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RESEARCH ARTICLE

Improving the efficiency of an optical-to-terahertz converter using sapphire fibers

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Abstract
Objectives. The study aims to improve the efficiency of a large-area photoconductive terahertz (THz) emitter based on an optical-to-terahertz converter (OTC) having a radiating area of 0.3 × 0.3 mm^2 for generating high-power THz radiation by using an array of close-packed profiled sapphire fibers having a diameter in the range of 100–300 μm as focusing optics.
Methods. As a photoconductive substrate, we used a semi-infinite LT-GaAs layer (low-temperature grown GaAs; GaAs layer grown by molecular beam epitaxy at a low growth temperature). Additional Si_3N_4 and Al_2O_3 layers are intended for reducing leakage currents in the OTC and reducing the reflection of the laser pump pulse from the air/semiconductor interface (Fresnel losses), respectively, at a gap width of 10 μm. For forming the antenna electrodes and feed strips, the Ti/Au metal system was used. The simulation was carried out by the finite element method in the *COMSOL Multiphysics* environment.
Results. The use of a profiled sapphire fiber whose diameter has been optimized with respect to the gap parameters to significantly increase the concentration of charge carriers in the immediate vicinity of the electrodes of an OTC is demonstrated. The integrated efficiency of a large-area photoconductive THz emitter was determined taking into account the microstrip topology of the array with a characteristic size of feed strips proportional to the gap width in the OTC and with the upper (masking) metal layer. The maximum localization of the electromagnetic field in close proximity to the edges of electrodes at the "fiber–semiconductor" interface is achieved with a profiled sapphire fiber diameter of 220 μm.
Conclusions. By optimizing the diameter of the sapphire fiber, the possibility of improving the localization of incident electromagnetic waves in close proximity to the edges of the OTC electrodes by ~40 times compared to the case without fiber, as well as increasing the overall efficiency of a large-area emitter by up to ~7–10 times, was demonstrated.

Keywords: pulsed terahertz spectroscopy, emitters and detectors of THz radiation, subwavelength radiation, terahertz optical elements and systems, optical-to-terahertz conversion, metalens

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НАУЧНАЯ СТАТЬЯ

Повышение эффективности оптико-терагерцового преобразователя за счет профилированных сапфировых волокон

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Резюме

Цели. Цель работы – повышение эффективности фотопроводящего ТГц-излучателя большой площади на основе оптико-терагерцового преобразователя (ОТП) (излучающая область составляет 0.3 × 0.3 мм^2) для генерации мощного ТГц-излучения с помощью применения в качестве фокусирующей оптики массива плотноупакованных профилированных сапфировых волокон диаметром в диапазоне 100–300 мкм.

Методы. В качестве фотопроводящей подложки использовался полубесконечный слой LT-GaAs (LT, low-temperature grown GaAs – слой GaAs, выращиваемый методом молекулярно-лучевой эпитаксии при пониженной температуре роста). Далее следуют слои Si_3N_4 и Al_2O_3 для снижения токов утечки в ОТП и уменьшения отражения импульса лазерной накачки от границы «воздух/полупроводник» (френелевские потери) соответственно. Ширина зазора составляет 10 мкм, система металлов Ti/Au используется для формирования электродов антенны и подводящих полосков. Моделирование проводилось методом конечных элементов в среде *COMSOL Multiphysics*.

Результаты. Продемонстрирована способность профилированного сапфирового волокна после оптимизации диаметра относительно параметров зазора значительно увеличить концентрацию носителей заряда в непосредственной близости к электродам ОТП. Определена интегральная эффективность фотопроводящего ТГц-излучателя большой площади с учетом микрополосковой топологии массива с характерным размером подводящих полосков, пропорциональным ширине зазора в ОТП, и с верхним (маскирующим) металлическим слоем. Максимальная локализация электромагнитного поля в непосредственной близости к краям электродов на интерфейсе «волокно/полупроводник» достигается при диаметре профилированного сапфирового волокна, равном 220 мкм.

Выводы. Путем оптимизации диаметра сапфирового волокна продемонстрирована возможность увеличения в ~40 раз локализации падающих электромагнитных волн в непосредственной близости к краям электродов ОТП по сравнению со случаем без волокна, а также повышение до ~7–10 раз общей эффективности излучателя большой площади.

Ключевые слова: терагерцовая импульсная спектроскопия, источники и детекторы ТГц-излучения, субволновая фокусировка излучения, терагерцовые оптические элементы и системы, оптико-терагерцовая конверсия, металинза

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INTRODUCTION

Today, optical-to-terahertz converters (OTCs) are widely used in terahertz (THz) spectroscopy systems for generating and detecting broadband THz radiation [1]. Due to the flexibility of their manufacturing technology (the possibility of variations in the topology and geometry of antenna electrodes, as well as the choice of photoconductive semiconductor material) OTCs are of considerable interest for creating single-channel and multi-channel detection systems for imaging objects in the THz range [2, 3].

However, the efficiency of OTC emitters is limited by the fact that only a small fraction of the laser pump pulse energy is converted into THz electromagnetic oscillations [4, 5]. One approach for increasing efficiency is to structuring electrode edges by forming periodic metallic (plasmonic) nanostructures in the antenna gap [4–7]. An alternative approach to plasmonic is based on dielectric structures, which are not subject to ohmic losses and overheating with Joule heat generation, allowing the laser pulse to be focused to form local caustics [8–10]. By localizing optical radiation, the efficiency of pump energy transfer to the photoconductive layer can be significantly increased (about 7-fold), leading to improved THz radiation generation efficiency by increasing photocurrent density [6]. The paper describes a means by which this effect can be achieved using lenses based on profiled sapphire fibers (PSF) with diameters of 100–300 μm. Such fibers allow a significant amount of energy to be focused along the entire electrode surfaces of the photoconductive THz emitter [7].

Previously, the formation of subwavelength local caustics (regions of maximum concentration of charge carriers) at the interface with semiconductor have been described [10]. Due to high refractive index of sapphire in a wide range of the electromagnetic spectrum [11], a significant optical contrast at the “fiber–semiconductor” interface can be created, thus allowing localizing photo-excited charge carriers fundamentally near OTC electrodes (at optimum fiber diameter). Localization (focusing) results in increased efficiency of the pump energy transfer into photoconductor and improved THz generation power due to the increase in the photocurrent density [12].

SIMULATION

In the present paper, a large-area photoconductive THz OTC-based radiator concept (with an emitting region is 0.3 × 0.3 mm^2) for generating powerful THz radiation is proposed, in which an array of densely packed PSFs having diameters in the range of 100–300 μm, manufactured by the Bauman Moscow State Technical University, Russia, is used as the focusing optics. The OTC model and the cross section of the structure is shown in Fig. 1; here, *d* is the PSF diameter, *g* is the gap size between electrodes, and *a* is diameter of the pulsed laser pump beam.

The OTC was created at the V.G. Mokerov Institute of Ultra High Frequency Semiconductor Electronics of the Russian Academy of Sciences (IUHFSE RAS, Russia). The OTC structure comprised a sequence of semiconductor and dielectric layers. The LT-GaAs (LT, low-temperature grown GaAs is the GaAs layer grown by molecular beam epitaxy at reduced growth temperature) was used as photoconductive substrate. The next Si_3N_4 and Al_2O_3 layers were intended to reduce leakage currents in OTC and reduce the Fresnel reflection of laser pumping from the air/semiconductor interface, respectively. The gap width was 10 μm. Gold was used to form antenna electrodes and feeder strips. All technological procedures (in particular,

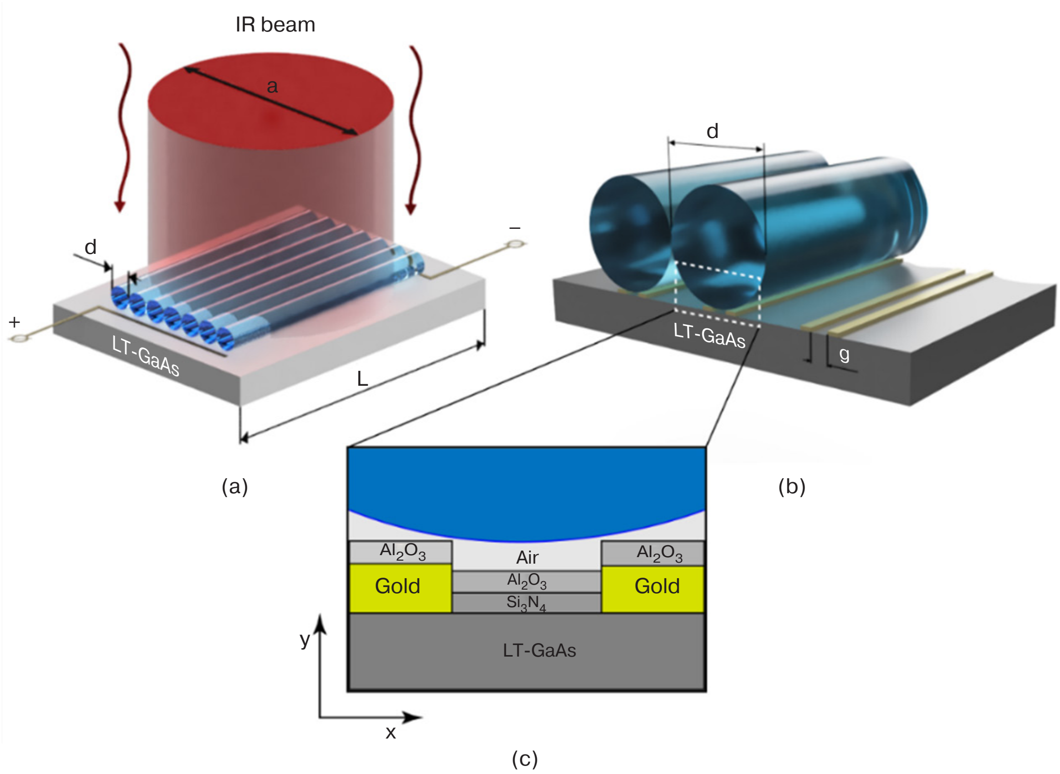

Fig. 1. OTC model (a); enlarged image of the OTC element with focusing optics based on PSF (b); cross-section (c)

deposition of Si_3N_4, Al_2O_3, and gold) were performed at IUHFSE RAS. Further, the resulting substrate was used to create OTC.

The electromagnetic calculation was carried out using the finite element method in the *COMSOL Multiphysics*[1] software environment. The sizes of the finite-element mesh were varied from λ/8 for the gap region to λ/4 for other regions (λ is the wavelength of the laser pumping pulse; in calculations, λ = 780 and 1560 nm). It should be noted that the obtained electromagnetic field distributions for both wavelengths are almost identical due to the optical properties (in particular, the refractive index) of PSF samples differing only to the second decimal place. The electric field propagation vector of the laser pump pulse is oriented along the normal to the OTC surface. The parameter (x/g), where x is the lateral coordinate, was used to make the solution dimensionless and scale simulation results for different PSF diameters (d) and gap sizes (g). The results of simulating the spatial distribution of the electromagnetic wave (EMW) electric field square for three different values of d/g = 14, 18, and 22 are shown in Fig. 2.

[1] https://www.comsol.ru/. Accessed February 01, 2022 (in Russ.).

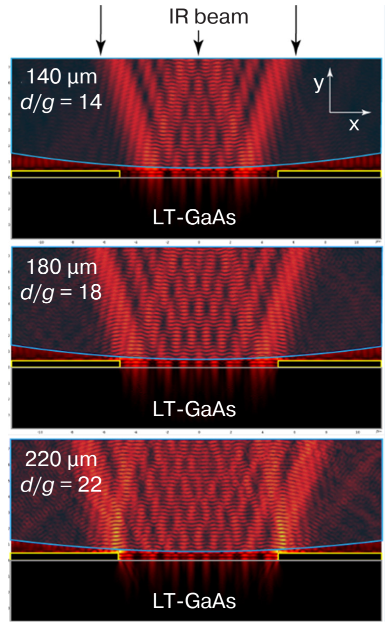

Fig. 2. EMW distribution for different values of parameter d/g

The EMW distribution patterns clearly show subwavelength caustics (characteristic regions of maximum localization of the laser pumping field in the semiconductor) formed near OTC electrodes. The size of the caustics is observed to increase with increasing ratio (d/g) to reach its maximum (in other words, the maximum localization of the laser pump pulse energy) at $d/g = 22$.

The intensity of the electromagnetic field in the OTC gap region is integrated in the following way to qualitatively estimate the number of photoexcited charge carriers that can reach OTC electrodes before their recombination in the semiconductor:

$$I = \int_{-g/2}^{g/2} |E^2(x)| \exp\left(-(|x - g/2|)/r_d\right) dx,$$

where r_d characterizes the drift length for charge carriers.

Typical values r_d = 100, 300, and 500 nm are selected based on the characteristic values of saturated velocities and carrier lifetime in LT-GaAs [13, 14]. Then, the coefficient of the EMW intensity increase (K) is introduced to quantify the degree of localization of the laser pump pulse in the OTC gap; this is determined by the ratio between integrals I_s and I_0, where I_s and I_0 are calculated both for the case of OTC with PSF and without it, respectively. The simulation results are shown in Fig. 3.

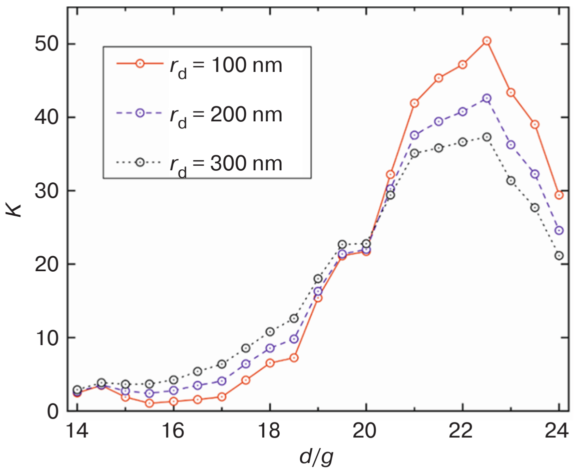

Fig. 3. Coefficient of the EMW intensity increase in the gap

It can be seen that all three curves (corresponding to different r_d values) retain their shape, thus confirming the calculation correctness, while the coefficient K value monotonically increases with increasing parameter d/g reaching its maximum of ~40 at $d/g = 22$. It should be noted that this value characterizes the case when the subwavelength caustics are located strictly at the edges of OTC electrodes, thus allowing a larger number of photoexcited charge carriers to contribute to THz radiation generation. The latter, in turn, results in the increasing photocurrent generated by OTC and potentially increases the efficiency of the optical-THz conversion.

Based on the calculation results obtained, the integral efficiency K of the large-area photoconductive THz emitter with allowance for the microstrip array topology with the characteristic size of feed strips proportional to the gap width in OTC and with an upper (masking) metal layer can be estimated as:

$$K \sim I_s(a/d)/I_0(a/4g) = 4K(d/g)/(d/g),$$

where parameter a characterizes the typical spot diameter of laser pump pulse (1.0–1.5 mm), while digit 4 corresponds to the period of microstrip array structure consisting of two photoconductive gaps and two widths of feed strips.

Possible approaches for the optimization of the design of the large-area THz emitter using PSF should also be noted. As shown in Fig. 1a, the laser beam covers $n = a/d$ of fibers. It would be logical to reduce both the PSF diameter and the gap size for increasing the power of THz radiation generation. However, the decrease of the gap is equivalent to a sharp increase in the electric field strength due to decreasing distance between two adjacent metal strips. This significantly increases the probability of electrical breakdown in LT-GaAs (especially, in photoconductors for IR laser radiation pumping—with relatively small band gap width, for example, InGaAs). In other words, "lower" boundary values for d and g in practice would be: g ~ 3–5 μm, d ~ 100 μm. In addition, any reduction in the gap width imposes additional requirements on the accuracy of PSF alignment with the surface of the OTC sample. According to our estimates, the number of adjoining radiating elements with microstrip topology for the large-area THz emitter should not exceed 10. In this case, the combination of OTC + PSF is arranged so as to achieve maximum efficiency.

CONCLUSIONS

The paper proposes using an array of lenses made of sapphire fiber to increase the efficiency of the large-area photoconductive THz emitter. Using numerical simulation, each lens is shown to provide spatial redistribution of the density of photoexcited charge carriers in the gap between electrodes of single antenna. By optimizing the diameter of the sapphire fiber, the possibility of increasing the localization of incident EMWs in close proximity to the edges of OTC electrodes by ~40 times compared to the case without fiber, as well as increasing to ~7–10 times the overall efficiency of the large-area radiator is demonstrated.

Since the incident laser beam has the diameter of 1.0–1.5 mm in practice, the number of pairs of strip lines on the large-area THz emitter crystal is about 5 at d = 220 μm and g = 10 μm. Therefore, 10 pairs of strip lines with 5 μm gap (d = 110 μm) may be used for increasing the performance of a large-area THz emitter.

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Authors' contributions

N.V. Zenchenko—numerical simulation of OTC.

D.V. Lavrukhin—methodology for calculating the enhancement coefficient for the intensity of the EMW in the OTC.

I.A. Glinskiy—numerical simulation of OTC.

D.S. Ponomarev—project management.

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