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# Waveguide-integrated graphene terahertz detector

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**Abstract.** Terahertz (THz) integrated circuits is a promising platform to create low cost and efficient components for high-speed sixth-generation (6G) communication networks. One of the key components for this application is detectors and mixers integrated on THz silicon waveguide. Graphene, due to its unique and tunable properties such as zero band gap, high charge mobility and low electronic heat capacity, has already demonstrated promise in free space THz detectors, mixers and modulators development. Moreover, graphene photodetectors integrated on the waveguide have already been demonstrated in visible and near infrared regions. In this work we present an electromagnetic model of graphene terahertz detector integrated on silicon waveguide. Graphene THz detector was designed for operation at 150 GHz and can be used in the next-generation wireless communications for an ultrafast on-chip THz signal processing.

**Keywords:** terahertz, dielectric waveguide, photonic-integrated circuit, dielectric effective-medium waveguide

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# Терагерцовый графеновый детектор, интегрированный на волновод

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**Аннотация.** В данной работе представлено электромагнитное моделирование терагерцового фотодетектора на основе графена, интегрированного на кремниевый волновод. Этот детектор, рассчитанный на работу на частоте 150 ГГц, может быть использован в сетях связи шестого поколения (6G) для высокоскоростной обработки терагерцовых сигналов на чипе. Графен, благодаря своим уникальным свойствам, таким как нулевой зазор, высокая подвижность заряда и низкая электронная теплоемкость, является перспективным материалом для создания терагерцовых детекторов, смесителей и модуляторов.

**Ключевые слова:** терагерцы, диэлектрический волновод, фотонная интегральная схема, волновод с эффективной диэлектрической средой

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## Introduction

The development of 6G mobile networks involves the use of the terahertz (THz) spectrum band, which plays a key role in enabling high-speed data transmission of up to one terabit per second over long distances via wireless networks [1]. At present, existing THz systems are quite bulky as they consist of separate components: transmitter, receiver, hollow metal waveguides. The creation of THz waveguides based on dielectrics opens up the possibility of creating a compact system for signal transmission and processing. To date, several attempts have been made to integrate various THz detectors on a silicon waveguide: Schottky diodes [2], resonant tunnel diodes [3] and hot electron bolometers (HEB) [4]. In the case of Schottky diodes and resonant tunnel diodes commercial detectors are welded on top of the silicon waveguide, which results in inefficient radiation coupling as well as difficulties in mass production. Hot electron bolometers require cryogenic temperatures, which limits the range of its potential applications.

In this paper we propose to use graphene to develop a THz detector integrated on silicon waveguide. Graphene is characterised by its broad light absorption spectrum [5], ease of fabrication and integration on various substrates, high light response rate [6] and tunable electrical and optical properties [7, 8], making it ideal for use in photonic and optoelectronic devices [8, 9]. Moreover, graphene has been already proved as a perspective material for the development of THz detectors in free space [10], as well as integrated photodetectors in the visible and near-IR range [11]. Here, we present an EM model of graphene THz detector integrated on silicon waveguide. Graphene THz detector was designed for operation at 150 GHz and can be used in the next-generation wireless communications for an ultrafast on-chip THz signal processing.

## Results and Discussion

Currently, there are several implementations of dielectric waveguides: ribbon, photonic crystal and effective dielectric medium [12]. In this paper, we investigated the implementation of a waveguide based on an effective dielectric medium, as this approach enables the creation of waveguides with larger bandwidth [13]. To simulate an effective dielectric medium, it is necessary to create through-holes with a period smaller than the wavelength on the sides of the waveguide core. These holes form a triangular lattice with a constant $a$ = 132 μm and a hole radius $r = d/2$= 38.5 μm (see Fig. 1, *a*). The fill factor for this lattice is $\zeta = 2\pi r^2/a^2\sqrt{3} = 0.327$. The dielectric permittivity around the waveguide can be calculated using the equations $\varepsilon_{TE} = \varepsilon(1 + \zeta + \varepsilon(1 - \zeta))/(1-\zeta + \varepsilon(1 + \zeta))$ and $\varepsilon_{TM} = \zeta + \varepsilon(1 - \zeta)$. For our calculations, we used permittivity values of 11.9 for silicon and 1 for air. Consequently, the permittivity of the effective dielectric medium was determined to be $\varepsilon_{TE}$ = 6.8 and $\varepsilon_{TM}$ = 8.4 for the two polarizations. In this configuration, the waveguide operates on a principle akin to that of an optical fibre, where light propagates via total internal reflection. To couple radiation from a metal waveguide into a dielectric one, a silicon taper with an opening angle α = 10° was employed.

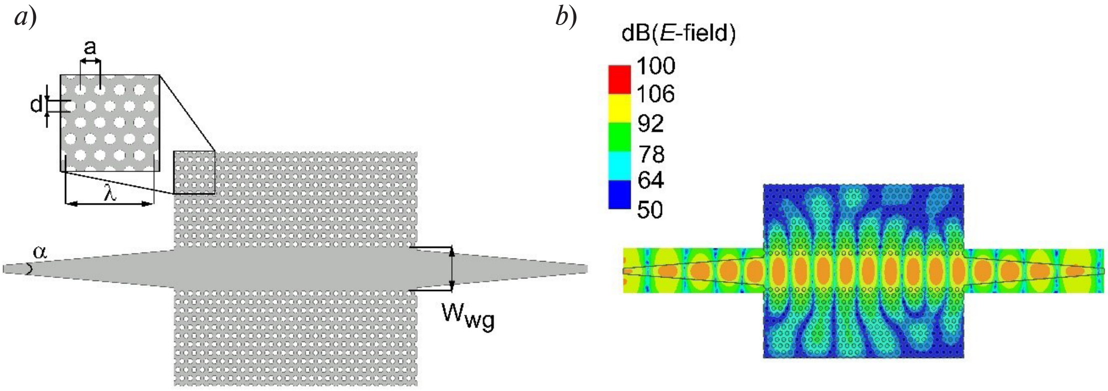


Fig. 1. Schematic illustration of a silicon waveguide with tapered (*a*) and electromagnetic model of a 150 GHz silicon waveguide (*b*)

Electromagnetic modelling was conducted using the Ansys Electronics program, employing the finite element method. The waveguide utilised was a silicon wafer with a thickness of $H_{wg}$ = 400 μm and width $W_{wg}$ = 585 μm. The dielectric constant of silicon was 11.9. Two waveguide ports (ports 1 and 2) were used to excite radiation in the structure at a frequency of 150 GHz (see Fig. 1, *b*). The waveguide was flanked by quarter-wave vacuum inserts with radiation boundary conditions.

Graphene was selected as the detecting material, showing promise for the development of THz radiation detectors [10]. The wavelength λ of electromagnetic radiation in silicon is 0.5 mm, necessitating detectors with larger working areas. This requirement increases the heat capacity of graphene, leading to a reduction in detector sensitivity. To enhance the absorption of electromagnetic radiation emitted from the waveguide by graphene, we are considering the implementation of a tapered slot line [4]. This approach reduces the graphene area to a 2×2 micron square, thereby improving detector sensitivity. The detector design incorporates asymmetric contacts, which have proven effective in graphene THz detector fabrication, leveraging both photovoltaic and thermoelectric effects [14].

The electromagnetic model of the detector was calculated on a dielectric waveguide of the ribbon type in order to facilitate the calculations (see Fig. 2, *a*). At the centre of the ribbon, a tapered slot line with a length of $L_{tsl}$ = 1287 μm, made of gold plates, was positioned with a concentric port (port 3). Fig. 2, *b* shows the optimal aperture angle θ = 165°. Graphene with a resistance of 500 ohms was chosen as the detection material for the third port. For this configuration, reflection and transmission coefficients were observed with values of $S33 = -10$ dB and $S31 = S32 = -4.3$ dB.

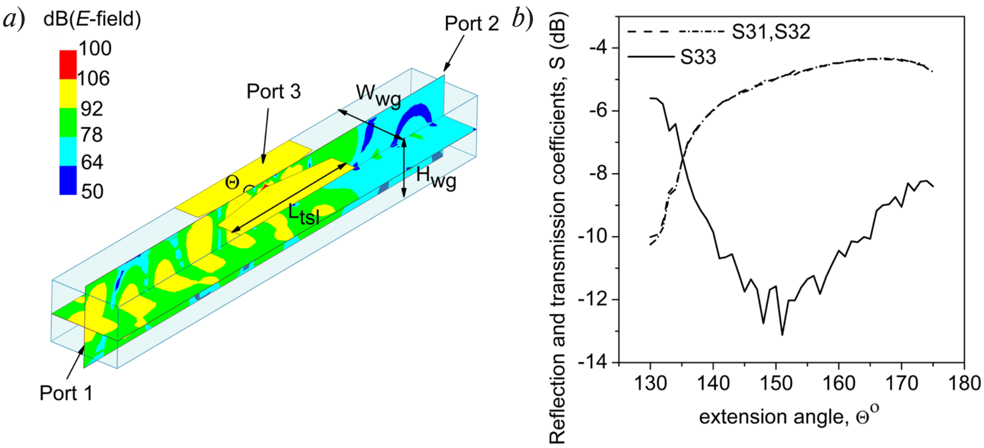


Fig. 2. Electromagnetic model of 150 GHz silicon ribbon waveguide with graphene detector (*a*) and dependence of reflection and transmission coefficients on opening angle θ (*b*)

## Conclusion

A EM model of graphene-based photodetector integrated on silicon photonic crystal waveguide has been demonstrated. The design has been evaluated by electromagnetic modelling, resulting in an input loss of 0.18 dB. Reflection and transmission coefficients are observed for a graphene photodetector structure with values of $S33 = -10$ dB and $S31 = S32 = -4$ dB. The graphene THz detector was designed to operate at 150 GHz and can be used in next-generation wireless communications for ultrafast on-chip THz signal processing. The ease with which graphene CVD films and flakes can be transferred allows for the fabrication of detectors on waveguides based on two-dimensional materials.

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