Wavenumber-Splitting Metasurfaces for Multi-Channel Diffusive Invisibility

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***Abstract*—Parabolic phase is commonly utilized for concave or convex metalens. Here, we report for the first time using such approach for determinant diffusion of scattering waves in wide incident angles by arranging parabolic-phased subarrays in arbitrary coding sequences. To engineer multi-spectrum polarization-dependent bifunctional scatterings, multi-mode anisotropic meta-atoms are utilized without polarization cross-talking. For verification, two proof-to-concept coding metasurfaces are designed, fabricated and measured at microwave regime. Numerical and experimental results show that the -10 dB backscatter radar cross-section (RCS) reduction is clearly observed in C, X and Ku band. Moreover, the diffusion behavior can be engineered dual-polarized and even bifunctional by integrating vortex scattering. Our findings, free of time-consuming optimizations, opened a rapid, easy but very efficient way for stealth applications under bistatic detection.**

***Keywords*—bifunctional; dual-polarized; multiband radar cross section (RCS) reduction; metasurface; parabolic phase**

I. Introduction

Invisibility and cloaking have intrigued renewed interest due to the pressing demand on stealth and anti-stealth technology in military field. Various strategies have been proposed and extensively studied by scientists and engineers, e.g., transformation optics (TO) based metamaterial cloak [1], Salisbury screen used absorption materials [2], artificial absorber relied on simultaneous electric and magnetic resonant loss [3], plasmonic and mantle cloak utilized scattering cancellation technique [4], etc. These techniques have their own advantages and drawbacks. For example, TO method manifests ideal cloaking performances but requires rigorous inhomogeneous material profile of artificial structures which are bulky in volume. Although absorber and Salisbury screen transform the scattering electromagnetic (EM) energy into heat, the heat radiation from the target increases the possibility of detection by infrared detectors. Moreover, the required quarter wavelength spacing for Salisbury screen is very thick especially at low frequencies. Plasmonic and mantle cloak affords an alternative for ultrathin stealth, however the non-negligible higher-order Mie scatterings cannot be cancelled out at high frequencies.

Metasurface, a two-dimensional (2D) equivalence of metamaterials and composed of sub-wavelength artificial meta-atoms in an ultrathin plate, has been extensively researched as an alternative to reduce radar cross section (RCS) in recent years [5]-[9]. The versatile EM functions with strong wave controllability, and potential to conform it to any curved object enable it to be an elegant candidate for target stealth. One important approach was implemented by arranging perfect electric conductor (PEC) and the artificial magnetic conductor (AMC) with 180° phase reversal in chessboard like configuration [5]. The principle mechanism is using destructive interference of scattered fields to reduce the total normal/specular reflections. Most recently, the concept of coding metasurface has been employed to implement broadband RCS reduction by distributing different subarrays corresponding to specific coding sequence [7].

Despite fruitful progress toward RCS reduction, most work and techniques are endeavored to improve the bandwidth and engineer mono-scattering behavior. In practice, low RCS in multiple operation bands is highly desirable for smart and dynamical stealth application since it enables low cost, high reliability and integrity of a system. To this end, dual-band RCS reduction was actualized combining the absorption and destructive interference of a chessboard metasurface [6]. To date, a metasurface that exhibits multi-band diffusion behavior was rarely reported. Here, we proposed an approach to diffuse scattering waves in triple frequency spectrums and wide angles by constructing convergent/divergent parabolic-phased subarrays in arbitrary coding sequence [8],[9]. Moreover, the vortex scattering was integrated to diffusion by individually controlling the phases of dual polarizations. Both numerical and experimental results on 1-bit and 2-bit coding metasurfaces have validated the desirable tri-band polarization-dependent bifunctional scattering behavior.

II. Fundamentals and Theory and Results

The realized functionality of parabolic-phased coding metasurface is conceptually illustrated in Fig. 1. The EM wave scattering from the metasurface is dispersed into all angles in free space under dual orthogonal polarizations of incidence. Such full-diffusion behavior is intrinsic at operation band by employing subarrays with convergent/divergent parabolic-phased profile shown in the inset. The principle physics can be understood by a Fourier transform (FFT) from real space to k space ($F(k_x)=\int_{-L/2}^{L/2} e^{i\xi_0 x^2} e^{-ik_x x}dx \Big/ L$, L is the size of metasurface), which is analogue to a transform from field/current distributions in near-field domain to scattering patterns in far-field domain based on array theory. Take linear phase profile $\xi(x)=\xi_0 x$ as an example, its FFT counterpart is a Dirac-delta function $\sin c(\frac{1}{2}(\xi_0-k_x)L)$. This indicates that the metasurface with linear-phased profile would direct the scattering wave to a beam with wave component $k_x=\xi_0$ at predefined elevation angle $\theta_0=\sin^{-1}(\xi_0/k_x)$, see Fig. 2(a). However, the FFT pattern fluctuates across a broad range of k_x if parabolic phases are utilized, see Fig. 2(b). This is a very exciting feature which reveals that a metasurface with such phase distribution will disperse the scattering wave to a mass of beams with near uniform amplitude.

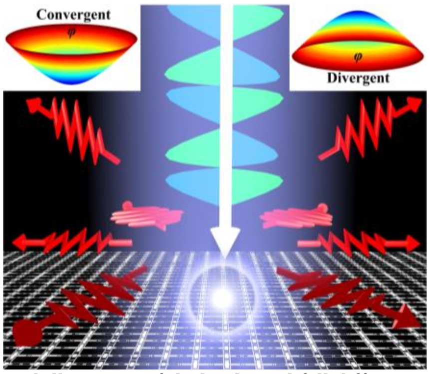

Fig. 1. Conceptual illustration of dual-polarized full diffusion using proposed parabolic-phased metasurface. The inset shows the convergent/divergent parabolic phase profile of a basic subarray.

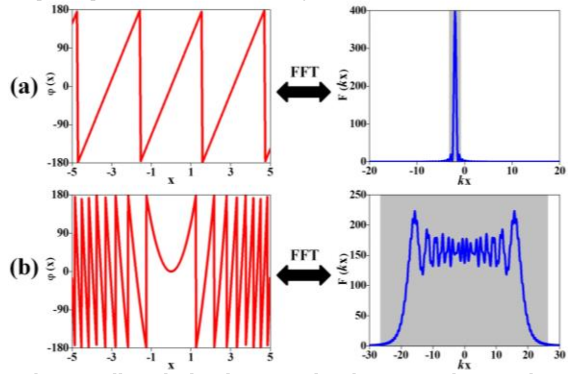

Fig. 2. Theoretically calculated energy distributions in k space by FFT to indicate the scattering behavior of a metasurface. (a) Linear phase. (b) Parabolic phase. In both cases, L=10 and $\xi_0=2$.

Dual-polarized multi-spectrum diffusion is highly desirable for smart and dynamical stealth applications. A multi-mode meta-atom without polarization cross-talking is necessary. In this regard, the phase tolerances would be minimized at frequencies other than the designed band when similar phase response with parallel phase slope is satisfied at these resonant bands. Otherwise, the diffusion behavior would deteriorate with raised RCS value. Most importantly, a polarization-dependent diffusion can be engineered when an anisotropic meta-atom is utilized without polarization talking. Taking into account these aspects, we utilize the dual-layer multi-mode meta-atom shown in Fig. 3(a) [10] to demonstrate our proposal and realize completely different scattering behavior dependent on polarization. It is consisted by dual metallic layers of the same composites separated by two dielectric spacers (F4B substrate boards with εr=2.65 and h=2.5mm). The backed continuous metallic ground enables it to be a complete reflection scheme. Each composite metallic pattern contains an external wire loop and an inner cross which resonate at different frequencies. As depicted in Fig. 3(b), the meta-atom with single-layer aforementioned composite manifests dual reflection dips, corresponding to two magnetic modes generated by the couplings between cross/loop and the metallic ground. However, interlayer couplings between different layers split the two resonances into four when adding another composite to form a double-layer meta-atom. Such multi-resonant behavior is the key factor for multi-band diffusion in this work and affords us more freedoms to engineer the phase slope. Moreover, it has been demonstrated that the varied geometrical parameters which are sensitive to σ_1-polarized EM wave affect substantially the gradients $\xi_x(\sigma_1)$ and $\xi_y(\sigma_1)$ but possess eliminated effects on $\xi_x(\sigma_2)$ and $\xi_y(\sigma_2)$ [10], here the subscript x/y denotes the gradient direction. Such exciting feature makes it possible to accurately realize four gradients simultaneously which are necessary to arbitrarily control the scattering behavior.

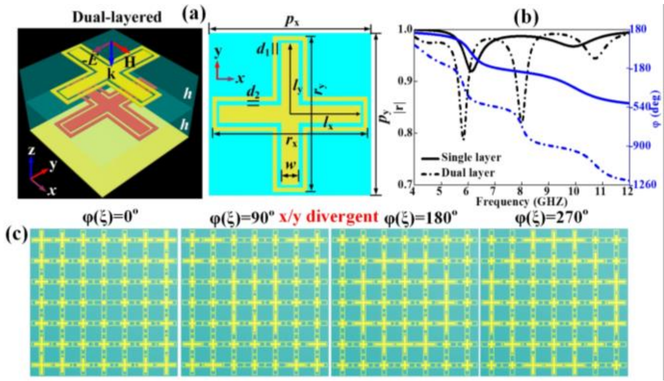

Fig. 3. Illustration of the anisotropic dual-layer meta-atom and corresponding parabolic-phased subarray. (a) Layout of the meta-atom. (b) Numerically calculated reflection coefficients of the meta-atom with geometrical parameters of $p_x=p_y=8.3$, $r_x=r_y=8.1$, $l_x=l_y=3.65$, $d_1=d_2=0.25$ and w=1 mm, and unit cell boundary to mimic an infinite array. (c) Layouts of different subarrays with x/y divergent, x/y convergent and composite x-divergent/y-convergent parabolic phase.

With basic meta-atom and phase profile determined, it is easy to determine the layouts of different subarrays by varying lx and ly based on root-finding algorithm, see Fig. 3(c). Therein, using these subarrays we can synthesize any metasurface with specific diffusion according to its coding sequence. In this particular design each metasufface contains a total of 35×35 basic meta-atoms and accommodates an overall size of 290.5×290.5 mm^2. All coding sequences are randomly generated without optimizations to demonstrate the general scattering behavior. To engineer a multi-spectrum stealth behavior, we synthesize the subarrays and metasurfaces at f_2=9.8 GHz (third resonance) such that they still exhibit desirable parabolic phase gradient around f_1=5.8 (second resonance) and f_3=12.8 GHz (fourth resonance). By changing lx or ly within 0.5~3.65 mm, these resonances are consistently shifted and thus the reflection phases are altered accordingly. During this process, the reflection magnitude remains stable while the reflection phases are almost parallel and linear around f_1, f_2 and f_3. This is the key reason that we can concentrate on phase design at f_2, while that at f_1 and f_3 are automatically fulfilled. To integrate the function of radio vortex beam carrying orbital angular momentum for bifunctional devices, spiral phase with $\exp(-il\varphi)$ is necessary to combine with the parabolic one in either polarization channel, whereas l=2 is the topological charges of vortices. Additional phase $\varphi(m,n) = \frac{2\pi}{\lambda}(\sqrt{(mp)^2 + (np)^2 + F^2} - F)$ with F=200 mm is deducted from above spiral phase by compensating different optical path from the feed to metasurface.

Fig.4(a) illustrates the fabricated prototype of the metasurface with different global coding sequences in x and y-polarized channel. As can be seen from Fig. 4(b), the RCS reduction is obviously observed at three bands around 5.85, 9.8 and 12.9 GHz in dual polarization channels, whereas the dip value is obtained as -10.1, -17.7 and -18.1 dB for X polarization while is as -12, -17.8 and -18.8 dB for Y polarization. From Fig. 4(c), it is learned that E- and H-plane scattering energy in both cases is re-distributed toward innumerable directions at three operation bands, coinciding well with the numerical results. The similar scattering behavior in dual channels further reveals our strategy is immune to the coding sequence.

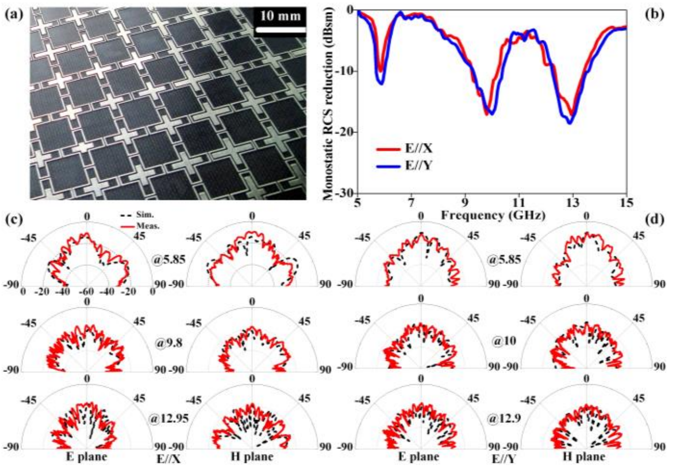

Fig. 4. Measured scattering behavior of the 2-bit parabolic-phased coding metasurface. (a) Photograph of the fabricated sample. (b) Monostatic RCS reduction. E- and H-plane scattering patterns under (c) x and (d) y polarization.

The versatile functionality of our bifunctional metasurface is verified by experimentally characterizing the fabricated prototype shown in Fig. 5(a). Again, in both cases three backscatter dips are clearly inspected around 6, 9.7 and 12.9 GHz, see Fig. 5(b). The RCS reduction is measured as -10.11, -17.8 and -22.4 dB for X polarization while is -14.5, -20.5 and -23.88 dB under Y polarization, which are in good consistency with the numerical ones, i.e., -10.1, -16.8, -15.7 dB and -10.56, -17.7, -19.34 dB for X and Y polarization, respectively. Nevertheless, the scattering behavior in above dual channels is completely different. In former case, it manifests diffusion scattering patterns while in latter case vortex patterns are generated with a null at the normal, see Fig. 5(c) and 5(d). The realized full diffusion behavior and desirable vortex beam indicates effectiveness and eliminated cross-talking of our method.

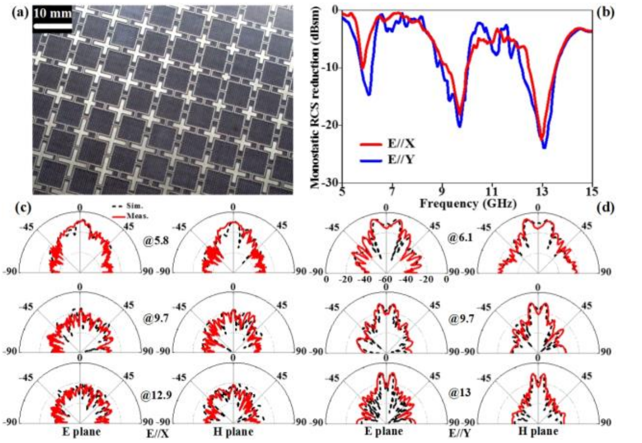

Fig.5. Measured scattering behavior of the bifunctional metasurface. (a) Photograph of the fabricated sample. (b) Monostatic RCS reduction. E- and H-plane scattering patterns under (c) x and (d) y polarization.

III. CONCLUSIONS

To sum up, we have established while also numerically and experimentally validated a determinant approach for diffusion in multi frequency spectrum and wide angle. By arranging the parabolic-phased subarrays in arbitrary coding sequence, the scattering energy can be distributed more uniformly without optimizations. For verification, two proof-of-concept devices are realized at microwave regime: a dual-polarized invisible device and a bifunctional device of combined invisibility and vortex. In all cases, elegant RCS reductions are achieved in three well-separated operation bands and are robust against the coding bits and sequences. Our approach with versatile scattering behavior in multi-spectrum promises great perspective in smart defense applications, and also opens up a fascinating opportunity for dynamic scattering in subarray level.

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