

DESIGN OF HIGH GAIN SLOTTED WAVEGUIDE ANTENNA USING METAMATERIALS

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ABSTRACT

Numerical simulations of antennas based on periodic metamaterials fed by a slotted waveguide can be excessively time consuming because of the large number of unknowns involved in such structures. This paper depicts how the analysis of the metamaterial can be carried out separately from the waveguide by defining interior and exterior equivalent problems. Moreover, we will show how the combination of both equivalent problems allows a fast computation of the antenna impedance properties. Finally, a method resorting to infinite array simulations and the Array Scanning Method (ASM) is presented that allows a very efficient analysis of the periodic superstrate in the exterior problem.

1. INTRODUCTION

It is now well known that periodic metamaterials can be used as antenna superstrates to collimate energy in a narrow lobe. For instance, it is shown in [1] and [2] how periodic metallic grids can behave as an ultrarefractive metamaterial to enhance the gain of monopole and dipole antennas. Another approach which consists of using frequency selective surfaces (FSS), made of short dipole arrays, to increase the directivity of a patch antenna is described in [3]. FSS superstrates can also be used in conjunction with metamaterial ground planes [4], that exhibit zero degrees reflection phase, to reduce antenna profile. Metamaterials can then also be used, for example, to increase the directivity of a slotted waveguide. For instance, in Fig. 1, a superstrate made of six layers of metallic strips is used. The strips are 4.9cm long and 0.071cm wide. The spacings between them are 0.58cm horizontally and 0.63cm vertically. Fig. 2 shows the radiation pattern obtained at 14GHz. However, brute force simulations of such structures require a large computing power, because of the large number of unknowns, especially in the feeding structure. Another and more efficient approach consists of analyzing separately the waveguide and the metamaterial. Such a separation of the problem into two regions, an internal and an external one, was already used and validated in [5] for the analysis of slotted waveguide arrays. The method proposed in this paper is

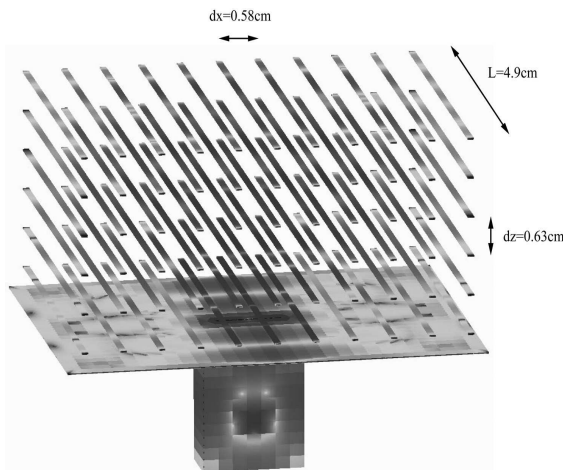


Figure 1. Slotted waveguide exciting a periodic metamaterial superstrate made of 6 layers of metallic strips.

based on the use of a MoM simulation code developed at UCL [6] and the separate analysis of equivalent interior and exterior problems. Section 2 defines these interior and exterior equivalent problems and validate this approach on simple examples. It is then shown in Section 3 how both interior and exterior problems can be combined to obtain easily the impedance properties of the antenna. Section 4 depicts a very efficient method based on the Array Scanning Method to analyze the periodic metamaterial and finally, conclusions are drawn.

2. INTERIOR AND EXTERIOR PROBLEMS

The structure under study is illustrated in Fig. 3. It consists of a slotted waveguide or cavity, whose top wall is extended into a ground plane. A slot is cut in this top wall and the cavity is excited by some sort of feed probe. The interior problem, depicted in Fig. 4 can then be seen as a closed waveguide (the slot is short-circuited) with two different excitations. The first excitation is the voltage source V at the feed probe, modeled as a delta-gap, and the second one comes from magnetic currents $\vec{M} = -\vec{n} \times \vec{E}$ equivalent to fields in the slot. By exciting

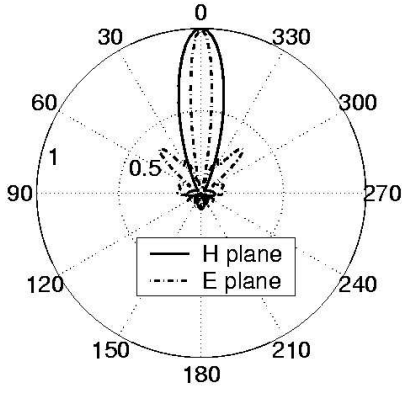


Figure 2. Radiation pattern of the structure in Fig. 1 at 14GHz.

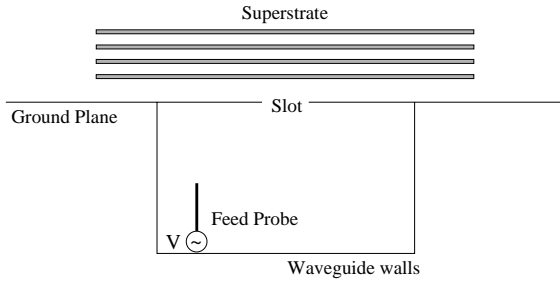


Figure 3. Schematic view of the structure studied.

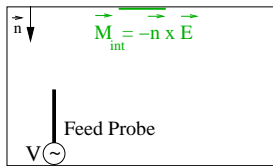


Figure 4. Interior equivalent problem.

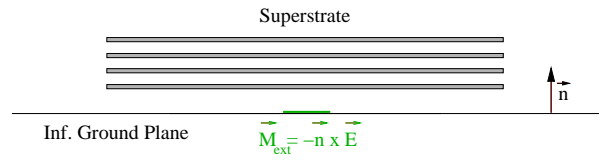


Figure 5. Exterior equivalent problem.

only the TE_{10} mode in the waveguide, one can assume that \vec{M}_{int} and \vec{H}_{int} , respectively the magnetic currents and H field in the slot for the interior problem both have a sinusoidal distribution along the slot. Hence, by simulating this structure, and using the superposition principle, it is possible to find on one side the ratio Y_{int}^{HM} of the amplitudes H_{int} and M_{int} when the probe is not excited ($V = 0$) and on the other side, the ratio Y^{HV} of the amplitudes H_{int} and V (the voltage source), when there is no magnetic current ($M = 0$). This yields for the interior H field amplitude.

$$H_{int} = Y^{HV} V + Y_{int}^{HM} M_{int} \quad (1)$$

Then, the exterior problem consists of a periodic meta-material superstrate excited by a slot cut in the ground plane extending the top wall of the waveguide. Assuming that this ground plane is large enough, the problem can be seen as a periodic structure excited by magnetic currents $\vec{M} = -\vec{n} \times \vec{E}$, equivalent to fields in the slot, and flowing on an infinite ground plane, as shown in Fig. 5. This structure can also be simulated, and using the same assumption of sinusoidal field distribution as in the interior problem, we now have for the H field amplitude in the exterior problem.

$$H_{ext} = Y_{ext}^{HM} M_{ext} \quad (2)$$

3. COMBINING BOTH PROBLEMS

By enforcing the continuity of tangential fields along the slot, i.e. $H_{int} = H_{ext}$ and $M_{int} = -M_{ext}$, one can find the amplitude of equivalent magnetic currents using equations (1) and (2).

$$M_{ext} = -M_{int} = \frac{Y^{HV} V}{Y_{int}^{HM} + Y_{ext}^{HM}} \quad (3)$$

Then, using again the superposition principle in the interior problem, one can obtain the relations binding I (amplitude of the current on the probe at the delta-gap feed point) with both V (amplitude of the voltage excitation applied to the probe delta-gap feed point) and M_{int} (amplitude of magnetic currents along the slot).

$$I = Y^{IV} V + Y^{IM} M_{int} \quad (4)$$

Then introducing (3) into (4), the current along the feed probe is obtained and the input impedance of the antenna,

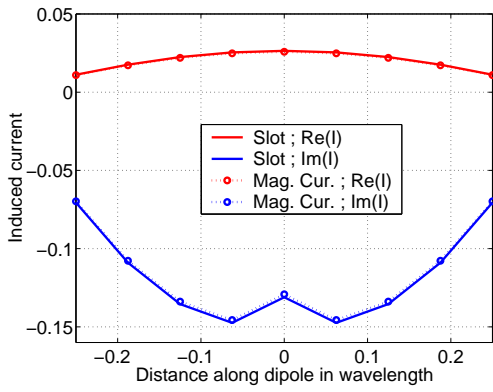


Figure 6. Comparison of current induced on a half-wave dipole in a slotted cavity. Solid lines: Slot open, Dotted lines: Slot is short-circuited and replaced by a sheet of magnetic currents.

V/I at the probe level, can be determined.

$$Z = \frac{V}{I} = \frac{1}{Y_{IV} - \frac{Y_{IM}Y_{HV}}{Y_{int}^{HM} + Y_{ext}^{HM}}} \quad (5)$$

With this method, the radiation pattern can be optimized in the exterior problem by tuning the properties of the superstrate. Then, under the single-mode approximation for fields in the slot, Eq. (5) will allow the determination of the impedance at the waveguide feed level. This input impedance can be optimized by tuning the waveguide parameters in the interior problem. The procedure that consists of replacing the electric field along the slot by magnetic currents with a sinusoidal distribution has been validated on three simple examples. In the first one, a small metallic box containing a half-wave dipole and with a slot cut in its top wall was simulated. Fig. 6 shows the current induced on the dipole (solid lines) when it is excited by a delta-gap. Then the slot was short-circuited and replaced by a sheet of magnetic currents with a sinusoidal distribution. The current induced on the dipole is also shown in figure 6 (dotted lines) and is almost exactly the same as in the previous case. The second example consists of a metallic cavity fed by a probe and also with a slot cut on its top broad wall. Its cross-section is 1.5cm X 0.75cm and its length is 2cm. A 1cm long slot is cut in the top wall. The input impedance at the probe level around the resonant frequency of the cavity is shown in Fig. 7. Solid lines show the impedance with the slot open and the small bullets and squares when the slot is short-circuited and replaced by a magnetic current sheet. Again the agreement is excellent. Finally, the third example is the simulation of a FSS made of two layers of 41X11 dipoles each, above an infinite ground plane and excited by magnetic currents. The structure is described in [3]. The radiation pattern obtained at 12GHz is shown in Fig. 8. The achieved gain is about 25dB and corresponds to the directivity obtained in [3] by full-wave simulations.

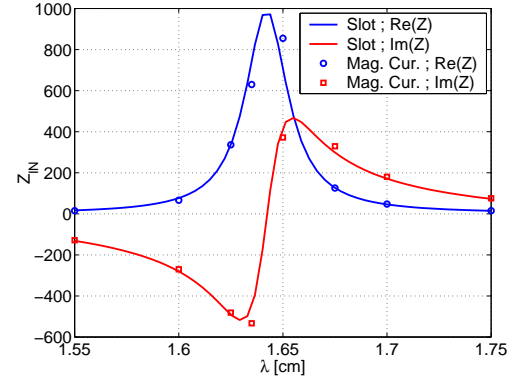


Figure 7. Comparison of the input impedance of a slotted cavity (1.5cm X 0.75cm X 2cm). Solid lines: Slot open, Bullets and Squares: Slot is short-circuited and replaced by a sheet of magnetic currents.

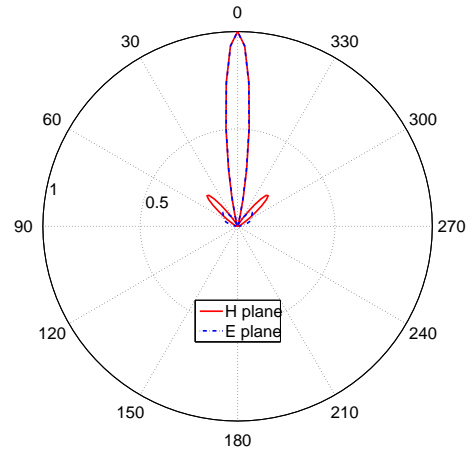


Figure 8. Radiation pattern at 12GHz of a FSS described in [3] made of two layers of 41X11 dipoles and excited by magnetic currents on the ground plane.

4. ARRAY SCANNING METHOD

For the optimization of the superstrate in the exterior problem, in a first instance, infinite array simulation can be used, which reduces the unknowns of the problem to one unit cell. We have developed a Method-of-Moments simulation code that can efficiently analyze infinitely periodic metallic structures [6]. This code is based on a very efficient representation of the doubly periodic Green's function. Infinite-array simulations greatly reduce the computation time; but, doing this, the excitation of the structure will also be periodized. To consider a single source, we resort to the Array Scanning Method [7]. This technique allows us to compute the response of a periodic structure to an excitation every N unit cell in both directions as a sum of N^2 responses where every unit cell is excited. This is expressed in one dimension by Eq. (6), in which I_n is the current in the n^{th} cell when one cell every N is excited. $I^\infty(\psi_p)$ is the current flowing in a cell in the infinite array conditions, with every cell excited, and an inter-element phase shift ψ_p .

$$I_n = \frac{1}{N} \sum_{p=0}^{N-1} I^\infty(\psi_p) e^{-jn\psi_p} \quad \text{where} \quad \psi_p = p \frac{2\pi}{N} \quad (6)$$

The sources are now repeated every N cell in each direction. If N is taken large enough, depending on the strength of the coupling between cells, the response of the cells surrounding the excitation will be close to the response obtained when only one cell is excited. Hence, the radiation pattern of this N -by- N array will be close to the infinite-array element pattern. In order to determine how large N should be to avoid interactions between successive sources, we can compare the pattern computed using the ASM with the radiation pattern of the infinite array where only one cell is excited:

$$\bar{F}(\hat{u}) = \int \int_S \bar{J}^\infty(\bar{r}) \cdot \hat{e}_p e^{jk\hat{u} \cdot \bar{r}} dS \quad (7)$$

where $\bar{F}(\hat{u})$ is the radiation pattern in direction \hat{u} , \bar{J}^∞ is the current in the unit cell of the infinite array when every cell is excited, \hat{e}_p is the desired E field polarization and S is the unit cell surface. Fig. 11 shows the radiation pattern computed with Eq.(7) for the simple case of the dipole array depicted in Fig. 9. When N is large enough, depending on the strength of the coupling between cells, the pattern obtained with the ASM will be very close to the pattern of the infinite array with only one cell excited. Figs. 10 and 11 illustrate, in the simple case of a dipole array whose unit cell is shown in Fig. 9, the convergence of the radiation patterns with three values of N . The excellent agreement between the pattern obtained by Eq. (7) and the pattern obtained with the ASM considering $N = 41$ (Fig. 11) means that the current distribution computed with the ASM in this case must be very close to the current distribution in the case of only one cell excited. In practical situations, one should stop increasing N when the normalized RMS deviation between the infinite array pattern and the pattern computed with ASM is

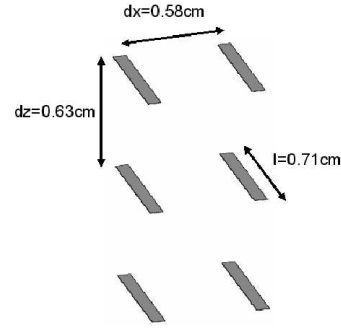


Figure 9. Unit cell for an array of dipoles excited by magnetic currents on a ground plane below them. Unit cell size is 1.16 cm in both directions

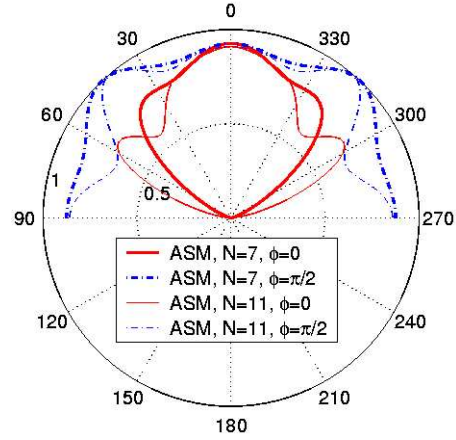


Figure 10. Radiation patterns for the array of dipole obtained with ASM for $N=7$ and $N=11$. $\phi = 0$ corresponds to the H-plane and $\phi = \pi/2$ to the E-plane.

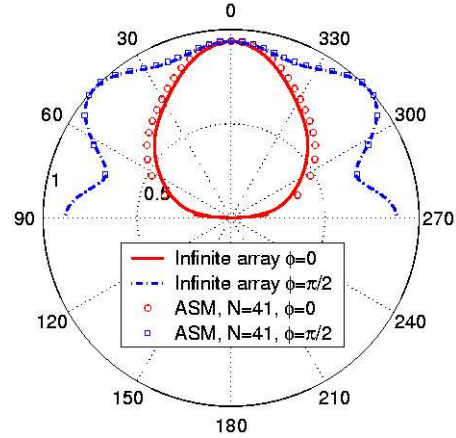


Figure 11. Radiation patterns for the array of dipole obtained with ASM, $N=41$ and with Eq. (7). $\phi = 0$ corresponds to the H-plane and $\phi = \pi/2$ to the E-plane.

below a given value ϵ :

$$\int \frac{|\vec{E}^\infty(\theta) - \vec{E}^{ASM}(\theta)|^2}{|\vec{E}^\infty(\theta)|^2} d\theta < \epsilon \quad (8)$$

One should note that in addition to the optimization of the superstrates, the determination of Y_{ext}^{HM} in Eq. (2) can also benefit from the ASM. The last issue is now the finite size of the superstrate. An approximate way of computing finite-array radiation patterns is to apply a simple windowing technique [8] that consists of the truncation to the desired size of the results provided by ASM, as described in [9]. After performing the ASM with large enough N , as described above, infinite array currents when only one cell is excited are known in the excited cell and the surrounding cells. To obtain the radiation pattern of a M -by- M finite array, with $M < N$, one only computes the fields radiated by currents in the M^2 cells around the excited element. We may regard the currents in the finite array as a wave launched by the excited element. In a finite array, this wave can be partially reflected by the array edges. The windowing referred to above obviously neglects these reflections. However, this effect can be partially accounted for by resorting to finite-by-infinite array simulations as shown in [9].

5. CONCLUSION

In the design of slotted waveguide antennas using metamaterials, numerical simulations can be excessively time-consuming because of the large number of unknowns involved in these structures. We proposed an elegant method allowing the waveguide and the superstrate to be studied separately, hence greatly reducing the total computing time. This is done by defining two separate regions, an internal and an external one. The internal problem consists of the waveguide whose slot is short-circuited and replaced by a sheet of magnetic currents equivalent to fields in the slot. On the other hand, the metamaterial can be studied alone over an infinite ground plane supporting magnetic currents. Then, under the single-mode approximation for fields in the slot, and by enforcing the continuity of those fields along the slot, we showed that the input impedance of the waveguide can be very easily obtained. Moreover, resorting to infinite array simulations allows to efficiently analyze and optimize the properties of the periodic superstrate. The non-periodicity of the excitation of the metamaterial can be easily dealt with by using the Array Scanning Method and the effect of the finiteness of the structure can be studied by applying a simple window on the ASM results. The proposed design method has been validated numerically in both the internal and external regions.

ACKNOWLEDGEMENTS

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