Radiation Efficiency of Printed Slot Antennas Backed by a Ground Reflector

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1.0 Introduction

A single slot antenna printed on a thin dielectric substrate is essentially a bi-directional radiator. In order to restore the back radiation, the slot can be backed by a metallic cavity which, however, complicates the fabrication process beyond the use of simple photolithography[1]. Alternatively, the slot can be backed by a ground-reflector in an effort to re-direct the back radiation through the substrate[2]. However, this approach can trap the parallel-plate TEM mode between the slot and reflector ground-planes and degrade the overall radiation efficiency. Recently, an electromagnetic bandgap (EBG) material has been proposed to reduce the parallel-plate mode[3]. However, once more, the fabrication is complicated, requiring milling techniques to define the EBG substrate. Another way to reduce the back radiation is by utilizing an electrically thick substrate. Indeed, on a quarter dielectric wavelength substrate, the front-to-back power density ratio at broadside is equal to the substrate relative permittivity ε_r. However in this case, the strong coupling to the dominant surface-wave TMo mode is unavoidable.

Although in the literature the back-reflector technique has been extensively used as a means of rendering the slot patterns unidirectional, there is no quantitative information on the effectiveness of this approach. In this work, the use of a back reflector as a means of increasing the efficiency and antenna gain of printed slot antennas is evaluated. For this purpose, the radiation efficiency of reflector-backed printed slot antennas on either electrically thin or thick substrates is thoroughly characterized; Both single and twin slot elements are considered. Twin slot elements have been previously proposed for the reduction of the coupling to the dominant surface-wave mode in the case of electrically thick substrates [4]. In this article, twin slot elements are explored as a means of enhancing the radiation efficiency of printed slots backed by a ground reflector. It is shown that in the case of thick substrates, simultaneous partial cancellation of the surface-wave and the parallel-plate TEM modes can be achieved. On the other hand, in the case of thin substrates where the back radiation is severe, the twin slot element can be utilized for the drastic reduction of the parallel-plate TEM mode.

2.0 Theoretical Analysis

Consider a twin slot antenna printed on one side of a substrate with a relative permittivity ε_1 and height h_1 as shown in Fig. 1. A conducting plane is placed at the back of the substrate at a distance h_2 from the slot ground plane and a low-permittivity (ε_2, $\varepsilon_2 < \varepsilon_1$) material is utilized to support the conducting plane at this distance. For the convenience of illustration, we refer to the (ε_1, h_1) structure as the processing substrate, the added low-permittivity (ε_2, h_2) structure as the supportive sub-

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strate, and the added conducting plane as the back reflector. Obviously, due to the existence of the back reflector, the twin slot cannot leak power directly into the air from the back side. Instead, the parallel-plate TEM mode will be excited. The theoretical analysis for determining the coupling to the TEM mode is similar to that used for calculating the coupling to surface-wave modes [5]. In particular, by using the reciprocity theorem, one can find the strength of the TEM mode for a given magnetic slot current distribution. The radiation efficiency is defined in equation (1) similarly to [4] and [5]. In this equation, P_{rad} stands for the radiated power through the substrate and P_{sw} stands for the power coupled to surface-wave modes. Furthermore, P_{back} designates either the power coupled to the TEM mode between the slot and reflector ground planes or, in the absence of a back reflector, the power that leaks from the back into the air.

$$\eta_e = \frac{P_{rad}}{P_{rad} + P_{sw} + P_{back}} \qquad \text{(EQ 1)}$$

3.0 Numerical Results

In the initial assessment, the back reflector is positioned a quarter free space wavelength ($\varepsilon_2 = 1.0$, $h_2 = \lambda_0/4$) away from the slot ground plane. It is expected that at this position, the effect of the back reflector on the slot input impedance is small since the reflector appears as an open circuit at the terminals of the slot. The length of each slot is assumed to be one effective wavelength λ_{eff}, which is defined as $\lambda_{eff} = \lambda_0/(\sqrt{(\varepsilon_1 + \varepsilon_2)/2})$. The corresponding radiation efficiencies as a function of the slot separation on a substrate with relative permittivity $\varepsilon_1 = 4.5$ and thickness of one quarter dielectric wavelength $h_1 = \lambda_d/4$, with and without a backing reflector are shown in Fig. 2. It is observed that when $d = 0$, which corresponds to the case of a single slot, there is *almost no efficiency improvement* when placing a back reflector. That is, all the back reflector accomplishes is to convert the back radiation into the TEM mode instead. On the other hand, when the twin slots are placed half a guided wavelength apart $d = 0.5\lambda_g$ (for the TMo substrate mode), the presence of a backing reflector results to a significant radiation efficiency improvement from 75.4% to 91.4%. This slot separation of $d = 0.5\lambda_g$ is quite important because it leads to the most efficient phase cancellation of the dominant TMo surface-wave mode [4]. Similar observations have been made for higher permittivity substrates, though the efficiency improvement is less significant. The observation that the backing reflector appears more effective in the case of lower permittivity materials can be explained by the fact that for these substrates, the back radiation is stronger while the wavelength of the parallel-plate mode is closer to that of the surface-wave mode in the processing substrate. Therefore a more effective simultaneous phase cancellation of the surface-wave and parallel-plate modes is achieved for the case of a lower permittivity substrate. This in fact is desirable since the most severe back radiation leakage takes place for substrates of low permittivity.

Next, the distance between the ground planes (h_2 in Fig. 1) is varied whereas the distance between the two slots is kept constant at $d = 0.5\lambda_g$. This is shown in Fig. 3 from which it is observed that the efficiency is not improved much when the added back reflector is close to the slot ground plane and from then on the efficiency increases monotonically until the distance between the ground planes becomes $h_2 = \lambda_0/4$. For greater reflector separations, the radiation efficiency remains almost constant. However, the distance should be kept shorter than half a free space wavelength in order to avoid the excitation of higher order parallel-plate modes. From HP-Momentum simulations, it is found that the resonant frequency slightly shifts upwards or downwards when a back reflector is present, depending on the exact distance h_2. This last observation implies that the backing reflector can be positioned within the range $\lambda_d/4 \leq h_2 < \lambda_d/2$, enabling its use as a slot impedance tuner without degrading the radiation efficiency.

The case of a thin substrate (one-hundredth dielectric wavelength) is treated in Fig. 4 which corresponds to slots printed on a substrate with $\varepsilon_1 = 4.5$. As shown in Fig. 4, a single slot (d=0) without a back reflector, results to a radiation efficiency of only about 50% since the slot radiates almost equally on both sides of the substrate. On the other hand, the use of a back reflector *only slightly increases* the radiation efficiency to 56%. However, the situation drastically changes when a twin slot element is used instead of a single slot. As Fig. 4 shows, optimum radiation efficiency is achieved when the slots are separated by about half a free-space wavelength, resulting to strong TEM mode suppression due to phase cancellation along the array axis. Indeed in this case, the twin-slot efficiency reaches a value of 90%.

4.0 Conclusion

The effectiveness of using a back reflector for increasing the radiation efficiency of printed single and twin slot elements has been evaluated. Both electrically thin and thick substrates have been considered. It was shown that for single slots, the placement of a back reflector brings about only a marginal improvement to the radiation efficiency due to the strong excitation of the parallel-plate TEM mode. The situation changes dramatically when a broadside arranged twin slot element is used instead. On thin substrates, the twin-slot element can effectively suppress the TEM mode and drastically increase the radiation efficiency. The same is true on low permittivity electrically thick substrates due to the possibility of a simultaneous phase cancellation of the dominant surface-wave and the TEM modes. Furthermore, it was also shown that the position of the back reflector can be exploited for input impedance tuning without affecting the radiation efficiency improvement. Further numerical and experimental results will be presented at the conference.

5.0 References

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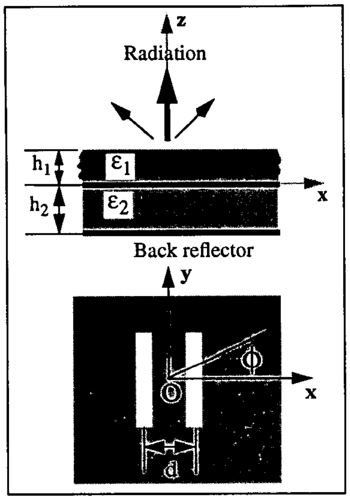
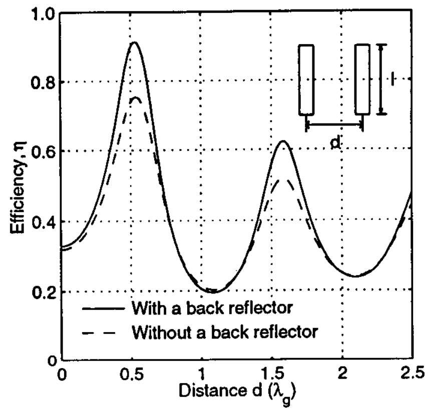


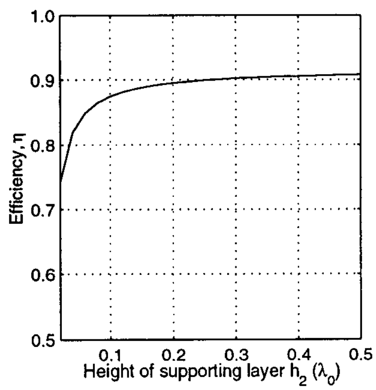
Twin-slot antenna backed by a back reflector.

Figure 1



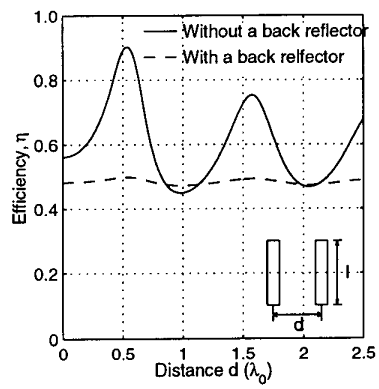
Twin slot printed on a thick substrate, with and without a back reflector, $\varepsilon_1 = 4.5$, $h_1 = \lambda_d/4$, $l = \lambda_{eff}$, $\varepsilon_2 = 1.0$, $h_2 = \lambda_0/4$.

Figure 2



Twin slot printed on a thick substrate backed by a back reflector, $\varepsilon_1 = 4.5$, $h_1 = \lambda_d/4$, $l = \lambda_{eff}$, $d = 0.5\lambda_g$, $\varepsilon_2 = 1.0$.

Figure 3



Twin slot printed on a thin substrate, with and without a back reflector, $\varepsilon_1 = 4.5$, $h_1 = 0.01\lambda_d$, $l = \lambda_{eff}$, $\varepsilon_2 = 1.0$, $h_2 = \lambda_0/4$.

Figure 4