Current Distribution Dynamics in Microstrip Patch Antenna Arrays

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Abstract

This paper presents a novel way for achieving endfire radiation pattern using microstrip patch antenna array. The extensively used microstrip patch antennas i.e. rectangular and circular microstrip patch antennas, either single patch or in an array configuration do not have an endfire radiation pattern. The antenna array presented in this paper is designed by changing the geometry of the antenna and current distribution. Array consists of U-shaped radiating elements which alter the radiation pattern of individual radiating element and a partial ground plane is used to change the current distribution. In start, the paper presents the parametric study of novel single U-shaped antenna and afterwards a complete analysis of current distribution for two element, four element and eight element U-shaped microstrip antenna arrays is given.

Keywords: *Antenna array, broadside, endfire, U-shaped patch, current distribution, partial ground plane.*

1. Introduction

The extensive, rapid and explosive growth in wireless communication technology and communication systems is prompting the extensive use of low profile, low cost and easy to manufacture antennas. All these requirements are efficiently realized by microstrip antennas. Microstrip antennas grant RF engineers with innumerable advantages as compared to conventional antennas; such as small size, low profile, low cost, light weight, mechanically robust, easy integration in electronic and communication systems [1,2] and bulk production.

In terms of performance, single element microstrip antennas have limited performance and mostly do not fulfill the requirements of systems in which they are integrated because of certain demerits such as low gain, narrow bandwidth, high side lobe levels etc., but in real time applications, efficient performance is required [3,4]; which leads towards designing of microstrip antenna arrays [4]. The significant advantages of microstrip antenna arrays are that they are highly directive and have higher performance in terms of bandwidth and gain. The most significant advantage of antenna arrays is that the direction of maximum radiation can be changed and thus they can be used in beam scanning capabilities [1,3]. The significant change in radiation pattern of arrays can be achieved by changing current distribution array [1,3], incorporating phase delay between from element to element [2,4], change in the radiation characteristics of individual radiating structure in an array [1,5], change in the geometry of the array and by changing the inter-element spacing [2,5].

The two main classifications of array on the basis of direction of maximum radiation are broadside and endfire antenna arrays. Broadside arrays are those arrays in which the direction of maximum radiation is perpendicular to the axis of the array i.e. if an array is placed in x-y plane along x-axis, then the direction of maximum radiation is along y-z plane; and on the other hand endfire arrays have direction of maximum radiation parallel to the axis of the array i.e. in this case if an array is placed in x-y plane along x-axis, then the direction of maximum radiation should be along x-axis. Generally, rectangular and circular microstrip antennas are extensively used and they have a broadside radiation pattern. Some other printed microstrip antennas such as Yagi and tapered slot antenna inherently have an endfire radiation pattern [1,3,4].

In this research, a novel U-shaped antenna has been designed which provide an endfire radiation pattern when laid down in an array configuration. It has been observed that arrays consisting of 4 and eight elements produce an endfire radiation pattern when their current distribution is changed. The analysis procedure adopted for observing the change in radiation pattern is that initially the effect of change in current distribution on radiation pattern is analyzed for single U-shaped microstrip antenna. Afterwards, a two, four and eight element array have been designed, and the same analysis of change in radiation pattern with change in current distribution is observed. The critical aspect of designing an array is designing the array feeder. In the arrays designed, corporate feed networks with quarter wave transformers for impedance matching are used. SMA connector of 50Ω and FR-4 substrate is used.

The design specifications are summarized in the table 1. Rest of the paper is organized as follows. In the section 2 of the paper, a novel U-shaped microstrip antenna is proposed, the designing aspects and parametric study of single U-shaped element is discussed in section 3. In section 4, simulated and fabricated results are compared for single element, designing aspects of two, four and eight element arrays are also discussed in detail. Section 5 is devoted to discuss the effects of change in current distribution on single element and two, four and eight element array. Finally, sections 6 conclude and summarize the work.

Table 1. Design Specifications of U-shaped Antenna

Design Specifications of U-shaped Antenna	
Operating Frequency	2.6 GHz
Substrate	FR-4
Dielectric constant of substare	4.4
Height of substrate	1.6mm
Loss tangent of substrate	0.025
Operating wavelength (λ)	55mm

2. Proposed Antenna Design

A U-shaped microstrip patch antenna is proposed in this section which when laid in array configuration produce an endfire pattern with change in the current distribution in the array. The proposed design of antenna is provided in Fig.1 and the dimensions of the proposed antenna are listed in Table 2.

3. Effect of Design Parameters

The proposed U-shaped antenna is designed at 2.6GHz. After designing the antenna, parametric analysis is done in order to show the effect of different parameters on frequency. The parameters are change in length and width of the arms and change in the width of the base of proposed antenna structure. In the subsequent subsections, the effects on frequency with respect to above mentioned parameters are discussed.

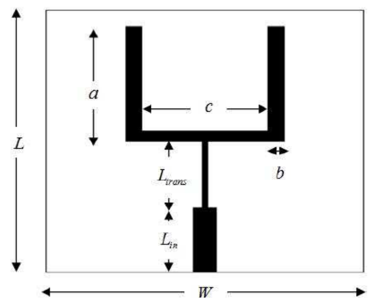

Fig.1. Single U-shaped Patch Antenna

Table 2. Design Specification of Single U-shaped Antenna

Parameters of Single U-shaped Antenna	
L	50 mm
W	40 mm
A	22 mm
B	2 mm
C	16 mm
L_{trans}	13.75 mm
L_{in}	12.25 mm

3.1. Effect of variation of Arm Length

The first parameter of the designed to be analyzed is the length of the arm of U-shaped microstrip antenna. This parameter is denoted by *a* in Fig 1. Fig 2 shows the effects on resonant frequency because of variation in the length of the arm of designed antenna. It is observed that if the arm length is increased the resonant frequency starts to decrease and if the arm length is decreased the frequency starts to increase. The return loss results are shown in Fig 2. It is clear that there is a regular pattern in change of resonant frequencies with change in the arm length. After optimizing the arm length along with other parameters discussed later, the required operating frequency is achieved i.e. 2.6 GHz.

3.2. Effect of variation of Arm Width

Other parameter to be analyzed is arm width of designed microstrip antenna denoted by *b* in Fig 1. Fig 3 shows the return loss results with change in arms widths. It is observed that the increase in the width of arms increases the resonant frequency of the antenna and a regular trend exits in the change of resonant frequency with change in arm width.

3.3. Effect of variation of width of base

One of the crucial factor is the width of the base of designed antenna represented by *c* in Fig 1. Fig 4 shows the return loss results achieved by changing width of the base of designed antenna. It is been analyzed that if the width of the base is decreased, the resonant frequency increases and if the width is increased, the resonant frequency starts to decrease; width of rectangular microstrip antenna has same affect on the resonant frequency.

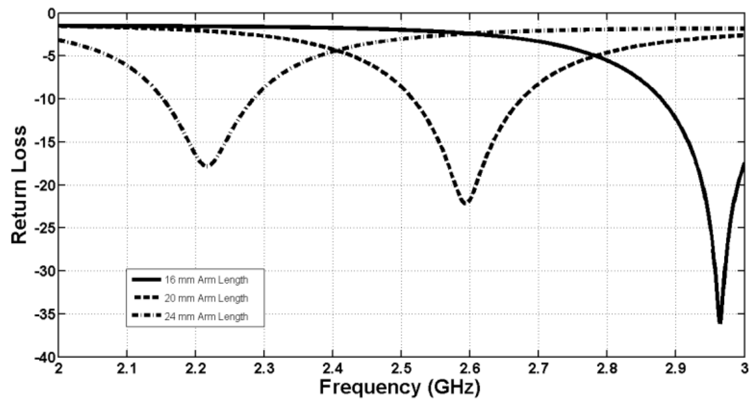

Fig. 2. Analysis of change in arm length of designed U-shaped Antenna

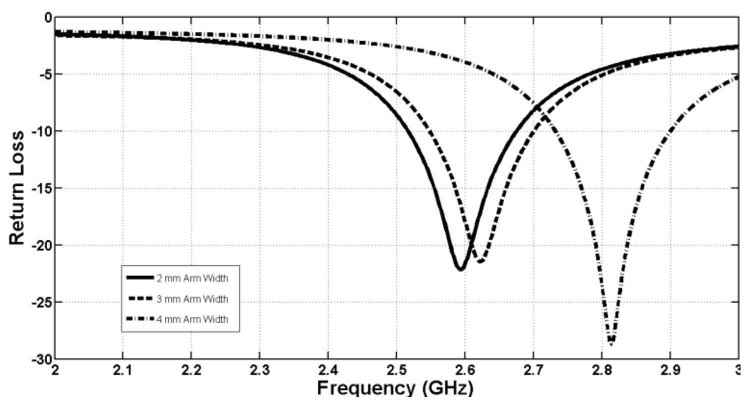

Fig. 3. Analysis of change in arm width of design U-shaped Antenna

4. Design of Antenna Array

It is a known fact that changes in current distribution maneuvers the radiation pattern in case of arrays. In order to analyze the affect of current distribution on arrays, U-shaped microstrip antenna arrays consisting to two four and eight elements are designed at the specified frequency. The most critical aspect of designing antenna array is the inter-element spacing, the spacing can be between 0.5λ to λ; but after rigorous simulations, it is observed that the results are best when the inter-element spacing is set to be 0.743λ=40.9 mm. The feeding network of all the designed arrays consists of corporate feeding technique with quarter wave transformers and patch used in arrays have same dimensions as that of single U-shaped patch antenna. In order to make the design clear all the specifications of designed antenna arrays are listed in Table 3 and designs of arrays in subsequent subsections.

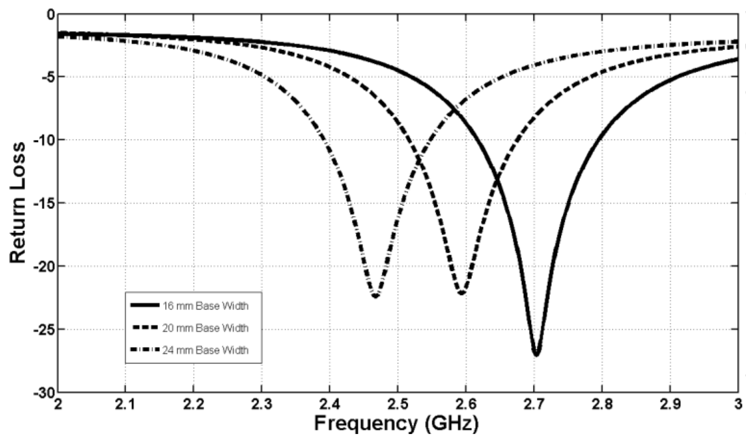

Fig. 4. Analysis of change in base width of design U-shaped Antenna

Table 3. Design Specifications of Antenna Arrays

Design Specifications of Antenna Arrays	
Operating Frequency	2.6 GHz
Substrate	FR-4
Dielectric constant of substare	4.4
Height of substrate	1.6mm
Loss tangent of substrate	0.025
Operating wavelength (λ)	55mm
Inter-element Spacing	0.743λ=40.9 mm

4.1. Two Element Antenna Array

The designed two element antenna array consists of two U-shaped patch of similar dimensions as that of single U-shaped antenna with corporate feeding technique and have quarter wave transformers for impedance matching. The input impedance of the feeding network is of 50Ω and SMA connector of same impedance is used. The inter-element spacing is kept to be 0.743λ. All the necessary dimensions of two element array is listed in Table 4 and the designed array is shown in Fig 5.

4.2. Four Element Antenna Array

The designed four element array consists of four U- shaped patches configured in the form of an array. The same feeding technique of corporate feed with transformers for impedance matching, SMA connector of 50Ω and inter-element spacing of 0.743λ is used for designing the array. All the dimensions are listed in Table 5. It is important to note that L_{gp} in Table 5 represents the length of ground plane at which an endfire radiation pattern is achieved for the designed array and array design is shown in Fig 6.

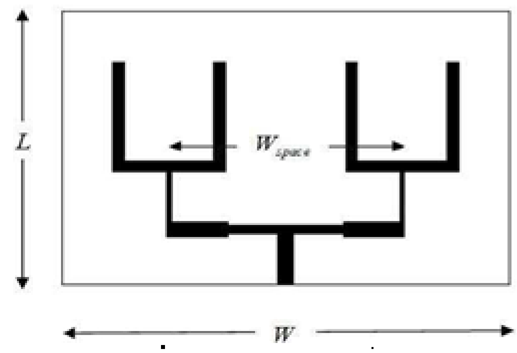

Fig. 5. Two Element Antenna Array

Table 4. Design Specifications of Two Element Antenna Array

Parameters of Two Element of Antenna Array	
L	55 mm
W	80 mm
W_{space}	40.9 mm

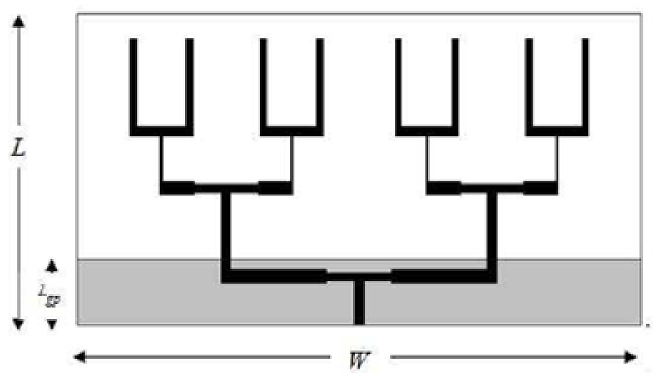

Fig. 6. Four Element Antenna Array

Table 5. Design Specifications of Four Element Antenna Array

Parameters of Four Element of Antenna Array	
L	70 mm
W	180 mm
L_{gp}	15 mm

4.3. Eight Element Antenna Array

After designing and analyzing two and four element antenna arrays, an array consisting of eight elements is designed for analysis. All parameters such as dimensions of array elements, inter-element spacing and same impedance SMA connector are used. All the necessary dimensions are listed down in Table 6 and the array design is shown in Fig 7. The dimension of L_{gp} corresponds to the length of ground plane at which the endfire radiation pattern is achieved.

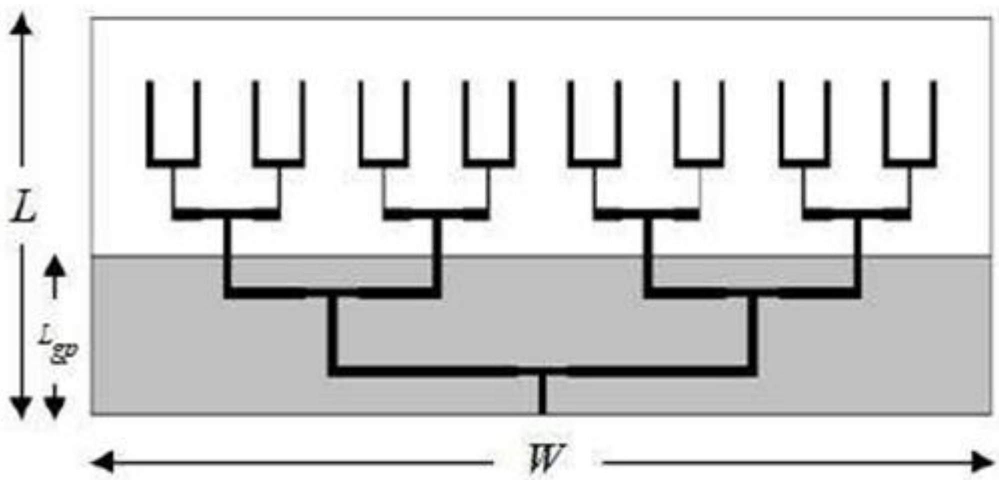

Fig. 7. Eight Element Antenna Array

Table 6. Design Specifications of Eight Element Antenna Array

Parameters of Eight Element of Antenna Array	
L	100 mm
W	350 mm
L_{gp}	40 mm

5. Results and Discussions

The methodology adopted for changing the radiation pattern is to first design a single element antenna, two, four and eight element arrays at the specified frequency of 2.6 GHz and afterwards analyze the change in radiation pattern with change in current distribution. Theaim was to achieve a desired endfire radiation pattern, so the analysis is done only for the radiation pattern rather than achieving certain frequency of operation or some other characteristics. For designing a certain frequency of operation is selected and the antennas are optimized. Fig. 8 shows the return loss of the entire designed antennas either single element of arrays and Fig. 9 shows the measured return loss for the designed antennas. It is observed that resonating frequency of four element array is less i.e. less than 2.6 GHz.

It is noted that numerous classes of printed microstrip antennas such as Yagi, Vivaldi (Tapered Slot) antennas etc produce an endfire radiation pattern whether alone or configured in the form of an array. In this research novel U-shaped printed microstrip antenna arrays are designed which will produce an endfire radiation pattern with change in current distribution. It is also observed that a single U-shaped antenna do not produce an endfire radiation pattern at any value of current distribution, but when the same designed antenna is laid down in an array fashion, the arrays produce an endfire radiation pattern with change in current distribution. The radiation pattern of single U-shaped patch, two element array, four element array and eight element arrays with change in current distribution are shown in Fig. 10.

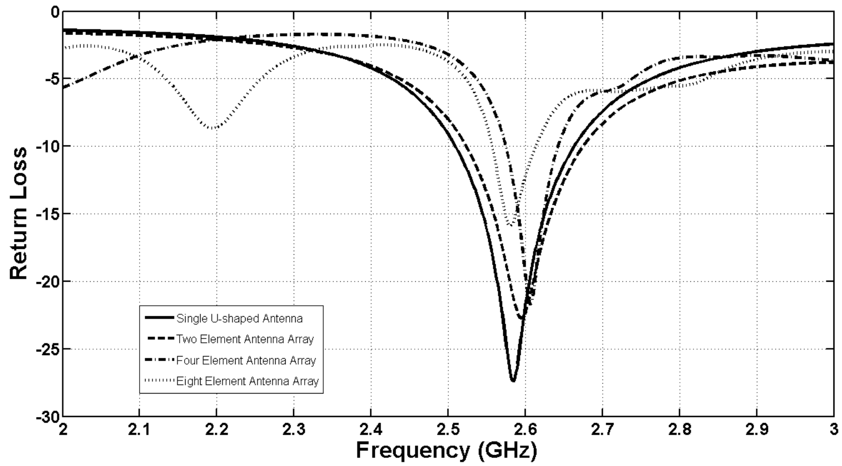

Fig. 8. Simulated Return Loss of U-shaped Antenna and Arrays

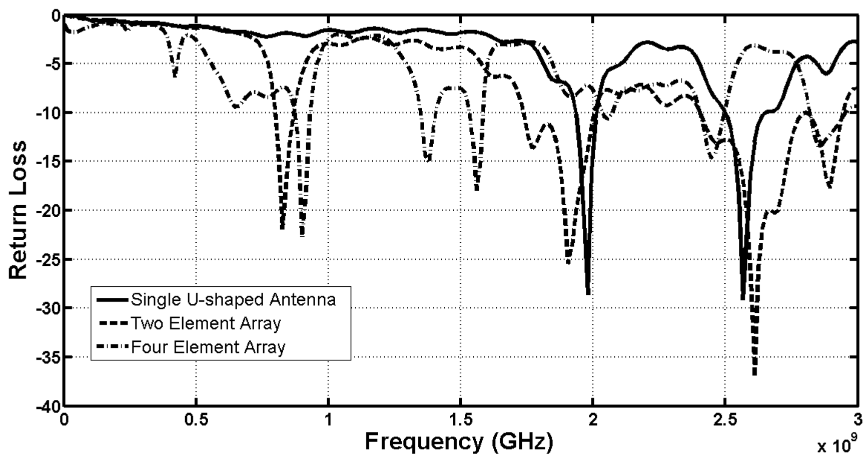

Fig. 9. Measured and Simulated Return Loss of Single U-shaped Antenna

5.1. Current Distribution Analysis on Single U-shaped Patch

Current distribution is changed by changing the length of ground plane. It is observed that single U-shaped patch do not produce an endfire radiation pattern for any change in current distribution. It is a known fact that the current distribution changes the radiation pattern only in antenna arrays and no significant change in the radiation pattern of single element antenna is reported in literature. It is clear from the analysis of change in current distribution that an endfire radiation pattern is not achievable by single U-shaped antenna; and there are minute changes in radiation pattern with change in current distribution. The effect of change in current distribution on radiation pattern in single U-shaped patch is shown in Fig. 10 (a).

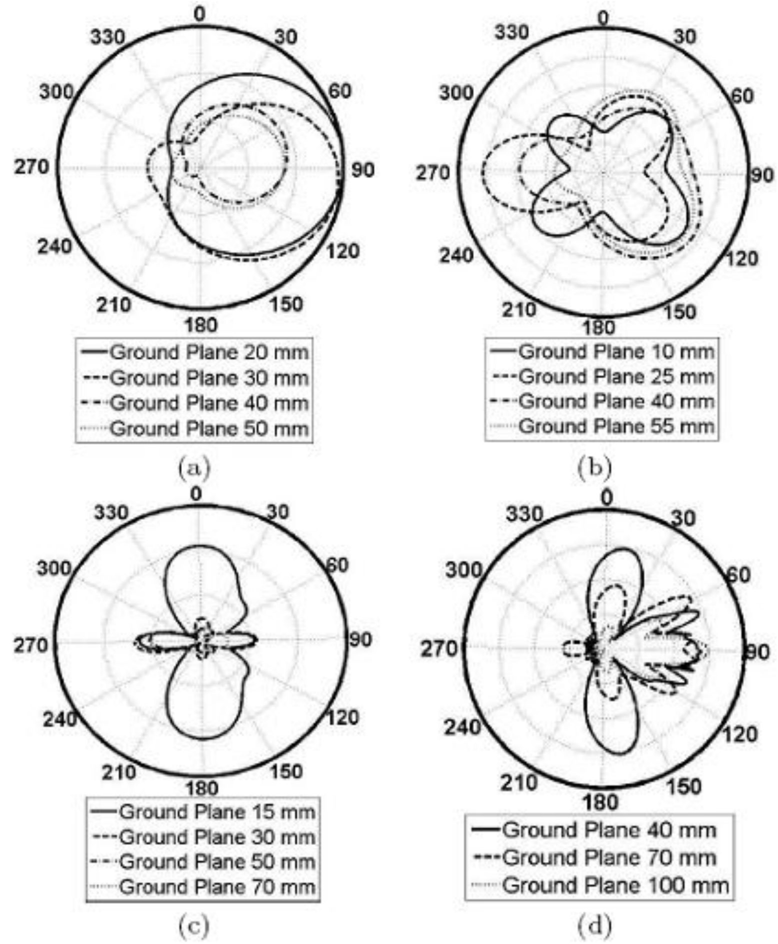

Fig. 10. a) and b) radiation patterns corresponding to single element antenna and two element antenna array, whereas c) and d) radiation patterns corresponding to four element antenna array and two element antenna array.

5.1. Current Distribution Analysis on Single U-shaped Patch

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5.2. Current Distribution Analysis on Two Element Array

As a systematic method of analysis was adopted, so, after analysis on a single U-shaped patch, the same change of current distribution is analyzed for two element antenna array. Here, 55 mm length of ground plane represents the length of full ground plane. The results show that there is a significant change in the radiation pattern; these results were previously anticipated because now the current distribution is changed in antenna arrays which change the radiation pattern. The required endfire radiation pattern is also not achieved from two element antenna array at any value of current distribution. The results of change in radiation pattern with change in current distribution for two element antenna arrays are shown in Fig. 10 (b).

5.3. Current Distribution Analysis on Four Element Array

There was a clear hint in two element antenna array that the current distribution changes the radiation pattern significantly. Thus the same analysis of change in current distribution is done on four element antenna array. Form analysis it was observed that with a complete ground plane, the radiation pattern of the antenna array was broadside but as the ground plane's length is reduced, there are significant changes in the radiation pattern. It is observed that when the length of ground plane reaches 20 mm, the endfire radiation pattern is achieved, when the length of ground plane was further reduced to 15 mm, the gain of the radiation pattern is further enhanced and an endfire beam is retained. The change in radiation pattern with change in current distribution for four element antenna array is shown in Fig. 10 (c). Here, full ground plane has a length of 70mm.

5.4. Current Distribution Analysis on Eight Element Array

The same analysis of change in current distribution is done on the designed eight element antenna array. In eight element antenna array when the length of the ground plane reaches 40 mm, an endfire pattern is achieved with a narrower beam width as compared with the beam of four element antenna array. The narrow beam in eight element array is justified because with increase in number of elements in the antenna array, beam width also decreases. The only problem with the endfire radiation pattern in eight element antenna array is that the side lobe levels are quite high and a large amount of power is leaked in undesired directions. The analyzed results of change in radiation pattern with change in current distribution are shown in Fig. 10 (d).

5.5. Binomial Array Current Distribution

After achieving the required radiation pattern, the current distribution in the array is analyzed. The current distribution in the endfire array approximately follows the current distribution in a binomial array. In a binomial array the current distribution is maximum in the middle element of the array and least in the elements at the end. The array factor of binomial array is given in equation 01 and 02 below.

$$(AF)_{2M}(even) = \sum_{n=1}^{M} a_n \cos\left[(2n-1)\frac{\pi d}{\lambda}\cos\theta\right] \qquad (01)$$

$$(AF)_{2M+1}(odd) = \sum_{n=1}^{M+1} a_n \cos\left[2(n-1)\frac{\pi d}{\lambda}\cos\theta\right] \qquad (02)$$

The excitation coefficients of the binomial arrays are determined by the function proposed by J. S. Stone [11]. The proposed function suggests that the coefficients of the function $(1-x)^{m-1}$ can be determined in series using the binomial expression as:

$$(1+x)^{m-1}=1+(m-1)x+\frac{(m-1)(m-2)}{2!}x^2+\frac{(m-1)(m-2)(m-3)}{3!}x^3+\ldots \qquad (03)$$

The series of coefficients determined forms a Pascal Triangle. In equation 03, *m* represents the number of elements in the array, and the series coefficients represents the relative amplitude of current in the elements in the array. In the array designed for endfire radiation pattern, the amplitude of current distribution approximately follows the current distribution determined by binomial array. For simplicity Fig. 14. shows the current distribution in the four elements of eight element antenna array, which can be approximately determined by binomial series. The current distribution values can be seen in Table 7.

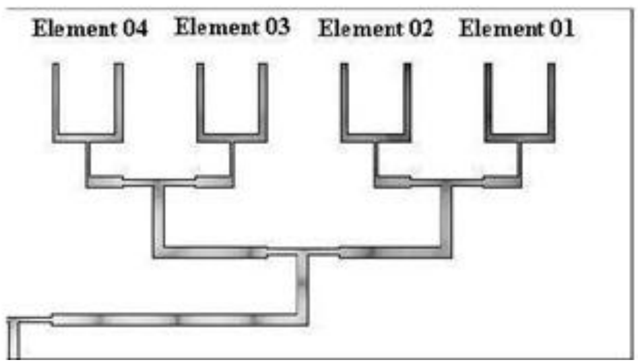

Fig. 11. Binomial Current Distribution

6. Conclusion

From rigorous simulations and testing it can be concluded that change in current distribution and change in antenna geometry play a major role in manipulating the radiation pattern of antenna arrays, but the same change in parameters does not play a significant role in maneuvering the radiation pattern of single patch antenna. Form analysis it is also concluded that the same results cannot be achieved by rectangular microstrip patch antenna arrays either by changing the current distribution of the antenna array. It has also been analyzed that the effect of change of current distribution in rectangular microstrip antenna arrays is different form U-shaped antenna array.

Table 7. Current Distribution Values in Antenna Arrays

Current Distribution Values	
Element 01	4.8132×10^{-2} A/m
Element 02	2.7877×10^{-1} A/m
Element 03	6.7088×10^{-1} A/m
Element 04	3.8515×10^{0} A/m

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