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Empirical Relation for Designing a Bifolded Printed Bent Monopole Antenna

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Abstract:

Applications like airborne navigation, communication, etc. require broadband omnidirectional antennas with simple structure, compactness and aerodynamic shape. Planar monopole antennas possess these qualities and are preferred more for these applications. But the limited space available on installing platform provide insufficient ground plane to these antennas which deteriorate the antenna radiation characteristics. Printed monopole antennas reduce the ground plane dependency of planar monopole antennas as the radiator and the ground are designed in the same plane of the antenna. A Bifolded printed bent monopole antenna with L shaped ground plane, operating in VHF band is discussed in this paper for airborne applications. An empirical relation between frequency and each dimension of the antenna is derived and is validated for different frequencies of operation as well as for different substrates. A relation for calculating the resonant frequency of the antenna for various dimensional values is also obtained and verified based on the experimental and simulation analysis.

Keywords: Bifolded, printed monopole, bent monopole, design equation

INTRODUCTION

Monopole antenna is attractive for airborne communication due to simple design, wide bandwidth and nearly omnidirectional radiation coverage. The impedance bandwidth of a wire antenna can be improved by increasing its diameter. Such antennas where the wire element is replaced by flat square plate or circular disc are termed blade monopole or planar monopole antennas. The main handicap of a conventional planar monopole antenna is the requirement of large ground plane. For ground plane constrained applications, this results in deteriorated radiation characteristics. In airborne antennas, compactness is also a major concern. To comply with this, low profile monopole antennas are preferred. Literature presents printed monopole antennas as a solution to the backing ground plane constrained monopole antenna applications [1].

A printed monopole consists of a strip or a flat plate printed on a dielectric substrate and a ground plane printed either on same side or opposite side of substrate depending upon the feeding method chosen. The optimum length for designing a printed strip monopole antenna is 0.2 λ [2]. Also, it is reported that the bandwidth fell sharply as the ground-plane size deviates from 0.35λ. This requirement is quite large when considering antenna for HF/VHF frequencies. Folding or bending technique is a conventional method used for reducing antenna dimension.

The bent monopole or inverted L monopole antenna is a short monopole with the addition of a horizontal segment of wire at the top. The bending of the monopole results in a reduced size and low profile. These antennas were first designed for missile applications in 1960 [3]. Various other configurations of bent monopole antennas were developed since 2003 for achieving different characteristics like compactness, multiband operation, and even wideband characteristics [4-8].

The design and development of a bifolded printed bent monopole VHF antenna is discussed in [9].In this paper, a detailed analysis of this antenna is presented. The effect of each dimension of the antenna on its radiation characteristics is analyzed. The frequency response of the antenna with dimensional variations are explained based on the variation in the distributed capacitance and inductance. An empirical relation between the dimension and resonant frequency is derived and validated for various set of values.

ANTENNA GEOMETRY

The antenna is designed on FR4 epoxy substrate of relative permittivity 4.4 and loss tangent 0.02. The size of the substrate is 145mm X 270mm X 3.2mm. The antenna has two layers of 1.6mm thick substrates, the top layer contains the radiating element and bottom layer contains the ground patch, placed back to back. The bent monopole antenna is folded twice in order to reduce antenna dimension for a lower resonant frequency. The ground plane consists of L shaped patch. This shape was chosen for ground plane as it was found that the vertical length of ‘L’ improves the impedance matching. To achieve wide band characteristics, resistance loading method was employed to the radiating patch. Resistance loading method is an efficient method for bandwidth enhancement at the expense of gain of the antenna. A resistor value of 23.5Ω was used to achieve this. A 50Ω TNC connector is used to excite the antenna. The center conductor is connected to the printed radiating element of the antenna and outer to the bottom portion of the patch and to the aluminium base plate. Figure 1 depicts the antenna geometry. The dimensional details of the antenna are shown in Table 1.

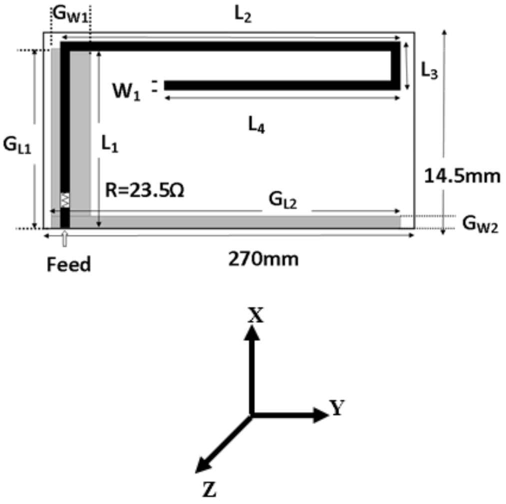


Figure 1. Antenna Geometry

Table 1. Dimensions of proposed antenna

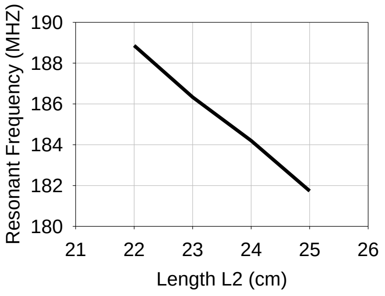
Parameters	**L$_1$**	**L$_2$**	**L$_3$**	**L$_4$**	**W$_1$**	**G$_{L1}$**	**G$_{L2}$**	**G$_{W1}$**	**G$_{W2}$**
Value (mm)	140	250	56	180	12	130	255	30	10

PARAMETRIC ANALYSIS

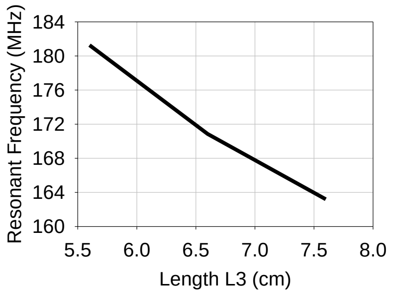
A parametric study on the proposed antenna design was carried out to investigate the influence of each dimension on the antenna performance. One parameter is varied while the other parameters are kept constant, as they are in Table 1.

Effect of radiating patch dimensions

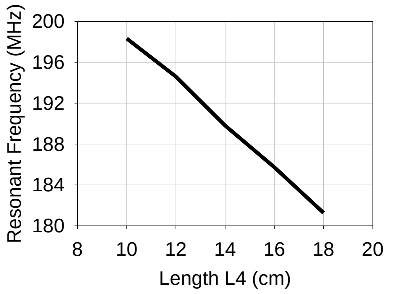
The length of the radiating element determines the resonating frequency. It was found that the resonant frequency is determined by the length $L_2+L_3+L_4$. The contribution of L1 towards resonant frequency is less as it acts as a microstrip feed line to couple RF power to radiator. The decrease in the resonant frequency with the increase in the dimensions L_2, L_3 and L_4 is plotted in the figures Figure 2(a-c). The contribution of L_3 towards resonant frequency is comparatively high as its variation significantly changes the capacitance between the folded arms.



(a)



(b)



(c)

Figure 2. Effect of (a) L_2 (b) L_3 (c) L_4 on resonant frequency

The antenna was simulated for various patch widths and the effect of this parameter on the return loss characteristics is shown in Figure 3(a). The radiating patch width (W_1) is varied from 2mm to 12mm in step of 2mm. It can be observed from the figure that the 3:1 VSWR bandwidth of the antenna increases as the radiating patch width increases, where, the lower edge of the bandwidth remains almost constant and the upper edge of the bandwidth increases. It can be seen from Figure 3(b) that the increase in bandwidth with W_1 is due to the increase in the distributed capacitive reactance.

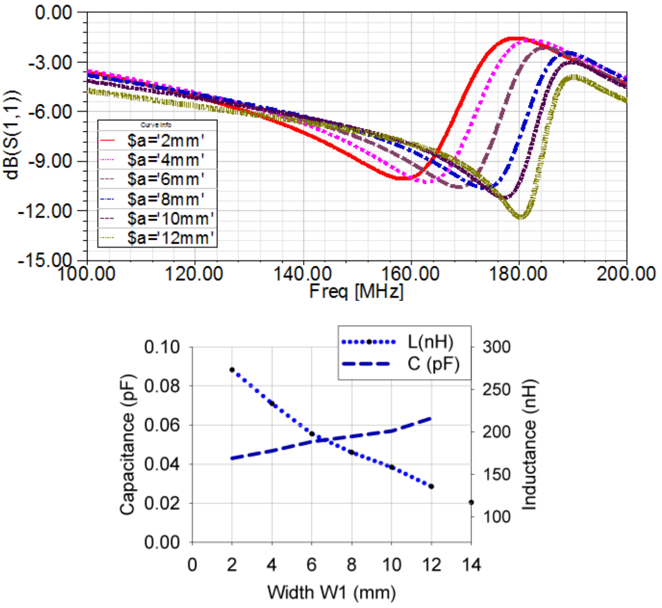


Figure 3. (a). Effect of patch width W_1 on return loss of antenna (b) Variation in distributed reactance with W_1

Effect of ground plane dimensions

The antenna was simulated for various ground plane dimensions. The effect of G_{W1} on the return loss of antenna was studied by varying G_{W1} from 1cm to 4cm in step of 1cm and is plotted in Figure 4 (a). The bandwidth of the antenna for S11 < -6dB, increases with increase in G_{W1}. The lower edge of the bandwidth remains almost constant and the upper edge of the bandwidth increases. The effect of G_{W1} on the impedance of the antenna is plotted in Figure 4 (b). It is evident from the figure that the distributed capacitance increases with G_{W1} which results in increase in the bandwidth of the antenna.

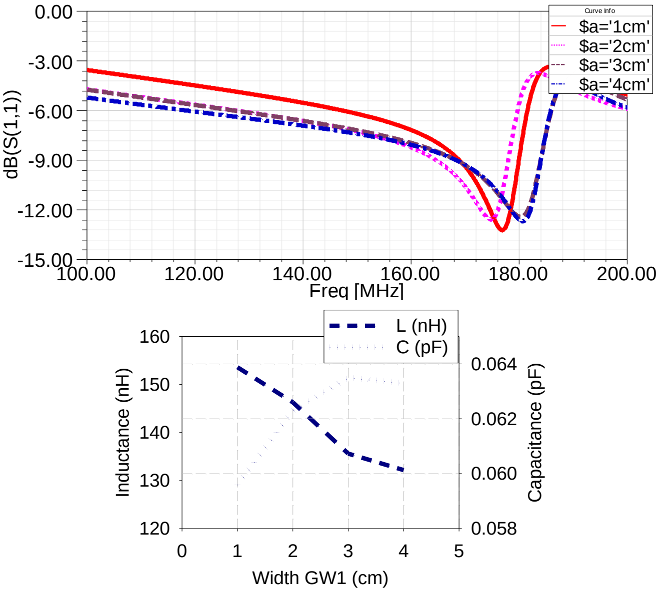


Figure 4. (a). Effect of ground plane dimension G_{W1} on return loss of antenna (b) Variation in distributed reactance with G_{W1}

To study the effect of ground plane length $G_{L1,}$ the parameter was varied from 1cm to 13cm in step of 3cm. The effect of G_{L1} on the return loss of the antenna is shown in Figure 5. It can be seen from figure that increase in G_{L1} improves the impedance matching of the antenna at lower frequency.

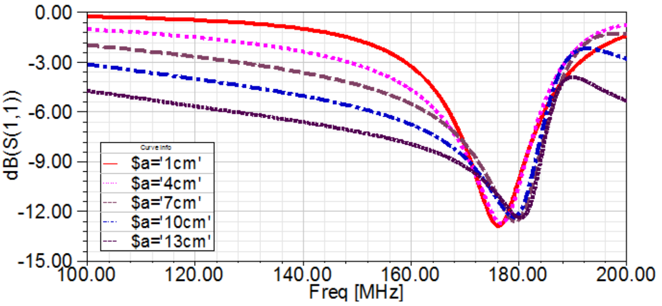


Figure 5. Effect of Ground plane dimension G_{L1} on return loss of the antenna

The effect of G_{L2} on the radiation characteristics of the antenna was studied by varying G_{L2} from 1cm to 25cm in step of 5cm. The effect of G_{L2} on the return loss of the antenna is shown in Figure 6. It was found that, the increase in G_{L2} decreases the resonant frequency shifting the higher edge of the frequency band towards lower side. The lower edge frequency of the band remains almost constant with increase in G_{L2}. The bandwidth decreases with increase in G_{L2}. It was also observed that the polarization of the antenna changes with increase in G_{L2}. The simulated 3D radiation pattern of the antenna at two extreme values of G_{L2}, ie 3cm and 25cm is plotted in Figure 6 (b) & (c). An omnidirectional coverage in Y-Z plane is obtained when G_{L2} is 25cm.

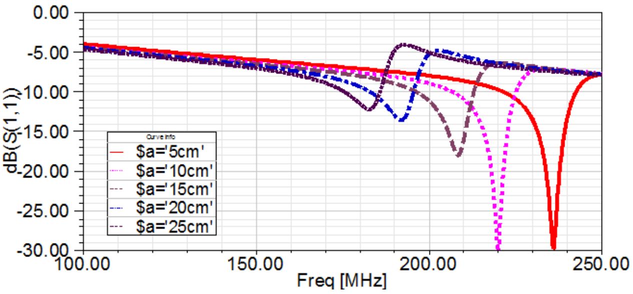
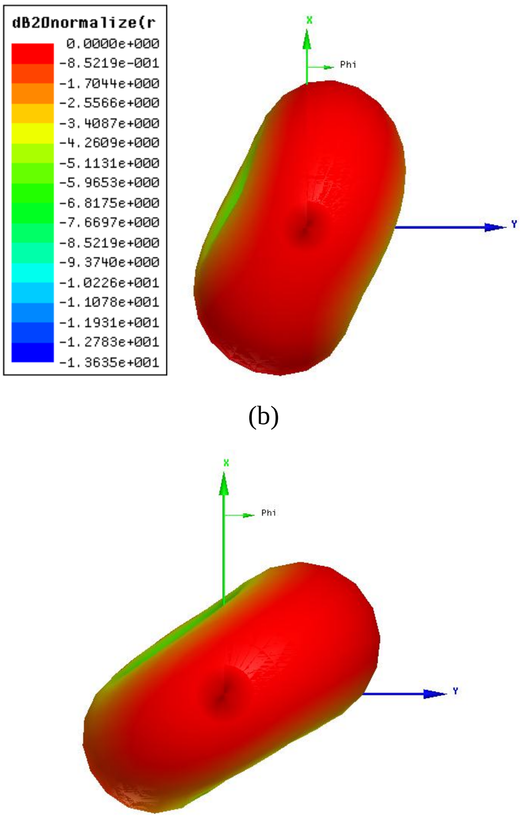


Figure 6. Effect of G_{L2} on return loss of the antenna



(b)

(c)

Figure 6. Effect of G_{L2} on the radiation pattern of the antenna (b) G_{L2} =3cm (c) G_{L2} =25cm

The effect of G_{W2} on the return loss of the antenna was studied and is plotted in Figure 7. It can be seen that the increase in G_{W2} decreases the bandwidth of the antenna slightly by shifting the upper edge frequency of the band towards lower side.

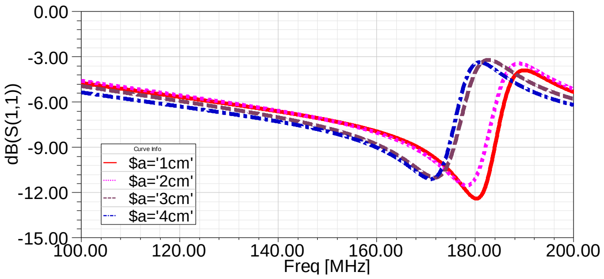


Figure 7. Effect of ground plane dimension G_{W2} on return loss of the antenna

Effect of substrate parameters

The effect of substrate dielectric constant on the antenna resonant frequency was studied by varying ε values from 1 to 10 and is plotted in Figure 8. By curve fitting technique, it can be found that the effect of dielectric constant of the substrate on decreasing the resonant frequency of printed monopole antenna is not prominent as in other microstrip antennas. This is because printed monopole antennas can be considered as a monopole antenna on a substrate above a very thick air dielectric substrate, that the effective permittivity is closer to unity [10].

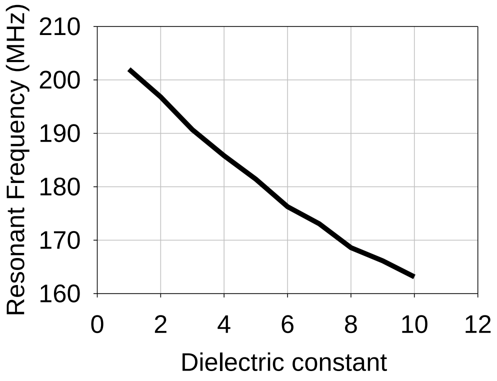


Figure 8. Effect of substrate dielectric constant on resonant frequency

DESIGN EQUATION

Based on the parametric studies aforementioned and surface current distribution, a design equation for the resonant frequency of the antenna is developed. It was evident from the parametric analysis that the length L_1, L_2, L_3 and L_4 determine the resonant frequency. Also it was seen that there is a λ/4 current variation along the length of the radiating patch. It was also observed that the substrate dielectric constant contribute to the reduction of resonant frequency of a printed monopole antenna by a factor closer to unity. Based on these observations, the resonant frequency is calculated as

$$f = \frac{c}{4 * k * (0.2L1 + 0.75L2 + 0.93L3 + 0.75L4)}$$

Where c is the velocity of light in free space in m/s. The value of k for substrate of dielectric constant ε_r=4.4 is 1.115.

The equation was verified for different values of L_1, L_2, L_3 and L_4; varying one dimension at a time, keeping other dimensions constant. The calculated frequency was compared with the simulated result and the error was calculated. The resonant frequency calculation for FR4 substrate and RT Duroid 5880 (ε_r=2.2) substrate are tabulated in Table 2 and Table 3 respectively. A percentage error less than 4% was obtained.

Table 2. Resonant frequency calculation for FR4 substrate

L1 (cm)	L2 (cm)	L3 (cm)	L4 (cm)	Simulated Frequency (MHz)	Calculated Frequency (MHz)	% Error
14	25	5.6	18	183.38	184.82	0.78
13	25	5.6	18	184.46	185.74	0.69
12	25	5.6	18	185.58	186.67	0.58
14	**25**	5.6	18	183.38	184.82	0.78
14	**24**	5.6	18	185.28	188.33	1.64
14	**23**	5.6	18	184.74	191.97	3.91
14	**22**	5.6	18	189.56	195.56	3.16
14	25	**4.6**	18	193.44	189.19	2.19
14	25	**5.6**	18	183.38	184.82	0.78
14	25	**6.6**	18	175.3	180.65	3.05

L1 (cm)	L2 (cm)	L3 (cm)	L4 (cm)	Simulated Frequency (MHz)	Calculated Frequency (MHz)	% Error
14	25	5.6	**18**	183.38	184.82	0.78
14	25	5.6	**17**	186.18	188.33	1.15
14	25	5.6	**16**	188.74	191.97	1.71
14	25	5.6	**15**	191.6	195.76	2.17
14	25	5.6	**14**	194.88	199.7	2.47

Table 2. continued….

Table 3. Resonant frequency calculation for RT Duroid 5880 substrate (k=1.008)

L1 (cm)	L2 (cm)	L3 (cm)	L4 (cm)	Simulated Frequency (MHz)	Calculated Frequency (MHz)	% Error
14	25	5.6	18	195.3	193.77	0.82
13	25	5.6	18	196.2	194.79	0.71
12	25	5.6	18	196.6	195.81	0.4
14	**25**	5.6	18	195.3	193.7	0.82
14	**24**	5.6	18	198.25	197.63	0.31
14	**23**	5.6	18	201.8	201.65	0.09
14	**22**	5.6	18	204.95	205.83	0.43
14	25	**5.6**	18	195.3	193.7	0.82
14	25	**6.6**	18	185.35	189.19	2.07
14	25	**7.6**	18	177.15	184.32	4.0
14	25	5.6	**18**	195.3	193.7	0.82
14	25	5.6	**17**	197.75	197.6	0.06
14	25	5.6	**16**	200.25	201.6	0.67
14	25	5.6	**15**	202	205.8	1.8
14	25	5.6	**14**	204.2	210.1	2.8

DESIGN PROCEDURE

The values for designing the antenna for any resonant frequency f is given in Table 4. The guided wavelength $\lambda_g = \lambda_0/k$, where λ_0 is the free space wavelength at resonant frequency f.

In order to justify the design equations, the antenna parameters are computed for FR4 and RT Duroid 5880 substrates and are tabulated in Table 5 and Table 6 respectively.

Table 4. Geometrical parameters in terms of λ_g

L_1	**0.094 λg**	**W_1**	**0.013 λg**
L_2	**0.17 λg**	**G_{L1}**	**0.088 λg**
L_3	**0.0373λg**	**G_{L2}**	**0.172 λg**
L_4	**0.12 λg**	**G_{W1}**	**0.02 λg**

Table 5. Computed geometrical parameters of the antenna on FR4 substrate for different frequencies

Design Frequency (MHz)	L_1 (cm)	L_2 (cm)	L_3 (cm)	L_4 (cm)	W_1 (cm)	G_{L1} (cm)	G_{L2} (cm)	Resonant Frequency (MHz)
181.6	14	25	5.6	18	2	13	25.5	181.6
210	12	21.7	4.8	15.4	1.72	11.2	22	213.875
240	11	20.5	4.59	14.5	1.6	10.6	20.8	242.38

Table 6. Computed geometrical parameters of the antenna on RT Duroid 5880 substrate for different frequencies

Design Frequency (MHz)	L_1 (cm)	L_2 (cm)	L_3 (cm)	L_4 (cm)	W_1 (cm)	G_{L1} (cm)	Gw1 (cm)	G_{L2} (cm)	Resonant Frequency (MHz)
181	15.3	27.8	6.2	19.6	2.2	14.4	3.4	28	179
210	13.2	23.9	5.4	17	1.9	12.4	2.9	24.2	207.93
240	11.4	21	4.7	14.8	1.7	10.9	2.5	21.4	238.5

EXPERIMENTAL RESULTS

The performance of the antenna was evaluated using E5071C Vector Network Analyzer [Agilent]. The measured return loss of the antenna is found to be less than -6dB over the referred frequency band. The antenna exhibits a 3:1 VSWR bandwidth of 32% at the center frequency 150 MHz as shown in Figure 9. Measured result shows a good agreement with the simulated result. The slight discrepancy is due to the fabrication tolerance.

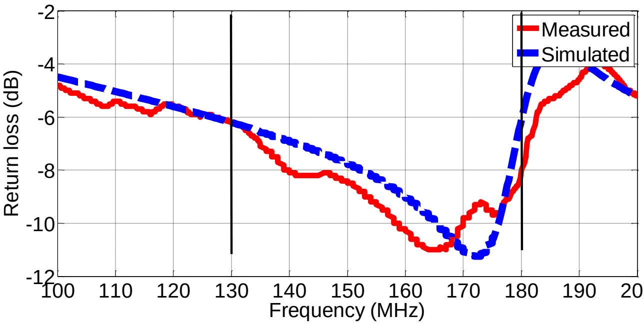
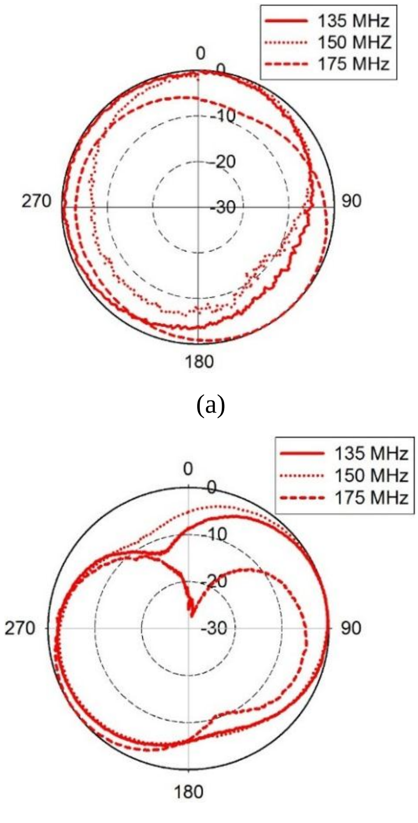


Figure 9. Measured return loss

The antenna was tested for its far field radiation characteristics in an open field. The measured H plane and E plane radiation patterns of the antenna at 135, 150 and 175 MHz is shown in Figure 10 (a) & (b). It can be seen that the H plane radiation pattern of the proposed antenna is nearly omnidirectional at all frequencies.



(a)

(b)

Figure 10. Radiation pattern at (a) azimuth plane (b) elevation plane

The boresight gain was measured using gain comparison method. The measured gain of the antenna at three discrete frequencies 135, 150 and 175 MHz is shown in Table 7. The low gain value is expected as the loaded resistance absorbs a part of the energy.

Table 7. Measured gain of the antenna

Frequency (MHz)	Measured gain (dB)
135	-16.9
150	-15.4
175	-9.2

CONCLUSION

A bifolded bent printed monopole antenna with resistance loading and L shaped ground plane has been investigated for operating over VHF band in the ground plane constrained applications. A parametric study was carried out to study the effect of the dimensions of the radiator as well as the ground plane on the antenna performance. An empirical equation for the resonant frequency of this antenna was deduced and verified for different set of dimension. The antenna exhibits a 3:1 VSWR bandwidth of 32% and it achieves a height reduction of 75% compared to conventional quarter wave monopole antenna.

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