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Perfect Sub-Wavelength Metamaterial Fishnet-Like Film Absorbers for THz Applications

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Abstract—We present two designs of robust, easy to manufacture metamaterial-based films of sub-wavelength thickness capable of full absorption of the incident terahertz (THz) radiation at certain frequencies. Both designs can be either made polarization sensitive, or have 90° rotation symmetry, which works equally well for waves of any polarization provided the incident angle is zero. All our designs work for a wide range of angles of incidence, and even if the films are optimized for normal incidence the absorption remains greater than 99% for angles up to ~35° in the TE and ~65° in the TM case. In the first design the maximum absorption frequency shifts considerably with angle, and in the second design the maximum absorption frequency remains almost the same at any angle. Theory, simulation data, and recent experimental results are all in a good agreement, and will be reported in the presentation. Having a low heat capacity these absorbers combined with thermo detectors can be utilized for precise frequency-selective detection of THz radiation.

I. INTRODUCTION AND BACKGROUND

METAMATERIALS are artificially-created media with uniquely engineered electric permittivities and magnetic permeabilities [1]. With metamaterials one can create resonant left-handed media with a negative index of refractive and negative phase velocity, and also a non-reflecting medium with a wave impedance equal to that of the free space. Due to the lack of naturally occurring materials for radiation control the THz frequency band is considered to be the one that can greatly benefit from the metamaterial technology.

II. RESULTS

The last few years saw a blossom in development of different kinds of metamaterials for THz frequencies, including those for absorber applications. There are already many known metamaterial film absorbers, including sub-wavelength film absorbers, which were experimentally demonstrated to have close to 100% wave absorption efficiency [2]. The main drawback of those designs is that they employ resonators with rather complicated shape with many fine details and therefore are not easy to fabricate and are sensitive to distortions. We propose novel absorbers based on a simple resonator design similar to the one that has already been successfully fabricated at optical frequencies: the fishnet structure (Fig. 1a) [3]. A gold ground plate is used on the back side of the absorber to limit the absorber thickness and prevent any transmission. The front side of the absorber has a gold fishnet pattern and the space between these two layers of gold is filled with a lossy dielectric. In our case this dielectric was Kapton with loss tangent of 0.05 and permittivity of 3.4. The principle of operation is similar to a Fabry-Perot cavity with a semi-transparent mirror and the ohmic loss equal to the radiation

loss through this mirror. However our design has a sub-wavelength thickness.

Fig. 1. The elementary cell of the metamaterial film: an absorbing Kapton layer is contained in between two layers of gold, one of which has a rectangular opening in it. The absorber consists of a 2D array of the above elementary cells (a). Losses in the center section of the film, proportional to the distribution of the electric field energy density (b).

Fig. 2. Measured absorption for the TE (a) and the TM (b) incident waves for different angles of incidence. In the experiment the kapton layer thickness was 23 μm , gold layer thickness 0.3 μm , period of the structure 180 μm and the size of the rectangular openings 150 $\mu\text{m} \times 75 \mu\text{m}$. Maximum absorption frequency is red-shifted with angle for the TM case, and blue-shifted for the TE case.

The robustness of our design is determined by two factors.

First, the absorber performance depends mostly on integral geometry characteristics of the structure. Second, the electromagnetic power is dissipated mostly in the dielectric and only a very small fraction is dissipated in the metal. This makes it less sensitive to the conducting properties of the metal surfaces, which are hard to measure and control. The simulated loss distribution inside the Kapton is shown in Fig. 1b. We did all the absorber simulations in CST Microwave Studio® [4].

The fishnet-like absorber shown in Fig. 1a was tested experimentally. Our set-up allowed us to measure reflection in the range of incident angles in between 20 and 60 degrees and to use any of two primary linear polarizations. Due to a small period of the pattern, there could only be a specular reflection. Although the fabricated sample thickness of the Kapton layer came out to be 40% bigger than the optimum value derived from simulations, the absorber demonstrated close to the 100% absorption up to the very large angles of incidence, and it worked better for the TM incident waves than for waves incident in the other plane (Fig. 2). The absorber showed almost no absorption for the orthogonal polarization, having electric field component parallel to the longer sides of the rectangular opening.

Our second version of the absorber is based on a natural generalization of the fishnet structure pattern for the polarization insensitive case (Fig. 3a). Similar to the previous version (Fig. 1a), it can also be optimized to provide the full absorption at any chosen frequency and it also works for a wide range of incidence angles (Fig. 3b). The thickness of the Kapton layer corresponds to the one-way wave phase advance of only about 30 degrees.

Fig. 3. The elementary cell of the polarization insensitive metamaterial film absorber (a). Corresponding reflected power as a function of frequency for different incident angles, θ , for the TM wave obtained from simulations (b). The perfect absorption takes place at both 0° angle of incidence and at about 55°.

In both designs versions (Fig. 1a, 3a) the frequency corresponding to the absorption peak depends strongly on the angle of incidence (Fig. 2, 3b). This can benefit some applications such as the mechanically frequency tunable absorbers but can be a disadvantage for others. It is possible to eliminate this angle dependence almost completely by implementing a complementary pattern designs: non-continuous stripes and crosses shown in Fig. 4. Note that the electromagnetic field orientation in Fig. 4a is different from

the one in Fig. 1a. The absorber in Fig. 4b resembles circuit analog absorbers in [5], which have one of the best bandwidth for given thickness, with the only difference that in our case the loss is not in the metallic cross, but in the dielectric.

Fig. 4. Perfect absorbers of a complementary shape to those shown in Fig. 1a and 3a. Periodic cell of the absorber film for a single linear polarization (a), and for an arbitrary polarization (b) of the incident waves.

Simulated absorber performance of the cross-patterned film for the angles of incidence up to 70 degrees is presented in Fig. 5. Maximum absorption frequency shifts almost negligibly with an angle and the shift has the opposite sign compared to the first set of absorbers.

Fig. 5. Absorptivity of a cross-patterned film shown in Fig. 4b as a function of frequency for different incidence angles and two kinds of linear polarization.

It is worth noting, that the designs described above can be modified to dynamically control the maximum absorption frequency by implementing dielectrics with controlled permittivity or to dynamically control the value of the absorption peak by implementing semiconductors with controlled conductivity.

The metamaterial absorbers may be utilized in THz detectors, nonreflecting surfaces, thermal imaging, and narrow band THz sources.

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