

TUNABLE REFRACTIVE INDEX SENSOR MADE USING GRAPHENE WITH A HIGH FIGURE OF MERIT

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Plasmonic effects can be used in high sensitivity sensors, which have attracted widespread attention. However, most of the previously reported refractive index sensors can no longer be adjusted once fabricated, and their figure of merit (FOM) is undesirable. Concerning this, we propose a refractive index sensor consisting of a graphene waveguide and a graphene elliptical cavity working in the mid-infrared range. Its performance can be adjusted in real time by applying a bias voltage to the graphene patterns. The sensitivity of the proposed sensor can reach 2850/refractive index unit and FOM up to 633, respectively. Owing to its excellent sensing properties of high sensitivity and high FOM, the proposed sensor can be applied in gas sensing.

Keywords: graphene waveguide, gas sensing, high figure of merit, mid-infrared range.

ВЫСОКОЭФФЕКТИВНЫЙ ПЕРЕСТРАИВАЕМЫЙ СЕНСОР ПОКАЗАТЕЛЯ ПРЕЛОМЛЕНИЯ НА ОСНОВЕ ВЫСОКОКАЧЕСТВЕННОГО ГРАФЕНА

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Разработан сенсор показателя преломления, состоящий из графенового волновода и графенового эллиптического резонатора, работающего в среднем ИК-диапазоне. Производительность можно регулировать в режиме реального времени, прикладывая напряжение смещения к паттернам графена. Чувствительность предлагаемого датчика 2850/отн. ед, показатель качества 633. Благодаря высоким чувствительности и показателю качества датчик может применяться для обнаружения различных газов.

Ключевые слова: графеновый волновод, определение газа, высокая добротность, средний ИК-диапазон.

Introduction. Graphene has been studied and used in many fields because of its outstanding photoelectric properties [1]. In particular, graphene is superior to traditional materials such as gold and silver in the near-field confinement of guided electromagnetic waves [2]. Surface plasmon polaritons (SPPs) propagating along the graphene surface can break the limit of diffraction and make it possible to manipulate a light field on subwavelength scales [3–6]. The electromagnetic field on graphene plasma shows a strong spatial confinement ability, which can enhance the interaction between light and matter and has a lower transmission loss [7–13]. Therefore, graphene deserves more research and investment in the sensing field.

The mid-infrared range (MIR) is particularly suitable for sensing research because it contains most of the biometric fingerprints [14]. More importantly, researchers can obtain key biological information by analyzing absorption spectra without any destructive labels [15, 16]. This method can also be applied to the field of gas sensing [17–19]. In detail, when the gas composition detected around the sensor is different, the refractive index around the sensor will change accordingly. This series of changes can be analyzed and studied through the electromagnetic information on the sensor such as the change of phase or amplitude.

Owing to the excellent sensing advantages of graphene in MIR, many graphene refractive index sensors have been reported. Yan et al. studied a PIT-based nano sensor [20] and reported that its sensitivity (S) and figure of merit (FOM) are 2600 nm/refractive index unit (RIU) and 54, respectively. Wei et al. investigated a cavity resonator-based sensor with a continuous graphene plasmon with a maximum FOM reaching 20.15 [8]. Recently, Wenger et al. introduced a graphene plasmon-based refractive index sensor and found a large bulk FOM of 11 [21]. However, the complex structure and unsatisfactory sensing characteristics limit their applications.

A graphene refractive index sensor working in the MIR is proposed, which consists of an elliptical cavity and a waveguide. There is a Fabry-Pérot (FP) coupling effect on the elliptical cavity and the waveguide. When the refractive index around the sensor is changed, the absorption peak of the sensor transmission spectrum shifts linearly. In the development process, the sensing performance of the sensor is analyzed using CST software. The result shows that the sensitivity of the proposed sensor is 2850 nm/RIU and the FOM up to 633. In addition, the working frequency of the sensor can be flexibly adjusted by changing the bias voltage of graphene. The proposed sensor has a good application prospect owing to its simple structure and excellent sensing performance.

Simulation and principles. Figure 1 shows the proposed sensor 3D structure and parameters. A graphene waveguide and a graphene elliptical cavity with a thickness of 1 nm are placed on the SiO_2 substrate. To save computer resources, the high absorption of SiO_2 substrate in the MIR band is ignored in the simulation. The sensor model is suspended in the airbox and the transverse magnetic wave is transmitted on the graphene waveguide. The detailed structural parameters of the sensor are shown in Fig. 1b. The distance between the graphene waveguide with a width wg and the graphene elliptical cavity with a long radius $L_c/2$ and a short radius $wc/2$ is dis . The energy in the graphene waveguide can be effectively coupled into the adjacent graphene elliptical cavity. The sensors with a graphene waveguide structure have the following two advantages:

(1) Compared with precious metals, graphene SPPs have strong space limitation, lower loss, and good adjustability [22–24].

(2) Compared with the transmissive sensor, the fabrication of this sensor is more convenient and the performance is better. For example, the sensitivity of the transmissive type graphene sensor reaches 2000–3000 nm/RIU [8, 25], whereas the SPP mode (especially the boundary mode) of the graphene waveguide is more local to the electromagnetic field, so it is more sensitive to the refractive index change peripherally, and the sensitivity can reach 4160 nm/RIU [26].

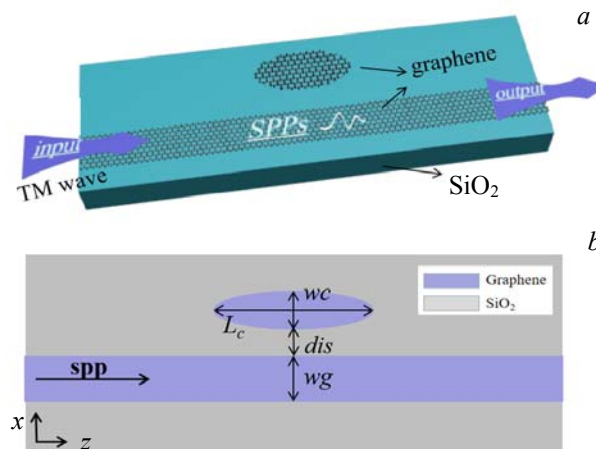


Fig. 1. (a) The 3D structure of the proposed sensor. (b) The schematic of the proposed structure. The optimized parameter values: $wc = 50$ nm, $L_c = 145$ nm, $dis = 50$ nm, $wg = 50$ nm.

Relative permittivity $\epsilon_{GR}=1+i\sigma_{GR}/\omega\Delta\epsilon_0$ is used to characterize the electrical property of graphene in a finite integral simulation, and the graphene surface conductivity σ_{GR} can be derived by calculating the Kubo formula as [27]:

$$\sigma_{GR} = \sigma_{inter}(\omega, \mu_c, \Gamma, T) + \sigma_{intra}(\omega, \mu_c, \Gamma, T), \quad (1)$$

$$\sigma_{inter}(\omega, \mu_c, \Gamma, T) = \frac{je^2}{4\pi\hbar} \ln\left(\frac{2|\mu_c| - (\omega + j2\Gamma)\hbar}{2|\mu_c| + (\omega + j2\Gamma)\hbar}\right), \quad (2)$$

$$\sigma_{intra}(\omega, \mu_c, \Gamma, T) = \frac{je^2 k_B T}{\pi\hbar^2 (\omega + j2\Gamma)} \left(\frac{\mu_c}{k_B T} + 2 \ln(e^{-\mu_c/k_B T} + 1) \right), \quad (3)$$

$$|\mu_c| = \hbar v_F \sqrt{\pi |a_0 (V_g - V_{Dirac})|}, \quad (4)$$

where k_B is Boltzmann's constant, e is the electron charge, and $\hbar$ is Planck's constant, T is the temperature and has a value of 300 K, μ_c is the chemical potential of graphene and 2Γ accounts for the intrinsic losses defined as the ratio of $\hbar$ to the electron-phonon relaxation time τ . We assumed $\Gamma = 0.1$ meV according to the theoretical estimation of the maximum mobility in graphene [28]. In Eq. (4), $a_0 \approx 9 \times 10^{16} \text{ m}^{-1} \text{ V}^{-1}$, v_F is the Fermi velocity of Dirac fermions in graphene, $|V_g - V_{Dirac}|$ can be considered as the bias voltage [29]. To get the graphene conductivity in MIR, we set the wavelength within the range from 6000 to 7000 nm and assume various μ_c in MATLAB software. Finally, we export the result of the graphene conductivity to CST Studio Suite. After comparison, the conductivity and loss characteristics of graphene used in this sensor simulation are consistent with the experimental test [30, 31]. Moreover, the value of the conductivity is changeable by applying a bias voltage to adjust the chemical potential for graphene according to Eq. (4). It is useful to optimize the sensor or regulate the working band using the characteristic above.

To understand the working principle of the sensor, the electric field distributions of the sensor are analyzed. First, a single graphene waveguide without a graphene elliptical cavity is simulated. By observing the electric field distribution at the graphene waveguide's surface and port (Fig. 2a), the energy is mainly concentrated at the edge of the graphene waveguide, the graphene waveguide with $w_g = 50$ nm supports the symmetric hybridized edge graphene surface plasmons (EGSP) mode. Then, the complete sensor model is simulated (Figs. 2b,c), and the sensor model is placed in a rectangular box filled with gas with a refractive

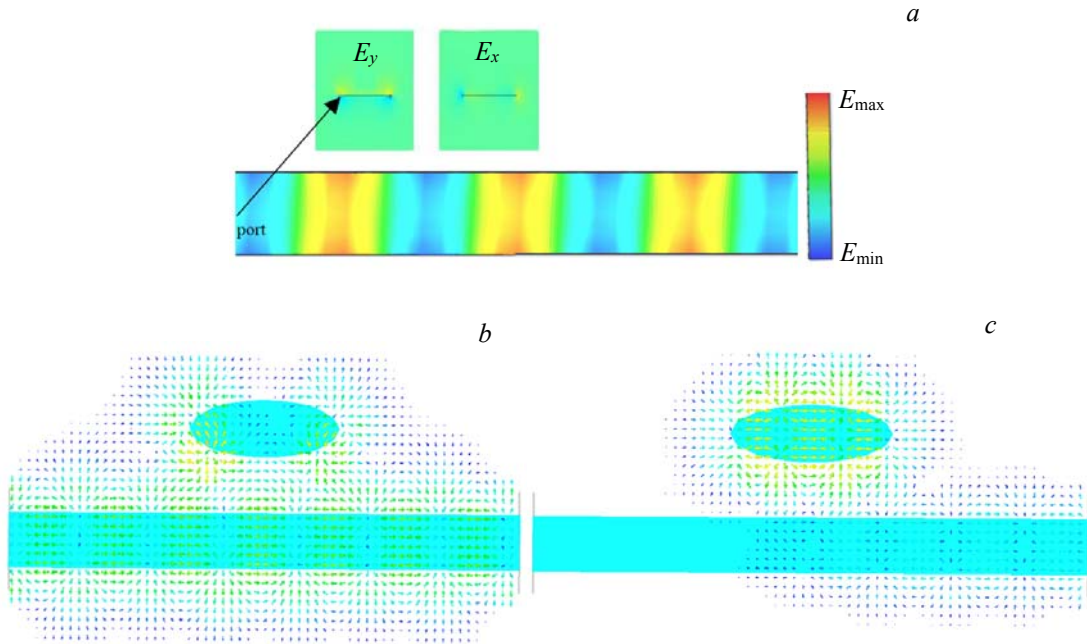


Fig. 2. The electric field distribution of the sensor, $\mu_c = 0.3$ eV. (a) The electric field distribution of the single ribbon waveguide and port; (b) the electric field distribution of the proposed sensor at 6600 nm; (c) the electric field distribution of the proposed sensor at 6575 nm.

index n . Figure 2b shows that SPPs can be well transmitted on the graphene waveguide when the graphene cavity does not produce resonance, and the induced electric field is generated around the graphene cavity, but there is almost no electric field energy in the cavity. Figure 2c shows that the electric field distribution on the graphene waveguide is coupled into the graphene cavity when the graphene cavity produces resonance. The FP resonance is formed between the graphene elliptical cavity and the graphene waveguide. The graphene elliptical cavity works as a resonator when satisfying:

$$\lambda_m = 2n_{\text{eff}}L_c/m, \quad (5)$$

where λ_m , m , L_c , and n_{eff} are the resonant wavelength, the resonance order, the resonator length, and the effective index of the guided mode in the resonator, respectively.

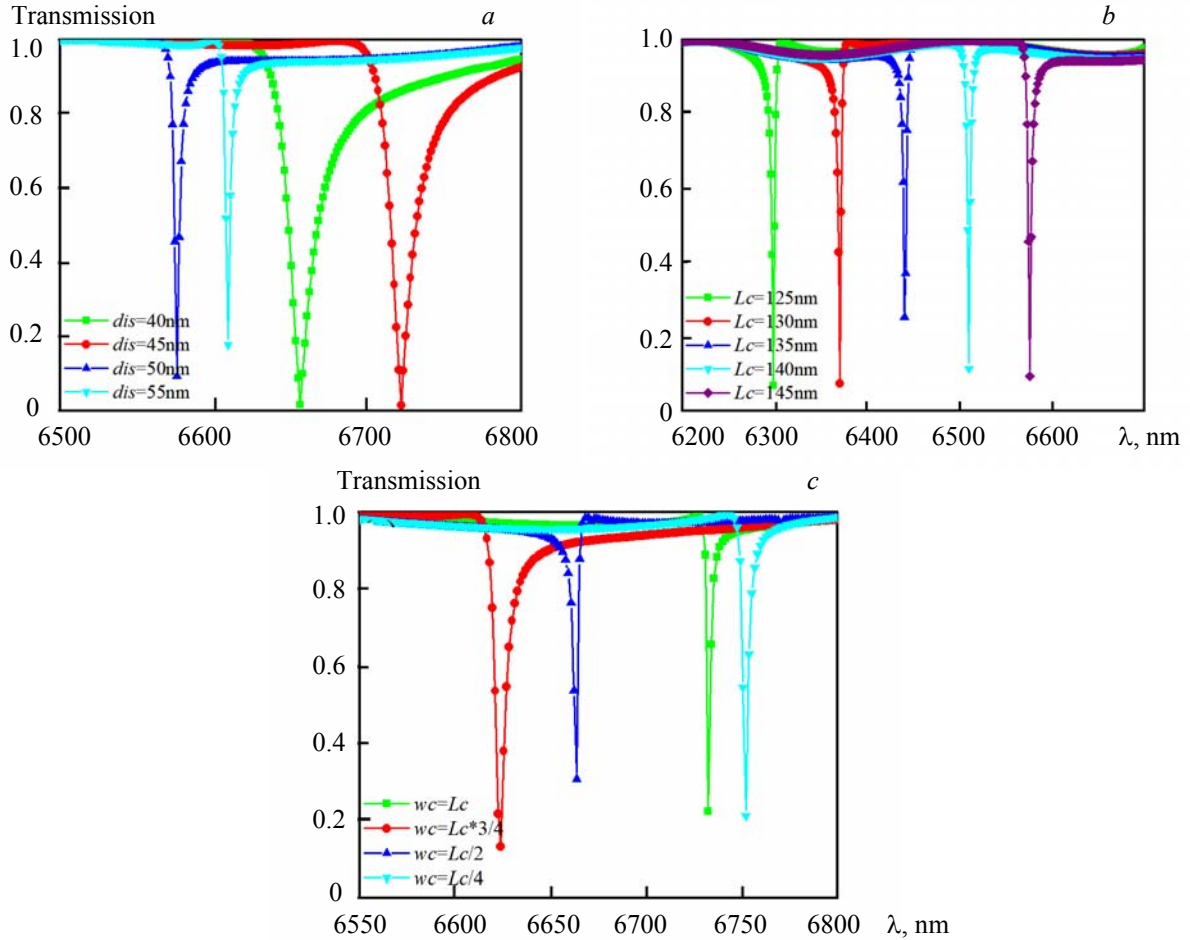


Fig. 3. Transmission spectra of (a) the different distance dis between the waveguide and the elliptical resonator; (b) the different ellipses with different L_c ; (c) the elliptical resonator with different w_c .

Parameter analysis. The impact of different parameters on the sensor is analyzed to understand the working principle and obtain better performance. Through theoretical and simulation analysis, the performance of the proposed sensor is mainly affected by three parameters, the distance from the graphene elliptical cavity to the graphene waveguide dis , the length of the graphene elliptical cavity L_c , and the shape of the graphene elliptical cavity. It should be noted that other parameters remain unchanged when one parameter is analyzed; dis between the graphene waveguide and the graphene elliptical cavity mainly controls the degree of coupling to SPPs between the graphene waveguide and the graphene elliptical cavity. Hence, the degree of coupling and resonance sharpness is in negative and positive correlation with dis , respectively. It can be seen from Fig. 3a that with the increase in dis , the resonance sharpness is improved, but the coupling degree is weakened. To better balance the coupling degree and resonant sharpness to obtain a better sensing performance, $dis = 50\text{ nm}$ was finally selected.

On the other hand, the electromagnetic energy does not change obviously when the long radius of the resonator changes but only the position of the resonant wavelength peak moves. Figure 3b shows that the resonant wavelength position alters when we vary the resonator length L_c from 125 to 145 nm. Equation (5) is responsible for this. Some researchers previously thought that this could be applied to realize the adjustability of the working wavelength band.

The S and FOM are usually used to evaluate the sensing performances, which are defined as

$$S = \Delta\lambda/\Delta n, \quad (6)$$

$$\text{FOM} = S/\text{FWHM}, \quad (7)$$

where $\Delta\lambda$ is the variation of the resonance wavelength induced by the refractive index change Δn . The FWHM is the full width at half maximum of the absorption spectrum that can be used to evaluate the performance of the sensor.

Then we investigate the impact of the shape of the elliptical cavity on the sensor performance by varying the short radius. As follows from Fig. 3c, there is no obvious linear dependence here, different values wc are related to different FWHMs. Table 1 gives the FWHM and FOM corresponding to different wc in detail. It can be seen from the table that when $wc = L_c/4$, the width of the resonance valley is the narrowest, the FWHM reaches 4.5 nm, and at this time the FOM is as high as 622. When $wc = L_c$, that is, the resonant cavity is circular, the FOM is only 268. This also explains the higher quality factor of the elliptical cavity.

TABLE 1. Different FWHM and FOM with Different Ratios of wc to L_c

wc/L_c	FWHM	FOM
1/4	4.5	622
1/2	8	355
3/4	5.1	553
1	11	268

Results and discussion. The geometrical parameters of the conventional sensor can be adjusted only during fabrication, which indicates that the working frequency of the sensor cannot be adjusted. Therefore, we further consider an active working band by changing the chemical potential μ_c of graphene. The transmission spectra in Fig. 4 indicate that the sensor with graphene can operate within a wide range of the MIR band by applying an external bias voltage. In the simulation, a layer of conductive gel is laid on the graphene strip and elliptical cavity to realize the control of the bias voltage on the chemical potential of graphene, and the addition of conductive gel has little effect on the experiment [32]. There is a redshift of the plasmonic resonance when we enlarge the chemical potential of graphene in Fig. 4a, where the depth of the spectra and the FWHM are almost unchanged. As shown in the left axis of Fig. 4b, the resonance frequency of the sensor changes linearly with the increase in the chemical potential. When the chemical potential increases by 0.01 eV, the resonance frequency increases by 1.12 THz. The right axis of Fig. 4b shows that different μ_c have an impact on the FOM, which can remain above 615, with the maximum FOM reaching 690.

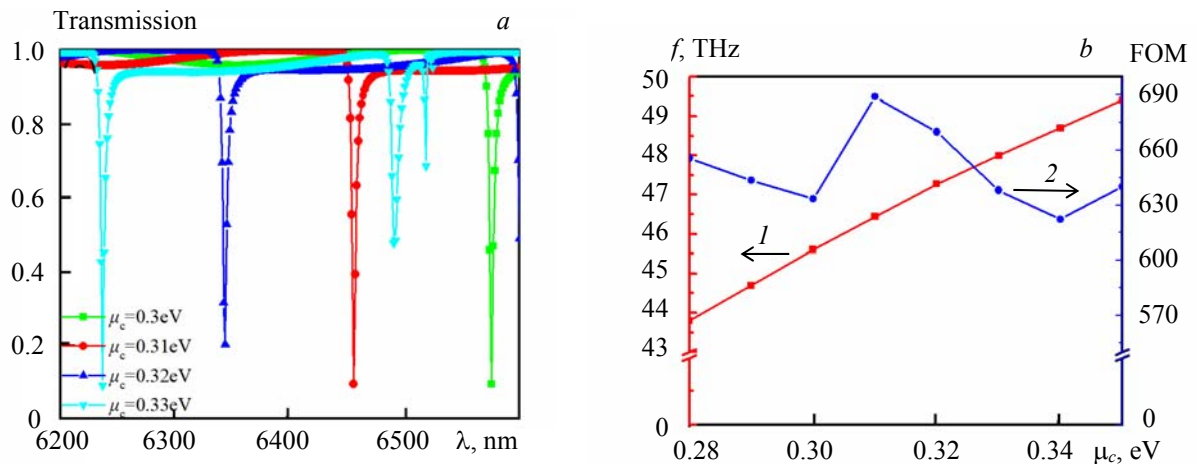


Fig. 4. (a) Transmission spectra with different chemical potentials μ_c of graphene from 0.30 to 0.33 eV; (b) resonance frequency (1) and FOM (2) under different chemical potentials.

As the refractive index n of the surrounding environment of the sensor changes, the wavelength of the resonant peak changes linearly. It follows from Fig. 5 that there is a deep valley with an extremely narrow FWHM (about 4.5 nm), and the valley shifts $\Delta\lambda$ can reach 57 nm if the n changes by 0.02. It means that the plasmonic mode changes when the gas around the sensor changes. Meanwhile, we have high sensitivity (nearly 2850 nm/RIU). According to Eq. (7), the FOM at this time is as high as 633. Let us compare the proposed sensor with the one represented in Zhang and Cui [33] with a sensitivity of 1268 nm/RIU and a FOM as high as 280. It is seen that the performance of this sensor is lower than that proposed by us. The performance comparison with other reported MIR sensors are given in Table 2. It can be seen that its sensitivity and FOM are higher than those of other refractive index sensors [8, 20, 22, 33].

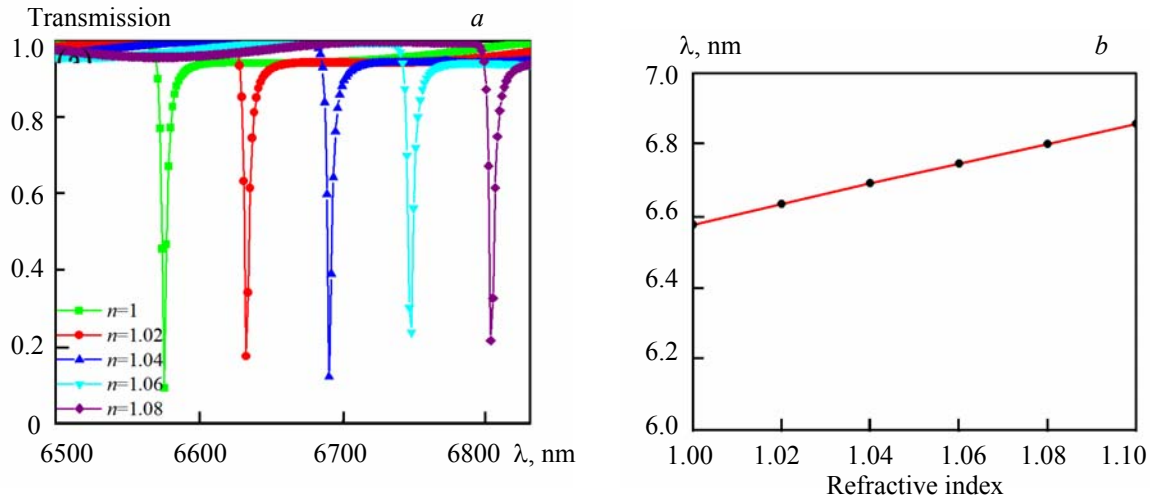


Fig. 5. (a) Transmission spectra of different refractive indices n of the environment, $\mu_c = 0.3$ eV; (b) variation of the resonance wavelength with a refractive index.

TABLE 2. Comparison with the Reported MIR Sensor

Ref.	[8]	[20]	[22]	[33]	This work
Adjustable	YES	YES	YES	NO	YES
S	—	2600 nm/RIU	—	1268 nm/RIU	2850 nm/RIU
FOM	20.15	54	11	280	633

Conclusions. We propose a graphene-based refractive index sensor with a high figure of merit including a waveguide coupled with an ellipse resonator structure. This sensor can support a tunable operating frequency band. Full-wave electromagnetic simulator software, CST Studio Suite, is used to optimize the structure and investigate the impact of the correlation parameters (distance between the elliptical resonator and the waveguide, length of the elliptical resonator, and shape of the resonator) on the device performance. The revealed results indicate that this sensor yields an ultrahigh sensitivity of 2850 nm/RIU and a figure of merit up to 633 in the mid-infrared band; furthermore, this graphene-based waveguide sensor with a simple structure could be manufactured easily.

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