Consistent Integral Equation Modeling of Cloaking Planar Microstrip Antennas

Athanasios N. Papadimopoulos[1], Nikolaos L. Tsitsas[2], Constantinos A. Valagiannopoulos[3], Nikolaos V. Kantartzis[1], Christos S. Antonopoulos[1], and Theodoros D. Tsiboukis[1]

[1]Dept. of Electrical & Computer Eng., Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece, tsibukis@auth.gr
[2]Dept. of Informatics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece, ntsitsas@csd.auth.gr
[3]Dept. of Radio Science & Eng., Aalto University, 00076 Aalto, Finland, konstantinos.valagiannopoulos@aalto.fi

In this paper, an efficient integral equation methodology is developed in order to compute the response and scattering characteristics of cloaked two-dimensional planar microstrip antennas. The featured technique combines the expressions of the Green's function for the strip-free structure, the decomposition of the strip into cylindrical thin wires, and the radiation integral algorithm for the evaluation of the scattered field. In essence, the desired cloaking and low-profile operation of the receiving antenna are achieved by overlaying a superstrate slab atop of the antenna. To this objective, the electric and magnetic constitutive parameters together with the thickness of the slab are appropriately determined so that an optimally-reduced scattering performance is obtained, as verified by the corresponding computational results.

***Index Terms*—Computational electromagnetics, electromagnetic metamaterials, integral equations, microstrip antennas, cloaking.**

I. Introduction

Several advantageous attributes of microstrip antennas, such as light weight, integration into microwave circuits as well as low-cost and ease of fabrication, compared to common elements, have led to their broad use in modern communication systems [1]-[3]. Also, potential traits, like low-profile operation and limited electromagnetic interaction with nearby components, have attracted serious interest, both from a theoretical and practical perspective [4], [5]. Mainly hiding the electromagnetic presence of a device from its environment or cloaking it, without affecting its reception competence, has launched impressive challenges in terms of prototype material evolution and modeling schemes [6], [7].

Based on the prior aspects, in this paper, a rigorous integral equation method is developed for the efficient computation of the scattered field from a cloaked planar microstrip antenna with a perfectly electric conducting (PEC) strip and infinite 2-D slabs. The systematic algorithm blends the appropriately determined Green's functions with the radiation integral technique. For the current flowing on the PEC strip, required by the latter approach, it is assumed that the strip consists of an adequately large number of thin cylindrical PEC wires. Thus, the current in each wire can be presumed constant. Then, by imposing PEC boundary conditions on the surface of the wires and utilizing a thin-wire approximation, a linear system of equations for the unknown current values is obtained. In this way, the total field in the region above the antenna along with its far-field response are acquired. To effectively reduce the scattered field of the antenna, while retaining its reception to a satisfactory level, a superstrate is placed atop the structure. A key asset of the algorithm is its capability to rapidly and precisely evaluate electromagnetic fields for arbitrary dimensions and constitutive parameters, as the expressions of the above current coefficients include these values as inputs.

II. Development of the Combined Methodology

Let us consider the antenna configuration of Fig. 1, where the PEC strip width is $2w$ and the radius of each thin cylindrical wire is r. Also, the angle of incidence of the impinging electromagnetic z-polarized plane wave is φ_i. Firstly, we derive the induced electric and magnetic field expressions of the homogenous strip-free structure, since they are required for the formulation of our methodology. In this context, the induced transmitted electric field in the substrate (region 2) with $\varepsilon_2 = \varepsilon_{r2}\varepsilon_0$ and $\mu_2 = \mu_{r2}\mu_0$ is given by

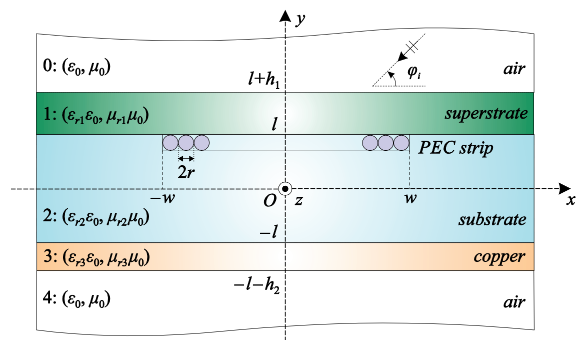

Fig. 1. Geometrical depiction of the cloaked planar microstrip antenna.

$$\mathbf{E}_2^{\text{ind}}(x,y) = \left[A_1 e^{jy\sqrt{k_2^2-(k_0\cos\varphi_i)^2}} + A_2 e^{-jy\sqrt{k_2^2-(k_0\cos\varphi_i)^2}} \right] e^{jxk_0\sin\varphi_i}\,\hat{\mathbf{z}}\,, \quad (1)$$

where k_n is the wave number in the n-th region and A_1, A_2 constant coefficients that depend on angle φ_i as well as the constitutive parameters and dimensions of every layer. Obviously, similar formulas can be derived for every slab region. Furthermore, for our scheme, the Green's function expressions for the strip-free configuration of Fig. 1 should be obtained. To this aim, we apply the Sommerfeld method, with the excitation located inside region 2, where the strip would be present. Hence, and after the proper mathematical analysis, the secondary part of the desired Green's function is found to be

$$G_2^{\text{sec}}(x,y) = \frac{1}{4\pi}\int_{-\infty}^{+\infty}\Big\{ B_1\cosh\left[(y+l)(\beta^2-k_2^2)^{1/2}\right] + B_2\sinh\left[(y+l)(\beta^2-k_2^2)^{1/2}\right]\Big\} e^{-j\beta(x-x')}d\beta\,, \quad (2)$$

where (x', y') indicates the position of the Green's function current source, while $B_1(\beta, y')$ and $B_2(\beta, y')$ are, again, constant coefficients that depend on the constitutive parameters, the size of every layer, and the relative position of the excitation with regard to each layer.

Next, the PEC strip is decomposed into a suitably large number of cylindrical thin wires N [5], as in Fig. 1. The surface current on each wire is considered to be constant and, thus, by applying the radiation integral method [8], the expression for the scattered electric field in the substrate can be written as

$$\mathbf{E}_2^{\text{scat}}(x,y) = -j\omega\mu_0 \sum_{n=1}^{N} J_n \int_{C_n} \left[G_2^{\text{pr}}(x,y) + G_2^{\text{sec}}(x,y) \right] dS \,, \quad (3)$$

for J_n the current coefficient of the n-th thin wire, C_n the surface of the corresponding wire where integration is performed, and $G_2^{\text{pr}}(x,y)$ the primary part of Green's function in region 2.

Having derived the scattered field, we apply the PEC boundary conditions on the surfaces of the thin wires, which, for $N \to \infty$, are assumed to coincide with their centers. This implies that when N is large, the wires' radii tend to zero and, consequently, the preceding conventions and approximations are very accurate. So, the resulting $N \times N$ linear system has the subsequent form

$$j\omega\mu_0 \sum_{n=1}^{N} J_n \int_{C_n} \left[G_2^{\text{pr}}(x,y) + G_2^{\text{sec}}(x,y) \right] dS = E_2^{\text{ind}}(x_m, l-r) \,, \quad (4)$$

with l the half-length of the substrate and $(x_m, l-r)$ the Cartesian coordinates of the center of the m-th wire. The first term in (4) is calculated through typical integration techniques, whereas the second term may be further simplified via the Pocklington approximation for thin wires, which yields

$$\int_{C_m} G_2^{\text{sec}}(x,y) dS \approx 2\pi r G_2^{\text{sec}}(x_m, l-r) \,. \quad (5)$$

Thus, the scattered electric field in the region 0 (air) becomes

$$\mathbf{E}_0^{\text{scat}}(x,y) = -j\omega\mu_0 2\pi r \sum_{n=1}^{N} J_n G_0^{\text{sec}}(x,y) \,, \quad (6)$$

where $G_0^{\text{sec}}(x,y)$ stands for the secondary part of the free-space (region 0) Green's function. Finally, from (6), the far-field response of the microstrip antenna can be precisely resolved.

III. Cloaking Process – Numerical results

In order to enhance the antenna's low-profile operation, a cloaking process is proposed by overlaying a superstrate slab (Fig 1). The selection of its constitutive parameters and length is based on the optimized concealing of the antenna strip, without seriously reducing the level of the received signal. In particular, numerical studies revealed that such an operation can be achieved via media, whose relative permittivity or permeability is below unity or equivalently through a thin slab comprising a low-index metamaterial.

Proceeding with our computational simulations, we consider an FR4 substrate ($\varepsilon_{r2} = 4.2 - j0.084$; thickness: $2l = 5$ mm) and a copper slab ($\varepsilon_{r3} = 2.8 - j5.96\times10^7$; thickness: $h_2 = 35$ μm), while for the cloaking a metamaterial superstrate ($\varepsilon_{r1} = 5.5$; $\mu_{r1} = 0.26$; thickness: $h_1 = 7.5$ mm). Moreover, the width of the strip is $2w = 1$ cm, its thickness $2r = 161.29$ μm, and the number of PEC cylindrical wires $N = 31$. It should be mentioned that the resulting linear system of equations (4) is diagonally dominant and, hence, satisfactory numerical convergence can be accomplished, even for relatively small N. Finally, the incidence angle is set to $\varphi_i = 45^\text{o}$.

In this framework, the scattered far-field of the planar microstrip antenna is presented in Fig. 2 for two cases, namely, in the presence and absence of the metamaterial superstrate slab. The operating frequency is $f = 8$ GHz, whereas for a reliable far-field calculation the sufficiently large radius of $\rho_0 = 10\lambda$ (with λ the respective wavelength) has been chosen. As, readily, observed, the incorporation of the superstrate slab leads to a very significant reduction of the scattered field for all azimuthal angles φ. Therefore, the specific outcome proves the modeling efficiency

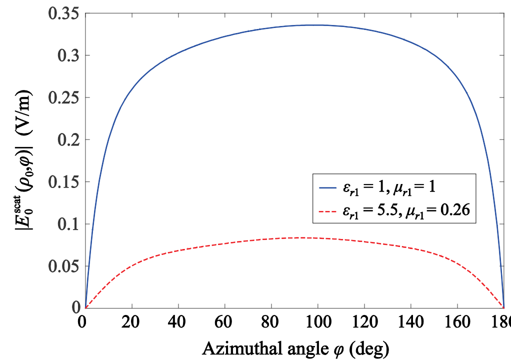

Fig. 2. Scattered far-field versus angle φ for the planar microstrip antenna.

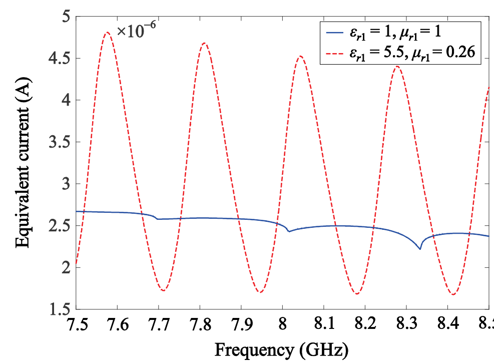

Fig. 3. Equivalent current versus frequency for the planar microstrip antenna.

of the proposed methodology in the analysis of this demanding scenario, without any non-physical assumptions.

Then, the equivalent current K, which is proportional to the received voltage and an indicator of the signal strength, defined as

$$K = \frac{2\pi r}{N} \sum_{n=1}^{N} |J_n| \,, \quad (7)$$

is evaluated for the spectrum of 7.5-8.5 GHz, as illustrated in Fig. 3. Again, both cases are examined, i.e. with and without the superstrate slab, which clearly certify the contribution of the cloaking concept in the low-profile response of the antenna, while preserving the strength of the signal at acceptable levels. Further numerical results from various FDTD simulations will be reported in the full paper. Preliminary comparisons already display promising coincidence for diverse N and a wide frequency range.

References

[1] R. Garg, *Microstrip Antenna Design Handbook*, Norwood, MA: Artech House, 2001.

[2] H. Attia, L. Yousefi, M. Bait-Suwailam, M. S. Boybay, and O. M. Ramahi, "Enhanced-gain microstrip antenna using engineered magnetic superstrates," *IEEE Antennas Wireless Propag. Lett.*, vol. 8, pp. 1198–1201, 2009.

[3] N. Ramli, M. Islam, A. Yousof, and S. Muhamud-Kayat, "Aperture-coupled frequency and patterns reconfigurable microstrip stacked array antenna," *IEEE Trans. Antennas Propag.*, vol. 63, no. 3, pp. 1067–1075, Mar. 2015.

[4] A. Alù and N. Engheta, "Cloaking a sensor," *Phys. Rev. Lett.*, vol. 102, pp. 233901(1–4), 2009.

[5] C. A. Valagiannopoulos and N. L. Tsitsas, "Integral equation analysis of a low-profile receiving planar microstrip antenna with a cloaking superstrate," *Radio Sci.*, vol. 47, pp. RS2022(1–12), 2012.

[6] R. Sabariego, C. Geuzaine, P. Dular, and J. Gyselinck, "Time-domain surface impedance boundary conditions enhanced by coarse volume FE discretization," *IEEE Trans. Magn.*, vol. 49, no. 2, pp. 631–634, Feb. 2012.

[7] U. C. Resende, M. V. Moreira, and M. M. Afonso, "Evaluation of singular integral equation in MoM analysis of arbitrary thin wire structures," *IEEE Trans. Magn.*, vol. 50, no. 2, art. no. 7011204, Feb. 2014.

[8] C.-T. Tai, *Dyadic Green Functions in Electromagnetic Theory*, 2nd ed., Piscataway, NY: IEEE Press, 1994.