Design of phased array antenna for active beamforming at 2.4 GHz

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Received 13 July 2009; revised 08 December 2009; accepted 09 December 2009

This paper presents design of phased array antenna (PAA) using RF beamformer and emphasizes design of planar microstrip patch antenna array with right hand circular polarization (RHCP) operating at 2.4 GHz. Comparison of two responses of antenna array for two non-uniform amplitude distributions in terms of beam width and side lobes at different scan angles has been made. RF beamformer for electronic beamsteering is also simulated.

Keywords: Patch antenna, Phased array antenna (PAA), RF beamformer

Introduction
RF beamforming has found many applications in wireless communication. Phased array antenna (PAA) is capable of steering beam electronically in a particular direction, and gives very narrow beam width and minimum side lobe levels. This study presents design and simulation of PAA that produces a narrow pencil beam at 2.412 GHz with 20MHz bandwidth and right hand circular polarization (RHCP) is considered. Beam can be steered in both azimuth and elevation planes using beamformer circuit, designed at 2.4 GHz.

Experimental
Single Circularly Polarized Patch Design
Selection of substrate dielectric constant ($\mu_r$) and substrate thickness (h) plays important role in antenna design. Low $\mu_r$ increases radiated power but at the cost of larger size. A thicker substrate increases radiated power and improves impedance bandwidth, but increases weight and dielectric loss. Thicker substrates with low $\mu_r$ increases radiated power, thereby provide better efficiency and larger bandwidth but with larger element size1. This study presents selection of dielectric (RT Duroid 5870) parameters (loss tangent, 0.0012; height, 1.6 mm; and $\mu_r$, 2.32) followed by calculation of patch dimension. Patch width ($W$) can be calculated with resonant frequency ($f_r$) and velocity of light (c) as

$$W = \left[ \frac{c}{2f_r} \right] \sqrt{\frac{2}{(\epsilon_r + 1)}} \quad \text{...(1)}$$

Effect of fringing field can be included through effective dielectric constant ($\epsilon_{re}$), therefore effective length $L_e$ is given as

$$L_e = \frac{c}{(2f_r \sqrt{\epsilon_{re}})} \quad \text{...(2)}$$

$\epsilon_{re}$ and line extension ($\Delta L$) can be calculated as

$$\epsilon_{re} = \frac{(\epsilon_r + 1)}{2} + \frac{(\epsilon_r - 1)}{2} \left[ 1 + 12 \frac{h}{W} \right]^{\frac{1}{2}} \quad \text{...(3)}$$

$$\Delta L = 0.412 h \left( \frac{\epsilon_{re} + 0.300 \frac{W}{h} + 0.264}{\epsilon_{re} - 0.258 \frac{W}{h} + 0.813} \right) \quad \text{...(4)}$$

Based on this approach, design value of L is given as

$$L = L_e - 2\Delta L \quad \text{...(5)}$$

Coaxial line feed is used for design work. Feed point F ($x_o, y_o$) is located at $x_o = x_r$ and $0 \leq y_o = y_l \leq W$, where $x_r$ is inset distance from radiating edge. It is better

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A simple method for calculating \( x_f \) that does not need radiation resistance is given as \(^2,^3\)

\[
x_f = L/(2\sqrt{\varepsilon_{eq}(L)}) \quad \ldots (6)
\]

where, \( \varepsilon_{eq}(L) = (\varepsilon + 1)/2 + (\varepsilon - 1)/2[1+2h/L]^{-1/2} \quad \ldots (7) \)

Circular polarization can be achieved by dual feed or single feed method. In this work, single feed type is chosen because antenna should be compact and bandwidth required is 20 MHz (< 1%). Hybrid coupler is not required in single feed method. Single point feed can be of two types: i) Type A, where feed location is on X or Y axis; and ii) Type B, where feed is placed on diagonal axis of a patch. Type A perturbation is chosen for design work and design Eq. (5) for type A perturbation as

\[
|\Delta s /S|Q_o = 1/2 \quad \ldots (8)
\]

where, \( \Delta s \), area of perturbation; \( S \), area of square patch; and \( Q_o \), unloaded Q factor. Using Eq. (8) along with dimensions and dielectric thickness of single patch, perturbation size is calculated. Using simulation software (IE3D), dimensions are optimized to meet required specification (Fig. 1).

VSWR and return loss (Fig. 2) are low at designed frequency. Resonant frequency of designed antenna is obtained as 2.412565 GHz as per the specification. Simulation results at \( f_o \) of designed single patch are as follows: VSWR, 1.005; return loss, -51.705 dB; axial ratio (AR), 0.145 dB; impedance at feed point, 49.8 + j 0.211 W; gain, 6.6 dBi; bandwidth, 20 MHz; \( f_o \), 2412.565 MHz; polarization, RHCP; and antenna efficiency, 84.5865%. Radiation pattern at elevation plane (Fig. 3a) and 3D beam pattern (Fig. 3b) are plotted. With respect to frequency, it is clear that input impedance (Fig. 4a) obtained is close to 50 W and gain (Fig. 4b) is 6.6 dBi at 2.4125 GHz for a single patch antenna. Simulation results meet required specifications.

**Planar Array Design**

Required specification of array is to produce a beam (width, 15°) in both planes; scannable to 45° in both planes and side lobe should be less than 25 dB than main lobe. Design procedure is same as reported\(^4\). A planar array (size, 8 x 8; element spacing, 0.53 l) in both axes is
designed to meet specifications (Fig. 5). Designed and simulated single patch is used as array element for planar array. Simulation results of designed planar patch antenna array at $f_r$ as follows: VSWR, 1.0615; return loss, -30.49 dB; AR, 1.1 dB; impedance at feed point, 49.3-j 0.16 W; gain, 19.7 dBi; bandwidth, 20 MHz; $f_r$, 2412.565 MHz; Polarization, RHCP; 3 dB beam width, elevation plane & azimuth plane, 15º each; and side lobe level, -25 dB. VSWR (Fig. 6a) & return loss (Fig. 6b) as well as elevation pattern (Fig. 7a) & main lobe (Fig. 7b) are plotted.

**Experimental Results**

**Array Beamsteering**

In order to steer beam electronically, necessary phase shifts along with excitation amplitudes has to be
applied. For M x N array, phase steering command at each element is

\[ \phi_{mn} = m \beta_x + n \beta_y, \text{ where, } n = 1, 2, \ldots, M \]

\[ \text{and } m = 1, 2, \ldots, N \]

\[ \beta_x = kd_x \sin \theta \cos \phi_0, \beta_y = kd_y \sin \theta \sin \phi_0 \]

\[ k = \frac{2\pi}{\lambda}, \theta_0 \text{ and } \phi_0 \text{ are scan angles in elevation and azimuth planes.} \]

Phase shift to be applied for element at (m, n) position of array is

\[ \beta_{mn} = \frac{2\pi}{\lambda} \left[ md_x \sin \theta \cos \phi_0 + nd_y \sin \theta \sin \phi_0 \right], \text{ where } d_x, d_y \text{ are element spacing in X and Y axis respectively.} \]

Excitation amplitude applied to each element is

\[ V_{mn} = |V_{mn}| e^{-j\beta_{mn}}, \text{ where, } V_{mn} \text{ is excitation coefficient calculated from non-uniform amplitude distribution.} \]

In order to obtain a narrow main beam with lowered side lobe, non-uniform amplitude distribution has to be used. Two methods [Taylor & Dolph-Chebyshev (D-C)] of non-uniform amplitude distribution were compared with respect to designed array. Taylor distribution array pattern has a wider main lobe and low side lobes than D-C.
et distribution. Thus array with smoothest amplitude distribution will have smallest side lobes and larger half power beam widths. Designing of an array with Taylor distribution as compared to a design with D-C distribution is that it yields low side lobes at the expense of approx. 2° increase in half power beam width. A comparison of half power beam widths and side lobe of array at different scan angles for both distributions is presented (Table 1). Radiation patterns of array are shown for maximum and minimum scan angles. Radiation pattern of array, in elevation and azimuth plane (scan angle, -45°, -45°) is shown (Fig. 8) with dotted line showing D-C distribution and thicker line showing Taylor distribution pattern. Similarly, radiation pattern of array (scan angle, 45°, 45°) is shown (Fig. 9).

**RF Beamformer**

PAA is composed of a group of similar antennas, each with its variable attenuator, phase shifter and a

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<th>Scan angle (°)</th>
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<th>Dolph - Chebyshev distribution</th>
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<td>Side lobe (dB)</td>
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![Fig. 8— Elevation (a) and Azimuth (b) pattern of array (scan angle, -45°, -45°)](image1)

![Fig. 9— Elevation pattern of array (scan angle, 45°, 45°)](image2)
Table 2—Magnitude (dB) of elements of array

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Table 3—Phase values (°) of elements of array

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Fig. 10—RF beamformer to combine output of 8 columns of a row
summing network, which give a resulting signal representing a beam on an expected location (Fig. 10). 8 RF beamformers are used to combine all 8 columns of each row separately. For a scan angle (45°, 0°), excitation coefficients are calculated in terms of magnitude (Table 2) and phase (Table 3). Magnitude is applied to attenuator and phase to phase shifter. From 8 rows and 8 columns in array, elements of each column and each row are combined. Magnitude and phase are proportional with excitation coefficients after combining of each column and each row.

Pout (magnitude and phase) at each column of array are as follows: 1, (0.261, 90); 2, (2.274, 180); 3, (5.582, 90); 4, (88.647, 0); 5, (7.0468, 90); 6, (9.403, 180); 7, (2.161, 90); 8, (0.261, 0). Values are proportional to magnitude and phase of excitation coefficients. Next stage in a PAA would be to combine all 8 outputs in receiver system through any beamforming technique like FFT. Amplitude and phase can accordingly be changed and given as input to the array.

Conclusions

Design of PAA to give AR of 2.1 dB maximum at desired scan angle of ±45° is proposed. Two methods of non-uniform amplitude distributions (D-C and Taylor) were compared with respect to designed array. D-C distribution gives narrow beam width than Taylor distribution but side lobes are constant. Taylor distribution gives tapering side lobes with 2° broader beam width. Also, beam broadening was more for scan angles > 45°. AR also degrades when scanning away from broadside.

References

4. Elliot R S, Antenna Theory and Design (John Wiley & Sons, Canada) 2002