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WIDE BAND LINEAR PRINTED ANTENNA ARRAY WITH LOW SIDELOBE COSECANT SQUARE-SHAPED BEAM PATTERN

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Abstract—A wide band, integrated linear printed antenna array with low sidelobe cosecant square-shaped beam pattern is presented. Array synthesis mainly about the wide shaped coverage, low ripple and sidelobe level (SLL) has been done using the modified least square method by matrix inversion. A printed dipole integrated with wideband balun has been chosen as the array element for wide bandwidth and good integration with the feeding network. Simulated results have shown good agreement with the measured results of the antenna array, which has a VSWR ≤ 1.3 bandwidth 15% and good pattern with cosecant square-shaped region beyond 30° and SLL $\leq -27\,\text{dB}$ in L-band.

1. INTRODUCTION

Ground-Mapping airborne radars and ground-based search radars typically use a variation of a cosec^2 shaped beam, which can get the required elevation coverage where the received power is independent of the radar range for a constant height target [1]. In this paper, the synthesis and implementation of a wideband linear printed antenna array with low sidelobe cosec^2 shaped beam pattern is presented. This work is part of the complete planar array antenna system realized for a ground-based surveillance radar system.

In the array pattern synthesis, the desired output is usually the excitation of the radiating elements, which can produce an acceptable pattern shape. The two principal methods for synthesizing shaped

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beams from a linear array are the Woodward-Lawson [2] and Orchard-Elliot [3] methods. When the synthesis problem being seen as a general optimization problem, where optimal complex element excitation values are sought for, the global optimization methods are usually used, such as genetic algorithm [4, 5], simulated annealing [6], or particle swarm optimization [7] or the hybrid approaches [8, 9]. This optimization can include maximizing the directivity, minimizing the sidelobes to a certain level, design of the shaped beam using some complex excitation distribution. The global optimization methods are flexible to use, but they need a large amount calculation of directivity patterns. In the recent years, the least square method and its modification have often been applied to the array synthesis [10, 11], which in its basic form give directly a solution for the unknown excitation values and be found a very fast process. However, the least square optimization is not directly suitable for phase synthesis, which is a nonlinear optimizing problem. The projection matrix algorithm given in literature [12] can obtain the complex element excitation directly by matrix calculation using the concept of orthogonal vector space. Here, a modified least square method is presented in which the partial derivative formulas of sum least square error are deformed to transform a nonlinear optimization about element amplitudes and phases to a linear equation, which can be directly solved by the matrix inversion.

The antenna array element chosen is a printed dipole integrated with the wide band microstrip balun above the metal ground, which can be extended to print the feeding network [13]. Comparing to the probe-fed U-slot rectangular microstrip array element used in literature [14], it has the merit of high integration with the feeding part and not use of the complex and fragile probe excitation. An air-dielectric stripline feeding network has been designed for realizing the array excitations. Finally, the measured printed array antenna has wide elevation coverage beyond 30°, good patterns with the shaped ripples in the mainlobe less than 2.0 dB and the SLL less than −27.0 dB within the 15% frequency bandwidth are also obtained.

2. ARRAY ANALYSIS

The far-field pattern of an equi-spaced 1-D array can be written in the form

$$f(\theta) = \sum_{n=1}^{N} I_n e^{jk(n-1)d\sin\theta} \tag{1}$$

where N is the total number of elements in the array, I_n is the complex excitation (magnitude $|I_n|$ and phase ϕ_n) of the nth element and $I_n = |I_n| e^{j\phi_n}$, $j = \sqrt{-1}$, k is the free-space wave number, d is the spacing between elements, θ is the scan angle ($\theta = 0°$ corresponds to the broadside).

In the direction of $\theta = \theta_i$, the least square error Δ_i between synthesized array pattern $f(\theta_i)$ and desired pattern $D(\theta_i)$ is

$$\begin{aligned}\Delta_i &= |f(\theta_i) - D(\theta_i)|^2 \\ &= \left[\sum_{n=1}^{N} I_n e^{jk(n-1)d\sin\theta_i} - D(\theta_i)\right]\left[\sum_{n=1}^{N} I_n^* e^{-jk(n-1)d\sin\theta_i} - D^*(\theta_i)\right] \\ &= \sum_{m=1}^{N}\sum_{n=1}^{N} I_n I_m^* e^{jk(n-m)d\sin\theta_i} - D^*(\theta_i)\cdot\sum_{n=1}^{N} I_n e^{jk(n-1)d\sin\theta_i} \\ &\quad -D(\theta_i)\sum_{n=1}^{N} I_n^* e^{-jk(n-1)d\sin\theta_i} + |D(\theta_i)|^2 \end{aligned} \tag{2}$$

For a shaped pattern the radiation pattern can be divided into the shape region and sidelobe region, both regions are sampled every half degree. Then the sum error function Δ to be minimized is given by

$$\Delta = \sum_i \Delta_i \tag{3}$$

Note that all terms $\frac{\partial\Delta}{\partial I_n}$ and $\frac{\partial\Delta}{\partial I_n^*}$ are zero at the desired solution point, then

$$\begin{cases} \sum\limits_{n=1}^{N} I_n \sum\limits_i e^{jk(n-1)d\sin\theta_i} = \sum\limits_i e^{-jk(1-1)d\sin\theta_i} D(\theta_i) \\ \vdots \\ \sum\limits_{n=1}^{N} I_n \sum\limits_i e^{jk(n-N)d\sin\theta_i} = \sum\limits_i e^{-jk(N-1)d\sin\theta_i} D(\theta_i) \end{cases} \tag{4}$$

By deforming the partial derivatives of sum error function, the linear equation shown in Equation (4) is obtained using the modified least method and can be written in the matrix form

$$\mathbf{AX} = \mathbf{B} \tag{5}$$

where

$$\mathbf{A} = \begin{bmatrix} \sum\limits_i e^{jk(1-1)d\sin\theta_i} \dots \sum\limits_i e^{jk(N-1)d\sin\theta_i} \\ \vdots \\ \sum\limits_i e^{jk(1-N)d\sin\theta_i} \dots \sum\limits_i e^{jk(N-N)d\sin\theta_i} \end{bmatrix}$$

$$\mathbf{X} = \begin{bmatrix} I_1 \\ \vdots \\ I_N \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} \sum\limits_i e^{-jk(1-1)d\sin\theta_i} D(\theta_i) \\ \vdots \\ \sum\limits_i e^{-jk(N-1)d\sin\theta_i} D(\theta_i) \end{bmatrix}$$

The solution for solving the excitation valves $\mathbf{X}$ can be found by the matrix inversion, which has been used to achieve a close agreement between simulated pattern and the desired coverage as shown in Figure 1, for a 24-element linear array with $d = 0.55\lambda_0$. The synthesized patterns in the low and high frequency (f_l and f_h) are also shown in the figure for comparison. In can be seen that the theoretically simulated cosec^2 shaped beam in the elevation plane peaked at $-15°$ and has shown a good agreement with the with the desired pattern having coverage beyond 30° with an antenna array gain better than 23 dB, the ripple of the mainlobe lower than 2 dB and SLL lower than -27 dB, as shown in Figure 1. Moreover, the patterns are stable in the 15% frequency bandwidth. The synthesized complex magnitude and phase distribution of elements obtained based on above-mentioned technique for cosec^2 shaped beam are shown in Figure 2.

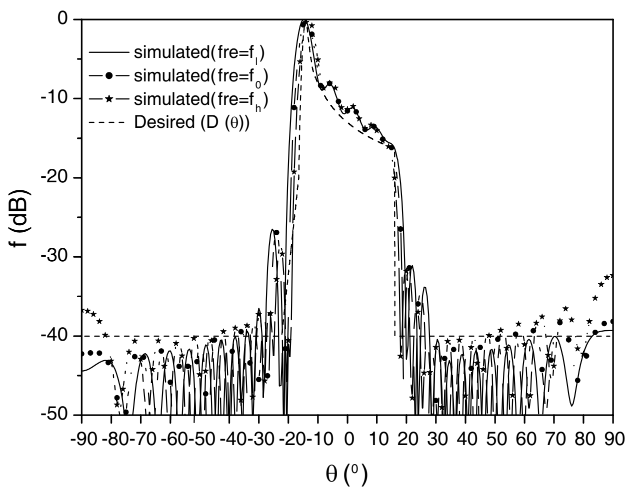


Figure 1. Theoretically simulated cosecant square radiation pattern for the 24-element linear array.

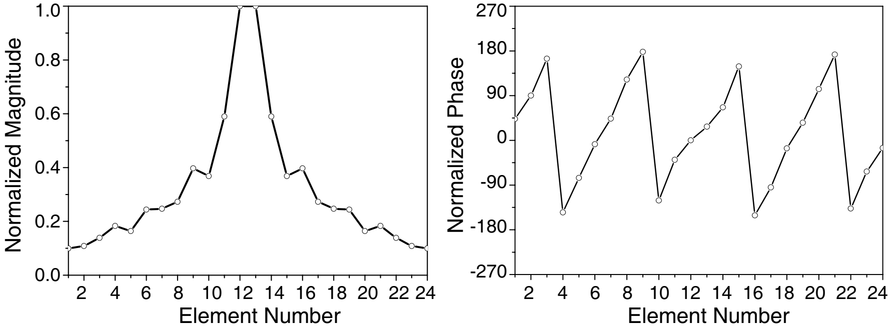
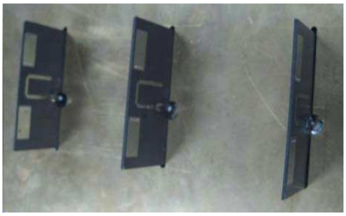
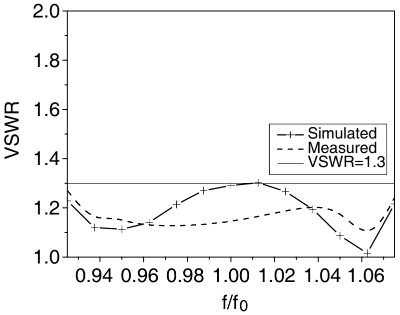


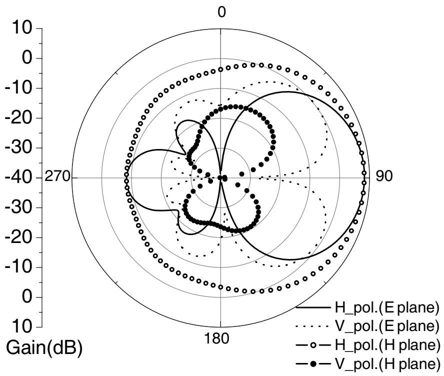
Figure 2. Current magnitude and phase distribution for the 24-element linear array.



(a)



(b)



(c)

Figure 3. Printed dipole element: (a) Element photograph of the realized antenna; (b) Comparison of the simulated and measured VSWR; (c) Simulated radiation patterns in E-plane and H-plane at the center frequency.

3. DESIGN REALIZATION

The antenna array ($N = 24$, $d = 0.55\lambda_0$) has been realized in printed microstrip technology, which working in L-band (center frequency

$f_0 = 1.3\,\mathrm{GHz}$) with frequency bandwidth 15%. The printed dipole above the metal ground with integrated balun has been chosen as an array element to achieve desired bandwidth, integration with the feeding network and good patterns. In the practical applications, the printed dipole substrate is perpendicular to the ground and can be extended to print the feeding network. The design of wide band printed dipole has been done using FEM-based Ansoft HFSS software.

The element is printed on the substrate with dielectric constant $\varepsilon_r = 2.65$ and thickness $t = 1\,\mathrm{mm}$, as shown in Figure 3(a). The printed dipole and wideband balun is in one side and the microstrip feeding line and matched network is in the other side [13]. Below the printed dipole is the metal ground and the impedance transformer is between the open circuit and the feeding microstrip line. The measured and simulated VSWR is given in Figure 3(b), which showing VSWR < 1.3 within 15% frequency bandwidth. Figure 3(c) shows the horizontal and vertical polarization radiation pattern in E-plane and the H-plane at

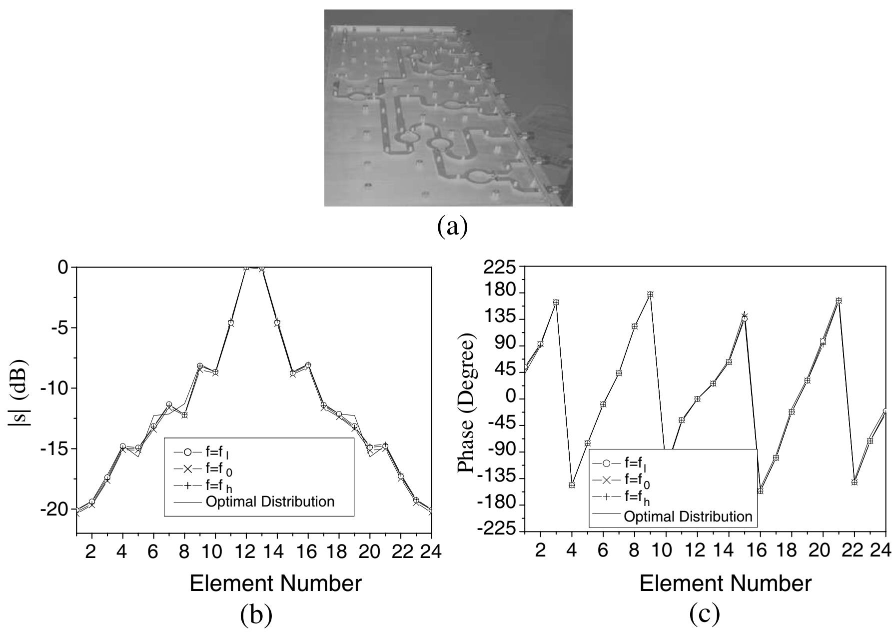


Figure 4. Air-dielectric Strip line feeding network: (a) the part photograph of the realized feeding network; (b) Comparison of the optimized and measured amplitude distribution at typical frequencies; (c) Comparison of the optimized and measured phase distribution at typical frequencies.

the centre frequency. The gain within the 15% frequency bandwidth is 7.8–8.0 dB.

A 1 : 24 air-dielectric strip line feeding network with dielectric thickness 10 mm and metal thickness 1 mm has been designed to realize the shaped array excitation distribution, which is composed of several 1 : 2 wilkinson power dividers with unequal power ratios. The cascaded analysis method of scattering matrix suitable for large and complicate feeding system is applied for good isolation and input/output port transmission and match properties. After dividing the whole network into several sub-networks, its performances can be obtained by cascading the partial scattering matrix. Figure 4(a) shows the photograph (part) of the power divider and the measured excitation (amplitude and phase) distributions at the low, centre and high frequency are given in Figure 4(b). The feeding network has been tested with amplitude and phase accuracies of 0.3 dB and 2°, respectively over 15% BW. The total loss of the feeding network is 0.5 dB $\sim$ 0.7 dB for the application of strip line form with lower loss. It is noted that the weak coupling between ports of the power divider can result in high impedance and then very narrow strip line, which is caused by steep taper of the amplitude excitation. The taper is expected to be improved iteratively by "phase only" synthesis.

The measured radiation patterns in the elevation plane at the typical frequencies along with the photograph (planar) of the printed dipole antenna array are shown in Figure 5, which exhibit a good

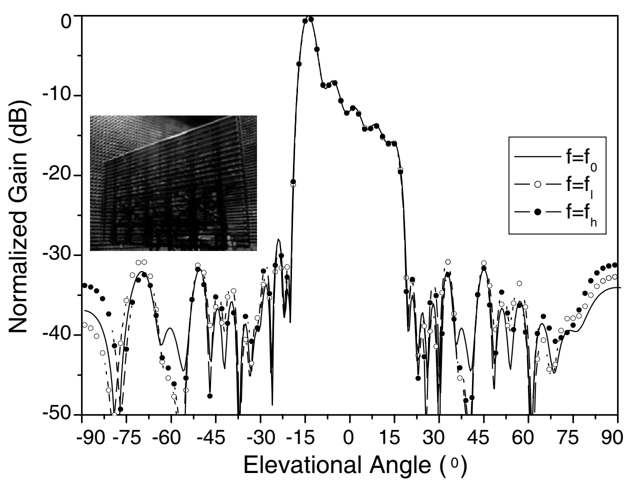


Figure 5. Measured cosecant square radiation pattern at typical frequencies.

agreement with the desired pattern. It can be seen from the figure that the shaped beam peaks at $-14.0°$ with the shaped coverage beyond $30°$ and SLL lower than -27 dB.

4. CONCLUSION

This paper has presented a new design architecture of a 24-element linear printed antenna array with a wide coverage cosec^2 radiation pattern using the modified least square method. The array antenna having a wide coverage beyond $30°$ with fairly low side lobe levels lower than -27 dB and a good gain has been realized. The frequency bandwidth of the array reaches 15% because of the application of the wideband printed dipole, which also has the merit of high integration with the array feeding network. This work has a direct usage in the surveillance radar antenna applications.

REFERENCES

1. Buckley, M. J., "Synthesis of shaped beam antenna patterns using implicitly constrained current elements," *IEEE Trans. Antennas Propag.*, Vol. 44, 192–198, Feb. 1999.
2. Woodward, P. M. and J. D. Lawson, "The theoretical precision with which an arbitrary radiation pattern may be obtained from a source of a finite size," *J. IEE*, Part H, Vol. 95, 363–370, Section 3, 1948.
3. Orchard, H. J., R. S. Elliott, and G. J. Stern, "Optimizing the synthesis of shaped beam antenna patterns," *Proc. IEE*, Vol. 132-H, 63–68, Feb. 1985.
4. Ares Pena, F. J., J. A. Rodríguez-Gonzalez, E. Villanueva-Lopez, and S. R. Rengarajan, "Genetic algorithms in the design and optimization of antenna array patterns," *IEEE Trans. Antennas Propag.*, Vol. 47, 506–510, Mar. 1999.
5. Mahanti, G. K. and A. Chakrabarty, "Phase-only and amplitude-phase synthesis of dual-pattern linear antenna arrays using floating-point genetic algorithms," *Progress In Electromagnetics Research*, Vol. 68, 247–259, 2007.
6. Rodríguez, J. A., L. Landesa, J. L. Rodríguez Obelleiro, F. Obelleiro, F. Ares, and A. García-Pino, "Pattern synthesis of array antennas with arbitrary elements by simulated annealing and adaptive array theory," *Microw. Opt. Technol. Lett.*, Vol. 20, No. 1, 48–50, Jan. 1999.

7. Boeringer, D. W. and D. H. Werner, "Particle swarm optimization versus genetic algorithms for phased array synthesis," *IEEE Trans. Antennas Propag.*, Vol. 52, 771–779, Mar. 2004.
8. Donelli, M., S. Caorsi, F. De Natale, M. Pastorino, and A. Massa, "Linear antenna synthesis with a hybrid genetic algorithm," *Progress In Electromagnetics Research*, Vol. 49, 1–22, 2004.
9. Perez, J. R. and J. Basterrechea, "Hybrid particle swarm-based algorithms and their application to linear array synthesis," *Progress In Electromagnetics Research*, Vol. 90, 63–74, 2009.
10. Vaskelainen, L., "Iterative least-squares synthesis methods for conformal array antennas with optimized polarization and frequency properties," *IEEE Trans. Antennas Propag.*, Vol. 45, 1179–1185, Jul. 1999.
11. Vaskelainen, L., "Constrained least-squares optimization in conformal array antenna synthesis," *IEEE Trans. Antennas Propag.*, Vol. 55, 859–867, Mar. 2007.
12. Bhattacharyya, A. K., "Projection matrix method for shaped beam synthesis in phased arrays and reflectors," *IEEE Trans. Antennas Propag.*, Vol. 55, 675–683, Mar. 2007.
13. Eward, B. and D. Rees, "A broadband printed dipole with integrated balun," *Microwave Journal*, Vol. 5, 339–344, 1987.
14. Kedar, A., P. N. S. Kutiyal, M. Garg, and U. K. Revankar, "Wide band low profile linear microstrip antenna array with cosecant square-shaped beam pattern," *Microw. Opt. Technol. Lett.*, Vol. 49, No. 4, 964–965, Apr. 2007.