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Design, Simulation and Tests of a Low-cost Microstrip Patch Antenna Arrays for the Wireless Communication

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Abstract

Typical low-cost, low-weight microstrip base station antenna arrays with beam-scanning capabilities are taken into account. In downtowns of large cities like New York, Chicago, and in historical cities like Istanbul, where high buildings are separated by narrow but densely occupied streets, antenna arrays with approximately $20^\circ - 35^\circ$ *beam-widths are required to complete the cellular communication coverage. To meet this requirement, new antenna arrays are designed with* 35° *beam-widths and* 60° *electronic scanning capabilities. Their characteristics are investigated both numerically and experimentally. An FDTD-based antenna simulation package (M-PATCH) is prepared, tested on canonical structures and against the literature first, for verification and calibration. Then, the characteristics of the designed arrays are investigated via M-PATCH. Finally, the arrays are experimentally verified. It is illustrated that, the results of simulations and experiments agree very well, and the arrays meet the design criteria.*

Key Words: *Wireless communication, microstrip, patch antenna array, beam scanning, beam forming, FDTD, numerical simulation.*

1. Introduction

Parallel to the rising importance of wireless communication systems and personnel IT (information technologies) services (e.g., Bluetooth) increasing efforts are devoted to the design and implementation of novel microstrip structures from miniaturized electronic circuits to the antenna arrays. One major application is design of microstrip antenna arrays which are attractive candidates for adaptive systems in the present and future communication systems. Their main advantages are light weight, low cost, planar or conformal layout, and ability of integration with electronic or signal processing circuitry [see, e.g., 1].

Designing active / passive microwave circuits, on the other hand, requires understanding of both mathematical relations (i.e., the theory) and applications (i.e, computer simulations as well as measurements). Mathematical relations exist for only simple, idealized microstrip structures and may help to understand only the fundamentals. Fortunately, powerful numerical simulation methods are available which can be used to design complex microstrip structures. Among the others are the finite-difference time domain (FDTD), the transmission line matrix (TLM), the finite element (FE) and method of moments (MoM). All of these methods have continuously been applied to broad range of physical problems, from electromagnetics to mechanics and the reader may reach hundreds of references for different topics via a simple internet search (therefore no references are given in this article for their pioneering and characteristic applications).

This article describes the design, simulation and testing of microstrip patch array antenna for the current wireless communication systems which operates at 1.8 GHZ band, with 35° beamwidths, up to 60° electronic scanning capabilities. These beamwidths are chosen because they become almost standard for base station applications [2]. The antennas are analyzed with FDTD-based, in-house prepared M-PATCH package. The FDTD [3] is chosen just because it is simple to implement, widely accepted, and very effective in visualisation [4,5].

2. Design Principles

The designed antenna is a 3×3 array. The first step in the design is to specify the dimensions of a single microstrip patch antenna. The patch conductor can be assumed at any shape, but generally simple geometries are used, and this simplifies the analysis and performance prediction. Here, the half-wavelength rectangular patch element is chosen as the array element (as commonly used in microstrip antennas) [6]. Its characteristic parameters are the length L, the width w, and the thickness h, as shown in Figure 1.

To meet the initial design requirements (operating frequency = 1.8 GHz, and beamwidth = 35°) various analytical approximate approaches may be used. Here, the calculations are based on the *transmission-line model* [7]. Although not critical, the width w of the radiating edge is specified first. The square-patch geometry is chosen since it can be arranged to produce circularly polarized waves. In practice, the length L is slightly less than a half wavelength (in the dielectric). The length may also be specified by calculating the half-wavelength value and then subtracting a small length to take into account the fringing fields [8-10], as:

$$L = \frac{c}{2f_0\sqrt{\varepsilon_e}} - 2\Delta L \tag{1}$$

Where c is the velocity of light and

$$\Delta L = 0.412h\frac{(\varepsilon_e+0.3)\left(\frac{w}{h}+0.264\right)}{(\varepsilon_e-0.258)\left(\frac{w}{h}+0.813\right)} \quad , \quad \varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(\frac{1}{\sqrt{1+12h/L}}\right), (w/h \geq 1) \tag{2}$$

Here, ε_e and f_o, ΔL are effective relative permittivity, the operating frequency, and the fringe factor, respectively.

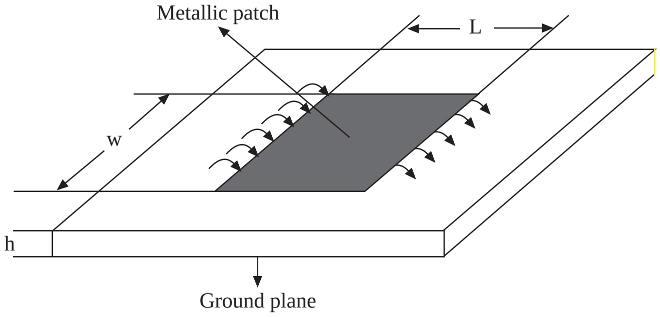
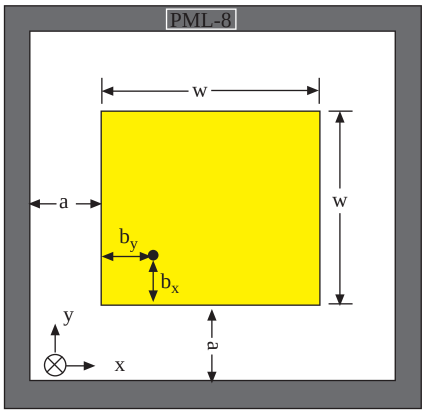


Figure 1. A rectangular patch antenna.

From these approximate calculations, the dimensions of the square-shaped microstrip patch antenna element are specified as shown in Figure 2. For a linear array with a uniform excitation, the beamwidth is given by [11],

$$\theta_{3dB} = \cos^{-1}\left[\sin(\theta_0) - 0.443.\frac{\lambda_0}{\ell}\right] - \cos^{-1}\left[\sin(\theta_0) + 0.443.\frac{\lambda_0}{\ell}\right] \tag{3}$$

where θ_0 is the main beam pointing angle, λ_0 is the free-space wavelength, and ℓ is the total array length. The total array length is found to be $\ell \cong$ *23 cm* for the 35° beamwidth.



w = 5.52 cm
h = 1mm
ε_r = 2.2
a = 2.758 cm

Figure 2. The square patch element and the dimensions.

When the inter-element distance is selected to be half-wavelength the 3 × 3 array satisfies 35° beamwidth on both planes normal to the patch surface. The 3x3 patch array is pictured in Figure 3.

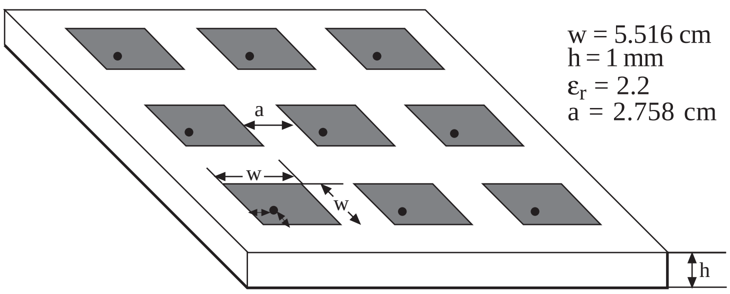


Figure 3. The 3 × 3 patch array that operates at 1.8 GHz, and with 35° beamwidth.

3. M-PATCH Package, its Calibration and Canonical Comparisons

The FDTD (finite difference time domain) technique developed by K.S. Yee [3], discretizes the two Maxwell curl equations directly in time and spatial domains, and put them into iterative forms. The physical geometry is divided into small (mostly rectangular or cubical, but non-orthogonal in general) cells. Both time and spatial partial derivatives are handled with finite central difference approximation and the solution is obtained with a marching scheme in iterative form. The characteristics of the medium are defined by three parameters, permittivity, conductivity and permeability, and three electric and three magnetic field components are calculated at different locations of each cell. Beside the spatial differences in field components, there is also a half time step difference between electric and magnetic field components, which is called as leap-frog computation. The three dimensional (3D) FDTD Yee cell is shown in Figure 4.

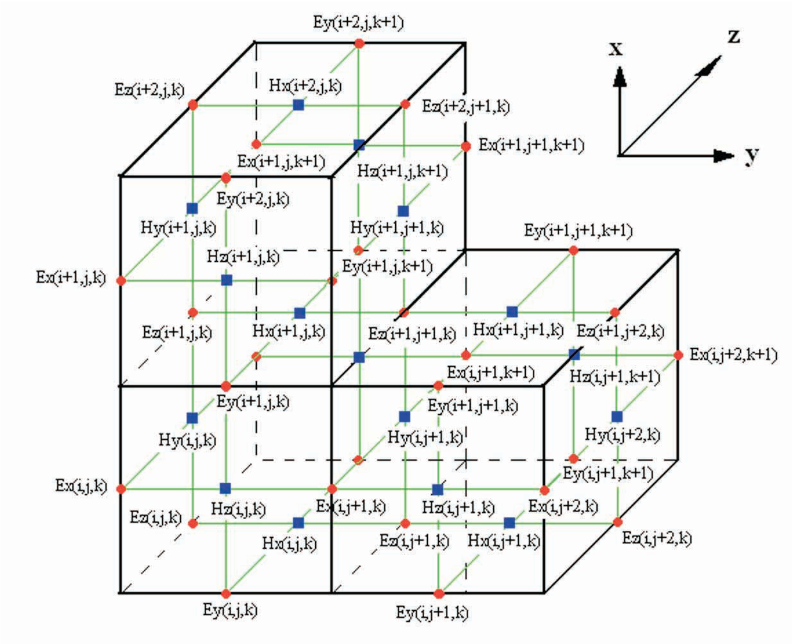


Figure 4. Locations of three neighbouring Yee cells in 3D.

The differential time domain Maxwell equations in a linear, isotropic and non-dispersive medium are

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad , \quad \nabla \times H = \frac{\partial D}{\partial t} + J \tag{4}$$

$$\nabla . D = \rho \quad , \quad \nabla . B = 0 \tag{5}$$

where $D = \varepsilon E$ and $B = \mu H$. Here,

E [V/m]	: electric field	J [A/m^2]	: the current density
H [A/m]	: magnetic field	ρ [q/m^3]	: vol. charge density
D [q/m^2]	: el. displacement vector	ε [F/m]	: permittivity
B [Wb/m^2]	: mag. flux density	μ [H/m]	: permeability
		σ [S/m]	: conductivity

All the parameters are vector quantities, except ε, σ, ρ and μ. This is all the information needed for linear isotropic materials to completely specify the field behaviour over time so long as the initial field distribution is specified and satisfies the Maxwell's equations.

Using the Taylor's expansion and discretizing partial derivatives directly in time and spatial domain yield the well-known FDTD iterative equation. Three electric and three magnetic field components are calculated at different locations within the reference cell in such a way so as to minimize the computational effort after the discretization of two curl equations by using central-difference approach (or by taking up the second order terms in their Taylor's expansion). Besides, there is also a half time step difference between electric and magnetic field components, which is called as leap-frog computation (i.e., electric and magnetic fields are calculated at time instants t=Δt, 2Δt, 3Δt, ... and t=Δt/2, 3Δt/2, 5Δt/2, ..., respectively, where $\Delta t$is the time step size).

For a lossy and source-free region, e.g., two of the iterative FDTD equations are

$$\begin{aligned} H_x^{\tilde{n}}(i,j,k) = H_x^{\tilde{n}-1}(i,j,k) \quad &+\frac{\Delta t}{\mu_0 \Delta z}\left[E_y^n(i,j,k) - E_y^n(i,j,k-1)\right] \\ &-\frac{\Delta t}{\mu_0 \Delta y}\left[E_z^n(i,j,k) - E_z^n(i,j-1,k)\right] \end{aligned} \tag{6}$$

$$\begin{aligned} E_y^n(i,j,k) \quad = \quad & \frac{2\varepsilon - \sigma\Delta t}{2\varepsilon + \sigma\Delta t} E_y^{n-1}(i,j,k) \\ & -\frac{2\Delta t}{(2\varepsilon + \sigma\Delta t)\Delta x}\left[H_z^{\tilde{n}}(i,j,k) - H_z^{\tilde{n}}(i-1,j,k)\right] \\ & +\frac{2\Delta t}{(2\varepsilon + \sigma\Delta t)\Delta z}\left[H_x^{\tilde{n}}(i,j,k) - H_x^{\tilde{n}}(i,j,k-1)\right] \end{aligned} \tag{7}$$

Here, Δx, Δy and Δz are the spatial steps (cell dimensions) in (x, y, z) directions, respectively. One FDTD Yee cell occupies a Δx$\times\Delta$y$\times\Delta$z volume. The spatial steps Δx, Δy and Δz may be either taken as equal (Yee cube) or different (Yee rectangular prism). Everything inside this cell is assumed to be constant. Calculations are performed at distinct instants $t_1, t_2, t_3, \ldots$, where $t_1 = \Delta t$, $t_2 = 2\Delta t$, $t_3 = 3\Delta t$, $\ldots$, with a chosen time step Δt. The integer n is used to denote a number of time steps since the iterations starts. The integers i, j, k are used to mention number of cells from the origin in x, y and z directions, respectively. A half time-step difference between electric and magnetic fields is denoted by $\tilde{n} = n + 1/2$.

Numerical simulations used to investigate the designed patch arrays are performed via the M-PATCH package that is based on the FDTD method. The FDTD computation volume in the M-PATCH is terminated by PML (perfectly matched layer) (very often 6-10 cell length) blocks which simulates free-space effectively. Also, a near-to-far-field (NTFF) transformation module is added to handle far-field projections, which are necessary in antenna radiation pattern simulations.

The M-PATCH package is first calibrated against another powerful time domain simulator TLM-ANT [7,12], which is based on the transmission line matrix method. Sample microstrip structures are used during these tests and scattering (S) parameters are calculated via both packages. The S-parameters in frequency domain is obtained from time domain simulation data as follows (see figure 5):

Assume the microstrip structure as a two port device (with port 1 and 2).

First, observe and store y-component of the voltage at port 1 for an infinite microstrip line (without structure); this yields the incident voltage, $V_1^+(t)$.

Then, repeat the same observation (with the structure) at both ports, which yields $V_1^t(t)$ (total field) at port 1, and $V_2^-(t)$, (reflected field) at port 2.

Take the Fourier transforms of all and calculate S_{11} and S_{21} from

$$S_{11}(f) = \frac{V_1^-(f)}{V_1^+(f)} = \frac{V_1^t(f) - V_1^+(f)}{V_1^+(f)}, \quad S_{21}(f) = \frac{V_2^-(f)}{V_1^+(f)} \tag{8}$$

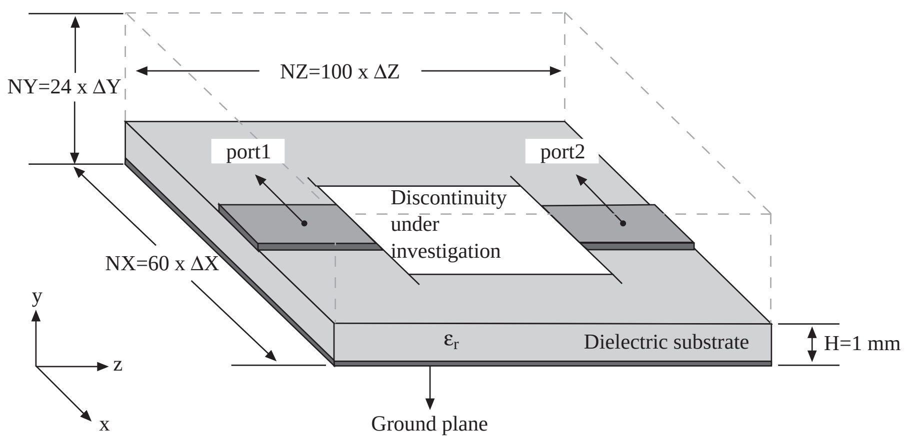


Figure 5. The configuration and dimensions.

Typical results are pictured in Figure 6, together with the investigated structures. Here, 60 × 24 × 100 FDTD space is used with $\Delta x = \Delta y = \Delta z = h/6$, where $h = w = 1$ *mm*. The time step is chosen as $\Delta t = \Delta x/(2c)$, where c is the velocity of light. Relative permittivity is fixed to$\varepsilon_r = 2.2$. As observed in these examples, a very good agreement has been obtained between the results of the packages.

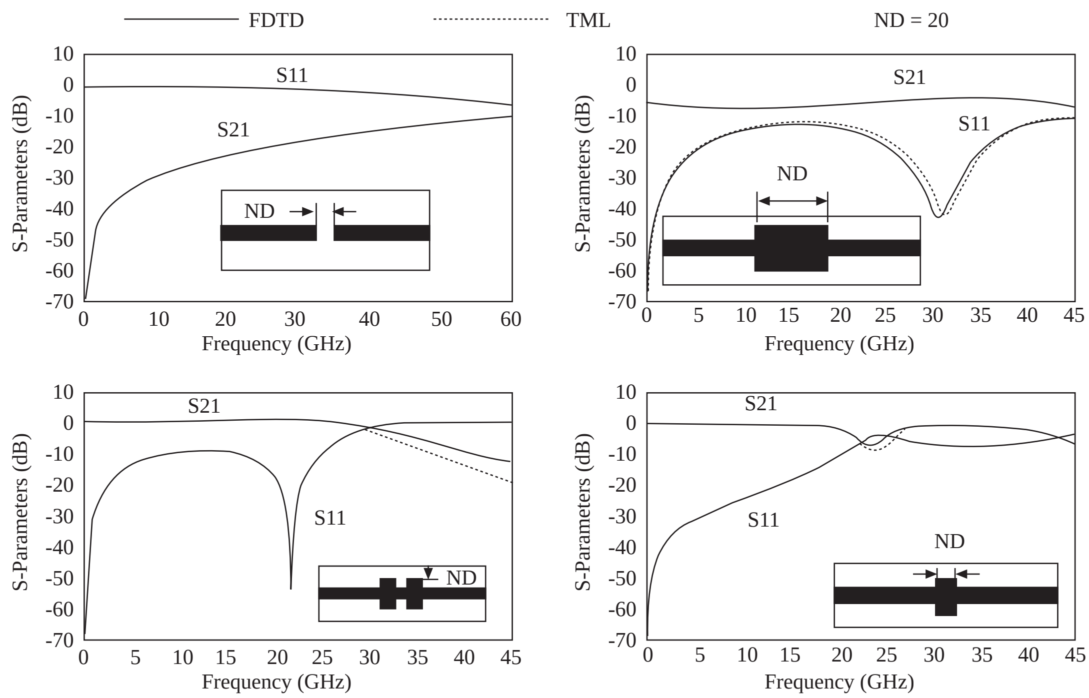


Figure 6. S parameters vs. frequency obtained via M-PATCH and TLM-ANT. (ND is the number of cells).

After the calibration against the TLM-ANT package the M-PATCH is compared with the results of three different problems from the literature; a line-fed rectangular patch antenna [13], three-element patch coplanar parasitic microstrip antenna [14], and four-element series-fed patch array antenna [15]. These structures are presented in Figure 7, together with the dimensions. The line-fed rectangular patch is designed to have a resonant frequency at 7.5 GHz, three-element coplanar parasitic is 3.9 GHz and the third one is at 9.5 GHz. These patches are etched on a dielectric substrate. The length of the fed-line from the source plane to the edge of the antenna is 20 Δz, and the reference plane for port 1 is *10* Δz from the edge of the patch for both of antennas. The 8-cell PML is applied as the absorbing boundary condition. Other parameters of the structures are given in Table 1.

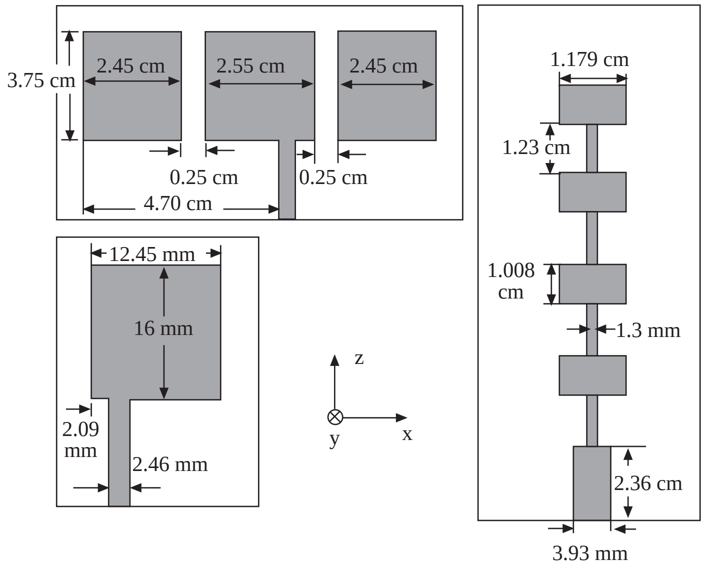


Figure 7. Structures from literature [13-15] that are tested with M-PATCH.

The spatial distribution of E_y *(x,y,z,t)* just beneath the microstrip antennas at different simulation time instants are presented in Figure 8. Since pulse propagation under the microstrip is simulated propagating and discontinuity-reflected pulses may be observed in the figure.

Table 1. The parameters of microstrip structures given in Figure 7.

	Line-fed single patch antenna	Three-element patch antenna	Series-fed patch antenna
Thickness (h)	0.8 mm	1.55 mm	1.574 mm
Space Steps	Δ x = 0.492 mm	Δ x = 0.15 cm	Δ x = 0.433 mm
	Δ y = 0.198 mm	Δ y = 0.038 cm	Δ y = 0.393 mm
	Δ z = 0.8 mm	Δ z = 0.15 cm	Δ z = 0.504 mm
Total Size	NX = 60	NX = 89	NX = 63
	NY = 20	NY = 20	NY = 20
	NZ = 66	NZ = 76	NZ = 250

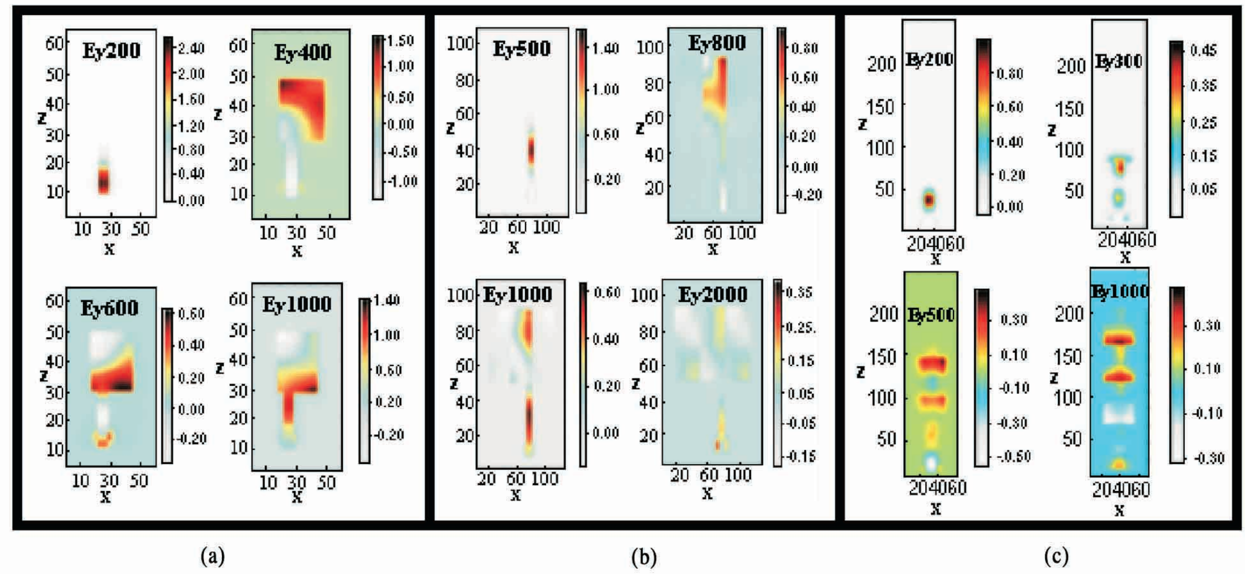


Figure 8. E_y on xz-plane, (a) line-fed rectangular patch, (b) 3-element coplanar patch (c) series-fed patch array.

Microstrip patch antenna is a one-port circuit and it has a scattering parameter of S_{11}, or simply the reflection coefficient. The frequency variation of the input reflection coefficient of the rectangular patch antenna (i.e., the first structure) is shown in Figure 9 (left). The operating resonance at 7.5 GHz is strongly traced via both the M-PATCH simulation package and in the measurement. Return loss vs. frequency of the 3-element microstrip patch antenna is also shown in the figure (right). The results with the literature are in good agreement.

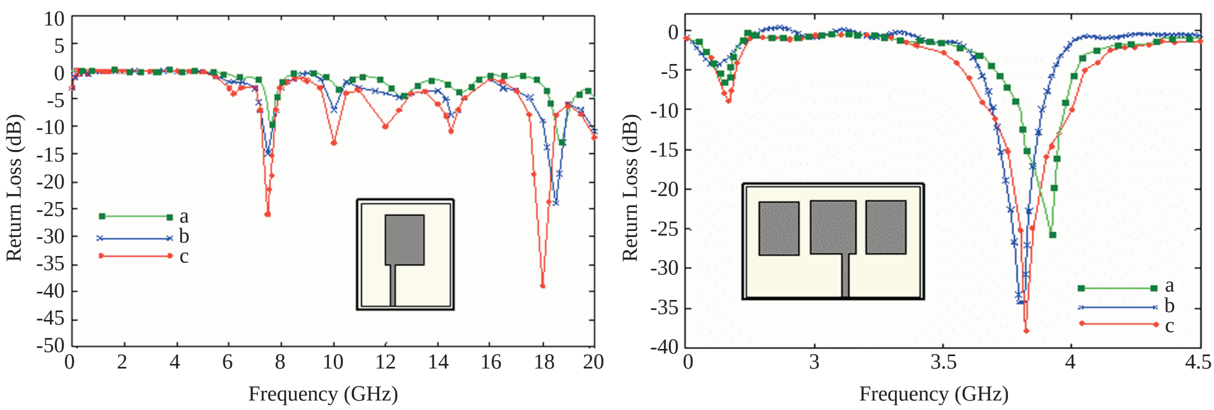
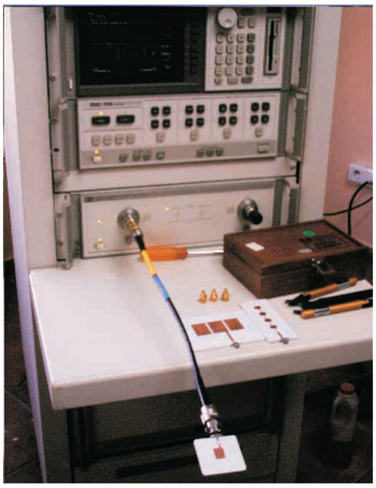


Figure 9. (Left) Return loss vs. frequency, (a) M-PATCH, (b) measurement [13], (c) FDTD [13]; (Right) Return loss vs. frequency, (a) FDTD [14], (b) M-PATCH, (c) measurement [14].

The series-fed patch array is also manufactured and measured. Figure 10 shows the measurement setup and input reflection vs. frequency. The scattering parameters are measured by using an *HP 8510C network analyzer*. As presented in the figure, the M-PATCH result is in good agreement with the measurements [16].



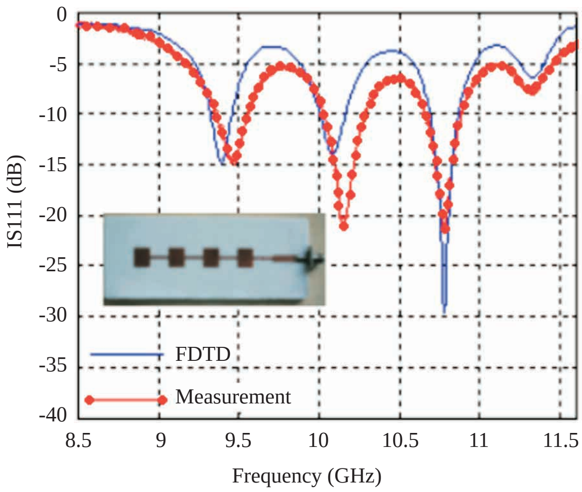


Figure 10. (Left) The measurement setup (HP 8510C Network Analyzer), (right) series-fed microstrip array, and return loss vs. frequency curves.

4. The 3×3 microstrip square patch array

The designed 3×3 array antenna is analyzed with the calibrated M-PATCH package. First, return loss vs. frequency of a square unit microstrip antenna is simulated and the result is given in Figure 11. As observed, the resonance frequency of the single patch is around 1.8 GHz.

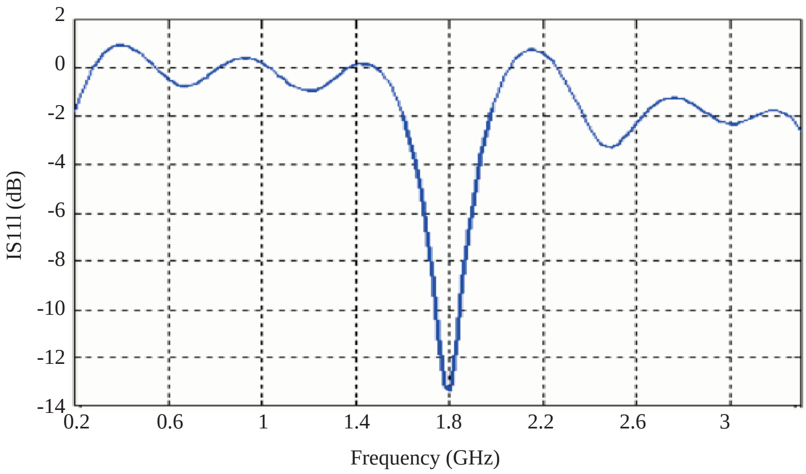


Figure 11. Return loss vs. frequency of a single patch ($\Delta x = \Delta y = 2.76$ mm, $\Delta z = 0.25$ mm, $w = 20\times\Delta$, $a = 18\times\Delta$, $b_y = 5\times\Delta$, $b_x = 7\times\Delta$).

The radiation patterns of the 3×3 patch array are also simulated via M-PATCH. Typical examples are plotted in Figure 12, together with the coordinates and array location. The patterns belong to ϕ=0° and ϕ=90° cases and equi-phase feedings. Nearly 34° beam-width is obtained with this 3×3 array.

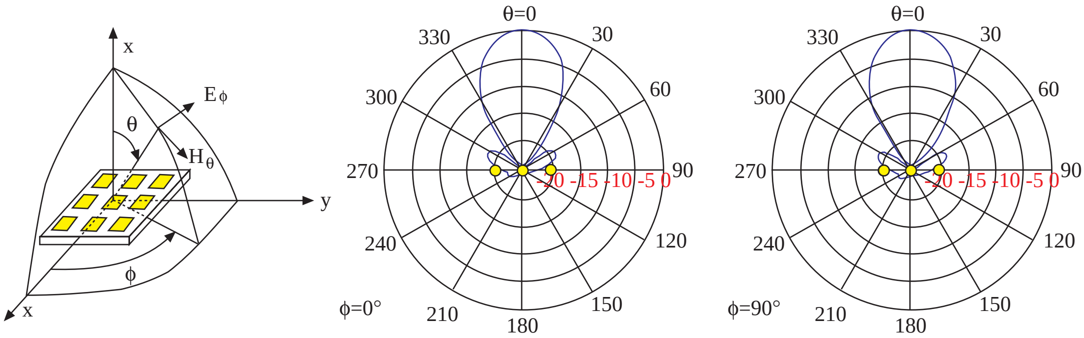


Figure 12. Radiation patterns at 1.8 GHz, left: ϕ=0°, right: $\phi = 90°$.

The position of the main beam can be moved or steered by introducing a phase shift (equivalently, a delay in time) between elements. To point the beam direction towards a desired θ-direction, $\Delta\tau$ time delay must be applied to the feeding pulses between the elements. The delay can be calculated as

$$\Delta\tau = \frac{d'}{c} \qquad (\, d' = d\sin(\theta)\,). \tag{9}$$

The 3×3 array elements are numbered from 1 to 9 and the delays of each element are calculated according to classic beam-forming approach [16]. Typical examples are given in Figure 13.

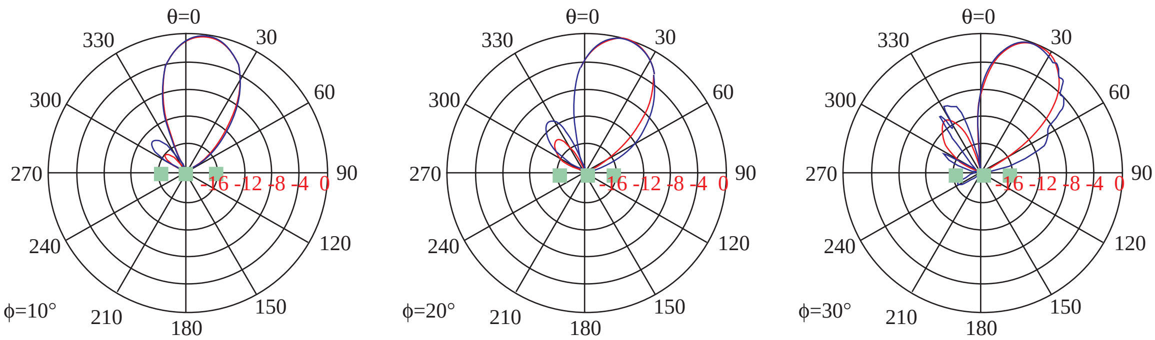


Figure 13. Beam forming with M-PATCH, 1.8 GHz, xz-plane, (solid: M-PATCH, dashed: M-PATCH plus analytical array factor formulation, β: beam steering direction).

5. Conclusions

The design, simulation and experimentation of microstrip patch arrays with beam-steering capabilities are discussed. A 3×3 square patch array is designed with approximately 35° beamwidth and up to 60° electronic scanning capability. Initial design is done via an analytical approximate approach (i.e., the transmission-line model), and then accurate characteristics are determined via numerical simulations. Finally, the parameters of the designed array are measured.

An FDTD based simulation package M-PATCH is prepared and calibrated against other powerful simulators, as well as on canonical microstrip patch structures that are investigated in the literature. The M-PATCH package is then used in performance evaluation of the arrays designed for 1.8 GHz cellular wireless communication systems. The M-PACH package is designed to calculate network parameters which requires near field simulations, as well as to obtain radiation patterns which requires near-to-far-field transformation. It is shown here that the package is very effective in simulating microstrip patch structures.

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