Compact Remote Spectral Terahertz Imager

K. Fedorov1,2 · P. Karataev1 · P. Sahafi3 · I. Antonov3,4 · M. Asada5 · V. N. Antonov3,6,7

Received: 23 July 2020 / Accepted: 11 June 2022 / Published online: 9 July 2022
© The Author(s) 2022

Abstract
We report on development of an array of spectral sensitive detectors cooled down to 70 K by the compact cryocooler. The spectral sensitive operation of the detectors, explored between 0.16 THz and 0.22 THz, is due to the resonant excitation of the plasma waves in the two-dimensional electron gas of GaAs/AlGaAs heterostructure. A typical responsivity of the detectors is 0.01 A/W at 70 K while it increases by two orders of magnitude when the detector array is cooled down to 0.5 K. The photo-response has surprisingly a narrow peak of spectral sensitivity, ∼ 2–5%, which are highly likely due to the dimensional resonances of the plasma waves. As a demonstration of the spectral sensitive operation we detect a spectral feature of LiNbO$_3$ crystal at 0.174 THz.

Keywords Photovoltaic effect · Plasmons · Two-dimensional electron gas · Terahertz spectroscopy

1 Introduction

Terahertz radiation, called also sub-millimeter waves, is a useful spectroscopy range for identification of materials. For many years it has been proven as a successful tool in astrophysics for observation of cold clouds of gases and the Cosmic Microwave...
Background (CMB) radiation. Less developed application of terahertz spectroscopy was in conventional fields, like remote gas analysis, security and health screening. Many solids and liquids made of complex molecules, like organic ones, have distinct spectral patterns for identification. It is used in local time-domain and direct terahertz spectroscopies [1–3]. There are however a number of difficulties in development of remote terahertz spectroscopy tools [4]. Firstly, the spectral lines of solids and liquids are fairly wide because of the internal interactions of atoms and molecules. As a consequence, one needs to familiarise oneself in detail with a wide part of the spectrum in order to differentiate between the materials. It is easy to do with the local time-domain spectroscopy (TDS), but it is hard for the remote spectroscopy, since a limited number of compact spectral sources and spectral sensitive detectors in the range from 0.1 THz to 2 THz. It is referred to as the “terahertz gap” located between the microwave and optical ranges of the spectrum, where there are a limited number of the tunable spectral sources for remote spectroscopy and sensitive detectors of high dynamical range. Also spectrum of material is modified depending on the state of a solid: a block and a powder of the same material would have different spectral characteristics. The information about the state of solids for remote spectroscopy is often lacking.

A few terahertz remote imaging systems have been reported [5–8]. The technologies are based on either a single frequency heterodyne downconversion of radiation emitted by objects or a broadband bolometric detection of temperature gradient. However, they did not allow to get spectroscopy information remotely. Recent progress in compact high power spectral terahertz sources, like resonance tunnelling diodes (RTD) [9], heterodyne [10] and direct spectral detectors [11] opens way to the next step in technology—a remote terahertz spectroscopy. One can envisage a remote spectroscopy system: an array of spectral sensors detects incoherent radiation reflected by the objects when consecutively illuminated by a number of narrow spectrum terahertz sources. A discrete spectrum of the object is thus constructed, which can be used by cognitive software for material identification. The sensitivity and operation range can be enhanced further with the heterodyne technique, when detecting coherent radiation in a way of mixing the reflected and direct signals of the spectral sources at the detector [12].

In this work we report a progress in development of remote spectral sensing technology. A spectral sensitive sensors detect radiation of the narrow line terahertz source reflected/transmitted by the remote object, see Fig. 1. Spectral sensitivity of the detectors enables to reduce influence of a strong terahertz background signal from the room environment, and to boost signal to noise ratio. The array of detectors is placed at the package with integrated Si lens, (7) in Fig. 1, which in turn is fixed at the cold finger of compact cryocooler. The THz radiation from the object is delivered to the detectors by optical system with a set of filters. We mostly concern about a study of the signal reflected from the remote object. Combination of spectral detectors and spectral sources allows to get spectral information about the material of the object. As a demonstration of capabilities, we perform spectroscopy of a LiNbO$_3$ crystal. We observe a prominent absorption peak in the reflected signal close to 174 GHz, see Fig. . The observation indicates the feasibility of remote spectral imaging of materials.
The detectors in the array have responsivity of about 0.01 A/W when operating at 70 K in a compact cryocooler. They have a distinct spectral resonances related to the excitation of plasma waves. In order to confirm a plasma wave origin of these resonances we study operation of the detectors down to 0.5 K using a standard cryo-free refrigerator. The responsivity increases by one order of magnitude, when the array is cooled down to 0.5 K. At the same time from the model of plasma waves one would expect a much larger effect at low temperatures. Reversely one would expect a much stronger suppression of the excitation of plasma waves when raising operation temperature from 0.5 K to 70 K.

An interesting phenomenon is observed below 1K: the direction of the source-drain current in the detector is reversed under terahertz radiation. The effect is, most likely, a consequence of interference and rectification of plasma waves excited in the detector’s 2DEG. The effect dies away at higher temperatures, so that it can be hardly noticed already at 4 K.

2 Experimental Setup and Operation of the Detectors

The detector array is attached to the cold finger of compact cryocooler, see Fig. 1. It takes 40 minutes to cool down the array from room temperature to 70K. The need for low temperature is dictated by the dramatic suppression of detector sensitivity, by factor 10^3, when the operation temperature increases from 70 K to 300
K [13]. The array is screened from the environmental infrared radiation by the Si lens: the GaAs/AlGaAs crystal with detector array is glued back to back to the Si lens using a 10 μm thick polymer, as shown in frame (7) in Fig. 1. The Si lens is in turn integrated to a 20 pin package. Terahertz radiation is guided to the detectors by a Teflon lens at the input window of the vacuum chamber followed by a 3 mm diameter and 4 cm long plexiglass light pipe (6). Finally, radiation is focused by the Si lens at the detector array.

We use tunable 40 GHz Gunn diode with a doubler and tripler to produce radiation within 160–220 GHz spectral range, with a mean power at the output of ~ 1 mW. The reflected signal from LiNbO$_3$ crystal is measured by the detectors, see Fig. 1. It is particularly important to explore the reflected signal, as a proof of remote THz spectral imaging. The detectors in the array are a narrow conductive channel formed in Two Dimensional Electro Gas (2DEG) of the GaAs/AlGaAs heterostructure by the negatively biased metal gates, see insert in Fig. 2(b). The 2DEG is formed 90 nm below the surface, it has the electron concentration of 1.45 × 10$^{11}$ cm$^{-2}$ and mobility of 1.2 × 10$^{5}$ cm$^2$/Vs at T=4 K. Two quantum dots are formed next to the conductive channel when biasing the gates. The quantum dots influence spectral sensitivity of the detector: the quantum dots of different sizes have the plasma wave resonances at different frequencies [14]. The conductive channel is in a focal point of a bow tie metallic antenna, which spans ~ 0.5 mm, see Fig. 2(a). The plasma waves are resonantly excited in the 2DEG by absorption of terahertz radiation. They are rectified at the non-uniform potential profile around the gates so that the offset dc voltage appears across the conductive channel. Close to the pinch-off of the conductance this additional offset voltage gives rise to a substantial variation of the photocurrent. A source-drain current, $I_{sd}$, and the photocurrent induced by THz radiation, $I_{ph}$, in a vicinity of the pinch-off are shown in Fig. 2(a).

Gated 2DEG terahertz detectors have been the subject of a number of publications. The rectification of plasma waves and direct bolometric effects were observed with the point contact detectors operating below 4 K at 1.5 THz at Buffalo University [15, 16]. A high power, above 20 mW, continuous source of THz radiation was used in the experiments. The photosensitive spectral operation of a gated 2DEG in a wide temperature range, from 4 K to 180 K, was reported by another group [17]. Their study focused on the lower end of the THz spectrum, around 100 GHz. Our interest lies in operation of the detector in between the frequency range of 0.1 THz and 1.5 THz, where potential application for the spectral terahertz imager is envisaged. In this work we report experiments in the range from 160 GHz to 220 GHz.

We have carried out spectroscopic characterisation of the detectors in the array. An example of photo-response to different frequencies is presented in Fig. 2(b). The photocurrent is normalised at the source power. The maximum of emitted power, ~ 1 mW at $\nu$=189 GHz, is taken as 1. The full width at half maximum (FWHM) of the resonance at 176 GHz is 2 GHz, ~ 1%. Despite not being in control of the position of resonances in the detectors of different gate design, it is a remarkable achievement to have such a narrow line in the plasmonic device. Typically the FWHM related to plasma resonance in 2DEG is around 30% [18, 19]. It can be reduced to few percent if the device is placed in the magnetic field, so that
the magneto-plasmons are excited upon absorption of the THz radiation [13, 20].

The sharp resonances can be attributed to the interference of the plasma waves in conductive channel, bow tie antennae, the wafer and effect of the quantum dots, formed next to the conductive channel. A precise modelling of the resonance position is notoriously challenging. However, systematic experimental study will be able to match detectors to the spectral line of terahertz source for spectroscopy.

As a demonstration of remote spectroscopy we measure reflection spectrum of the LiNbO$_3$ crystal using the THz source of variable frequency and a single detector. The experimental setup is shown in Fig. 1. The detector array is kept at 70K. The terahertz source can be placed in one of two positions, so that one measures either transmission or reflection signal of the LiNbO$_3$ crystal. Both transmission and reflection curves have a strong resonance absorption at $\nu=174$ GHz. It may be related to the multiple internal reflections in the sub-mm thick LiNbO$_3$ wafer. The
reflection signal is shown in Fig. 3. The resonance is nicely fitted by the Lorenzian curve with FWHM of \( \sim 16 \) GHz. The observation indicates the feasibility of remote spectroscopy using a reflected signal.

3 Plasma Wave Model of Photo-response

We have evidence that photo-response in our detector is due to resonant excitation of the plasma waves in the 2DEG upon absorption of terahertz photons. The rectification of these plasma waves at a non-uniform potential profile is then detected with the narrow conductive channel [11]. The explanation is widely accepted for the operation at low temperatures, below 4 K, where coherent plasma waves can be easily excited. It is less evident that the plasma wave operation survives as the temperature increases. Recently there were few reports, where the plasma wave nature of photo-response has been stated even at room temperature [21, 22]. Therefore, we make a bridge of the effect when operating between 0.5 K and 70 K.

Overall photo-response curve follows the trans-current gradient \( \partial I_{sd}/\partial V_g \) of the narrow conductive channel, being largest at the maxima of \( \partial I_{sd}/\partial V_{sd} \). We found that \( I_{ph} \) has weak sensitivity to \( V_{sd} \). This observation is in contrast to the experiments of Song et al. [16], where photo-response has been ascribed to the bolometric effect and photo-response current had a strong dependence on \( V_{sd} \).

The photosensitive operation can be modelled by the phenomenological approach. The photocurrent arises due to an additional potential at the gates, \( \delta V_g \), and between the source and drain \( \delta V_{sd} \) [15]:

\[
I_{ph} = \alpha(\partial^2 I_{sd}/\partial V_g \partial V_{sd}) + \beta(\partial^2 I_{sd}/\partial V_g^2)
\]

(1)

Fig. 3  Reflection spectrum of LiNbO\(_3\). Detector is kept at \( T \sim 70 \) K. There is a strong absorption at \( \nu=174 \) GHz. The absorption dip is fitted with the Lorenzian (red solid line). The FWHM of the resonance absorption is 16 GHz.
where $\alpha = \langle \delta V_g \delta V_{sd} \rangle$ and $\beta = 1/2 \langle \delta V_g^2 \rangle$. The $\alpha$ and $\beta$ are used as fitting parameters. The photo-response is largest at the lowest temperatures, see Fig. 4(a). It drops by two orders of magnitude when the operation temperature increases from 0.5 K to 70 K. We approximate the photo-response at different temperatures with (1). $\langle \delta V_{sd} \rangle$ varies from 1 $\mu$V to 30 $\mu$V, while $\langle \delta V_g \rangle$ gives only a small contribution, see Fig. 4(b). The $\langle \delta V_{sd} \rangle$ has a steep drop from 0.5 K to 2 K, then it decreases at a much slow rate. If we assume that the photo-response has its origin in the excitation of plasma waves in the 2DEG [17, 23], then we should expect that the amplitude of the plasma waves, and correspondingly $\delta V_{sd}$, would be suppressed by the exponential factor $\exp(-\omega \tau(T))$, where $\tau(T)$ is the temperature dependent scattering time of the electrons, and $\omega$ is the plasma wave frequency. $\tau(T)$ decreases at higher temperatures, and correspondingly the photo-response should be suppressed. From the fitting of $\langle \delta V_{sd} \rangle$ of Fig. 4(b) with the exponential suppression factor we find $\tau(0.5K) / \tau(45K) \approx 3.5$. However, the same ratio calculated from the transport measurements is much smaller. We use the Drude formula and calculate for the conductance and the electron’s scattering time $G(0.5K)/G(45K)=\tau(0.5K)/\tau(45K) \approx 1.35$, assuming that the 2DEG carrier concentration is constant. The shape of $\tau(T)$ incurred from the photo-response is also different from that derived from the conductance: it drops faster at temperatures up to 2 K, but it decays much slower at higher temperatures. We observe photo-response up to 70 K, where the excitation of coherent plasma waves should be strongly suppressed. Similar plasma wave operations of GaAs/AlGaAs devices have been seen at temperatures up to 150 K [13]. So far there is no clear-cut explanation of these observations.

One can state that the road to increase operation temperature of the detectors is in utilising materials, which have a high mobility and large carrier concentration at high temperatures. High mobility would ensure a long scattering time, $\tau$, and correspondingly a long plasmon lifetime, while large carrier concentration would ensure

![Graph](image-url)
a good coupling of the radiation to 2DEG. Graphene can be the material of choice for terahertz detectors as the pristine graphene has relatively high mobility even at room temperature [24, 25]. Recently the graphene field-effect THz detector operating at room temperature has been reported [26]. Unfortunately only encapsulated exfoliated flakes of graphene demonstrated such an outstanding parameter so far, which hinders fabrication of the array of detectors.

We observe phenomena, which further confirms the excitation of plasma waves in the device. At the lowest temperatures, below 1K, the source-drain current under terahertz radiation is varied with the frequency of terahertz radiation, see Fig. 5. It can even change sign when radiation of a particular frequency is applied, compare experiments with 180 GHz and 186 GHz. At 180 GHz the source-drain current becomes negative, while at 186 GHz it adds a positive contribution. There is no correlation between the sign of changes with the power of the source at a particular frequency. The effect indicates at an additional bias potential is built in the vicinity of the conduction channel, because of rectification of the interfering plasma waves. The exact interference pattern, and correspondingly the sign of induced potential, may depend on the radiation frequency, the geometry of mesa and metallisation in the vicinity of channel. Two QDs formed next to the channel should also contribute to the effect. One can potentially control the interference pattern by the geometry of the sample and design of the gates. The effect disappears when temperature increases, so it can hardly be seen already at 4 K.

![Fig. 5](image_url)

**Fig. 5** The source-drain current (black) and the absolute value of photocurrent (red) under illumination of two close frequencies, 180 GHz (solid curves) and 186 GHz (dotted lines). The source-drain current close to pinch-off changes sign from positive to negative when illuminated by radiation of 180 GHz. Under the radiation of 186 GHz, there is a positive contribution to the source-drain current. Power supplied by the source at two frequencies is different by the factor of 25: it is 1 mW at 180 GHz and 40 μW at 186 GHz.
4 Summary

We report on development of the compact terahertz camera for remote spectroscopy. The camera has an advantage of compact design, a box of $20 \times 20 \times 20$ cm$^3$. The array of detectors is fixed at the cold finger of the compact cryocooler with the base temperature of 70 K. For demonstration of feasibility of technology we detect resonance absorption of LiNbO$_3$ crystal at 176 GHz in the reflected signal. For further development of system we model operation of spectral detectors. There is evidence that the photo-response is due to rectification of plasma waves, excited in the 2DEG by absorption of terahertz radiation. The amplitude of the photo-response at 70 K is however larger than expected for the rectification of the plasma waves in the 2DEG. A plasma wave interference effect is observed when detectors are cooled below 1 K: the source-drain current is strongly varied under terahertz radiation, it may even change direction. The effect supports the plasma wave model of the photo-response.

Funding This work was supported by InnovateUK, Grant No. 84886-537366, and the Russian Science Foundation, Grant No. 16-12-00070.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

1. M. Usami, M. Yamashita, K. Fukushima, C. Otani, K. Kawase, App. Phys. Lett., 86, 141109 (2005)
2. N. Karpowicz, H.Zhong, C Zhang, K.-I. Lin, J.-S. Hwang, J. Xu, and X.-C. Zhang, App. Phys. Lett., 86, 054105 (2005)
3. Y. Divin, U. Poppe, V.N. Gubankov, K. Urban, IEEE Sensors Journal, 8, 750 (2008)
4. M.C. Kemp, IEEE Transactions on Terahertz Science and Technology, 1, 282 (2011)
5. E. Grossman, C. Dietlein, J. Ala-Laurinaho, M. Leivo, L. Gronberg, M. Gronholm, P. Lappalainen, A. Rautiainen, A. Tamminen, and A. Luukanen, App. Optics, 49, E106 (2010)
6. T. May; G. Zieger; S. Anders; V. Zakosarenko; M. Starkloff; H.-G. Meyer; G. Thorwirth; E. Kreysa, Proc. SPIE Terahertz for Military and Security Applications VI, 6949, 6949C (2008)
7. S. Nadar, H. Videlier, D. Coquillat, F. Teppe, M. Sakowicz, N. Dyakonova, W. Knap, D. Seliuta, I. Kaalyunas, and G. Valuis, J. Appl. Phys., 108, 054508 (2010)
8. M. Hégédüs, K. Fedorov, I. Antonov, P. Karataev, V.N. Antonov, App. Phys. Lett. 117, 231106 (2020)
9. J. Yun, D. Yoon, H. Kim, and J-S. Rieh, IEEE Transactions on Microwave Theory and Techniques, 62, 3053 (2014)
10. S. Lara-Avila, A. Danilov, D. Golubev, H. He1, K. H. Kim, R. Yakimova, F. Lombardi, T. Bauch, S. Cherednichenko and S. Kubatkin, Nature Astronomy, 3, 983 (2019)
11. S. Pelling, E. Otto, S. Spasov, S. Kubatkin, R. Shaikhaidarova, K. Ueda, S. Komiyama, V. N. Antonov, J. of App. Phys 112, 014322 (2012)
12. P.H. Siegel and R.J. Dengler, Int. J. of Infrared and Millimeter Waves, 27, 465 (2006)
13. V. M. Muravev and I. V. Kukushkin, App. Phys. Lett. 100, 082102 (2012)
14. O. Astafiev, S. Komiyama, T. Kutsuwa, V. Antonov, Y. Kawaguchi, K. Hirakawa, App. Phys. Lett. 80, 4250 (2002)
15. J.W. Song, N.A. Kabir, Y. Kawano, K. Ishibashi, G.R. Aizin, L. Mourokh, J.L. Reno, A.G. Markelz and J.P. Bird, App. Phys. Lett., 92, 223115 (2008)
16. J.W. Song, G. Aizin, Y. Kawano, K. Ishibashi, N. Aoki, Y. Ochiai, J.L. Reno, J.P. Bird, App. Phys. Lett., 97, 083109 (2010)
17. A.V. Muravjov, D.B. Veksler, V.V. Popov, O.V. Polischuk, N. Pala, X. Hu, R. Gaska, H. Saxena, R.E. Peale, M.S. Shur, App. Phys. Lett., 96, 042105 (2010)
18. O. Astafiev, V. Antonov, T. Kutsuwa and S. Komiyama, Phys. Rev. B, 65, 85315 (2002)
19. R. Shaikhaidarov, V.N. Antonov, A. Casey, A. Kalaboukhov, S. Kubatkin, Y. Harada, K. Onomitsu, A. Tzalenchuk, A. Sobolev, Phys. Rev. Applied, 5, 024010 (2016)
20. S. Komiyama, O. Astafiev, V. Antonov, T. Kutsuwa, H. Hirai, Nature, 403, 405 (2000)
21. F. Teppe, W. Knap, D. Veksler, M.S. Shur, A.P. Dmitriev, V.Yu. Kachorovskii, and S. Rumyantsev, App. Phys. Lett., 87, 052107 (2005)
22. M.S. Vitiello, D. Coquillat, L. Viti, D. Ercolani, F. Teppe, A. Pitanti, F. Beltram, L. Sorba, W. Knap, A. Tredicucci, Nano. Lett., 12, 96 (2012)
23. A. El Fatimy, F. Teppe, N. Dyakonova, W. Knap, D. Seliuta, G. Valuis, A. Shchepetov, Y. Roelens, S. Bollaert, A. Cappy and S. Rumyantsev, App. Phys. Lett., 89, 131926 (2006)
24. D.A. Bandurin, D. Svinitsov, I. Gayduchenko, S.G. Xu, A. Principi, M. Moskotin, I. Tretyakov, D. Yagodkin, S. Zhukov, T. Taniguchi, K. Watanabe, I.V. Grigorieva, M. Polini, G.N. Goltsman, A.K. Geim and G. Fedorov, Nat. Commun., 9, 5392 (2018)
25. V. Eless, T. Yager, S. Spasov, S. Lara-Avila, R. Yakimova, S. Kubatkin, T.J.B.M Janssen, A. Tzalenchuk, V. Antonov, App. Phys. Lett., 103, 093103 (2013)
26. L. Vicarelli, M.S. Vitiello, D. Coquillat, A. Lombardo, A.C. Ferrari, W. Knap, M. Polini, V. Pellegrein and A. Tredicucci, Nature Materials, 11, 865 (2012)