Coated Metasurfaces for Decoupling and Cloaking of Rectangular Patch Antennas

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***Abstract*—In this paper, we apply the concept of electromagnetic cloaking in order to reduce the mutual coupling between two rectangular patch antennas placed very close to each other (sub-wavelength separation). In particular, we show that by coating the top surfaces of the patch antennas with suitably patterned metasurfaces, it is possible to make each patch antenna electromagnetically *invisible* to the other antenna. Along with this, it is also shown that the individual radiation characteristics of each antenna is restored, as if they were isolated. The decoupling and cloaking action of the metasurfaces are demonstrated by various full-wave numerical simulation results. The novelty of our design lies in the fact that these specific metasurfaces accomplish cloaking of an electrically large surface (length equal to half of the wavelength within dielectric medium).**

Keywords—coated metasurfaces; patch antennas; cloaking; reduction of mutual coupling

I. Introduction

In the recent years, immense efforts have been devoted to achieving the phenomenon of electromagnetic invisibility and various methodologies have already been reported including transformation optics, transmission-line networks, plasmonic cloaking, among others. These techniques rely on the use of bulky volumetric metamaterials and might prove inconvenient for antenna applications with limited space availability. In this regard, the concept of mantle cloaking was introduced, which utilizes an ultra-thin metasurface to create anti-phase surface currents that results in suppression of the dominant scattering mode of the object to be cloaked [1]. For various practical functionalities such as MIMO, mobile communications, radar detection, etc., design engineers are keen on developing compact antenna configurations. However, crowding antennas in a small space leads to degradation in individual antenna performance. As a possible solution to this scenario, the mantle cloaking method has been used to curb the electromagnetic interaction between neighboring antennas [2]. It is seen that the metasurface cloaks not only suppress the mutual coupling but also restore the radiation properties of the antennas. Recently, this approach has been utilized to achieve cloaking of printed monopole antennas [3] and for cloaking of 1D and 2D microstrip dipole arrays [4]. The idea was further extended to decoupling and cloaking of slot antennas [5]. Very recently, a novel cloaking technique for bow-tie antenna and its array configurations was put forth, wherein the surface of the bow-tie antennas are coated with specifically engineered metasurfaces to make the coupling robust within closely arranged neighboring antennas.

Motivated by the design methodology in [6], we present a cloaking structure for the rectangular patch antennas in this paper. Here, the cloaking and decoupling effects are established for the patch antennas placed in close vicinity. Accordingly, we have investigated two patch antennas, namely Patch I and Patch II, designed to operate at gigahertz (GHz) frequencies (C-Band frequencies are targeted for 5G applications). We demonstrate that when the top surface of each patch antenna is coated by the specially tailored metasurface (Fig. 1), they are decoupled from each other and at the same time, their radiation patterns are restored as if they were radiating independently. The uniqueness of our cloak structure stems from the fact that it facilitates cloaking of an electrically large antenna surface (in this case, resonant length is equal to half of the wavelength within dielectric medium). The design procedure and all the numerical full-wave simulations presented in this paper are obtained with the CST Microwave Studio.

II. Coated Metasurfaces for Cloaking of Patch Antennas

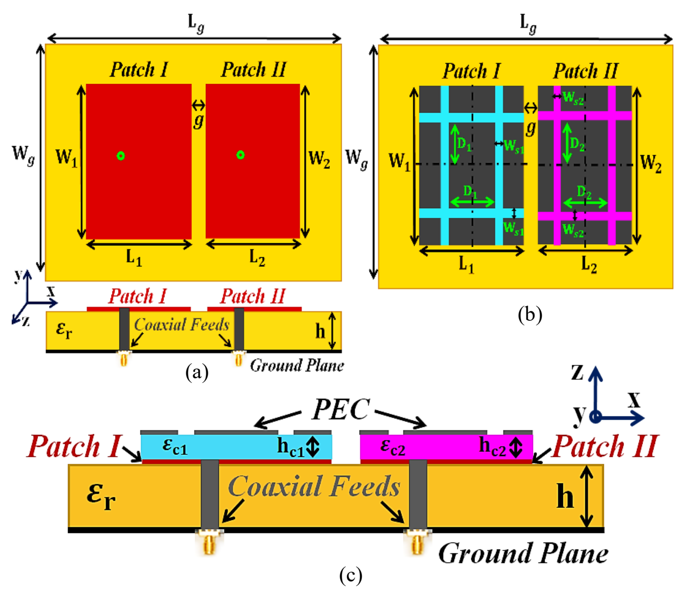
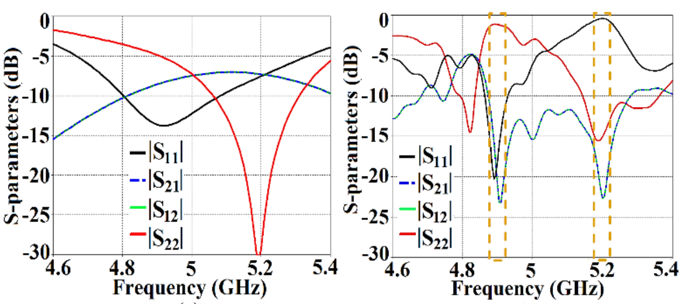


Figure 1. (a) Top-view and side-view of uncloaked patch antennas, (b) Top-view and (c) side-view of cloaked patch antennas.

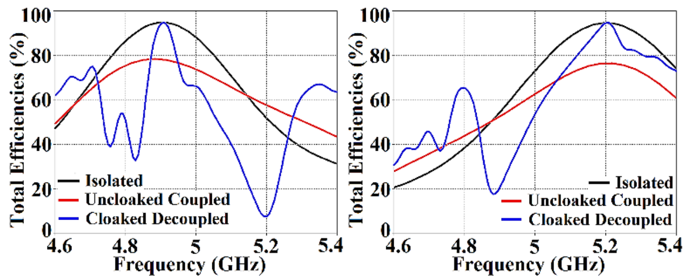
Simple, coaxially fed patch antenna configurations are taken into account with Patch I and II operating at frequencies $f_1 =$ 4.9 GHz and $f_2 = 5.2$ GHz, respectively. All the geometrical dimensions shown in this paper are measured in mm. These patch antennas are embedded on a dielectric substrate (length $L_g = 57.55$ and width $W_g = 43$) with height $h = 1.8$ and dielectric permittivity $\varepsilon_r = 2.2$, backed by a ground plane (see Fig. 1-(a)). The two antennas are separated by a sub-wavelength distance of $g = 2$ ($\approx 0.048\,\lambda_1$, where λ_1 is the wavelength corresponding to frequency f_1 within the dielectric medium). The parameters characterizing the uncloaked patch antennas are: $L_1 = 18$, $W_1 = 23$, $L_2 = 17.55$, and $W_2 = 23$. As is typical, the close proximity of the antennas causes a mutual interference in the near-field as well as the far-field, thereby deteriorating the matching and radiation properties of both the patch antennas. Now, we attempt to minimize the detrimental effects of mutual coupling by implementing the metasurface structures as shown in Fig. 1. The top surface of each patch antenna is first coated with a supporting dielectric material (permittivity $\varepsilon_{c1} = 15.15$ and $\varepsilon_{c2} = 16.71$, with heights $h_{c1} = 1$ and $h_{c2} = 0.9$, for Patch I and II, respectively). A PEC patch is then placed directly on each of the dielectric substrates, with thin slots cut on its surface (slot widths are $w_{s1} = w_{s2} = 0.75$ and spacing between the slots are $D_1 = 8.55$ and $D_2 = 8.25$). The optimum values for each of these parameters was found by conducting extensive parametric analysis (i.e., varying one parameter within the ranges while keeping the other parameters constant). The use of these metasurfaces leads to a considerable reduction in the mutual coupling (validated by the S-parameter plots in Fig. 2), thereby decoupling the slot antennas at the desired frequencies.



(a) (b)

Figure 2. S-parameter plots for (a) uncloaked coupled, (b) cloaked decoupled patch antennas

From Fig. 2(a), it is evident that the mutual coupling is very high (i.e., $|S_{12}| = |S_{21}| > -10$), whereas from Fig. 2(b), a substantial decrement (more than 10 dB) in $|S_{12}|$ and $|S_{21}|$ is noted at both the frequencies f_1 and f_2 (highlighted by the dashed yellow sections). Next, we present a comparison of the total efficiencies plots in Fig. 3(a) for Patch I ($f_1 = 4.9$ GHz) and for Patch II ($f_2 = 5.2$ GHz) in Fig. 3(b). The total efficiency is calculated as: $\eta_{\text{total}} = (1 - |\Gamma|^2)\eta$, where η_{total} is the total efficiency, Γ is the reflection coefficient (S_{11} or S_{22}) and η is the radiation efficiency for the respective patch antennas. It is manifested in these plots that the total efficiency of one patch antenna reduces significantly at the resonance frequency of the other, whereas remains unaffected at its resonating frequency. We should mention here that the patterned metasurfaces do not perturb the radiation aspects of the patch antenna on which it is coated; rather its effect is apparent at the frequency of the other patch antenna in its vicinity. The electric field (E-field) distributions shown in Fig. 4 and the polar plots in Fig. 5 further substantiate this claim. We show the cross-sectional view of the E-field contours for the patch antennas in Fig. 4. The uncloaked and cloaked E-fields for Patch I are presented in Fig. 4(a) and (b), respectively. (Here Patch I is kept active, whereas Patch II is inactive). Similarly, Fig. 4(c) and (d) correspond to the uncloaked and cloaked cases, respectively, when Patch II is excited, keeping Patch I inactive.



(a) (b)

Figure 3. Total Efficiencies plots for (a) Patch I ($f_1 = 4.9$ GHz) and (b) Patch II ($f_1 = 5.2$ GHz).

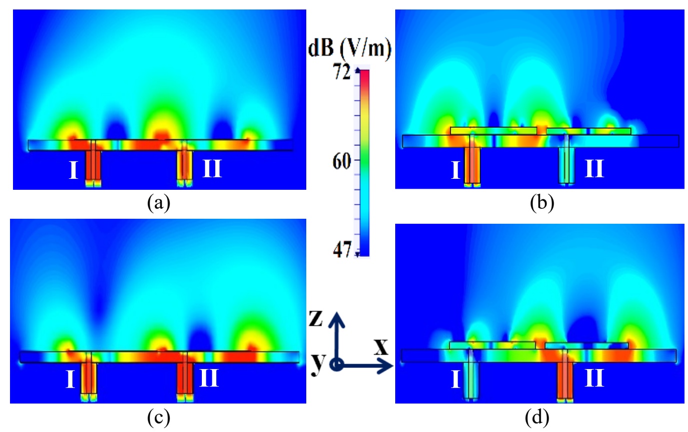


Figure 4. E-field distributions for, (a) Uncloaked coupled, (b) Cloaked decoupled, when Patch I is active, (c) Uncloaked coupled and (d) Cloaked decoupled, when Patch II is active.

Consider Fig. 4(a), (only Patch I is active) the presence of mutual coupling is demonstrated for the uncloaked case, where it is clearly seen that power is coupled from the input port of Patch I (Port I) to the neighboring Port II (indicated by a high concentration of fields, shown by red color, in the region of Port II). However, when the metasurfaces are employed, they evidently reduce the E-field interaction between the patches (cloaked case, see Fig. 4 (b)) in the sense that the power coupling from Port I is negligible at the input port of Patch II (Port II), illustrating the decoupling effect of the metasurface. Similar observations can be made from Fig. 4 (c) and (d), where Patch II is active and Patch I is kept passive. We finally present the polar plots in Fig. 5 for the realized gain of the patch antennas, at $\varphi = 0^\circ$ and $\theta = 90^\circ$ (XOZ and YOZ planes respectively, for our structure) reference planes. The realized gain of each patch antenna in its isolated scenario is around 7.5 dBi. However, when the antennas are placed close to each other (uncloaked coupled case), it leads to the distortion in the gain patterns for both Patch I and Patch II (observe the solid red curves in Fig. 5).

Nevertheless, for the cloaked decoupled case (shown by solid blue curves), it is apparent that the engineered cloaks faithfully rehabilitate the realized gain patterns for both the patches, at both planes of reference. It was observed that the restoration of the gain patterns is even better when the separation 'g' between the patch antennas is increased.

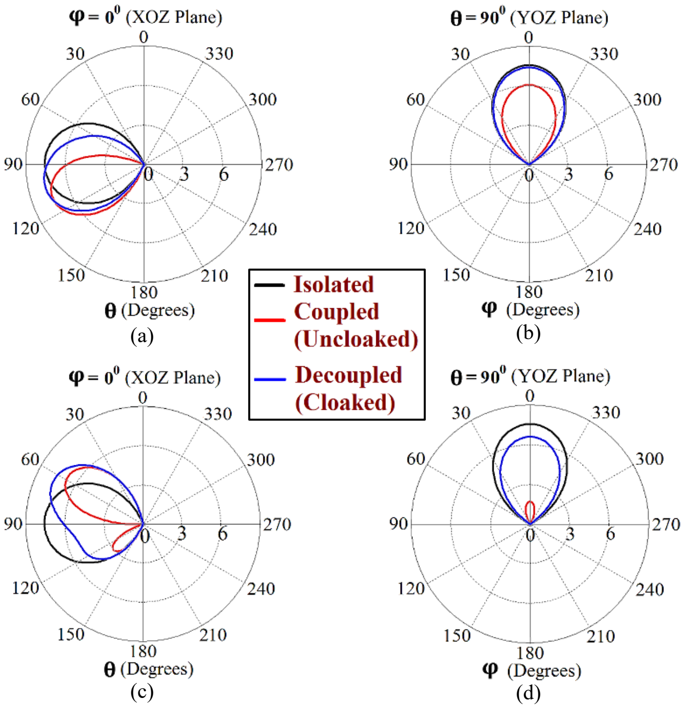


Figure 5. Polar plots at (a) $\varphi = 0^{\circ}$, (b) $\theta = 90^{\circ}$ for Patch I ($f_1 = 4.9$ GHz) and at (c) $\varphi = 0^{\circ}$, (d) $\theta = 90^{\circ}$ for Patch II ($f_2 = 5.2$ GHz).

III. CONCLUSION

We propose a unique cloak structure in order to decouple two patch antennas, placed very close to each other (subwavelength separation), and to recover their matching properties and restore their radiation characteristics. The numerous simulation results presented in the paper corroborate the fact that by coating the top surface of each patch antenna with their respective metasurfaces, it is possible to eliminate the mutual coupling between the antennas and additionally, the radiation properties of the patch antennas are also reinstated in a manner that emulates an isolated operation of each antenna. It is our understanding that this design has a potential to facilitate densely packed patch antenna and array systems with improved performance and high efficiency.

ACKNOWLEDGMENT

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