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Simulation of Shaped Metasurface antennas, including the Feeder Coupling

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***Abstract*—An effective Method of Moment (MoM) tool able to rapidly and accurately analyze arbitrarily shaped metasurface (MTS) antennas is provided. The MTS is assumed to be fed by a coax probe as is usually the case in practice. The feed as well as the MTS are meshed with local basis functions. The calculation of the interactions between the MTS basis functions, which are the dominant unknowns, is accelerated with the FFT. The surface current is then computed iteratively using the GMRES algorithm. Once the currents on the MTS and on the feed are obtained, the efficiency of the antenna can be derived. The method is validated with an in-house numerical tool developed for the particular case of circular MTSs. An excellent comparison is observed.**

I. Introduction

Interest in metasurface (MTS) is rapidly growing in the antenna community [1] -[4]. Indeed, those planar and thin structures offer the possibility to generate through leaky-wave (LW) radiation, high gain [1], shaped beams [2] and/or multibeams [3], [4] at low cost and with low losses. The feeder is designed to excite surface waves (SW) in a planar grounded slab, on which the MTS is printed to transform the propagating SW into a LW. The accurate analysis of MTS antennas is not easy due to the electrically small and dense array used to implement an equivalent surface impedance distribution. Moreover, the coupling between the feeding structure and the MTS itself is difficult to accurately analyze and is often overly simplified. In order to accelerate the computation time, the MTS modeled as a surface impedance distribution, is usually assumed to be designed on a canonical shape (e.g circular or elliptical shape) and the feeder illumination is assumed to be a priori known. Those assumptions allow one to introduce properly adapted entire-domain basis functions, resulting in an extremely small computation time [5] -[7]. This paper introduces two extensions. First, the MTS is no longer assumed to be of a particular shape, i.e. the shape of the antenna can be arbitrarily chosen in a planar domain. Second, the feeder coupling is fully taken into account. This will be demonstrated in this paper using advanced MoM schemes. This paper is structured as follows. Section II presents the antenna modeling, Section III provides numerical validations and Section IV concludes the paper.

II. MTS and feed modeling

A planar MTS antenna modeled as a sheet transition impedance boundary condition and fed by a coax probe is considered (see Fig. 1). The MTS lies on a laterally infinite

Fig. 1. Illustration of a coax probe feeding the MTS.

grounded substrate. The vertical conductor in Fig. 1 represents the inner conductor of a coaxial cable and is modeled here as a cylinder with octagonal cross section. Both the MTS and the vertical conductor are meshed with rooftop basis functions. The slot in the ground plane is modeled as a magnetic frill current excitation on an infinite ground plane [8] - [10]. The resulting MoM modeling leads after Galerkin testing to the following system of equations:

$$\begin{bmatrix} (\mathbf{Z}_G - \mathbf{Z}_{IBC}) & \mathbf{Z}_{GF} \\ \mathbf{Z}_{GF}^t & \mathbf{Z}_{FF} \end{bmatrix} \begin{bmatrix} \mathbf{i}_G \\ \mathbf{i}_F \end{bmatrix} = \begin{bmatrix} \mathbf{v}_G \\ \mathbf{v}_F \end{bmatrix}, \qquad (1)$$

where $\mathbf{Z}_G$ and $\mathbf{Z}_{IBC}$ are the substrate and the IBC (impedance boundary condition) matrices respectively [5], [6]. $\mathbf{Z}_{FF}$ is the interaction matrix between the vertical feed basis functions and $\mathbf{Z}_{GF}$ models the coupling between the vertical feed and the horizontal currents on the MTS. Consistently, $\mathbf{i}_G$ and $\mathbf{i}_F$ are the unknown coefficients of the current expansion on the MTS and on the feed, respectively. Finally, [$\mathbf{v}_G$; $\mathbf{v}_F$] is the excitation vector.

The entries of the matrix in (1) are computed in the spatial domain after tabulation of the Green's function [11], [12]. The unknown current coefficients are computed iteratively using GMRES. The fast matrix-vector product required at each iteration is accelerated with FFTs [13]. Once the currents are obtained, the conversion efficiency (ϵ_{conv}) and the aperture/tapering efficiency (ϵ_{tap}) of the antenna can be deduced. The conversion efficiency is defined as the ratio between the radiated power and the power delivered by the feed. Approximating the current at the antenna port by the MoM current $i(0)$ at the base of the coaxial probe [10], the total active power delivered by the feed can be obtained as the real part of:

$$P_{tot} = \frac{i(0)\ U}{2}, \tag{2}$$

where U is the magnetic frill excitation voltage. The radiated power is computed after integrating in the spectral domain the fields in the horizontal plane of the antenna as done in [14].

III. Numerical Results

First, the developed MoM tool is validated using the analysis results from an in-house MoM code based on Fourier-Bessel basis functions (FBBF). The FBBF based MoM code has been itself validated in [6], [14]. The MTS antenna of Section V.A in [5] is considered. This antenna is designed to radiate a circularly polarized broadside pencil beam at 17 GHz with a sinusoidally modulated reactance surface. Fig. 2 shows a comparison between the efficiency results (as a function of the modulation index) obtained with the present method and the one from the FBBF tool. An excellent agreement is observed on the aperture and conversion efficiencies, despite those methods are based on different basis functions and modeling approaches.

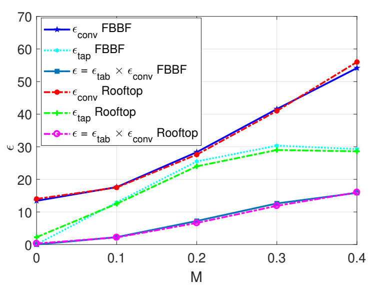

Fig. 2. Efficiency versus modulation index M for a broadside beam MTS.

In the next example, the developed tool is used to optimize the modulation index of a cross-shaped MTS (see Fig. 3(a)). The MTS is designed to generate at 24 GHz a circularly polarized pencil beam pointing at $\phi = 30^o$. The corresponding impedance distribution is given by [1]:

$$\begin{aligned} Z^{\rho\rho} &= jX_0 \left[1 + M\cos(k_{sw}\rho - k_0\rho\sin\theta_0\cos\phi - \phi)\right] \\ Z^{\rho\phi} &= jX_0 M\sin(k_{sw}\rho - k_0\rho\sin\theta_0\cos\phi - \phi) \\ Z^{\phi\phi} &= jX_0 \left[1 - M\cos(k_{sw}\rho - k_0\rho\sin\theta_0\cos\phi - \phi)\right], \end{aligned} \tag{3}$$

where $X_0 = -772\ \Omega$ is the average impedance and $k_{sw} = 1.35\ k_0$ is the supported SW mode wavenumber. (ρ, ϕ) are classical polar system of coordinates, with origin at the center of the MTS. The resulting tapering and conversion efficiencies as a function of the modulation index are shown in Fig. 3(b). It can be observed that the optimum efficiency is obtained for $M \approx 0.6$.

IV. Conclusion

A MTS analysis tool in which the feed coupling is fully taken into account has been developed. This tool can handle MTS antennas designed on arbitrarily shaped domains, and fed with a coax probe. Excellent validation of the efficiency has been provided.

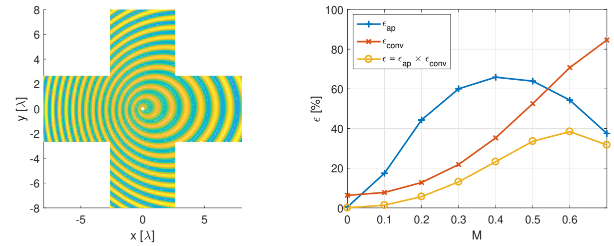

Fig. 3. Cross-shaped MTS antenna. (a) Illustration of the reactance modulation; λ is the free-space wavelength. (b) efficiency (in %) versus modulation index M.

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