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3D Array Element Design for Pattern Shaping

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Abstract—In this work, antenna arrays with tilted dipoles are investigated in terms of radiation and impedance properties. A spectral method of moments (MoM) was developed for the analysis of doubly-periodic arrays (i.e. periodic in both x and y -directions) with arbitrarily tilted dipole elements, in free space or in the presence of a backing reflector. By the aid of this analysis method, the radiation characteristics of arrays of stacked dipoles over a ground plane are studied, highlighting the variation of the patterns as a function of the inter-element distance and the angle of inclination of the elements.

Index Terms— antenna array, pattern shaping, low-profile.

I. INTRODUCTION

Antenna arrays located on airplanes or other mobile platforms for satellite communication applications are typically required to support very large scan angles (close to end-fire), to be able to point to the satellite in any direction within a nearly hemispherical field of view. However, planar antenna arrays are typically characterized by scan loss, i.e. a reduction of gain when the beam is pointed at angles away from broadside. To increase the scan range, conformal arrays [1] or multi-panel configurations [2] have been proposed, but the height of the structure is still too large to be installed on airplanes without significant impact on the aircraft drag. To obtain wide-scan capability while still maintaining a low antenna profile, hybrid scanning methods are currently implemented [3], [4]. The idea is to scan the beam electronically from broadside to a positive, as high as possible, angle and then to achieve the full coverage by mechanical rotation of the array along the azimuth, as depicted in Fig. 1.

In [3] an array of stacked patches for digital video broadcast terminals was presented, where each row of array elements is placed at an inclination angle to maximize the radiation in a given angular sector. The array provides a 20° to 70° coverage in elevation through electronic scan and 360° in azimuth through mechanical scan. The design choices were aimed at minimizing the number of active modules, and thus the cost of the array. A triangular lattice was implemented, with spacing of about one wavelength (λ) between the rows of tilted elements. The asymmetric embedded element pattern allowed weighting with a low amplitude the grating lobes in the desired half hemisphere and thus working with array spacings larger than $\lambda/2$. With this configuration however, the grating lobes level remains still rather high, only 5.8 dB lower than the main lobe [4]. Further attempts have been done to reduce the radiation toward undesired directions, while maintaining a large element spacing, e.g. in [4], by resorting to an overlapped

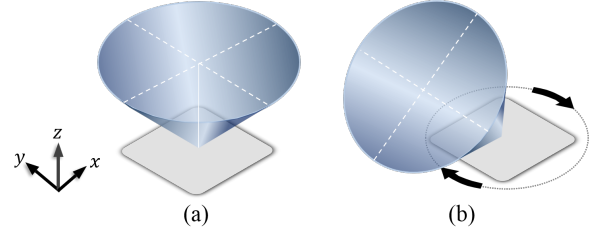


Fig. 1. Radiating aperture with (a) limited scan range and (b) with increased scan range by hybrid electronic steering and mechanical rotation.

beam-forming network. However, the improvement in terms of pattern selectivity is achieved at the cost of a more complex feeding architecture.

Although the mentioned works employ skewed antenna elements, the properties of this type of arrays in terms of radiation characteristics have not been investigated in detail. For this purpose, we derive here a periodic spectral Method of Moments (MoM) capable of modeling skewed dipoles. The method is applied to the analysis of arrays with different geometrical parameters, to provide useful design guidelines for tilted element arrays to achieve desired radiation characteristics.

II. PERIODIC METHOD OF MOMENTS

To investigate the radiation properties of arrays of tilted elements, a full-wave periodic MoM is developed. For the sake of simplicity, we first consider array elements as the ones shown in Fig. 2 (a), which represents the unit cell of an array of planar dipoles in free space tilted by an angle α with respect to the x -axis. The dipoles are excited with a delta-gap source. Although the derivation is described for an array of tilted dipoles in free space, a similar procedure can be used to describe also dipole elements in the presence of a backing reflector and stacked dipole elements (as in Fig. 2 (b)).

To solve the problem, we write the current density on the dipole in terms of a rotated reference system (x_R, y_R, z_R) as follows

$$j(x_R, y_R, z_R)\hat{x}_R = i_0 b(x_R)e(y_R)\delta(z_R)\hat{x}_R \quad (1)$$

where i_0 is an unknown coefficient and we applied the separation of variables. A single entire domain basis function is used to describe the dipole current: the distribution $b(x_R)$

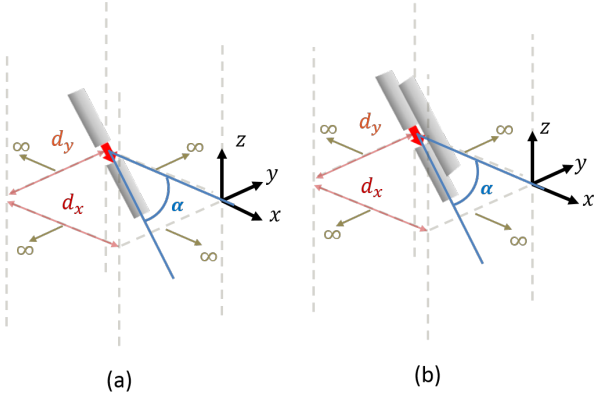


Fig. 2. Unit cell of an infinite array of (a) tilted single dipoles and (b) tilted stacked dipoles.

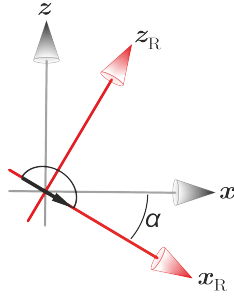


Fig. 3. Representation of the rotation of axes

represents a piece-wise sinusoidal longitudinal current profile along the dipole, $e(y_R)$ is the edge-singular transverse distribution and $\delta(z_R)$ is a Dirac delta function, since the dipole thickness is assumed to be infinitesimal. The unit vector $\hat{x}_R$ is aligned with the orientation of the dipole axis.

To express the current in the xyz -reference system (see Fig. 3), an axis transformation is needed and it can be written as follows

$$\begin{aligned} x_R &= x \cos \alpha - z \sin \alpha \\ z_R &= x \sin \alpha + z \cos \alpha \end{aligned} \quad (2)$$

so that the current distribution can be expressed as

$$j(x, y, z) = i_0 b(x \cos \alpha - z \sin \alpha) e(y) \delta(x \sin \alpha + z \cos \alpha) \quad (3)$$

The three-dimensional Fourier transform of the current distribution is given by

$$J(k_x, k_y, k_z) = i_0 J_0(k_y w/2) B(k_x \cos \alpha - k_z \sin \alpha) \quad (4)$$

where J_0 is the Bessel function of zeroth order, representing the Fourier transform of the edge singular distribution and w is the width of the dipole. The function B is the Fourier transform of the sinusoidal profile, given by

$$B(k) = \frac{2k_0(\cos(kl/2) - \cos(k_0 l/2))}{(k_0^2 - k^2) \sin(k_0 l/2)} \quad (5)$$

where k_0 is the free-space wavenumber at the considered frequency and l indicates the dipole length.

By applying the Galerkin method, we can define the active input impedance of the dipole as the projection of the field scattered by the current onto a test function equal to the basis function. After some algebraic steps, the expression of the input impedance for a tilted dipole in free space is derived as

$$Z_{in} = \frac{-1}{2\pi d_x d_y} \sum_{m_x=-\infty}^{\infty} \sum_{m_y=-\infty}^{\infty} J_0^2\left(\frac{k_{ym} w}{2}\right) \int_{-\infty}^{\infty} B(k_i) B(-k_i) G_{rot}(k_{xm}, k_{ym}, k_z) dk_z \quad (6)$$

where $k_{xm} = k_{x0} - 2\pi m_x/d_x$, $k_{ym} = k_{y0} - 2\pi m_y/d_y$ are the Floquet wavenumbers, $k_i = k_{xm} \cos \alpha - k_z \sin \alpha$ and $G_{rot} = G_{xx}^{ej} \cos^2 \alpha - G_{xz}^{ej} 2 \cos \alpha \sin \alpha + G_{zz}^{ej} \sin^2 \alpha$. G_{xx}^{ej} , G_{xz}^{ej} and G_{zz}^{ej} are the components of the dyadic Green's function in free space.

With the chosen sinusoidal basis function to represent the current on the dipole, the integrand in (6) can be written explicitly in closed form. The resulting expression presents a number of polar singularities, thus the integral can be solved analytically using the residue theorem.

Knowing the active input impedance, we can calculate the unknown coefficient of the equivalent current i_0 , as well as the radiated electric field. Considering only the fundamental Floquet mode, the radiation pattern can be computed from the expression of the electric field in the point (r, θ, ϕ) :

$$E(r, \theta, \phi) = j k_{z0} \frac{e^{-jk_0 r}}{2\pi r} i_0 B(k_{x0} \cos \alpha - k_{z0} \sin \alpha) J_0(k_{y0} w/2) \mathbf{G}^{ej}(k_{x0}, k_{y0}) \hat{x}_R \quad (7)$$

The method described can be used to analyze arrays of arbitrarily tilted dipole elements in free space or in the presence of a ground plane. In the latter case, the Green's function is defined as the summation or subtraction (for the z - and x -components of the current, respectively) of Green's function of the real dipole and the one of its image. Moreover, also a structure as the one in Fig. 2 (b) can be studied, consisting of an active dipole with a parasitic strip to increase directivity. In this case, an impedance matrix has to be derived with both self and mutual impedance terms, with expressions similar to (6).

III. RADIATION CHARACTERISTICS OF SKEWED DIPOLES

A. Skewed Dipoles with Backing Reflector

Let us consider an infinite array of dipoles tilted by $\alpha = 30^\circ$, with inter-element spacing of $0.5\lambda_0$ and $0.6\lambda_0$, being λ_0 the wavelength at 10 GHz. The dipoles are half-wavelength long and $0.1\lambda_0$ wide, and located with their center at a distance of $0.25\lambda_0$ from a backing reflector. As it can be seen in Fig. 4, the active element pattern, for both considered inter-element distances, is symmetric. This property can be explained with the fact that, as the dipole radiates the same power upwards and downwards, the power reflected by the ground plane is equal to the one radiated upward, but in the specular direction.

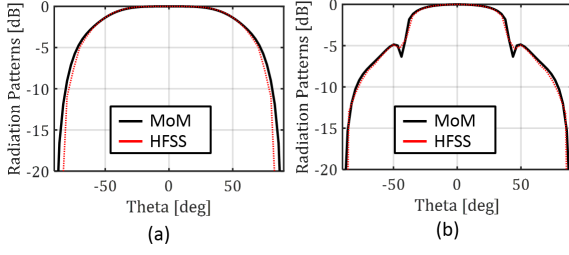


Fig. 4. Active element pattern for an infinite array of dipoles tilted 30° with a spacing between elements of (a) 0.5λ and (b) 0.6λ comparing HFSS simulation with MoM code.

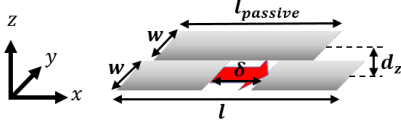


Fig. 5. Stacked dipole element, made of two parallel dipoles with different length, centered around the same x -coordinate and displaced in z . The active dipole is excited with a delta-gap source, while the parasitic dipole is a passive metal strip.

Therefore, in order to achieve an asymmetric active radiation pattern, directive elements with high front-to-back ratio are needed.

B. Skewed Stacked Dipoles with Backing Reflector

We now consider the structure in Fig. 5, which consist in a stacked dipole element. The passive metal strip has the purpose to enhance the radiated power in one direction, thus increasing the element gain. The dimensions chosen for the element are: $l = 0.5\lambda_0$, $l_{\text{passive}} = 0.4\lambda_0$, $d_z = 0.07\lambda_0$, the width $w = 0.12\lambda_0$, the length of the port $\delta = 0.1\lambda_0$, where λ_0 is the wavelength at 10 GHz.

Figure 6 shows the active element patterns of the stacked dipoles, considering the same tilt and spacing between elements as for the case of a single dipole array. It can be noted that the pattern is symmetric for period of 0.5λ . This property, known from Floquet theory for planar elements [5], is shown here to be also occurring for radiating currents with a z -component. However, an asymmetric active element pattern can be achieved for inter-element distance higher than half wavelength. Thus, only in the condition of higher order Floquet modes entering in the visible region, pattern asymmetry can be obtained by employing directive elements.

A parametric analysis on the radiation pattern of the tilted stacked dipole array is carried out to determine the parameters that affect the power radiated in specific directions. The considered geometrical variables are the inter-element spacing (d_x , d_y) and the inclination angle of the dipoles (α). Figure 7 and Fig. 8 show the active element patterns when varying the inter-element distance (d_x and d_y) or the tilt angle (α), respectively. The steep drop of the gain is strongly dependent from the inter-element spacing, since it corresponds to the angle at which grating lobes appear in the visible region:

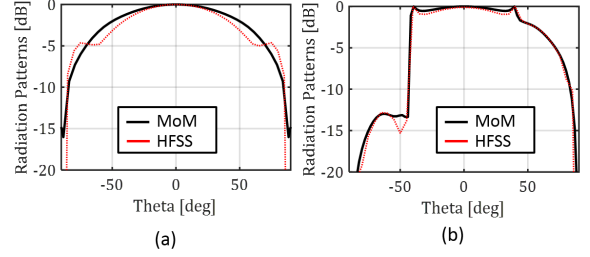


Fig. 6. Active element pattern for an infinite array of stacked dipoles tilted 30° with a spacing between elements of (a) 0.5λ and (b) 0.6λ comparing HFSS simulation with MoM code.

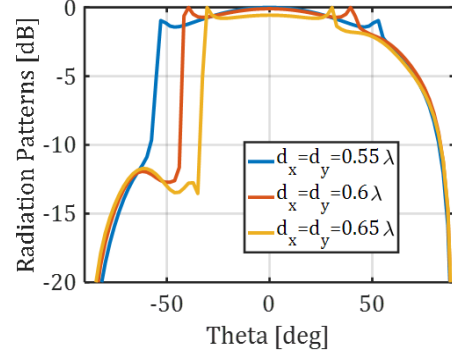


Fig. 7. Active element pattern for an infinite array of stacked dipoles tilted 30° for different spacing between elements d_x and d_y .

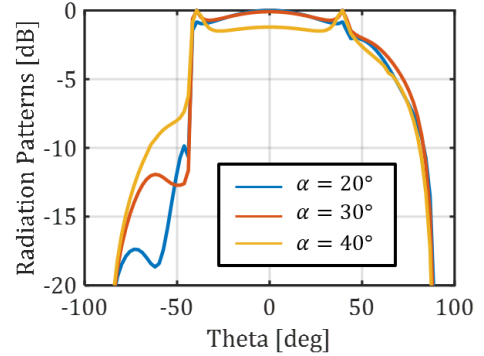


Fig. 8. Active element pattern for an infinite array of stacked dipoles with an inter-element distance of 0.6λ for different tilted angles α .

$$\theta_{GL} = \sin^{-1} \left(\frac{\lambda}{d_x} - 1 \right) \quad (8)$$

From Fig. 8, it is apparent that the tilt angle affects the gain levels in the suppressed angular region.

IV. CONCLUSION

In this contribution, a study of the design parameters of infinite arrays with tilted elements was carried out with respect to their radiation characteristics. A periodic method of moments was developed to analyze the structure with analytical expressions. It was shown that skewed stacked

dipole elements can be used to achieve asymmetric radiation when used in combination with a backing reflector, for inter-element spacings larger than half wavelength. The dependence of the active element pattern on the inclination of the elements and the array periodicity was discussed. These two parameters can be varied to control the pattern profile, thus the proposed elements can be effectively employed to implement pattern shaping.

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