Conformal Anisotropic Metasurfaces for Controlling Scattering, Guidance, and Radiation of Electromagentic Waves

Zhi Hao Jiang(1) and Douglas H. Werner(2)
(1) State Key Laboratory of Millimeter Waves, School of Information Science and Engineering, Southeast University, Nanjing, 210096, P.R. China.
(2) Electrical Engineering Department, The Pennsylvania State University, University Park, PA 16802, USA
zhihao.jiang@seu.edu.cn, dhw@psu.edu

Abstract

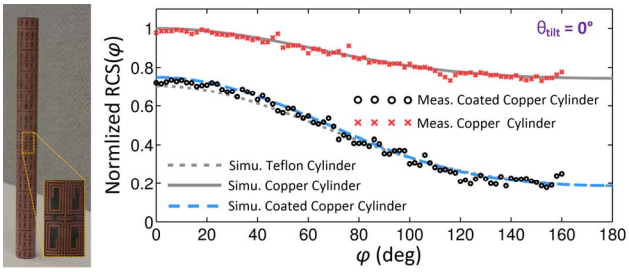
In this paper, we provide a summary of recent progress on the research on conformal anisotropic metasurfaces and their applications in controlling the scattering, guidance, and radiation of electromagnetic waves. Specifically, several illustrative examples of microwave applications are presented, including coatings for scattering signature manipulation, coatings for dielectric chiral waveguides with highly-confined modes, as well as substrates for compact and flexible wearable antennas. By offering a conformal and ultrathin platform, the flexible metasurfaces with tailored anisotropy in their building blocks will open up new venues for achieving novel physical wave phenomena and improving performance metrics of conventional devices.

1. Introduction

As the two-dimensional counterparts of three-dimensional metamaterials, metasurfaces have garnered a tremendous amount of research interest over the past few years, owing to their capability of providing unprecedented freedom in controlling electromagnetic waves [1, 2]. These structured surfaces have a thickness of only one meta-atom, thereby offering a unique platform that is fully-planarized and low-loss [3]. By engineering the electromagnetic response of the sub-wavelength building blocks of metasurfaces, including their dispersion and anisotropy, and cascading different metasurface layers while maintaining a sub-wavelength total thickness, a plethora of wave manipulation components can be devised that exhibit novel physical properties. So far, a number of interesting wave phenomena enabled by metasurfaces have been demonstrated from microwave frequencies to visible wavelengths, such as anomalous refraction [4] and reflection [5], photonic spin Hall effect [6], vector Bessel beam generation [7], diffusion-like scattering reduction [8], broadband polarization control [9], and so on. Moreover, these metasurfaces, when properly integrated with conventional electromagnetic components, can facilitate the development of advanced devices with previously unattainable functionalities or enhanced performance [10-13]. In this paper, we present a summary of research efforts on conformal anisotropic metasurfaces for applications ranging from scattering control coatings, dielectric waveguide coatings for mode confinement and chirality, to highly efficient compact wearable antennas with anisotropic artificial substrates.

2. Coatings for Scattering Signature Control

By exploiting the anisotropy of conformal metasurfaces, the scattering signature of an object can be modified based on the scattering cancellation technique. As an extension of the mantle cloak, which is comprised of an isotropic impedance surface [14], the anisotropic metasurface cloak with a non-vanishing radial magnetic response is capable of achieving scattering reduction for an object with a size beyond the quasi-static limit [15]. In addition to scattering reduction, a single-layer conformal anisotropic metasurface can also be employed to tailor the scattering signature of an object to mimic that of another pre-defined object, thereby achieving electromagnetic illusion [16]. As presented in Fig. 1, a single-layer metasurface coating comprised by an array of I-shaped dipoles and spiral resonators can be used to make the radar cross section of a copper cylinder appear similar to that of a dielectric (Teflon) cylinder. This indicates that not only the magnitude of the scattered fields but also their angular distribution can be controlled.

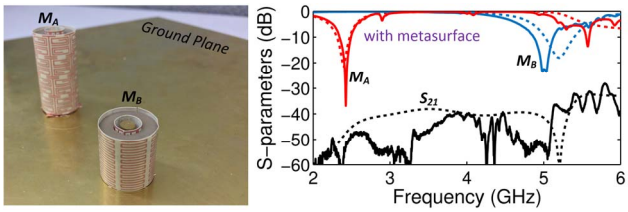


(a) (b)

Figure 1. (a) Photograph of the metasurface illusion coating. (b) Simulated and measured radar cross section at 2.5 GHz.

Applying such a concept in antenna engineering, the coatings can be utilized to achieve simultaneous suppression of mutual coupling and scattering-induced radiation pattern distortion of antennas. Such a goal is realized by introducing an additional metasurface layer with bandpass filtering functionality into the original

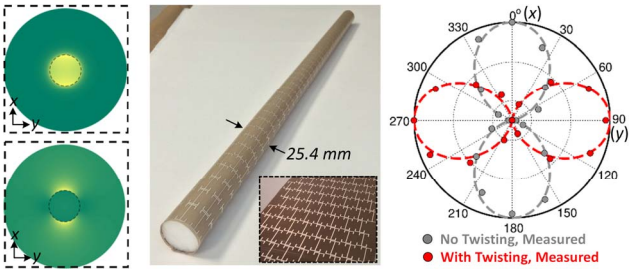
scattering reduction coating [17]. As shown in Fig. 2, two practical monopole antennas M_A and M_B, operating at 2.4 and 5.2 GHz, respectively, are considered. The conformal metasurface coating around monopole M_A appears to be transparent at 2.4 GHz while providing the cloaking effect at 5.2 GHz, and vice versa for the coating around monopole M_B. In such a way, each of the two monopoles will not "see" the other one in its own operational band, thereby maintaining its original radiation pattern. The filtering metasurface layer around each monopole is transparent at the operational band of the coated monopole and opaque at the operational band of the other monopole, thus significantly reducing the mutual coupling between the two antennas. By further incorporating additional metasurface layers into the coating while maintaining a sub-wavelength total thickness, multi-spectral functionality in the coatings can be achieved [18].



(a) (b)

Figure 2. (a) Photograph of two monopole antennas with dual-layer metasurface coatings. (b) Simulated and measured scattering parameters.

3. Coatings for Dielectric Waveguides



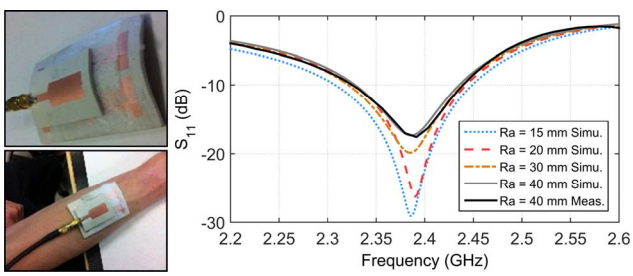
(a) (b) (c)

Figure 3. (a) Power distributions in the transverse plane for the Teflon rod waveguide with (top) and without (bottom) the metasurface coating. (b) Photograph of the Teflon rod waveguide coated by the twisting metasurface. (c) Measured SOP pattern for the coated waveguide with and without twisting perturbation in the metasurface.

Dielectric waveguides are fundamental building blocks for various microwave, millimeter wave and photonic systems, due to their extremely low loss. However, when using a low dielectric constant material for reducing the component weight, the associated poor mode confinement hampers the ability for dense deployment of low-index dielectric waveguides. Conformal anisotropic metasurface coatings provide an ultrathin, lightweight, and low-loss solution to greatly enhance the confinement of the most commonly utilized hybrid mode, *i.e.* the HE_{11} mode, in a dielectric waveguide. By controlling the tangential (along the φ direction) and longitudinal (along the z direction) responses of the metasurface, the dispersion of the HE_{11} mode can be tailored to enable a highly confined mode profile. As shown in Fig. 3(a), for a Teflon rod waveguide with a radius of 12.7 mm, the power distribution in the transverse plane at 3.4 GHz with and without the anisotropic metasurface coating are compared. It can be seen that, with the presence of the metasurface, the majority of the power is concentrated inside the rod, which is dramatically different from the case of the rod alone. The mode area, *i.e.* the cross sectional area encompassing 90% of the power, reduces from $39.4\lambda_0^2$ to $0.18\lambda_0^2$ when the metasurface is present. By using an array of capacitively coupled dipoles to implement the desired anisotropic surface impedance, it was found that an improved mode confinement can be supported within a broad bandwidth of more than 40%.

Moreover, by introducing a helical perturbation into the adjacent unit cells in the longitudinal z direction, *i.e.* the discrete unit cells of the metasurfaces are twisted (see Fig. 3(b)), a broadband optical activity can be achieved, thereby forming a chirowaveguide. This is distinct from previously reported methods where the optical activity was obtained by twisting the entire waveguide around a virtual external axis [19] or by incorporating bulky three-dimensional chiral materials [20]. The polarization rotation effect was experimentally verified by recording the transmission between two matched short dipoles placed at the two ends of a fabricated metasurface-coated Teflon rod waveguide. Specifically, the transmitting dipole was polarized along the x direction while the receiving dipole was rotated around the z axis. The measured patterns indicating the state-of-polarization (SOP) at 3.45 GHz for the coated waveguide with and without a twisting perturbation in the metasurface are displayed in Fig. 3(c). It can be seen that for both cases, linear polarization of the mode is well-maintained, as manifested by the "figure 8" shaped SOP patterns. The presence of a twisting perturbation of the metasurface unit cells induces a polarization rotation with a rotation angle of nearly 90°, indicating that the oscillation plane of the electric field is transformed from the x-z plane to y-z plane as the wave is transmitted through the metasurface-coated waveguide. It was further confirmed that such a frequency-dependent optical activity was obtained within a bandwidth of more than 50% (not shown here).

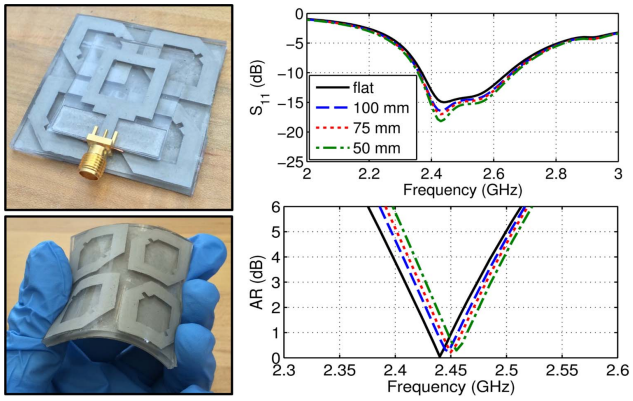
4. Artificial Substrates for Compact Wearable Antennas



(a) (b)

Figure 4. (a) Photographs of a metasurface-enabled linearly-polarized wearable antenna. (b) Simulated and measured S_{11} of the antenna deformed with different radii of curvature (R_a).

In addition to flexible coatings for scattering signature control and mode manipulation of a dielectric waveguide, conformal anisotropic metasurfaces can be utilized as custom engineered substrates in the design of compact wearable antennas. By exploiting the inter-element coupling, the metasurface can be highly truncated to enable a compact footprint. In such a case, instead of using a single resonator of about a half wavelength, the aperture is divided into a few small unit cells, thereby greatly improving the performance robustness of the antenna under structural deformation and human body loading. Furthermore, such a design strategy can be employed to realize robust wearable antennas with either linearly-polarized or circularly-polarized radiation.



(a) (b)

Figure 5. (a) Photographs of a metasurface-enabled circularly-polarized wearable antenna. (b) Simulated S_{11} (top) and axial ratio (bottom) of the antenna deformed with different radii of curvature.

As shown in Fig. 4(a), the linearly-polarized integrated antenna, operating at around 2.4 GHz, consists of a linearly-polarized planar monopole antenna on top and a strongly truncated metasurface-based artificial ground on the bottom. The anisotropic metasurface contains an array of only 2 by 2 capacitively coupled I-shaped short dipoles, possessing an inductive response within the band of interest [21]. The overall footprint of the antenna is only $0.15\lambda_0^2$ while the total thickness is around $0.03\lambda_0$. Here, the metasurface not only functions as a reflector, but also serves as the radiator where the slots at the two ends of the I-shaped elements form an array of three magnetic current sources with tapered amplitudes. As a result, the S_{11} of the integrated antenna remains nearly unchanged when it is bent, as revealed in Fig. 4(b). Importantly, the metasurface provides a very small back radiation, making the antenna an ideal candidate for narrowband wearable applications. In order to generate circularly-polarized radiation, a 2 by 2 array of loop resonators with a pair of corners truncated were used to construct the metasurface, giving rise to a super wide axial ratio beamwidth of more than 180°. The integrated antenna, with an overall footprint of $0.16\,\lambda_0^2$ and a thickness of about $0.045\lambda_0$, was implemented using a polydimethylsiloxane (PDMS) and silver nanowire composite material system, yielding a highly-flexible and efficient device (see Fig. 5(a)). Both the S_{11} and axial ratio of the integrated antenna show very robust properties under structural bending (see Fig. 5(b)), which is superior to a conventional circularly-polarized patch antenna of the same size. As the same time, a gain reduction of less than 0.5 dB was achieved when the antenna is bent, while maintaining a radiation efficiency of more than 75%.

5. Conclusions

We have presented a summary of recent progress on the applications of conformal anisotropic metasurfaces for controlling the scattering, guidance, and radiation properties of electromagnetic waves. Several illustrative examples were discussed, including scattering signature control coatings, dielectric waveguide coatings, and compact wearable antenna with artificial substrates. Conformal metasurfaces with complex electromagnetic responses hold great promise for enabling advanced electromagnetic wave manipulation as well as future high-performance electromagnetic devices.

6. Acknowledgement

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7. References

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