Sinusoidally-Modulated Graphene Leaky-Wave Antenna for Electronic Beamscanning at THz

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Abstract—This paper proposes the concept, analysis and design of a sinusoidally-modulated graphene leaky-wave antenna with beam scanning capabilities at a fixed frequency. The antenna operates at Terahertz frequencies and is composed of a graphene sheet transferred onto a back-metallized substrate and a set of polysilicon DC gating pads located beneath it. In order to create a leaky-mode, the graphene surface reactance is sinusoidally-modulated via graphene’s field effect by applying adequate DC bias voltages to the different gating pads. The pointing angle and leakage rate can be dynamically controlled by adjusting the applied voltages, providing versatile beamscanning capabilities. The proposed concept and achieved performance, computed using realistic material parameters, are extremely promising for beamscanning at THz frequencies, and could pave the way to all-graphene reconfigurable transceivers and sensors.

Index Terms—graphene, terahertz, sinusoidally-modulated surfaces, leaky-wave antennas, beamscanning, reconfigurability.

I. INTRODUCTION

Graphene unique electric properties hold significant promises for the future implementation of integrated and reconfigurable (potentially all-graphene) THz transceivers and sensors. However, only few studies have considered the use of graphene in antenna applications. Initial works employed graphene as a component parasitic to radiation [1], [2], for instance as a switch element to chose among different states of a reconfigurable antenna. Then, the propagation of transverse-magnetic (TM) surface plasmon polaritons (SPPs) in graphene [3], [4] was exploited in [5] to propose patch antennas in the THz band. This study was the first to consider graphene an actual antenna linking free space waves to a lumped source/detector, as needed in most communication and sensing scenarios. Several works have further studied the capabilities of graphene in antenna design [6] and even the integration of graphene in beam steering reflectarrays [7].

On the other hand, different mechanisms have been proposed to excite SPPs in graphene structures, including the use of diffraction gratings [8], [9] or polaritonic crystals obtained by modulated graphene conductivity [10]. However, the applications of THz transceivers which include chemical and biological remote sensing, image scanning, pico-cellular and intrasatellite communications, or high resolution imaging and tomography [11]–[14], require antennas with specific capabilities in terms of beamscanning and directivity.

In this context, we propose the concept, analysis, and design of a graphene sinusoidally-modulated leaky-wave antenna (LWA) for electronic beamscanning in the THz band. The antenna is based on the
principle of sinusoidally-modulated reactance surfaces to achieve leaky-wave radiation \([15]–[17]\). The proposed structure, shown in Fig. [1] is composed of a graphene sheet transferred onto a back-metallized substrate and several polysilicon DC gating pads located beneath it. The graphene sheet supports the propagation of transverse-magnetic (TM) surface plasmon polaritons (SPPs) \([4]\), which can be controlled via the voltages applied to the different pads. Indeed, as illustrated in the inset of Fig. [1] and explained in more detail below, the application of a DC bias to the gating pads allows to control graphene’s complex conductivity \([18]\). This property is exploited to sinusoidally modulate the sheet surface reactivity by applying adequate bias voltages to the different pads, thereby creating a leaky-wave mode \([15]–[17]\).

Moreover, antenna radiation features such as pointing angle \((\theta_0)\) and leakage rate \((\alpha_{\text{rad}})\) can be dynamically controlled by modifying the applied voltages, thus allowing electronic beamscanning at a fixed operating frequency. This simple and fully integrated antenna structure is designed and analyzed using leaky-wave antenna theory \([19]\) and validated by full-wave simulations.

II. TUNEABILITY OF GRAPHENE CONDUCTIVITY

Graphene is a two-dimensional material composed of carbon atoms bonded in an hexagonal structure. Its surface conductivity can be modeled using the well-known Kubo formalism \([20]\). In the low terahertz band and at room temperatures, interband contributions of graphene conductivity can safely be neglected \([21]\). This allows to describe graphene conductivity using only intraband contributions as

\[
\sigma = -\frac{j q_e^2 K_B T}{\pi \hbar^2 (\omega - j 2 \Gamma)} \left[ \frac{\mu_c}{K_B T} + 2 \ln \left( e^{-\frac{\mu_c}{k_B T}} + 1 \right) \right],
\]

where \(K_B\) is the Boltzmann’s constant, \(\hbar\) is the reduced Planck constant, \(-q_e\) is the electron charge, \(T\) is temperature, \(\mu_c\) is graphene chemical potential, \(\Gamma = 1/(2 \tau)\) is the electron scattering rate, and \(\tau\) is the electron relaxation time.

Graphene conductivity can be tuned by applying a transversal electric field via a DC biased gating structure (see Fig. [1]). This field modifies the graphene carrier density \(n_s\) as

\[
C_{ox} V_{DC} = q_e n_s,
\]

where \(C_{ox} = \epsilon_{sp}/t\) is the gate capacitance and \(V_{DC}\) is the applied DC bias field. The carrier density is related to graphene chemical potential \(\mu_c\) as

\[
n_s = \frac{2}{\pi \hbar^2 v_f^2} \int_0^\infty e\left[ f_d(\epsilon - \mu_c) - f_d(\epsilon + \mu_c) \right] d\epsilon, \tag{3}
\]

where \(\epsilon\) is energy, \(v_f\) is the Fermi velocity (\(\sim 10^8\) cm/s in graphene), and \(f_d\) is the Fermi-Dirac distribution

\[
f_d(\epsilon) = \left( e^{(\epsilon - \mu_c)/k_B T} + 1 \right)^{-1}. \tag{4}
\]

The chemical potential \(\mu_c\) is accurately retrieved by numerically solving Eq. (3). Hence, we can see from Eq. (1) that the graphene conductivity \(\sigma\) or surface impedance \(1/\sigma\) can be dynamically controlled by \(V_{DC}\). This property can be used to create leaky-wave antennas with dynamic control as introduced in Section I and further detailed next.

III. SINUSOIDALLY-MODULATED REACTANCE SURFACES

Electromagnetic propagation along a sinusoidally-modulated reactance surfaces was theoretically investigated in the 50s \([15]\), but is still drawing significant interest as a powerful way to control radiation properties \([16], [22]\). Surfaces with a dominant positive reactance impedance (such as graphene) allow the propagation of TM surface waves. If a modulation is then applied along the \(y\) axis, the modal surface reactance \(X_s\) can be expressed as:

\[
X_s = X_s' \left[ 1 + M \sin \left( \frac{2 \pi y}{p} \right) \right], \tag{5}
\]

where \(X_s'\) is the average surface reactance, \(M\) the modulation index and \(p\) the period of the sinusoid.

The interaction between surfaces waves and the reactance modulation produces a Bragg radiation effect thus creating a leaky wave radiation. The wavenumber \(k_y\) of the fundamental space harmonic along the impedance modulated graphene sheet can be written as \([15]\):

\[
k_y = \beta_{spp} + \Delta \beta_{spp} - j(\alpha_{spp} + \alpha_{\text{rad}}), \tag{6}
\]

where \(\beta_{spp}\) is the propagation constant of the SPP on the unmodulated graphene sheet (i.e., with \(M = 0\)), \(\Delta \beta_{spp}\) a small variation in \(\beta_{spp}\) due to the modulation, \(\alpha_{spp}\) the attenuation constant due to losses and
The attenuation constant due to energy leakage.

In this kind of periodic LWAs, the fundamental space harmonic is slow and usually the higher-order -1 space harmonic is used for radiation [15]. In this case, the pointing angle $\theta_0$ of the radiated beam is approximated as [19]

$$\theta_0 \simeq \arcsin \left( \frac{\beta_{spp}}{k_0} - \frac{\lambda_0}{p} \right)$$

(7)

where $\lambda_0$ is a free space wavelength and $\Delta \beta_{spp}$ is assumed much smaller than $\beta_{spp}$ [22]. Since the average surface reactance $X'_S$ mainly determines $\beta_{spp}$ and the modulation index $M$ mainly determines $\alpha_{\text{rad}}$, these LWAs allow for nearly independent control of the pointing angle and the beamwidth [16].

In the next Section, a graphene LWA based on this radiation principle is proposed taking into account realistic technological parameters for future implementation.

IV. PERIODICALLY MODULATED GRAPHENE LWA

A. Proposed Structure

The proposed sinusoidally-modulated graphene LWA is shown in Fig. 1. It consists of a graphene sheet transferred on a back-metallized substrate and several independent polysilicon DC gating pads beneath it. The surface impedance $Z_S = R_S + jX_S$ at the graphene position $(z = h)$ determines the propagation characteristics of the SPPs, i.e., $k_{y,spp} = \beta_{spp} - j\alpha_{spp}$.

In an unmodulated graphene sheet, the dispersion relation of the SPPs can be computed by applying a transverse resonance equation (TRE) to the equivalent circuit shown in Fig. 2 [23], where the width $w$ of the graphene sheet is considered infinite. Then, by enforcing $Y_{UP} + Y_{DOWN} = 0$, where

$$Y_{UP} = \frac{\omega \varepsilon_0}{\pm \sqrt{k_0^2 - k_{y,spp}^2}},$$

(8)

$$Y_{DOWN} = \sigma + \frac{\omega \varepsilon_r \varepsilon_0}{\pm \sqrt{\varepsilon_r k_0^2 - k_{y,spp}^2}} \coth \left( \pm \sqrt{\varepsilon_r k_0^2 - k_{y,spp}^2} h \right),$$

(9)

the desired dispersion relation is obtained as

$$\frac{\omega \varepsilon_0}{\pm \sqrt{k_0^2 - k_{y,spp}^2}} + \frac{\omega \varepsilon_r \varepsilon_0}{\pm \sqrt{\varepsilon_r k_0^2 - k_{y,spp}^2}} \frac{1}{\coth \left( \pm \sqrt{\varepsilon_r k_0^2 - k_{y,spp}^2} h \right)} = -\sigma.$$

(10)

In the above expressions, $\varepsilon_0$ is the vacuum permittivity, $\varepsilon_r$ is the dielectric permittivity, $k_0 = \omega / c$ is the free space wavenumber and $h$ is the dielectric thickness. The surface impedance $Z_S$ is then computed as $1/Y_{DOWN}$. It can be shown that the polysilicon pads can be safely neglected since they are extremely thin ($\sim 100$ nm) and with a relatively permittivity $\varepsilon_r \approx 3$ [24] similar to the one of the SiO2 substrate used.

As explained in Section III, in order to modulate the surface impedance $Z_S$, the graphene conductivity $\sigma$ is modified by applying adequate bias voltages $V_{DC}$ to the different pads. This allows to generate the desired periodic reactance modulation. Here, one modulation period $p$ is sampled in $N$ points according to the number of gating pads used, namely, $p = N(s + g)$, where $s$ is the pad length and $g$ the distance between pads (see Fig. 3). Therefore, $p$ can be dynamically controlled according to the periodicity imposed by the different $V_{DC}$. Consequently, from Eq. (7), the proposed structure offers electronic beamscanning at a fixed frequency. This is a novel property absent when usual techniques such as the use of sub-wavelengths printed elements or dielectric slabs with variable thickness [16], [22], [25] are employed to implement sinusoidally-modulated LWAs.

The impedance-modulated graphene sheet of Fig. 1 may radiate towards both the upper and lower

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**Fig. 2.** Schematic of graphene sheet transferred onto a back-metallized substrate (a) and its equivalent transverse network along the z-axis (b). The polysilicon pads have been neglected since they are extremely thin and with permittivity similar to the one of the SiO2 substrate used.
half-spaces depending on the substrate permittivity $\varepsilon_r$. The metallic plane is then used as a reflector to focus the radiated beam towards the upper half-space. In addition, it is important to remark that, although SPPs on graphene sheets are very confined into the layer [4], the presence of a metallic plane at a distance $h$ from the graphene sheet might affect their propagation characteristics. This is particularly important when dealing with this type of LWA due to their high dispersive nature, where a small variation on $\beta_{spp}$ can considerably tilt the pointing angle $\theta_0$. Here, this phenomenon is rigorously taken into account in the equivalent circuit of Fig. 2.

B. Design Strategy

The design flow of the proposed graphene LWA must take into account the technological limitations of current graphene fabrication processes. Therefore, given the parameters of a graphene sample ($\tau$, $T$, $t$, $V_{DC}$), the substrate ($\varepsilon_r$) and the frequency of operation $f_0$, the design steps are the following:

1) Given $t$ and the available range of $V_{DC}$, compute the achievable values of $\mu_c$ with Eqs. (2) and (3).

2) Knowing the range of $\mu_c$, the graphene conductivity $\sigma$ can be computed with Eq. (1) and, in turn, the wavenumber of the SPPs $k_{y,spp}$ with Eq. (10).

3) Knowing $k_{y,spp}$, compute the surface impedances $Z_S = R_S + jX_S$ as a function of $\mu_c$.

4) Choose the desired range of reactances ($X_{S_{min}} - X_{S_{max}}$ in Fig. 3) according to the available values of $Z_S$. As described in Section III, the mean reactance $X'_S$ mainly determines $\beta_{spp}$ and, along with the period $p$, $\theta_0$. The impedance variation, i.e., the modulation index $M$, mainly determines $\alpha_{rad}$ [15].

5) With the chemical potential required for $X'_S$, compute $\beta_{spp}$ and $\alpha_{spp}$ with Eqs. (1) and (10).

6) Select the different modulation periods $p$ according to the desired pointing angles $\theta_0$ with Eq. (7).

7) Find the required dimensions of the gating pads $s$ and $g$ and the different values of $N$ needed to synthesize the desired periods.

8) Select the substrate thickness $h$ such that the radiated beams in the scanning region are mainly in phase.

9) Knowing $X'_S$, $M$ and $p$, compute $\alpha_{rad}$ [15].

Finally, the complex propagation constant $k_y$ is determined by Eq. (6) and the radiation pattern of the LWA can be easily computed using standard techniques [19].

V. Design Example

In this example we consider a SiO$_2$ substrate of permittivity $\varepsilon_r = 3.8$ [26]. We assume graphene with a relaxation time $\tau = 1$ ps, temperature $T = 300^\circ$ K and design the antenna for operation at $f_0 = 2$ THz. The value of $\tau$ was estimated from the measured impurity-limited DC graphene mobility on boron nitride [27] of $\mu \simeq 60000 cm^2/(V s)$, which leads to $\tau = \mu E_F/(q_e v_F^2) \simeq 1.2$ ps for a Fermi level of $E_F = 0.2$ eV. Note that even higher mobilities have been observed in high quality suspended graphene [28].

The width $w$ of the graphene strip is chosen to be electrically very large (200 $\mu$m) in order to support the propagation of SPPs with the same characteristics as in 2D infinite sheets [29] thus allowing to use the simplified model of Fig. 2.

The graphene chemical potential $\mu_c$ as a function of the DC bias voltage $V_{DC}$, computed using Eqs. (2) and (3), is shown in Fig. 4 for different values of $t$. A distance $t = 20$ nm is chosen which offers values of $\mu_c$ until 0.8 eV using $V_{DC}$ values below 45 V.

The surface impedance $Z_S$ is plotted in Fig. 5 as a function of $\mu_c$. It is observed that, while the graphene resistance $R_S$ remains fairly constant, the reactance $X_S$ can be considerably modified. Under
these conditions, an average surface reactance $X'_s = 1302 \Omega/\sqrt{\omega}$ and a modulation index $M = 0.35$ are chosen. According to Fig. 4 and 5, this requires a range of chemical potentials between 0.3 and 0.8 eV, i.e., a range of DC voltages between 6.4 V and 45 V.

The voltage $V_{DC}$ needed for the desired $X'_s$ is 13.5 V, i.e., $\mu_c = 0.436$ eV. This corresponds to $\beta_{spp}/k_0 = 3.59$ and $\alpha_{spp}/k_0 = 0.21$. In order to illustrate the effect of the metallic plane on the propagation of SPPs, $\beta_{spp}$ and $\alpha_{spp}$ are plotted in Fig. 6 as a function of $h$. The solid blue lines indicate the values obtained in the case of a graphene sheet on a semi-infinite substrate. It can be seen that for $h > 30 \mu m$ the effect of the metallic plane is negligible and thus the plasmon is indeed highly confined to the graphene layer.

Once $\beta_{spp}$ is known, Eq. (7) allows determining that the -1 space harmonic is in the fast-wave radiation region for values of $p$ comprised between 33 and 57 $\mu m$ (see Fig. 7). Depending on the size of the polysilicon pads, a different number of scanning beams can be obtained. Although smaller pads offer the possibility to generate more beams, the complexity of the antenna also increases. As a trade-off, the dimensions of the pads are here chosen as $s = 4.8 \mu m$ and $g = 0.2 \mu m$. This configuration can generate 4 different beams at $-45.4, -9.3, 15.4$ and $37.5^\circ$ by varying $N$ from 7 to 10 (see Fig. 7). The radiation patterns obtained with LWA theory and full-wave simulations for these values of $N$ are plotted in Fig. 8.

![Fig. 4. Graphene chemical potential $\mu_c$ as a function of the DC bias voltage $V_{DC}$. Parameters: $\tau = 1$ ps, $T = 300^\circ K$, $f_0=2$ THz and $\varepsilon_r = 3.8$.](image)

![Fig. 5. Surface resistance $R_S$ and reactance $X_S$ at the graphene sheet (position $z = h$ in Fig. 2) as a function of the chemical potential $\mu_c$. Parameters: $\tau = 1$ ps, $T = 300^\circ K$, $f_0=2$ THz and $\varepsilon_r = 3.8$.](image)

![Fig. 6. Normalized phase constant $\beta_{spp}/k_0$ (a) and dissipation losses $\alpha_{spp}/k_0$ (b) of a SPP on the structure shown in Fig. 2 as a function of the substrate thickness $h$. Parameters: $\tau = 1$ ps, $T = 300^\circ K$, $f_0=2$ THz, $V_{DC} = 13.5$ V and $\varepsilon_r = 3.8$.](image)

![Fig. 7. Poiting angle $\theta_0$ as a function of the period $p$. $N$ is the number of polysilicon pads used to define one modulation period $p$. Parameters: $\tau = 1$ ps, $V_{DC} = 13.5$ V, $T = 300^\circ K$, $f_0=2$ THz, $\varepsilon_r = 3.8$, $s = 4.8 \mu m$ and $g = 0.2 \mu m$.](image)
In the scanning region, the proposed LWA presents a leakage factor $\alpha_{rad}/k_0 \approx 0.025$ and dissipation losses $\alpha_{spp}/k_0 \approx 0.21$. The effective length of the antenna for a 95% of dissipated power is $L_e = 3/(2(\alpha_{rad} + \alpha_{spp}))$ [19]. The radiation efficiency $\eta_{rad}$ of LWAs with non-negligible dissipation losses is given by [30]:

$$\eta_{rad} = \frac{\alpha_{rad}}{\alpha_{rad} + \alpha_{spp}} \left(1 - e^{-2(\alpha_{rad}+\alpha_{spp})L_e}\right). \quad (11)$$

In our case, $L_e \approx \lambda_0$ and $\eta_{rad} \approx 11\%$. The radiation efficiency could be further increased by using a wider range of $V_{DC}$ to achieve higher values of $M$, e.g., $M = 0.5$ leads to $\eta_{rad} \approx 19\%$. These results are really satisfactory for an antenna working at the THz range and offering dynamic reconfiguration. Note that the final value will always depend on the scattering rate $\tau$ of graphene used.

More directive antennas can also be designed using lower permittivity substrates. Reducing $\varepsilon_r$ reduces $\beta_{spp}$ and $\alpha_{spp}$, and thus the effective length of the antenna is increased. For instance, using the same graphene sheet on a substrate with $\varepsilon_r = 1.8$ implies $\beta_{spp}/k_0 = 2.23$, $\alpha_{spp}/k_0 \approx 0.117$ and $\alpha_{rad}/k_0 \approx 0.02$. Obviously, since $\beta_{spp}$ is reduced, the values of $p$ needed to scan with the -1 harmonic are larger. In this case, using pads of $s = 8.8\mu m$ and $g = 0.2\mu m$ and values of $N$ between 6 and 9 generates the beams shown in Fig. 9. The effective length of the antenna is now $1.74\lambda_0$, allowing for higher directive beams and a radiation efficiency around 15%. The drawback of this configuration is that low permittivity substrates are difficult to implement and a higher number of polysilicon pads is required.

VI. CONCLUSIONS

A graphene leaky-wave antenna which allows electronic beamscanning at a single frequency has been proposed. Its radiation principle is based on sinusoidally-modulated reactance surfaces which can be easily implemented using a graphene sheet thanks to its tunable characteristics when applying electric field biasing.

This novel antenna concept offers unprecedented performances at the THz band such as electronic control of several radiation characteristics preserving a radiation efficiency above 10%. The main limitations in its design are imposed by graphene properties (such as the relaxation time $\tau$), the range of feasible voltages that can be applied to the gating pads, and the availability of substrates in the THz band.

The overall performances of this simple antenna structure are very promising for its integration in future all-graphene reconfigurable THz transceivers and sensors.

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