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Frequency-Agile Sliding Metagratings for Dynamic Wave Control

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***Abstract*—The wave control capabilities of metagratings are extended by allowing them to laterally slide relative to each other. This reconfigurability is implemented by a stack of printed circuit boards (PCBs) containing capacitively loaded wires. The PCBs are slid to different optimized locations to obtain efficient refractive scattering in different directions. Although ideal for beam switching, this reconfigurability can attain frequency agility or compensation for unforeseen fabrication discrepancies. Analytical model predictions compare well with full-wave simulations.**

I. Introduction

Metagratings (MGs), sparse arrays of subwavelength polarizable particles, have been shown capable of scattering waves in anomalous directions [1]. A popular realization at microwave frequencies consists of periodic loaded wires etched onto a printed circuit board (PCB) [Fig 1(a)]. For a given period of loaded wires, the wave scattering characteristics of a stack of such PCBs would depend on the properties of the substrate, wires, and their relative positions. Judiciously designed stacks can realize intricate diffraction engineering, including anomalous refraction in directions compatible with Floquet-Bloch (FB) modes [Fig. 1(b)] [2].

Dynamic control of microwaves scattered by complex media has traditionally been accomplished with the aid of non-linear components (diodes) [3], [4]. However, their use is often accompanied by non-negligible losses which become more severe as the frequency increases. Herein, we propose an alternative path, relying instead on subtle mechanical movements: by altering the lateral location of each PCB on the stack the inter-element coupling is varied, thereby modifying the scattering pattern in real time [Fig. 1(c)]. Relying on the high-fidelity models previously developed for MG synthesis [2], one configuration of the PCBs might be optimized to produce a transmitted wave in one modal direction, while a different configuration of the same (static and passive) stack might yield a wave in a different modal direction [Figs. 1(b) and 1(c)].

Beyond being readily applicable at high frequencies (similar to other mechanically tunable platforms [5]), we show that this sliding mechanism encompasses yet another benefit. Specifically, the dynamic wave control efficacy of a given stack can also be enhanced outside the designed bandwidth, via minor lateral offsets from the original configuration, evaluated with the aid of the analytical model. As verified using full-wave simulations, the devised approach facilitates frequency agile beam-switching MGs; equivalently, it may offer a convenient path for coping with fabrication errors and laminate tolerances.

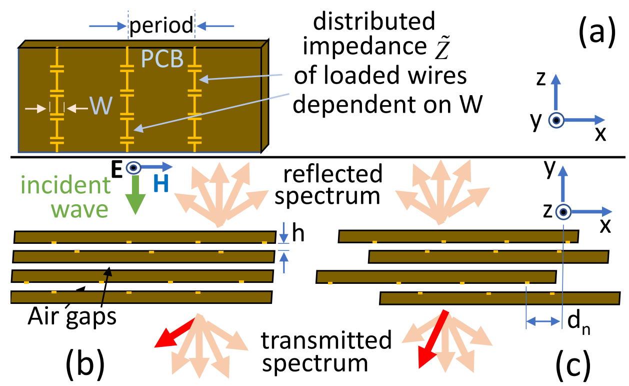

Fig. 1. (a) PCB MG featuring capacitively loaded wires as meta-atoms. (b) A stack of N PCBs as in (a), each with the same period but with its own distributed load impedance $\tilde{Z}$ (corresponding to the capacitor width W), and separated by air gaps of uniform thickness h. For the nth PCB, the value of $\tilde{Z}_n$, and the lateral location of that PCB measured by the x-distance d_n from $x = 0$ of the wire closest to the origin, are optimized so that all propagating FB amplitudes vanish except for the one shown by the red arrow. (c) Sliding the same PCBs of (b) to new locations determined by our optimization method will produce a wave in yet another direction, again indicated by the red arrow.

II. Theory, Results and Discussion

Consider a transverse electric (TE) polarized plane wave ($E_x = E_y = H_z = 0$) normally incident on a stack of N PCB MGs that is invariant in the z-direction and separated by air gaps [Fig. 1(b)]. Etched on each PCB is an x-periodic array of wires with a given load impedance per unit length $\tilde{Z}_n$ (for the nth PCB) [2]. From FB theory, the reflected and transmitted fields, E_{ref} and E_{trans}, can be written as a discrete sum of plane waves polarized in the z-direction, and consisting of both propagating and evanescent components:

$$E_{\text{ref}} = \sum_{p=-\infty}^{\infty} \rho_p e^{ik_{xp}x} e^{ik_{yp}y}, E_{\text{trans}} = \sum_{p=-\infty}^{\infty} \tau_p e^{ik_{xp}x} e^{ik_{yp}y} \quad (1)$$

$$k_{xp} = 2p\pi/d, \;\; k_{yp} = \sqrt{k^2 - k_{xp}^2} \;\; d = \lambda/|\sin\theta_{-1}| \quad (2)$$

where d is the period, $k = 2\pi/\lambda$, λ is the wavelength in free space, θ_{-1} is the transmission angle of the $p = -1$ wave, and $e^{-i\omega t}$ is suppressed. The propagating components of (1) are those for which k_{yp} are real, and are illustrated in Fig. 1 as the "reflected spectrum" and the "transmitted spectrum". Using expressions analogous to (1) for regions within the PCBs and the air gaps, and accounting for the interaction of these fields with the loaded wires with the aid of Ohm's law, we can solve for the ρ_p and τ_p in (1) [2]. Using this analytical model as the

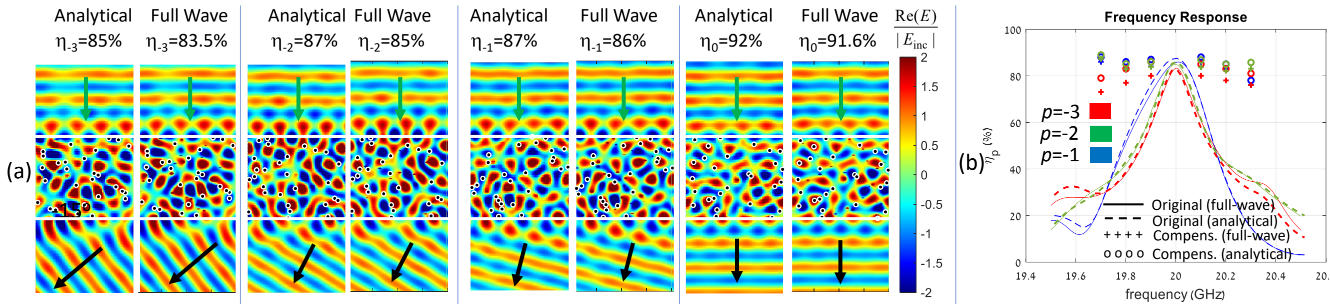

Fig. 2. (a) Total E-field for scattering of a normally incident TE wave from the devised reconfigurable PCB MG stack For each FB mode ($p = -3, -2, -1, 0$) both analytical and full-wave results are shown (single period), along with the coupling efficiencies η_p. The green and black arrows indicate, respectively, the incident and refracted waves for the respective mode p. The stack is located between the horizontal white lines, with the locations of the loaded wires indicated by black dots. Results for the remaining $p = 1, 2, 3$ propagating modes are not provided since they are symmetrically related to $p = -1, -2, -3$. (b) For modes $p = -1, -2, -3$ (blue, green, red), analytical (dashed) and full-wave-calculated (solid) frequency response for the prototype device. Additionally shown are the analytical (o) and full-wave (+) values after sliding the PCBs to new locations that were optimized to compensate for the frequency change.

basis for multi-functional optimization, the values of $\tilde{Z}_n$ and d_n for each PCB can be found that will provide the desired scattering behavior: shifting all N layers to their respective $d_n^{(p)}$, would result in optimal coupling to the pth FB mode (beam steering towards θ_p). Finally, the prescribed $\tilde{Z}_n$ may be translated into actual capacitor widths W_n [2], yielding fabrication-ready layouts for the entire stack of PCBs.

To demonstrate and verify these ideas, we design a reconfigurable MG which can switch between beams in seven discrete directions when illuminated at 20 GHz ($\lambda \approx 15$ mm). From (2), we can accomplish this by choosing $\theta_{-1} = 15°$, which dictates $d = 3.86\lambda$. The values of p for which k_{yp} are real are $p = [-3 : 3]$, corresponding to propagation angles $\theta_p = [-50.94°, -31.17°, -15.00°, 0°, 15.00°, 31.17°, 50.94°]$. This would imply a total of 14 propagating waves: seven for reflection and seven for transmission. To control these, we utilize a total of 28 copper wire arrays (trace width of 4 mil), etched onto Rogers RO3003 substrates 30 mil thick characterized by relative permittivity 3 and $\tan\delta = 0.001$; to enable sliding, the substrates are separated by air gaps of $h = 1$ mm. To reach the MG stack design, we first optimize the distributed wire impedances $\tilde{Z}_n$ and the wire locations d_n so that all the scattered energy is concentrated in only *one* of the 14 possible propagating waves; the $p = -2$ transmission wave ($\theta_{-2} = -31.17°$) was chosen for this purpose. After thus fixing the wire loads for all 28 PCBs, we proceed to determine their optimum lateral locations $d_n^{(p)}$ for providing efficient scattering in each of the *other* propagating directions θ_p, maximizing the coupling efficiency η_p to the pth mode.

Fig. 2(a) displays the color snapshot E-field images produced by MGs that have been correspondingly designed to provide the beam-switching reconfigurability. As can be seen, the analytically predicted fields and efficiencies are almost precisely the same as the ones recorded in full-wave simulations (CST), verifying the successful dynamic steering from θ_p to θ_q, obtained by merely sliding the PCBs from one prescribed location set $d_n^{(p)}$ to another $d_n^{(q)}$, $(p, q \in \{-3, -2, -1, ..., 3\})$.

For three of the propagating FB modes, the solid and dashed curves in Fig. 2(b) display the degradation in efficiency when the device is operated at frequencies which differ from the design frequency. It is interesting to note the extent of agreement between our analytical model (which assumes that $\tilde{Z}_n$ varies with frequency as an ideal capacitive reactance) and full-wave calculations. Even more interesting is the fact that we can compensate for any such degradation by re-optimizing the sliding metagratings to new positions compatible with these offset frequencies, without altering the already-etched metallic traces whatsoever. This is also shown in Fig. 2(b), which displays the efficiencies which can be attained for several frequencies, if the PCB locations are re-optimized for these frequencies. Indeed, the proposed approach is shown to nearly completely restore the original η_p values, enhancing the efficiency by more than twofold at the edges of the band.

III. Conclusion

Slidable MGs have been shown not only to enable beam switching, but also to compensate for frequency deviations (or, potentially, other design deficiencies). The proposed reconfigurable and robust devices, relying on low-loss fine mechanical control of semi-analytically evaluated lateral positions, may be appealing for timely high-frequency applications.

Acknowledgement

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