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Analog optical computing by half-wavelength slabs

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A B S T R A C T

A new approach to perform analog optical differentiation is presented using half-wavelength slabs. First, a half-wavelength dielectric slab is used to design a first order differentiator. The latter works properly for both major polarizations, in contrast to our previously design based on Brewster effect (Youssefi et al., 2016). Inspired by the proposed dielectric differentiator, and by exploiting the unique features of graphene, we further design and demonstrate a reconfigurable and highly miniaturized differentiator using a half-wavelength plasmonic graphene film. To the best of our knowledge, our proposed graphene-based differentiator is even smaller than the most compact differentiator presented so far.

1. Introduction

Despite the prevalence of digital computers, analog computing is still of great significance since it can overcome certain inherent limitations of digital computation such as data conversion loss. For instance, analog computation is presented as an important theoretical frame work for discussing computation in many natural systems [1–4]. These advantages and applications, together with the recent advances in optical technology, has led to the emergence of analog optical computing as a new concept [4–9].

The proposed approaches to perform analog optical computing can be fundamentally divided into two major classes, according to whether the computations are performed in temporal or spatial domain. Devices based on time domain calculations [10–17], however, are relatively large, making spatial computation more attractive.

To perform spatial analog computations two different methods have been investigated: metasurface approach and Green's function(GF) approach. The GF method has attracted more attention due to less complex fabrication and ease of miniaturization [18]. Here, mathematical computation is carried out using a multilayered slab which is homogeneous along two directions, and the operator of choice is realized by processing the optical field as it travels through the individual layers of the structure.

Yet, there were two major weaknesses restricting the performance of the GF approach. First, due to the reflection symmetry of such systems, it was until recently not feasible to realize the associated Green's functions of many important operators having an odd symmetry in the spatial Fourier domain such as the operator of first-order differentiation [18]. Second, the simplex optimization method used to calculate values of relative permittivities and thicknesses of slabs led to non-realistic values reducing the practical value of such structures [18].

In a recent report [19], by breaking the reflection symmetry using an obliquely incident wave, and by exploiting Brewster effect, we demonstrated a first-order differentiator for the first time. This method circumvented the aforementioned drawback of GF method in realizing odd operators, and could be readily implemented. However, the design proposed still suffers from two major shortcomings. First, it is polarization-dependent since Brewster effect only occurs for incident waves with TM polarization. Second, it only works properly for a specific incident angle, i.e. the Brewster angle.

In this paper, we aim to overcome these limitations by introducing a new approach based on a half-wavelength dielectric slab. We shall show that the resulting first order differentiator works appropriately for both TE and TM polarizations of the incident wave. Motivated by the performance of the proposed half-wavelength dielectric slab differentiator, and by exploiting the unique features of recently proposed promising graphene [20–25], we then design and demonstrate a differentiator using a planar half-wavelength plasmonic graphene film. It is worth noting that this device can be tuned by electrically adjusting the chemical potential of the graphene film through a gate. Moreover, because of the short wavelength of the plasmonic waves, the graphene-based differentiator is very compact. In fact, it is much smaller than the previously reported graphene-based analog optical differentiator in [26].

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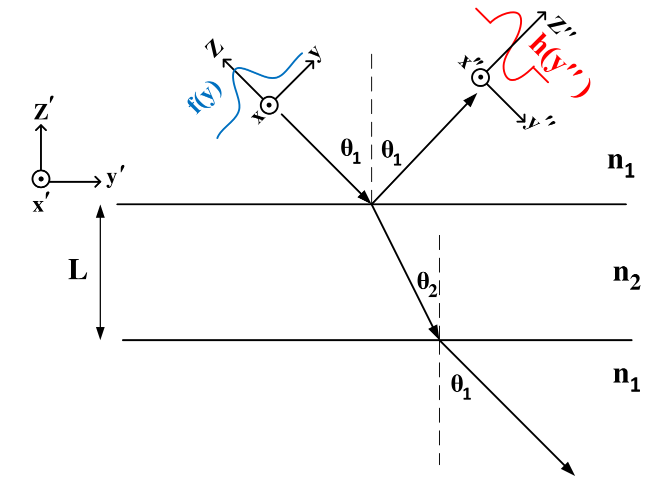

Fig. 1. Configuration of the proposed structure to perform the operator of first order derivative.

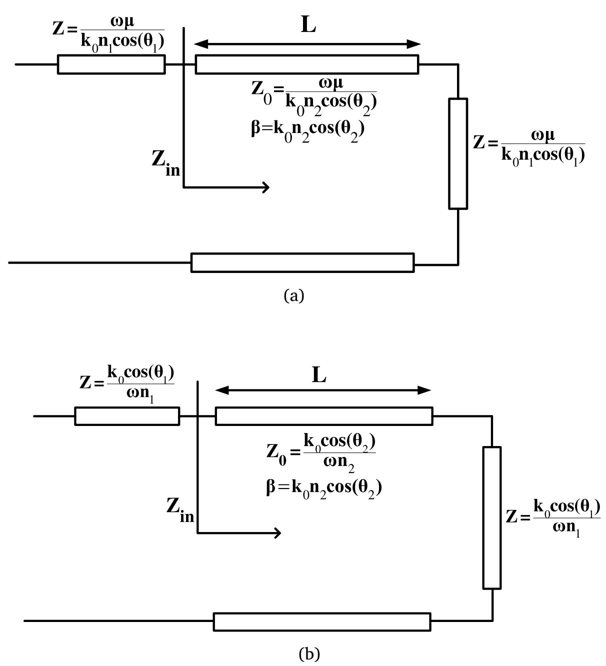

Fig. 2. Equivalent circuit model of presented structure for (a) TE and (b) TM polarization of incident wave.

2. Half-wavelength dielectric slab differentiator

The schematic diagram of our first proposed structure is shown in Fig. 1, in which a dielectric slab is used to perform first order differentiation. An arbitrary wave with the profile $f(y)$ is obliquely incident on a dielectric layer with length L and refractive index of n_2, which is surrounded by two semi-infinite dielectric media having the refractive index of n_1. The angles of incidence and refraction are assumed to be θ_1 and θ_2, respectively. By suitably adjusting the parameter L, the reflection coefficient of the proposed structure vanishes for both TE and TM polarization. As outlined in [19], if the corresponding reflection coefficient is then considered to be the Green's function of the structure, the reflected field $h(y'')$ will be the first order derivative of $f(y)$, provided that the spatial bandwidth of $f(y)$ is small.

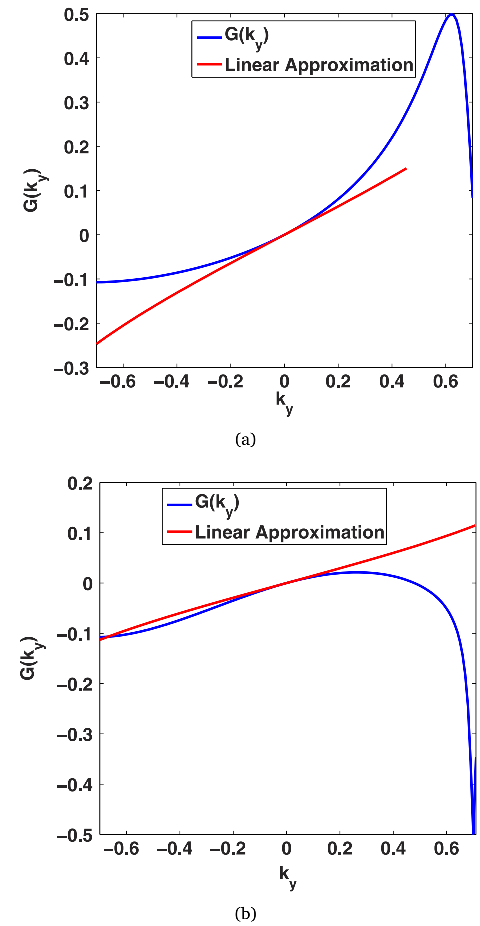

Fig. 3. Green's function $G(k_y)$ of the structure for (a) TE and (b) TM polarization.

Figs. 2(a) and (b) show the equivalent circuit models of the proposed differentiator for TE and TM polarizations. The semi-infinite dielectric media are modeled by the impedances $Z = \frac{\omega\mu}{k_0 n_1 \cos(\theta_1)}$ and $Z = \frac{k_0 \cos(\theta_1)}{\omega n_1}$ for the TE and TM polarizations, respectively. The dielectric layer (the layer sandwiched between the two semi-infinite media) is modeled as a transmission line with characteristic impedance of $Z_0 = \frac{\omega\mu}{k_0 n_2 \cos(\theta_2)}$ for the TE case and $Z_0 = \frac{k_0 \cos(\theta_2)}{\omega n_2}$ for TM case [27], propagation constants of $\beta = k_0 n_2 \cos(\theta_2)$, and length of L. Using the equivalent circuits shown, the reflection coefficient of the structure for both TE and TM polarizations can be expressed as [27]

$$R = \frac{Z_{in} - Z}{Z_{in} + Z} \tag{1}$$

in which

$$Z_{in} = Z_0 \frac{Z + jZ_0 \tan(\beta L)}{Z_0 + jZ \tan(\beta L)}. \tag{2}$$

If L is chosen such that $\beta L = \pi$, the reflection coefficient of the structure will be zero. In this case, the dielectric layer with the refractive index n_2 behaves just like a half wavelength transmission line transforming the load impedance Z to the input side of the line. As a result, the input impedance of the line matches the impedance of the first semi-infinite dielectric medium, i.e. $Z_{in} = Z$, and consequently the reflection coefficient vanishes. As shown in [19], such a zero of the reflection coefficient can then be exploited to perform the operator of first order derivative.

Here, we design our structure so as to realize the first order derivative of the input field $f(y)$ for the incident angle of $\theta_1 = 45°$. For the sake of simplicity, the two semi-infinite dielectric media are taken to be