A Monopole Loaded with a Loop Antenna

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Abstract — A traveling-wave distribution of current can be produced on a monopole over a ground plane by inserting a resistance of suitable magnitude one-quarter wavelength from its end. It has been shown that the resistor can be replaced with a modified folded dipole which has a radiation resistance approximately equal to that of the resistor. In this paper, the resistor is replaced with a loop antenna. The main objective is to obtain an antenna having hemispherical coverage and is circularly polarized. Input impedance, current distribution, and radiation patterns of this antenna are computed using the numerical electromagnetics code (NEC); radiation patterns are also measured. Most computations and measurements were made at a frequency of 1.6 GHz. The frequency dependence was examined and it was found that these antennas can operate over the band from 1.4-2.0 GHz. These very simple, low-cost antennas have potential application for systems such as IRIDIUM and Global Positioning System.

I. INTRODUCTION

A traveling-wave distribution of current can be produced on a linear antenna by inserting a resistance of approximately 240 Ω one-quarter wavelength from its end [1]. The main disadvantage of the resistive-loaded traveling-wave antenna is that it is only about 50% efficient because part of the input power is absorbed by the resistor. It is possible to replace the resistor with a resonant antenna having a radiation resistance approximately equal the matching resistor [2], [3]. Thus, the input section still has a traveling-wave distribution of current up to the inserted element, but now the power previously dissipated in the resistor is also radiated. In this paper, the resistor is replaced with a loop antenna [4]. It is shown that the directional and polarization properties of this loaded antenna can be varied by changing the loop configuration. Both circular and square loop insertions are investigated. The input impedance, current distribution, and radiation patterns of this antenna over an infinite ground plane are computed using the numerical electromagnetics code (NEC) [5]. Radiation patterns are also measured, but over a finite ground plane. This limitation leads to a discrepancy between computed and measured patterns. This antenna can be designed to operate at any frequency as long as it does not become too small, physically. Most computations and measurements were made at 1.6 GHz; the frequency dependence was also examined.

II. APPROACH

The procedure that was used in this investigation was first to calculate the antenna properties using NEC, construct the antenna, measure its characteristics, and then compare the computed and measured results where possible. The NEC computations were only used as a guide for the antenna design; obtaining good agreement between computations and measurements was of secondary concern. The proposed antenna has two mutually perpendicular radiating elements—the horizontal loop and the vertical monopole. The loop provides coverage in the zenith direction and higher elevation angles; the monopole coverage is at the low elevation angles. Ideally, we would like the currents in the orthogonal elements to be of comparable magnitude and in phase quadrature so that a circularly polarized field is radiated. This is obviously not possible for all directions. We have chosen to concentrate on obtaining right-hand elliptical polarization down to elevation angles as low as possible. A general expression for the power received by an elliptically polarized antenna from an elliptically polarized transmitting antenna is [6]

\[
P_R = \frac{1}{2} \frac{2r_1r_2}{(1 + r_1^2)(1 + r_2^2)} + \frac{1}{2} \frac{1 + r_1^2}{(1 + r_2^2)(1 + r_2^2)} \cos 2\alpha
\]

where

1) \(r_1\) is the axial ratio of the receiving antenna and the axial ratio is defined as the ratio of the minor axis to the major axis;
2) \(r_2\) is the axial ratio of the transmitting antenna;
3) \(\alpha\) is the angle between the major axes of the two ellipses of polarization;
4) \(P_R\) is the power received; and
5) \(P_0\) is the maximum power.

The (+) sign is used if the senses of polarization are the same, while the (−) sign is used if the senses are opposite. If we assume that the transmitting antenna is right-hand circular polarization \(r_2 = 1\) and the polarization loss in dB is

\[
10 \log_{10} \left[ \frac{1}{2} \pm \frac{r_1}{1 + r_1^2} \right]
\]

Note that as long as the receiving antenna has the same sense polarization as the transmitter, then a maximum polarization loss of 3 dB occurs when the receiver is linearly polarized. If, however, the receiving antenna has the opposite sense polarization then the polarization loss becomes very large. Thus, it is of utmost importance to limit the presence of opposite-sense polarization in the receiver. Many configurations of circular- and square-loop insertions were investigated.
Comparable results were obtained from both types of loops. Computations were made as a function of loop perimeter, height of the loop over the ground plane, and the method used to excite the loop. Loop perimeters of approximately one wavelength produced the best results. Increasing the height of the monopole (and the corresponding distance of the loop over the ground plane) enhanced the low elevation angle radiation; however, nulls also appeared. When the monopole was 0.75\( \lambda \) (and the loop was 0.5\( \lambda \) above the ground plane) there was, as expected, a deep null in the zenith direction. The best results were obtained when the loop was approximately 0.25\( \lambda \) above the ground plane. A number of approaches for exciting the loop were examined. Two types of excitations that produced interesting results were a series-fed loop and a parallel-fed loop as are shown in Fig. 1. With the series-fed loop Fig. 1(a), near hemispherical coverage could be obtained; with the parallel-fed loop Fig. 1(c), a more directional pattern was produced. Finally, the directional properties of this antenna could be modified by changing the length of the end section of the monopole. Usually it is 0.25\( \lambda \); making the total length of the end section plus the length of the wire from the perimeter of the loop to the monopole near 0.25\( \lambda \) produced slightly better results.

The NEC computations were done for a set of circularly polarized radiation patterns for the \( \theta \) and \( \phi \) planes over an infinite ground plane. These data were generally sufficient to assess the performance of the antenna. The antenna was constructed from #18 copper wire which has a diameter of about 1.0 mm. However, for the wire to hold its desired shape it had to be stretched; this process reduced the wire diameter slightly. The antennas were hand made. Although the antenna dimensions were only approximately those that were used for the NEC computations, they were believed to be close enough to make a qualitative comparison. For example, the circular-loop numerical model was approximated by 16 short segments, each about 1 cm, and thus, slightly different from the continuous circular loop that was used in the measurements. Directional properties were measured in an indoor pattern range. Unfortunately, this range was not equipped to measure the \( \phi \)-plane patterns. The antenna was mounted over a 1.2 m \( \times \) 1.2 m (6.5\( \lambda \) \( \times \) 6.5\( \lambda \) at 1.6 GHz) ground plane. The effect of a finite ground plane on the antenna pattern is twofold. Reflections from the edge of the ground plane produce ripples in the pattern; the circularly polarized coverage along the horizon is limited.

III. RESULTS

The input impedance, current distribution, and circularly polarized directive gain were computed for series and parallel-
fed circular and square-loop monopole insertions. Radiation patterns for these antennas were also measured.

A. Monopole with a Series-Fed Circular-Loop Insertion

For the series-fed insertion, shown in Fig. 1(a), a circular loop with a circumference of 0.92λ, which was about 0.3λ above the ground plane, produced good results. The monopole was designed so that the length of the end section plus the radial wire from the loop to the monopole was about 0.25λ, thus placing a current maximum at the end of the loop. The computed input impedance was 171.5 $-$ 1.2 ohms, almost resonant. The input section of the monopole along with the segment from the monopole to the loop perimeter approximated a traveling wave. The distribution around the loop, the wire from the loop perimeter to the monopole, and the end section of the monopole had a standing wave distribution with a current minimum in the loop segment opposite the feed to the loop.

A set of circularly polarized patterns in the $\theta$ plane were computed for azimuth angles of 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, and 157.5° at a frequency of 1.6 GHz. The patterns show a gradual change as a function of azimuth angle. Those corresponding to angles of $\phi = 0°$, 45°, 90°, and 135° are plotted in Fig. 2; the others are omitted for clarity. Note that the 0° cut has almost uniform coverage over the hemisphere; the 45° and 135° cuts show a null forming at a zenith angle of about 60°. For the 90° cut the pattern has a much deeper null. A set of $\phi$-plane cuts are plotted in Fig. 3 for zenith angles of 50°, 60°, and 70°. It is seen that the coverage is good except for azimuth angles near $\phi = 75°$. Antenna patterns for this antenna were also computed over the frequency range from 1.2–2.0 GHz. Patterns in the $\theta$ plane are plotted for an azimuth angle of 0° in Fig. 4. It is seen that the patterns do not change very much until the frequency drops below 1.4 GHz. The impedance was also computed for the same frequency band and with some impedance matching this antenna could operate over the band from 1.4–2.0 GHz. A set of circularly polarized antenna patterns were measured for an antenna having dimensions approximately equal to those for which the computations were made. The $\theta$-plane cuts were for the same azimuth angles as the computations and are shown in Fig. 5. As for the computed patterns, the $\phi = 0°$ cut has almost hemispherical coverage, whereas that for the other cuts show some nulls. The comparison between computed and measured patterns is very good considering the differences that were pointed out earlier. The measured patterns for $\theta$-plane cuts at other frequencies were similar to the computed; as an example, the $\theta$-plane cuts corresponding to $\phi = 0°$ are shown in Fig. 6. The gain level has not been corrected for frequency so these are only relative gain patterns. However, it is seen that the pattern shape is almost frequency independent over this range.

B. Monopole with a Series-Fed Square-Loop Insertion

In a series-fed square-loop insertion, shown in Fig. 1(b), the sides of the loop are about 0.25λ. The total length of the end section, including the wire from the loop to the monopole, is slightly longer than 0.25λ. The loop was 0.33λ above the ground plane. This antenna had an input impedance of 184.1 $-$ 5.5 ohms, not too different from that with the circular-loop
insert; the current distribution and radiation patterns were also similar, so they are not shown. A set of circularly polarized patterns was computed for this antenna in the $\theta$ plane for azimuth angles of 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, and 157.5°, and in the $\phi$ plane for zenith angles of 50°, 60°, and 70°. The measured circularly polarized patterns for a series-fed square-loop insertion having dimensions approximately equal to those computed, were made and once again the comparisons with the computed patterns are good. The radiation patterns were also measured over the frequency range from 1.4-2.0 GHz and found to be very similar to those for the series-fed circular-loop insertion.

C. Monopole with a Parallel-Fed Circular-Loop Insertion

With parallel-fed loop insertions a more directional pattern is obtained. The configuration shown in Fig. 1(c) has a loop circumference of about one wavelength; the loop is 0.15λ above the ground plane and the end section is 0.21λ. The computed input impedance of this antenna was $123 + j243$ ohms. The current distribution was more complex than that for the series-fed loop. The computed and measured circularly polarized patterns in the $\theta$ plane for azimuth angles of 0°, 45°, 90°, and 135° are shown in Figs. 7 and 8, respectively. It is seen that these patterns are almost identical and symmetrical. As for the previous antennas, the radiation patterns were reasonably constant over the frequency range from 1.4-2.0 GHz.

D. Monopole with a Parallel-Fed Square-Loop Insertion

The sides of the antenna, shown in Fig. 1(d), were about 0.25λ; the square loop was 0.2λ above the ground plane, and the end section was 0.25λ. The input impedance of this antenna was $482 - j306$. As before, the current distribution was more complex than that of the monopole with a series-fed loop. The circularly polarized radiation patterns for this antenna were computed and measured in the $\theta$ plane for azimuth angles of 0°, 45°, 90°, and 135°. As for the monopole with a parallel-fed circular loop this antenna is more directional.
than that with a series-fed loop. As before, the patterns did not change significantly over the frequency band from 1.4–2.0 GHz.

IV. CONCLUSION

It has been shown that circular polarization can be obtained from a monopole loaded with a loop antenna. Series-fed circular and square-loop insertions produced radiation patterns with omnidirectional coverage over most of the hemisphere; only in some directions did nulls begin to appear. The monopoles with parallel-fed circular and square-loop insertions were slightly more directional than those with the series-fed insertions. The radiation patterns were very symmetrical.

All loaded monopoles operated satisfactorily over the frequency band from 1.4–2.0 GHz. The agreement between computed and measured results was very good considering the computational model and the actual antenna were not exactly alike. Whereas this type of antenna can produce circular polarization over most of the hemisphere and over a broad bandwidth without the use of phasing networks, it may prove to be a very low cost alternative for systems such as IRIDIUM and the Global Positioning System. Finally, the null that is usually present over a limited range of azimuth angles may be useful for some applications. For example, there is concern that radiation from a handset held to one’s head may be dangerous. This antenna can easily be designed so that the null is in the direction of the head, thus minimizing the radiation in that direction.

ACKNOWLEDGMENT

The author would like to thank R. A. Wing for assisting in the measurements and S. Hollman for typing the manuscript.

REFERENCES


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