Genetically Optimized Metasurface Pairs for Wideband Out-of-Phase Mutual Response

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***Abstract*—This letter deals with the design of a pair of "metasurfaces" made of dense periodic arrays of electric dipoles laid on thin metal-backed dielectric substrates, capable of maintaining out-of-phase reflection coefficients over a wide frequency band. Our design is based on the genetic optimization of the dipole dimensions and spacings, and the substrate thickness. For performance assessment and illustration of potential applications to reduction/control of radar cross-section signatures, we present an example involving Bragg-scattering suppression in strip arrays.**

***Index Terms*—Frequency-selective surfaces (FSSs), genetic algorithms (GA), radar cross-section, scattering.**

I. Introduction

FREQUENCY-SELECTIVE SURFACEs (FSSs) made of dense periodic arrays of thin dipoles [1], commonly referred to as "gangbuster-type," constitute a subject of longstanding interest, which has recently received a renewed attention in theoretical [2], [3] and experimental [4] studies, motivated by a variety of applications, including thin absorbers [5], polarization-dependent reflecting lenses [6], compact cavity resonators [7], and reflectarrays [8].

In particular, the application in [6] provides a nice illustration of the capabilities of gangbuster-based "metasurfaces" of synthesizing a given spatially inhomogeneous reflection-phase profile, with rather easy and independent control of both polarizations. These capabilities can find important applications to the design of low-profile structures for radar cross-section (RCS) reduction/control, such as "simulated corrugated surfaces" [9] or "virtual shaping" [10], where one is interested in suppressing/reducing the scattering in certain (typically, backscattering and specular) directions by acting on the surface reflection properties rather than on its shaping. Recently, the combined use of electric and artificial magnetic conducting (AMC) surfaces, in periodic [11] and aperiodic [12] spatial arrangements as well as in time-switched modality [13], has been suggested as an effective device for controlling the RCS signatures. The basic idea is to exploit the cancellation effects arising from the well-known 180° phase-difference between the corresponding reflection coefficients. However, AMC surfaces can only be synthesized within narrow frequency regions, resulting in severe bandwidth restrictions.

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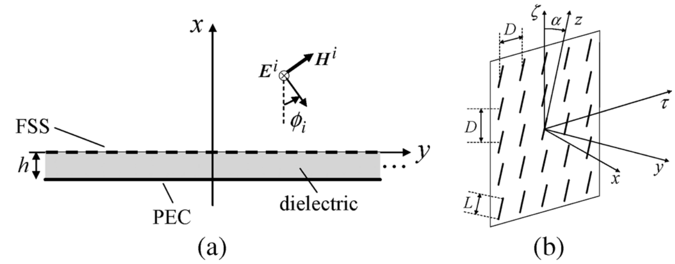

Fig. 1. Geometry of the single prototype metasurface. (a) Infinitely extent gangbuster-type FSS laid on a PEC-backed dielectric layer, illuminated by a plane wave. (b) Illustration of the gangbuster dipole arrangement in the $y-z$ (and tilted $\tau-\zeta$) plane.

To overcome the above limitations, in this prototype study, we address the design of a pair of gangbuster-type reflective metasurfaces capable of maintaining an out-of-phase mutual response over a wide frequency band. Our approach is based on genetic algorithm (GA) optimization [14], [15], which has been extensively applied in the past to the design of FSS-based devices.

II. Genetically Optimized Metasurfaces

A. Geometry of the Problem and Formulation

Referring to Fig. 1(a), the prototype of the *single* metasurface geometry of interest consists of a gangbuster-type FSS, made of an infinite periodic array of closely spaced perfectly electric-conducting (PEC) z-oriented dipoles of length L and radius R, laid on a PEC-backed dielectric slab of thickness h and relative permittivity ε_r. The dipole spatial arrangement in the $y-z$ plane, illustrated in Fig. 1(b), is characterized by a constant interelement spacing D (referred to the dipole center) in the tilted $\tau-\zeta$ reference system, whose tilt angle $\alpha=\arctan(1/n)$ defines, via the integer number n, the gangbuster type (see [1]–[3] for more details). The present prototype study is restricted to the two-dimensional (2-D) scalar case, and for time-harmonic $[\exp(j\omega t)]$ plane-wave illumination with electric field parallel to the dipoles.

The electromagnetic (EM) modeling of such a single, infinite metasurface is addressed as in [2], [3]. First, the plane-wave-excited gangbuster FSS *alone* (in free space) is studied via a rigorous full-wave technique based on the periodic method-of-moment (MoM). Our implementation, detailed in [2], [3], utilizes

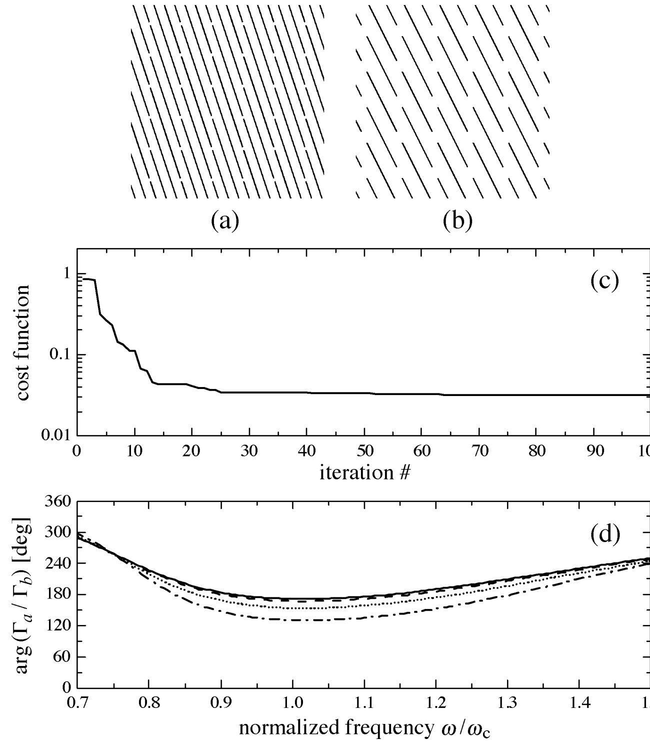

Fig. 2. GA optimization of the infinite metasurfaces. (a), (b) Square-patch samples ($0.25\lambda_c$ sidelength) of the a- and b-type (infinite) gangbuster FSS, respectively, optimized for normal incidence ($\phi_i = 0$) and $\varepsilon_r = 1$. Optimized parameters: $D_a = 0.081\lambda_c$, $L_a = 0.247\lambda_c$, $n_a = 3$, $h_a = 0.086\lambda_c$, $D_b = 0.092\lambda_c$, $L_b = 0.173\lambda_c$, $n_b = 2$, $h_b = 0.091\lambda_c$; the dipole radius is kept fixed at $R = 0.001\lambda_c$. (c) Cost function in (1) vs. GA iterations. (d) Phase difference between the (unit magnitude) reflection coefficients pertaining to the optimized infinite metasurfaces as a function of frequency (continuous curve: $\phi_i = 0$; dashed: $\phi_i = 15°$; dotted: $\phi_i = 30°$; dashed-dotted: $\phi_i = 45°$).

entire-domain basis and test functions, and a Floquet-series representation of the scattered field. Next, in view of the assumed *tight* electrical spacing of the dipoles (which renders the higher-order *evanescent* Floquet-waves in the field expansion *negligible* even at relatively small distances from the array plane), the gangbuster FSS is effectively modeled as a *reactance sheet*. Accordingly, the interaction with the PEC-backed dielectric slab is studied via a simple equivalent transmission-line circuit (along the x-direction), where the gangbuster FSS is represented by an equivalent shunt reactance which can readily be extracted from the MoM solution (see [2] and [3] for details). Our parameters are constrained to fall within the calibrated ranges of applicability (derived in [2] and [3]) of the above approximation.

As anticipated, the goal of our investigation is to design a pair of gangbuster-type metasurfaces capable of preserving a nearly 180° phase-difference between their reflection coefficients over a wide frequency band.

B. GA Optimization

In order to pursue the above goal, we now consider *two* infinite metasurfaces, labeled as a and b. For each of the two, taken *alone*, we can compute the EM response (following the procedure described earlier) in terms of a reflection coefficient $\Gamma_{a,b}$, which, in view of the assumed infinite extent, ground-plane backing, and absence of losses, has *unit magnitude*. Then, for a given incidence angle ϕ_i, we minimize the cost function

$$\Omega[D_a, L_a, h_a; D_b, L_b, h_b] = \frac{1}{M}\sum_{m=1}^{M} |\Gamma_a(\omega_m, \phi_i) + \Gamma_b(\omega_m, \phi_i)|^2 \quad (1)$$

where ω_m, $m = 1, \ldots, M$ denote angular frequency samples. In order to understand the reason of this choice, note that the cost function in (1) vanishes for $\Gamma_b = -\Gamma_a$ over the frequency range of interest. The design parameters include the dipole lengths $L_{a,b}$ and spacings $D_{a,b}$, and the substrate thicknesses $h_{a,b}$, whereas the dielectric slab relative permittivity ε_r and the dipole radius R are assumed to be fixed. For a given parameter configuration, the gangbuster indexes $n_{a,b}$ are chosen so as to maximize the dipole density while preventing any touching, cf. [2, Eqs. (B.0.2) and (B.0.3)]

$$n_{a,b} = \frac{1}{\tan\alpha_{a,b}} = \min\left\{\left\lceil\sqrt{\frac{L_{a,b}}{D_{a,b}}} - 1\right\rceil, \left\lfloor\sqrt{\left(\frac{D_{a,b}}{2R}\right)^2 - 1}\right\rfloor\right\} \quad (2)$$

where $\lceil\cdot\rceil$ and $\lfloor\cdot\rfloor$ denote the "ceiling" and "floor" function, respectively. Our minimization strategy is based on the use the general-purpose PIKAIA GA engine [16], in view of its free availability [17], as well as its updated, flexible and well-documented architecture. The chosen implementation is based on a 50-individual population, four-digit discretization, one-point crossover (with probability 0.9) and mutation (with probability 0.005), roulette-wheel selection, and elitism. The cost function in (1) is computed using $M = 11$ samples equispaced within the angular frequency range $[0.9\omega_c, 1.1\omega_c]$, with ω_c denoting the desired center angular frequency (chosen as $2\pi c$ in our simulations, with c denoting the free-space wave speed). The following variation ranges are assumed for the design parameters: $D_{a,b} \in [0.05\lambda_c, 0.13\lambda_c]$, $L_{a,b} \in [0.15\lambda_c, 1.5\lambda_c]$, $h_{a,b} \in [0.06\lambda_c/\sqrt{\varepsilon_r}, 0.1\lambda_c/\sqrt{\varepsilon_r}]$, with $\lambda_c = 2\pi c/\omega_c$ denoting the center wavelength.

Fig. 2 illustrates the results from an optimization example for normal incidence ($\phi_i = 0$), assuming $\varepsilon_r = 1$ and $R = 0.001\lambda_c$. Specifically, Fig. 2(a) and (b) shows two square-patch samples of the optimized infinite gangbuster FSS geometries, whereas Fig. 2(c) illustrates the GA evolution (cost function versus iteration number), from which it can be observed that convergence to a reasonably small value of the cost function (~0.03) is practically reached within ~50 iterations. Fig. 2(d) shows the phase difference between the (unit-magnitude) reflection coefficients of the two optimized infinite metasurfaces over a moderately wide neighborhood of the design center frequency, for incidence angles ranging from 0° to 45°. It is observed that, for normal incidence (for which the structures were optimized), the response is rather flat and close to 180° within (and even slightly beyond) the targeted frequency region $[0.9\omega_c, 1.1\omega_c]$. Departures of the incidence direction from normal obviously result into poorer responses. Nevertheless, the structures turn out to be rather robust

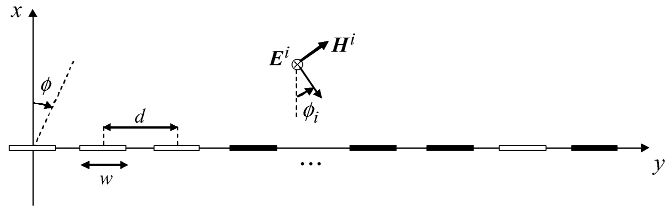

Fig. 3. Strip array geometry. Strips made of a- and b-type metasurfaces (indicated by black and white rectangles, respectively) of equal width w are arranged with uniform interelement spacing d.

with respect to such changes, exhibiting only moderate degradations for oblique incidence up to 30°. Actually, one may think of a different strategy where *both* frequency and angular sensitivities are minimized, with a suitable tradeoff.

III. Example: Bragg Scattering Suppression

As a possible example of application of the above jointly optimized metasurfaces, we consider the plane-wave scattering from an array of N strips (infinitely long in the z direction) made of a- and b-type metasurfaces, with identical width w and (center-to-center) interelement spacing d, as illustrated in Fig. 3. In view of the uniform interelement spacing, the scattered field exhibits Bragg-type peaks at wavelengths and directions satisfying the condition $\lambda_\nu = d(\sin\phi - \sin\phi_i)/\nu$, $\nu = 0, \pm 1, \pm 2, \ldots$, with amplitude dependent on the single-strip scattering pattern as well as on the reflection coefficients $\Gamma_{a,b}$ and their spatial arrangement. In [12], using an approximate Physical Optics (PO) modeling, it was shown, for the ideal case of arrays made of perfectly electric ($\Gamma_a = -1$) and magnetic ($\Gamma_b = 1$) strips, that a Rudin-Shapiro (RS) *quasirandom* arrangement could be used to suppress the Bragg scattering and achieve a rather *flat* angular distribution of the scattered power, resembling that of random scatterers. Here, we move a step forward, considering our metasurface pair optimized for out-of-phase response ($\Gamma_b \approx -\Gamma_a$). As in [12], we use an approximate PO modeling, neglecting the interelement coupling. The metasurface strips are modeled in terms of their reflection coefficients $\Gamma_{a,b}$, approximated via the infinite-surface values computed as in Section II-A (see [1] for a discussion of the truncation, coupling, and possible surface-wave effects neglected in our simplified model).

Fig. 4 illustrates the results pertaining to a 32-element array of strips with $w = 1.2\lambda_c$ and $d = 2.5\lambda_c$, in terms of the 2-D bistatic RCS as a function of the observation angle ϕ, at the center frequency, for normal incidence ($\phi_i = 0$). The array parameters were chosen so as to guarantee the applicability of the PO approximation, and to include in the visible range of angles several Bragg peaks in order to highlight their subsequent suppression. Specifically, Fig. 4(a) shows the response of a quasi-random array with optimized-metasurface strips arranged according to the RS sequence *bbbabbabbbbaaabaaaabaababbbaaaba* (see [12] for details), while Fig. 4(b) shows the reference response of an array made of PEC ($\Gamma_a = \Gamma_b = -1$) strips. While Bragg peaks are clearly visible for the PEC case, a rather *uniform* angular response (modulated by the sinc-type single-strip scattering

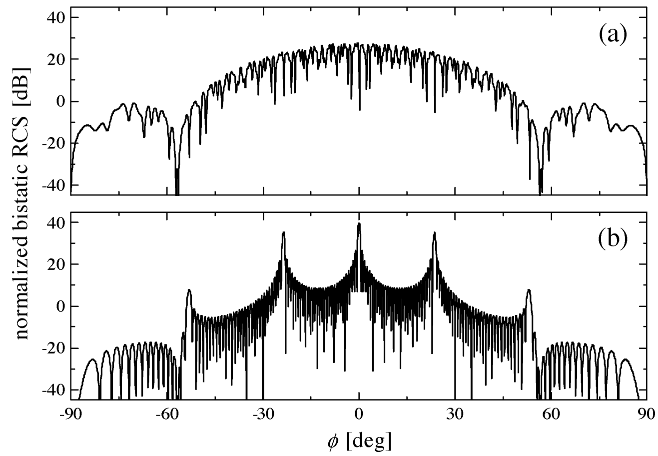

Fig. 4. Bistatic RCS (scaled to the center wavelength) at the center frequency for an array of $N = 32$ strips of width $w = 1.2\lambda_c$ and interelement spacing $d = 2.5\lambda_c$, for normal incidence ($\phi_i = 0$). (a) GA-optimized metasurface strips with RS-type arrangement. (b) PEC ($\Gamma_a = \Gamma_b = -1$) strips.

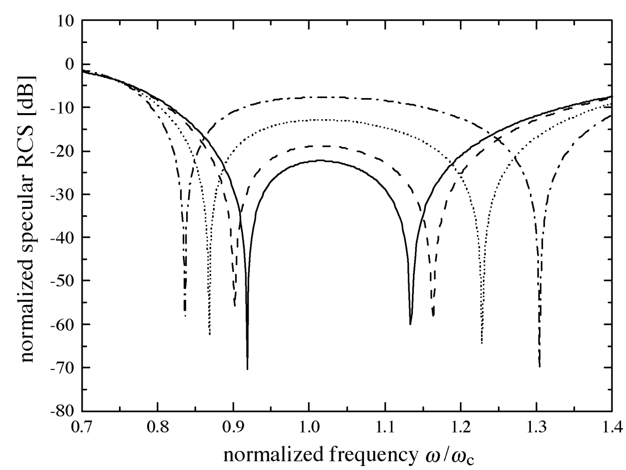

Fig. 5. As in Fig. 4, but specular ($\phi = \phi_i$) RCS frequency response of the optimized-metasurface RS array, scaled by the reference PEC-array RCS, for various incidence angles (continuous curve: $\phi_i = 0$; dashed: $\phi_i = 15°$; dotted: $\phi_i = 30°$; dashed-dotted: $\phi_i = 45°$).

pattern) is observed for the optimized-metasurface RS case, with *pronounced dips* at backscattering ($\phi = 0$) and other Bragg directions. The more uniform power distribution, which can be locally higher than the PEC case, arises from the angular spread of the power otherwise concentrated in the Bragg peaks.

For the same parametric configuration, Fig. 5 shows the frequency response at specular ($\phi = \phi_i$) direction of the optimized-metasurface RS array, scaled by the reference PEC-array RCS, for various incidence angles. For normal incidence (at which the metasurfaces were optimized), one observes a reduction of more than 20 dB over a ~40% bandwidth. Again, moderately poorer responses are observed for oblique incidence, but a reduction of more than 10 dB is still attained for incidence angles up to 30°.

Finally, Fig. 6 shows the monostatic ($\phi = -\phi_i$) RCS response for oblique incidence $\phi_i = 30°$. Also in this case, the response of the optimized-metasurface RS array is significantly (~15 dB) below the peak value exhibited by the PEC array (associated to the $\nu = -3$ Bragg-wavelength).

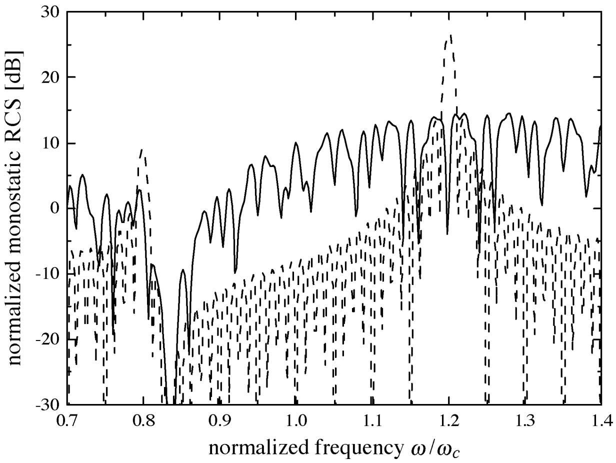

Fig. 6. As in Fig. 5, but monostatic ($\phi = -\phi_i$) RCS (scaled to the center wavelength) frequency response for oblique ($\phi_i = 30°$) incidence (continuous curve: RS array with GA-optimized metasurface strips; dashed: PEC strips).

IV. Conclusion

In this letter, we presented a GA-based design of gangbuster-type metasurfaces capable of maintaining out-of-phase reflection coefficients over a wide frequency range. Application examples of our prototype study, involving Bragg-scattering suppression in strip arrays, have demonstrated interesting potentials for RCS signature control. Current and future studies are aimed at extending this prototype 2-D study to the more realistic 3-D full-vector case, along the lines, e.g., of [11]. Also worth of interest is the exploration of possible applications to compact resonators and Fabry-Perot antennas.

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