An Idea for Low-Profile Unidirectional Slot Antennas Based on Its Complementary Dipoles

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***Abstract*-In this paper, a novel scheme of constructing low-profile unidirectional slot antennas has been proposed. The scheme is based on the complementary dipole concept. The basic principle of the complementary concept has been revisited, with a discussion on the effect of excitation amplitude on the unidirectional radiation performance. The practical antenna configuration has then been given, followed by some preliminary simulated results. Compared to some conventional techniques for designing unidirectional slot antennas, the proposed structure has several advantages such as low profile, low Q, and ease of fabrication.**

I. INTRODUCTION

Slot antennas are promising candidates for military, wireless communication, and medical applications, due to its attracting features such as compact size, light weight, low profile, conformability to planar or nonplanar surfaces, and compatibility with MMIC designs [1-3]. Particularly, compared to their planar counterpart, i.e. microstrip patch antennas, they have generally wider bandwidth, less interaction via surface waves and better isolation from feed net-works [1]. However, one salient drawback of a slot radiator cut on the metallic plane is its inherent bi-directional radiation, which means half of the fed power radiates in most cases in the unwanted direction. To mitigate this undesired characteristic, one traditional solution is to place a metallic plane reflector on one side and parallel to the slot surface. However, a minimum distance of a quarter wavelength between the slot and the reflector is required to guarantee an optimal matching [4]. In addition, if one wishes to reduce this distance, the parallel plate TEM mode between the two layers dominates and causes great energy leakage [3], [5], [6]. Another commonly used technique is to replace the reflector by a closed cavity to form a cavity-backed slot (CBS) antenna [7]-[10]. However, the CBS antenna can hardly be low-profile, and due to its closed form, the bandwidth, which is an advantage of a slot antenna, is inevitably affected. Other techniques include using shorting pins around the slot [11], twin slot configuration for phase cancellation [5], [11], and EBG or AMC as the reflector [12], [13].

The concept of complementary electric dipole and magnetic dipole was first studied by Clavin [14], [15], and recently based on this concept Luk et al. have proposed a series of novel antennas with improved characteristics such as wide band, symmetric radiation pattern in the E- and H-planes [15]-[17]. In this paper, we try to discuss the possibility of constructing novel unidirectional radiating slot antennas based on the complementary dipole concept. The basic scheme of the antenna configuration and its working principle is discussed in section II. The practical antenna structure and some initial simulation results are given in section III. Finally the conclusion is given in section IV.

II. BASIC PRINCIPLE AND DISCUSSION

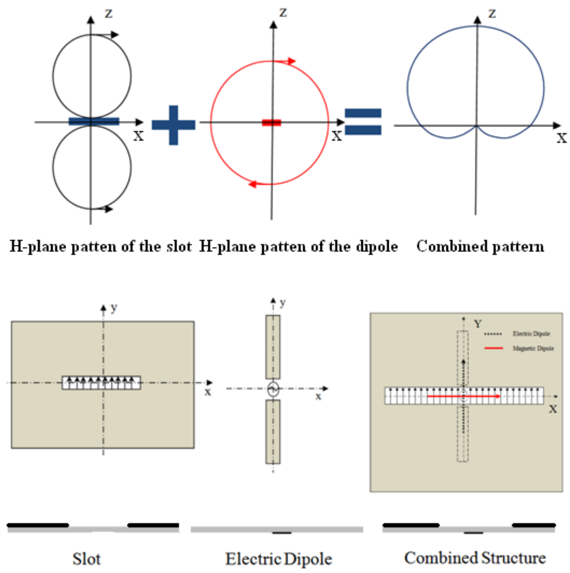


Figure 1. The scheme of combining a slot and its complementary E-dipole to produce a unidirectional radiation.

Previous studies have shown that an electric dipole and a magnetic dipole that are simultaneously excited with proper amplitudes and phases can have a unidirectional beam and symmetric cardiac pattern, where in ideal case the backward radiation is completely suppressed [14], [16]. As a thin slot cut on an infinite ground plane can be viewed as a magnetic dipole [18], it is straightforward to infer that if an electric dipole is placed orthogonally near the slot (e.g. on the opposite side of the very electrically thin substrate to the slot plane, see the right column of Fig. 1) with proper excitation, the backward radiation of the conventional bi-directional slot antenna can also be similarly suppressed and unidirectional pattern can be obtained. This aforementioned scheme, with the antenna configuration and corresponding radiation pattern, is plotted in Fig. 1. Note in Fig. 1 only H-plane pattern is given, and according to the complementary dipole concept the same effect can be observed in the E-plane.

Previous study has already shown that the unidirectional pattern with effective backward radiation suppression largely depends on the excitation of the two complementary sources with proper amplitude and phase. Here a set of complete mathematical derivation is given below, followed by a discussion on the excitation amplitude. Suppose the finite length slot (i.e. magnetic dipole) and its complementary electric dipole are placed along y and x axis, respectively, and the magnetic and electric current on these dipoles are

$$\vec{I}_e(x',y',z') = \begin{cases} \hat{a}_y I_e \sin[k(\frac{l_e}{2}-x')], 0 \le x' \le \frac{l_e}{2} \\ \hat{a}_y I_e \sin[k(\frac{l_e}{2}+x')], -\frac{l_e}{2} \le x' \le 0 \end{cases} \qquad (1)$$

$$\vec{I}_m(x',y',z') = \begin{cases} \hat{a}_x I_m \sin[k(\frac{l_m}{2}-y')], 0 \le y' \le \frac{l_m}{2} \\ \hat{a}_x I_m \sin[k(\frac{l_m}{2}+y')], -\frac{l_m}{2} \le y' \le 0 \end{cases}$$

where $\vec{I}_e$, l_e and $\vec{I}_m$, l_m are the current and length of the electric and magnetic dipole, respectively. The electric field of the electric dipole ($\vec{E_e}$) and magnetic dipole ($\vec{E_m}$) are then

$$\vec{E}_e = j\eta \frac{I_e e^{-jkr}}{2\pi r}(-\vec{a}_\theta \cos\theta\cos\varphi + \vec{a}_\varphi \sin\varphi)\cdot[\frac{\cos(\frac{kl_e}{2}\sin\theta\cos\varphi)-\cos(\frac{kl_e}{2})}{1-\sin^2\theta\cos^2\varphi}]$$

$$\vec{E}_h = j \frac{I_m e^{-jkr}}{2\pi r}(-\vec{a}_\theta \cos\varphi + \vec{a}_\varphi \cos\theta\sin\varphi)\cdot[\frac{\cos(\frac{kl_m}{2}\sin\theta\sin\varphi)-\cos(\frac{kl_m}{2})}{1-\sin^2\theta\sin^2\varphi}]$$

(2)

The total field of the two sources is a combination of the field in (2). Let A_1 and A_2 be the amplitude of $\vec{E_e}$ and $\vec{E_m}$, the total field is thus

$$E_\theta = -\cos\varphi\cdot\{A_1\cos\theta[\frac{\cos(\frac{kl_e}{2}\sin\theta\cos\varphi)-\cos(\frac{kl_e}{2})}{1-\sin^2\theta\cos^2\varphi}] + A_2[\frac{\cos(\frac{kl_m}{2}\sin\theta\sin\varphi)-\cos(\frac{kl_m}{2})}{1-\sin^2\theta\sin^2\varphi}]\}$$

$$E_\varphi = \sin\varphi\cdot\{A_1[\frac{\cos(\frac{kl_e}{2}\sin\theta\cos\varphi)-\cos(\frac{kl_e}{2})}{1-\sin^2\theta\cos^2\varphi}] + A_2\cos\theta[\frac{\cos(\frac{kl_m}{2}\sin\theta\sin\varphi)-\cos(\frac{kl_m}{2})}{1-\sin^2\theta\sin^2\varphi}]\}$$

(3)

It can be readily concluded that when $A_1 = A_2$ and $l_e = l_m$ are satisfied, the backward radiation ($\theta = \pi$) can theoretically be zero. Fig. 2 shows 2D and 3D radiation pattern of such half-wavelength complementary dipoles ($l_e = l_m = \lambda/2$).

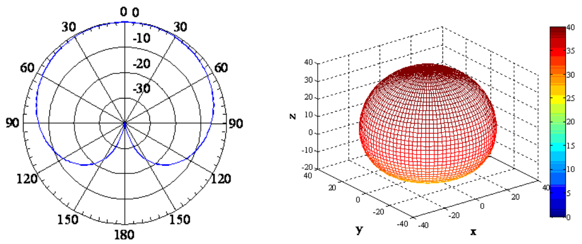


Figure. 1 The (a) E-plane and (b) 3D pattern of $\lambda/2$ complelemtary E- and M- dipoles

If the two dipoles are not excited with the same amplitude, an increased backward radiation is observed. This is illustrated in Fig.3, and the ratio of the field intensity with different feeding amplitude is listed in Table I. This indicates if one wishes to construct such a slot antenna with good unidirectional radiation, it is vital to apply a proper excitation amplitude ratio of the slot and its complementary electric dipole.

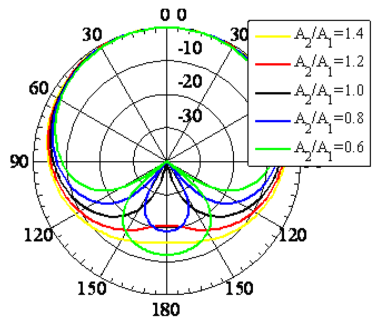


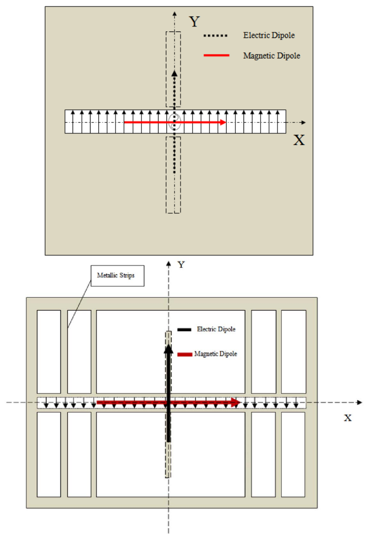
Figure. 2 $\lambda/2$ complelemtary E- and M- dipoles with different excitation amplitude

TABLE I

THE RATIO OF THE FIELD INTENSITY WITH DIFFERENT FEEDING AMPLITUDE

A_1 / A_2	1.4	1.2	1.0	0.8	0.6
$\frac{E_\theta \mid_{\theta=\pi}}{E_\theta \mid_{\theta=0}} (dB)$	15.5630	20.8279	∞	19.0849	12.0412

III. Practical Antenna Configuration and Preliminary Simulated Results



(a) (b)

Figure. 3 The configuration of the (a) idealized and (b) practical slot and its complementary E-dipole.

In section II, the radiation performance of an idealized complementary E- and M-dipoles has been discussed. However, when a practical antenna configuration is considered, the E-dipole can not be directly placed near the surface of the slot plane to form complementary dipoles. This is because, according to the image theory, an E-dipole near an parallel to a conducting plate has an image with opposite direction and thus the actual and image sources together produce very poor radiation. In [2], a conventional slot but with modified ground plane has been studied. It has been demonstrated that when the metallic conducting plate around the slot is replaced by a series of strips, the matching and radiation performance of the slot is not significantly altered. Therefore, when the E-dipole is orthogonally placed near such a slot, as shown in Fig. 3 (b), it is reasonable to believe that its radiation properties, particularly along the ground plane surface normal, will almost keep unchanged.

From the practical configuration point of view, the antenna in Fig. 3 (b) can be taken as a combination of two parts, a slot on a finite ground plane and an E-dipole surrounded by a metallic frame. In this paper we only conduct separate full-wave simulation for these two parts, and investigate the combination of their radiation pattern.

Fig. 4 and Fig. 5 show our model in CST and corresponding 3D radiation pattern of the slot and E-dipole, respectively. In accordance with Fig. 3, the E-dipole and slot are along x and y axis, respectively, and they both are excited by a discrete port (voltage source of 1V). One sees that, with the existence of the surrounding metallic frame, the radiation of the E-dipole on the metallic plane (also the plane of the slot) is zero. As to the slot radiator, the finite plane also brings a radiation null on this plane and introduces ripples on the E-plane as well [4]. However, one sees that the radiation property in $\pm z$ direction is not significantly altered, and this allows us to believe that a unidirectional pattern can still be obtained by a combination of such two patterns (if proper excitation ratio of the two sources is applied).

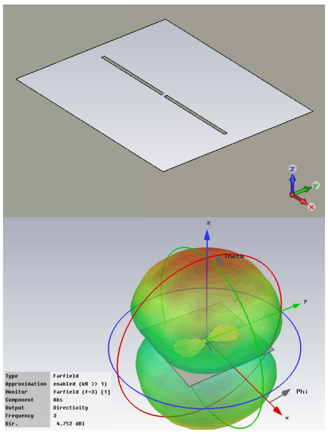


Figure. 4 The (a) CST model and (b) simulated 3D radiation pattern of the E-dipole with a surrounded metallic frame.

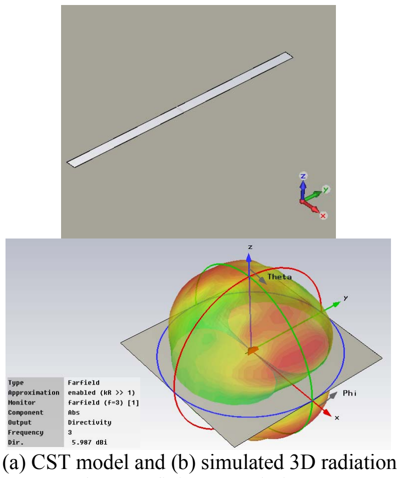


Figure. 5 The (a) CST model and (b) simulated 3D radiation pattern of the slot on a finite ground plane.

As discussed in section II, the backward radiation suppression largely depends on the excitation amplitude of the slot and the E-dipole, which is denoted by k in what follows. Fig. 6 shows the E-plane radiation pattern of the separate E-dipole, slot and their combination when k=0.96. One sees that in this case, the backward radiation is greatly suppressed, and particularly, the radiation in $\theta=\pi$ is theoretically zero. Two tiny side lobes are observed, which comes from the incomplete field cancellation. In fact, the pattern is very alike to the cardiac pattern in Fig. 1, except that due to the ground plane effect, radiation along this plane ($\theta=\pi/2, 3\pi/2$) is also zero. In fact, the magnitude of back lobes can be regulated by k. Fig. 7 plots the combined pattern of the complementary E-dipole and slot on the E-plane when k is set to be three different values, and one sees that an optimized k (around 1.4) can be obtained to keep all three back lobes equally small (Fig. 7 (b)).

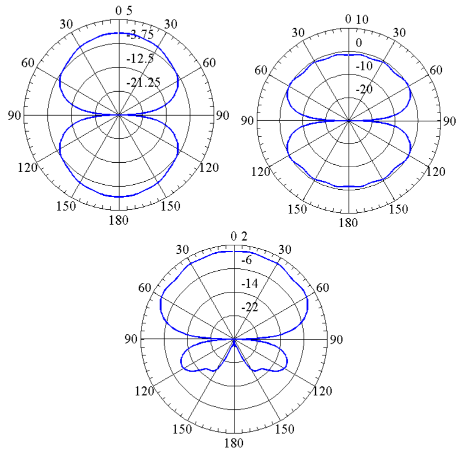


Figure. 6 The E-plane pattern of (a) the E-dipole, (b) the slot, and (c) their combination.

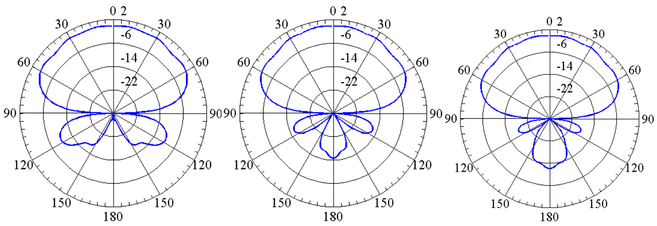


Figure. 7 The E-plane pattern of the complementary E-dipole and slot when k is (a) 0.96, (b) 1.4, and (c) 1.6, respectively.

Here in this paper we only report our idea and some preliminary simulated results. The next step of our work includes the arrangement of the feeding for the practical structure, elimination of mutual coupling of the two sources, and fabrication and measurement, and these are currently under study.

IV. Conclusion

Based on the complementary dipole concept, a novel scheme for constructing low-profile unidirectional slot antennas has been proposed. Preliminary study shows that when the original slot and its complementary E-dipole are excited with proper amplitude, unidirectional radiation with low backward radiation can be achieved. Compared to conventional unidirectional slot techniques, the proposed structure has several advantages such as low profile, low Q, and ease of fabrication.

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