Tuning Optical Absorption in an Ultrathin Lossy Film by Use of a Metallic Metamaterial Mirror

Junghyun Park, Ju-Hyung Kang, Soo Jin Kim, Erez Hasman, and Mark L. Brongersma

***Abstract*— We present a way to tune the spectral light absorption properties of an ultrathin planar superabsorbing semiconductor film placed on a metallic metamaterial mirror. It is shown that we can change the wavelength of maximum absorption in a lossy film with a fixed thickness by tailoring the filling ratio of the metallic metamaterial. This remarkable ability of tuning originates from the control of the reflection phase pickup of light impinging from the lossy film upon the metallic metamaterial mirror. Full-field electromagnetic simulations show good agreement with the theoretical predictions. The proposed approach allows for a convenient and highly controllable way to achieve spatially variant tuning of absorption in a semiconductor film.**

***Index Terms*— Electromagnetic wave absorption, metallic metamaterial, optical reflection, optical tuning.**

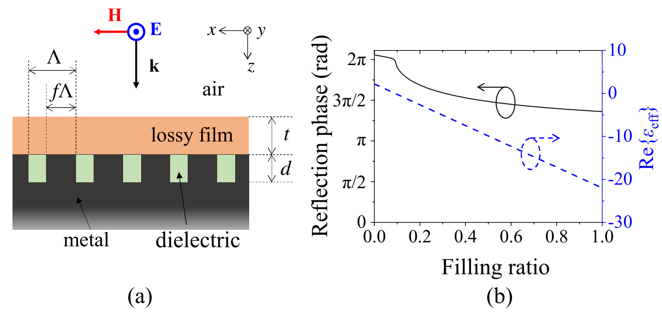

Fig. 1. (a) Schematic diagram of an asymmetric cavity configuration composed of a lossy film on a metallic metamaterial mirror. (b) Reflection phase (the left y-axis) and the real part of the effective dielectric constant (the right y-axis) as a function of the filling ratio of the metallic metamaterial mirror.

I. Introduction

DEVELOPING semiconductor films with highly efficient light absorption has been very important due to its various applications, including photodetectors, solar cells, and optical sensors [1]–[4]. Considerable research is devoted to scaling down device feature sizes to increase operation speed, lower power usage, and reduce material usage. A myriad of approaches are proposed such as manipulating the local density of states [5], increasing the electric field intensity at the location of absorbing components [6], or designing metamaterials for broad angle absorption [7], to name a few.

Recent reports showed that it is possible to achieve extreme light absorption by using an asymmetric cavity in which an ultrathin lossy semiconductor film is placed on top of a metallic mirror without any dielectric spacer [8]–[11]. The lossless case of such a configuration corresponds to the Gires-Tournois interferometer [12]. Kats and colleagues demonstrated that an ultrathin lossy film can afford very high optical absorption [8]. The high absorption comes from the coupling of the incident light to the surface mode supported in the configuration [9]. This surface wave exhibits a flat mode dispersion both for the transverse electric (TE) and magnetic (TM) modes, which results in omni-directional and polarization-independent near-unity absorption. Further research revealed the underlying physics of such configurations in terms of an admittance matching analysis [10] or constant tangential electric or magnetic fields [11]. In addition, it turned out that there is a certain range in the optical constants in lossy materials that guarantees near-unity absorption [13]. However, it still remains as a challenge to implement an efficient way to tune the absorption spectrum in such optical absorbers using this simple geometry.

In this letter, we present a novel approach to tune the optical absorption properties in an ultrathin planar lossy film on top of a metallic metamaterial mirror in the visible regime. This goal is achieved by engineering the reflection phase pickup experienced by the electromagnetic wave impinging from the lossy film to the metallic metamaterial mirror. The ability of spatially-varying spectral absorption is also presented.

II. Tuning of Reflection Phase Pickup

The condition for strong absorption in an asymmetric cavity (Fig. 1(a)) is related to a propagating phase inside the lossy film and a reflection phase pickup of light impinging from the lossy film on the metallic mirror. A study on the destructive interference between partially reflected waves in the given configuration reveals that unity absorption can occur [8], [9] if

$$2nk_0t + \phi_b - \phi_t = 2m\pi. \tag{1}$$

Manuscript received January 27, 2015; revised May 6, 2015; accepted May 10, 2015. Date of publication May 13, 2015; date of current version July 7, 2015. This work was supported in part by the National Research Foundation of Korea through the Korean Government within the Ministry of Education, Science and Technological Development under Grant 2013R1A6A3A03060952, in part by the Air Force Office of Scientific Research, Arlington, VA, USA, under Grant FA9550-14-1-0117, and in part by the fruitful discussion and valuable comments from Majid Esfandyarpour.

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Digital Object Identifier 10.1109/LPT.2015.2432756

Here n is the refractive index of the lossy film, k_0 the free space wave number ($=2\pi/\lambda_0$, with λ_0 the wavelength), t the lossy film thickness, ϕ_b and ϕ_t the reflection phases at the bottom and top interfaces, respectively, and m an integer indicating the order of the resonance.

We can deduce two approaches for tuning the wavelength that satisfies (1). One way is to change the thickness t; as the lossy film becomes thicker, the wavelength that suffices the destructive interference needs to increase [14]. The other way is to tailor the reflection phase pickup ϕ_b by changing geometrical parameters of the metallic metamaterial mirror that consists of 1-D subwavelength gratings composed of metal and dielectric material. Fig. 1(b) shows the relationship between the reflection phase pickup (left y-axis) and the filling ratio f, which is defined as the volume fraction of the metal. We assume that the semi-infinite ($d \to \infty$) metallic metamaterial mirror is composed of silver (Ag) and polymethyl methacrylate (PMMA)-filled grooves with infinitely small period ($\Lambda \ll \lambda_0$).

The effective permittivity of the metallic metamaterial mirror is given by an anisotropic tensor with $\varepsilon_{xx} = \varepsilon_\perp$ and $\varepsilon_{yy} = \varepsilon_{zz} = \varepsilon_\parallel$, where ε_{xx}, ε_{yy}, and ε_{zz} denote the permittivity along to x-, y-, and z-directions, respectively. $\varepsilon_\perp$ and $\varepsilon_\parallel$ correspond to the effective permittivity perpendicular to and parallel along the interface between the dielectric and metal whose normal vector is along the x-direction, respectively. Here, we consider a case where the electric field is parallel to the gratings (Fig. 1(a)). Because E_x and E_z electric components vanish and E_y electric component plays a role, $\varepsilon_\perp$ does not matter and only $\varepsilon_\parallel$ matters. In a circumstance with the electric field perpendicular to the gratings, we need to consider the anisotropic property with both $\varepsilon_\perp$ and $\varepsilon_\parallel$, which is beyond the scope of this letter.

The effective permittivity $\varepsilon_{eff}(=\varepsilon_\parallel)$, the right y-axis in Fig. 1(b), of the metallic metamaterial mirror is obtained by invoking the Maxwell-Garnett formula [7]:

$$\varepsilon_{eff} = f\varepsilon_m + (1-f)\,\varepsilon_d. \quad (2)$$

The lossy film is chosen to be copper indium gallium selenide (CIGS) for demonstration of the proposed configuration in solar cells. We can extract generated carriers by using separated backside electron and hole contacts [9]. At the wavelength of 600 nm, the dielectric constants of Ag, PMMA, and CIGS are $\varepsilon_m = -22 + 0.32i$, $\varepsilon_d = 2.2$, and $\varepsilon_l = 8.7 + 2.4i$, respectively. We consider the TE case, where the electric field is parallel to the grating, as shown in Fig. 1(a).

We observe in Fig. 1(b) that the reflection phase ϕ_b is larger than π for the planar metallic mirror ($f = 1.0$). Here the reflection phase π corresponds to the reflection phase from the perfect electric conductor (PEC). Due to the finite conductivity of the metal, which is linked to the finite-valued permittivity (ε_m), the electric field can penetrate into the metallic mirror, resulting in a reflection phase larger than π. As we decrease the volume fraction of metal and increase that of dielectric, the electric field can penetrate deeper into the metallic metamaterial, giving rise to an increased reflection phase. Consequently, the real part of the effective dielectric constant changes from -22 to 2.2, as the filling ratio f is decreased from 1 to 0. This leads to a change in the reflection phase from 1.36π to 2.06π. Owing to this change in the reflection phase, it is possible to tune the wavelength that satisfies (1). For example it is expected that the wavelength for the destructive interference exhibits a redshift as the filling ratio decreases.

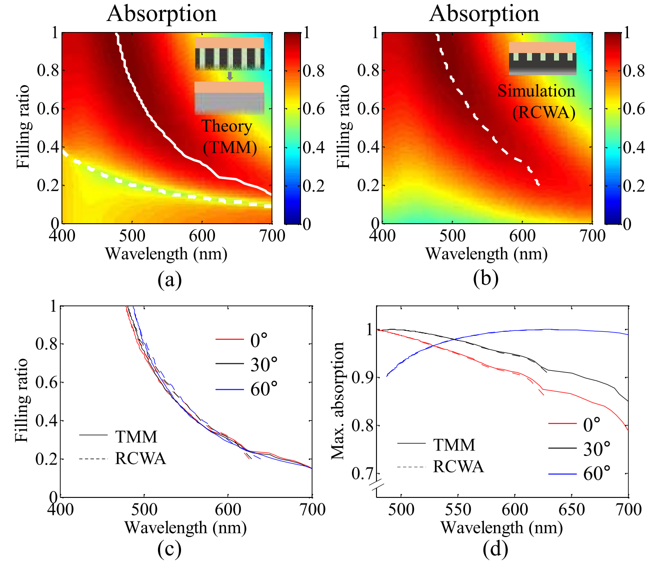

Fig. 2. (a) Absorption for various wavelengths and filling ratios obtained by using the TMM while assuming a semi-infinite ($d \to \infty$) metallic metamaterial mirror and an infinitely small period ($\Lambda \ll \lambda_0$). Solid white line for the maximum absorption wavelength and the black dashed line for a regime where $\mathrm{Re}(\varepsilon_{\mathrm{eff}}) = 0$. (b) Absorption calculated by using the RCWA technique with $d = 60$ nm and $\Lambda = 100$ nm. Dashed white line for the maximum absorption wavelength. (c), (d) Maximum absorption wavelength (c) and the maximally achievable absorption (d) for various incident angles of 0° (red), 30° (black), and 60° (blue), obtained by using TMM (solid) and RCWA (dashed).

To analyze the effect of the reflection phase change, we carry out a theoretical analysis the results of which are shown in Fig. 2(a). A transfer matrix method (TMM) is used [15]. The materials are the same as in Fig. 1(b), and the thickness of the lossy film t is 20 nm. We assume the metallic metamaterial is semi-infinite in depth and features an infinitely small period, so that the metallic metamaterial mirror itself can be modelled as a homogeneous material (inset of Fig. 2(a)). For the planar metallic mirror ($f = 1.0$), the peak absorption occurs at a wavelength of 478 nm. As we decrease the filling ratio of the metal, the wavelength for a maximum absorption (solid white line in Fig. 2(a)) exhibits redshift. The filling ratio $f = 0.3$ features a maximum absorption wavelength of 607 nm. This spectral shift confirms the prediction above. The dashed black curve denotes the filling ratio at a certain wavelength below which the real part of the effective dielectric constant becomes positive, and thus the metallic metamaterial mirror does not play a role of mirror anymore.

Meanwhile, the Maxwell-Garnet formula in (2) is based on the assumption that the electromagnetic field distribution in each material is almost uniform, so that the optical response is homogeneous. This can be satisfied if the period of an alternatively stacked structure is very small compared to the wavelength, and the size is large enough with regard to the penetration depth of light into the metamaterial. It is thus

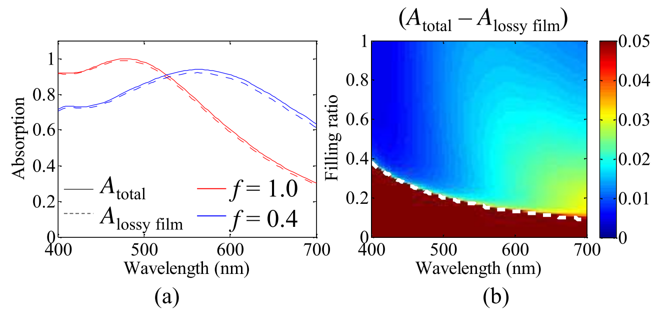

Fig. 3. (a) Separately calculated absorption spectrum for $f = 1.0$ (red) and $f = 0.4$ (blue). (b) Absorption in metallic metamaterial mirror.

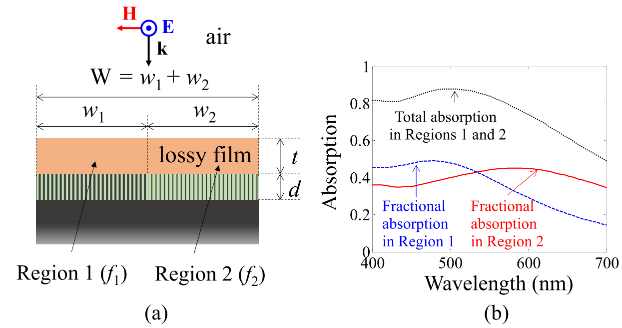

Fig. 4. (a) Schematic diagram of the unit cell of the lossy film on spatially varying metallic metamaterial mirror. (b) Fractional absorption A_1 (blue dashed line) and A_2 (red solid line) in the lossy film on the region 1 (the filling ratio f_1 of 1.0 and the width w_1 of 10 μm) and the region 2 ($f_2 = 0.3$ and $w_2 = 10$ μm), respectively. The black dotted line is the total absorption in region 1 and region 2 ($A_1 + A_2$). $t = 20$ nm, $d = 60$ nm.

required to implement a thick grating with a small period. However, the fabrication of such structures is limited by the pattern resolution and the achievable aspect ratios. It is necessary, therefore, to investigate the appropriate regime that results in the convergence and is also feasible in terms of fabrication.

For this purpose full-field electromagnetic simulations are performed (Fig. 2(b) and the inset) by the rigorous coupled-wave analysis (RCWA) technique [16]. The material combination is the same as those used in Fig. 2(a). The period is 100 nm and the depth is 60 nm. These specifications are plausible in standard fabrication technologies [17]. It is noteworthy that the overall behavior of the absorption calculated from the full-field simulation is in good agreement well with that from the TMM analysis. The maximum absorption wavelength (the dashed white line) exhibits a redshift as the filling ratio decreases.

In addition to a normal incidence case, we also examine the oblique incidence case. The red, black, and blue lines in Figs. 2(c) and 2(d) denote the maximum absorption wavelength and the maximally achievable absorption for the incident angles of 0°, 30°, and 60°, respectively. The solid and dashed lines correspond to the results from TMM and RCWA, respectively. The absorption property is not sensitive to the change of the incident angle. The maximally achievable absorption remains over 80% (Fig. 2(d)). The angle-robustness can be ascribed to the high refractive index of the lossy film, which leads to negligible variation in the longitudinal wavevector in the lossy film under the change of the incident angle. A more detailed discussion can be found in [9].

It would be worthwhile to examine where the optical absorption occurs. By using TMM, we separately calculated absorption spectrum for the configuration in Fig. 2(a), and show the result in Fig. 3(a). The red and blue lines correspond to the filling ratios of 1.0 and 0.4, respectively. The solid line denotes the total absorption (A_{total}) in both the lossy film and the metallic metamaterial mirror, whereas the dashed line is the absorption only in the lossy film ($A_{\text{lossy film}}$). Most absorption takes place in the lossy film. Fig. 3(b) shows a colormap of the absorption in the metallic metamaterial mirror ($A_{\text{total}} - A_{\text{lossy film}}$) as functions of the wavelength and the filling ratio. Below the white dashed line, the metallic metamaterial mirror becomes transparent with the positive sign of the real part of the permittivity, and is shown with a saturated color. We note that the overall absorption is less than 5% over the region of interest, indicating that most light is actually absorbed by the lossy film.

In addition to the observed spectral absorption control, this approach also affords an easy and controllable way to spatially manipulate the absorption with a high spatial resolution. A complicated combination of various metallic metamaterial mirror with different filling ratios can be designed and fabricated in a single patterning process such as the e-beam lithography or focused ion beam milling. This property is advantageous because the spatially variant thickness control of a semiconductor layer requires a multi-step lithography [8] or involves lower spatial resolution [14]. Moreover, the proposed configuration facilitates a quasi-continuous spectral change by spatially grading the filling ratio.

In Fig. 4(a), we present the schematic diagram of a unit cell composed of two regions with the same lossy film thickness but different filling ratios of the metallic metamaterial mirror. The material set is the same as in Fig. 2(b). The lossy film thickness t is fixed as 20 nm, and the groove depth d is 60 nm. The region 1 and the region 2 have the metallic metamaterial mirror with the filling ratios f_1 and f_2, respectively. We assume the period of the metallic metamaterial mirror in each region is small enough that it behaves as an effective medium. The absorption in the lossy film in each region is separately calculated as A_1 and A_2, respectively. The width of these regions are set to $w_1 = w_2 = 10$ μm in common, and the period of each unit cell is W= $w_1 + w_2$.

Fig. 4(b) shows the absorbed energy in the lossy film calculated by RCWA for cases of $f_1 = 1.0$ and $f_2 = 0.3$. A_1, which corresponds to the high filling ratio, exhibits the maximum absorption at 478 nm, whereas A_2 has its maximum at the wavelength 586 nm. This result indicates the absorption spectrum in the lossy film with a constant thickness can be separately controlled by tailoring the filling ratio of the metallic metamaterial mirror on which the lossy film is located. We also carried out numerical investigations for smaller widths such as 1 μm, and the results remained almost the same as in the result for the width of 10 μm.

Let us address what distinguishes the proposed approach from other methods. The magnetic mirror based on groove arrays can capitalize on the phase retardation of the gap plasmons supported by the grooves to modify the reflection phase of incident light [18]. The proposed approach and the magnetic mirror are similar in terms of the reflection phase control from the nano-structured metallic metamaterial mirror. However, the magnetic mirror utilizes the surface plasmons supported by gaps in the groove, and thus requires transverse magnetic TM polarization (the electric field perpendicular to the groove), whereas our configuration can be used for the TE polarization (the electric field parallel to the groove). There has also been a letter reporting the absorption control in a lossy film on a hyperbolic metamaterial [19], [20]. The difference is that it is based on the alternatively stacked structure in the vertical direction, and thus does not allow for the spatially-varying spectral control at high spatial resolution.

One may also be inclined to ask about the relationship between the proposed metamaterial mirror and surfaces supporting spoof plasmons. The spoof plasmon assumes a PEC [21]. We consider the operation in the visible wavelength regime, in which the permittivity of metal is finite and thus there is considerable penetration of electromagnetic wave into metallic mirror.

III. Conclusion

We showed that the optical absorption in an ultrathin lossy film can be tuned by engineering an underlying metallic metamaterial mirror. A decrease in the filling ratio of metal gives rise to an increase of the reflection phase, which in turn leads to the redshift in the absorption spectrum. This novel approach facilitates spatially varying control of the optical absorption in a constant lossy film thickness with small feature sizes. We believe our finding presents great potential for a number of applications such as photo-detectors and energy harvesting devices.

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