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Transmission Line Models of Planar Slot Antennas

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***Abstract*—We propose a systematic approach to describe planar slot antennas, embedded in generic stratified media. An equivalent transmission line model for the slot is proposed, based on a spectral domain analysis. First, we introduce a method of moments solution to model semi-infinite slots, fed by a delta-gap excitation. The solution entails only two basis functions, one located at the feed and the other at the termination. The latter basis function is chosen to properly account for the field diffractive behavior at the antenna end point. An approximate circuit model is then introduced, which describes the main mode propagating along the slot as an equivalent transmission line. Lumped impedances are extracted to accurately describe the source and the end point. This procedure can be used to derive the input impedance of planar antennas with arbitrary length in generic layered media or the interaction between multiple feeds within the same slot.**

***Index Terms*—Equivalent circuit, input impedance, slot antenna.**

I. Introduction

A convenient way to describe a center-fed slot is by an equivalent transmission line model, where the excitation is modeled as a shunt generator and the slot arms are represented as two transmission line sections. Transmission line models for slot antennas were given in [1], [2], which considered short circuits to describe the slot terminations, thus did not account for the reactance associated with the end points. An improved model was proposed in [3], where the inductance of the slot shorted ends was considered. However, all the existing models do not account for the reactance of the feed and the diffraction from the edge. Moreover the radiation is modeled as a distributed resistance through a lossy line or as a single lumped resistance.

A different approach is presented here, where an improved model is proposed that accurately describes the reactive nature of both the feed and the terminations of the slot. A Method of Moments (MoM) solution allows representing the radiation from the slot in terms separate resistances, one associated with the feed point and one located at each termination. This configuration give more physical insight, as the radiated field can be interpreted as individual space waves, emerging from the feed and the end points.

An additional advantage of the proposed method is that the characteristic impedance of the transmission line is derived by extracting the polar singularity contribution of the spectral domain Green's function as in [4], thus can be generalized to arbitrary stratified media, as long as the polar and the branch singularity do not coincide.

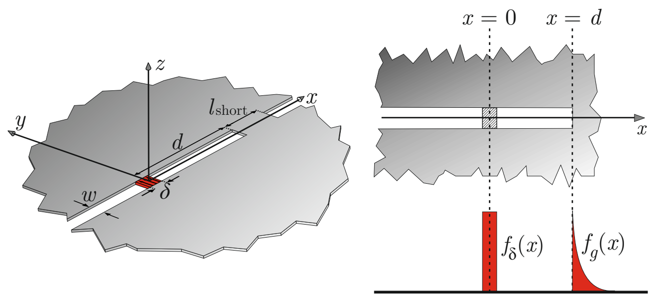

Fig. 1. (a) Interrupted infinite slot in free space. (b) Space domain basis functions with respect to their location along the semi-infinite slot.

II. MoM Solution for Semi-infinite Slot

We interrupt a narrow, x-oriented, infinite slot with a short circuit at a certain distance d from the feeding gap, which is small in terms of the wavelength (δ-gap excitation), as shown in Fig. 1(a). The short is realized with a metallic interruption of length l_{short} that is assumed to be sufficiently large, so that the magnetic current induced in the slot for $x > d + l_{\text{short}}$ does not influence the current at $x < d$. This assumption allows modeling a semi-infinite slot with infinitely extended metal (for $x > d$) as an infinite slot with a finite metal termination. Such approximation is convenient due to the availability of the infinite slot spectral Green's function [5]. To satisfy the boundary conditions on the metal, an electric current is induced with an edge-singular behavior, as shown in Fig. 1(b). The edge singular basis function is described in the spectral domain by:

$$F_g(k_x) = e^{jk_xg/2}\times \left(J_0\left(\frac{k_xg}{2}\right) - j\mathbf{H}_0\left(\frac{k_xg}{2}\right) - \frac{2}{\pi}\text{sinc}\left(\frac{k_xg}{4}\right)e^{-jk_xg/4}\right) \quad (1)$$

where $\mathbf{H}_0$ is the zeroth order Struve function and k_x is the spectral counterpart of the spatial variables x. The parameter g in (1) is related to the width of the current distribution on the metallic interruption. The value of g was found empirically to be linked to the width of the slot and the free-space wavelength as

$$g = \frac{5}{3}\sqrt{w\lambda}. \quad (2)$$

The input impedance of the slot can be found as

$$Z_{\text{in}} = Z_{\delta\delta} - \frac{Z_{\delta g} Z_{g\delta}}{Z_{gg}} \tag{3}$$

where the self and mutual impedances are given by

$$Z_{j,i} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{F_i(k_x) F_j(-k_x) e^{j k_x (x_i - x_j)}}{D_s(k_x)} dk_x \tag{4}$$

The subscripts i and j are either δ or g and $x_\delta = 0$ and $x_g = d$. $F_\delta(k_x)$ is the spectral basis function representing the magnetic field excited in the gap and $D_s(k_x)$ is the spectral longitudinal Green's function of an infinite slot [5].

III. Equivalent Transmission Line Model

The integrand in (4) presents two types of singularities: square-root branch points representing the space waves radiating away from the slot, and poles associated with quasi-TEM waves launched along the slot. In the presence of a thin dielectric substrate, the pole singularity moves away from the branch point in the complex k_x-plane, so that the polar contribution can be isolated. The location of the pole, k_{xp}, can be found using a local-search algorithm starting from k_0. Using Cauchy's theorem the polar contributions to the to the mutual impedances are evaluated, which are good approximations for the total integral of (4) for sufficiently large d. This allows us to draw an equivalent transmission line circuit representing the semi-infinite slot as shown in Fig. 2(a). The self impedances are split into the contributions of the transmission line and remaining terms $Z_{\delta\delta,\text{rem}}$ and $Z_{gg,\text{rem}}$. The turn ratios of the two transformers are $n_\delta = F_\delta(-k_{xp})$ and $n_g = F_g(-k_{xp})$. The characteristic impedance of the transmission line, $Z_{0,s}$, is found as in [4].

We define a single impedance to represent the end-point of the semi-infinite slot:

$$Z_{\text{end}} = \frac{\left(Z_{gg,\text{rem}}/n_g^2\right) Z_{0,s}}{\left(Z_{gg,\text{rem}}/n_g^2\right) + Z_{0,s}}. \tag{5}$$

The two impedances in the circuit are represented explicitly as resistors accounting for radiation and inductors accounting for the reactive energy at the feed and the end point, such that the transmission line circuit is drawn as shown in Fig. 2(b).

Figure 3 shows the input impedance of a semi-infinite slot, both in free space and in the presence of a thin dielectric slab, calculated with (3), compared to CST. The result of the transmission line model is also presented in Fig. 3(b).

The analysis of a finite slot is done as described above, except that the infinite slot is interrupted on both sides of the feed.

IV. Conclusion

An efficient method of moments solution for planar slots embedded in generic stratified media was presented, with only two basis functions, one located at the feeding point and one at the termination of the slot. The basis functions were chosen such that they properly account for the reactive energy localized at these points.

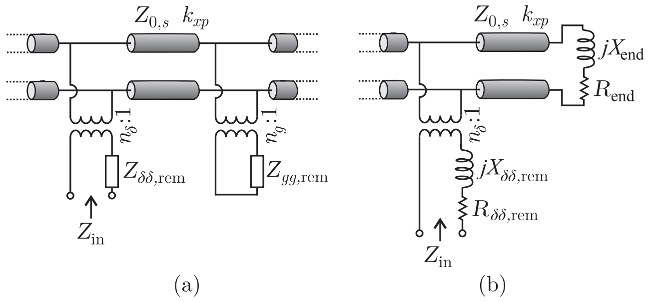

Fig. 2. Equivalent transmission line circuit representing the two basis functions of the semi-infinite slot. (a) The end-point is represented by a transformer and a remaining impedance in parallel to an infinite line. (b) The impedances are represented as resistor accounting for radiation and an inductor accounting for the reactive energy at the feed and the end point.

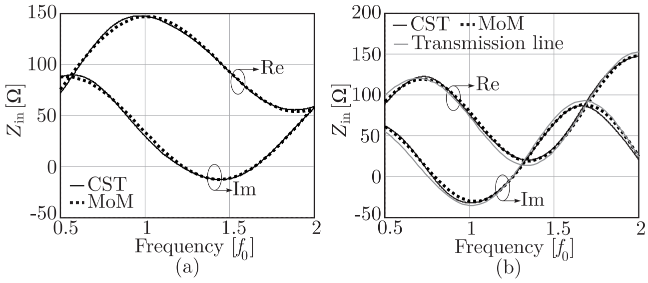

Fig. 3. Comparison between the input impedance of a semi-infinite slot calculated with our method and CST. The geometrical parameters of the structure are $d = \lambda_0/4$, $w = \lambda_0/50$ and $\delta = \lambda_0/40$. λ_0 is the wavelength in free space at f_0. (a) The slot is surrounded by free space. (b) A thin dielectric substrate is added: $\varepsilon_r = 4$, $h = \lambda_d/20$ when λ_d is the wavelength in the dielectric at f_0.

Based on the numerical solution, an equivalent transmission line circuit was derived. The radiation is described in the model as resistances located at the feed and the end point. This approach allows representing the radiation from the slot as the generation of different space waves, one associated with the feeding gap and one emerging from the end point. The physical dimensions and the shape of the basis functions was accounted for in the circuit by means of transformers.

The method can be used to describe finite slots by terminating the slot on both sides of the feed.

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