Analysis of Edge Terminated Wide Band Biconical Antenna

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Abstract **─** A finite length biconical antenna has standing waves existing due to its abrupt discontinuity at the terminals and results in band width limitation. An appropriate termination of these terminals can enhance its bandwidth to a considerable extent and make it truly wide band. A finite biconical antenna with its edges terminated in thick loop (circular) is proposed and its radiation characteristics are analyzed for different values of 'βr'. Where 'β' is the wave number and 'r' is the length of the antenna. Compact antennas for ultra wide band (UWB) and above are in demand for modern communications and the proposed antenna meets the wide band requirement at UWB and above such as X, Ku, K bands with very low return loss.

Index Terms **─** Biconical, discontinuity, loop, return loss, termination.

I. INTRODUCTION

The research paper proposes, investigates and analyzes a biconical antenna with its edges terminated in circular metal loop. The antenna provides wide band width and is appropriate for the use in present day wireless communication applications. The addition of metallic loop of appropriate radius at the terminals makes the edges smoothly curved. It minimizes reflections and results in enhanced bandwidth and reduced return loss. Biconical antenna was first analyzed by S. A. Schelkunoff who stated that the cones are enclosed in a sphere with its center coinciding with the apex of the biconical antenna. Input impedance of small angle biconical antenna has been presented and is the basis for further investigations of the element. A spherical boundary surface has been used for calculation of fields [1-2]. Smith [3], Tai [4-6], Papas, King [7-8] have proposed spherically capped biconical antenna. Badii and Tomiyama have reported the numerical analysis of biconical antenna in transmitting mode and obtained solutions to near and far fields. Normalized complex power for electrically long biconical antenna is presented [9]. S. S. Sandler and King [10], in recent times S. N. Samaddar and E. L. Mokole [11], D. Ghosh and T. K.Sarkar [12], have proposed and investigated the wide angle spherically capped biconical antenna. Radiation characteristics such as pattern, input impedance, return losses and transient response of the element are established with formulations. A small biconical antenna using shorting pins has been designed by Amert and Whites that operates up to UWB [13]. Lu, et al., have presented top-loaded biconical antenna for UWB indoor base station applications. But this antenna is complex to fabricate and is heavy. Radiation pattern and return loss characteristics exhibit oscillations [14]. Jacobs and others presented a truncated asymmetric conical dipole for wide band applications up to 17 GHz [15].

Smith [3] is the first researcher to propose enhancement of band width in wide angle conical antennas with the edges terminated properly. He has considered cones with angles 61.8° and 101.2° with reduced length. Tai has presented the analysis of biconical antennas with small cone angles and also the E.M.F method of analysis for the spherically capped conical antennas.

King and Papas have reported the determination of input impedance and expression for the radiation from spherically capped conical antenna fed by coaxial line.

Sandler and King have proposed biconical antennas of different lengths for operation from 20 MHz to 1 GHz. Samaddar and Mokole have reported the analysis of a 20 inches wide angle cones up to 10 GHz [10]. They have also established the direction of maximum radiation in cones with unequal angles.

Ghosh and Sarkar have extended the analysis of wide-angle (106.2° and 140°) spherically capped biconical antennas. The height of each cone is 56 mm. The spherical cap termination at the end of each cone minimizes the reflections due to sudden discontinuity at

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the ends of the cone and enhances the band width of the antenna. The spherical cap termination widens its band width, but it is limited by poor efficiency for $\beta r \ll 1$. For electrically large structure such as $\beta r \gg 1$, the radiation pattern breaks in to smaller lobes and loses its directivity and shape. The proposed element is satisfactory around $\beta r \approx 1$.

Analysis of spherically capped wide angle biconical antenna has been widely reported by researchers. These elements which are terminated at the ends by spherical cap are large in height and are widely flared with cone angles above 100°. Their limitations are also presented in the corresponding results.

The paper presents a new technique of termination of cone edges. The cone angle of the proposed radiator is 90° and is small in length as compared to those proposed so far. Each cone of this small antenna is terminated at its ends by a thick circular conductor with a diameter of 1 mm, made of the same material. The cones are not totally covered by spherical cap and this reduces the weight of the antenna considerably. The curved conductor at each point on the edge of the cone provides appropriate matching. This reduces the reflections from the termination.

The antenna is modeled and simulated in CST and HFSS from 1 to 40 GHz frequency range. The research work is analyzed for βr = 0.524, 3.14, 5.2, 10.47, 15.7, 21.

II. ANTENNA STRUCTURE

An infinite biconical antenna is non-resonant and standing waves do not exist, which results in wide band performance. A finite biconical antenna is not perfectly non-resonant, due to its sudden discontinuity at the ends that causes band width limitation and high return loss.

An appropriate termination of the ends of the cones enhances its band width. It is established that the spherical cap acts as a sink for the surface current and provides a smooth transition for current flow from the cone edges. Biconical antennas of different heights and varying cone angles have been proposed for wide band operation. The authors have proposed a biconical antenna with ends terminated in circular loop of appropriate radius that is of relatively small in height compared to those reported earlier. The proposed ring terminated biconical antenna is shown in Fig. 1.

Total length of the proposed antenna is 25 mm. Length of each cone is 12.5 mm. Separation between the cones is 1 mm. Radius of the cone at the apex is 0.9 mm. Dimensions of the loop have to be carefully considered and the upper radius of the cone and outer radius of the loop should be the same. The outer diameter of the loop is 25 mm and its inner diameter is 22 mm for good termination of the cone. Diameter of loop conductor is 1.5mm. Optimum return loss is realized for 1-2 mm radius of the loop conductor. When the outer radius of the loop is greater than the cone top radius then it results in low return loss and distorted radiation pattern.

The loop is correctly fused on the outer edge of the cone. This converts the sharp and abrupt discontinuity of the top end of the cone in to a smooth curved termination for the current flow. The biconical antenna is modeled in method of moment based CST and HFSS soft wares and simulated using both to obtain its performance for optimization. Time domain solver is used for simulation which is faster and takes less time as compared to frequency domain solver and is good for wideband structures. The solver generates field results for many frequencies with one simulation run. There is no restriction on mesh configurations. The volume of occupancy of this element is very small which is on par with those of microstrip antennas. All the design parameters are listed in Table 1.

Fig. 1. Antenna structure - biconical antenna with ring.

Table 1: Design parameters of the antenna

Parameter Name	Dimensions (mm)
Upper radius of top cone	12.5
Bottom radius of top cone	0.9
Upper radius of bottom cone	0.9
Bottom radius of bottom cone	12.5
Length of each cone	12.5
Separation between the cones	1
Outer radius of the terminating loop	12.5
Inner radius of the terminating loop	11
Diameter of termination loop	1.5
Position of termination loop	±13
Volume of the structure	4.0625 cm^3
Cone angle	90°

III. SIMULATION

The proposed design is simulated in CST and HFSS from 1 to 40 GHz. In CST the far-field monitor of field monitor window is used for the radiation pattern generation. In HFSS the far-field radiation sphere is used for the pattern. Hexahedral mesh configuration with minimum mesh step of 0.45 and maximum of 1.259 is used. The results are analyzed by optimizing the design parameters of the element such as the radius, position of the loop and the separation between the cones at the apex. Design parameters listed in Table 1 are selected for obtaining optimum results.

Antenna simulation results with and without termination at 6 and 40 GHz are presented in Figs. 2-5. Comparing the current distribution on the cones at the corresponding frequencies of the element with and without termination reveals that the current density is uniform on the surface of the cone with ring termination. The current density reduces gradually with maximum at the apex or feed point towards the end. Each circular contour on the cone shows equal current density points.

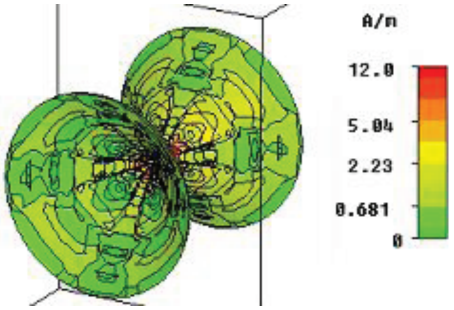

Fig. 2. Surface current distribution on cone without ring at 6 GHz.

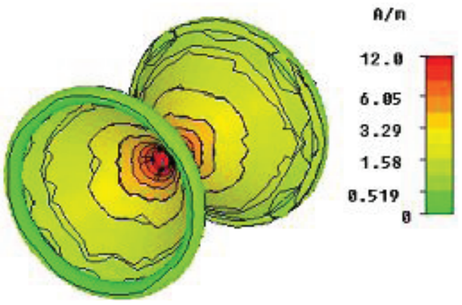

Fig. 3. Surface current distribution on cone with ring at 6 GHz.

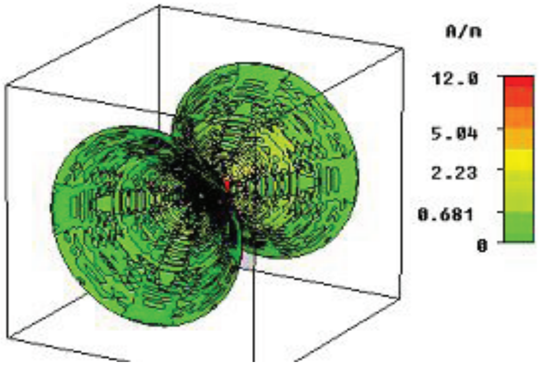

Fig. 4. Surface current distribution on cone without ring at 40 GHz.

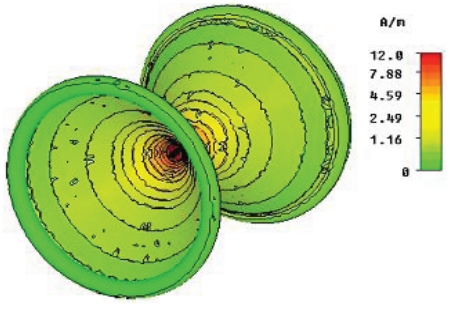

Fig. 5. Surface current distribution on cone with ring at 40 GHz.

At the joint where the cone end meets the loop, the current density is smooth and continuous around the neck and on the loop as well. The contour lines show equal current density points. Hence, there's an improvement in the band width and return loss. The current density on the cones without termination in Fig. 2 and Fig. 4 is non-uniform. It appears like small patches on the surface of the cones.

The simulation results show that the terminated cones have uniform current distribution as depicted in Fig. 3 and Fig. 5. The ring with its gradual curvature at the end provides smooth transition at each point on the edge of the cone. The spherical cap termination is not as smooth at the joint as the proposed loop discussed in this paper. Termination with loop is simple and reduces weight and volume as compared to that of a spherical cap. Analysis was done using current distribution on the cones at two frequencies (6 & 40 GHz). The same current distribution is observed at other frequencies also.

IV. RADIATION PATTERNS

The far zone broad side normalized electric field in E-plane is presented in Eq. (1). For a biconical antenna the radiation pattern is independent in azimuth direction. This equation depicts E-field of the biconical antenna that has no standing waves and represents radiation at low and high frequencies as well for cone angles greater than 40 degrees. The formula cannot be used for cones with small angles.

$$R(\theta,\omega)=\frac{E_\theta^{rad}(r,\theta,\omega)}{E_\theta^{rad}\left(r,\pi/2,\omega\right)}=\frac{\sum_{n=1}^{\infty}\frac{i^{n-1}(2n+1)}{2n(n+1)}\frac{p^1(\cos\theta)g_n(\mu_1,\mu_2)}{h_{n-1}^{(2)}(ka)-\frac{n}{ka}h_n^{(2)}(ka)}}{\sum_{n=1}^{\infty}\frac{i^{n-1}(2n+1)}{2n(n+1)}\frac{p^1(0)g_n(\mu_1,\mu_2)}{h_{n-1}^{(2)}(ka)-\frac{n}{ka}h_n^{(2)}(ka)}}. \quad (1)$$

The omnidirectional pattern with maximum of the main beam is perpendicular to the axis of the cone and the radiation is confined between the two cones. Radiation patterns in vertical plane are shown and are omitted in horizontal plane for brevity. Elevation plane patterns at βr = 0.524, 3.142, 5.24, 10.47, 15.7 & 21 are shown in Figs. 6-11 respectively. These patterns are smooth without ripples, side lobes and grating lobes. The low frequency patterns for βr = 0.524 are perfectly omnidirectional. Radiation patterns at specific frequencies are obtained in dB and normalized in both CST and HFSS, and are superimposed. Radiation patterns for βr = 15.7 and 21 are depicted in Fig. 10 and Fig. 11 respectively shows ripples or oscillations in the main beam and is not as smooth as those of βr < 10.47.

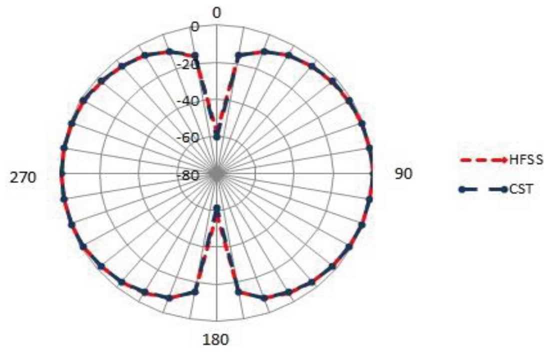

Fig. 6. Radiation pattern at 1 GHz (βr = 0.524).

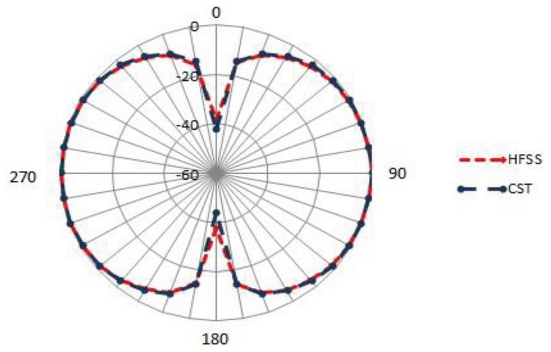

Fig. 7. Radiation pattern at 6 GHz (βr = 3.142).

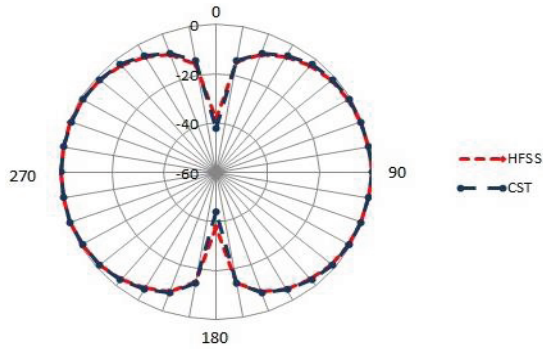

Fig. 8. Radiation pattern at 10 GHz (βr = 5.24).

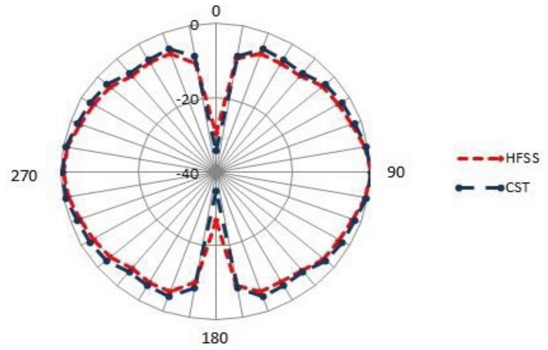

Fig. 9. Radiation pattern at 20 GHz (βr = 10.47).

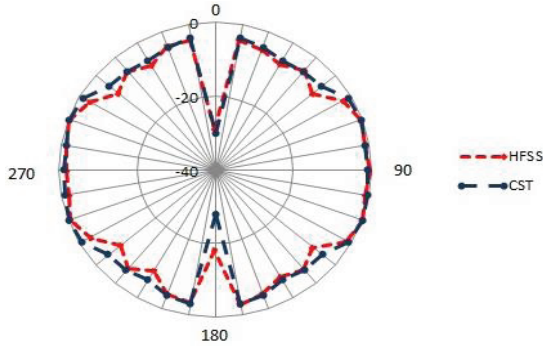

Fig. 10. Radiation pattern at 30 GHz (βr = 15.7).

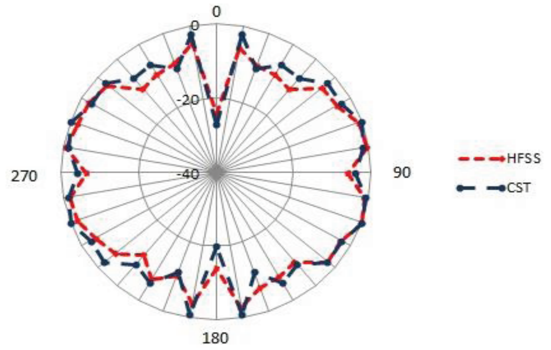

Fig. 11. Radiation pattern at 40 GHz (βr = 21).

V. RETURN LOSS

Another important parameter that shows considerable improvement is the return loss. The return loss is the negative of the reflection coefficient (S_{11}) when expressed in decibels. The S-parameter (input reflection coefficient) S_{11} for antenna without and with termination is shown in Fig. 12 and Fig. 13, respectively. Return loss for cone without termination is less than that of ring termination for most of the frequency range. The parameters of the cone and the loop are optimized to get best value of return loss, i.e., 10 dB and more from 7.5 to 25 GHz. This frequency range covers X, Ku and K bands which are important for modern wireless applications. In the low frequency range 1-7.5 GHz and at high frequency range, i.e., 25-40 GHz the return loss is varying up to 5 dB and is omitted for brevity. It can be used as receiving antenna for short distance communication in the above mentioned ranges. The input impedance of biconical antenna involves resistance and reactance. As ‘βr’ increases the resistance and reactance of the conical antenna oscillates around its characteristic values and these oscillations cause fluctuations in the reflection coefficient. Papas and King [7] reported that the input resistance and reactance of biconical antenna with cone angles greater than 40° vary with frequency over wide frequency ranges. Consequently, the reflection coefficient also exhibits similar variations with frequency. Reflection coefficient of the antenna without termination shows dip at 9 & 17 GHz, whereas the element with edge termination shows similar oscillations at much reduced levels. The return loss of the terminated cone at each frequency has increased nearly by 5 dB. The inner circumference of the loop is 69.12 mm.

For large loops the circumference C = wavelength (λ):

$C = \lambda = 2*\pi*r = 69.12$ mm ~ 4.5 GHz,
$C/2 = \lambda/2 = 34.55$ mm ~ 9 GHz,
$C/4 = \lambda/4 = 17.28$ mm ~ 17 GHz.

The antenna is resonant at half wavelength intervals and causes a dip at these frequencies which is characteristic of the loop. Table 2 shows the values of gain and return loss at different values of ‘βr’ for both terminated and non-terminated cones.

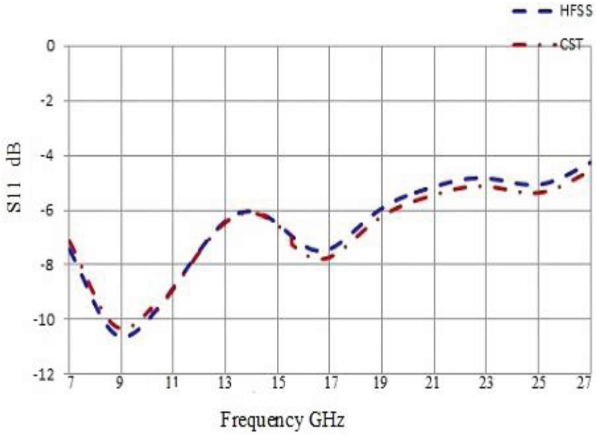

Fig. 12. S_{11} vs. frequency - without edge termination.

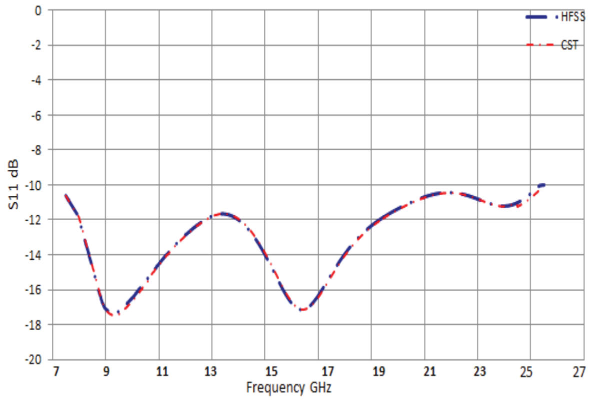

Fig. 13. S_{11} vs. frequency - with edge termination.

Table 2: Gain and return loss

βr	Gain		Return Loss	
	Without Ring	With Terminating Ring	Without Ring (dB)	With Terminating Ring (dB)
0.524	-0.825	0.37	0.2	1
3.142	-0.4033	0.9	6	8
5.24	0.0625	0.6	10	17
10.47	0.6912	0.8	5.5	11.5
15.7	0.2127	1.21	5	7.5
21	1.44	1.532	3.5	4

All the results have been obtained by using two Hi-end EM simulation soft wares CST and HFSS. These results are superimposed to analyze their similarities and deviations. Radiation patterns from 1 GHz to 10 GHz are perfectly omnidirectional at all the angles without any deviation. Above 10 GHz there are slight deviations at certain angles such as 0° and 180°, values in HFSS shows some increase in minima as compared to that of CST and this is negligible.

The S_{11} values in both simulators closely follow at each frequency. Radiation results shown using both solvers are in close agreement at each frequency. This establishes that the proposed design parameters are optimum.

VI. CONCLUSION

The proposed wide band biconical antenna with ring termination is novel and hasn’t been reported previously. It is presented that the curved conductor at the top edge of the cone provides smooth transition for current flow and provides an appropriate termination for the current. This causes smooth and uniform current density on the terminated cone surface preventing reflections from the edge of the cone. A uniform current distribution is realized from the feed to the open end. It results in improvement of the return loss of the proposed antenna in the mid frequency range covering three major frequency bands X, Ku and K. It is also observed by the authors that at low and high frequencies the return loss varies up to 5 dB, whereas the radiation pattern is perfectly omnidirectional from 1 to 40 GHz in the region between the cones. Hence, the proposed technique has enhanced the band width of the finite biconical antenna considerably.

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