Efficient Graphene Microstrip Plasmonic Mode Converter Utilising Bend Geometries

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***Abstract*—The comprehensive investigation and analysis of a dual bend graphene microstrip geometry is conducted in the present paper to enable the effective and consistent conversion of the propagating surface wave modes. Numerical results via an accurate finite-difference time-domain algorithm validate successfully the desired performance of the proposed device.**

***Keywords*—Bulk modes, conversion efficiency, FDTD, intraband conductivity, mode coupling**

I. Introduction

The various outstanding properties of graphene, the truly two-dimensional carbon allotrope, are attracting the research community's interest until nowadays. From an electromagnetic perspective, despite graphene's negligible thickness, a finite conductivity is measured. The latter enables various exotic phenomena such as the propagation of strongly confined surface plasmon polariton (SPP) waves beyond the far-infrared regime. Consequently, a wide class of devices have been presented, including plasmonic waveguiding systems, like graphene microstrips. These apparatuses are utilised for the long-range propagation of surface waves and several modes are supported due to their finite dimensions [1]. In essence, two major categories of propagating modes appear; the edge and the bulk ones, related to the energy distribution on the microstrip. In spite of the larger cut-off frequencies of the bulk modes, their waveguiding features are generally advantageous. Therefore, it is deemed critical to determine their coupling characteristics as well as any arrangements that permit an efficient mode conversion.

To this objective, a family of graphene microstrip bend geometries is introduced in this work to study the plasmonic mode conversion traits. Initially, the basic electromagnetic properties of graphene are presented, focusing on its surface conductivity and the SPP propagation constant. Then, a dual bend microstrip setup is designed, inspired by similar models of metallic waveguiding systems at the microwave regime [2]. The functionality of this novel graphene plasmonic converter is thoroughly examined by means of a properly tailored finite-difference time-domain (FDTD) technique, which enables the accurate modeling of graphene as an equivalent surface current [3].

II. Theoretical Aspects and Design Process

A. Graphene Surface Conductivity

Graphene is considered as a truly two-dimensional material and is adequately described by its surface conductivity $\sigma_{\rm gr}(\omega,\mu_c,\Gamma,T)$, where ω is the radian frequency, μ_c is the chemical potential, controlled either by chemical doping or by an applied gate voltage, Γ a phenomenological scattering rate assumed to be independent of energy, and T the temperature. Actually, the conductivity of graphene is evaluated by the compact expression resulting from the Kubo formula [4], involving only the dominant, at the far-infrared spectrum, intraband term

$$\sigma_{\rm gr}(\omega,\mu_c,\Gamma,T) = \\ = -j\frac{e^2 k_B T}{\pi\hbar^2(\omega - j2\Gamma)}\left[\frac{\mu_c}{k_B T} + 2\ln\left(e^{-\mu_c/k_B T}+1\right)\right], \quad (1)$$

with $-e$ the electron charge, $\hbar$ and k_B the reduced Planck and Boltzmann constants, respectively. Furthermore, the propagation properties of the SPP wave on an infinite graphene layer are evaluated in terms of the complex wavenumber k_ρ, that is extracted through [5]

$$k_\rho = \sqrt{1-\left(\frac{2}{\sigma_{\rm gr}\eta_0}\right)^2}\,k_0 = n_{\rm eff}k_0\,, \quad (2)$$

where k_0 and η_0 are the free-space wavenumber and wave impedance, correspondingly. The SPP effective index term $n_{\rm eff}$ constitutes an important quantity, since it provides an intuitive expression of the propagation features. Also, it is beneficial to compare the characteristics between the different propagating modes on a graphene microstrip.

B. Graphene Microstrip Dual Bend Geometry

The new graphene plasmonic converter is depicted in Fig. 1, including a microstrip of width w and two consecutive bends of curvature R with a bending angle θ. The core idea toward this design stems from the metallic waveguide counterpart at microwave frequencies [2]. Herein, the coupled-wave differential equations in an curvilinear orthogonal system are solved for the generalised propagation constants and the conversion efficiency $C_{\rm eff}$ is evaluated via

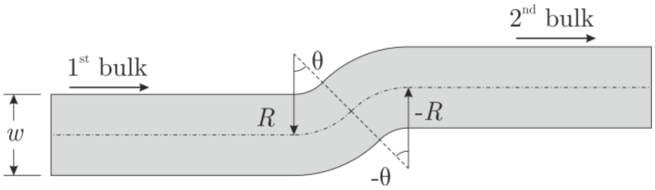

Figure 1: The proposed dual bend graphene microstrip configuration, consisting of two bends with an arbitrary curvature and bending angle.

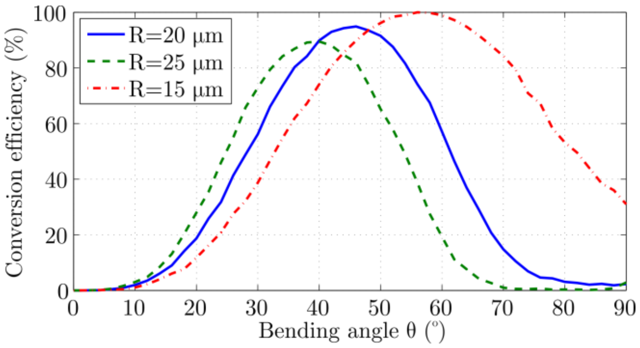

Figure 2: Conversion efficiency of the proposed device for different curvature radii and bending angles.

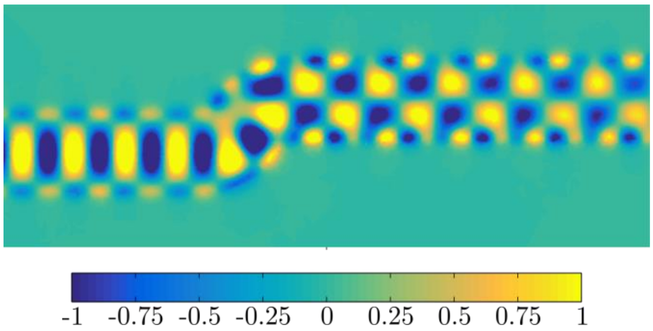

Figure 3: Electric field distribution on a graphene mictrostrip dual bend geometry with $R=15$ μm and $\theta=57^{\circ}$.

$$C_{\mathrm{eff}}=\frac{4\alpha^2\xi^2R^2}{\left(\alpha^2+\xi^2R^2\right)^2}\sin^4\left(\sqrt{\alpha^2+\xi^2R^2}\theta\right), \qquad (3)$$

where α depends on the coupling coefficient between the involved modes and ξ is the difference of their propagation constants. The key deduction from this expression is the fact that a suitable adjustment between the curvature radius and the bending angle can provide a full mode conversion. It should be stressed that the latter is achieved as long as $\alpha^2=\xi^2R^2$ and $\sqrt{\alpha^2+\xi^2R^2}\theta=\pi/2$.

III. Numerical Verification

The aforementioned promising theoretical estimation is validated via a thorough investigation of the proposed setup, shown in Fig. 1. Specifically, the conversion of graphene microstrip bulk modes is considered, since the edge modes are separated sufficiently and their coupling is negligible. For this reason, a graphene microstrip is stimulated with the first bulk mode and the conversion efficiency is extracted through the amplitude ratio of the second to the first one. The basic characteristics of graphene are $\mu_c=0.1$ eV, $\Gamma=0.11$ meV at room's temperature, while the microstrip width is set to $w=20\,\mu$m, in order to adequately support both bulk modes at the frequency of $f=3$ THz.

In this context, our numerical analysis is performed by means of an appropriately modified FDTD scheme that leads to precise and consistent graphene models, inducing an equivalent surface current [3]. The computational domain is divided into $250\times100\times100$ elementary cubic cells with an edge dimension of $\Delta=1$ μm, whereas the time increment of the technique is set to $\Delta t=1.9$ fs to guarantee its overall stability. It is noteworthy to mention that the cell size is almost 100 times smaller than the free-space wavelength owing to the seriously decreased graphene SPP wave one. Finally, the infinite open-space boundaries are truncated through an 8-cell thick perfectly matched layer (PML) absorbing boundary condition, tuned to drastically annihilate all outgoing surface waves [6].

Focusing on the simulation results, the featured device is examined in terms of the conversion efficiency for different curvature radii and bending angles, as illustrated in Fig. 2. It is interesting that the higher-order harmonic pattern is indeed observed, as anticipated from the theoretical analysis in (3). Moreover, the mode conversion efficiency is maximised at lower bending angles as the radius increases, revealing a corresponding periodicity. Nonetheless, this maximum value decreases, as well, for higher radii; thus, a complete mode conversion is feasible for the dual bend geometry at exactly $R=15$ μm and $\theta=57^{\circ}$.

Considering the prior geometric values, the electric field distribution of the specific configuration is extracted for the normal (to graphene surface) component and illustrated in Fig. 3. From the outcomes, it becomes apparent that the graphene microstrip is excited via the first bulk mode, which, in turn, is fully converted to the second one, due to the selected bending geometry, hence validating the promising efficiency of the proposed device.

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