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Parametric Analysis of Vertically Oriented Metamaterials for Wideband Omnidirectional Perfect Absorption

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***Abstract*—Metamaterials provide a means to tailor the spectral response of a surface. Given the periodic nature of the metamaterial, proper design of the unit cell requires intimate knowledge of the parameter space for each design variable. We present a detailed study of the parameter space surrounding vertical split-ring resonators and planar split-ring resonators, and demonstrate widening of the perfect absorption bandwidth based on the understanding of its parameter space.**

I. Introduction

Split-ring resonators (SRRs) have become a common element in metamaterial structures [1]–[8]. However, conventional fabrication techniques at infrared and visible frequencies often include a combination of lithography and plating [2,9] or deposition. These techniques bind the SRRs to the top surface of the substrate, precluding them from being vertically displaced. Membrane Projection Lithography [10,11] removes this constraint, enabling vertical SRRs (VSRR) to be vertically displaced from the substrate surface [12]. In doing so, additional degrees of freedom are added to the design space of the unit cell, including rotation of the VSRR about the axis perpendicular to the face of the SRR and the addition of multiple resonators within a single unit cell. We explore intra-cell electromagnetic coupling between a VSRR and planar SRR (PSRR) within a single unit cell. Without increasing the area occupied by the PSRR in the XY plane, placing the VSRR and PSRR on orthogonal surfaces within the unit cell enables spectral broadening of the perfect absorption bandwidth of the device under plane wave illumination. While multiple planar resonators have been used to increase the absorption band [8,13], no previous work has demonstrated the use of vertical resonators for this purpose.

II. Structure Under Analysis

Computer Simulation Technology (CST) Microwave Studio software [14] was used to perform full-wave simulations in support of this investigation and compute absorption as $A = 1-R-T$, where R and T are the reflectance and transmittance, respectively. In each simulation, the unit cell (illustrated in Fig. 1) is treated as an infinitely periodic structure along the X and Y directions.

The SRR is defined by the gap width w_g, trace width w_t, SRR width w_s, SRR height h_s, and SRR thickness t_s. The unit cell is defined by a lateral width w_l, front-to-back width w_{ftb}, wall height h_w, and total wall thickness t_w. The structure is supported by a silicon nitride membrane with thickness t_m and gold layer with thickness t_{au}. The gold layer decreases the transmittance to $T = 0$.

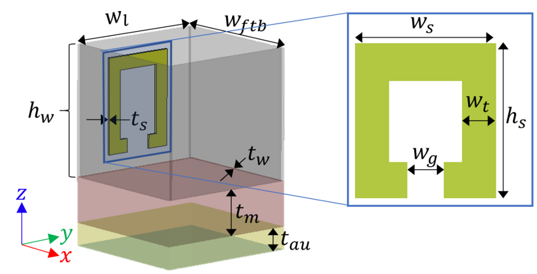

Fig. 1. Parameters defining a split-ring resonator and unit cell are illustrated.

III. Results

We first consider a unit cell containing a single VSRR, defined by the parameters tabulated in Table 1. All units are in μm.

Table 1. Unit cell and VSRR design parameters (μm).

w_g	w_t	w_s	h_s	t_s	w_l	w_{ftb}	h_w	t_w
0.60	0.30	1.60	2.12	0.05	2.30	2.30	2.90	0.16

The membrane and gold layer have thicknesses of 1.0 μm and 0.5 μm, respectively. As illustrated in Fig. 2, three distinct absorption resonances are produced by this geometry.

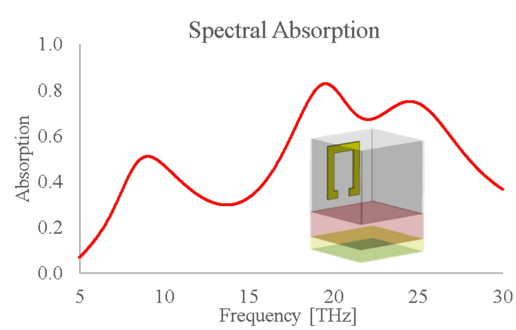

Fig. 2. Absorption is plotted against frequency for the case of a single VSRR.

The characteristics of each resonance will change as a function of the incident plane wave (angle of incidence and polarization), as well as the design parameters of the unit cell and SRR. For instance, changes in w_l will alter the spectral absorption profile based on inter-cell coupling.

Similarly, a unit cell containing a single PSRR may be considered as in the inset of Fig. 3. With the exception of $h_{s,PSRR}$, the unit cell and SRR dimensions are identical to those in Fig. 2; for the single PSRR geometry, the value of this parameter is 1.50 μm. As illustrated in Fig. 3, this geometry produces two absorption peaks, and has a spectral profile significantly different from the previous case.

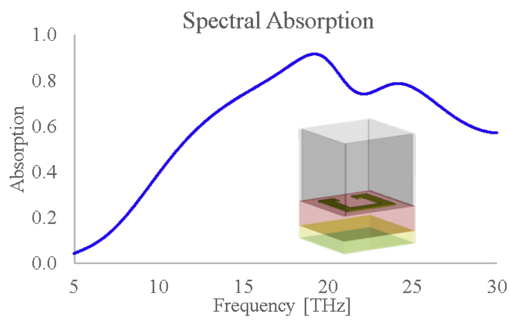

Fig. 3. Absorption is plotted against frequency for the case of a single PSRR.

Plots of the electric field profiles of the resonant SRRs (not shown) indicate that the largest field concentration for both resonators occurs near or across the SRR gap. Intra-cell coupling between the VSRR and PSRR is investigated by considering a unit cell containing both the previous VSRR and PSRR as shown in the inset of Fig. 4, with the SRR gaps placed near each other.

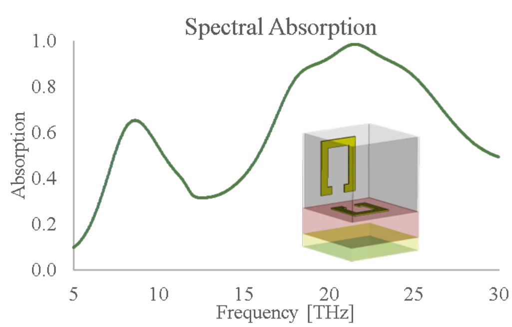

Fig. 4. Spectral absorption is plotted against frequency for the case of a unit cell containing both a VSRR and PSRR.

Strong intra-cell coupling is indicated by the spectral absorption (Fig. 4). The coupled SRR pair produces a strong, near-unity resonance at 21.85 THz, a spectral location where both previous designs experience a dip in absorption. This coupling between the two SRRs gives rise to bandwidth widening of the spectral absorption to 14.17 THz, as well as a near-unity peak absorption amplitude of 98.3%.

IV. Conclusions

Our investigation indicates that intra-cell coupling between multiple resonant structures can be exploited to enhance the spectral response of a device, and in particular widen its perfect absorption band. However, further investigation is required to better understand the inter-cell and intra-cell coupling, given the complexity of the parameter space.

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References

[1] D. Schurig, et al., "Metamaterial electromagnetic cloak at microwave frequencies", *Science*, vol. 314, pp. 977–980, 2006.

[2] I. Faniayeu and V. Mizeikis, "Vertical split-ring resonator perfect absorber metamaterial for IR frequencies realized via femtosecond direct laser writing", *Applied Physics Express*, vol. 10, pp. 062001, 2017.

[3] W. Wang, F. Yan, S. Tan, H. Zhou, and Y. Hou, "Ultrasensitive terahertz metamaterial sensor based on vertical split-ring resonators", *Photonics Research*, vol. 5, pp. 571–577, 2017.

[4] N. Katsarakis, et al., "Magnetic response of split-ring resonators in the far-infrared frequency regime", *Optics Letters*, vol. 30, pp. 1348–1350, 2005.

[5] S. Campione, F. Mesa, and F. Capolino, "Magnetoinductive waves and complex modes in two-dimensional periodic arrays of split ring resonators", *IEEE Transactions on Antennas and Propagation*, vol. 61, pp. 3554–3563, 2013.

[6] F. Monticone and A. Alu, "The quest for optical magnetism: from split-ring resonators to plasmonic nanoparticles and nanoclusters", *Journal of Materials Chemistry C*, vol. 2, pp. 9059–9072, 2014.

[7] D. B. Burckel, B. M. Adomanis, M. B. Sinclair, and S. Campione, "Three-dimensional cut wire pair behavior and controllable bianisotropic response in vertically oriented meta-atoms", *Optics Express*, vol. 25, pp. 32198–32205, 2017.

[8] L. Huang, et al., "Experimental demonstration of terahertz metamaterial absorbers with a broad and flat high absorption band", *Optics Letters*, vol. 37, pp. 154–156, 2012.

[9] K. Fan, A. C. Strikwerda, H. Tao, X. Zhang, and R. Averitt, "Stand-up magnetic metamaterials at terahertz frequencies", *Optics Express*, vol. 19, pp. 12619–12627, 2011.

[10] D. B. Burckel, et al., "Micrometer-scale cubic unit cell 3D metamaterial layers", *Advanced Materials*, vol. 22, pp. 5053–5057, 2010.

[11] D. B. Burckel, P. J. Resnick, P. S. Finnegan, M. B. Sinclair, and P. S. Davids, "Micrometer-scale Fabrication of complex three-dimensional lattice+basis structures in silicon", *Optical Materials Express*, vol. 5, pp. 2231–2239, 2015.

[12] D. Burckel, S. Campione, P. Davids and M. Sinclair, "Three dimensional metafilms with dual channel unit cells", *Applied Physics Letters*, vol. 110, pp. 10.1063, 2017.

[13] X. Liu, et al., "Taming the Blackbody with Infrared Metamaterials as Selective Thermal Emitters", *Physical Review Letters*, vol. 107, pp. 045901, 2011.

[14] CST Studio Suite. (2017). Dassault Systemes. https://www.cst.com/