07.3

Laser pulse energy localization in a photoconductive THz emitter via sapphire fibers

© *D.S. Ponomarev*[1], *D.V. Lavrukhin*[1,2], *N.V. Zenchenko*[3], *I.A. Glinskiy*[3], *R.A. Khabibullin*[1,2], *V.N. Kurlov*[4], *K.I. Zaytsev*[5]

[1] Institute of Ultra High Frequency Semiconductor Electronics of RAS, Moscow, Russia
[2] Bauman Moscow State Technical University, Moscow, Russia
[3] MIREA — Russian Technological University, Moscow, Russia
[4] Osipyan Institute of Solid State Physics RAS Russian Academy of Sciences, Chernogolovka, Moscow District, Russia
[5] Prokhorov General Physics Institute of the Russian Academy of Sciences, Moscow, Russia
E-mail: ponomarev_dmitr@mail.ru

Received August 3, 2022
Revised September 21, 2022
Accepted October 10, 2022

We report a seminal approach for localization of photocarriers in a photoconductive antenna (PCA)−emitter via a focusing element comprising the sapphire fiber. Using numerical simulation, we showed that at a certain ratio between the fiber diameter and antenna gap size ($d/g \sim 22.5$), one can attain a $\sim$ 35-fold enhancement of laser irradiation in the vicinity of the PCA electrodes. This provides the formation of subwavelength electromagnetic wave caustics located at the edges of the PCA electrodes, which potentially promotes an increase in the optical−to−terahertz conversion efficiency.

Keywords: terahertz frequency, terahertz emitters, semiconductors, photoconductive antenna, IR radiation.

DOI: 10.21883/TPL.2022.12.54936.19332

Spectrometers and imaging systems based on photoconductive antennas (PCA) are actively used in solving a wide range of fundamental and applied problems [1–3]. The use of PCA in optical time−domain spectroscopy (TDS) makes it possible to get information simultaneously on the amplitude and phase of the received wide−band THz radiation, which increases the efficiency of image restoration algorithms in the tomography and nondestructive testing tasks [4]. One of the topical directions of the THz technology evolution aimed at making TDS systems more compact and cost−effective is transition to PCA pumping by IR fiber lasers without frequency multiplication (at the wavelength of $1.03-1.56\,\mu$m). For this purpose, it is necessary to change over to PCA based on narrow−band photoconductors, e. g., InGaAs.

Despite the technology evolution and advantages of narrow−band materials [5,6], the PCA emitter based on them exhibits the efficiency of laser pump pulse conversion into THz electromagnetic oscillations [7,8] of no more than $\sim$ 1%; this makes it necessary to continue searching for new design solutions.

This paper proposes an original approach to increasing the conversion efficiency by using a special focusing element, namely, profiled sapphire fiber (PSF) mounted on the PCA surface. PSF was selected for this purpose because its refractive index remains high in a wide electromagnetic spectrum range, which gived rise to a significant optical contrast at the fiber/semiconductor and fiber/air interfaces [9]. Using numerical simulation, we showed that at a certain ratio between the fiber diameter and PCA gap width ($d/g \sim 22.5$) it is possible to increase the near−electrode laser pump intensity by ~ 35 times.

Fig. 1 illustrates the proposed concept of laser pumping (a) and the 2D model of PCA used in calculations (b). The calculations employed a photoconductive semi−infinite $In_{0.53}Ga_{0.47}As$ layer with a pair of golden electrodes on the surface. Thickness of the PCA electrode Ti/Au metallization was $0.45\,\mu$m, inter−electrode gap width was $g = 10\,\mu$m, PSF diameter varied from 140 to $240\,\mu$m.

Numerical simulations were performed by the finite−element method using code COMSOL Multiphysics at wavelength $\lambda = 1.56\,\mu$m. Mesh size of the finite−element network varied from $\lambda/8$ in the gap to $\lambda/4$ in other areas. To change over to dimensionless variables, we have introduced parameters (x/g) and (d/g) that are the lateral coordinate and PSF diameter, respectively. Fig. 2, a presents the results of simulation, namely, spatial distribution of power density of the pump electrical field ($\sim |E|^2$) for two characteristic values $d/g = 14$ and ~ 22.5 which correspond to the minimal and maximal radiation localization.

Fig. 2, a clearly demonstrates the formation of subwavelength pump caustics within the InGaAs layer. The pump efficiency I depends on the number of photocarriers that succeed in reaching the PCA electrodes prior to recombination. To estimate this parameter, it is necessary to integrate $|E|^2$ with a weight factor exponentially decreasing

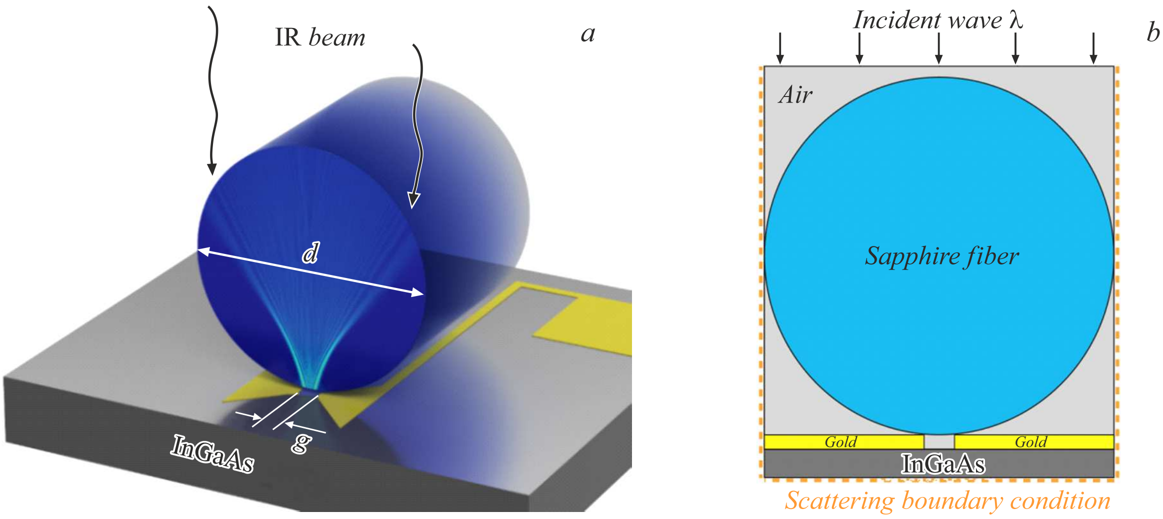

Figure 1. The concept of PCA pumping via PSF mounted on its surface (a) and the 2D-domain design diagram (b).

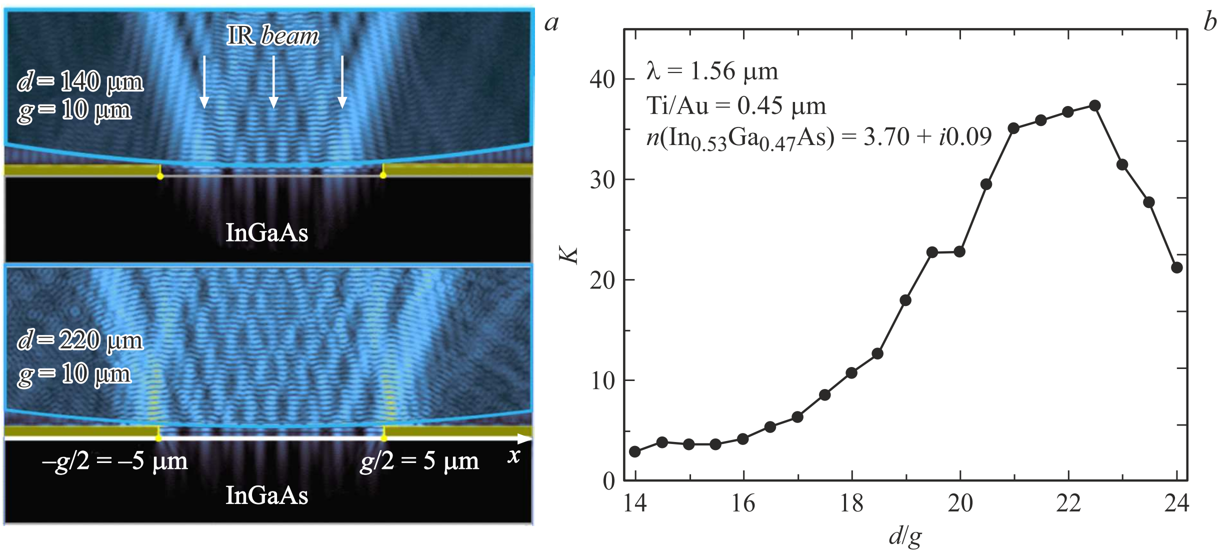

Figure 2. Normalized power density of the pump electric field in the PSF cross−section and photoconductive layer (a) and pump intensity gain factor K (b) for different d/g.

from the edges to the center:

$$I \sim \int_{-0.5g}^{0.5g} |E(x)|^2 e^{-\left(\frac{|x-0.5g|}{l}\right)} dx, \quad K = I_s/I_0, \qquad (1)$$

where $l = 0.3\,\mu$m is the characteristic length of the InGaAs region where photocarriers drift in external field till getting recombined, K is the pump intensity gain factor, indices s and 0 mean integration for PCA with the fiber on the surface and without it, respectively. Fig. 2 presents the calculated $K(d/g)$ dependence. One can see that coefficient K increases monotonically and reaches maximum $K \sim 35$ at $d/g \sim 22.5$. This corresponds to the case when subwavelength caustics are located near the PCA electrode edges thus allowing a larger number of photocarriers to contribute to the THz radiation [11].

Thus, the paper has proposed and theoretically justified a seminal approach to localization of the laser pump pulse near the THz emitter electrodes by using PSF that creats high optical contrast at the fiber/photoconductor interface. It has been shown that in the case of optimal ratio between the fiber diameter and PCA gap width it is possible to create areas of maximal energy localization in the vicinity of electrodes and, thus, to potentially increase the energy conversion efficiency.

Financial support

The study was supported by the Russian Scientific Foundation (project 19-79-10240).

Conflict of interests

The authors declare that they have no conflict of interests.

References

[1] A.I. Romero, A. Mukherjee, A.F. Olvera, M.M. Aller, S. Preu, Nature Commun., **12**, 7091 (2021). DOI: 10.1038/s41467-021-27264-x
[2] A.E. Yachmenev, R.A. Khabibullin, D.S. Ponomarev, J. Phys. D: Appl. Phys., **55** (19), 193001 (2022). DOI: 10.1088/1361-6463/ac43dd
[3] A. Singh, J. Li, A. Pashkin, R. Rana, S. Winnerl, M. Helm, H. Schneider, Opt. Express, **29** (13), 19920 (2021). DOI: 10.1364/OE.427247
[4] P. Fosodeder, S. Hubmer, A. Ploier, R. Ramlau, S. van Frank, C. Rankl, Opt. Express, **29** (10), 15711 (2021). DOI: 10.1364/OE.422961
[5] A. Singh, A. Pashkin, S. Winnerl, M. Helm, H. Schneider, ACS Photon., **5** (7), 2718 (2018). DOI: 10.1021/acsphotonics.8b00460
[6] D.S. Ponomarev, A. Gorodetsky, A.E. Yachmenev, S.S. Pushkarev, R.A. Khabibullin, M.M. Grekhov, K.I. Zaytsev, D.I. Khusyainov, A.M. Buryakov, E.D. Mishina, J. Appl. Phys., **125** (15), 151605 (2019). DOI: 10.1063/1.5079697
[7] D.V. Lavrukhin, A.E. Yachmenev, A.Yu. Pavlov, R.A. Khabibullin, Y.G. Goncharov, I.E. Spektor, G.A. Komandin, S.O. Yurchenko, N.V. Chernomyrdin, K.I. Zaytsev, D.S. Ponomarev, Semicond. Sci. Technol., **34** (3), 034005 (2019). DOI: 10.1088/1361-6641/aaff31
[8] A.V. Gorbatova, D.I. Khusyainov, A.E. Yachmenev, R.A. Khabibullin, D.S. Ponomarev, A.M. Buryakov, E.D. Mishina, Tech. Phys. Lett., **46**, 1111 (2020). DOI: 10.1134/S1063785020110218.
[9] K.I. Zaytsev, G.M. Katyba, N.V. Chernomyrdin, I.N. Dolganova, A.S. Kucheryavenko, A.N. Rossolenko, V.V. Tuchin, V.N. Kurlov, M. Skorobogatiy, Adv. Opt. Mater., **8** (18), 2000307 (2020). DOI: 10.1002/adom.202000307
[10] C.W. Berry, M. Jarrahi, New J. Phys., **14**, 105029 (2012). DOI: 10.1088/1367-2630/14/10/105029
[11] I.A. Glinskiy, N.V. Zenchenko, D.S. Ponomarev, Ros. tekhnol. zhurn., **8** (6), 78 (2020). (in Russian) DOI: 10.32362/2500-316X-2020-8-6-78-86