Metallic subwavelength structures for a broadband infrared absorption control

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We present a method to control the absorption of a resonator by using a subwavelength structure consisting of thin metallic plates that behaves as a metamaterial film. We demonstrate the ability to tailor the conductivity of such a metallic subwavelength structure to achieve a resonator with the desired impedance matching for the mid-infrared range. This approach provides for broadband, as well as broad-angle, enhanced absorption. Theoretical analyses, as well as experimental results of the optical properties of a metallic NiCr structure at 8–12 μm spectral range are introduced. © 2007 Optical Society of America

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The use of highly absorbing thin metallic films is crucial in applications such as microbolometric and pyroelectric cameras and thermal detectors, which are used in the mid-infrared to the microwave radiation region.[1,2] These cameras are mostly used in stellar imaging[1] and in the detection of covered objects,[3] as well as for biological imaging. When describing the structure of absorbing metallic films, several methods have been employed. The "black metal absorber" design[4–6] consists of a thin, granular metal film with a statistical distribution of grain diameters. Such an absorber yields broadband, as well as broad-angle, enhanced absorption. However, the process of forming such a film is not repetitive. Another approach is based on utilizing a thin metallic film with thickness in the nanometer range in a resonator configuration. The absorption property of a thin metallic film is a function of the layer conductivity, σ, and its thickness, h.[7,8] Calculating the absorption of a thin film in the resonator configuration depicted in Fig. 1(a) using Fresnel coefficients results in

$$A = 4Z_0\sigma h/(Z_0\sigma h + 1)^2, \tag{1}$$

where $Z_0 = 377\Omega$ is the vacuum impedance. This equation is calculated for a gap of $\lambda/4$, where λ is the wavelength. As we assumed that the film thickness is smaller than the skin depth as well as the wavelength ($h < \delta \ll \lambda$) a lumped circuit method was applied, i.e., the film was replaced by an equivalent lumped resistor, $R_{eq} = 1/\sigma h$.[8] The skin depth is defined as $\delta = \lambda/2\pi k$, where k is the absorption coefficient. According to Eq. (1), 100% absorption can be achieved for $\sigma = 1/hZ_0$. In terms of the refractive index, n, and the absorption coefficient, k, of the absorbing metallic film, the condition for obtaining complete impedance matching is given by

$$n \cdot k = \sigma/\omega\epsilon_0 = \lambda/4\pi h, \tag{2}$$

where ω is the light's angular frequency and ϵ_0 is the dielectric constant of the vacuum.[9] For a given σ, the required thickness of such a film for most metals is a few nanometers. For example, the required thickness for NiCr, Ti, and Au are 10, 8, and less than 5 nm, respectively.[1,2] Unfortunately, fabricating a uniformly thin metallic film is not repetitive and suffers from adhesion problems. Furthermore, a thickness error leads to a deviation from the unit absorption of the optimal resonant absorber. For a given thickness error, this deviation is proportional to $1/h^2$, as can be calculated [using Eq. (1)] when assuming a constant σ in the proximity of the ideal film thickness. As can be seen, the absorption of a film with a lower thickness would be more sensitive to thickness error. This sensitivity is increased due to the inhomogeneity of thin metallic films with nanometric-scale thicknesses, which can include texture discontinuity, islands and clusters, variations in substrate roughness, and differences in the purity or composition of the metal.[7,10–13]

In this Letter, we propose using a subwavelength periodic structure embedded in a thin metal film to control absorption in a resonator configuration. By varying the structure's parameters, e.g., period (Λ), fill factor (q), thickness, and shape (S, the shape of the subwavelength groove and the periodic structure), we can tailor the conductivity of the subwave-

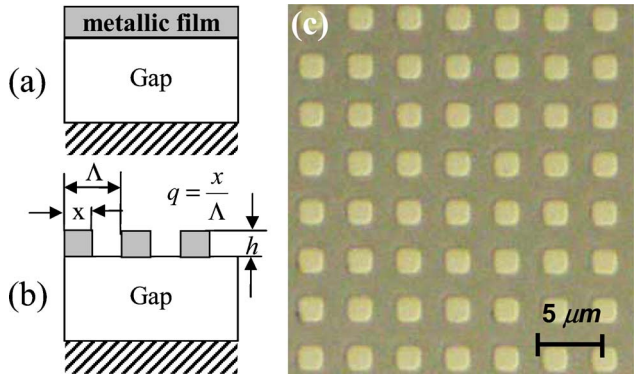

Fig. 1. (Color online) (a) Concept of a resonant absorber using a metallic thin film. The metallic film is placed $\lambda/4$ away from a perfect mirror. (b) Concept of a resonant absorber using a metallic subwavelength structure as a metamaterial absorbing layer. (c) Optical microscope image of the metallic NiCr subwavelength structure with a 4 μm period, 30 nm thickness, and $q = 0.5$.

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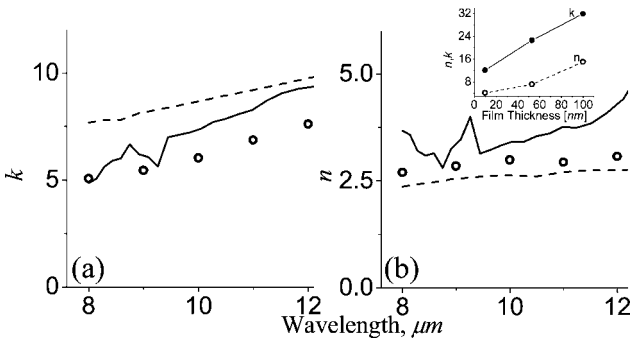

Fig. 2. Measured (solid curve), simulated (circles), and theoretical (dashed curve) values of (a) absorption coefficient k and (b) refractive index n as a function of the wavelength for the metallic NiCr structure shown in Fig. 1(c). The simulation was calculated by use of FDTD, and the theoretical result was obtained by use of the effective medium theory [Eq. (3), $L_m=0$]. Inset in (b), measured n and k of a uniform metallic NiCr thin film for different thickness at 11 μm wavelength illumination.

length structure, i.e., $\sigma=\sigma(\Lambda,q,h,S)$ to achieve a resonator with the desired impedance matching. We demonstrated the ability to obtain an absorber that has a thickness of tens of nanometers, effectively overcoming the difficulties encountered by the thin (nanometric) film method. The concept of the resonant absorber based on a metallic subwavelength structure is depicted in Fig. 1(b). A subwavelength metallic grating is placed $\lambda/4$ away from a total reflector. We experimentally demonstrated a formation of an optimal subwavelength NiCr structure, to have a thickness of 30 nm, a period of 4 μm, and a fill factor of 0.5, as evaluated by the effective medium theory of a structure of metal plates. The optimal structure was realized, and its optical properties were measured for the spectral range of 8–12 μm. A resonant absorber, which was calculated using the measured subwavelength grating's properties, manifested broadband and broad-angle absorption. Such an absorber can be used for any desired spectral range. The thickness of such an absorber is not restricted to a few nanometers. Furthermore, space-variant manipulation of the absorption can be achieved using a single mask photolithographic process, simply by locally changing the grating structure.

The optical properties of the subwavelength structure can be evaluated using the effective medium theory. By using this analytical approximation, the optical properties as a function of volume fill factor, f, is given by[14]

$$\frac{\epsilon(\omega)-\epsilon_i(\omega)}{L_m\epsilon(\omega)+(1-L_m)\epsilon_i(\omega)}=f\frac{\epsilon_m(\omega)-\epsilon_i(\omega)}{L_m\epsilon_m(\omega)+(1-L_m)\epsilon_i(\omega)}, \tag{3}$$

where L_m is the characteristic depolarization factor, $\epsilon_i=n_i^2$ is the surrounding dielectric constant, $\epsilon_m=(n_m-ik_m)^2$ is the metal dielectric constant, and $\epsilon=(n-ik)^2$ is the dielectric constant of the subwavelength structure. For the case of a configuration of metal plates, as depicted in the inset of Fig. 3(b), i.e., $L_m=0$, Eq. (3) degenerates into the simple relation of $\epsilon(\omega)=q^2\epsilon_m(\omega)+(1-q^2)\epsilon_i(\omega)$.[14] In terms of the refractive index and the absorption coefficient, this relation can be rewritten as

$$n(\omega)k(\omega)=q^2n_m(\omega)k_m(\omega). \tag{4}$$

Equation (4) manifests a linear dependence between the layer conductivity, σ, of the structure and the area fill factor, q^2, which allows us to control the absorption of a resonator configuration.

To calculate the performance of the metallic subwavelength structure for a certain thickness, the optical properties of the uniform thin metallic film of the relevant thickness must first be measured. These optical properties were found to be thickness dependent.[7,14] As mentioned above, this dependence mostly results from the inhomogeneity of the film. To fully evaluate this dependence, we deposited three different NiCr films with thicknesses of 10, 53, and 100 nm onto GaAs wafers with an antireflection coating on the backside. The deposition of the NiCr (80% Ni and 20% Cr) was performed by use of a Temescal 1800 deposition system with pressure of 2×10^{-7} Pa. We determined the optical properties of the thin films by utilizing the measured transmission and reflection for TE- and TM-polarized illumination from six different incident angles and by using the Fresnel coefficients.[9] The measurements were performed with an infrared Fourier transform spectrometer (Vertex 70, Bruker) equipped with a cooled HgCdTe detector in the range of 8–12 μm wavelength. The inset in Fig. 2(b) shows the optical properties as a function of the thickness for 11 μm wavelength illumination.

According to Eq. (2), the impedance-matching condition for a thickness of 30 nm at the 11 μm wave-

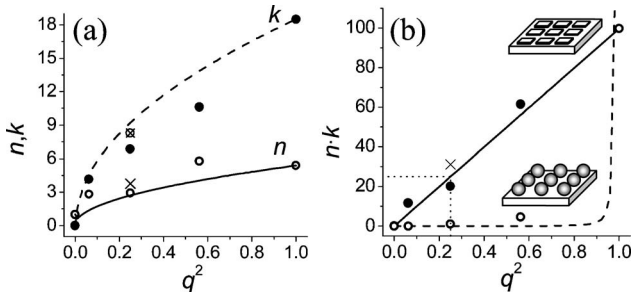

Fig. 3. (a) Simulated (FDTD; open and closed circles), theoretical (effective medium theory [Eq. (3), $L_m=0$]; solid and dashed curves), and measured (cross and circled cross points) values of n and k as a function of area fill factor, q^2, for the structure of metallic NiCr plates shown in Fig. 1(c) at the 11 μm wavelength. (b) Simulated (FDTD; closed circles), theoretical (effective medium theory [Eq. (4)]; solid curve), and measured (cross point) values of nk as a function of area fill factor, q^2, for the metallic NiCr plates structure depicted in Fig. 1(c) at the 11 μm wavelength. The dashed curve represents the effective medium approximation for a structure composed of metallic NiCr spheres [30 nm diameter; Eq. (3) $L_m=1/3$]. The open circles represent FDTD calculation of a NiCr structure (0.1 μm period with 30 nm thickness).

length results in $nk \cong 28$. As can be calculated, the skin depth of bulk NiCr for illumination of 8 to 12 μm wavelength is about 50 nm, which is larger than the film thickness, thus the use of Eq. (2) is legitimate. Using the effective medium theory for subwavelength NiCr plates embedded in air [Eq. (4)], the required fill factor of our structure is approximately $q \approx 0.5$. We have realized the metallic structure with a period of 4 μm, fill factor $q = 0.5$, and $h = 30$ nm on a GaAs wafer by use of a NiCr deposition and a lift-off process. Figure 1(c) shows the optical microscope image of the metallic structure. Next, we measured the metallic structure's optical properties, using the same method that was described earlier. Figures 2(a) and 2(b) present the measured and calculated n and k values of the metallic structure as a function of the wavelength. Note the close agreement between measurement and calculations, using Eq. (4) (dashed curve) and a finite difference time domain algorithm (FDTD) (circles). In both calculations, the measured dielectric constant of the NiCr film composing the subwavelength structure was used.

Figures 3(a) and 3(b) describe n, k, and σ, respectively, at the 11 μm wavelength as a function of q^2 for our metallic structure, for the effective medium approximation and the FDTD calculation, as well as the measured results. A close agreement between the calculations and the measured results is clearly observed. In addition, we see the expected linear dependence of σ as a function of q^2 for the subwavelength metallic plates. Figure 3(b) also depicts the case of an extremely small period, $\Lambda = 0.1$ μm. This structure approaches the case of small metallic spheres [$L_m = 1/3$ in Eq. (3)], which is approximated by the Maxwell–Garnett effective medium theory.[14] In the mid- and far-infrared illumination of a structure composed of small metallic spheres, $\epsilon_m \gg \epsilon_i$ and ϵ is approximately a real value [from Eq. (3)]; therefore, nk is approximately zero as a function of q^2 for values less than 0.9. Using this structure, one can see the small dynamic range provided by structural property modification. This configuration is not applicable, and thus we resort to the periodic region, where the structure can be considered to be subwavelength metallic plates.

As a final stage, we calculated the resonant absorber using the measured properties of the metallic structure. The gap of the resonator, which is depicted in Fig. 1(b), is an air gap of 2.3 μm. Figures 4(a) and 4(b) show the absorption of the resonator based on the metallic structure as a function of the incident angle and the wavelength, respectively. Broadband, as well as broad-angle, enhanced absorption is obtained. For comparison, we present the resonator configuration for two NiCr thin film absorbers with thicknesses of 30 and 10 nm, where the second one is the optimal absorber, for a conventional resonator using a thin metallic film approach. As is evident, a significant modification of the absorption is obtained using the metallic structure compared with a thin metallic film. Note that the broadband behavior results from obtaining enhanced absorption with only a few passes through the thin film (a single pass absorbs about 50% from the incident light[8]), thus enabling a low resonance condition; i.e., the resonator gap is not obligated to be exactly $\lambda/4$.

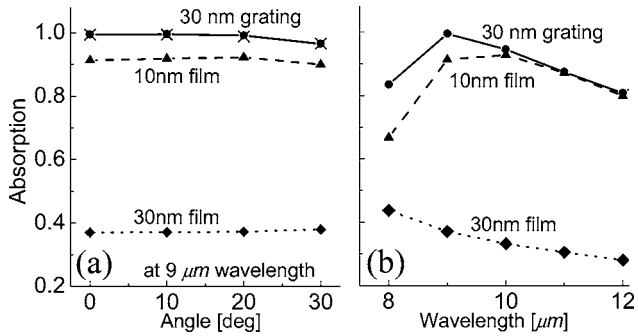

Fig. 4. Calculated absorption of a resonator configuration (air gap 2.3 μm) as a function of (a) incident angle (at 9 μm wavelength) and (b) incident wavelength (at normal incident angle) for the NiCr subwavelength structure depicted in Fig. 1(c) [solid curve; based on the measured n, k shown in Fig. 2] and for 10 nm (dashed curve) and 30 nm (dotted curve) of uniform NiCr thin films.

To conclude, we have presented a method to control the absorption of a resonator by using a subwavelength structure consisting of metallic plates that behaves as a metamaterial film. The manipulation of the absorption is performed by controlling the structure's parameters. Such an approach is applicable for advanced microbolometric cameras for any spectral range. Furthermore, a space-variant manipulation of the absorption can be achieved by locally changing the metallic grating structure.

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