SERIES-FED-TYPE LINEAR ARRAYS OF DIPOLE AND SLOT ELEMENTS TRANSVERSELY COUPLED TO A MICROSTRIP LINE†

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1. Introduction

Printed dipole elements and their complement, linear slots, are elementary radiators that have found use in low-profile antenna arrays. Low-profile antenna arrays, in addition to their small size and low weight characteristics, offer the potential advantage of low-cost, high-volume production with easy integration with active integrated circuit components. Such dipole and slot elements may be used in dipole and slot series-fed-type linear arrays where line losses must be kept to a minimum. Specifically, an active K/K_a-band antenna array is currently under development for NASA's ACTS Mobile Terminal (AMT) [1-2]. Satellite tracking for the land-mobile vehicular antenna system involves "mechanical dithering" of the antenna, where the antenna radiates a fixed beam 46° above the horizon, transmitting horizontal polarization] and receiving vertical polarization at 30 and 20 GHz, respectively. The AMT active antenna array, as shown in Figure 1, is a multi-layered assembly in which a receive array of radiating slots and and transmit array of microstrip dipoles are interleaved such that they share the same aperture to provide a compact, dual band antenna.

The subarrays of the above antenna are linear series-fed-type arrays consisting of nearly identical dipole, or slot, elements transversely electromagnetically coupled to a microstrip transmission line. The design of the linear series-fed-type arrays is achieved using transmission line theory with equivalent circuit models for the radiating elements. The element offsets and interelement line lengths are used to obtain the desired amplitude distribution and beam direction, respectively. Summarized in the following are the design and test results of both a dipole and slot series-fed-type linear array, assuming the impedance characteristics of the radiating elements are known.

2. Interelement Line Length for Linear Array

Consider a "symmetrically-fed" linear dipole and slot arrays shown in Figures 2 and 4, respectively, where the spacing between elements is d and the length of the interconnecting transmission line is $\ell > d$. To direct the main beam at the proper scan angle θ_0, measured from broadside, or normal to the antenna, the following phase relationship (using $e^{j\omega t}$ time dependence) between the elements should be satisfied

$$\psi = -\beta\ell = +k_0 d \sin\theta_0 - m\pi \qquad m \text{ an even integer} \tag{1}$$

where $\beta = k_0\sqrt{\epsilon_{r,\mathrm{eff}}}$, $k_0 = 2\pi/\lambda_0$ is the free space wavenumber, λ_0 is the free space wavelength, and $\epsilon_{r,\mathrm{eff}}$ is the effective dielectric constant. (For an "anti-symmetrically-fed" linear dipole array, m would be an odd integer.) To minimize ℓ, i.e., minimize line loss, the above equation is solved when $\ell = d$ to obtain

$$\frac{\ell}{\lambda_0} = \frac{m/2}{\sqrt{\epsilon_{r,\mathrm{eff}}} + \sin\theta_0} \tag{2}$$

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3. Dipole Linear Array Design

In an equivalent circuit model of a linear array of N series-fed-type dipoles [3], each dipole i represents a shunt impedance, $Z_i = R_i + jX_i$, to the transmission line as show in Figure 3, where Z_i is a function of the dipole offset, length, and width. The transmission line is characterized by its characteristic impedance Z_0 and propagation constant $k = \beta - j\alpha$, where α is the attenuation constant. Each dipole is to be operated at resonance, such that $Z_i = R_i$, where the desired value of R_i is obtained by selecting the appropriate offset δ_i. A unit cell of the array of length ℓ, determined by (2), may be defined as shown in Figure 6. The voltage and current on the transmission line of the unit cell are given by

$$\begin{aligned} V(z_i) &= V_{i+1} e^{-jkz_i}\left[1 + \Gamma_{L,i} e^{j2kz_i}\right] \\ Z_0 I(z_i) &= V_{i+1} e^{-jkz_i}\left[1 - \Gamma_{L,i} e^{j2kz_i}\right] \end{aligned} \tag{3}$$

where

$$\Gamma_{L,i} = \frac{Z_{L,i} - Z_0}{Z_{L,i} + Z_0} \tag{4}$$

$$Z_{L,i} = Z_i \parallel Z'_{L,i-1} \tag{5}$$

$$Z'_{L,i-1} = \frac{Z_{L,i-1} + jZ_0 \tan k\ell}{jZ_{L,i-1} \tan k\ell + Z_0} Z_0 \tag{6}$$

By taking the ratio of V_{i+1}/V_i

$$\frac{V_{i+1}}{V_i} = \frac{V(z_i = -\ell)}{V(z_i = 0)} = \frac{\left[1 + \Gamma_{L,i} e^{-j2k\ell}\right]}{\left[1 + \Gamma_{L,i}\right]} e^{jk\ell} \tag{7}$$

a recursive expression for the voltage at successive points along the array is obtained. The power dissipated in each dipole radiator is given by $P_i = |V_i|^2/(2R_i)$. For a given amplitude distribution, $\sqrt{P_i}$ $(i = 1, 2, \ldots, N)$, a given transmission line length $k\ell$ and R_1, the desired resonant resistances R_i are specified by the following recursive expression

$$R_i = \frac{1}{2}\frac{|V_i|^2}{P_i} = \frac{1}{2}\frac{|V_{i-1}|^2}{P_i}\frac{|1 + \Gamma_{L,i-1} e^{-j2k\ell}|^2}{|1 + \Gamma_{L,i-1}|^2} \tag{8}$$

When the main beam direction is broadside, or normal, to the antenna, $\theta_0 = 0$, R_1 ***should*** be specified larger than Z_0 to maintain a good input impedance match to the array. For a main beam direction off broadside, $\theta_0 \neq 0$, R_1 is set equal to Z_0 to prevent reflections that result in a second, undesired scanned beam. It should be noted that the above equation (8) accounts for multiple reflections on the transmission line, resulting in a progressive phase shift along the radiating elements that nearly approximates that specified by equation (1).

4. Slot Linear Array Design

Similarly, in an equivalent circuit model of an array of series-fed-type slots [4], each slot i represents a series impedance, $Z_i = R_i + jX_i$, to the transmission line as shown in Figure 5. A unit cell of the array may be defined, as shown in Figure 6, similar to that of the dipole array, with the exception that

$$Z_{L,i} = Z_i + Z'_{L,i-1} \tag{9}$$

By taking the ratio of I_{i+1}/I_i and noting that the power dissipated in each slot radiator is $P_i = |I_i|^2 R_i/2$, a recursive expression for the slot resistances R_i is given by

$$R_i = \frac{2P_i}{|I_i|^2} = \frac{2P_i}{|I_{i-1}|^2}\frac{|1 - \Gamma_{L,i-1}|^2}{|1 - \Gamma_{L,i-1} e^{-j2k\ell}|^2} \tag{10}$$

when the amplitude distribution, $\sqrt{P_i}$ $(i = 1, 2, \ldots, N)$, the transmission line length $k\ell$, and R_1 are specified.

5. Experimental Results

A linear, cavity-backed slot array, consisting of 8 elements with an interelement spacing of $0.46\lambda_0$, has been fabricated and tested, operating at 20 GHz with a main beam direction approximately 40° from broadside. The slot elements were characterized both theoretically and experimentally as a function of offset, with the experimental characterization performed using TRL calibration techniques. Due to the fact that the element resonant frequency is a function of Offset, the element slots lengths are all slightly different. Shorting pins are used to suppress undesirable cavity modes. As shown in Figure 7, good agreement between predicted and measured patterns was obtained. Total loss in the slot array was measured to be approximately - 1.3 dB. (Note that the loss of a shielded microstrip line is measured to be approximately -0.24 dB/λ_0.) Experimental results will be presented for a similar linear series-fed-type array of dipoles operating at 30 GHz.

6. References

[1] "AMT Active Array Antenna System Design," A. Tulintseff, R. Crist, L. Sukamto, and A. Densmore, JPL IOM 3365-91-094 (internal document), Sep. 24, 1991.

[2] "Two K/K_a-band mechanically steered, land-mobile antennas for the NASA ACTS Mobile Terminal," A. Densmore, V. Jamnejad, A. Tulintseff, R. Crist, T.K. Wu, and K. Woo, *ACTS Conference '92 Proceedings*, pp. 177-188, Washington, DC, Nov. 18-19, 1992.

[3] "Analysis and design of series-fed arrays of printed-dipoles proximity-coupled to a perpendicular microstripline," N. K. Das and D. M. Pozar, *IEEE Trans. AP*, 435-444, Apr. 1989.

[4] "A reciprocity method of analysis for printed slot and slot-coupled microstrip antennas," D. M. Pozar, *IEEE Trans. AP*, Vol. AP-34, No. 12, pp. 1439-1446, Dec. 1986.

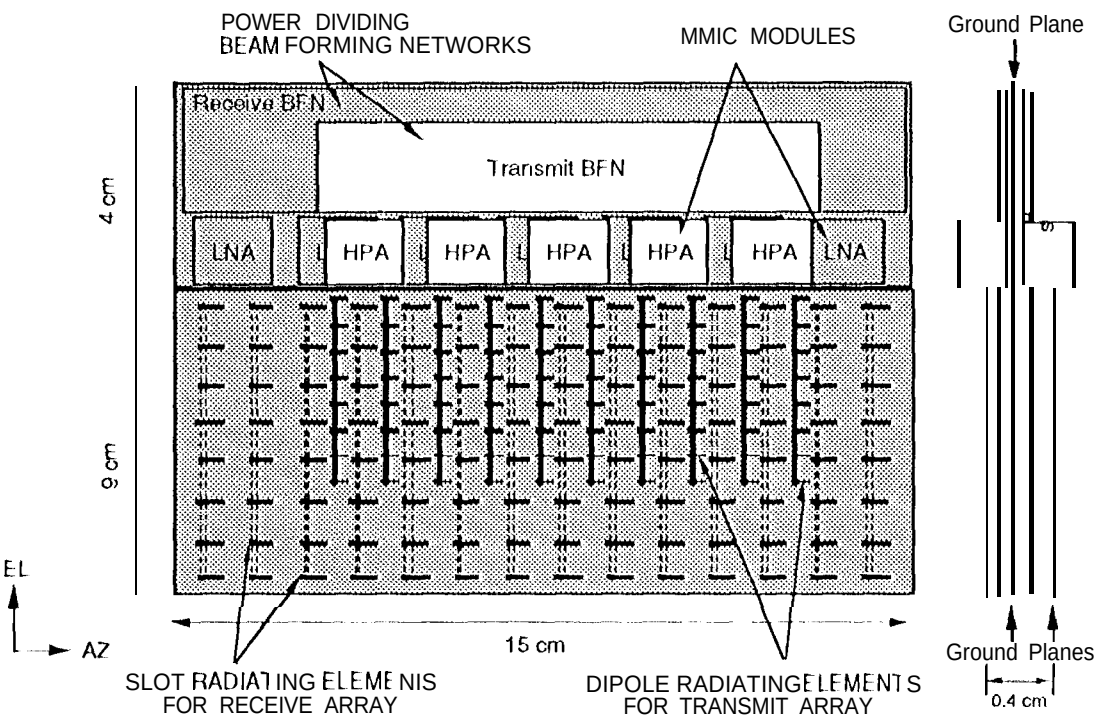

Figure 1. AMT active array of dipoles and slots.

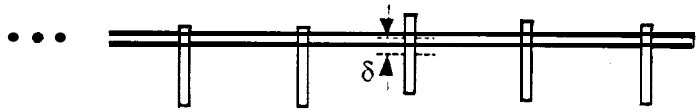

Figure 2. Linear dipole array.

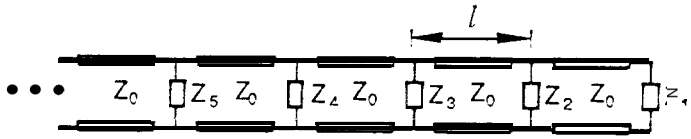

Figure 3. circuit for linear dipole array.

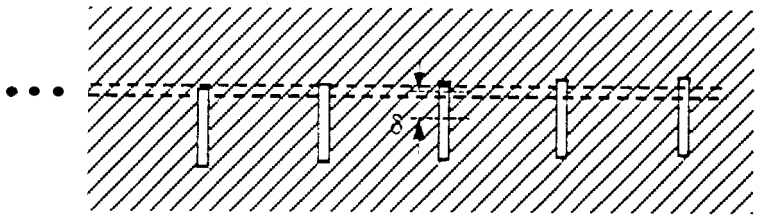

Figure 4. Linear slot array.

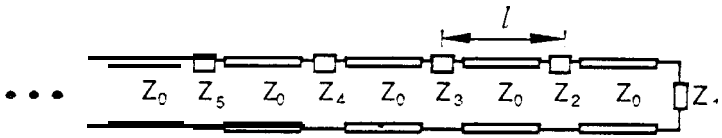

Figure 5. Equivalent circuit for linear slot array.

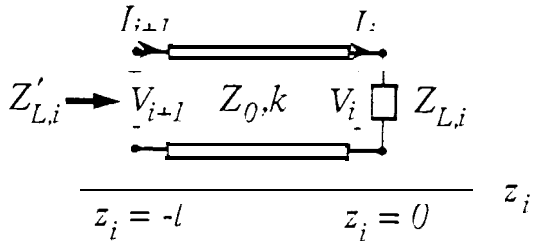

Figure 6. Linear array unit cell equivalent circuit.

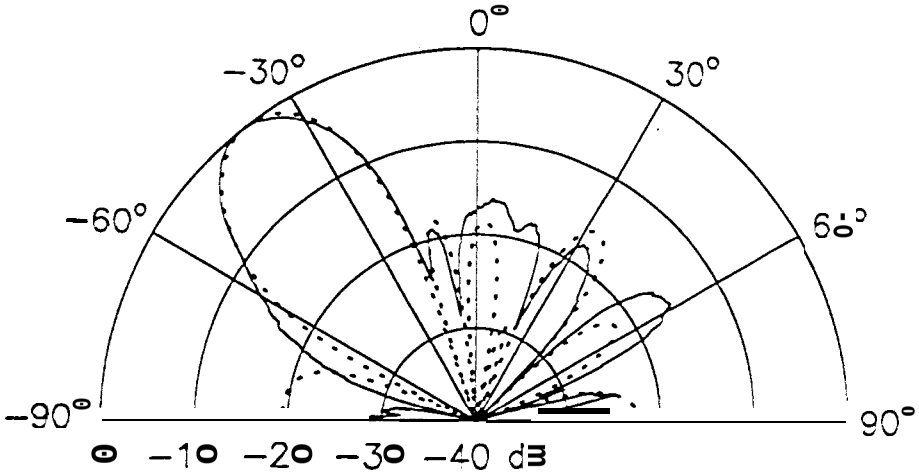

Figure 7. Radiation pattern of linear slot array.
Measured (—). Calculated (- - -).