detection mechanism we performed the same measurements at temperature of 77 K. Our experimental data show no significant change in the responsivity and operation speed of the detectors. These results are in a good agreement with photo-thermoelectric model for highly doped graphene devices [8].

![Figure 3. IF bandwidth of the graphene based heterodyne detector. Black dots are experimental data, black line is the result of fitting using formula (1).](image)

4. Conclusion
We have demonstrated that a two-terminal device based on graphene can be used as a THz radiation mixer with a 5.8 GHz bandwidth. Our previous work on the direct detection of THz radiation with graphene detectors showed that the equivalent noise power of such detectors does not exceed 1 nW/Hz$^{0.5}$. These characteristics are close to the best commercial Schottky diodes, but still inferior to them. We also note that the characteristics of our detectors are determined not by internal processes in graphene (which occur at much shorter times of the order of ps), but by the external connections and parasitic capacitances. Further research on optimization and identification of physical mechanisms limiting the characteristics of graphene THz detectors may lead to the creation of fast mixers for next-generation wireless networks.
Acknowledgments
The reported study was funded by RFBR and DFG, project number 21-52-12041 (DFG project number 449506295).

References
[1] Elayan H, Amin O, Shubair R M and Alouini M S 2018 2018 International Conference on Advanced Communication Technologies and Networking (CommNet) 1-5
[2] Koppens F, Mueller T, Avouris P, Ferrari A, Vitiello M and Polini M 2014 Nature nanotechnology 9(10) 780-793
[3] Sun D, Aivazian G, Jones A, Ross J, Yao W, Cobden D and Xu X 2012 Nature nanotechnology 7(2) 114-118
[4] Gayduchenko I et al 2018 Nanotechnology 29(24) 245204
[5] Cai X et al 2014 Nature nanotechnology 9(10) 814
[6] Krause S, Mityashkin V, Antipov S, Gol'tsman G, Meledin D, Desmaris V, Belitsky V and Rudziński M 2016 IEEE Transactions on Terahertz Science and Technology 7(1) 53-59
[7] Generalov A, Andersson M, Yang X, Vorobiev A and Stake J 2017 42nd International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz) 1-2
[8] Bandurin D A, Gayduchenko I, Cao Y, Moskotin M, Principi A, Grigorieva I V, Goltsman G, Fedorov G and Svintsov D 2018 Applied Physics Letters 112(14) 141101