Design of a High Gain Pencil Beam Dipole Antenna Using Parasitic Elements in X-Band

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Using parasitic elements in different configurations, many parameters of an antenna can be modified. Most of these approaches were found to alter the fundamental characteristics such as input impedance, gain, polarization and radiation pattern of an antenna. Array antennas with high gain comprise of complex feed distribution which is a major hurdle design at higher microwave frequencies. Using parasitic elements show promise in addressing the complexity of amplitude and phase distribution in a very large array. Simulated results during research using parasitic elements with a dipole has shown promise in achieving desired radiation pattern characteristics without employing a complex feed network. The gain and beamwidth are both optimized to obtain the desired solution for a narrow beam high gain antenna providing high isolation when used in a bistatic configuration. The effect of parasitic elements on a dipole in relation to gain is also discussed; based on which an analytical model is proposed for the design in X-Band.

***Index Terms*—Parasitic Elements, Dipole Array Antenna, Bistatic Frontends**

I. Introduction

Parasitic element loaded with reactance effects were first published in a research by Harrington [1]. Recently it gained significant interest due to its applications in varying input impedance, gain, polarization and radiation pattern of an antenna [2],[3],[4] with certain tradeoffs. Input impedance can be tuned closer to 50 ohm using parasitic elements (PE) in the ground plane for microstrip antennas [5]. Variable length parasitic elements are used for beam forming to steer antenna pattern direction [6].Similarly the direction of the radiation beam for phased array antenna system can also be varied by open-circuiting or short-circuiting parasitic elements without any use of phase shifters [7]. Use of parasitic elements terminated with varactors has also found its application in cognitive radios for spatial spectrum sensing employing frequency agility features [8]. Early study has also shown enhancement of printed antenna gain using stacked parasitic elements on multilayer PCB [9]. Up to 21 dBi gain patterns were obtained using a planar PEA geometry and a dipole at 1.6 GHz, where sidelobe levels were around 14 dB [10].

Work done is aimed to design a high gain antenna for FMCW Navigation Radar front end. In this paper study and analysis is performed to design a model to obtain high gain and directivity in the azimuth and elevation using only one active feed element with parasitic elements in X-band. One element is actively fed with the parasitic array to drive the overall structure of the antenna. Optimum solutions are calculated for a model antenna to achieve narrow beamwidth up to 10 degrees with gain>30 dBi and minimum sidelobe levels. Such a sharp beam will result in high isolation when used in bistatic configuration. Main advantage of this approach is that it will not involve any feeding network as array will be passively used in vicinity of the active element to shape the radiation pattern through mutual coupling. Work done here is aimed to maximize the gain and isolation while minimizing sidelobes of the antenna for optimum performance in LPI mode.

Study on different geometric formations of parasitic array and its effect on gain is analytically modeled to predict the gain of the antenna. An analytical model is proposed at the conclusion for design of the antenna. The analysis and modeling is performed using Ansoft HFSS employing Hybrid Finite Element Boundary Integral Method. This technique allows us for solving large models as compared to the wavelength of interest.

II. Design and Analysis

1) Antenna Model

Dipole antenna was selected as a starting point for the analysis as its gain is maximum at right angles to the dipole. This characteristic makes it suitable as a reference for observing parasitic elements effects. Secondly it exhibits a broadside radiation pattern which favors a planar antenna design. 9.4 GHz is taken as a frequency of interest as the intended application of the antenna is for navigation radars. To enhance the gain a metal reflector is used at $\lambda/4$ distance from the dipole. This increases the gain of the dipole to around 4 dBi from 2 dBi.

Dipole is also selected as the parasitic element to have conformance in the field distributions and calculation for mutual impedances. For simplicity 2-D array of parasitic elements is used for the model as shown in Fig.1. Following variables were considered for the geometric construction of the antenna model for analysis:

i) Number of Elements, ‘N’
ii) Spacing between the PE and the active element, ‘S’
iii) PE spacing along z-axis, ‘Δz’

Influence of above parameters will form the basis for analytical model in predicting gain of the antenna in X-band. Simulations will be performed on 135 variations to converge on a solution curve fit for the observed results to determine an approximate gain.

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2) Parasitic Element Array Analysis

Antennas exhibit a specific radiation pattern. The overall radiation pattern changes when several antenna elements are combined in an array. Gain of an antenna is given by

$$G = \frac{4\pi\eta A_e}{\lambda^2} \qquad (1)$$

Gain is directly proportional to the effective aperture area 'A_e', so an increase in the number of parasitic elements increases the total 'A_e'.

We consider an antenna consisting of a 2-D array of N

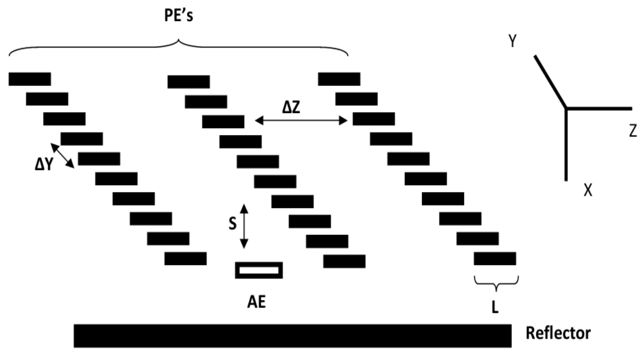

Fig. 1. Antenna Model composed of 2-D PE dipole array fed by an active dipole. Geometry of the antenna, composed of a planar array of parasitic dipoles fed by an active dipole with a reflector at λ/4 distance

centre-fed cylindrical dipoles placed parallel to the zy axis. The intended parametric solution for the antenna is optimized with 35 PE's. The vector **I**, the current distribution on these antenna elements is given by Kirchhoff's law

$$[\mathbf{I}] = [\mathbf{Z}]^{-1}[\mathbf{V}] \qquad (2)$$

Where **I** and **V** are the current and voltage vectors respectively and **Z** is the array impedance matrix.

The exact field form a sinusoidal can be written as three spherical waves, keeping the field components in cylindrical coordinates. Mutual impedance is then the product of integral of this electric field (due to each dipole) and the current distribution on the other dipole. Keeping L constant with the geometry of Fig.1, using the exact near electric field formulations of Schelkunoff and Friss [11] the mutual impedance expression to calculate the impedance matrix can be reduced to

$$\mathbf{Z} = -\frac{j30}{S^2}\int_0^{L/2}\left[\psi_1 - \left(2(\psi_2+\psi_5)\left(\cos\left(k\frac{L}{2}\right)\right)\right) + \psi_3+\psi_4+\psi_6\right] \times \sin\left[k\left(\frac{L}{2}-x\right)\right]dx \qquad (3)$$

Where

$$S = \sin\left(k\frac{L}{2}\right) \qquad \psi_i = \frac{\exp(-jkR_i)}{R_i}$$

Where k is the wave number and R_i is given by

$$R_1 = \sqrt{\Delta y_n^{\,2} + \left(\Delta z_n + \frac{\lambda}{4} - x\right)^2 + S^2}$$

$$R_2 = \sqrt{\Delta y_n^{\,2} + (\Delta z_n - x)^2 + S^2}$$

$$R_3 = \sqrt{\Delta y_n^{\,2} + \left(\Delta z_n - \frac{\lambda}{4} - x\right)^2 + S^2}$$

$$R_4 = \sqrt{\Delta y_n^{\,2} + \left(\Delta z_n - \frac{\lambda}{4} + x\right)^2 + S^2}$$

$$R_5 = \sqrt{\Delta y_n^{\,2} + (\Delta z_n + x)^2 + S^2}$$

$$R_6 = \sqrt{\Delta y_n^{\,2} + \left(\Delta z_n + \frac{\lambda}{4} + x\right)^2 + S^2}$$

Impedance matrix is given as

$$\mathbf{Z} = \begin{bmatrix} Z_{1,1} & Z_{1,2} & . & . & Z_{1,N} & Z_{1,N+1} \\ Z_{2,1} & Z_{2,2} & . & . & . & Z_{2,N+1} \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ Z_{N,1} & Z_{N,2} & . & . & Z_{N,N} & Z_{N,N+1} \\ Z_{N+1,1} & Z_{N+1,2} & . & . & Z_{N+1,N} & Z_{N+1,N+1} \end{bmatrix} \qquad (4)$$

Where, taking in the effect of image currents

N = 2 x No. of Total Elements (Active + Passive)
n =1 to N+1

Radiation pattern for the PE's 3D geometric configuration is calculated using the following relation

$$E(\theta,\varphi) = f(\theta).\left[\sum_{n=1}^{N+1} I_n\left(e^{\left\{jk\sin\theta\left(\Delta z_n\cos\varphi + \Delta y_n\sin\varphi + S_n\tan^{-1}\theta\right)\right\}} - e^{\left\{jk\sin\theta\left(\Delta z_n\cos\varphi + \Delta y_n\sin\varphi - S_n\tan^{-1}\theta\right)\right\}}\right)\right] \qquad (5)$$

Where element factor for a dipole is [12][13]

$$f(\theta) = \frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta}$$

Impedance matrix is given by Eq (4), and I_n is calculated using Eq (2) to determine the radiation pattern using Eq (5).
An antenna model is realized using HFSS consisting of 1 active dipole and N parasitic dipoles, Δz and Δy are kept equal to λ/2 for initial simulation model. Distance S is varied from λ/8 to λ. After initial analysis Δz and Δy are varied with S kept constant. Observations and results are presented in the next section.

III. RESULTS

The purpose of parasitic array is active exploitation of mutual coupling between parasitic elements. In X-band the inherent advantage is the size of the antenna as dipole has a very small λ which makes the overall size of the antenna realizable. Keeping in mind that count of elements increases the effective aperture area; simulations were performed using HFSS with 2,9,15, 25 and 35 elements. It was observed that as we keep on increasing the number of PE's the overall effect of gain increases at certain regions. It was observed that as we keep on decreasing Δz the sidelobe patterns are suppressed. As the intended solution with resonant frequency of 9.4 Ghz was aimed to obtain gain >30 dBi and 3 dB beamwidth of at least 10 degree; with 35 PE's the solution was realized with Δy= λ/2, Δz →λ/16 and S=5.5 mm. Results were promising and final solution gave a gain of 33 dBi with a sharp beam having a 3 dB beamwidth of 9 degrees in elevation and azimuth. The simulated results for different characteristics of the optimized model antenna are shown. A sidelobe level of 30 dB was achieved after optimizing the model as shown in Fig 2. Peak gain acquired after converging solution was 33.2 dBi with a sharp beamwidth as shown in Fig 3. It was observed decreasing Δz has reduces beamwidth in the azimuth plane, until azimuth and elevation plane beamwidths are almost equal. Conversely, we can increase Δz to get beamwidth up to 5 degrees in elevation plane but at the cost of gain and increase in azimuth plane beamwidth. Keeping in view the placement of antennas in bistatic configuration, one of the above trends can be followed to attain maximum isolation.

It was observed that changing Δz and S has profound effect on the radiation pattern of the modeled antenna, when Δy is kept

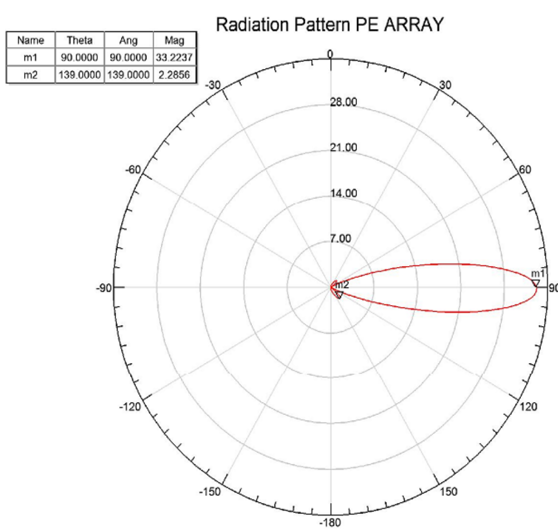

Fig. 2. Simulated Result of Radiation pattern at Phi=180 degree. A SLL of 30 dB.

to λ/2. As S is vertical distance between the PE array and active element the induced current intensity changes with the change in S. Next section discusses the analytical results regarding gain in relation to distance 'S'. As the maximized

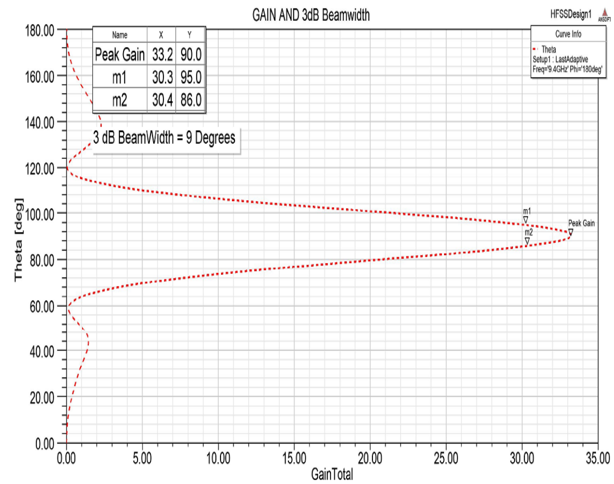

Fig. 3. Simulated Result of Antenna Gain and 3 dB beamwidth with Δy= λ/2, Δz →λ/16 and S= 5 mm. With 35 PE's

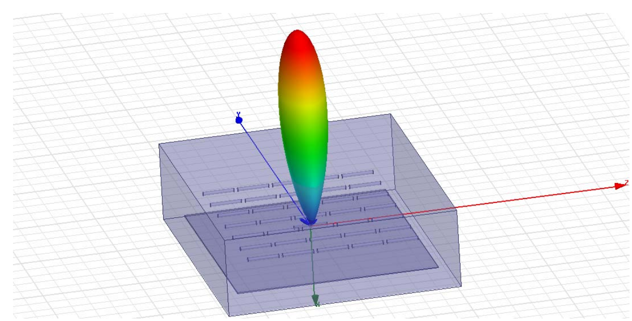

Fig. 4. PE Antenna Array Model with 3D Far-Field Pattern

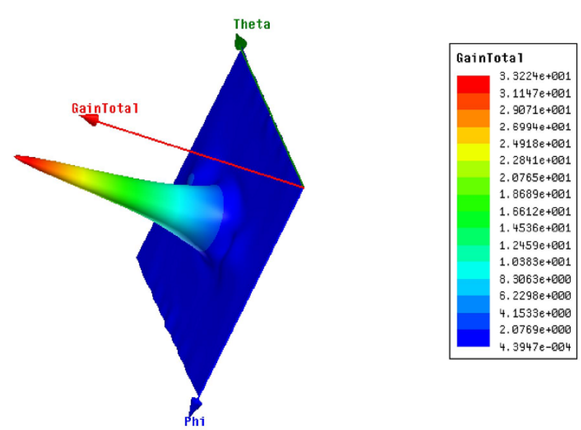

Fig. 5. Azimuth and Elevation 3D Beam Pattern

gain was found at a distance S closer to λ/4, the input impedance exhibits a imaginary resistance, which is matched to 100+30i ohms. The resulting return loss after matching with centre frequency of 9.3 GHz and a percentage bandwidth of 3 percent is shown in Figure 6. Isolation analyzed in bistatic configuration with a distance 15 mm is shown in Fig 7. Isolation is around 60 dB which is much desired for LPI operation of the Radar.

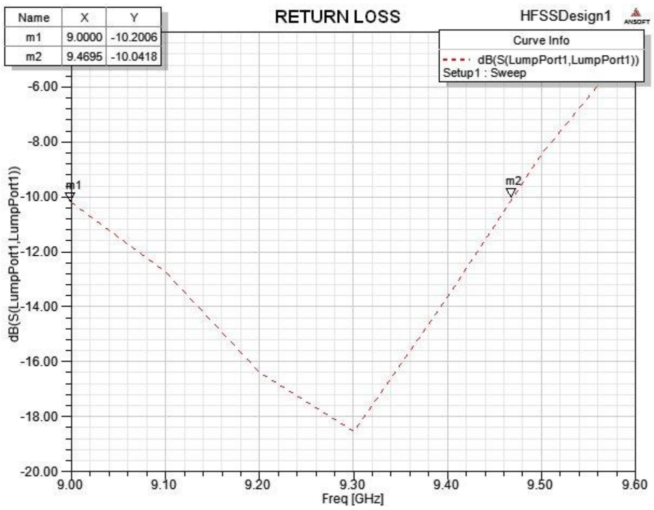

Fig. 6. PEA Return Loss with f_c= 9.3 GHz, S= 5.5 mm

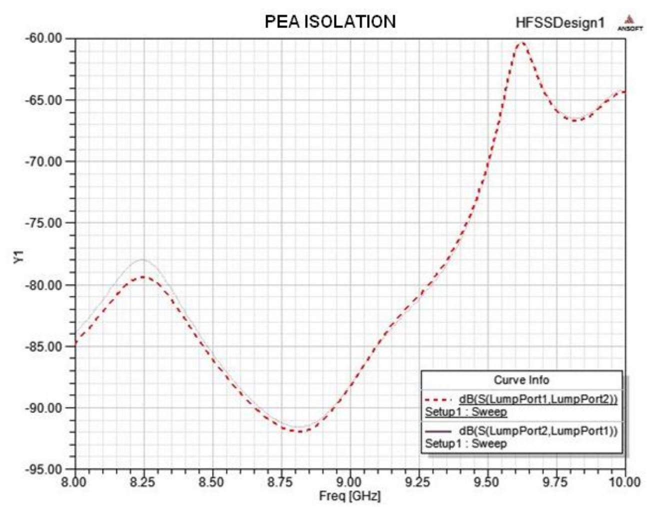

Fig. 7. Isolation, S_{21} and S_{12} , Separation Distance = 15 mm

IV. ANALYTICAL ANALYSIS

Analytical results were formulated using results of 135 model simulations. The relative distance Δy ≈ λ/2, gives the optimum results. As Δy is increased or decreased, grating lobes occur among the 135 cases that were analyzed. Whereas Δz is decreased from λ/2 to λ/16, antenna gain is increased at the cost of beamwidth. The main parameter observed was spacing between the PE's and the active element, 'S' and the distance Δz. Curve fitting was performed to get a solution of approximate gain relative to the parameter 'S', Δz and number of PE's 'N'. The equation formulated using polynomial curve fitting is given as

$$G_{approx} \approx G_D + G_N + 2.6S - 0.4S^2 + 0.02S^3 \tag{6}$$

Where,
Percentage Error = 3% ~ 5%
And,
Δy=λ/2

$$G_D = 4\text{ dB (Dipole Gain With Reflector)}$$

$$G_N = \frac{N^2}{10 \times \Delta z} \quad (N \le 35,\ \Delta z \le \lambda/2))$$

G_N=0 dB for S = 0.25λ to 0.75λ

$$\text{Error Bounds} = \left.\begin{array}{l} 0\ \lambda \text{ to } 0.25\lambda \\ 0.75\lambda \text{ to } \lambda \end{array}\right\} \text{(Compensated using } G_N \text{ in Eq.6)}$$

Antenna gain realized was same for S = 0.25λ to 0.75λ for all N values with distorted radiation patterns having many sidelobes. 'S' distance from 0.2 λ to 0.3 λ was found to be best region for obtaining a pencil beam pattern with minimal sidelobes. The same region gives the highest gain achievable when using PE's which is due to strong inductive fields at quarter wavelength proximity.

The analytical model proposed, is for PEA gain approximation in X-Band. The model predicts performance of the proposed design in terms of gain using model design variables as mentioned above. The model is intended to reduce design and simulation time as overall model is large w.r.t targeted λ.

V. PRACTICAL CONSTRUCTION

Proposed model is recommended to be constructed using a Teflon sheet supporting all the parasitic elements with 6 Teflon screws on each side connected with the reflector. Initial simulations show promising results as gain is increased by 1 dBi i.e 34.5 using a 1 mm thick Teflon sheet under the parasitic elements. The results will be further verified using materials having dielectric permittivity close to Teflon. The final practical measurements will be based on the same construction and results will be published after measurements and results obtained in anechoic chamber.

VI. CONCLUSION

An antenna is designed with PE's compromising of dipole elements to study the mutual coupling effects on radiation pattern and gain of a PE based antenna. 135 samples in X-band were analyzed to obtain an optimum solution giving a main lobe of 9^0x9^0 with 33 dBi gain. Analytical analysis is performed using Ansoft HFSS and KaleidaGraph to predict gain of the antenna using curve fitting. Effects of number of PE's and separation between the PE's and the active element are also presented. The scope of this study may be extended to obtain gain and beamwidth depicting superdirectivity. Minimization of side lobes and constant decrease in 3 dB beamwidth with sharp increase in gain show promise of obtaining superdirectivty using PE's. Also anisotropic properties of a metamaterial layer, when designed appropriately, can be employed to achieve impedance matching to compensate strong mutual couplings among the elements which causes strong impedance mismatches [14]. Metamaterials may further be incorporated in the proposed model to study effects on the radiated fields of the antenna.

REFERENCES

[1] R. Harrington, "Reactively controlled directive arrays," IEEE Trans.Antennas Propag., vol. 26, pp. 390–395, May 1978.

[2] Islam, R. Adve, R.," Beam-forming by mutual coupling effects of parasitic elements in antenna arrays," Antennas and Propagation Society International Symposium, 2002. IEEE Volume 1-126

[3] Takano, T. Imura, T. Okumura, M. Kazama ,"A partially driven array antenna with parasitic elements of 60% in number," Antennas and Propagation, 2006. IEEE, EuCAP 2006,Pg-1

[4] Kojiya, T. Kuwahara, Y.,"Improvement of gain of the phased array antenna by the parasitic elements," Antennas and Propagation Society International Symposium, 2001. IEEE, Volume 3-812

[5] Sato, K. Amano, T. ,"Improvements of impedance and radiation performances with a parasitic element for mobile phone," Antennas and Propagation Society International Symposium, 2008. AP-S 2008. IEEE

[6] Elkamchouchi, H.S.M.; Hafez, H.E.D.M. "Switchable beam diversity antenna," Microwave and Millimeter Wave Technology, 2002. Proceedings. ICMMT 2002.IEEE

[7] Nakano, H. Aoki, R. Kobayashi, R. Yamauchi, J. "A patch antenna surrounded by parasitic Y elements for beam scanning," ntennas and Propagation Society International Symposium 2006, IEEE

[8] Tsakalaki, E.P. Alrabadi, O.N. Papadias, C.B. Prasad, R. "Spatial spectrum sensing for cognitive radios via miniaturized parasitic antenna systems," Cognitive Radio Oriented Wireless Networks & Communications (CROWNCOM), 2010 IEEE

[9] Lee, R.Q. Zimmerman, M. Lee, K.F, "Enhancement of array gain with stacked parasitic elements," Antennas and Propagation Society International Symposium, 1994. IEEE

[10] M. Alvarez-Folgueiras, J. A. Rodriguez-Gonzalez and F. Ares-Pena, "Pencil beam patterns obtained by a planar array of parasitic dipoles fed by only one active element," in proc. European Conf. on Antennas and Propagat., Apr. 2010

[11] S.A. *Schelkunoff* and H.T. *Friis*, Antenna Theory and Practice

[12] Alvarez-Folgueiras, M. Rodriguez-Gonzalez, J.A. Ares-Pena, F. "Low-Sidelobe Patterns From Small, Low-Loss Uniformly Fed Linear Arrays Illuminating Parasitic Dipoles," Antennas and Propagation Society 2009, IEEE

[13] R. J. Mailloux, Phased Array Antenna Handbook, 2nd ed., Artech House

[14] Sajuyigbe.S, Ross.M, Geren.P, Cummer, S.A, Tanielian, M.H, Smith. D.R, "Wide angle impedance matching metamaterials for waveguide-fed phased-array antennas", Microwaves, Antennas & Propagation, IET,2010