Graphene-Based Fourier Optics

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Abstract

In this paper, we theoretically show that by tailoring specific conductivity distribution on graphene, one can create a region on this material to perform as a lens. Our numerical studies indicate that this "one-atom thick" lens obtains spatial Fourier transform of the optical signal similar to a standard optical lens in 3-dimensional optics. The possibility to create inhomogeneous patterns of effective index for SPP surface waves on the graphene may allow for reimplementation of Fourier optics devices on a monolayer of carbon atoms.

1. Introduction

To achieve optical systems that process information at higher rates and smaller scales compared to what current optical signal processing systems do, is vital to bring forth novel ideas, strucures, and maybe even new materials. In this paper, we suggest graphene—a single atomic layer of carbon atoms [1], [2]—as a new platform for "one-atom-thick" optical signal processing. Using graphene as platform for Fourier optics, one can contrive optical system as thin as diameter of a carbon atom. Moreover, using this carbon flatland, the optical signals propagate along the graphene as highly-confined transverse-magneric (TM) surface-plasmon-polariton (SPP) surface waves with guided wavelength much shorter than free-space wavelength [3-5]. This allows for the other dimensions to have subwavelength size, yielding ultra-compact optical systems. Although graphene is a very promising material in optoelectronic applications, in our present work its interaction with the electromagnetic waves is considered for the purpose of optical signal processing.

2. Manipulating SPP surface waves on Graphene

Graphene's complex conductivity ($\sigma_g=\sigma_{g,r}+i\sigma_{g,i}$) is function of the radian frequency ω, charged particle scattering rate Γ representing the loss mechanism, temperature T, and chemical potential μ_c [6]. The chemical potential depends on the density of carriers and can be controlled by gate voltage or electric magnetic field biasing or combination of these methods [1-6]. The imaginary part of graphene conductivity, computed from Kubo Formula [6], can attain negative and positive values in different ranges of frequencies depending on the level of chemical potential. As detailed in our work [7], assuming that graphene has a vanishingly small thickness, corresponding to the graphene complex conductivity, one may define an equivalent complex permittivity. Based on this notion, with proper control of the chemical potential, a graphene layer with positive imaginary part of conductivity (assuming $e^{-i\omega t}$ time harmonic) may act analogous to a thin metal layer which can support SPP waves with relatively low loss, high lateral confinement, and very small guided wavelength at the IR wavelengths [7]. Therefore, relying on the freedom in varying graphene conducitivty by using the methods mentioned above, by tuning the level of chemical potential locally, we can create desired patterns of effective index for SPP surface waves. This could be useful for designing one-atom-thick metamaterial and transformation optics devices based on graphene [7]. As an exmple in this work we demonstrate that by having a specific gradient in the conductivity of graphene, we can create a region on this material

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that has higher effective index for the Transverse Magnetic (TM) SPP surface waves that can effectively act as a 2-dimensional (2D) lens.

3. Fourier Transform using a 2D graphene-based Lens

A simple lens is the most fundamental component of an optical data processing system. Lens provides spatial Fourier transform of optical signals [8-9]. The concpet of designing a one-atom-thick lens on graphene is on the basis of how a regular 3-dimensional (3D) optical lens works. The nonuniformity in phase differnce distribution, due to higher index for the lens, results in curved phase fronts that become focused at focal point of the lens. One can visualize the same phenomenon for the SPP surface waves on a single sheet of graphene by introducing a region with different conductivity and associated SPP effective index.

In order to show that the proposed inhomogenity performs as a 2D lens, three following questions should be addressed:

(1) Does the lens obtain the Fourier transform of a point-like object, which generates circular SPP phase fronts, placed at its front focal point as linear phase fronts at exit.

(2) Does the lens obtain the Fourier transform of a uniform object, which generates uniform linear phase fronts,placed at the front focal line, as circular phase fronts converging at back focal point of the lens.

(3) Except for a linear phase shift ,does the lens output stay invariant, with respect to shift in the input in the transverse direction; in other words, does moving the object along the front focal line result in only a phase shift in the spatial frequency domain at the back focal line.

We will show, through our numerical simulations, that the proposed lens provides the Fourier transform of a function located at its front focal line at the back-focal line (as compared to a 3D lens which obtains the Fourier transform of functions at its back focal plane). This confirms that the one-atom-thick inhomogeneity indeed acts similar to a 3D lens.

In our talk, we will present the results of our numerical simulations of several scenarios related to the Fourier optics on graphene, confiriming three conditions above for the double convex conductivity variation on the graphene..

4. Conclusion

Our theoretical studies indicates that graphene can serve as a low-loss platform for Fourier Optics functionalities, resulting in single-atomic-layered optical signal processing systems. To achieve such functionalities, we show that we have to create inhomogeneous nonuniform patterns of conductivity on graphene to control and redirect SPP surface waves at will. This exciting platform, thus, could open new possibilities to have massively parallel platforms for high-speed information processing at nanoscale.

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