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Timed Arrays for Radiating Impulse-Like Transient Fields

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Abstract

One approach to making a transient radiating and/or receiving antenna, involves a timed array which allows one to steer the beam without physically rotating the antenna. An array of interconnected elements (unit cells) can be used give a very broadband characteristic. Various designs of such unit cells are reviewed and discussed for single and dual polarization. The low-frequency part of the pulse spectrum is governed by the electric and magnetic dipole moments of the array and additional conductors (impedance loaded) connected to the array.

I. Introduction

As discussed in [18] one can make an impulse radiating antenna (IRA) by applying a step-function-like plane wave to some aperture of finite dimensions on a plane. This can be achieved in a practical way by launching a spherical TEM wave on a conical transmission line (two or more perfectly conducting cones with arbitrary cross sections and common apex) and then converting this spherical TEM wave to a planar TEM wave via a lens or a paraboloidal reflector. This is physically a single antenna with a single port (or two ports for dual polarization [19]) with a beam (pattern) fixed on a single direction. This beam can be steered by physically rotating the antenna.

Another way to synthesize this desired aperture field is by means of a planar array of antenna elements which turn on in a prescribed plane-wave sequence. Analogous to a phased array (a frequency-domain concept) one can have a timed array. If one can electrically vary the sequence of exciting the elements then one has what is referred to as electronically scanning the beam. The associated greater complexity of the antenna array has to be weighed against the performance improvements for the specific applications in mind.

This kind of timed array has various features in common with distributed sources (distributed switches, etc.) used in EMP simulation [1-4, 6-17, 22]. In such applications one is often concerned with matching the spatial distribution of the TEM mode on some waveguiding structure. For the present timed array this same kind of structure is appropriate for synthesizing the aperture distribution. Such distributed sources are not arrays of elementary dipoles since the individual elements or wave launchers are electrically connected together to allow current to pass through the entire array, thereby giving better low-frequency performance for wavelengths greater than the element spacing. The high-frequency performance is achieved by the use of conical-wave launcher (TEM-horn) concepts.

II. Arrays of Interconnected TEM Horns

There are many ways that conical transmission lines can be assembled to form an array, particularly for a single polarization [13]. Fig. 2.1 shows one of many. This is a staggered arrangement of symmetrical conical transmission lines with a period of 2b in the direction of the electric field and 2a transverse to this, these two dimensions defining a unit cell for the array. The unit cells can also be shifted to an in-line configuration. The cells need not be symmetric in that one of the conical plates can be replaced by a flat strip continuous from one cell to the next.

Dual polarization can be achieved by imposition of appropriate rotation and reflection symmetry C_{Na} [23] for the unit cells and array where the rotation axis (say the z axis) is perpendicular to the aperture plane and reflection planes contain this axis. As discussed in [3] this leads to three kinds of arrays based on the symmetries of the unit cells and the requirement that they fit into the array. These are equilateral triangular cells (C_{3a}), square cells (C_{4a}), and regular hexagonal cells (C_{6a}). Note that this restricted set of unit-cell geometries comes about by the additional imposition of translational symmetry among the unit cells of the array (translation group T_2 with two periods for discrete translation).

Figure 2.2 illustrates a few cells of a square array, suitable for dual polarization. There are two TEM conical structures in each cell to give the two polarizations (h (horizontal) and v (vertical) in radar parlance). As such there are two sources near each cell's conical apex to drive the two orthogonal field components. These can operate separately or in combination. The sources can be of various kinds. Note, however, the need not to place conductors (signal cables, low-impedance power-supply conductors, etc.) on paths which interfere with (short out) the array elements [1], whether in front of or behind the array. Another concept has high-voltage charging resistors distributed around the array in a form similar to a Marx generator [12]. There would then be capacitors near the source locations or at some other convenient positions in the cell for DC isolation, but high-frequency connectivity when switches are triggered. The switches (two per cell, one for each polarization) have to be triggered in the desired plane-wave sequence [18], using appropriately electrically isolated paths for the trigger signals (e.g. through the use of fiber optics). Note that the above considerations are for a transmitting array. For a receiving array the geometry of the antenna elements is the same, but there is the requirement to get the signals from the conical apexes to some position for processing and comparison (adjusting relative delays, etc.), again with the requirement that the signal transmission conductors not significantly interfere with the array.

The early-time/high-frequency performance of the array is governed by the design of the unit cells. For planar bicones ($\ell = 0$) the cell size (say 2b) gives a characteristic time t_1 with ct_1 of the order of b, limiting the far-field performance at high frequencies [10]. Basically t_1 represents the average rise time of the tangential electric field on the aperture plane (as compared to the desired step-rising plane-wave

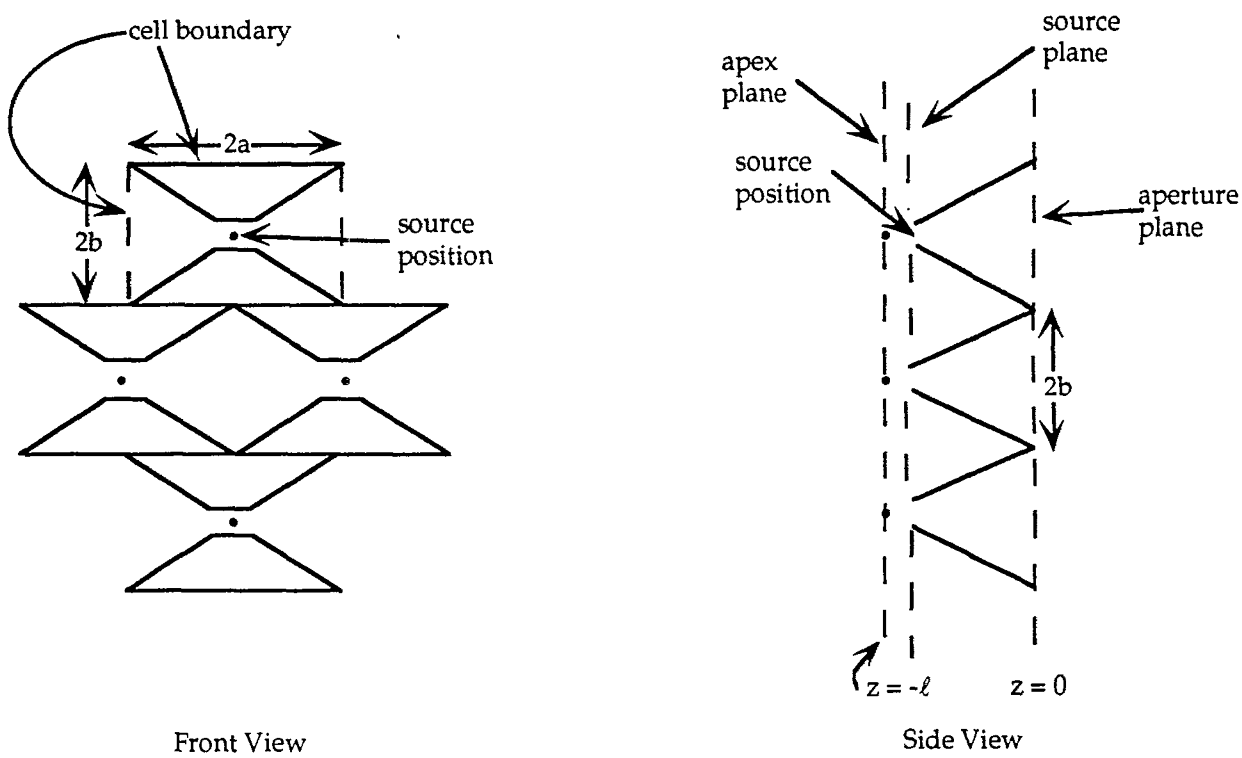
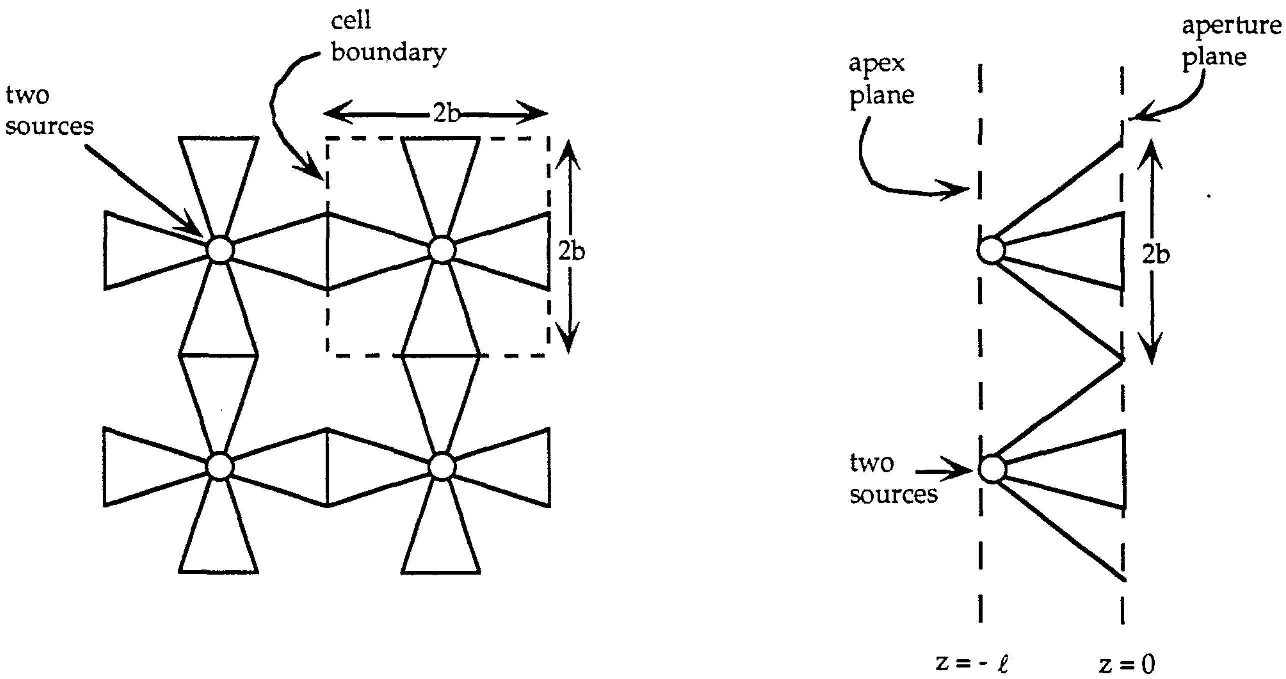


Fig. 2.1. Staggered Array of Flat-Plate Conical Wave Launchers in a Symmetrical Configuration.



Front View

Side View

Fig. 2.2. Square Cell Geometry for Dual Polarization.

field on the aperture). By moving the apex plane behind the aperture plane ($\ell > 0$) one can decrease t_1 [13], at least near boresight (direction normal to the aperture plane). Basically extending the apex behind the aperture makes the conical TEM wave arrive over the aperture plane, specifically the portion for one unit cell), at more nearly the same time [1]. Note, however, that for large ℓ/b there is a significant mutual interaction between the individual cells (wave launchers) before the wave reaches the aperture plane which may make it desirable to reshape the plates to deviate from a true conical shape [14-17, 22]. An alternate approach involves combining a lens with each TEM horn to match the wavefront with the aperture plane.

If, however, one steers the beam away from boresight, a uniform time of arrival of the fields on the aperture plane from an individual cell is not optimal. When compared to the optimal sweep of the desired plane wave across the aperture the field for an individual cell deviates from this for a time proportional to $2 \sin(\theta_0)\, b/c$ where θ_0 is the angle that the beam is steered away from the z axis. So making $\ell >> b$ may not be helpful if $\theta_0 > 0$ is desired to be a significant maximum angle of deviation of the beam from the array normal. As a rule of thumb one might make the dispersion time [1] across the cell aperture due to finite ℓ/b equal to the dispersion time above due to the sweep of the desired plane wave aperture field across a single cell. For faster time performance (narrower far-field impulse) and extension of the high-frequency performance, then one can reduce 2b, the size of the unit cell. For a given array area

$$A = N_c (2b)^2 \tag{2.1}$$

this increases the number N_c of cells (individual array elements). So this illustrates the trade off between complexity of the array and performance.

At high frequencies (early times for step-function excitation) the array is excited so as to radiate a beam in the $\vec{1}_o$ direction with

$$\vec{1}_o \cdot \vec{1}_z = \cos(\theta_o) \tag{2.2}$$

Now θ_0 may vary from 0° to some $\theta_{o_{\max}}$, say 45° or some other convenient angle. Depending on the details of the array design (e.g. number of elements) and the frequencies of interest one can have a modestly narrow beam centered on $\vec{1}_o$. One would like to $\theta_{o_{\max}}$, at least for the higher frequencies of interest. Otherwise, the beam steering and the array design has not achieved much.

III. Low-Frequency Behavior

For good low-frequency performance, as previously observed, the cells are designed to allow current flow between adjacent cells by appropriate interconnection. For wavelengths λ large compared to the array dimensions (say h x h), i.e. $\lambda >> h$, the array then acts as one large antenna with a total voltage of $-E_{tan}h$ where E_{tan} is the average tangential electric field over one unit cell in the direction of interest. If there are no additional conductors attached to the array, then we have an electric dipole moment as a charge times a distance which is proportional to $\epsilon_o E_{tan} h^3$. If the unit cells are not so interconnected, then the voltage $-E_{tan}2b$ for each cell is not additive along the array due to field reversal between the elements, thereby giving a much smaller electric dipole moment.

In order to increase this low-frequency (or late-time) electric dipole moment of the array one could add metal (or resistive extensions) as indicated in fig. 3.1. Of course this increases the overall size of the antenna array, but without additional complex elements. Note now that for single polarization one can use a metal sheet or mesh for the extension. However, for dual polarization one needs to be able to produce two electric dipole moments $\vec{p}^{(1)}$ and $\vec{p}^{(2)}$ associated respectively with tangential fields $\vec{E}^{(1)}$ and $\vec{E}^{(2)}$ on the array aperture. The extensions for one component should not interfere with the other component. One way to achieve this is to use conductive strips parallel to the direction of desired current flow. One should note that a parallel set of perfectly conducting strips (or wires) supports differential TEM modes of a number equal to one less than the number of strips. With open-circuit or short-circuit conditions at the ends this gives undesirable resonances. These can be suppressed (without allowing currents in the transverse direction) by insertion of series resistors in the strips (one or more in each strip) with positions chosen to damp as many modes as possible.

Instead of relying only on the electric dipole moment for the low frequencies one can construct balanced electric and magnetic dipole moments [5, 18, 20] such that

$$\vec{p}^{(1)} = p^{(1)} \vec{1}_x \quad , \quad \vec{m}^{(1)} = m^{(1)} \vec{1}_y \quad , \quad p^{(1)} = \frac{m^{(1)}}{c}$$

$$\vec{p}^{(2)} = p^{(2)} \vec{1}_y \quad , \quad \vec{m}^{(2)} = -m^{(2)} \vec{1}_x \quad , \quad p^{(2)} = \frac{m^{(2)}}{c} \tag{3.1}$$

$$\vec{1}_x \times \vec{1}_y = \vec{1}_z \quad \text{(unit normal to array aperture)}$$

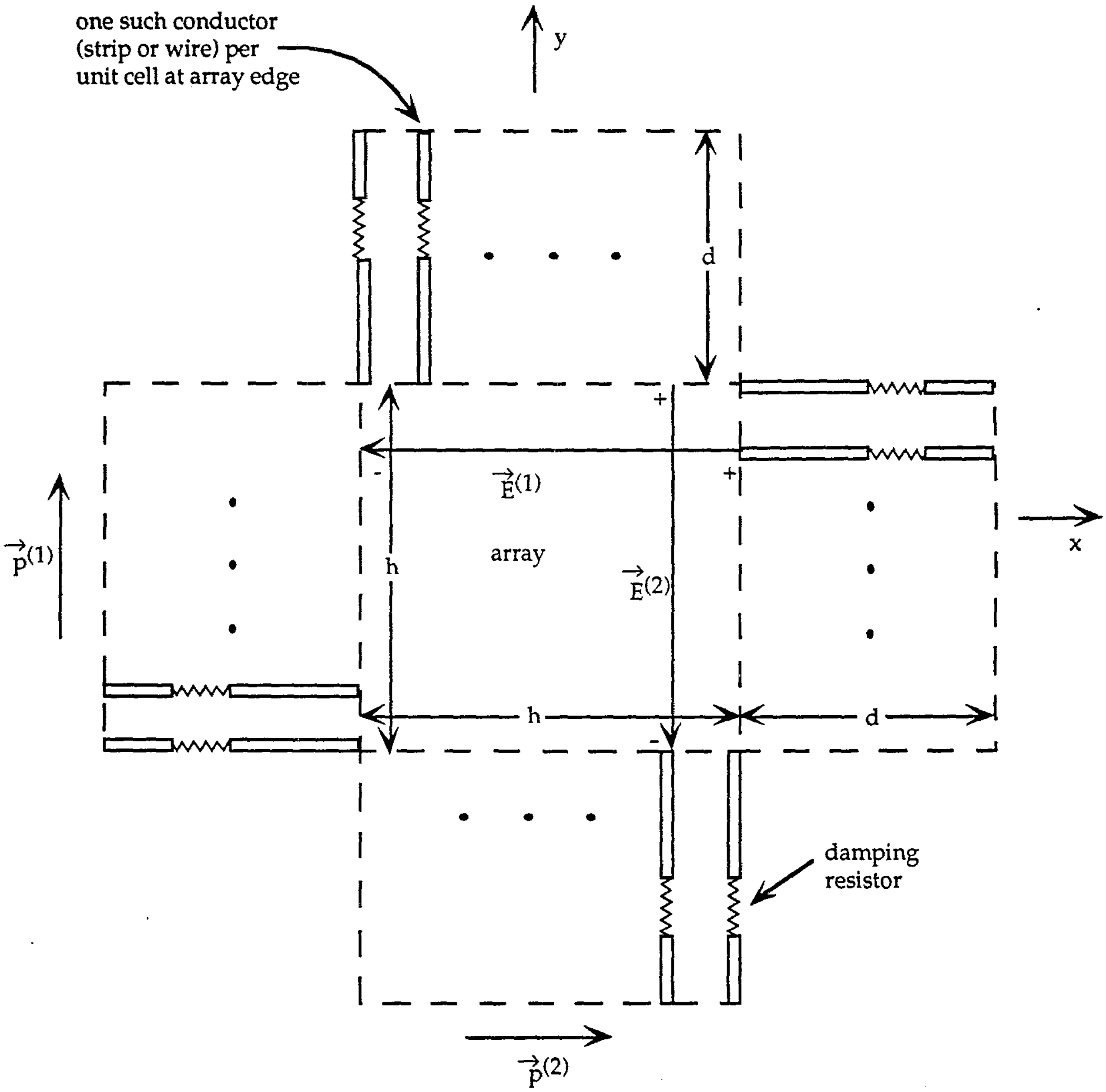


Fig. 3.1. Extensions of Array for Increased Low-Frequency Electric Dipole Moment

Here the low-frequency radiation is in the $\vec{p} \times \vec{m}$ direction (i.e. in the $\vec{1}_z$ direction normal to the array aperture) for both polarizations. As indicated in fig. 3.2, one way to realize this performance involves extending conducting strips or wires from the unit-cell conductors at the array edges back from the array aperture (i.e. in the $-\vec{1}_z$ direction) say a distance ℓ to an array of terminating resistors on the $z = -\ell$ plane. Note that when one polarization is excited (say the direction indicated by superscript 1), then the charge separation produces a $\vec{p}^{(1)}$ in the $\vec{1}_x$ direction and the current $I^{(1)}$ produces a loop giving an $\vec{m}^{(1)}$ in the $\vec{1}_y$ direction. Adjusting the values of the terminating resistors the condition in (3.1) can be achieved. Allowing for the fringe fields the equivalent sheet resistance will not be precisely Z_0 $(\simeq 377\ \Omega)$, but this requires more detailed calculations and/or measurements. Note that the resistor array in fig. 3.2C, when operated in the "1" polarization has the strips for the "2" polarization in a configuration which does not short out the sources for the "1" polarization, as these strips are made to float on equipotentials (at low frequencies).

Compared to the beam steering in the $\vec{1}_0$ direction discussed in the previous section for high frequencies, the low-frequency radiation is dominated by dipole moments which give very broad patterns. Some improvement is gained by the combined electric and magnetic dipoles as in fig. 3.2 by producing a null in the $-\vec{1}_z$ direction, but the cardioid-like pattern is still rather broad [20]. For practical θ_0 as in (2.2) the narrow-beam high-frequency portions are still within the broad low-frequency "beam". One may decide to accept this performance or design yet more elaborate antenna structures to steer the low-frequency dipole moments to make $\vec{p} \times \vec{m}$ point in the $\vec{1}_0$ direction.

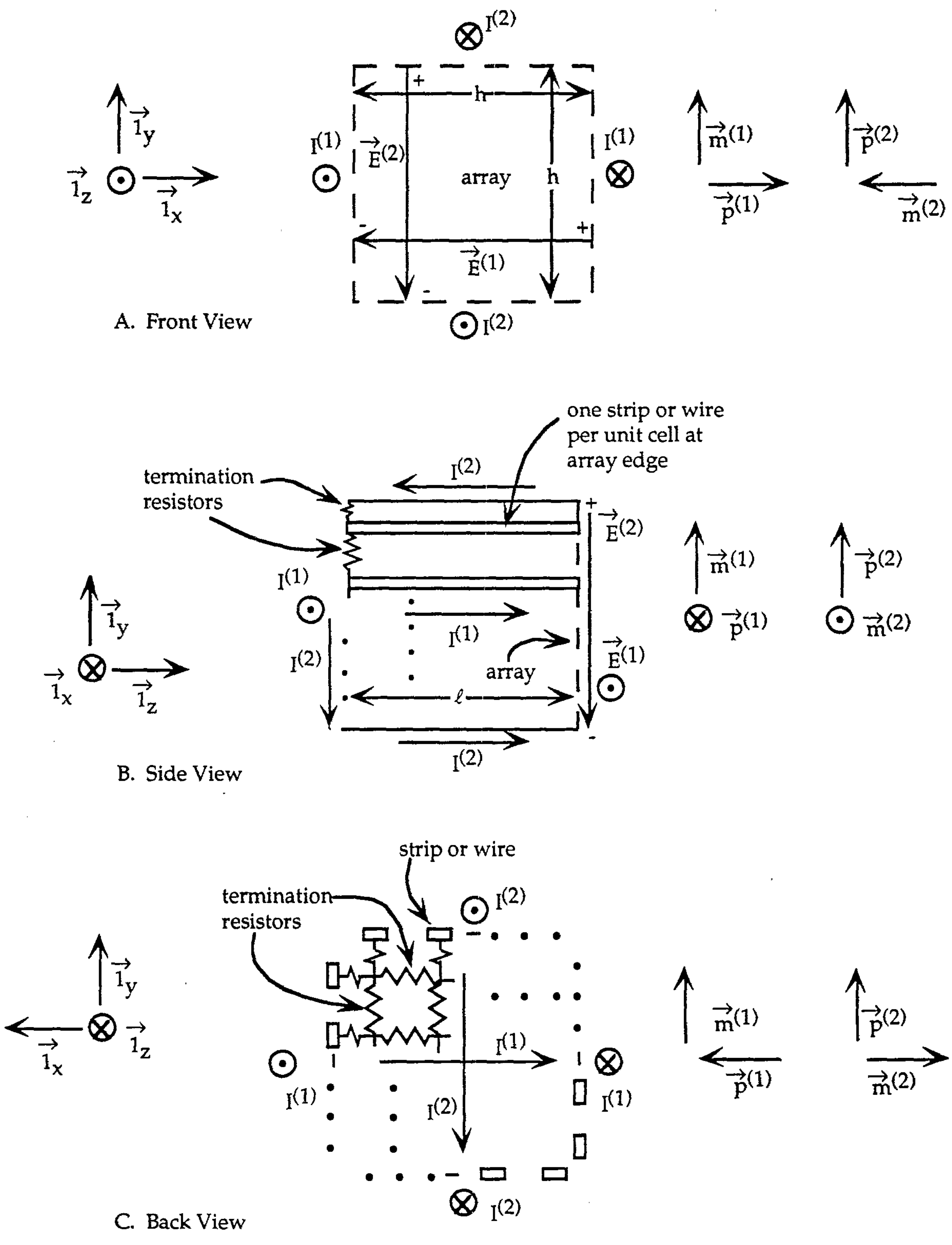


Fig. 3.2. Extensions of Array for Balanced Low-Frequency Electric- and Magnetic-Dipole Moments

IV. Concluding Remarks

There are many details of the design of such transient arrays to be worked out. They are much more complex than, for example, a reflector IRA. What they potentially offer is the capability of electronic beam steering in transmission and reception. However, it is easier to make a narrow steered beam at high frequencies than at low frequencies. For certain applications, such as radar target identification, a broad range of frequencies (perhaps covering a decade) in the radiated transient is sometimes very desirable. This whole subject of appropriate parameters for describing the performance of this class of transient antennas is discussed in [21]. There is still much to be done in the characterization of such transient antennas, including the influence of the associated frequency spectrum, both in transmission and reception.

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