Design of a Terahertz Leaky-Wave Long-Slot Antenna Using Graphene

Ehsan Zarnousheh Farahani ∙ Alireza Mallahzadeh∗

Abstract

In this paper, a novel graphene-based leaky-wave antenna is presented. The frequency of the proposed antenna is in the terahertz range, and it is composed of a straight long slot covered with a graphene sheet. To tune the leakage constant along the slot, DC voltage biases are applied using gating pads. A transverse equivalent network model that includes the graphene slot structure is also presented. A design procedure for a lossy structure leaky-wave antenna with an unknown loss value is proposed. The antenna is designed and simulated in HFSS and CST software. An interesting feature of this antenna is the ability to control its radiation characteristics across its entire working frequency range through graphene conductivity tunability with DC voltage bias.

Key Words: Graphene, Leaky-Wave Antenna, Slot Antenna, Terahertz.

I. INTRODUCTION

Recently, graphene materials have attracted great attention in antenna, microwave, and terahertz applications due to their electromagnetic characteristics. Many graphene antennas have been proposed using graphene conductivity tuning [1–5]. A major class of antennas using graphene materials is the leaky-wave antenna (LWA) introduced in the 1940s [6], whose radiation mechanism is based on a traveling wave inside the structure that leaks outside via a long slot [7]. In general, depending on the structure of the slot, LWAs can be classified into two categories: long slots or periodic apertures [8, 9]. Periodic apertures have been used to better control the leakage constant [10].

The main advantage of LWAs is that they provide a high-directivity beam with no need for a complex and costly feed structure design [11]. Moreover, such antennas have a wide bandwidth capable of beam scanning with frequency, which makes them a suitable choice for 5G and radar applications [12]. However, improving their pattern bandwidth, defined as radiation power density at a fixed observation angle, is an ongoing effort.

Non-radiating microstrip structures can be utilized to create a planar and low-profile LWA. These structures are periodically modulated to create a radiating leaky mode [11]. Metamaterials have also been used to obtain broadside beam angle radiation [13], which could not be attained using a typical LWA. Low-profile LWAs have been presented using substrate-integrated waveguide (SIW) technology [14–16]. In [17], a low cross-polarization SIW-LWA was proposed by placing the slots on the centerline of the SIW.

Recently, research attention has shifted toward working in the terahertz regime due to the demand for high bandwidths and low profiles in new communication networks. A low-loss, low-profile, wide-aperture radar was developed in [18] using a...
terahertz LWA. More recently, in [19] and [20], two LWAs were presented having wide-angle beam scanning abilities at sub-THz frequencies.

Graphene-based LWAs have also been proposed using the surface conductivity tunability feature of graphene sheets simply by using a DC voltage bias [21–23]. Esquius-Morote et al. [21] presented a leaky-wave terahertz antenna that could alter the radiation beam angle at a fixed frequency using electric tuning. This could be used to increase the pattern bandwidth. Later, Cheng et al. [22] presented a new sinusoidally modulated graphene LWA that could scan the beam angle at a fixed frequency while requiring only one biasing voltage. A graphene LWA that could alter the radiation pattern at a fixed frequency was presented in [23] based on a dielectric grating.

Fuscaldo et al. [24–27] have been working on 2D graphene-based LWAs since 2015. A graphene Fabry–Perot cavity (FPC) LWA has been proposed with the ability to beam steer along both the E-plane and H-plane simultaneously by affecting transverse electric (TE) and transverse magnetic (TM) modes via bias voltage [27]. Different configurations of LWAs based on graphene metasurfaces have also been studied [24]. A systematic approach for modeling homogenized metasurfaces in graphene-based LWAs was presented in [25]. Efforts have also been made to experimentally realize graphene-based FPC-LWAs [28]. New formulas for the beam properties of 1D LWAs have been derived that could provide more accuracy in finite structures [29].

In this paper, a novel long-slot leaky-wave waveguide antenna based on graphene sheets in the terahertz regime is proposed. A novel transverse equivalent network (TEN) model is also presented for a graphene slot. The sidelobe level (SLL) of the antenna is controlled using graphene conductivity over the slot. The antenna radiation characteristics are tunable across the entire working frequency of the antenna using DC biasing pads under the slot.

Controlling the SLL and other radiation characteristics of the antenna is the main problem addressed in this paper, which is achieved by using graphene conductivity over the slot length instead of the typical way of providing an offset along the slot. This results in a more convenient and dynamic way of tuning the radiation characteristics. A design procedure for a lossy structure LWA with an unknown loss value, is also studied, which has not been previously reported.

The rest of this paper is organized as follows. In Section II, the theory and design principles of LWAs are presented, in which a long-slot leaky-wave waveguide antenna, graphene conductivity, graphene slot TEN, and the antenna design method are discussed. An example of the antenna design and the simulation results are presented in Section III. Finally, conclusions are drawn in Section IV.
LWA, the slot offset over the length is used to control the antenna SLL.

2. Graphene Conductivity

Graphene is a 2D material whose electric conductivity is calculated as follows [31]:

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

(5)

where $q_e$ is the electron charge, $K_B$ is Boltzmann constant, $T$ is the temperature, $\hbar$ is reduced Planck constant, $\omega$ is the angular frequency, $\tau$ is the electron relaxation time, and $\mu_c$ is the chemical potential. The chemical potential is tunable by applying a variable DC bias voltage to the graphene sheet. The relationship between the bias voltage $V_{DC}$ and chemical potential is

$$\mu_c = \hbar V_F (\pi \varepsilon_0 \varepsilon_s / q_e t)^{1/2},$$

(6)

where $V_F$ is the Fermi velocity in graphene, $\varepsilon_0$ is the vacuum permittivity, $\varepsilon_s$ is the relative permittivity, and $t$ is the thickness of the dielectric. As can be seen from Eqs. (5) and (6), graphene conductivity can be tuned using the DC bias voltage.

If we use a graphene sheet as a slot in the waveguide LWA, changing the conductivity of graphene would alter its leakage rate.

3. Graphene Slot Transverse Equivalent Network

To design a waveguide slot antenna, the value of the leakage rate of the slot over its length is required. A TEN model [32] is presented to calculate the $\beta$ and $\alpha$ of the structure.

To calculate the propagation and leakage parameters of a graphene slot, we present a transverse equivalent circuit (Fig. 1).

The presented model consists of two parts:

(i) The graphene slot on the upper wall of the waveguide, which is modeled with $B_g$ and the admittance $Y_g$ besides the $T_r$ transformer, transmission line ended by the graphene conductivity $\sigma_g$ and radiation admittance $Y_r$.

(ii) The left and right sides of the waveguide with respect to the center of the slot; each side can be considered a waveguide and can be modeled with transmission lines with $a'/2 + d'$ and $a'/2 + d$ lengths and short-circuited at the end, where $a'$ is the slot width and $d$ and $d'$ are the distance of the slot from right and left sides of the waveguide.

The model is created using the method presented in [33] for waveguide LWAs. To obtain the propagation behavior of the structure, it is reduced to a simple circuit, as displayed in Fig. 2. $Y_{up}$ is the total admittance observed looking up from $T_r$ with graphene conductivity $\sigma_g$ and radiation admittance $Y_r$. $Y_L$ and $Y_R$ are the total admittance observed from the right and left sides of the slot center, respectively. Now, we have

$$Y_{up} = \frac{1}{n_{es}} (Y_r + Y_g),$$

(7)

$$Y_R = j B_a - j Y_0 \cot k_x \left( \frac{a'}{2} + d \right),$$

(8)

$$Y_L = j B_a - j Y_0 \cot k_x \left( \frac{a'}{2} + d' \right),$$

(9)

Setting $Y_{up} + j B_L + \frac{Y_L}{Y_R + Y_L} = 0$ and normalizing to $Y_0$ results in
\[
\frac{1}{n_x^2} \left( \frac{Y_e}{V_0} + \frac{Y_o}{V_0} \right) + j \frac{B_k}{V_0} + \frac{B_o}{V_0} - \cot k_x \left( \frac{a'}{2} + d' \right) \right] \\
+ j \frac{2R_a}{V_0} - \left[ \cot k_x \left( \frac{a'}{2} + d' \right) + \cot k_x \left( \frac{a''}{2} + d'' \right) \right]
\]

\begin{equation}
= 0
\end{equation}

where \( \beta, \gamma, n_x, \) and \( Y_c = \sigma G \) are defined in the appendix and is graphene sheet conductivity. Now, the values of \( \beta \) and \( \alpha \) of the structure can be obtained as

\[
k_x = \beta - j \alpha = \sqrt{k_0^2 - k_x^2}.
\]

The leakage of the structure consists of two losses: the radiation loss, modeled using \( Y_r \) admittance, and the loss due to the real part of graphene conductivity.

4. Antenna Design Method

Designing a graphene slot antenna with a specific SLL requires the radiation leakage to be known. The leakage value calculated from the presented model contains both radiation loss and graphene loss. Assuming that the radiation fields near the slot are perpendicular to the graphene sheet with conductivity \( \sigma_G \), reflection, transmission, and loss can be simply calculated:

\[
P_r = |S_{21}|^2 = \left[ \frac{2}{2 + \sigma_G Z_0} \right]^2, \quad (12)
\]

\[
P_t = \left| \frac{\sigma_G Z_0}{2 + \sigma_G Z_0} \right|^2, \quad (13)
\]

\[
P_l = 1 - P_r - P_t = \frac{4 \sigma_G Z_0}{(2 + \sigma_G Z_0)^2}, \quad (14)
\]

where \( Z_0 \) is the nominal impedance of the structure.

In the proposed antenna, we have two radiation leakage control parameters: offset from the waveguide centerline and graphene conductivity.

For a fixed offset distance, Fig. 3 depicts the variation of \( \beta/k \) and \( \alpha/k \) versus the chemical potential in a graphene slot waveguide. The waveguide is air-filled, with \( a = 170 \mu m \) and \( b = 85 \mu m \), so the cutoff frequency is \( < 1 \) THz, and the tunability range with the graphene conductivity change is clearly shown. The results obtained from the presented TEN and HFSS (High Frequency Structure Simulator) simulations show good agreement, except for the small values of \( \mu_e \) due to which \( \alpha \ll \beta \) is not justified; therefore, the presented TEN is validated only for higher \( \mu_e \) values.

The offset is varied for a fixed chemical potential, and the results are presented in Fig. 4. This shows the tenability of leakage using offset variation.

Varying \( \frac{B_o}{k_0} \) over the frequency shows beam direction scan-
ning with frequency. As demonstrated in Fig. 5, as the frequency is altered, \( \beta/k_0 \) varies. At \( \beta/k_0 = 0 \), the antenna’s main beam direction is broadside, and when \( \beta/k_0 = 1 \), the antenna’s main beam radiation direction is end-firing.

To further simplify the design, we fix the offset of the slot over the length and change the graphene conductivity. This simplifies the manufacturing process. Graphene conductivity can be controlled using DC voltage pads placed under the graphene sheet.

III. DESIGN EXAMPLE AND SIMULATION RESULTS

A LWA is designed for a main beam angle \( \theta_m \) toward 30° at 1 THz. The SLL and the required 3 dB beamwidth are set to −35 dB and 1°, respectively. The dimensions of the waveguide are calculated according to \( \theta_m \) and the working frequency as follows [34]:

\[
a = \frac{\lambda_0}{2 \times \sqrt{\varepsilon_r - \sin^2 \theta_m}}
\]  

(15)

where \( a \) (as depicted in Fig. 1) is the waveguide’s broad wall and \( \varepsilon_r \) is the electrical permittivity of the waveguide fill material, which in our case is free space and equal to 1. The narrow wall of the waveguide is specified by the maximum power handling of the antenna and is usually defined as \( b = a/2 \). Therefore, the waveguide dimensions are \( a = 173 \) μm and \( b = 86.5 \) μm.

The length of the antenna is obtained according to the 3 dB beamwidth as follows [9]:

\[
\Delta \theta \approx \frac{U_F}{L_0/L_0 \cos \theta_m}
\]  

(16)

where \( U_F \) is the aperture factor, which is dependent on the field amplitude distribution and is approximately 1. \( U_F \) is lower for a constant aperture distribution and greater for a sharply peaked distribution, which results in a wider beamwidth. Considering \( U_F = 1 \), the antenna length is calculated as \( L \approx 19500 \) μm. Note that in our design, the distribution has a sharp peak due to the graphene loss effects; therefore, higher values for \( U_F \) are expected, resulting in a wider beamwidth. However, a more accurate relationship is presented in [29], which requires the antenna leakage to be constant along the antenna length. As the leakage is not known at this step, the new formulation is not applicable.

To obtain the desired SLL, a Taylor distribution with −35 dB SLL is to be followed. To avoid grating lobes, the distance between the biasing pads should be equal to or less than \( \lambda_0/2 \). Here, it is set to \( \lambda_0/2 = 150 \) μm which results in 130 biasing pads.

The required leakage over the slot length should be obtained from Eq. (3). When \( \alpha_R(z) \) is determined, the graphene conductivity and the required chemical potential value under the pads are calculated using Eqs. (10) and (11), respectively. In Eq. (3), the loss constant over the antenna length is considered to be known. However, this is an invalid consideration here, as graphene loss is dependent on graphene conductivity. To overcome such a problem, graphene loss is neglected and \( \alpha_L \) is calculated using Eq. (1). After that, an initial value for \( \alpha_L \) is calculated using Eqs. (12)–(14). Now, the calculation of Eq. (3) is repeated, and the new \( \alpha_L \) and, consequently, the new \( \alpha_R \) are calculated. This procedure is repeated until \( \alpha_R \) and \( \alpha_L \) converge. The main condition guaranteeing convergence is the value of antenna efficiency \( \eta \), which should not exceed the maximum value calculated by Eq. (4). The exact value is not known at the onset of the design procedure, so we set it to 70%.

The procedure is followed for four iterations, and the values of \( \alpha_R \) are illustrated in Fig. 6. The values obtained in iterations 3 and 4 are approximately equal. The final values for the chemical potential along the slot are illustrated in Fig. 7.

The proposed antenna is simulated using HFSS. Its return loss is presented in Fig. 8. The antenna is also simulated in CST using a different solution method to verify the results. The value of the maximum efficiency obtained is 74%.
The antenna contains a long slot covered by a graphene sheet. A total of 130 silicon pads are placed at equal distance under the graphene sheet to bias each part with different DC voltages.

The antenna radiation pattern is also simulated using CST software and compared with the HFSS results (Fig. 9). At the center frequency, the main beam direction is 30° from the antenna’s normal plane. By changing the frequency, the $\beta$ of the structure varies, and the beam direction will be altered. With a fixed chemical constant, the antenna’s main beamwidth changes with frequency. However, such a problem can be addressed by tuning the leakage constant. This is a beneficial characteristic of the designed antenna, in which the leakage constant can be tuned by changing the chemical potential values over the slot. The new values could be calculated again at each working frequency. A comparison of the antenna patterns between the tuned and untuned values is illustrated in Fig. 10 for 0.9, 1.1, and 1.2 THz frequencies.

A comparison between the presented graphene-based LWA and earlier works is provided in Table 1.

Referring to Table 1, the presented graphene-based LWA is the only design which provides beamforming capability over the
antenna’s entire working frequency range. In addition, it is the only antenna that considers graphene loss in the design procedure.

IV. CONCLUSION

A novel waveguide LWA using a graphene slot is presented. The proposed antenna consists of a straight long slot covered by a graphene sheet on a waveguide working in the THz frequency regime. A TEN model is introduced to model the structure. The conductivity tunability of graphene is used to control the aperture distribution along the slot by means of DC electric biasing pads under the slot. The design procedure is provided while considering graphene loss, and a design example is also presented. The aperture distribution tunability of the antenna over the frequency range is introduced as a beneficial characteristic for controlling the radiation characteristics over the entire working frequency range.

APPENDIX

For the equivalent network depicted in Fig. 1 and for Eqs. (7)–(10),

\[ \frac{B_{a}}{Y_{0}} = \frac{\pi}{16} \frac{a'}{b} \frac{k_{x}a'}{2} f_{0}(k_{x}a') \]

where \( f_{0} \) is a Bessel function of order zero.

\[ \frac{B_{r}}{Y_{0}} = \frac{\pi}{y} \frac{a'}{\epsilon} \ln \left[ \frac{\pi}{y} k_{x}a' \right], \]

where \( \epsilon = 2.718 \) and \( y = 1.781 \).

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Ehsan Zarnousheh Farahani
received his B.S. degree in electrical engineering from Arak University, Arak, Iran, in 2013, and his M.S. degree in communication engineering from Imam Khomeini International University (IKIU), Qazvin, Iran, in 2015. He is currently working toward a Ph.D. in communication engineering at Shahed University, Tehran, Iran. His main areas of interest are leaky-wave antennas, graphene-based antennas, and metamaterials.

Alireza Mallahzadeh
received his B.S. degree in electrical engineering from Isfahan University of Technology, Isfahan, Iran, in 1999 and his M.S. and Ph.D. degrees in electrical engineering from Iran University of Science and Technology, in 2001 and 2006, respectively. He is a faculty member in the Faculty of Engineering, Shahed University, Tehran, Iran. He has participated in many projects related to antenna design, which resulted in him fabricating different types of antennas for various companies. He is also interested in numerical modeling and microwaves.