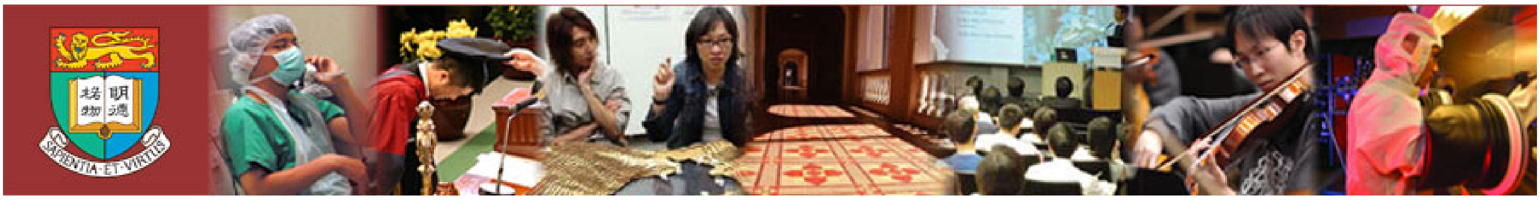

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Unveiling Magnetic Dipole Radiation in Phase-Reversal Leaky-Wave Antennas

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***Abstract*—The radiation principle of traveling-wave-type phase-reversal antennas is explained in detail, unveiling the presence of magnetic-dipole radiation in addition to well-known electric dipole radiation. It is pointed out that such magnetic-dipole radiation is specific to the case of traveling-wave phase-reversal antennas, whereas only electric-dipole radiation exists in resonant-type phase-reversal antennas. It is shown that a phase-reversal traveling-wave antenna alternately operates as an array of magnetic dipoles and an array of electric dipoles during a time-harmonic period. This radiation mechanism is confirmed through both full-wave and experimental results.**

***Index Terms*—Balanced transmission line, full-space scanning, leaky-wave antenna, phase-reversal, magneto-electric antennas.**

I. Introduction

PERIODIC leaky-wave structures are a versatile class of traveling-wave antennas capable of frequency-controlled beam steering, offering high directivity and simple feeding mechanism [1]. With the advent of composite right/left-handed (CRLH) leaky-wave antennas capable of full-space scanning, from backward to forward including broadside directions, there has been a renewed interest in such structures [2]. Full-space scanning was made possible by suppressing the open stopband and equalizing the impedance around broadside [2]–[4]. Following these advances, periodic leaky-wave antennas have become most attractive as a low-cost alternative to phased array antennas [5].

One approach to achieve a full-space beam scanning in leaky-wave structures is to use the phase-reversal technique. This technique involves introducing a 180° phase shift along the axis of the structure, so that $\lambda_g/2$-spaced periodical elements get excited in phase and therefore radiate. This technique is common in slot-waveguide antenna arrays where the required extra 180° phase shift is induced by proper location of the slots along the waveguide aperture [6]. A transmission-line counterpart of this structure is the Sterba-curtain antenna, which utilizes periodic transmission-line crossovers, placed $\lambda_g/2$ apart, to produce electric-dipole radiation from the crossovers [7]. However,

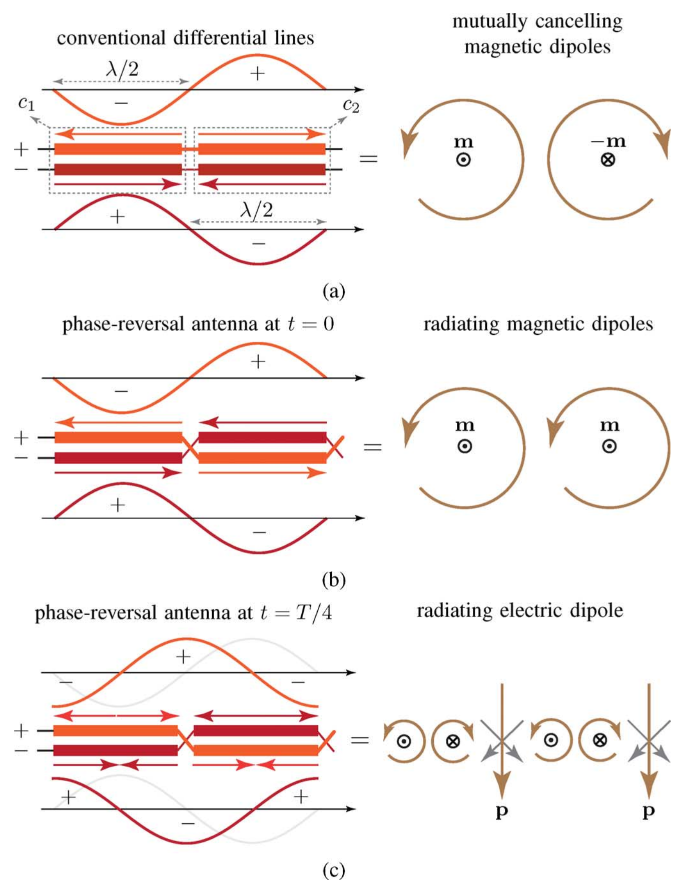

Fig. 1. Principle of phase-reversal antenna explained in terms of current distributions in two adjacent unit cells. (a) Differential transmission line without phase reversal. (b) Phase-reversed differential lines at $t = 0$ and (c) at $t = T/4$, where $T = 1/f_0$ is the time period of an assumed time-harmonic signal of frequency f_0.

these waveguide and transmission-line antennas were *resonant* in nature and therefore featured a small impedance-matching bandwidth product [8], [9]. This phase reversal concept was later extended to *traveling-wave* configurations, thereby both improving the impedance-matching bandwidth performance and providing full-space scanning. This configuration uses periodic phase-reversal radiating elements interconnected by balanced transmission-line sections [10].

While the radiation mechanism of traditional transmission-line-type phase-reversal antennas is well understood in resonant configurations and extensively discussed in the literature [11], *traveling-wave* phase-reversal antennas have not been exhaustively explored. Specifically, they have been described in terms of electric-dipole radiation only [10]. In this letter, the radiation mechanism of a traveling-wave-type

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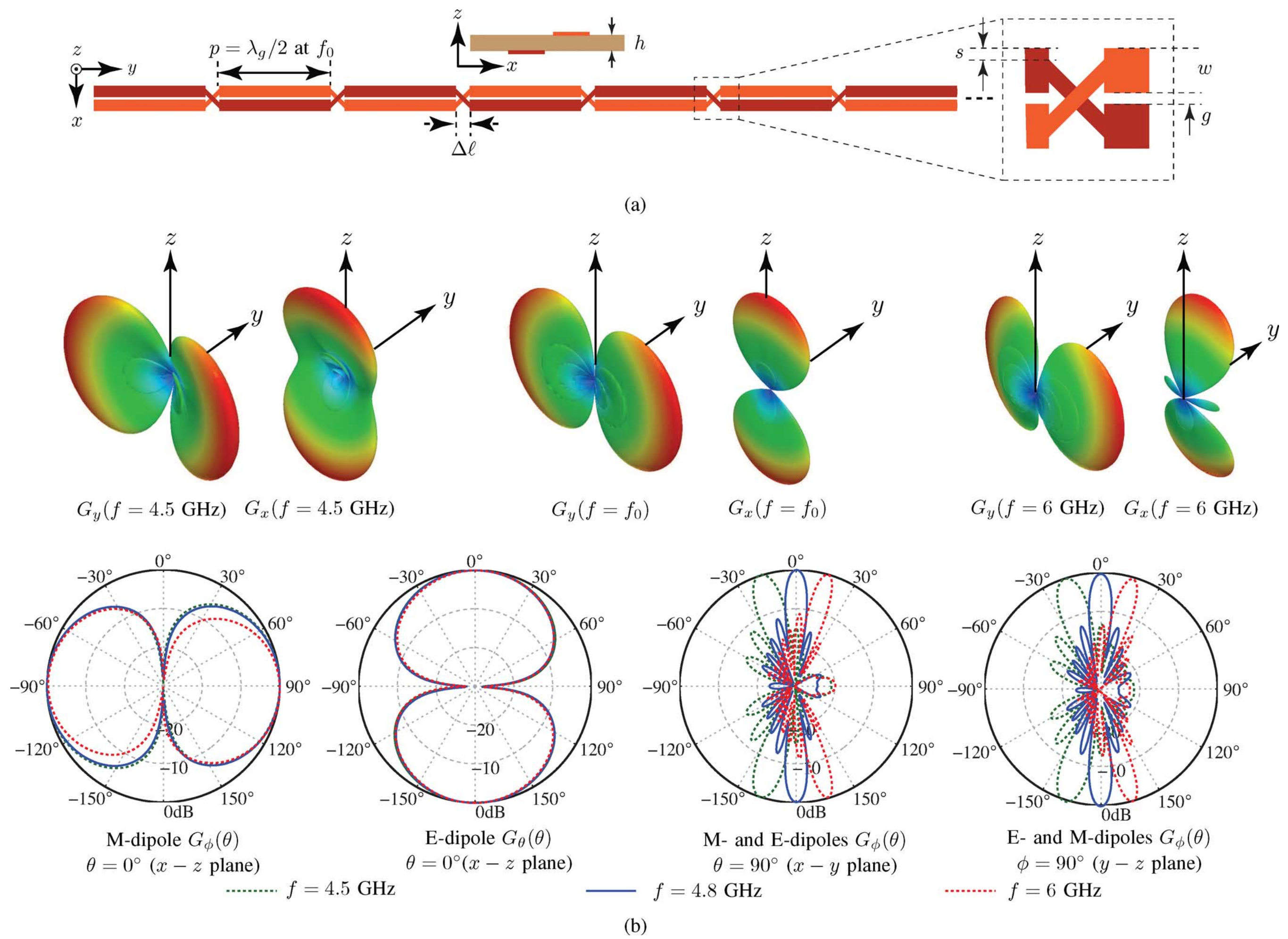

Fig. 2. Planar transmission-line implementation of a phase-reversal leaky-wave antenna and its typical radiation pattern characteristics [10]. (a) Antenna layout. (b) 3-D polar plot and the corresponding 2-D radiation patterns in three principal cuts, computed using FEM-HFSS. The broadside frequency $f_0 = 4.8$ GHz. The structural parameters are the same as in Fig. 4.

phase-reversal antenna is revisited in details and unveils the presence of *magnetic-dipole radiation* operating in conjunction with electric-dipole radiation. This dual-radiation mechanism is specific to traveling-wave-type phase-reversal antennas and does not exist in their resonant counterpart. They fall in the category of magneto-electric dipole antennas, where the electric and magnetic dipoles radiate together from a single radiating structure [12], [13]. The detailed principle of the phase-reversal antennas is explained next.

II. Principle of a Phase-Reversal Leaky-Wave Antenna

Consider a matched transmission line consisting of two closely spaced conductors of length $\ell = \lambda$ at a frequency f_0, as shown in Fig. 1(a). This transmission line can be considered as two half-wavelength-long lines connected in tandem via an ideal transmission line of zero length. Such a line supports a differential mode since the current distributions on the top and bottom conductors are mirror images of each other. In such a configuration, the pair of parallel half-wavelength transmission lines may be seen as one-wavelength-long current loops, c_1 and c_2, forming two adjacent magnetic dipoles, $\mathbf{m}$, as illustrated in Fig. 1(a). These two magnetic dipoles are *anti-parallel*, and therefore do not radiate since they produce mutually canceling far fields.

Fig. 1(b) shows a modified configuration of the differential line, where a π-phase shift, commonly called phase reversal, is introduced by crossing the connections between the conductor pairs. Consider a time-harmonic signal of period T. At a certain time instant $t = 0$, the two adjacent magnetic dipoles become *parallel* to each other, as a result of phase reversal that produces magnetic-dipole far-field radiation. At that instant, the currents in the crossover region are minimal and out of phase, and therefore do not radiate. The phase-reversal antenna may thus be seen as a series-fed array of magnetic-dipole antennas at time $t = 0$.

At a later time instant $t = T/4$, the current distribution on the phase-reversal antenna changes as shown in Fig. 1(c). In this case, the current currents are maximum and in-phase at the crossover region, leading to the formation of a radiating electric-dipole moment, $\mathbf{p}$, perpendicular to the axis of the lines. While part of the current distribution on the transmission lines may be mapped to small current loops, the corresponding adjacent magnetic-dipole moments are out of phase and therefore do not radiate. The phase-reversal antenna may thus be seen as a series-fed array of electric-dipole antennas, at time $t = T/4$ [10].

III. Radiation Characteristics and Results

Based on the above explanation, it is clear that a phase-reversal antenna is based on two distinct radiation mechanisms. It alternates between magnetic-dipole radiation and orthogonally polarized electric radiation, with a combination of the two in between these two instants. To further investigate the radiation properties of a phase-reversal leaky-wave antennas, it is designed in planar transmission-line technology, as shown in Fig. 2(a). The antenna consists of two conducting strips on each side of a dielectric substrate, with a strip width w and offset g, to form a transmission line of characteristic impedance Z_0. The crossover region is realized using a small transmission-line section of length $\Delta\ell$ with an impedance Z_c such that $Z_c \neq Z_0$. This crossover region with an impedance step acts as a matching element to suppress the well-known open stopband, typical of periodic structures [1], as proposed and demonstrated in [10]. Under the condition of complete stopband suppression, there is a zero phase shift across the unit cell at the design frequency, f_0, which is sometimes also referred to as the transition frequency of the antenna, corresponding to peak radiation at broadside.

Typical radiation patterns for the phase-reversal leaky-wave antenna at the transition frequency are shown in Fig. 2(b), shown also in a 3-D polar plot for better visualization. The electric- and magnetic-dipole radiation components are clearly apparent in the xz-plane. While an x-directed electric dipole, from the crossovers, produces a maximum along the z-axis, the z-directed orthogonally polarized magnetic dipole produces a null in this direction. Similarly, a magnetic dipole maximum along the x-axis aligns with the minimum of the x-directed electric dipole. In the other two planes, the magnetic-dipole component of the phase-reversal antenna with a maximum along the x-direction forms a directive beam in the xy-plane, and its orthogonally polarized electric-dipole component with a maximum along the z-direction forms a directive beam in the yz-plane. These two planes are also the frequency-scanning planes where the magnetic-dipole array and the electric-dipole array scan in the xy- and the yz-planes, respectively as seen in Fig. 2(b). Furthermore, it is to be noted that the structure radiates a fan beam while radiating broadside, and a conical beam off-broadside in forward and backward radiating regions.

Considering that this phase-reversal antenna ideally consists of two *orthogonally polarized electric and magnetic dipole radiators*, which are radiating in *quadrature*, as explained in Section I, one can suspect a presence of a circularly polarized radiating wave from this structure. Consider the radiation patterns corresponding to the electric and magnetic dipole radiation in the xz-plane, as shown in Fig. 3(a). The two patterns intersect at four distinct angles in this plane, where electric- and the magnetic-dipole gains are equal, thereby satisfying the third condition for obtaining a circularly polarized wave. However, the computed axial ratio shown also in Fig. 3(a) indicates an elliptically polarized wave with an axial ratio (AR) around 2, instead of a circularly polarized wave. This can be explained by considering two ideal radiators, orthogonal in space and radiating in quadrature, as illustrated in Fig. 3(b). When these two radiators are *collocated* in space, the two waves emanating from them maintain the quadrature phase relationship as they

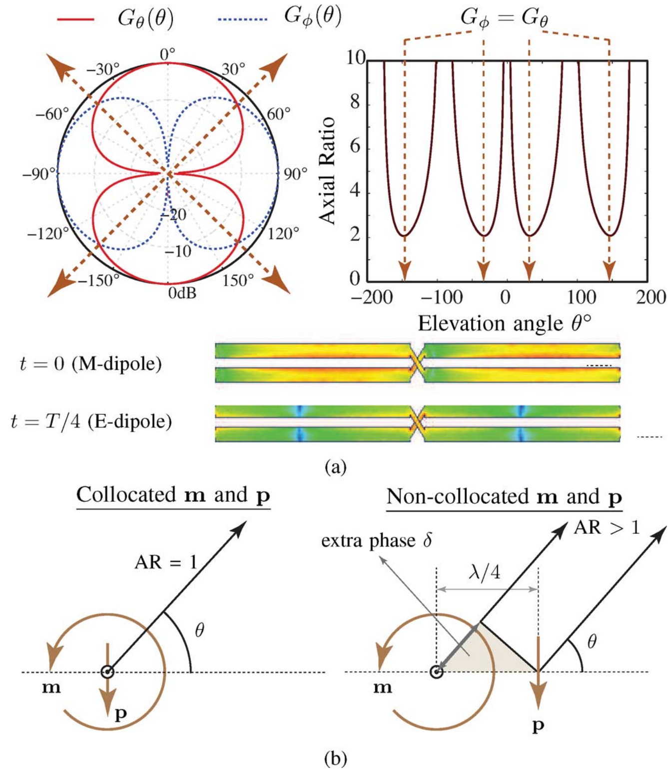

Fig. 3. Explanation for elliptic radiation in the xz-plane ($\phi = 0°$) of the phase-reversal antenna of Fig. 2. (a) Radiation patterns, axial ratio, and the current distribution on a small section of the structure at the transition frequency $f_0 = 4.8$ GHz. (b) Phase relationship between two collocated and noncollocated $\mathbf{m}$ and $\mathbf{p}$ dipoles radiators.

propagate in free space along a given direction, resulting in a perfect circularly polarized wave, i.e., $\mathrm{AR} = 1$. However, in the case of a phase-reversal antenna, the electric and the magnetic dipoles are *not collocated*, and their phase centers maybe considered $\lambda_g/4$ apart at the transition frequency f_0. This spatial separation introduces an extra phase shift $\delta \neq 2\pi$, which violates the quadrature phase relationship between the two radiators, along the same direction, as illustrated in Fig. 3(b). Furthermore, the finite lengths of the crossover region introduce more phase errors as seen from the current distributions of Fig. 3(a). Consequently, the phase-reversal antenna radiates an elliptically polarized wave along these four directions, rather than a purely circularly polarized wave.

To further confirm the radiation characteristics of the phase-reversal leaky-wave antenna, a prototype is built on an FR4 substrate ($\varepsilon_r = 4.4$ and $h = 0.8$ mm), as shown in Fig. 4(a). It is fed through a multistage quarter-wavelength transformer to excite the differential mode of the phase-reversal antenna using a 50-Ω microstrip feed [10]. Its measured return loss S_{11} is shown in Fig. 4(b) showing a satisfactory matching, with $S_{11} < -10$ dB within the band of interest. The corresponding radiation patterns in three principal plane cuts are plotted in Fig. 4(c). As expected, two distinct sets of radiation patterns, corresponding to the magnetic-dipole array and an electric-dipole array, are clearly seen in all planes with peak gains of 1.2 and 2.3 dB, respectively. A reasonable agreement is also observed between the measured and the full-wave simulated results, with a stronger agreement at higher gain values, due to higher measurement sensitivity.

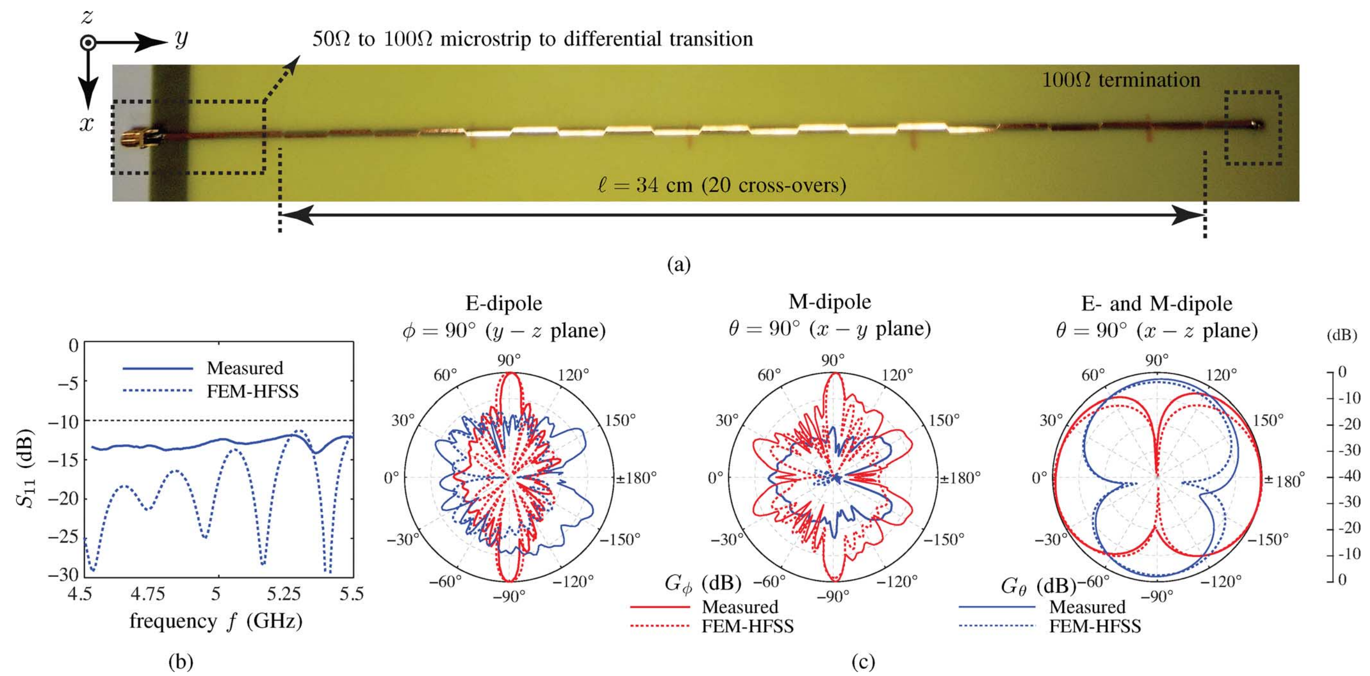

Fig. 4. Fabricated phase reversal antenna and measured results. (a) Photograph of the antenna. (b) Measured S-parameters. (c) Measured antenna gain. (d) 2-D radiation patterns in all three principal planes, for the transition frequency $f_0 = 4.8$ GHz. The layout parameters are as follows: $p = 16.51$ mm, $g = 0.8$ mm, $\Delta\ell = 1.27$ mm, $w = 1.27$ mm, $s = 0.254$ mm, and number of crossovers $N = 20$.

IV. Conclusion

The radiation principle of a traveling-wave-type phase-reversal antenna has been explained in detail, unveiling the presence of magnetic-dipole radiation that exists in addition to the electric-dipole radiation. This is in contrast to the resonant configuration where only electric-dipole radiation exists. It has been shown that the radiation characteristics of a phase-reversal antenna alternate between that of an array of magnetic dipoles and of an array of electric dipoles. While the crossover regions provide the electric-dipole radiation, the balanced transmission line between the crossovers form a wavelength-long current loop at the designed frequency, representing the magnetic-dipole radiation. This radiation principle has been confirmed using both full-wave and experimental results. This insight into the phase-reversal-type antenna highlights the complex radiation characteristics of phase-reversal antennas compared to what was previously understood and may lead to efficient and multifunctional leaky-wave antennas. The presence of a magnetic-dipole array radiation maybe seen as an undesired effect resulting in high cross polarization when the structure is operated as an electric-dipole array. To minimize this cross polarization will be a subject of future investigation.

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