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Design, fabrication and characterization of resonant metamaterial filters for infrared multispectral imaging

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ABSTRACT

We present the design of infrared filters for multispectral imaging applications, based on square annular aperture arrays in a thin gold film. These structures function as band pass filters with large bandwidth and high transmission at resonance. A modal analysis based on the Finite Element Method (FEM) is performed to obtain quickly the features of this resonance. The center wavelength can be tuned in the 7–12 μm range while keeping constant the quality factor and maximum transmission by scaling all transverse dimensions of the apertures, which allows to obtain filters with different centering on the same substrate in a single fabrication step. Large area samples have been fabricated on a silicon wafer by electronic lithography. Spectrophotometric measurements are in rather good agreement with numerical predictions. In addition, angle resolved measurements show that the filters are quite tolerant to the incidence angle up to 30° for both polarizations which is consistent with our FEM simulations. Finally, a complete sensitivity analysis allows us to evaluate acceptable opto-geometric tolerances of fabrication and thus to improve reproducibility on large areas. The impact of fabrication defaults (rounded corners, aperture anisotropy, aperture edge roughness, sloping aperture edges) on the filtering performances is analyzed. The simulations of realistic structures allow to explain and reduce the differences between measured and simulated spectra.

1. Introduction

Multispectral infrared imaging which brings rich information on thermal conditions and chemical composition of the observed scene is an essential tool in a wide range of applications (thermal diagnostic, environmental remote sensing, defense …). The development of multi-wavelength filter arrays in the infrared (IR) range compatible with IR sensor arrays, will pave the way to the realization of multispectral microcameras. Typical specifications of the IR multispectral filters are spectral tunability of the center wavelength in the 7–13 μm, a large bandwidth (>2 μm), angular tolerance of ±30° and polarization independence. For the development of microcameras the challenge is the ability to create pixelated filters with 4 to 9 spectral bands.

When carefully designed, thin nanostructured plasmonic materials deposited on bare substrates in particular annular aperture arrays (AAAs) can exhibit frequency bandpass filtering features with surprisingly high transmission levels regarding their surface filling fraction [1–5]. A key property of AAAs is the angular tolerance of the enhanced transmission as demonstrated theoretically in [6,7] and verified experimentally in [8,9].

Compared to interference multilayers relying on mono-dimensional resonances, 3D plasmonic structures offer various promising advantages thanks to additional opto-geometric degrees of freedom. In particular, (i) they can be designed to require only one single deposition and photolithography step, whereas thin films require several well controlled deposition and photolithography steps; (ii) a spectrally tunable bandpass behavior can be obtained by adapting only one single characteristic geometric feature (periodicity, etching width …). However, the 3D design of these filters with sub-λ patterning requires heavy calculations and their fabrication relies on sophisticated etching process steps.

In this context, we consider here arrays of square coaxial apertures in a gold film deposited on a silicon substrate that are designed to produce bandpass transmission filters for multispectral imaging applications in the far infrared region. The objectives of this work are the optimization of the design, the taking into account of actual fabrication process variability in order to evaluate the real AAAs potential to be used and to provide a tool for industrial development of this technology.

Besides the calculation of transmission spectra, our approach to study the resonant phenomena in such metamaterials is to compute

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the eigenmodes and eigenfrequencies of these open electromagnetic systems. This modal approach leads to significant insights into the properties of metamaterials [10,11] and eases the conception of diverse optical devices [12,13] because it provides a simple picture of the resonant processes at stake. We used this modal approach to design the AAA tunable filters: to reduce calculation time and memory space we have developed a design tool based on quasimodal analysis [9].

Large area samples have been fabricated on a silicon wafer by electronic lithography and characterized. To understand the discrepancies between modeling and experiments for the resonance features we have made a detailed parametric study to evaluate the sensitivity for each opto-geometric parameter, to deduce acceptable fabrication tolerances and thus to improve reproducibility on large areas.

2. Theory, design and experimental aspects

2.1. Description of the structure and numerical methods

The studied square coaxial apertures are depicted in Fig. 1. They have interior and exterior widths denoted w_1 and w_2 respectively and are arranged in a square array of period d. The thickness of the metallic gold film is h = 90 nm which is higher than the skin depth of gold in the investigated wavelength range, thus the unpatterned layer does not transmit any radiation. The structures are deposited on a silicon substrate. The permittivity of gold is described by a Drude–Lorentz model [14] and the refractive index of silicon is taken from the tabulated data [15].

We study transmission properties of AAAs by numerical simulations. A Finite Element Method (FEM) formulation [16,17] is used to solve the so-called *diffraction problem*. The array is illuminated from the air superstrate by a plane wave, we model a single period with Bloch conditions applied in x and y directions of periodicity and Perfectly Matched Layers (PMLs) are used in the z direction normal to the grating in order to damp propagating waves [18]. By varying the incident wavelength, we can compute transmission, reflection and absorption spectra.

The transmission spectra of these sub-wavelength nanostructured thin films are resonant in essence. Our central approach is thus to perform a modal analysis [19] of these nanoresonators. We developed a FEM formulation to solve the *spectral problem*, i.e., to find leaky modes (also known as quasimodes, quasi normal modes or resonant states) associated with complex eigenfrequencies $\omega_n = \omega_n' + i\omega_n''$ of those open waveguides [20], the real part corresponding to the resonant frequency and the imaginary part to the linewidth of the resonance. This method allows us to compute *with a single FEM calculation* the features of the resonance and their evolution when the opto-geometric parameters of the AAA are varied. The FEM formulation of the spectral problem is analogous to that of the diffraction problem and is described in Refs. [9,19,20].

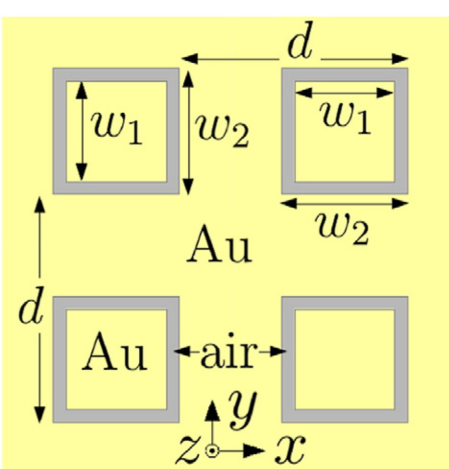

Fig. 1. Schema (top view) of the studied square annular aperture array.

2.2. Design of the filters

Three key transverse geometrical parameters are necessary to characterize the pattern of coaxial apertures: w_1, w_2 and d. We solved the spectral problem for homothetic structures with $f_1 = w_1 / w_2 = 0.8$, $f_2 = w_2 / d = 0.55$ and various periods d, such that all AAAs have the same opening area ratio $\rho = (w_2^2 - w_1^2) / d^2 = f_2^2(1 - f_1^2) = 10.9\%$. This homothetic scaling allows us to cover the entire spectral range 7–13 μm for the filter center wavelength while keeping the constant maximum transmission and spectral bandwidth. Because of the symmetry of the problem, we find two degenerated eigenmodes corresponding to TE and TM polarization associated with the same eigenfrequency ω. The electromagnetic field of the mode is concentrated in the annular apertures and it has been reported in previous studies that it behaves as a TE_{11}-like mode [4,9].

We find that the evolution of the corresponding resonant wavelength $\lambda^r = 2\pi c / \omega'$ is linear with the period d when dealing with these homothetic structures, as shown in Fig. 2(c) (plain red line). The modal analysis allows us to design four filters with given central wavelength $\lambda^r = 8$, 9.7, 10.3 and 12 μm thanks to a linear fit that gives us the geometric parameters of the filters denoted M1, M2, M3, M4 respectively: d = 1920, 2250, 2600, 2930 nm, $w_1 = 850$, 990, 1140, 1290 nm and $w_2 = 1060$, 1240, 1430, 1610 nm. These structures are approximately homothetic such that $f_1 = 0.8$ and $f_2 = 0.55$. The calculated transmission spectra under normal incidence in TM polarization are reported in Fig. 2(a) and show a resonant peak whose central wavelength can be redshifted by increasing the lateral dimensions of the AAA. The spectral width $\Delta\lambda = -4\pi c\omega'' / \omega'^2$ obtained by modal analysis varies from 2 to 3 μm as lateral dimensions increase (see Fig. 2(d), plain red line). The transmission value at resonance calculated with the diffraction problem remains unchanged around 0.58 (see Fig. 2(e), plain red line) and the quality factor $Q = \omega' / \Delta\omega = \omega' / (2\omega'') = 3.8$ is nearly constant due to the employed homothetic scaling.

2.3. Fabrication and characterization

Samples with the aforementioned parameters have been fabricated on the same double side polished (100) pure intrinsic silicon substrate. The nanostructuration has been performed by electronic lithography using a lift-off process with a negative tone resist. A relatively large area of 3×3 mm^2 has been nanostructured for each of the four samples to allow the measurements of FTIR spectra. Top SEM images of a fabricated AAA filter are reported in Fig. 3 and reveal good precision on the periodic arrangement of apertures. A zoom on a single aperture shows a well defined nanostructure, but with some fabrication imperfections such as rounded corners, slight differences between x and y engraved apertures, surface roughness and aperture-edge roughness, and sloping aperture edges (see insets in Fig. 3). Moreover, the study of depth profiles of apertures reveals a slight increase of gold thickness at the edges of the apertures (see insets in Fig. 3). These defects or features occur on the whole surface of the filter for every aperture. Furthermore we observe some drifts of the parameters w_1, w_2 and d at large scale because of the long writing time (more than 10^6 apertures on a filter of 3×3 mm^2).

Transmission spectra of the samples have been recorded with a Thermo Fisher-Nicolet 6700 Fourier Transform Infrared (FTIR) spectrophotometer. Measurements were performed with a focused polarized light beam with ±16° divergence and a spot diameter of 1.3 mm. A rotating deck allows us to tilt the sample in order to record transmission