Scanning of the Near-field Focused Beam by Changing Frequency

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***Abstract* –** A new antenna array system is introduced which enables the movement of a near-field focused beam by change of frequency. The shift in the beam is achieved by using multi-wavelength transmission lines between successive elements of the array. At the designed frequency the beam is focused at the focal point. Due to the differences in the transmission line lengths feeding the antenna elements, a progressive phase change occurs between these elements. These phase differences between the elements cause a shift in the beam position. An 8×8 patch antenna array system was designed at 2.4 GHz on a microstrip to implement the proposed system. Two substrates were used: one for the patch antenna array and the other one for the feed network and transmission lines. A full-wave simulation model was used to analyze this design and demonstrate the movement of the beam. For this design, the focused beam is moved 310 mm by changing the frequency from 2.2025 GHz to 2.5750 GHz.

***Index Terms* –** beam shifting, focused beam, hyperthermia, near-field focusing, patch antenna array.

I. INTRODUCTION

Focusing the radiated waves from antennas at the near field has received considerable attention recently and there have been many publications on the subject [1–4]. Near-field focusing provides high power density at certain limited regions (spots), making them preferable for some applications. The applications of near-field focusing range from Radio Frequency Identification (RFID) systems [5, 6], non-contact microwave industrial inspection [7], gate access control systems [8], wireless power transfer [9, 10] to biomedical applications such as imaging, hyperthermia, and treatment/diagnosis of diseases [11–14].

In some focused field applications, it is necessary to shift the beam to different positions to apply high power at different regions, such as in hyperthermia applications [15, 16] where it is necessary to heat tissues at different locations on the human body. The shift in the focused beam in medical applications is usually carried out by moving the whole antenna system which can be very bulky, and the required accuracy may not be achieved. A new and simple method is introduced in this paper for shifting the beam without any mechanical movement.

The novel technique introduced here moves the focused field by changing the frequency. The method is very simple and does not require any phase shifters. The antenna array will focus the radiated field at a predetermined focal point and this focused field will be shifted as a function of frequency. The proposed system will have a sound mechanism for shifting the focused beam to the desired point, as well as having greater accuracy compared to systems handled using human interaction.

The proposed antenna system is composed of an array antenna fed by a power divider network. The array antenna is designed to focus the beam at a point in space. Multiple wavelength transmission lines at the designed frequencies are then added to the feed lines between successive elements leading to an antenna. This does not add an extra phase to the elements at the designed frequency, but phases at the elements change when the frequency changes, resulting in a shift in the beam position.

The design of a near-field focusing antenna array is explained in Section II, after which the principle of the movement of the beam with frequency is demonstrated by using a 16×16 array of isotropic elements at 2.4 GHz. In Section III, an 8×8 frequency scanning antenna array and feed network including the additional transmission lines have been designed on FR-4 at 2.4 GHz, and the performance of the antenna system has been analyzed using CST Microwave Simulation software.

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II. METHODOLOGY

A. The method

The principle of focusing the near field at a point and the method of the movement of the focused beam is illustrated below.

A rectangular antenna array is used to explain the methodology. Figure 1 shows such an antenna lying in the x-y plane. F $(0,\ 0,\ z_f)$ is the focal point on the z-axis in the near-field and z_f is the distance from the array antenna to the focal point. As the fields are to be focused at the focal point F, the phase of the fields from each of the antenna elements should be equal at this point.

For achieving this phase equality, a set of phases are calculated to be fed to each element using quadratic phase distribution [11]. The formula for quadratic phase distribution is given by equation (1):

$$\phi_{n,m} = k \times \left(\sqrt{\left((x_n)^2 + (y_m)^2 + (z_f)^2 \right)} - z_f \right), \quad (1)$$

where $x_n,\ y_m$ are the position of $(n,m)^{th}$ element in the array and $(0,\ 0,\ z_f)$ is the focal point. k is the wave number in rad/m**.** The calculated phases are fed to respective elements and as a result of having the same phases at the focal point, constructive interference occurs forming a focused spot. The required quadratic phases at the antenna elements can be obtained by additional transmission lines. The lengths of the additional transmission lines are different for each element and are calculated by using equation (2). Given that the total electrical distance from the reference point to the focal point should be equal for all elements for phase equality,

$$w_{n,m} + \overline{PF}_{n,m} = w_0 + \overline{OF}, \quad (2)$$

where,

$$\overline{PF}_{n,m} = \sqrt{x_n{}^2 + \ y_m{}^2 + \ z_f{}^2}, \quad (3)$$

$$\overline{OF} = z_f. \quad (4)$$

Figure 2 is used to show the parameters of equation (2-4). This figure consists of a plane that includes an x_n = constant line array and the focal point. Parameter $w_{n,m}$ is the length of the transmission line for $(n,m)^{th}$ element, w_0 is the length of the transmission line corresponding to the element at the origin and $\overline{OF}$ is the distance of the focal point from the origin, P is the position of the $(n,m)^{th}$ and $\overline{PF}_{n,m}$ is the distance between the $(n,m)^{th}$ element of the array and the focal point.

The focused beam above is static and cannot be shifted unless a new set of phases are fed, or the antenna aperture is shifted physically. Moving the focused beam by physically changing the position of the antenna array system is less efficient, inaccurate, and time consuming.

In this study, the shift in the beam position is achieved by adding multiple wavelength transmission lines at the designed frequency to successive y-direction elements. (There will therefore be an additional λ_0 transmission line leading to $m = 2$ elements as compared to $m = 1$ elements, and there will be a $2\lambda_0$ transmission line leading to $m = 3$ elements compared to $m = 1$ elements, etc., where λ_0 is the wavelength at the design frequency).

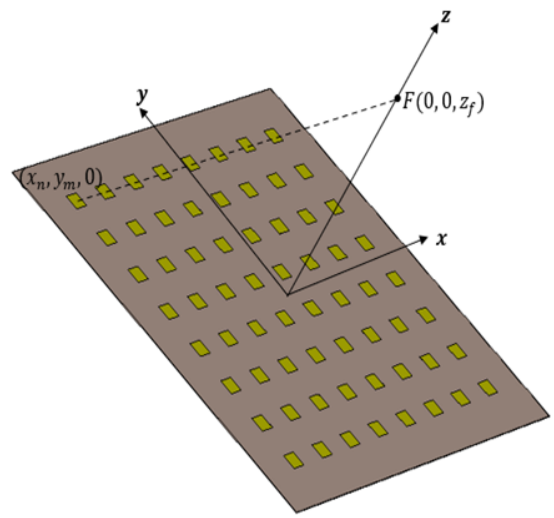

Fig. 1. Near-field focused patch antenna array.

Adding extra transmission line lengths at the design frequency does not add an extra phase to the elements of the array at this frequency. However, when the frequency is changed, the lengths of the transmission lines in terms of the wavelength are no longer equal to multiple wavelengths. This will cause a progressive phase change between the elements resulting in a shift in the beam position.

B. Movement of the beam by frequency change

In Section II A. above, it has been explained that the movement of the beam can be achieved by adding multiple wavelength transmission lines leading to the elements of an antenna array. A uniform 16×16 array antenna is used for this purpose. The elements of this antenna array are point radiators and they have equal amplitude. The design frequency is 2.4 GHz while the separation between the elements is 87.5 mm (0.7λ) in x and y-directions. λ is the free space wavelength. The focal point is F $(0,\ 0,\ z_f)$, with $z_f = 1250$ mm. The elements are fed through transmission lines having lengths $w_{n,m}$ calculated by using equation (2) and given in Table 1. In addition to $w_{n,m}$ long transmission lines, the successive elements of the array in the y-direction are fed with additional transmission lines of multiple wavelengths**,** as explained in Section II A. The total length of the additional transmission lines therefore becomes,

$$w'_{n,m} = \quad w_{n,m} + (m-1)\lambda_0. \quad (5)$$

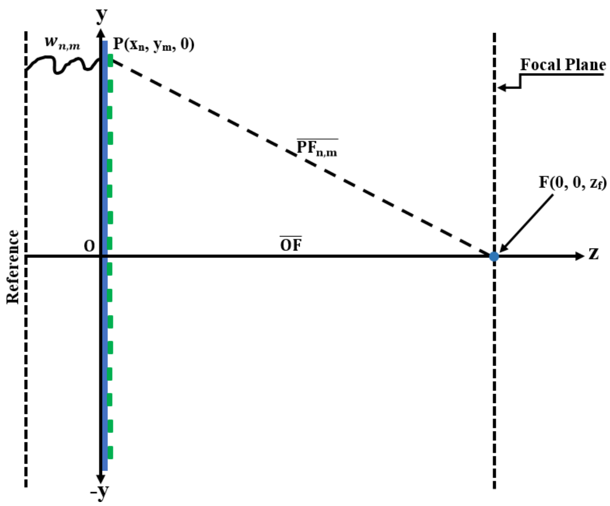

Fig. 2. The geometry of the focusing antenna array.

As the multiple wavelengths transmission lines above are added in the y-direction, the motion of the beam will be in the y-direction.

The transmission line lengths, $w_{n,m}$ for the 16×16 array, are given in Table 1. Only a sub-array of 8×8 is given due to the symmetry and large size of the array. The transmission line lengths are given in terms of wavelength at 2.4 GHz. The physical lengths of these additional lines will be dependent on the type and medium that they are constructed in.

Table 1: Transmission line lengths, $w_{n,m}$ for 8×8 sub-array

$w_{n,m}$	8	7	6	5	4	3	2	1
8	1.30 λ_0	0.99 λ_0	0.72 λ_0	0.49 λ_0	0.30 λ_0	0.16 λ_0	0.06 λ_0	0.01 λ_0
7	1.36 λ_0	1.04 λ_0	0.77 λ_0	0.54 λ_0	0.35 λ_0	0.20 λ_0	0.11 λ_0	0.06 λ_0
6	1.48 λ_0	1.16 λ_0	0.88 λ_0	0.65 λ_0	0.45 λ_0	0.31 λ_0	0.21 λ_0	0.16 λ_0
5	1.65 λ_0	1.32 λ_0	1.04 λ_0	0.81 λ_0	0.62 λ_0	0.47 λ_0	0.37 λ_0	0.32 λ
4	1.90 λ_0	1.57 λ_0	1.29 λ_0	1.05 λ_0	0.85 λ_0	0.69 λ_0	0.59 λ_0	0.54 λ_0
3	2.23 λ	1.90 λ_0	1.60 λ_0	1.36 λ_0	1.15 λ_0	1.00 λ_0	0.90 λ_0	0.84 λ_0
2	2.68 λ_0	2.33 λ_0	2.03 λ_0	1.76 λ_0	1.56 λ_0	1.40 λ_0	1.29 λ_0	1.23 λ_0
1	3.26 λ_0	2.90 λ_0	2.58 λ_0	2.31 λ_0	2.09 λ_0	1.92 λ_0	1.81 λ_0	1.75 λ_0

When the array is fed at 2.4 GHz the beam focuses at the focal point and when the frequency is changed, the phases at the radiators will change and the beam will move along the y-axis. The electric field intensity is calculated at each point along an observation line in the y-direction passing through the focal point. The field calculation is carried out by summing the electric field intensity from each of the array elements at the observation point by using equation (6) below:

$$E = A \sum_{n=1}^{16} \sum_{m=1}^{16} \frac{e^{-jkr}}{r}, \tag{6}$$

where A is a constant,

$$r = \sqrt{x_n^2 + (y_m - y)^2 + z_f^2}, \tag{7}$$

and y is the distance along the y-direction at the line of observation.

The radiation patterns calculated by equation (6) are shown in Fig. 3 for different frequencies along the y-axis passing through the focal point. It can be observed that the peak of the beam at the design frequency 2.4 GHz is at y=0, as expected. Figure 3 also shows that when the frequency is increased the beam moves in the positive y-direction, and as the frequency is decreased the beam moves in the negative y-direction.

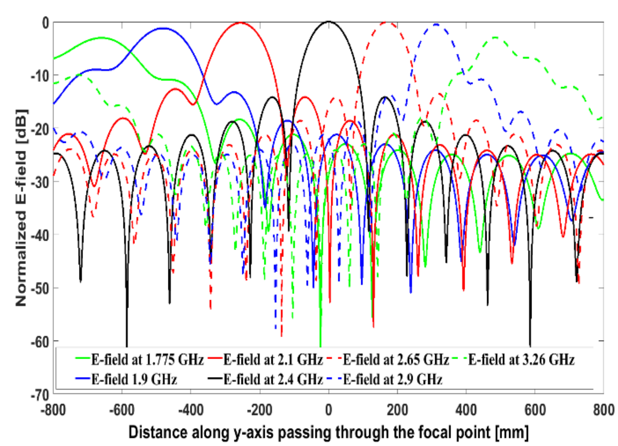

Fig. 3. Normalized E-field for 16×16 antenna array at different frequencies.

As the beam shifts away from the focal point, the beam deteriorates with lower gain, wider beamwidth, and higher sidelobes. The peak value drops by 3 dB for 3.260 GHz at positive 490 mm and the peak value drops by 3 dB for 1.775 GHz at negative 660 mm in the y-direction. The beam can therefore be scanned along a total distance of 1150 mm for this particular design.

III. DESIGN AND ANALYSIS OF SCANNING FOCUSED PATCH ANTENNA ARRAY

A. The design

A microstrip patch antenna array has been designed and analyzed to show the feasibility of the frequency scanning of the focused antenna array. As the design of a

16×16 or larger array having varied additional transmission line lengths would be very complex, an 8×8 element array has been chosen for the implementation. Two substrates have been used for implementing the system on the microstrip. The long transmission lines necessitated the use of two substrates. Having the feed network isolated from the patch array has the advantage of reducing the serious radiation from the power dividers. The two substrates use a common ground plane [17] as shown in Fig. 4 (c).

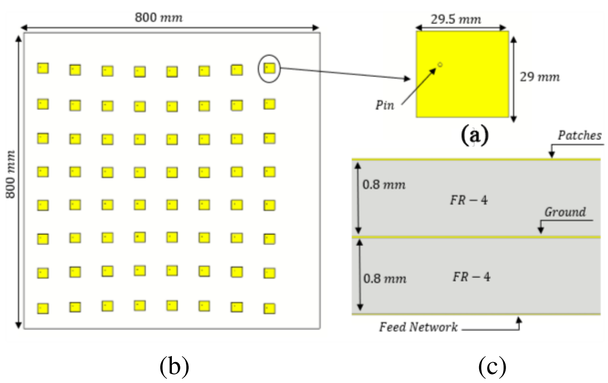

Fig. 4. Antenna array design (a) front view, (b) single element patch, and (c) side view.

Figure 4 (a) shows the front view of the patch antenna array. The separation between the elements of the patch antenna array is 87.5 mm and the total size of the microstrip antenna array is 800 x 800 mm. The feed network [18] and transmission lines of the above design are shown in Fig. 5.

The substrates are FR-4 with $\varepsilon_r = 4.3$, each having a thickness of 0.8 mm. The focal point of the array is 1250 mm from the origin of the array. The pin- fed rectangular patch antenna elements [19] are used as they are suitable for this antenna system which has two substrates. The position of the pin is (-6, 2.5) mm with reference to the center of the patch element. The feed network and the patches are connected through conducting pins as shown in Fig. 4 (b).The lower end of each pin is connected to the feedline while the upper end is connected to the patch, passing through both substrates and the ground plane. A section of 2.5 mm diameter around each pin is removed from the ground plane to avoid creating a short circuit. The pin position for patch antennas is calculated such that they are matched at the design frequency [20]. The length and width of the patch antenna elements are 29 mm and 29.5 mm respectively. These dimensions are obtained as in [11].

The phase delays required for each patch antenna element for focusing at the focal point at 2.4 GHz are obtained by using the transmission line lengths $w_{n,m}$ as shown in Table 2.

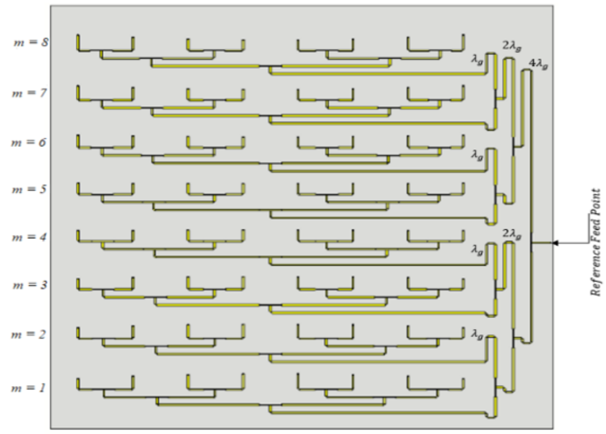

Fig. 5. Feed network and transmission lines of the antenna system.

Table 2: Transmission line lengths, $w_{n,m}$ in mm for 8×8 array

$w_{n,m}$	8	7	6	5	4	3	2	1
8	77.3	58.7	46.2	39.9	39.9	46.2	58.7	77.3
7	57.0	38.8	26.5	20.3	20.3	26.5	38.8	57.0
6	44.1	26.0	13.8	07.7	07.7	13.8	26.0	44.1
5	37.7	19.7	07.6	01.5	01.5	07.6	19.7	37.7
4	37.7	19.7	07.6	01.5	01.5	07.6	19.7	37.7
3	44.1	26.0	13.8	07.7	07.7	13.8	26.0	44.1
2	57.0	38.8	26.5	20.3	20.3	26.5	38.8	57.0
1	77.3	58.7	46.2	39.9	39.9	46.2	58.7	77.3

Additional one wavelength (approximately 67 mm) microstrip transmission lines are added between successive elements in the y-direction. The characteristic impedance of the transmission line is 50 Ω and the width of these lines is 3.05 mm. Equal power dividers are used to obtain equal power at each antenna array element. These power dividers are designed as in [11].

B. The analysis

The above design was analyzed by using CST Microwave Simulation software. Figure 6 shows the S_{11} of this 8×8 rectangular patch antenna array system. The magnitude of the reflection coefficient is in the order of −30 dB at the center frequency of 2.4 GHz and is less than −15 dB over the frequency range of interest. It can be observed that minimum reflections occurs at a frequency 1% below the center frequency which may have been caused by rounding up the transmission line lengths.

Figure 7 illustrates the normalized electric field along the x and y directions at the center frequency. As expected, at the design frequency both plots have maximum magnitudes at the focal point. The side lobe levels are below −10 dB in both x and y-directions. The half

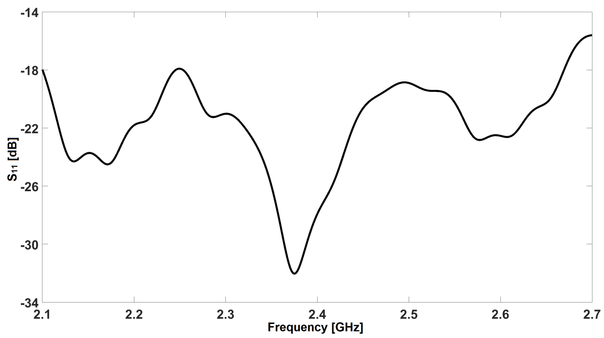

Fig. 6. S_{11} of the system.

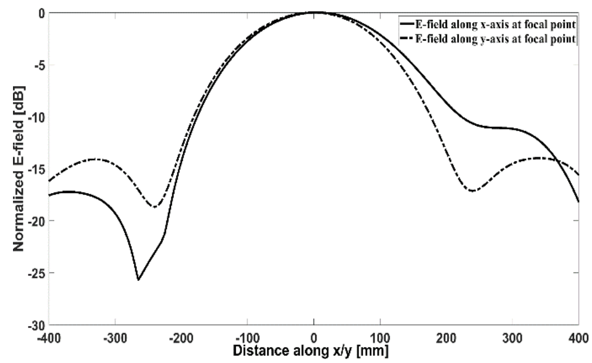

Fig. 7. Normalized E-field along x and y at the focal point.

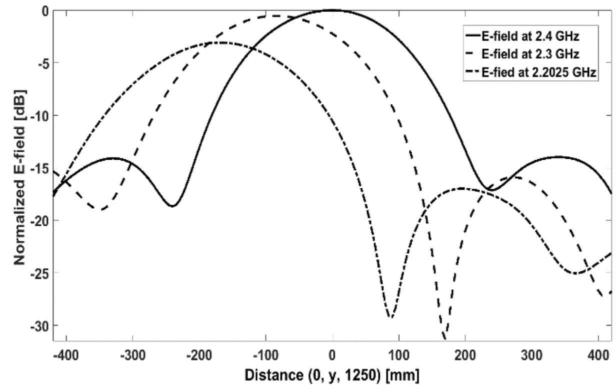

Fig. 8. Normalized E-field at the focal point for 2.2025 GHz, 2.3 GHz, and 2.4 GHz.

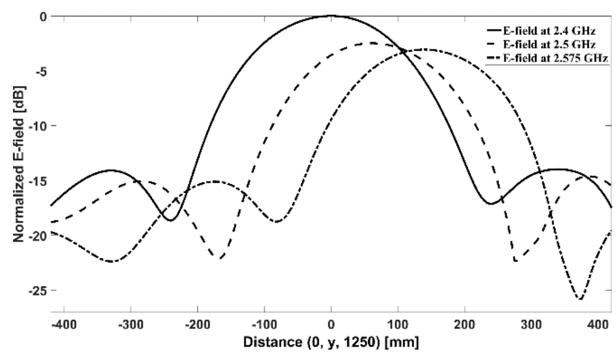

Fig. 9. Normalized E-field at the focal point for 2.4 GHz, 2.5 GHz, and 2.575 GHz.

power beamwidth of the focused beam at the center frequency is approximately 200 mm in both directions.

Figure 8 shows the shift in the focused beam along the y-axis in the negative direction as the frequency is decreased from 2.4 GHz to 2.2025 GHz. The peak magnitude of the focused field decreases as it moves away from the focal point. The distance between the peak values of frequencies 2.4 GHz and 2.2025 GHz, where the magnitude of the focused fields reduces by 3 dB, is 170 mm. The amount of shift in the focused beam depends on the distance of the focal point from the array, the separation between the array elements, and the change in the frequency. The shift due to the change in frequency is linear for small frequency changes but becomes nonlinear as the distance is increased from the focal point. For this design, the shift is approximately 74 mm per 0.1 GHz.

Figure 9 shows the shift in the focused beam along the y-axis in the positive direction as the frequency is increased from 2.4 GHz to 2.575 GHz. The peak magnitude of the focused field decreases as it moves away from the focal point. The distance between the peak values at 2.4 GHz and at the frequency 2.575 GHz, where the magnitude of the focused fields reduces by 3 dB, is 140 mm.

The above results show that the total shift of the focused fields along the y-axis is approximately 310 mm, therefore validating the principle that the focused beam can be shifted by a considerable distance by changing the frequency.

The shifting distance of the beam can be larger for larger-size arrays, as shown in Section II B. Although there have been many publications on near-field focusing and electronic beam scanning in the far field [21–23], no specific paper was found on the electronic scanning of fields in the near field. Although it was not possible to compare the focused scanned beams with any published paper, the results of the beam at the focal point compare well with [3].

IV. CONCLUSION

This paper presented a new antenna system for shifting the focused beam by change of frequency. The movement of the focused beam was achieved by using additional one wavelength transmission lines between successive elements of the array. After establishing the principle of the movement of the focused beam, a 16×16 element antenna array with point radiators was used to demonstrate this principle.

The antenna array was designed for 2.4 GHz and had a focal length of 1250 mm. It was shown that the beam of this antenna system could be shifted by 1150 mm in the focal plane by changing the frequency from 1.775 GHz to 3.26 GHz. As the design of a 16×16 array with varied additional transmission line lengths would be very complex, an 8×8 element array was used for the implementation of the frequency scanning antenna system. This antenna system was implemented on two microstrip substrates having patch antennas on one substrate and a feed network on the other.

The additional transmission lines were incorporated into the feed network design. A full-wave simulation study was carried out using CST simulation software. The simulation results show that the S_{11} of this antenna system is satisfactory, being less than -15 dB over the frequency range of interest. The focused beam moved by 310 mm by changing the frequency from 2.2025 GHz to 2.575 GHz. The study demonstrated that by changing the frequency, the focused beam can be shifted a considerable distance by using the system introduced in this paper.

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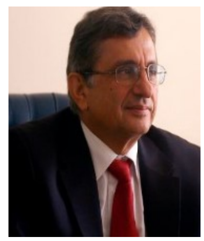

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