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Analysis of Synthesized Ka-Band Linear Array Antenna for Beam Steering Applications

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Abstract

As beam steering antennas are being an ideal solution for many satellite applications, this paper is concerned on the design of a 16-element linear array antenna, using an RT Duroid substrate at 20.2 GHz for Ka-Band satellite communications. The design is initiated with single element and thereby incremented in steps to 2, 4, 8 and 16 elements. An optimum inter element spacing of 0.73λ is considered for the purpose of fulfilling the desired scanning requirement. Performance analysis of the proposed antenna is analyzed mainly in terms of Relative Side Lobe level (RSLL) and Beam steering. To synthesize the antenna, weights of the antenna are considered according to Taylor's amplitude distribution along the antenna aperture to attain a relative side lobe level of -25dB. The proposed 16-element linear array antenna achieved a maximum gain of 19.5dB and the main beam direction can be switched up to 50^o (±25^o) without introduction any grating lobes. In addition to, other relevant antenna parameters such as reflection coefficient, VSWR, gain and efficiency of single, 2, 4, 8 and 16 element antennas are compared. The proposed linear array antenna is designed using Ansoft HFSS.

Keywords: Linear array antenna, Beam steering, Relative Side Lobe Level, Ka-Band, Satellite Communication Links, Taylor's Amplitude distribution.

I. Introduction

The Pattern reconfigurability is an intentional modification of the radiation pattern and beam steering is the most extended application of pattern reconfigurability. Beam steering antennas have attracted lot of attention in the past few decades due to increase in the demand for the applications of wireless local area networks, cognitive radio, cellular communications, remote sensing and satellite communications [XIV] [IX]. Currently most of the satellite applications demanding beam steering antennas i.e. the direction of main lobe be changed or scanned accordingly. In general, beam steering is done mechanically by rotating the antenna with fixed phase. However, mechanical scanning requires implementation of rotating systems that can be costly and scans slowly, reason which, phased array antennas are used to steer the beam electronically. Consistent pattern switching is observed using printed square loop and star antennas [I]. The current distribution is varied over the spiral arm by using switches in order to steer the main beam of the loop antennas but suffers from pattern variations [VII]. In [VIII] [IV] beam switching of parasitic elements is presented. Parasitic antennas of such kind are usually driven by one or more radiating elements and directed by several parasitic elements to steer the main beam in certain directions by varying the ON/OFF states of the switches. However, patch antennas fed with parasitic elements suffer from limited gain. To maintain a desired steering angle with a lower side-lobe level, the size and spacing among the elements are important.

In [XIII] [VI] [XII] presents an optimal spacing between the antenna array elements to maintain the side lobe levels to a desired value and without any introduction of grating lobes. Side Lobe Level is another important measurement in any array antenna configuration and its reduction is very essential. In [XI] the SLL is controlled by four 90-degree couplers to maintain the main beam in the broadside direction with a side lobe level of -17.5dB over the entire scanning range. The radiating part consists of an array of ridged waveguides designed in such a way that, the occurrence of grating lobes is avoided in the visible scanning range. A beam shift method is presented with a gridded parasitic patch resonant at antenna central frequency [II] and this gridded parasitic patch is composed by nine closely coupled rectangular microstrip patches. Using four switches of different configurations among the parasitic patches of the grid, a beam shift of 12^{o} is achieved to realize pattern reconfigurablity. In [X] an electronically reconfigurable beam steering antenna with a steering angle of 30^{o} with a peak gain of 6dBi, using a novel embedded RF PIN based parasitic array is demonstrated at 5.8GHz using two pairs of embedded RF PIN switches.

A quasi feed switching antenna, loaded with PIN diodes to switch the beam of about 65^{o} by introduction of slot ring structure is reported in [V] at the desired resonant frequency with a fixed beam width. Pattern reconfigurablity of the array elements is achieved using directional modulation technique. The modulation implemented at the antenna level, to gain control over the directions at which data must be transmitted and is unlike in baseband modulation as same data is transmitted with different of power levels in all directions [III]. Additionally, this method provides selectivity and switches the elements to transmit only in the direction with a narrower beam width. In this work, the design and analysis of 16-element linear array antenna is presented with its specifications as shown in Table 1.

The proposed antenna design operates at 20.2GHz satellite frequency and the rest of the work is organized as follows. The analytical formulation of inter element spacing for electronically scanning in arrays is presented in section II. In section III, the design of single, 2, 4, 8 and 16 element linear array antennas are discussed. Antenna synthesis is discussed in section IV and followed by conclusions in section V.

Table 1. Specifications of proposed 16-element Linear Array Antenna

Parameter	Value
Type	Linear Array
No. of elements	16
Frequency	20.2 GHz
Gain	19.5dB
Side Lobe Level	-25dB
VSWR	1.2:1
Reflection Coefficient	-21.7dB
Impedance	50 Ω
Polarization	Linear
Beam steering	±25°

II. Optimum Inter Element Spacing

In general, the spacing between the elements of the array is chosen to ensure a low correlation between signals received by adjacent antenna element channels, many theoretical results suggest that the low correlation level among the array elements is obtained when inter-element spacing is greater than λ/2, however, some experimental measurements show that this distance can even be less. Therefore, optimum inter element spacing is necessary to reduce the number of antenna elements for a specific beam width [XV].

Considering an identical system of N equally spaced isotropic antenna elements. Each phase shifter has a special electrical control circuit that can alter the phase of the received signal. Assuming, that the spacing between the elements of the linear antenna array is d, and the receiving signal of interest is arriving at an angular direction (θ_o).

Also, assume that electronically controlled phased shifters provide a progressive phase shift between the adjacent antenna elements $\Delta\delta=\Delta\delta(\theta_o)$ then

$$\Delta\delta(\theta_o) = -k * d * sin\theta_o \quad (1)$$

$$\delta_n = -k * d * n * sin\theta_o \quad (2)$$

The array factor of linear array antenna with uniform amplitude distribution can be expressed as

$$|AF_{linear}(\theta,\theta_o)| = \left| \frac{Sin(\frac{N}{2}*k*d*(sin\theta - sin\theta_o))}{Sin\left(\frac{k*d*(sin\theta - \sin\theta o)}{2}\right)} \right| \quad (3)$$

Equation 2.3 has a maximum value equal to N for the angle directions $\theta = \theta_r$

$$\theta_r = \text{arcsin}\left(\pm \frac{\lambda * r}{d} + sin\theta_o \right); \; r = 0, 1, 2\ldots. \quad (4)$$

Where r = 0 corresponds to the angle position ($\theta = \theta_o$) of the main lobe and $r \neq 0$ determines the angle positions of the grating lobes.

From the equation 4, it is clear that, the closest unwanted grating lobe will no longer appear within the visible space when

$$\frac{d}{\lambda} < \frac{1}{1+sin|\theta_o|} \quad (5)$$

Let us consider that the desired scanning angle range of the antenna is equal $|\theta_o < 25^o|$. From equation 5 the inter-element space 'd' in this case is less than 0.73λ. Therefore, in order to avoid grating lobes within scanning angle of -25^o to $+25^o$, one has to choose an inter-element spacing of about 0.73λ, and not beyond. The typical inter element spacing for the given frequency of operation is in the range of 0.7λ – 0.8λ. Therefore, 0.73λ is considered between the elements according to equation 2.5 to meet the requirement.

III. Antenna Design and Analysis

The pictorial view of the proposed antenna is as shown in figure 2. The 16-element linear array is initiated with the design of single element, as shown in Figure 1, a line fed rectangular microstrip patch printed on a 0.2mm RT Duroid dielectric substrate with bottom ground whose relative permittivity is 2.2 with a loss tangent of 0.0009. The optimized parameters of the proposed antenna are listed in Table 2.

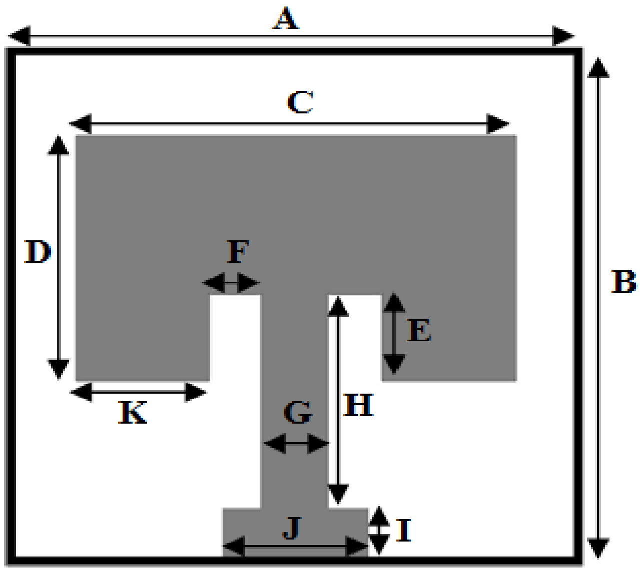
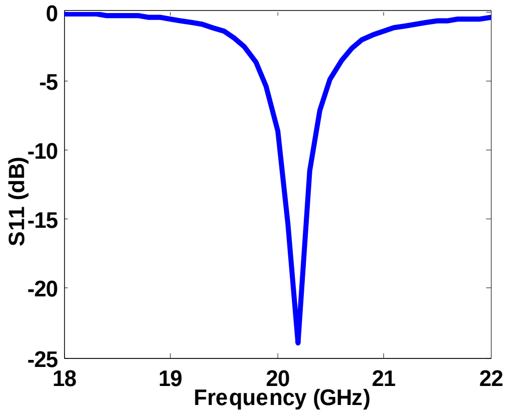


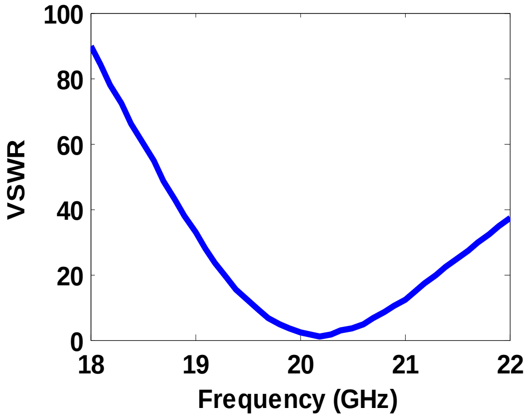
Figure 1: Single Element Design

Table 2. Design Parameters of the proposed antenna

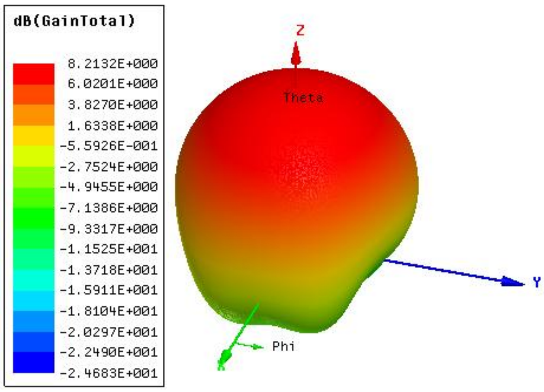
Parameter	Dimension (mm)
A	13.9
B	12.1
C	6.4
D	4.7
E	1
F	0.3
G	0.5
H	3.9
I	0.8
J	1.2
K	2.6



a)



b)



c)

Figure 2: Schematic of a) Reflection Coefficient, b) VSWR, c) Gain of the proposed Single element antenna

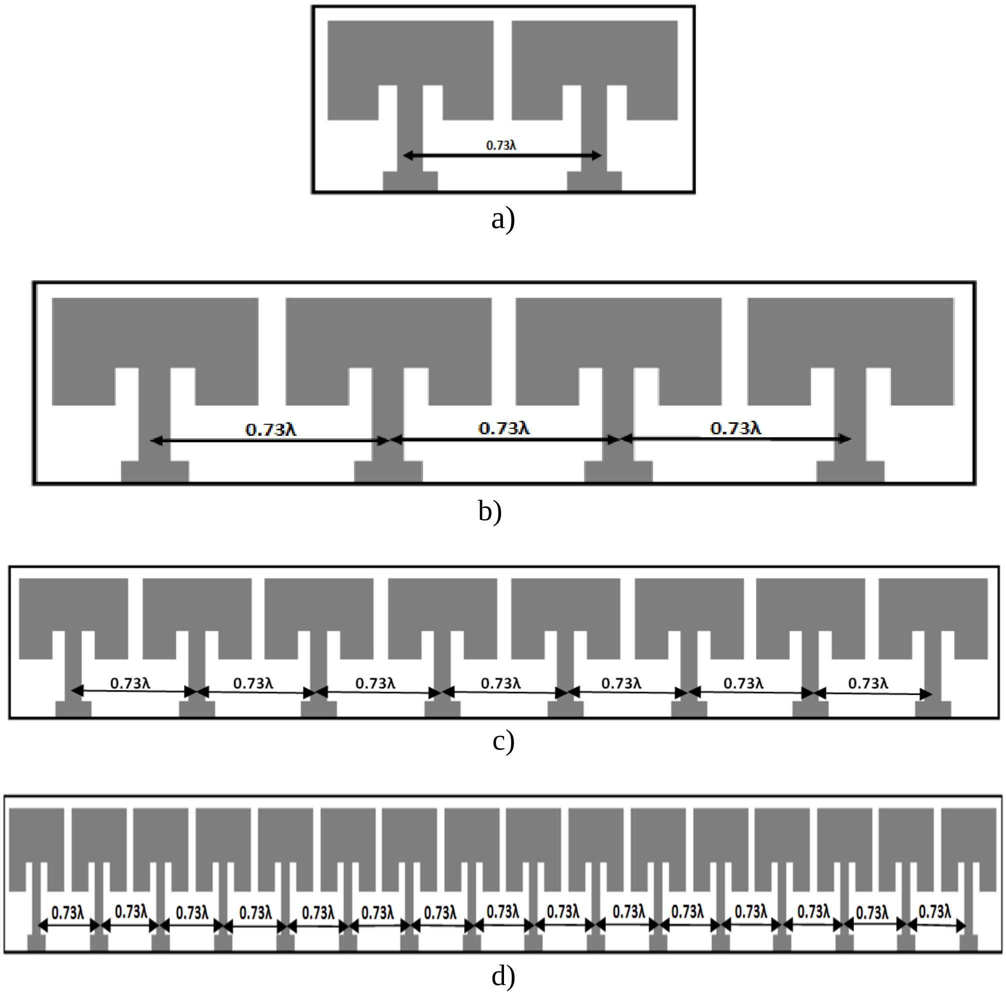
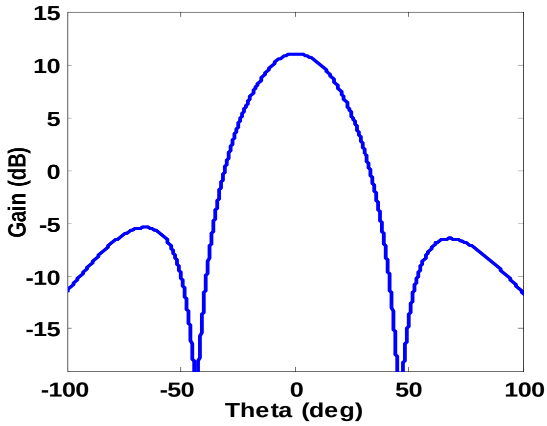
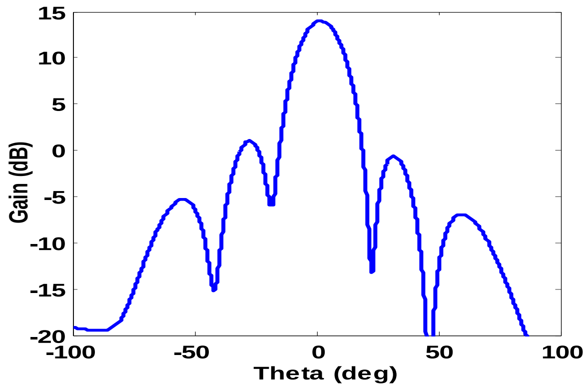


Figure 3: Schematic of a) 2-element, b) 4-element, c) 8-element, d) 16-element linear arrays

It is found that the designed antenna resonates at the desired frequency band as shown in figures 2(a), 2(b) & 2(c). A reflection coefficient of S11 < -10dB is ranging from 20.33GHz- 20.01GHz at a resonant frequency of 20.2GHz and a low VSWR of 1.2:1 with a gain of 8.2dB. The available 320MHz bandwidth is useful for Ka band satellite services. The desired array antenna is shown in figure 3(a), (b), (c) and (d) with an optimized element spacing of 0.73λ.


15
10
5
0
-5
-10
-15
Gain (dB)
-100
-50
0
50
100
Theta (deg)

a)


15
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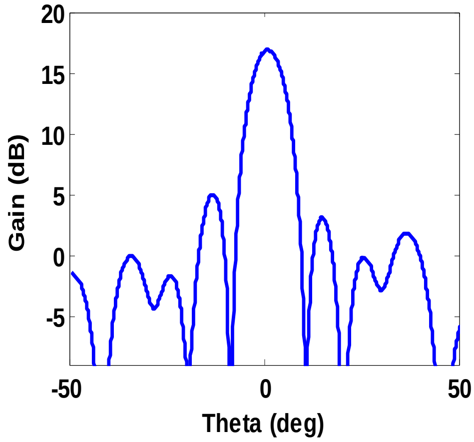
-5
-10
-15
-20
Gain (dB)
-100
-50
0
50
100
Theta (deg)

b)


20
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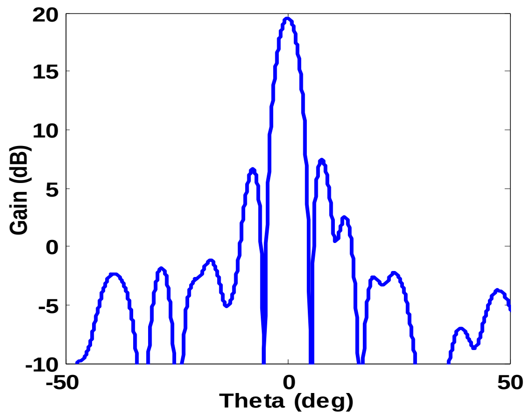
Gain (dB)
-50
0
50
Theta (deg)

c)



d)

Figure 4: Gain Patterns of a) 2-element, b) 4-element, c) 8-element, d) 16-element linear arrays

Figure 4 depicts the gain characteristics of the proposed 2, 4, 8 & 16 linear array designs, along with the performance metrics such as reflection coefficient, VSWR, gain, bandwidth, efficiency are summarized in Table 3.

Table 3. Comparative analysis of single, 2, 4, 8 & 16-element Linear Array Antennas

Parameter	1X1 Array	1X2 Array	1X4 Array	1X8 Array	1X16 Array
S11 (dB)	-23.88	-22.40	-19.93	-22.04	-21.74
VSWR	1.1:1	1.1:1	1.2:1	1.1:1	1.2:1
Gain (dB)	8.21	11.41	13.94	16.82	19.5
Bandwidth (GHz)	20.33-20.01	20.32-20.01	20.30-20.0	20.32-20.01	20.37-20.07
Efficiency (%)	97.8	98.8	99.2	99.5	99.5

The proposed array designs obtained almost similar performances of reflection coefficient, VSWR, bandwidth and efficiency but with an improvement in terms of gain from 8.21dB to 19.5dB of single element and 1X16 linear array respectively as shown in Table 3. From figure 4 it is observed that the relative side lobe level of the proposed linear array is almost 13.2dB.

IV. Array Antenna Synthesis

The array factor of an N element linear array antenna is expressed as

$$\mathrm{AF} = \sum_{n=0}^{N} \mathrm{a_n} e^{j(n-1)\psi} \tag{6}$$

where, a_n accounts to amplitude excitation of each element and $\psi = kd\cos\theta + \beta$

The far field pattern of the 16-element linear array antenna has a relative side lobe level of 13.2dB as shown in figure 4(d) and its normalized pattern is shown in figure 5. The far field pattern is plotted using Matlab and HFSS and shows good agreement. Relative Side lobe level of 13.2dB is considerably high and can cause interference. This is due to uniform amplitude excitation among the array elements. It is obvious that, desired side lobe level of any antenna should be as small as possible so that minimum power is radiated in undesired direction, and thereby maximizes the radiation in desired direction. Hence synthesizing the antenna eliminates the problem of interference by reducing the side lobe level.

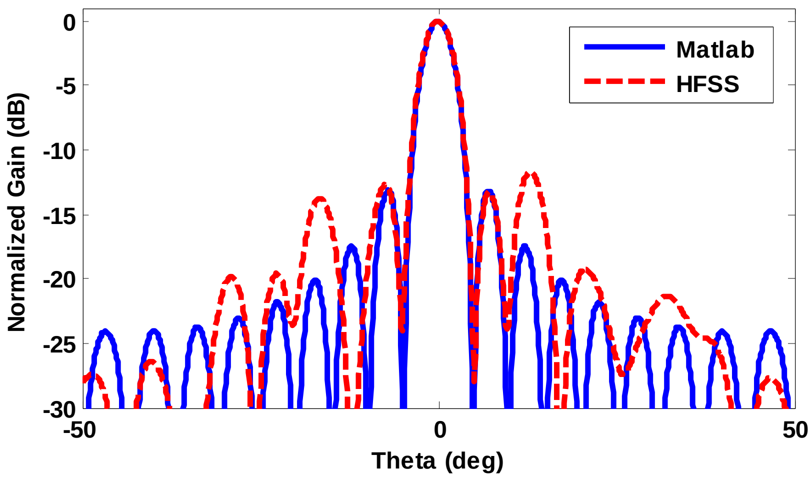


Figure 5: Normalized Gain pattern of 16 element linear array

To synthesize it various array synthesis methods are carried out of which Taylor line source method is chosen to control the side lobe levels of the array. Taylor method generates array coefficients which has a complete control over the required number of side lobe levels. The current distribution curve of 16-element linear array antenna is shown in figure 6, which resulted from Taylor current source expression for a required side lobe level of -25dB. The current curve takes the same shape for any given length of linear array antenna.

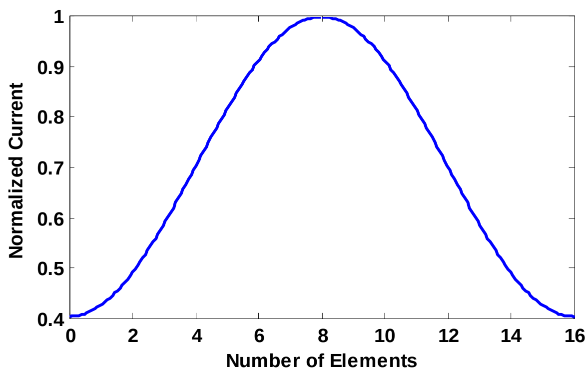


Figure 6: Normalized Current Distribution of 16 element linear array

As the main aim of beam steering is to have one main beam steered in entire scanning range without any possibility of grating lobes, the current distribution of the proposed array is tapered along the antenna elements to increase the reduction in the side lobe level. Further the current distribution is considered to steer its pattern to different scanning angles and is expressed in equation 7.

$$c_{ns} = c_n e^{j(\psi_n - \psi_{n_0})} \tag{7}$$

Where, $\psi_0 = nk\cos\theta_s$

Figure 7 shows a beam steering of 25° with variation in side lobe level with Taylor tapering coefficients. It is clear that there is an increase in the reduction of side lobe level from -13.2dB to -25dB (89.39% typically) by considering the tapered weights along the array as shown in Table 4.

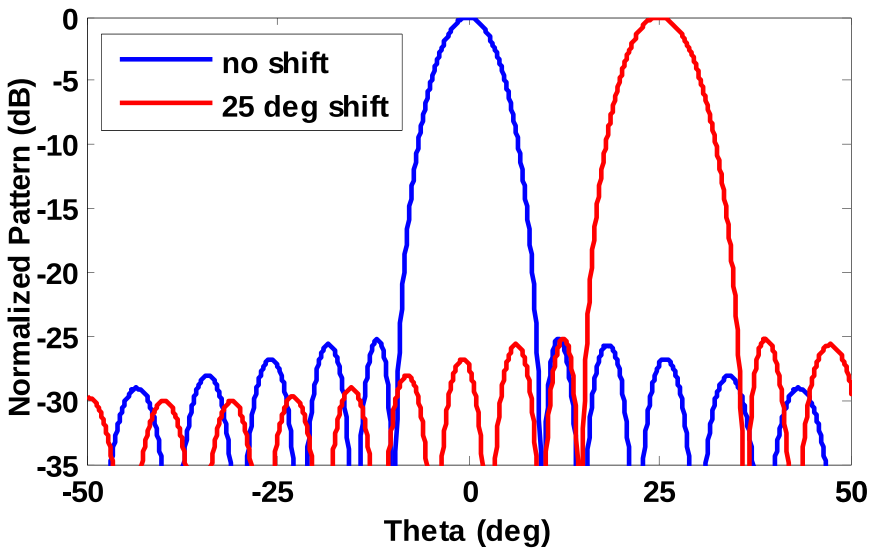


Figure 7: Beam Steering with low side lobe level

Table 4. Tapered Taylor Coefficients fed to the 16-element linear array

Element Number	Taylor Coefficients	Element Number	Taylor Coefficients
1	0.4271	9	0.9265
2	0.4957	10	0.8840
3	0.5977	11	0.7762
4	0.7165	12	0.6562
5	0.8329	13	0.5434
6	0.9280	14	0.4564
7	0.9863	15	0.4090
8	0.9985	16	0.4270

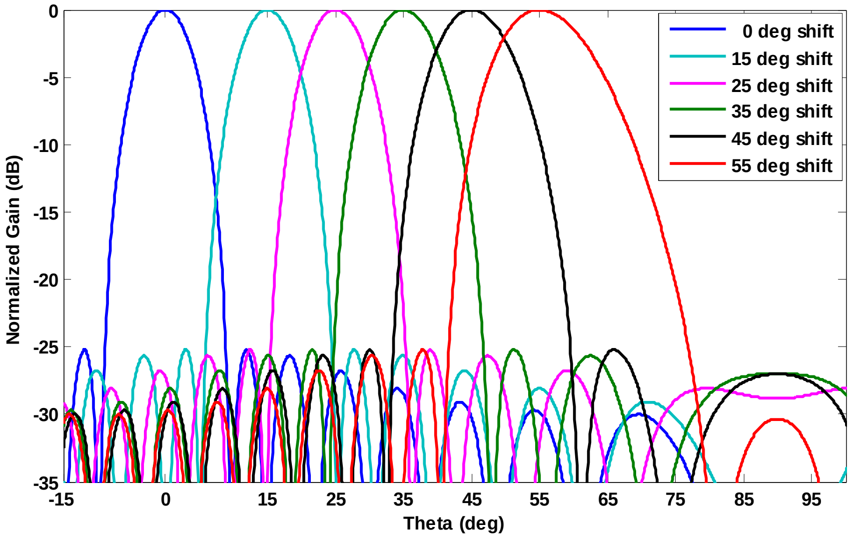


Figure 8: Beam steering for different scan angles

Figure 8 shows the normalized gain pattern for different scanning angles. An optimized pattern is achieved within the specified scanning range of 25^{o} with a specified side low lobe level of -25dB. Figure 9 shows the variation in HPBW with respective to scanning angle. As the curve takes an exponential rise in HPBW the broadening of the beam is dominant at higher scanning angles. A broadening of main beam is observed beyond the scanning range i.e. at 35^{o}, 45^{o} and 55^{o} shift in figure 8 that indicates the degradation in the array performance as it is a function of element spacing. Comparative study of the proposed antenna design with other earlier antenna designs is summarized in Table 5.

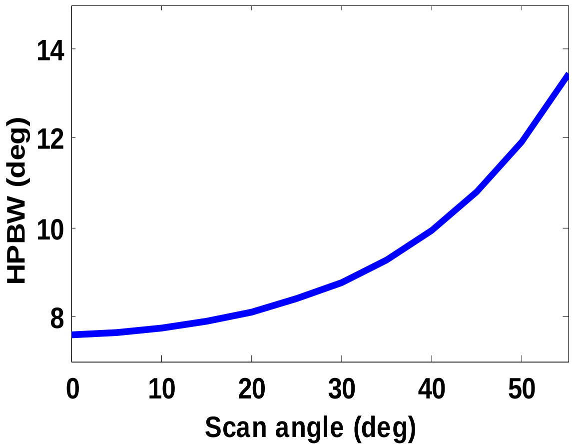


Figure 9: HPBW Vs Scan angle

Table 5. Comparison of proposed antenna design with earlier designs

Ref	Frequency	Beam steering	Side Lobe Level
[11]	60 GHz	12^o	-18.5dB
[12]	5.8 GHz	30^o	-6dB
[13]	2 GHz	65^o & 45^o	-
[15]	0.43 GHz	48^o	-17dB
Proposed antenna	20.2 GHz	50^o	-25dB

V. Conclusions

This work demonstrated a synthesized beam steering linear array antenna of 16 elements at 20.2GHz for Ka-band satellite communications. An optimum inter element spacing of 0.73λ is maintained among the array elements to eliminate the closest unwanted grating lobe within the scanning range. Therefore, the proposed antenna successfully achieved a scanning capability of 50^o i.e. $\pm 25^o$ on either side of 0^o with good impedance match as well as improved directivity in the entire scanning range. The weights of the antenna elements are tapered according to Taylor's amplitude distribution along its length to produce narrow beams with a low relative side lobe level typically of -25dB. Comparisons of single, 2, 4, 8 and 16 element linear arrays demonstrated an improvement in gain by maintaining constant performance in terms of reflection coefficient, VSWR, bandwidth and efficiency.

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