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Design of mid-infrared ultra-wideband metallic absorber based on circuit theory

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ABSTRACT

An ultra-broadband absorber of light is proposed by using periodic array of ultra-thin metallic ribbons on top of a lossless quarter-wavelength dielectric spacer placed on a metallic reflector. We propose a fully analytical circuit model for the structure, and then the absorber is duly designed based on the impedance matching concept. As a result, normalized bandwidth of 99.5% is realized by the proposed absorbing structure in mid-infrared regime. Performing a numerical optimization algorithm, we could also reach to normalized bandwidth of 103%.

1. Introduction

An absorber is an excellent electromagnetic wave collector which traps the incident wave in specific locations [1–3]. The trapped wave can be converted into various forms of energy [1,4]. Able to operate over all frequency ranges from microwave to optical regime, EM wave absorbers offer a wide variety of practical applications. They can be employed in radar systems for reducing the signature of targets [5]. They are also important to photodetectors, microbolometers, phase modulators [5] and photovoltaic devices [6]. Light absorbers can tightly trap the incident energy at certain wavelengths called resonant absorbers [7,8]. Some other EM absorbers would be able to operate within a wide range of frequencies [9]. Thereby they are classified into two types: narrowband absorbers and broadband absorbers [10]. A broad absorption bandwidth is a necessity in many applications such as solar energy harvesting and bolometers [11]. Recently, Somak Bhattacharyya et al. [12] demonstrated a broadband metamaterial absorber in microwave regime by use of two simple identical metallic patches placed diagonally in a periodic arrangement which could achieve normalized absorption bandwidth of 74% with absorption higher than 90%. A microwave ultrabroadband metamaterial absorber is also proposed in [13] with normalized absorption bandwidth of 61%. In addition, a comparison between the bandwidth of different absorbers at THz frequencies has been presented in Table 1 of [14] with the best result (normalized bandwidth of 84%) obtained by using a stack of three patterned graphene layers. More recently, a normalized bandwidth of 100% has also been demonstrated with a single-layered graphene structure at THz frequency [15]. However, this approach is limited to the frequencies below 10 THz.

In this paper, we propose a broadband absorber with a normalized bandwidth of 99.5% in the mid-infrared regime with a single-layered array of metallic ribbons. The absorber, which operates for the TM-polarization (magnetic field parallel to the ribbons), is designed by means of the impedance matching concept. To that end, an accurate and analytical circuit model is first derived for the absorber by extending the model in [16] to thin metallic ribbons. Possessing a dual capacitive–inductive nature, the periodic array of metallic ribbons exhibits resonances at specific frequencies, leading to a significant increase in absorption. By choosing the impedance of the structure close to that of free space, very high absorption values can then be achieved. Furthermore, by imposing an extra condition on the derivative of the input admittance of structure around the central frequency [15], an absorption bandwidth of 99.5% is attained. We also investigate the effect of several parameters such as ribbon width and thickness, array period and the angle of incidence on the performance of the proposed absorber. It will be shown that the performance of the proposed device is not very sensitive to these parameters which, as a result, relaxes the possible fabrication constraints imposed.

The rest of paper is organized as follows. In Section 2, the structure of the absorber is presented and an equivalent circuit for this structure is proposed. Section 3 outlines the design procedure and closed expressions are derived for the appropriate parameters required for achieving broadband absorption. Finally, conclusions

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are drawn in Section 4.

2. Extraction of equivalent circuit

Fig. 1 shows schematically the proposed absorber: a periodic array of metallic ribbons with the width W and thickness Δ is deposited on top of a uniform dielectric spacer whose refractive index is fixed at $n_s = 1.5$ (which is the refractive index of SiO_2 [17]) throughout this paper. Below the dielectric spacer layer is a sufficiently thick metallic film for blocking the transmission channel. The period of the array and the thickness of spacer are denoted by D and d, respectively. The structure is illuminated from above (free space) by a normally incident TM-polarized wave. We use the Drude model for the conductivity of both metallic parts,

$$\sigma(\omega) = \frac{\sigma_0}{1 + j\omega\tau} \tag{1}$$

where σ_0, τ and ω are the dc conductivity, the relaxation time of the metal and the angular frequency, in order. The circuit model for the device is shown in Fig. 2. In this model, the metallic backplate is considered as a short circuit due to its reflecting mirror property and is represented by an admittance $Y_b \longrightarrow \infty$ (although it is exact only for perfect electric conductors, it is accurate enough in the mid-infrared regime as long as the metallic backplate is sufficiently thick). The homogenous mediums, namely the free space and the dielectric spacer, are modeled as transmission lines. The admittance and propagation constant of these transmission lines are $Y = n/\eta_0$ and $\beta = \omega/v$, respectively, where n is the refractive index of the corresponding region, $v = 3 \times 10^8/n$ represents the speed of light in that region and $\eta_0 = 120\pi$ is the free space wave impedance.

The metallic ribbons can be modeled by a shunt admittance Y_m, originally derived in [16] for an array of graphene ribbons. If the ribbons are sufficiently thin, the results found in [16] can be readily used after replacing the surface conductivity of graphene by the equivalent surface conductivity

$$\sigma_s(\omega) = \sigma(\omega)\Delta \tag{2}$$

Take note that while Y_m represents an infinite number of parallel R–L–C branches [16], we just retain one series R–L–C branch corresponding to the first resonance mode of the ribbons:

$$Y_m \simeq \left(\sigma_s^{-1} + \frac{q_1}{2j\omega\varepsilon_{eff}}\right)^{-1} \frac{S_1^2}{D} \tag{3}$$

where q_1 is the first eigenvalue of the equation governing the current on the ribbons (values of q_1 for different W/D have been given in Table 2 of [16]), $S_1^2 \cong 8W/9$ and $\varepsilon_{eff} = \varepsilon_0(1 + n_s^2)/2$ is the average permittivity of the mediums surrounding the ribbons. This

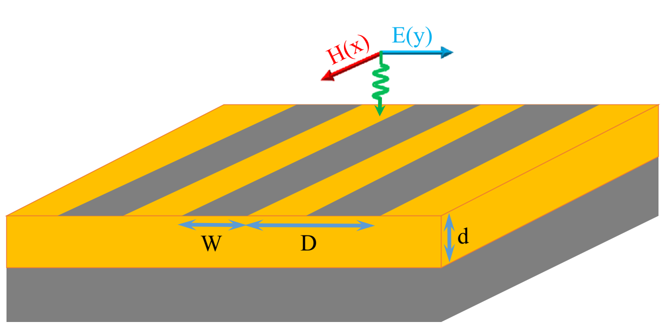

Fig. 1. The proposed absorber: a periodic array of metallic ribbons on top of a metallic reflector, separated by a quarter-wavelength dielectric layer with $n_s = 1.5$. The device is illuminated by a TM-polarized incident wave.

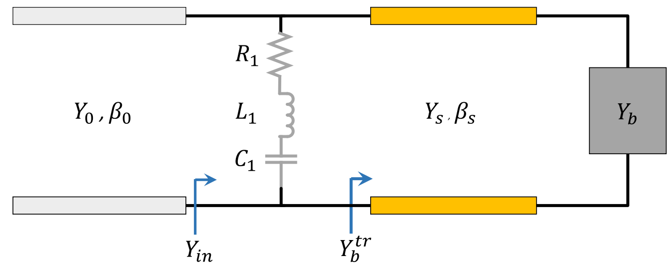

Fig. 2. The proposed equivalent circuit model for the absorber.

approximation, which is justified as the proposed device will operate near the first resonance frequency of the ribbon array, significantly simplifies the design procedure with negligible effect on the accuracy of the model [15]. After substituting Eq. (2) in Eq. (3) followed by some straightforward manipulations we obtain,

$$Y_m = \frac{1}{R_1 + L_1 j\omega + \dfrac{1}{C_1 j\omega}} \tag{4}$$

$$R_1 = \frac{1}{\Delta\sigma_0}\frac{D}{S_1^2} \tag{5}$$

$$L_1 = \frac{\tau}{\Delta\sigma_0}\frac{D}{S_1^2} \tag{6}$$

$$C_1 = \frac{2\varepsilon_{eff}}{q_1}\frac{S_1^2}{D} \tag{7}$$

3. Design procedure of the proposed absorber

We next outline the design procedure and provide closed expressions for the device dimensions. Since the transmission channel is closed by the metallic backplate, the absorption is maximized by minimizing the reflection from the structure. To achieve the latter, the input impedance of the device must be matched to that of the free space. Hence, at the central frequency f_0, the conditions $\mathrm{Re}(Y_{in}) = Y_0 = 1/\eta_0$ and $\mathrm{Im}(Y_{in}) = 0$ should be satisfied, where,

$$Y_{in} = Y_b^{tr} + Y_m \tag{8}$$

$$Y_b^{tr} = Y_s \frac{Y_b + jY_s \tan\beta_s d}{Y_s + jY_b \tan\beta_s d} \tag{9}$$

where Y_s and β_s are the admittance and propagation constant of the transmission line corresponding to the dielectric spacer. By setting $\beta_s d = \pi/2$ at f_0, the input admittance of the device will be Y_m, the admittance of the metallic array. Therefore, by setting $R_1 = \eta_0$ and $L_1 C_1 = 1/(2\pi f_0)^2$, perfect absorption is realized at the given central frequency. However, this device would not be broadband. In order to widen the absorption band width, the first condition should be relaxed, and replaced by

$$\mathrm{Re}\left(Y_{in}\right) = R_1^{-1} = \frac{\alpha}{\eta_0} \tag{10}$$

in which α is larger than unity, but should be small enough to guarantee reflection below 10% which it imposes the inequality