Large-Period Multichannel Metagratings For Broad-Angle Absorption

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Abstract — We present an alternative scheme for obtaining effective power dissipation in planar composites, extending the recently proposed concept of metagrating (MGs), sparse arrangements of polarizable particles (meta-atoms), to realize multifunctional absorbers. In contrast to typical metasurface solutions, where periodicities are limited to half of a wavelength at most to avoid high-order Floquet-Bloch modes, we purposely consider large-period MGs, relying on their proven ability to effectively mitigate spurious scattering. The absorption process is thus implemented via precise engineering of the mutual coupling between numerous individual scatterers fitting in the enlarged period, with these additional degrees of freedom further utilized to enforce the perfect absorption conditions for multiple excitation angles simultaneously. The resultant devices, utilizing a standard printed circuit board configuration obtained semianalytically while featuring relaxed fabrication demands, exhibit high absorption across a wide angular range, useful for radar cross section reduction and energy harvesting applications.

I. INTRODUCTION

Promoting absorption of electromagnetic waves in planar structures has been a topic of active research for many decades, due to its central role in a wide variety of applications, from solar cells and THz sensors to radar cross section reduction and wireless power transfer. In the classical Dallenbach absorbers and Salisbury screens, perfect absorption is obtained in stratified media formations which exhibit impedance matching to free space [1]. Realizing these via natural materials, however, would typically require a specific (resonant) thickness ($\approx \lambda/4$), and may result in limited bandwidth and acceptance angle. New avenues to realize low-profile absorbers have become possible with the emergence of metasurfaces (MSs), thin slabs composed of closely-packed subwavelength polarizable particles (meta-atoms). Treating the densely arranged elements as homogenized generalized sheet transition conditions (GSTCs) [2], capacitive sheets (e.g., patch arrays) with prescribed surface impedances could be conveniently devised, enabling the needed impedance matching even with ultrathin grounded dielectric substrates [3].

Nevertheless, typical absorption applications require wide-angle response to maximize the overall scattering suppression or energy harvesting potential. While the GSTCs may yield the abstract surface impedance values required to realize absorption for a given (single) excitation, they do not guarantee the performance in the entire desired angular range. Consequently, extended angular response is obtained via sophisticated meta-atom geometries, devised using heuristic intuitive approaches combined with full-wave optimization [5]. Alternatively, improvement can be achieved by harnessing specialized (e.g., spatially dispersive) meta-atoms, but these are not always straightforward to translate into practical designs [3, 6]. Importantly, all these homogenization-based MS solutions utilize closely-packed finely-discretized unit cells [2], posing fabrication challenges and restricting possible geometries. Additional degrees of freedom may be enabled by introducing spatial modulation to induce auxiliary surface waves as design parameters [7], but supercell dimensions are typically limited to half of a wavelength to avoid emergence of propagating higher-order Floquet-Bloch (FB) modes [8]. Thus, design freedom is still quite limited, requiring implementation via dense, deep-subwavelength, meta-atoms with high-resolution features.

Recently, an alternative paradigm for molding fields has been proposed, based on metagratings (MGs) [9]. In contrast to MSs, these periodic devices feature sparse meta-atom distributions, not governed by homogenization. To synthesize MGs, reliable models to predict scattering from given scatterer arrangements, properly accounting for mutual coupling, are devised within the FB framework, yielding direct relations between the MG structure and
the coupling to the various FB modes [2]. Subsequently, beam manipulation is obtained by judicious engineering of the meta-atom constellation and geometry such that the resultant interference pattern matches the desired functionality. At microwaves, we have derived theoretically and verified experimentally such a semianalytical synthesis scheme to enable highly-efficient diffraction engineering using printed-circuit-board (PCB) MGs based on loaded-wire meta-atoms, yielding fabrication-ready designs without resorting to full-wave optimization [10].

Herein, we extend the MG design formalism to enable realization of broad-angle planar absorbers, retaining its appealing semianalytical nature and relaxed realization constraints. To this end, the model is augmented to allow incorporation of lossy loads, and the desired MG layout is obtained by demanding that scattered power to all propagating (reflected) FB modes would be minimal. Importantly, as previously demonstrated, the meticulous control on the coupling to a large number of FB modes achievable by multilayer multielement MGs allows us to alleviate the conventional MS limitation on the periodicity, enabling introduction of additional meta-atoms in the augmented period \( \Lambda \); these, in turn, provide means to tailor the MG response for multiple excitation angles simultaneously following a multichannel scattering approach [8]. Beyond the simpler structure and reduced design time, these results establish a fundamentally different paradigm for broad-angle absorption, relying on orchestrated scattering from multiple particles and delicate interference engineering in large-period sparse composites.

II. THEORY, RESULTS, AND DISCUSSION

We consider a \( \Lambda \)-periodic MG configuration excited by transverse electric \( (E_z = 0) \) fields (Fig. 1). The MG features \( K \) wires per period, positioned at \( (y, z) = (d_k, h_k) \) along the interfaces of a \( M \)-layer conductor-backed PCB [10], each loaded by printed capacitors of width \( W_k \) and lumped resistors of resistance \( R_k \). To facilitate the desired multichannel response, we devise a symmetric MG configuration realizing simultaneous perfect absorption for \( 2N + 1 \) excitation angles \( \theta_n = \arcsin(n\lambda/\Lambda) \), \( n = -N, \ldots, N \). Given that \( N\lambda < \Lambda < (N + 1)\lambda \), the FB theorem implies that for each of these angles of incidence, power can only be scattered to the other channels \( \theta_n \) [8]. Treating the loaded wires as induced current sources, the scattered fields for given \( \theta_n, (d_k, h_k) \), \( W_k \), and \( R_k \), can be evaluated semianalytically by invoking Poisson’s formula and Ohm’s law [2, 10]. These relations can then be used to formulate a set of constraints requiring all scattering coefficients to vanish (perfect absorption) for all considered excitation angles, from which the optimal MG configuration is deduced. Considering symmetry and reciprocity, the number of overall constraints is greatly reduced from the general \( (2N + 1)^2 \) to \( (N + 1)^2 \), achieving the multifunctional response with a highly sparse configuration.

To demonstrate our methodology, we follow it to design the \( (2N + 1 = 5) \) multichannel MG absorber of Fig. 2(a), intended to absorb 20 GHz plane waves incident from \( \theta_{\pm 2} = \pm 57.7^\circ \), \( \theta_{\pm 1} = \pm 25^\circ \), and \( \theta_0 = 0^\circ \). Correspondingly, the MG periodicity is \( \Lambda = \lambda/\sin 25^\circ \); it was found that \( K = 5 \) meta-atoms per period are sufficient in this case. The nine unique constraints on the scattering matrix required to guarantee simultaneous perfect absorption from all input channels were resolved via MATLAB (lsqnonlin), yielding the optimal MG specifications. For lumped resistors of \( R_k = 37.7\Omega \), this semianalytical scheme placed the meta-atoms in two layers below the conductor at \( z = 0.2\lambda \), with wire coordinates and capacitor widths as listed in the table of Fig. 2 (symmetrical about \( y = 0 \)).

Without any further optimization, we have defined this structure in CST, and simulated the MG response to each of the considered input channels. The results indicate that the designed MG succeeds in suppressing almost all back-reflected fields for each of the considered excitations, with absorption of 90% (97%), 89% (98%), and 88% (89%) obtained in full-wave simulations (analytical predictions) for \( \theta_{\rm in} = \theta_0, \theta_{\rm in} = \theta_{\pm 1}, \) and \( \theta_{\rm in} = \theta_{\pm 2}, \) respectively. Indeed, slightly increased specular reflection reduces power dissipation by up to 9% compared to...
Fig. 2: Broad-angle MG absorber with N=2 (Fig. 1). (a) MG configuration as output by the semianalytical procedure (cf. table). (b)-(d) Analytically predicted total field distribution $\text{Re}(E_x(y, z))$ (one period) for the designated incidence angles (shown only for $\theta_n \geq 0$), (b) $\theta_{\text{in}} = 0^\circ$, (c) $\theta_{\text{in}} = 25^\circ$, and (d) $\theta_{\text{in}} = 57.7^\circ$. Meta-atoms are denoted by black circles; substrate/air interface is marked by a dashed line. (f)-(h) Corresponding total fields as recorded in full-wave simulation. (e) Full-wave simulated absorption as a function of the incident angle. Theory; however, as shown by the MG angular response extracted from CST for the entire range [Fig. 2(e)], effective broad-angle absorption is obtained overall (above 88% , $|\theta_{\text{in}}| < 85^\circ$). The excellent agreement between the theoretical [Fig. 2(b)-(d)] and simulated [Fig. 2(f)-(h)] fields further verifies the high fidelity of the analytical model, implying that larger periods can be considered to improve the angular coverage in the future.

III. Conclusion

We have presented an alternative route for obtaining effective broad-angle absorption from low-profile structures, relying on large-period PCB MGs comprised of sparsely distributed loaded wires. By tailoring the mutual coupling between the scatterers via a detailed analytical model to suppress coupling to propagating FB modes, high absorption is maintained while providing space for numerous meta-atoms per period. These additional degrees of freedom are harnessed to achieve absorption from multiple angles of incidence simultaneously, leveraging a symmetric multichannel approach for increased sparsity. Such insightful designs could lead to improved low-cost absorbers for radar evasion, fitting well also energy harvesting applications (power absorbed in a few loads).

REFERENCES

[1] Y. Ra’di, C. R. Simovski, and S. A. Tretyakov, “Thin perfect absorbers for electromagnetic waves: Theory, design, and realizations,” Phys. Rev. Appl., vol. 3, p. 037001, 2015.
[2] S. Tretyakov, Analytical Modeling in Applied Electromagnetics. Artech House, 2003.
[3] O. Lunkkonen, F. Costa, C. Simovski, A. Monorchio, and S. Tretyakov, “A Thin Electromagnetic Absorber for Wide Incidence Angles and Both Polarizations,” IEEE Trans. Antennas Propag., vol. 57, no. 10, pp. 3119–3125, 2009.
[4] X. Begaud, A. Lepage, S. Varault, M. Soiron, and A. Barka, “Ultra-Wideband and Wide-Angle Microwave Metamaterial Absorber,” Materials, vol. 11, no. 10, p. 2045, 2018.
[5] J. P. del Risco, I. S. Mikhalka, V. A. Lenets, M. S. Sidorenko, A. D. Sayanskiy, S. B. Glybovski, A. L. Samofalov, S. A. Khakhomov, I. V. Semchenko, J. D. Ortiz, and J. D. Baena, “Optimal angular stability of reflectionless metasurface absorbers,” Phys. Rev. B, vol. 103, no. 11, p. 115426, 2021.
[6] A. Epstein and G. V. Eleftheriades, “Synthesis of passive lossless metasurfaces using auxiliary fields for reflectionless beam splitting and perfect reflection,” Phys. Rev. Lett., vol. 117, no. 25, p. 256103, 2016.
[7] X. Wang, A. Diaz-Rubio, and S. A. Tretyakov, “Independent control of multiple channels in metasurface devices,” Phys. Rev. Appl., vol. 14, no. 2, p. 024089, 2020.
[8] Y. Ra’di and A. Alu, “Metagratings for efficient wavefront manipulation,” IEEE Photon. J., vol. 14, no. 1, pp. 1–13, 2022.
[9] O. Rabinovich and A. Epstein, “Arbitrary diffraction engineering with multilayered multielement metagratings,” IEEE Trans. Antennas Propag., vol. 68, no. 3, pp. 1553–1568, 2020.