Surface Electromagnetic Performance Analysis of a Graphene-Based Terahertz Sensor Using a Novel Spectroscopy Technique

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Abstract

In this paper, a novel terahertz (THz) spectroscopy technique and a new graphene-based sensor is proposed. The proposed sensor consists of a graphene-based metasurface (MS) that operates in reflection mode over a broad range of frequency band (0.2 – 6 THz) and can detect relative permittivity of up to 4 with a resolution of 0.1 and a thickness ranging from 5 μm to 600 μm with a resolution of 0.5 μm . To the best of author's knowledge, such a THz sensor with such capabilities has not been reported yet. Additionally, an equivalent circuit of the novel unit cell is derived and compared with two conventional grooved structures to showcase the superiority of the proposed unit cell. The proposed spectroscopy technique utilizes some unique spectral features of a broadband reflection wave including Accumulated Spectral power (ASP) and Averaged Group Delay (AGD), which are independent to resonance frequencies and can operate over a broad range of the spectrum. ASP and AGD can be combined to analyse the magnitude and phase of the reflection diagram as a coherent technique for sensing purposes. This enables the capability to distinguish between different analytes with high precision which, to the best of author's knowledge, has been accomplished for the first time.

Index Terms

Terahertz sensor, Terahertz spectroscopy, Graphene, Localized surface plasmon, Electromagnetic surface wave, Metasurface, Bloch impedance.

I. INTRODUCTION

IN recent decades, many researchers have described the Terahertz (THz) spectrum as being "underdeveloped" and as a "THz gap" due to the unavailability of sources, modulators and detectors in this range of the electromagnetic spectrum [1]. However, an increasing number of studies have revealed various advantages and potential uses of terahertz waves for different applications [2]. Though the problem related to signal attenuation for long-range THz communications is well known, there has been a growing interest in the THz technology for various applications that require near-field and short-range communications [3], [4]. Several studies have explored the unique capabilities of terahertz radiation to interact with material vibrations which has motivated the scientific community to evaluate terahertz technology for several non-destructive applications in imaging, spectroscopy and sensing [5], [6]. Analysing certain materials and biological tissues using THz radiation is considered quite attractive as it offers higher spatial resolution and safety as compared to some of the traditional methods which are based on x-ray and infrared technology [7]. This has tempted many researchers in the field of spectroscopy and imaging to further evaluate the capabilities of THz frequencies [8]–[10]. Recent advances in the techniques related to THz generation and detection have motivated researchers to apply THz waves for analyzing different materials using time-domain as well as frequency-domain THz spectroscopy.

The THz time-domain spectroscopy (TD-S) is a coherent method that simultaneously measures the amplitude and phase of the THz wave instead of just measuring the power [11]. Pulsed-THz spectroscopy and continuous-wave (CW) THz spectroscopy, uses spectral information to detect various characteristics of the materials. While pulsed-THz spectroscopy can operate over a broad range of frequencies, it offers a lower resolution when compared to CW spectroscopy. By contrast, CW spectroscopy which offers a much higher resolution operates over a much narrower bandwidth when compared to pulse-THz spectroscopy [12]. The data acquisition in various spectroscopy techniques can be carried out in either reflection or transmission mode depending on the application. The transmission mode of spectroscopy can be used for ex-vivo and in-vitro sensing applications, which requires that the analyte or specimen be taken out of the living organism or its original place. However, in reflection mode, there are different possibilities for in-vivo and in-situ sensing. In this type of spectroscopy, living organisms or analytes can be measured at their original place of location without the need of taking out a specimen. This capability enables scientists to measure the characteristics of a target without taking the analyte out of its operational environment [13].

Another approach for frequency-domain spectroscopy, which originates from optics, includes using resonance-based sensors. In optical sensing techniques, surface plasmon polaritons (SPPs) can be excited at the metal-dielectric interface by using light illumination. An optical resonance sensor, involving SPPs, can modulate the spectral response of the sensor depending on certain properties of the light such as amplitude, phase, polarization, wavelength [14]. The modulation triggered by the sensor can be interpreted to characterize the material that is superimposed on the structure. Specifically, the resonance-based sensing mechanism is based on the fact that any changes in the permittivity of the analyte can alter the propagation constant of the excited SPP at the metal-dielectric boundary [15]–[17].

At frequencies below the visible spectrum, it is not possible to excite the SPP as metals have a very high plasma frequency. However, structures with periodic grooved elements can support the propagation of electromagnetic surface (EMS) waves that mimic the SPPs [18]; EMS propagation modes at THz frequencies that imitate these SPP modes are referred to as Spoof Surface Plasmons (SSPs). Thus by using 2D periodic structures or metasurfaces, a THz resonance sensor can be engineered to operate based on a concept similar to optical sensors. For THz resonance sensors, several periodic structures have been reported in the existing literature that can detect different types of materials based on their thickness and permittivity [19], [20] but high attenuation at THz frequencies limits the range of thickness, permittivity and the mode that can be used for detection [21]–[23].

In this paper, a graphene-based metasurface has been studied, which has the capability to sense a variation in the relative permittivity of an analyte from 1 to 4 and can also sense a change in the thickness of an analyte from $5\ \mu\text{m}$ up to $600\ \mu\text{m}$. To the best of author's knowledge, these sensing capabilities are considerably higher than any of the previously reported research works. The achieved results have been analyzed from an electromagnetic point of view and are discussed and compared with conventional structures using an equivalent circuit model of the respective periodic structures. Finally, a novel spectroscopy technique has also been proposed, that utilises the spectral features of a broadband reflection wave to extract some unique information of different materials in order to generate a spectral fingerprint of the material. This fingerprint can then be employed to detect and identify materials with different permittivities and thicknesses.

II. DESIGN

The proposed THz spectroscopy system essentially comprises of a THz source and a detector along with an analyte as a sample target and a THz sensor, as shown in Fig. 1. The sensing system operates

Fig. 1: The spectroscopy system for THz sensing consisting of a pulse-THz source, sensor structure and an analyte.

based on the reflection-mode sensing which can be a practical approach for real-time chemical sensing or *in-vivo* spectroscopy of biological tissues. However, in reflection mode, the amplitude of the reflected wave gets attenuated heavily and therefore the system requires a very high power THz source or an ultra-sensitive sensor to successfully detect the reflected THz wave. A photoconductive antenna (PCA) has been chosen as the THz source in its pulse mode of operation because of its broadband spectral behaviour. The PCA has been excited with a femtosecond laser pulse having a wavelength of 1550 nm, an output power of 30 mW with a repetition rate of 80 MHz; Fig. 1 shows the time-domain representation of the THz excitation pulse. The spectral power of the THz pulse is very critical for this application because of the spectroscopy technique applied in this research. Hence, a narrower time-domain THz pulse with higher spectral power is preferred. An ultra-sensitive THz sensor has been designed using a graphene-based metasurface. Its unit cell is made up of a perforated stripe with several periodic grooves and at THz frequencies, the periodically grooved structure can confine the EM waves at subwavelength scale and can support surface waves at the conductor-dielectric boundary [24]–[26]. Moreover, the perforated stripe is made up of graphene which can not only localize the electric field with a lower loss as compared to some of the noble metals (Gold, Copper, Platinum etc.) but can also support surface plasmonic waves inherently [27], [28]. Fig. 1 represents the graphene elements which have been laid over the polyimide (PI) substrate which offers good mechanical flexibility and strength along with lower losses at the THz spectrum [29]. For the purpose of THz sensing, the sensor is placed on top of the analyte in such a way

Fig. 2: The unit cell of the graphene-based MS. (a) The graphene element laid over a polyimide substrate. (b) Dimensions of the unit cell (c) Different tips in the unit cell and their dimensions.

that the graphene elements are facing the analyte and are sandwiched between the Polyimide substrate and the analyte as illustrated in Fig. 1.

A. The unit cell of the sensor

The unit cell of the graphene-based MS is shown in Fig. 2a and it comprises of two parts: a graphene stripe and a substrate of polyimide. Fig. 2b and Fig. 2a shows that the graphene stripe is made up of three different types of periodic tooth-shape tips, labelled as C1, C2 and C3. The C tips are formed by perforating an array of grooves with different depths and widths on the inner edges of an H-shaped graphene stripe. All the tooth-shaped tips are periodic with distances between them as $T_{C1} = T_{C2} = T_{C3} = 1 \mu\text{m}$. Additionally, the length of each series of these tips has been optimized so that the maximum binding between the EM waves and the structure can be achieved. Fig. 2 represents all the dimensions that have been used to design the MS unit cell. The unit cell has been repeated on the substrate in two directions i.e. x and y with a periodicity of P_x and P_y , respectively. The stripe in this work is entirely based on graphene layers with a thickness of 1 nm and a relaxation time of 0.1 ps. The chemical potential (CP) of graphene has been

investigated for three different values of 0.1 eV, 0.5 eV and 1 eV as unbiased, low static bias and high dc bias. As the proposed sensor operates in reflection mode, the sensor needs the substrate material to be transparent to the THz wave throughout the operating frequency. Additionally, as the graphene elements need to be superimposed on the substrate, therefore the substrate must possess mechanical strength as well to endure the fabrication process. Since the THz waves can pass through Polyimide in reflection mode with negligible loss and due to its ability to endure the fabrication process, Polyimide is one of the best and common choices for such an application. Moreover, the effect of this substrate on the generated EM surface wave has been analysed and will be discussed later in the next section. The designed sensor can distinguish a variation in the relative permittivity of the analyte in the range of 1 to 4; which, at THz frequency, is an important range of permittivity for different types of materials including most of the biological tissues, many types of chemicals, polymers, etc. [30]–[34]. Another important criterion for a spectroscopy technique is the thickness of the analyte, which is very critical at THz frequency, because of the attenuation that it can cause. The proposed sensor has been designed to sense any change in the thickness or electrical characteristics at THz frequencies.

B. The Analysis of Surface Plasmonic Propagation in Graphene

Contrary to the optical frequencies, surface plasmons cannot originally exist in metals at THz frequencies however, graphene can support surface plasmon oscillations at THz frequencies. [35], [36]. A considerable amount of research shows that there are two types of outer electrons (σ and π) in the molecular structure of graphene and both can support plasmons. Low energy plasmons (*2D plasmons*), whose energy is $< 3\text{eV}$, are mainly caused by intraband transitions whereas high energy plasmons, which are of two different types (" π plasmons" and " $(\pi + \sigma)$ plasmons"), are caused by inter-band transitions [37], [38]. In the proposed structure, the excited surface plasmons are due to the *2D plasmon* oscillations because the operating band (resonance frequency) of the proposed sensor falls in the THz spectrum with an energy level of $< 3\text{eV}$. To establish the impact of a periodic structure on plasmonic frequency, the dispersion relation of surface plasmons must be taken into consideration and to determine the dispersion relation for graphene, there are two common approaches; (i) semi-classical model and (ii) Random-phased approximation (RPA). It is worth noting that both of these models have been considered in the pre-design calculations of this work. [39], [40]. Using the semi-classical model, low energy conductivity of 2D graphene (graphene sheet) can

(a)

(b)

Fig. 3: Dispersion diagram, E-field and surface current for unit cell (a) The dispersion diagram of the proposed unit cell for different values of chemical potential and different length of graphene element. (b) The distribution of Electric field and surface current calculated by eigenvalue solver for a CP= 0.1.

be expressed by using Kubo's formulae as shown below [39], [41]:

$$[\sigma(\omega, \mu, \Gamma, T) = -\frac{ie^2(\omega + i2\Gamma)}{\pi\hbar^2} \left[\frac{1}{(\omega + i2\Gamma)^2} \int_0^\infty E \left(\frac{\partial f(E)}{\partial E} - \frac{\partial f(-E)}{\partial E} \right) dE - \int_0^\infty \frac{f(-E) - f(E)}{(\omega + i2\Gamma)^2 - 4(E/\hbar)^2} dE \right] \quad (1)$$

In this equation, $\Gamma = 1/2\tau$, where τ is the electron relaxation time of the graphene sheet. The Fermi distribution function which is defined as $f(E) = \{1 + \exp[(E - \mu)/K_B T]\}^{-1}$, can have a substantial impact on the carrier transitions in the electronic structure of graphene [42]. The intraband (first term) and interband (second term) electron transitions contribute to the conductivity of graphene and can be expressed as below [43]:

$$\sigma_{Intraband}(\omega, \mu, \Gamma, T) \propto \frac{1}{(\omega + i2\Gamma)^2} \int_0^\infty E \left(\frac{\partial f(E)}{\partial E} - \frac{\partial f(-E)}{\partial E} \right) dE$$

,

$$\sigma_{Interband}(\omega, \mu, \Gamma, T) \propto \int_0^\infty \frac{f(-E) - f(E)}{(\omega + i2\Gamma)^2 - 4(E/\hbar)^2} dE.$$

In the THz frequency range, the intraband transitions are more dominant. Thus based on the relation $\hbar\omega \leq \mu_c$ (where μ_c is the chemical potential of graphene sheet), it can be said that the interband conductivity of graphene can be neglected at THz frequencies. As a result, the conductivity of 2D graphene sheet can be estimated by:

$$\sigma(\mu_c) = i \frac{e^2 K_B T}{\pi \hbar^2 (\omega + i\tau^{-1})} \left[\frac{\mu_c}{K_B T} + 2 \ln(e^{-\mu_c/K_B T} + 1) \right], \quad (2)$$

. By using this conductivity along with the boundary condition, the Maxwell's equations can be resolved to define the propagation modes in the graphene layer. In contrast to metals, graphene can support both TM and TE propagation modes within its 2D molecular structure depending on its conductivity [43]–[45]. It must be noted that the imaginary part of the conductivity controls the propagation mode and a graphene sheet with positive imaginary part can only support TM surface waves. The calculated conductivity based on (2), enforces that the TM surface waves are the only possible solutions for the 2D graphene sheet. Therefore, in order to find the dispersion relation of the graphene layer for TM modes, it has been assumed that $\mu_c/K_B T \gg 1$. Consequently, the wave vector of surface plasmons in graphene can be expressed by [41]:

$$K_{SP} \approx (\hbar^2/4e^2 E_F)(\epsilon + 1)\omega(\omega + i\tau^{-1}), \quad (3)$$

The wave vector of surface plasmons has a quadratic relationship with the frequency, which is natively a feature of 2D electron gases [46]. The dispersion relation of the 2D graphene sheet is calculated and

plotted in Fig. 4a. On the other hand, using the in-plane wave vector of surface plasmons $K_{sp\parallel}$, the degree of field confinement can be expressed by the ratio of in-plane surface plasmons to the free space wavelength as follow:

$$\frac{\lambda_{sp\parallel}}{\lambda_0} = \alpha \frac{4E_F}{\epsilon_r + 1} \frac{1}{\hbar\omega}, \quad (4)$$

where $\alpha = \frac{1}{4\pi\epsilon_0} \frac{e^2}{\hbar c}$ is the fine structure constant. Therefore, the in-plane SP confinements are calculated for different scenarios and are shown in Fig. 4b. At a macroscopic scale, the thickness of the ultrathin graphene layers can be regarded as infinitesimally small, this has also been considered in this work for the sake of simulations and calculation of the dispersion diagrams. According to this model, by applying voltage-gating technique and controlling the chemical potential of the 2D homogenous graphene sheet, surface plasmon propagation modes can be excited at sub-THz frequencies as well. However, based on the parameters that have been considered in this work (CP=0.1 and No voltage-bias), the surface plasmon resonances (SPRs) should occur at frequencies above 10 THz. Therefore, in order to have SPRs at lower frequencies, graphene should be highly doped and/or voltage-gated and thus the excitation of SPRs at even sub-THz or microwave frequencies can be justified. However, the source of excitation in this work is a THz photoconductive antenna working in a pulse mode of operation and therefore the generated THz wave is a narrow THz pulse with a frequency below 1 THz. This source of THz pulse cannot fully excite SPs in pristine graphene and therefore the electric confinement would not be strong enough to give rise to SPR below 10 THz. To address this challenge a modification is required in the graphene structure to excite SPR at lower THz frequencies. The proposed metasurface consists of a 2D periodic array of grooved structures that can cause very high field confinement in the graphene layer and can give rise to a strong surface plasmonic resonance at frequencies below 3 THz. As it can be seen in Fig. 3a, changing the chemical potential cannot alter the SPR frequency of the structure and hence it can be said that it is independent of the intrinsic SPs of graphene, which occurs at higher frequencies. Otherwise, with variation in the chemical potential, SP frequency must experience severe changes, but this is not what is being observed based on the calculations that are shown in Fig. 3a. In the proposed design, neither the voltage-gating nor the chemical potential control has been considered, but the main reason for the excitation of the SPR below 10 THz is the proposed periodic structure. As it can be seen from Fig. 4a, the main difference between a homogenous graphene sheet and the proposed periodic structure can be observed by referring to the relation between their in-plane SP wave-vectors ($K_{sp\parallel}$) and the plasma frequency where

the dispersion curve exhibits an asymptotic behaviour. The field confinement for graphene sheet and the proposed structure have been compared in terms of the ratio between their in-plane SP wavelengths (λ_{SP}) and free space wavelengths (λ_0) in Fig. 4b. On the other hand, the in-plane propagation distance ($\delta_{SP\parallel}$) can be estimated using the equation $1/\text{Im}(K_{SP}) = 1/K_{SP\perp}$. The in-plane propagation distance of inherent SPs and the proposed structure are compared in Fig. 4c in terms of their damping ratios of SPs, which can be defined as $\text{Im}(K_{SP\parallel})/\text{Re}(K_{SP\parallel})$. Fig. 4 shows a significant improvement in terms of surface waves for the proposed graphene-based metasurface as compared to a homogenous graphene sheet. Therefore, it can be stated that the generated surface wave is a combination of spoof surface plasmons (SSPs), originating from the metasurface design, and the inherent surface plasmon of graphene material. In fact, the SSP in the proposed metasurface is getting enhanced by the inherent SPs of graphene. It is worth mentioning that the excited SP in the proposed structure is the local surface plasmon (LSP) which is more accurate and can give a higher resolution than bulk SPs as can be seen in Fig. 3 and Fig. 5. This can be considered as the main advantage of LSPs over bulk plasmons as it determines the sensing volume of the sensor and can be obtained by their respective out-of-plane plasmonic fields ($\delta_{SP\perp}$). The LSPs generate precise signals that can measure and quantify the properties of the target accurately whereas the large plasma field of bulk plasmons results in the sensing of an area that is not actually bound at the sensor surface. This can result in the sensor giving a false reading and therefore using a periodic structure can significantly enhance the resolution and accuracy of the sensor.

However, a metasurface structure based on two-dimensional periodic elements can support the propagation of an SP-like wave at the conductor-dielectric interface. In [47], it has been shown that the dispersion characteristics of the SP-like wave or Localized Spoof Surface Plasmonic (LSP) wave around the tooth-shaped tips (grooved structures) can cause strong field confinement, which can support EMS wave propagation. To the best of author's knowledge, all of the existing works have mainly used metal as the material for the conductor in the sensor design. However, in the proposed design, a thin layer of graphene has been applied instead of a thicker metal layer, which can support inherent Surface Plasmons. To investigate the behaviour of the propagation modes at the surface of the graphene layer, the dispersion relation of the propagation modes has been calculated based on eigenvalue solutions of Maxwell's equations for this structure. One of the main parameters that can change the characteristics of graphene is its CP [48]. Hence, the dispersion relation of the structure has been plotted for different CPs as presented in Fig. 3. For this purpose, the graphene's CP has been varied across three different

Fig. 4: The comparison of SPs characteristics in a Homogenous 2D graphene sheet and the proposed graphene structure.

values of 0.1, 0.5 and 1 eV. This dispersion relation has been obtained by a numerical tool based on the Floquet-Bloch theorem. For different CPs the structure shows the same propagation characteristics as the dispersion curves asymptote towards the same plasma frequency, as can be seen in Fig. 3. However, changing the length of the graphene layer (L) can cause a variation in the plasma frequency which can be used for tuning the surface plasmonic resonance (SPR) frequency of the structure. The analysis of the propagation modes of the unit cell proves that different modes can be supported by this structure ranging from the fundamental one to higher-order modes. Moreover, it can be observed from Fig. 3, that the three fundamental propagation modes have an asymptotic behaviour at a certain frequency. As a result, it can be concluded that the variations in the CP of graphene do not impact the resonant frequency of SSP modes.

For the dispersion calculations shown in Fig. 3a, air has been considered as the analyte with $\epsilon_r = 1$. For

Fig. 5: The profile of the LSP propagation mode in the unit cell. (a) Excited LSP propagation mode in the unit cell. (b) The side view of generated LSP modes at the interface of graphene layer and the analyte. (c) Position of the graphene element, substrate and the analyte. (d) The real and imaginary parts of the z component of the electric field at the boundary region of graphene layer and the analyte. (e) The real and imaginary parts of the y-component of the magnetic field at the boundary region of graphene layer and the analyte. (f) The real and imaginary parts of the x-component of the electric field at the boundary region of graphene layer and the analyte.

this arrangement, an exact model of the graphene layer is needed to solve the generalized linear eigenvalue equations of the proposed periodic structure. A graphene layer can be modelled as an infinitesimally-thin surface characterized by its conductivity or a volumetric thin layer. Since the volumetric model needs very fine meshing to model it in the numerical tool (CST Studio Suite[®]), a thin layer of graphene has been used as surface conductivity can be estimated based on the Kobu's formulae [49]. From Fig. 3b, it can be seen that the electric field of the propagation modes in the proposed structure can resonate locally around the tips (E-field), which mimics the local surface plasmon oscillations at optical frequencies. An array of local SSPs can form a strong upward electric field that can penetrate the analyte. This vertical penetrative component can be considered as an evanescent electric field that is towards the dielectric region and is shown by δ_d in Fig. 5a and Fig. 5b. Moreover, there is a wave propagation over the surface of the structure denoted by δ_{LSP} , which is an LSP propagation component. The δ_d is a key parameter for sensing applications as it directly affects the maximum distance (from the surface) from which the sensor can detect the presence of an analyte and distinguish between different analytes. The distribution of the surface current on the graphene layer demonstrates a strong dipole resonance between C3 and C2 or C1.

Fig. 6: Comparison of amplitude and phase diagram of the normalized reflected waves for the proposed sensor with different chemical potentials. The plotted amplitude and phase diagrams are calculated for an analyte with a thickness of $100 \mu\text{m}$.

All these calculations have been performed with graphene in a no-bias state ($\text{CP} = 0.1 \text{ eV}$). The field components of the LSP mode have been calculated based on Fig. 5c and are shown in Fig. 5d, Fig. 5e and Fig. 5f. The solution of eigenvalue equations for the proposed graphene structure shows a symmetrical field component in the z-direction towards the analyte. The symmetrical behaviour between the graphene layer and the analyte can be interpreted with respect to the distribution of the tangential components of the magnetic field (h_y) at the interface of the graphene layer and analyte. However, in the X direction, the LSP modes decay drastically as can be seen from the imaginary part of its profile.

It is worth noting that, for the spectroscopy results in this work, the chemical potential of graphene has been considered as $\text{CP} = 0.1 \text{ eV}$. However, changing the CP can alter the behaviour of the reflection diagram. As shown in the numerical results of Fig. 6, by changing the CP of the graphene layer, the resonances are most likely to be weaker or can even disappear in the reflection amplitude diagram.

Fig. 7: Comparison of the equivalent circuit of the proposed structure with two conventional grooved-structures. (a) Equivalent circuit of U-shaped grooved-structure. (b) Equivalent circuit of ω -shaped grooved-structure. (c) Equivalent circuit of the proposed structure.

Similar behaviour can be observed for the reflection phase diagram as well. Higher CPs make the reflection information smoother with fewer resonance dips. As a result, the sensitivity of the structure might decrease in proportion to any change in the permittivity of the analyte. It can be seen from Fig. 9 that the resonance dips in the generated reflection diagram have characteristics similar to a Fabry-Perot resonance shape. These resonances originate from the back-and-forth movement of the EM field in the grooved structures, which are responsible for electric field confinement. The depth of the grooves and the conductivity of the elements are the most influential parameters for the field confinement of SPs, which can be measured by referring to the Quality Factor of the resonances. Changing the chemical potential can alter the conductivity of the element and can affect the field confinement of SPs. By increasing the chemical potential, the peak energy, which can be locally stored (confined) in the grooves, might reduce and this could lead to a drastic drop in the Q-factor ultimately leading to weaker resonances. The performance of the proposed sensor is achieved without any biased CP. The normalized reflection diagram for the amplitude and phase are plotted as shown in Fig. 6.

C. Circuit Model of the 2-D Periodic Structure

In the periodic structures with 2-D lattice, the electric field can be confined at a sub-wavelength scale, which can cause a strong surface propagation mode. These surface modes can propagate tangentially over the structure; such tangential propagation modes mimic a transmission line with guided modes inside the structure. Each transmission line can be modelled with its equivalent circuit model using conventional lumped elements. However, the transmission lines usually guide the propagation modes based on a conductor-ground structure, which is one of the major distinctive factors between the transmission lines and 2-D periodic MS without a ground plane. For the periodic grooved-structures without a ground plane, it can be assumed that the ground plane is at a far distance from the structure. In order to analyze the behaviour of the periodic grooved-structure, an equivalent circuit model of one period can be used to determine the relation between input and output parameters of the entire structure. Therefore, here in, one period of the MS is modelled and compared with two conventional grooved-structures using their equivalent circuits as shown in Fig. 7. These three models are introduced as U-shaped, ω -shaped and the proposed groove-shaped structures. The U-shaped and ω -shaped structures are the conventional grooved structures, which have been used in different periodic structures to support the EMS waves [50]–[52]. The circuit elements are classified into capacitors and inductors with different values. The values of inductance are calculated using (6), which is based on the equivalent circuit of transmission line [53].

$$L_i = \frac{\mu_0 l_i}{2\pi} \left(\ln \frac{2l_i}{w_i + t} + \frac{1}{2} \right) (H), \quad (5)$$

where l_i , w_i and t represent the length, width and thickness of the graphene strip respectively. Furthermore, there are two types of equivalent capacitors in the equivalent circuit model. The first one is due to the capacitance between the tips and the other one is due to the space between the tips and ground at infinite distance. Since there is no ground plane in the structure therefore it has been assumed that the ground is far from the structure. Based on this assumption, the capacitance values are calculated using electrostatic (ES) solver of CST Studio Suite[®]. The calculated parameters are summarised in Table I.

The input parameters are defined as V_n and I_n and the output parameters are defined as V_{n+1} and I_{n+1} . It is worth noting that the dispersion relations of the presented grooved-structure, which are calculated based on their circuit models are compliant with the dispersion relations calculated by the Maxwell's eigenvalue equations. In the proposed circuit models, V_{n+1} and I_{n+1} can be considered as input parameters to the next similar unit cell. These parameters can be related to each other using the transmission matrix

given in (6) [54].

$$\begin{bmatrix} V_n \\ I_n \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_{n+1} \\ I_{n+1} \end{bmatrix}. \quad (6)$$

The relation between the output and input parameters determines the amount of EM energy which is transferred from one period to the next one. This metric can be expressed by Bloch impedance as the ratio of V_{n+1} to I_{n+1} . In other words, Bloch impedance defines the characteristic impedance of an EMS wave, which can also be referred to as a Bloch wave. The Bloch impedance (Z_c) can be calculated using (7) [55].

$$Z_c = \frac{V_{n+1}}{I_{n+1}} = \frac{B}{\sqrt{A^2 - 1}}. \quad (7)$$

Based on the scattering parameters of the proposed equivalent circuit model, the transmission matrix is generated. The S-parameters and the transmission matrix are obtained by modelling the equivalent circuits in Advanced Design System[®].

The Bloch impedance $Z_c = R_c + jX_c$ is depicted in Fig. 8 and is split into normalized Bloch resistance and normalized Bloch reactance as plotted in Fig. 8. The calculated Bloch reactance of the proposed structure shows inductive behaviour, which is significantly greater than the reactance of the U-shaped and ω -shaped structures. The Bloch impedance of the electromagnetic surface wave has been analyzed in terms of two main parts, i.e. real part (Bloch Resistance) and the imaginary part (Bloch Reactance). It can be observed from Fig. 8 that both of them are varying with a change in the frequency. The frequency dependency is an inherent characteristic of reactance and for graphene, the frequency can also affect the resistance of the graphene layer as its conductivity is also related to the frequency. As can be seen in Fig. 8a, there are several fluctuations in the Bloch reactance of U-shape and ω -shape unit cells. For the conventional configurations, there are some frequencies at which the characteristic impedance has

TABLE I: Calculated values for the elements of the circuit model.

Inductance (atto H)	Values by formulae	Capacitance (atto F)	Values by ES-solver
L_1	10.0	Ct	5.40
L_2	245.0	Ct_2	7.07
L_3	54.0	Ct_3	5.10
L_4	300.0	Ct_4	8.10
L_5	456.5	Cg	31.8
L_6	900.0	-	-

Fig. 8: Normalized Bloch impedance of the grooved structures. (a) Normalized Bloch reactance. (b) Normalized Bloch resistance.

capacitive reactance, which is not desired for the performance of the sensor. For an inductive behavior, it is expected that there is an oscillating magnetic field around the surface, which is highly critical for sensing. A capacitive unit cell can store more in-plane standing energy whereas an inductive one causes out-of-plane oscillating magnetic field, which is preferred for sensing by SPs. Therefore, according to the desired application, the inductance of the equivalent transmission line is more effective than resistance. The current flow in a transmission line model interacts directly with inductance of structure, which is an indicator for the induced EM flux around the surface. Furthermore, The Bloch impedance is calculated at the terminal of the unit cell and it is defined as the ratio of voltage and current at the terminal of it. Therefore, according to the sign of the real part of the Bloch impedance, it is possible to determine

the direction of the energy flow of the EMS waves. In addition, since n -th unit cell is considered in the positive direction of the propagation, the negative sign of the Bloch resistance denotes a backward propagation of surface wave, which means a propagation constant with $k < 0$. As reflected in Fig. 8b, It can be interpreted that the propagation direction of SPs in the conventional shapes is not unidirectional for all frequencies in the specified range. This can occur due to the inherent momentum mismatch between the THz waves and the generated surface wave. It should be noted that both of the backward and forward propagation have same Bloch impedance (with opposite sign), which shows, that the equivalent circuit is a reciprocal network. As can be seen in Fig. 8, there is a negligible drop in the Bloch resistance throughout this frequency range, which means a unidirectional propagation of surface plasmons at all the frequencies of interest. This means that there is a high efficiency of coupling between the THz waves and surface plasmons. On the other hand, the quality factor of these type of resonance-based structures is a figure of merit and can be calculated based on the equivalent circuit model. Based on the equivalent Bloch impedance, the quality factor can be obtained by $Q = |\text{Im}(Z_B)|/\text{Re}(Z_B)$. This parameter has been calculated for three different structures and is presented in Fig. 8c. This figure shows that the quality factor of the proposed structure is significantly higher as compared to the conventional configurations, which is an important figure of merit of the resonance-based metasurfaces. Thus, it is possible to compare different unit cells from a circuit theory point of view.

The equivalent circuit model can pave the way for the design process of the MS in terms of dispersion behaviour and wave vector. It can be stated based on previous studies the periodic grooved-shaped unit cells can support surface plasmons propagation at THz frequencies. The design process starts with the calculation of widths and lengths of C1s, C2s and C3s and their respective periodicities. Thus, the first step of the design process is to define the C1 parameter which governs the back-and-forth movement of the electromagnetic waves and consequently, the field confinement in the structure. This type of field confinement causes high-frequency Fano-shaped resonances in the spectrum as can be seen in Fig. 9. Hence, C1s must be designed in such a way that these resonances occur at THz frequencies. Due to the field confinement of C1s and the propagation of surface waves in the U-shaped unit cell, they are modelled and controlled by C_t and L_1, L_2, L_3 as equivalent circuit elements. This ultimately results in an equivalent LC circuit model for the THz frequency range. For THz band, a range of widths and lengths can be considered for C1 in the U-shaped unit cell. Then, the equivalent capacitance and inductance for corresponding widths and lengths are calculated and the dispersion diagram of the equivalent circuit

can be plotted and studied using ADS[®] software. The dispersion diagram shows the relation between the wavenumber and the frequency of the designed structure. Consequently, it facilitates the required modifications in the dimensions in order to have a surface plasmon frequency in the THz frequency band. The next step is to design the C2s, which can improve the field confinement and can add resonances to the spectrum of the ω -shape unit cell. They follow a concept similar to the C1s in U-shaped unit cell and can increase the field confinement at a higher segment of the THz spectrum. This modification also increases the bandwidth of the frequency response of the structure by adding some poles to the transfer function of the system. The length and width of the C2s are optimized for the best field confinement using CST Studio Suite[®] 2020 and the plasmonic frequency of the unit cell is then calculated by using ADS[®] software using the equivalent circuit. In the third step, C3 is added to the design to improve the local electric field confinement. This configuration forms a dipole interaction between the C1s and C3s which results in resonances that are slightly different from the previously obtained Fano-shaped resonances. Due to the dimensions of C3; resonances are caused in the lower part of the THz frequencies, these can be seen in Fig. 9 with amplitude modulations. The dominant resonances in this part of the reflection spectrum originate from ct_4 , L_5 and L_6 . The primary values for the length and width of the L_5 , L_6 are calculated based on the dispersion relation of the proposed equivalent circuit and the value of C3 is added to the previously calculated equivalent circuit model of the ω -shape grooved unit cell. The dispersion diagram of the equivalent circuit in ADS is verified with the dispersion relation which is calculated in CST Studio Suite[®] by finding the eigenmode values of Maxwell's equations in presence of proper boundary conditions. From a circuit theory point of view, the conventional shapes, i.e. U-shape and ω -shape, have limited poles in their respective transfer functions. This restricts their resonances to a limited part of the frequency spectrum and can be defined based on various design requirements. However, due to the specific design of the proposed grooved structure, more inductances and capacitances are formed in the equivalent circuit model, which results in the addition of new poles in the transfer function. These new poles give rise to new resonances in the proposed sensor. Several meaningful resonances can be observed in the frequency range between 0.2-6 THz as compared to conventional structures. From Fig. 9, it can be said that there are three dominant types of resonances as per the reflection diagram. It can also be observed from the same figure that there are several resonances similar to Fano and Fabry-Perot resonances which are observed at higher frequencies while several dipole resonances are observed at the lower part of the inspected spectrum. Therefore, the main reason for achieving a broadband operation is the existence of different

types of electromagnetic interactions throughout the frequency band of operation.

III. NOVEL SPECTROSCOPY TECHNIQUE

In order to investigate the sensing capabilities of the proposed structure, different dielectric materials with different thicknesses have been superimposed on the sensor structure. This sensor is designed to work in reflection-mode sensing which makes it highly suitable for *in-vivo* or *in-situ* and real-time spectroscopy. In this type of spectroscopy, living organisms or analytes can be measured at their original place of location without the need of taking out a specimen. Figure 9 presents the amplitude of the reflected THz pulse wave from the analyte along with the phase of the reflected THz wave as can be seen in the inset. At THz frequencies, the reflection-mode sensing is very hard to achieve due to high attenuation. The thickness of the analyte that has been used for this result is $80\mu\text{m}$ and three different analytes with relative permittivity of 1.5, 2 and 2.5 have been considered for this graph. The relative permittivity of air has been considered as 1 and has been used as a reference permittivity for other analytes. The thickness of the analyte for Fig. 9, has been chosen arbitrarily, just as a sample to investigate the reflection mode behaviour of the sensor but other thicknesses have also been considered for calculating the resonance frequency shifts as shown in Fig. 10. To further elaborate on Fig.9, it should be noted that the proposed sensor can essentially operate based on two different sensing techniques i.e. amplitude modulation (at lower frequencies) and resonance shifts (at higher frequencies). Both of these techniques work based on the behaviour of the resonances in the reflection amplitude diagram. Different types of resonances can be observed in this grooved structure as shown in Fig. 9. These mainly include i) Fabry-Perot-shaped resonances, ii) Fano-shaped resonances and iii) Dipole resonances. The former two resonances occur at higher frequencies and the latter one gets formed at lower frequencies due to the size of the grooves. This characteristic of having multiple resonances lets the proposed sensor to operate in a broad range of THz spectrum. Any change in the analyte can either cause a frequency shift in the resonances or can cause an amplitude modulation as shown in Fig. 9. This behaviour can not only be seen in the amplitude but can also be observed in the phase by referring to their respective reflection diagrams as shown in Fig. 9.

It can be clearly observed that there are meaningful modulations in the resonant frequency of the phase and the amplitude of reflections due to the variation in the permittivity of the analyte. At higher frequencies, there are only red-shifts in resonance frequency but at lower part of the spectrum, the amplitude modulations are dominant, both, in terms of amplitude and phase of the reflection diagram. Based on different reflection measurements acquired for analytes with different thicknesses, it can be

Fig. 9: Normalized amplitude and phase of the reflected waves calculated for an analyte with a thickness of $80\ \mu\text{m}$ and relative permittivity ranging from 1 to 2.5 in steps of 0.5. All values of the amplitude and phase are normalized to the THz source.

established that there is a spectral boundary between the amplitude modulation region and the resonance modulation region, which can be shifted to higher and lower frequencies based on thicker and thinner analyte respectively. In order to elucidate this observation, it is necessary to investigate how resonances can occur in reflection mode. It has been observed that there are different dominant types of resonances due to light-matter interactions. Firstly, there are multiple dipole resonances at lower frequencies which appear in the “amplitude modulation” region as shown in Fig. 9. Other dominant resonances are those that occur at higher frequencies in the “Frequency modulation” region and originated due to the back-and-forth movements of the electromagnetic fields inside the corrugations. These resonances are quite similar to Fabry-Perot resonances as they exhibit similar behaviour (See Fig.8) and therefore the concept of Fabry-Perot resonance can be applied to these resonances as well. It must be noted that the wavenumber of Fabry-Perot resonances can be obtained by: $K_{FPR} = 2\pi q \Delta \nu_{FSR} / c$, where q is an integer and denotes free spectral range (FSR). The FSR is the spacing in optical wavelength between two successive reflected or transmitted optical intensity referring to the thickness of the analyte. There is a direct relationship between the wavenumber of the resonance and the FSR and based on this relation, it can be said that with an increase in the thickness of an analyte, the wavenumber and the frequency of the resonance shifts towards higher frequencies as the distance between the reflected and transmitted EM wave between the two surfaces of an analyte is getting increased. However, an interesting observation is that for analytes thicker than 150 μm the amplitude modulation is dominant throughout most of the spectral reflection diagram. Therefore, it is necessary to propose a spectroscopy technique that can convert the amplitude modulations into a powerful and unique feature to differentiate between various materials. The same phenomenon happens in the phase diagram of the reflected wave as well, as shown in Fig. 9. It is worth mentioning that the results in Fig. 9 are obtained based on an analyte with a thickness of 80 μm .

A sensitivity analysis has been carried out for the proposed sensor, which demonstrates the sensitivity of the sensor in comparison to some of the previous works [56]–[60]. In the primary calculations, as mentioned earlier, for an analyte with a thickness smaller than 150 μm the frequency shifts are obtained for permittivity range from 1 to 2.5. All the shifts are calculated in proportion to the resonance frequency of air (without analyte), which is considered as zero shift, and are presented in Fig. 10. As can be observed, the maximum sensitivity is approximately 1.5 THz/Permittivity unit, which is adequate for sensing purposes at this frequency range and with this thickness. The calculated thicknesses include different values between 10 μm and 150 μm . The calculated shifts are marked with red dots in Fig. 10 and are based on their values

Fig. 10: The frequency shifts interpolated by pre-calculated values (red dots) for different combinations of analyte thickness and relative permittivity. The analytes with thicknesses of $10\mu\text{m}$, $40\mu\text{m}$, $80\mu\text{m}$, $100\mu\text{m}$ and $150\mu\text{m}$ are included.

as sensitivity surface is interpolated for other thickness-permittivity combinations. From these results that have been obtained from sensitivity analysis it can be noticed that there is a linear relation between the variables (i.e thickness and permittivity) and frequency shifts over the considered range. The linearity of the transfer function between shifts and variables has an acceptable dynamic range, which can reduce the number of times for which sensor calibration is required.

Using shifted resonances for distinguishing between different materials is not a suitable approach for all range of thicknesses. Therefore, a more comprehensive spectroscopy technique should be applied that can detect different analytes irrespective of their thicknesses. To achieve this, an approach based on spectral features of the reflected wave is needed which can label a unique value to each permittivity. Various spectral features have been examined for this purpose but they cannot describe each permittivity value uniquely. Therefore, a novel spectroscopy technique has been proposed in this work that can extract

two unique features from the spectral reflection wave at THz frequency. These features are Accumulated Spectral Power (ASP) and Averaged Group Delay (AGD), which can provide unique information about the permittivity of the analyte and are independent of the thickness of analyte. In addition to this trait, another interesting characteristic of these spectral features is the spectrum range that they employ. These features use a broad range of frequencies ($\approx 0.2 - 6$ THz) to distinguish and sense the permittivity of a material. Due to this reason, the nature of the output is highly reliable and precise as it brings almost all of the THz spectrum into play.

A. Spectral feature 1: Accumulated Spectral Power

This feature provides the accumulated spectral power for each frequency. The spectral power for each frequency of f_n is defined by (8):

$$S(f_n) = \int_{f_0}^{f_n} |S(f)| \cdot df, \quad (8)$$

where f_0 can be any starting frequency of the reflected wave (0.2 THz for this work) and f_n is the frequency up to which the spectral power is calculated. Using this definition, it is possible to calculate an accumulated spectral power for each subsection of spectrum. Plotting all the calculated spectral powers can generate the ASP diagram for an analyte as can be observed in Fig. 11. In this figure, all ASPs have been

Fig. 11: Normalized ASP diagrams for analytes with different thickness and different relative permittivity. Each plot is normalized to the maximum ASP of its thickness.

normalized and are compared for different thicknesses. The results show that the proposed feature can distinguish between different values of permittivities even for analyte with a thickness of $600\ \mu\text{m}$, which, to best of author's knowledge, has not been reported in any previous works at these frequencies [61]–[66]. Furthermore, this feature is reliable for different thicknesses from $5\ \mu\text{m}$ to more than $600\ \mu\text{m}$. In this figure, the ASP is calculated up to 4.5 THz, however, this frequency can be lower or higher according to the desired accuracy. Regarding the effective frequency, It should be noted that ideally there is no limit for the start and end of integration when it comes to effective frequency, but, it can be defined for different materials according to their interactions with the THz waves and considering a specific bandwidth around the frequency of surface plasmon, can reveal quite a precise distinction between the analytes. Moreover, to determine the resolution of ASP it should be noted that there are different resolutions which depend on the spectral window of integration and as a future work, it is quite possible to define two or more spectral windows of integration to obtain different local ASPs. However, In this work, this parameter has been introduced just as a spectral feature for sensing but further work can be carried out to showcase the capabilities of using such a feature to distinguish between different materials uniquely as it is based on the spectral power of the reflected wave which is unique for every material. It is also noteworthy that for sensing purposes, there are some powerful characteristics that can be associated with this technique which can make ASP quite precise and a game-changer for various sensing applications. These characteristics can be enumerated as below:

- The ASP uses a broad range of frequencies to distinguish between different analytes, which can reduce the error probability significantly.
- The ASP utilizes the spectral density of the reflection diagram to distinguish between the analytes. This is highly beneficial as the spectral densities of different analytes are different and can also be referred to as their spectral fingerprint.
- The distinction between the ASPs of different materials can be investigated for various range of frequencies. Different parts of the spectrum can be analyzed and can be sampled to differentiate among various different analytes. This feature can be improved further by using AI and Machine learning algorithms for a precise distinction among various materials.
- The ASP plots in this work have been normalized w.r.t. the maximum ASP for different thicknesses to assist in readability, but there are significant differences between the ASP values of different

permittivities. These differences are unique and are quite valuable for identifying different analytes and thicknesses.

B. Spectral feature 2: Averaged Group Delay

In addition to the feature that has been extracted from the reflection amplitude diagram, the phase of the reflected waves can uncover distinguished information that can be used uniquely to identify different thicknesses. The proposed technique employs the group delay of the reflected waves and the group delay (τ_g) for each frequency is given by (9).

$$\tau_g = \frac{-d\phi(\omega)}{d\omega}, \quad (9)$$

where $\phi(\omega)$ is the phase of the reflected waves at a frequency of ω , the group delay is calculated for each frequency. Afterwards, all the group delays are averaged for each permittivity, to reach the AGD of the permittivity of the analyte. The AGD for different thicknesses is normalized to the maximum achievable AGD, which occurs for an analyte of thickness $600 \mu\text{m}$ and relative permittivity of 3.5 and is plotted in the form of bar graphs, shown in Fig. 13. According to the calculated AGDs, different values of permittivity can be differentiated more precisely in combination with ASP.

It should be emphasized that each diagram in Fig. 11 has been normalized based on the maximum average group delay (AGD) of their corresponding thickness. In other words, each analyte with a specific thickness and permittivity has a unique AGD in any particular sub-section of the THz spectrum which can be referred as its unique spectral fingerprint and it is this feature which makes it possible for different analytes to be distinguishable based on the proposed technique. Fig. 12 presents the normalized group delays for analytes of three different thicknesses i.e. $5\mu\text{m}$, $350\mu\text{m}$ and $600\mu\text{m}$ with relative permittivity ranging from 1 to 4 in a step size of 0.5. It can be observed that the group delay of each analyte has a distinctive spectral behavior corresponding to its thickness and relative permittivity throughout the frequency band ranging from 0.2 THz to 6 THz, but significant dissimilarities among them occur at frequencies around 1 THz and 5 THz. It is worth noting that both the amplitude and the phase of the reflected wave can be analyzed for sensing purposes. Therefore the ASP can be combined with AGD (Average Group Delay) to analyze the magnitude and phase of the reflection diagram respectively as a coherent technique for sensing purposes. Hence, it can be said that together they can sense different analytes with even higher precision. Table. II presents a comparative study of the proposed structure with

Fig. 12: Normalized group delay. (a) Analyte with thickness of $5 \mu\text{m}$. (b) Analyte with thickness of $350 \mu\text{m}$. (c) Analyte with thickness of $600 \mu\text{m}$.

Fig. 13: Normalized AGD diagrams for analytes with different thickness and different relative permittivity. Each plot is normalized to the maximum AGD of its thickness.

some of the state-of-the-arts in terms of range of frequency, relative permittivity, range of thicknesses, resolution of permittivity, resolution of thicknesses and mode of operation.

C. Measurement Set-up

The measurement setup consists of a spectroscopy system, which has been configured in reflection mode as shown in Fig. 14. The THz transmitter is a photoconductive switch with InGaAs/InP substrate and a 100 μ m long strip-line antenna electrode. The THz receiver is an InGaAs/InP photoconductive switch with a 25 μ m dipole antenna and a 10 μ m gap. Both the THz transmitter and receiver are connected to the laser

TABLE II: Comparative study of the proposed THz sensor with the state-of-the-art

SENSOR	FREQUENCY RANGE (THz)	RELATIVE PERMITTIVITY	RANGE OF THICKNESS (μ m)	RESOLUTION OF RELATIVE PERMITTIVITY	RESOLUTION OF THICKNESS (μ m)	Sensitivity (THz/Permittivity unit)	MODE OF OPERATION
PROPOSED SENSOR	0.2 – 6	1 – 4	5 – 600	≈ 0.1	≈ 0.5	1.5	Reflection
[56]	1.5 – 6	1 – 2	1 – 1.3	Not reported	6.35 μ gr/cm ²	0.36	Transmission
[57]	0.1 – 1.9	1 – 6	3 – 30	< 0.25	3	0.03	Reflection
[58]	< 2	1-15	< 10	=< 1	1	0.007	Transmission
[59]	1.5 – 3	1-2	1-4	0.3	1	23.7GHz/ μ m	Transmission
[62]	2 – 4.5	1 – 3.2	1 – 12	0.15	$\approx 0.02 – 1$	1.7	Transmission
[60]	0.3 – 2	0 – 100~ngrams/mL	0 – 2	Not Reported	0.01 mgr/Litre	Not reported	Reflection

Fig. 14: THz spectroscopy system.

source by two separate 2.5 m pigtail fibre. Additionally, Both of the photoconductive antennas benefit from hemispherical Si lens. The angles of incident and reflection are same and are chosen to be under 15 degrees. To measure the analytes, proper samples have been used and include different materials with dielectric constant ranging between 1 and 4 at THz frequencies. Most of them exhibit a constant spectral behaviour in the THz frequency range such as polyimide, SU-8, Ma-P, PMMA, polystyrene, PTFE, PP etc.

IV. CONCLUSION

In this paper, a graphene-based THz sensor is proposed in order to identify different materials based on their permittivity and thickness. The proposed sensor includes a 2D periodic structure of grooved unit cells to support EMS waves at THz frequencies and is capable of generating strong LSP propagation modes over a broad THz band (0.2 – 6 THz). The unit cell consists of a perforated graphene stripe overlaid on a Polyimide substrate. The proposed sensor can not only sense materials with relative permittivity ranging from 1 to 4 with a resolution of 0.1 but can also sense any variation in the thickness of an analyte in the range of 5 μ m to 600 μ m with a resolution of 0.5 μ m. The interaction of the EMS propagation with the ultrathin molecular lattice of the graphene layer is analysed to investigate the properties of LSP modes for sensing purposes. The electric field profile of EMS waves showcases that there are symmetrical LSP components at the interface of the graphene layer and the analyte, which can result in a slowly decaying LSP component over the surface of the structure. Due to the exceedingly confined electric field, the LSP

parameters such as vertical (δ_d) and tangential (δ_{LSP}) evanescent field components are strong enough to penetrate deep into the material, much more than any of the previously reported works. An equivalent circuit model is presented for the proposed sensor and is compared with two conventional grooved-structures from a circuit model point of view. Above all, a novel spectroscopy technique is proposed, which utilizes spectral amplitude and phase of the normalized reflection diagram to extract two new spectral features, namely Accumulated Spectral Power (ASP) and Averaged Group Delay (AGD). These features can use a broad range of frequencies to generate a unique set of values for each material. Furthermore, ASP and AGD can be combined to analyze the magnitude and phase of the reflection diagram respectively as a coherent technique for sensing purposes thereby making it possible to sense various different analytes with an even higher precision.

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