Design and Simulation of Narrow Beamwidth Dipole Array Antenna for Microwave Imaging

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Abstract - *This paper introduces a novel medical imaging approach with microwaves using a narrow-beam dipole antenna array. The proposed technique removes the hazards caused by imaging with X-rays and, at the same time, enhances diagnostic precision over traditional ultrasound. The dipole antenna array, with a narrow half-power beam width and reduced side-lobe, enables focused and precise imaging of biological targets. The study explores theoretical foundations, potential applications, advantages, and emphasizes its role in tumor and cancer detection. This innovative solution holds promise for safer diagnostics and improved accuracy in medical imaging technologies.*

Key Words: Dipole array, Microwave Imaging, Beamwidth, Array factor, Binomial Method, Woodward Lawson Method, Space factor

1.INTRODUCTION

Medical imaging stands as a cornerstone in the realm of healthcare, playing an indispensable role in the early detection and diagnosis of tumours and cancerous cells. A myriad of methodologies, ranging from the widely utilised X-rays to advanced techniques like CT scans, mammograms, ultrasound, MRI, PET scans, and nuclear medicine scans, offer valuable insights into the internal structures of the human body. However, each method carries its own set of limitations, sparking a critical need for exploration into alternative imaging modalities that not only address health concerns but also elevate the accuracy of diagnostic procedures.

One prominent challenge arises from X-ray imaging, a stalwart in medical diagnostics. Despite its widespread use, the technique raises apprehensions due to the potential health risks associated with ionising radiation exposure. Furthermore, ultrasound imaging, often considered a safer alternative, confronts limitations in precision, hindering its efficacy in accurate tumour detection. This imperative necessitates a paradigm shift in medical imaging approaches, prompting the introduction of innovative solutions that transcend the existing constraints.

In response to the limitations inherent in current imaging techniques, this paper introduces a groundbreaking approach—microwave imaging with a narrow beam dipole antenna array. This method seeks to address the health risks posed by X-ray exposure while concurrently enhancing the accuracy of tumour detection beyond the confines of conventional ultrasound methods. The design incorporates a dipole antenna array working on the 2.4 GHz microwave band with a very low 3 dB beamwidth, offering a nuanced and precise imaging capability..

2. LITERATURE REVIEW

The utilisation of microwave technology in medical imaging has gained attention in recent years due to its potential for non-ionising and safer imaging compared to X-rays. Nour [1] has proposed a working principle behind microwave imaging (MWI) and its various types, namely, microwave tomography and radar-based imaging. The permittivity and conductivity of malignant and benign breast tissues were examined by Joines et al. [2] in 1994 at frequencies spanning from 50 to 900 MHz, and their results were in line with the previously described investigations.. Mohammad Alibakhshikenar [3] presented a study of a planar antenna array inspired by the metamaterial concept where the resonant elements have sub-wavelength dimensions for application in microwave medical imaging for detecting breast cancer. The proposed antenna consists of square-shaped concentric rings, which are connected to a central patch through a common feedline. A small and ultra-wide band antenna on a flexible substrate has been reported by Ashiqur Rahman [4] using the 5-(4-(perfluorohexyl)phenyl)thiophene-2-carbaldehyde compound for microwave imaging. The compact antennas are 20 × 14 mm2 and designed for operating at frequencies from 4 to 6 GHz. Mohammad Shahidul Islam [5] has proposed a metamaterial (MTM)-loaded compact three-dimensional antenna with a folded parasitic patch that attains directional radiation patterns with 80% fractional bandwidth. The operating frequency of the antenna is 1.95–4.5 GHz. Johnathan [6] has proposed The dual antiphase patch antenna for osteoporosis operates at 2.4 GHz.

3. THEORITICAL BACKGROUND

Arranging the antenna in a precise configuration that maximizes each component's contribution in the intended direction and minimizes it in other directions is the best method to increase antenna performance without expanding its size. Antenna array is this. Some important parameters of antenna array are [7] :

1. Antenna Patterns : An antenna pattern (or radiation pattern) is a three-dimensional plot of radiation at its far field.
2. Directive Gain : The directive gain ($G_d(\theta,\phi)$) of antenna is a measure of the concentration of the radiated power in a particular direction (θ,ϕ).

   $$G_d = \frac{4\pi U(\theta,\phi)}{P_{rad}} \qquad (1)$$

   Where $U(\theta,\phi)$ is radiation intensity and P_{rad} is total average radiated power.
3. Beam Width : Beam width is the aperture angle from where most of the power is radiated
4. Half power Beamwidth: The angular separation, in which the magnitude of the radiation pattern decreases by 50% (or -3dB) from the peak of the main beam, is the Half Power Beam Width.
5. Array Factor : Array factor represents the radiation pattern of an antenna array. It describes how the individual antennas in an array combine to form a radiation pattern that is different from that of a single antenna element. General equation for N element linear array is

   $$AF = \sum_{n=1}^{N} a_n e^{j(n-1)(kd\cos\theta+\beta)} \qquad (2)$$

   Where $= \frac{2\pi}{\lambda}$, d = the spacing between adjacent antenna elements, N is the total number of antenna elements in the array, $\cos\theta$ is the directional cosine term, which takes into account the angle of radiation or observation.

4. RADIATION PATTERN

Very long arrays of discrete elements usually are more difficult to implement, as well as expensive, but have narrow beamwidths. For such application, antennas with continuous distributions would be convenient to use. A very long wire represents antennas with continuous line and a large reflector represents antennas with continuous aperture distributions. As the number of elements increases in a fixed-length array, the source approaches a continuous distribution. In the limit, the array factor summation reduces to an integral. For a continuous distribution, the factor that corresponds to the array factor is known as the space factor. For a line-source distribution of length l placed symmetrically along the z-axis , the space factor (SF) is given by [7]

$$SF(\theta) = \int_{-l/2}^{l/2} I_n(z')e^{j[kz'\cos\theta+\phi_n(z')]}dz' \qquad (3)$$

where$I_n(z')$ and $\phi_n(z')$ represent, respectively, the amplitude and phase distributions along the source.

According to Fourier Transform method for a continuous line-source distribution of length l, the normalized space factor can be written as

$$SF(\theta) = \int_{-l/2}^{l/2} I(z')e^{j[k\cos\theta-k_z]z'}dz' \qquad (4)$$

where k_z is the excitation phase constant of the source. For a normalized uniform current distribution of the form $I(z') = \frac{I_0}{l}$ equation (4) reduces to [7]

$$SF(\theta) = I_0 \frac{\sin[\frac{kl}{2}(\cos\theta - \frac{k_z}{z})]}{\frac{kl}{2}(\cos\theta - \frac{k_z}{z})} \qquad (5)$$

4.1 Woodward-Lawson method

A very popular antenna pattern synthesis method used for beam shaping was introduced by Woodward and Lawson [8], [9], [10]. The desired pattern is sampled at different discrete points to complete the synthesis. Every pattern sample has a harmonic current with a uniform progressive phase and amplitude distribution associated with it. The field that corresponds to this harmonic current is called the composing function. For a line-source, each composing function is of an $b_m \frac{\sin(\psi_m)}{\psi_m}$ form whereas for a linear array it takes an $b_m \frac{\sin(N\phi_m)}{N\sin(\phi_m)}$ form. Each harmonic current has an excitation coefficient b_m such that, at each corresponding sampled point, the field strength of the desired pattern equals the amplitude of the pattern. A finite summation of space harmonics makes up the source's overall excitation. A finite summation of composing functions, with each term denoting the field of a current harmonic with uniform amplitude distribution and uniform progressive phase, represents the matching synthesized pattern. The analytical formulation of this method is similar to the Shannon sampling

If the current distribution of a continuous source be represented, within $-\frac{l}{2} < z' < \frac{l}{2}$ range,then by a finite summation of normalized sources each of constant amplitude and linear phase of the form [7]

$$i_m(z') = \frac{b_m}{l}e^{-jkz'\cos\theta_m} \qquad (6)$$

θ_m represents the angles where the desired pattern is sampled.

Associated with each current source of equation (6) is a corresponding field pattern of the form given by [7]

$$s_m(\theta) = b_m\left[\frac{\sin[\frac{kl}{2}(\cos\theta - \cos\theta_m)]}{\frac{kl}{2}(\cos\theta - \cos\theta_m)}\right] \tag{7}$$

whose maximum occurs when $\theta = \theta_m$. The total pattern is obtained by summing 2M (even samples) or 2M + 1 (odd samples) terms each of the form. So

$$SF(\theta) = \sum_{-M}^{M} b_m\left[\frac{\sin[\frac{kl}{2}(\cos\theta - \cos\theta_m)]}{\frac{kl}{2}(\cos\theta - \cos\theta_m)}\right] \tag{8}$$

To satisfy the periodicity requirements of 2π for real values of θ (visible region) and to faithfully reconstruct the desired pattern, each sample should be separated by

$$kz'\Delta|_{z'=l} = 2\pi \tag{9}$$

$$\Delta = \lambda/l \tag{10}$$

4.2 Binomial Array

The binomial array method is used to create small side lobes of the antenna pattern. As a matter of fact, binomial arrays with element spacing equal to or less than one-half of a wavelength have no side lobes. It is apparent that the designer must compromise between side lobe level and beamwidth. [7]

The array factor of a binomial array is represented as

$$AF_{2M}(even) = \sum_{n=1}^{M} a_n \cos[(2n-1)u] \tag{11}$$

$$AF_{2M+1}(odd) = \sum_{n=1}^{M+1} a_n \cos[(2n-1)u] \tag{12}$$

Where $u = \frac{\pi d}{\lambda}\cos\theta$

To determine the excitation coefficients of a binomial array, J. S. Stone [6] suggested that the function $(1+x)^{m-1}$ be written in a series, using the binomial expansion, as [7]

$$(1+x)^{m-1} = 1 + (m-1)x + \frac{(m-1)(m-2)}{2!}x^2 + \frac{(m-1)(m-2)(m-3)}{3!}x^3 + \cdots \tag{13}$$

The above represents Pascal's triangle. If the values of m are used to represent the number of elements in the array, then the coefficients of the expansion represent the relative amplitudes of the elements.

For example, for 5 elements excitation amplitudes will be 1,4,6,4,1.

5. PROPOSED METHOD

The amplitude excitation coefficients for a specific number of elements are one of the prerequisites for the binomial technique, just like for any other nonuniform array method. One can use equation (13) or its extensions to do this. Side lobe level, half-power beamwidth, and directivity are further figures of merit. When the spacing between the elements is equal to or less than half of a wavelength, binomial arrays don't show any minor lobes. However, the primary drawback is that the beamwidth cannot be reduced using a binomial array. Additionally, it works best with fewer array elements.

Conversely, the Woodward-Lawson technique allows for the development of the overall pattern in the following ways: The primary beam placement of the pattern generated by the first composing function is based on the value of its uniform progressive phase, and the innermost sidelobe level is around −13.5 dB. The level of the remaining sidelobes falls monotonically. With the exception of adjusting its uniform progressive phase to align its major lobe maximum with the innermost null of the first composing function, the second composing function follows a pattern that is comparable to the first. As a result, the innermost null of the first composing function's pattern fills in; the second composing function's amplitude excitation regulates how much filling-in occurs. From equation (10)

$$\cos\theta_m = m\Delta = \frac{m\lambda}{l}, m = \pm 1, \pm 2 \ldots \text{ for odd samples} \tag{14}$$

$$\cos\theta_m = \left\{\frac{(2m-1)}{2}\Delta = \frac{(2m-1)}{2}\left(\frac{\lambda}{l}\right)\right\} \tag{15}$$

$$m = +1, +2 .. for\ even\ samples$$

$$\cos\theta_m = \left\{\frac{(2m+1)}{2}\Delta = \frac{(2m+1)}{2}\left(\frac{\lambda}{l}\right)\right\}, \tag{16}$$

$$m = -1, -2 .. for\ even\ samples$$

$$\theta_m = \cos^{-1}\left(m\frac{\lambda}{l}\right) \tag{17}$$

In the proposed method 11 elements have been taken. So $l = 5\lambda$ and $M = 5$, odd samples.

So angles and excitation coefficients are calculated as.

Table-1: Excitation Coefficients (Woodward Lawson)

m	θ_m	$b_m = SF(\theta_m)_d$	m	θ_m	$b_m = SF(\theta_m)_d$
0	90°	1	-1	101.54°	1
1	78.46°	1	-2	113.58°	1
2	66.42°	1	-3	126.87°	1
3	53.13°	1	-4	143.13°	0
4	36.87°	0	-5	180°	0
5	0°	0			

From equation (13), for 11 elements excitation amplitudes will be as follow

Table-2: Excitation amplitudes (Binomial)

m	Excitation amplitude	m	Excitation amplitude
0	252	-1	210
1	210	-2	120
2	120	-3	45
3	45	-4	10
4	10	-5	1
5	1		

So in the proposed method excitation phases of the array elements has been taken according to Woodward-Lawson method and excitation amplitudes has been taken as Binomial array method.

6. RESULT AND DISCUSSION

The parameters of proposed antenna array is given below.

Table-3: Antenna parameters

Antenna Parameter	Value
Arm Length	27.5mm
Diameter	2.08mm
Gap between arms	2.08mm
Spacing between two dipoles	62.5mm

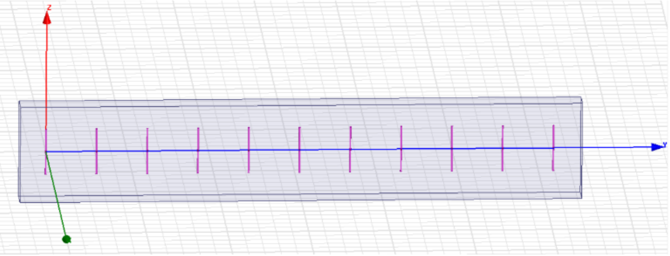

Fig -1: Structure of proposed antenna array

The proposed design was simulated in HFSS(Fig-1). The antenna specifications are taken from table no. 3, and feeding excitation amplitude and phase has been taken from table 1 and 2.

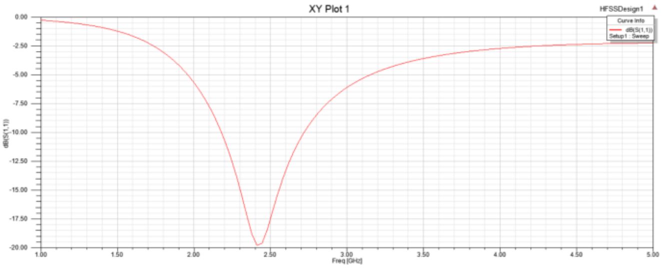

Fig -2: S parameter of proposed design

From the simulation results it is found that the S parameter had a center frequency at 2.4 GHz with a return loss value of -19.78dB. And the bandwidth had been found to be 1.9GHz.

Figure -3: 3D polar plot

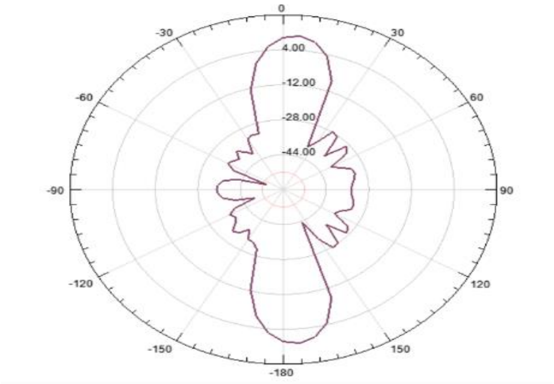

Figure -4: Radiation pattern at theta=90°

From the 3D polar plot it is observed that the main lobe maximum gain is 10.53dB. HPBW is 18.9° and minimum sidelobe gain is -69.2dB. Maximum side lobe gain is -27.48dB.

Comparison of the results of the proposed design with various similar designs are as follows :

Table -4: Comparison with similar work

Works	Frequency	No. of elements	Main lobe gain (dB)	HPBW(degree)	Side lobe gain(dB)	Bandwidth
Aras Saeed Mahmood [11]	1.8GHz	10	10.7	80	0.13	-
Aras Saeed Mahmood [11]	1.8GHz	9	12.4	80	1.68	-
Tianfan Xu [12]	5.9 GHz	16	11.3	24.4	-11.4	579 MHz
B. Narasimha Reddy [13]	300 MHz	19	0	10	-28	-
Richard W. Ziolkowski [14]	2.45 GHz	9	12.5	155	-11.9	78 MHz
A. Trastoy [15]	-	19	2.6	3.6	-25.4	
Proposed Method	2.4Ghz	11	10.53	18.9	-27.48	1.9Ghz

7. CONCLUSIONS

In conclusion, this paper introduces a transformative approach to medical imaging—microwave imaging with a narrow beam dipole antenna array. Addressing limitations in existing modalities, the proposed technique leverages microwave radiation for safer diagnostics and improved accuracy. The precise design of the antenna array, with a 3 dB beam width of 18.9 degrees, a main lobe gain of 10.59 dB, and a maximum side-lobe value of -27.48 dB, offers focused imaging. The study explores theoretical foundations, including binomial feeding and the Woodward-Lawson method. With potential applications in tumor detection, the comparative analysis simulated in HFSS forecasts this innovation as a promising advancement in medical imaging, prompting further research for enhanced precision and patient care.

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