

A Monopole Antenna Loaded with a Modified Folded Dipole

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Abstract— A traveling-wave distribution of current can be produced on a linear antenna by inserting a resistance of suitable magnitude one-quarter wavelength from its end. In this paper the resistor is replaced with a modified folded dipole which has a radiation resistance approximately equal to that of the matching resistor. Thus the input section has a traveling wave distribution up to the inserted antenna, as before, but now the power that was previously dissipated in the resistor is also radiated. Input impedance, current distribution, and radiation patterns of this antenna are computed using the Numerical Electromagnetics Code (NEC). Input impedance and radiation patterns are also measured. Results are obtained for half lengths varying from 0.35 to 2.0 wavelengths at a frequency of 1.2 GHz.

Horizontally polarized patterns are similar to those of a horizontal dipole over a ground plane, and vertically polarized patterns in a plane orthogonal to the folded element are similar to those of a monopole over a ground plane. In addition, coverage is also obtained in the zenith direction in the plane of the folded element, as long as it is not an integral number of half wavelengths above the ground plane. The peaks and nulls can be controlled by adjusting the monopole height accordingly and it is possible to achieve near hemispherical coverage.

I. INTRODUCTION

A traveling-wave distribution of current can be produced on a linear antenna by inserting a resistance of approximately $240\ \Omega$ one-quarter wavelength from its end [1]. This antenna is very broadband and has much weaker mutual coupling than a conventional linear antenna [2]. Traveling-wave antennas also have directional properties that are useful for special applications (i.e., long beverage type antennas) [3]. 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 with a radiation resistance approximately equal the matching resistor. 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. The antenna replacing the resistor is a modified folded dipole. By adjusting the length of this folded element accordingly, a radiation resistance of about $240\ \Omega$ can be obtained. This traveling-wave antenna will not be as broadband as the resistive loaded antenna since the impedance of the folded element is more frequency sensitive than that of the resistor. Similar results may be obtained by using either a loaded dipole or a loaded monopole over a ground plane.

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The latter is used since the measurements can be carried out more easily. The input impedance, current distribution, and radiation patterns of this monopole over an infinite ground plane are computed using the Numerical Electromagnetics Code (NEC) [4]. Input impedance and radiation patterns are also measured. Results are obtained for half lengths varying from 0.35 wavelengths to 2.0 wavelengths at a frequency of 1.2 GHz.

II. THEORETICAL CONSIDERATIONS

A linear antenna with a suitable resistor one-quarter wavelength from its end has a traveling wave distribution of current to the resistor and a standing wave distribution of current from the resistor to the end. This is analogous to an open-ended transmission line that has a matched load placed in series with the line, one-quarter wave length from its end. As is the case for the transmission line, the input impedance of the traveling-wave monopole remains constant as a function of length, as long as the resistor is kept one-quarter wavelength from the end. If the resistor is replaced by a modified folded dipole, which has a radiation resistance comparable to that of the resistor, we have a new type of antenna which will also have a traveling wave distribution of current up to the folded element.

The modified folded dipole inserted in place of the resistor, has properties different from those of a conventional folded dipole. The conventional folded dipole is normally fed by a two-wire transmission line [5]. Both transmission line currents and antenna currents are excited; if the folded dipole is a approximately a half wavelength and short-circuited at both ends the transmission line currents are suppressed, and this antenna with its balanced and codirectional antenna currents behaves as a thick dipole. The modified folded dipole, on the other hand, is series fed by a single wire and has unbalanced currents and thus has directional properties that are somewhat different from those of the conventional folded dipole. The radiation pattern of the loaded monopole can be represented as a superposition of fields produced by currents on three radiating elements: the input section, the folded section, and the end section. The input section has a traveling-wave distribution of current which decays very slowly. The quarter-wavelength end section has a standing-wave distribution of current which has a magnitude that is approximately sinusoidal and decreases to zero at its end point. The folded section is more complex since it has unbalanced currents.

Consider the loaded antenna shown in Fig. 1. Five radiation pattern cuts describe the directional properties of this antenna. In the θ plane the E_θ pattern for the $\phi = 90^\circ$ cut is

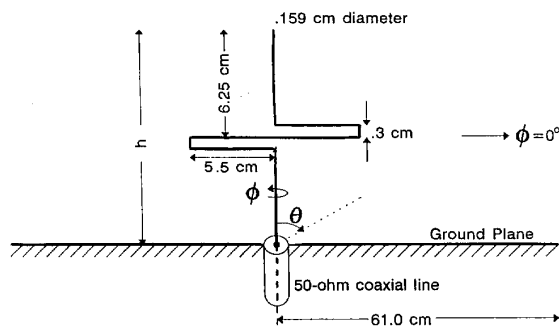


Fig. 1. Monopole antenna loaded with a modified folded dipole.

similar to that of a monopole over a ground plane, and the E_ϕ pattern is similar to that of a horizontal dipole over a ground plane. For the $\phi = 0^\circ$ cut the E_θ pattern is a superposition of contributions from both the vertical monopole and the horizontal folded element. In the ϕ plane the E_θ and E_ϕ patterns are once again similar to those of the vertical monopole and horizontal folded element over a ground plane respectively.

III. COMPUTATIONS AND MEASUREMENTS

The NEC is a computer code for calculating the electromagnetic response of antennas. Modeling a wire structure involves both geometrical and electrical factors. Each wire is divided into segments that are generally within the range from 0.01λ to 0.1λ ; shorter and longer segments should be avoided. The circumference of the wire is very small compared with the wavelength and the wires should not be too close together. For these computations, the wire had a circumference of about 0.02λ and the segments were typically 0.05λ in length. Using NEC it was possible to compute input impedance, current distribution on the wires, and radiation patterns of this antenna.

The measurements were made using an antenna constructed of 1.59-mm-diameter copper wire; spacing between the wires that made up the folded element was about 3 mm. The antenna was mounted over a $1.2\text{ m} \times 1.2\text{ m}$ ($4.8\lambda \times 4.8\lambda$) ground plane. All data were collected at a frequency of 1.2 GHz. Directional properties were measured in an indoor pattern range. The performance of this range was limited because of reflections from the absorbing material; thus some of the patterns have ripples which should not have been present.

A. Input Impedance

The input impedance of a traveling wave antenna should remain essentially constant as a function of monopole height. In order to determine optimum dimensions of the modified folded dipole inserted one-quarter wavelength from the end of the monopole, the input impedance of this antenna was computed as a function of height while the length and spacing of the folded element were varied. It was found that a folded element having a length of 11 cm (0.44λ) and a spacing of 3 mm (0.012λ) produced a reasonably constant input impedance as a function of monopole height, as is shown in Fig. 2,

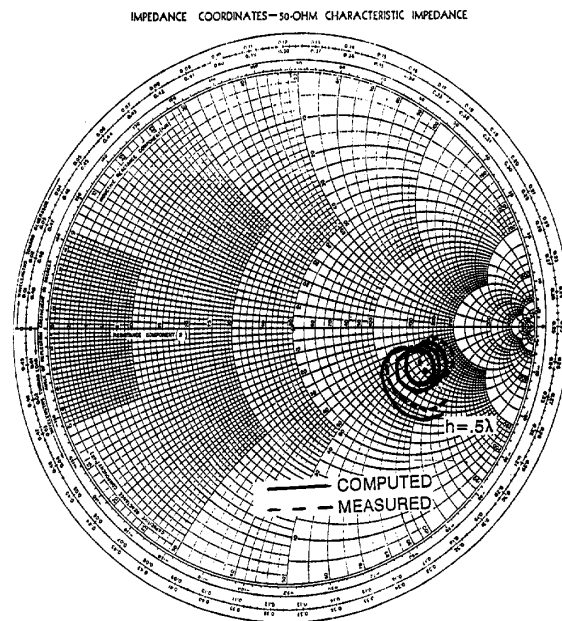


Fig. 2. Computed and measured input impedances of loaded monopole as a function of half length.

for heights from 0.5λ to 2.0λ . It is seen that the impedance shows more variability as the monopole becomes shorter. This divergence in impedance is due to mutual coupling effects between the folded element and its image. However as the height is continually increased, the input impedance of the folded monopole approaches a value of about $150 - j60\ \Omega$.

For comparison the impedances were also measured. First the input impedance of a monopole with a $240\ \Omega$ resistor inserted one-quarter wave length from its end point was measured as a function of half length at a frequency of 1.2 GHz. This impedance had an almost constant value of $163 - j54\ \Omega$ over the range from $0.5\lambda < h < 2.0\lambda$, thus indicating that the resistor produced an almost perfect matched load for the monopole. A modified folded dipole was then inserted in place of the resistor and the previous measurements were repeated. By using a sliding tubular section for the folded element it was possible to vary its length from 10 cm to 13 cm. As was the case for the computed input impedance it was found that a folded element length of about 11 cm (0.44λ) produced a set of input impedances, as a function of monopole height, which showed the least variability. This impedance plot is also shown in Fig. 2; it is in good agreement with the computed impedances. The fact that the input impedance is relatively constant as a function of half length is evidence that an approximate traveling wave distribution of current is present from the input of the monopole up to the folded element.

B. Current Distributions

Ideally the computed currents on the input section and end section of this antenna should be similar to those on the

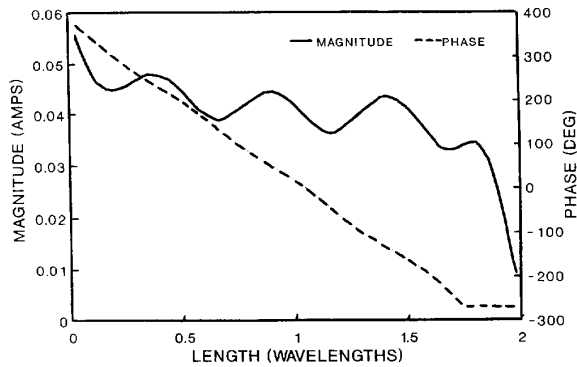


Fig. 3. Computed current distributions on resistive-loaded monopole, $h = 2\lambda$.

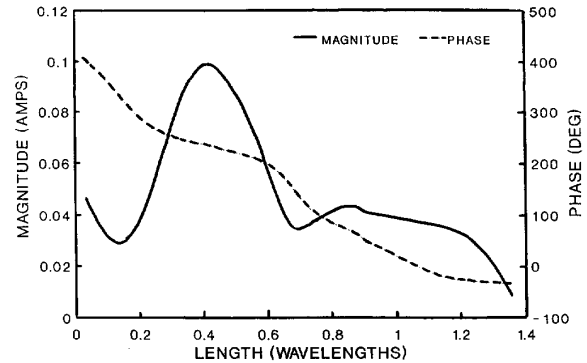
resistive-loaded monopole, which are shown in Fig. 3. Note the very linear behavior of the phase as a function of distance; the magnitude does, however, show some periodicity even though the resistance is nearly optimal. Current magnitude and phase distributions were also computed for half lengths from 0.35λ to 2.0λ . Examples of these distributions are shown in parts (a), (b), and (c) of Fig. 4 for half lengths of 0.5, 1.0 and 2.0 wavelengths respectively. The horizontal axis represents the distance along the monopole, starting from the input and including the folded section. Note that all monopoles have similar current distributions. The linear phase dependence on the input section is very apparent in Fig. 4(c), somewhat less apparent in Fig. 4(b), and not apparent at all in Fig. 4(a), primarily because the input section is so short. In all cases the current magnitude reaches a peak value near the end of the first section of the fold. The magnitude then decreases to a value on the last section of the fold that is comparable to that at the beginning of the first section. The phase distribution is between that of a traveling wave and a standing wave.

C. Radiation Patterns

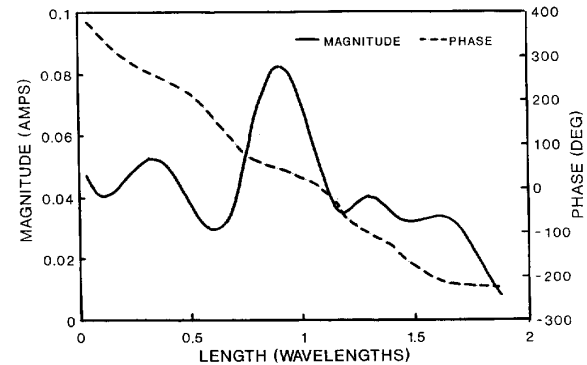
Radiation patterns described in Section II were computed and measured for antennas having half lengths from 0.375λ to 2.0λ . The results were found to be consistent with those predicted by theory. Since it was not possible to measure the absolute gain of this antenna, measured and computed patterns were normalized for a best fit. A discrepancy in the comparison of patterns arose because the measurements were made over a finite ground plane, whereas the patterns were computed for an infinite ground plane. As a result, the vertically polarized computed patterns often had maximum values in the direction of $\theta = \pm 90^\circ$, while the peak values for the measured patterns were generally at zenith angles less than about 65° . However, even with these limitations, the agreement between measured and computed patterns was excellent.

1) E_θ Component:

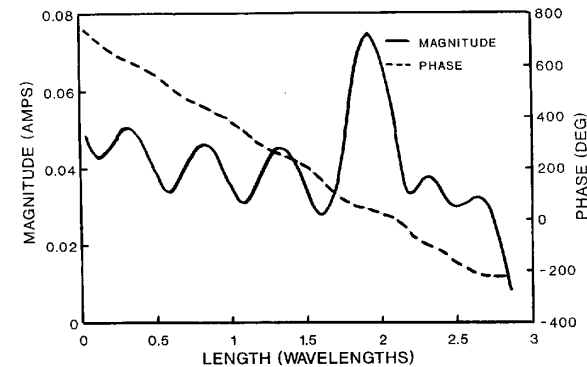
a) $\theta = 90^\circ$; $0^\circ < \phi < 180^\circ$: This radiation pattern has the omnidirectional property typical of a conventional monopole. Representative computed and measured patterns are shown in Fig. 5 for a half length of 0.5λ . The effects of range reflections are clearly seen in the measured radiation



(a)



(b)



(c)

Fig. 4. Computed currents distributions on loaded monopole: (a) $h = 0.5\lambda$; (b) $h = 1.0\lambda$; (c) $h = 2.0\lambda$.

pattern. Whereas the computed pattern is smooth with a slight asymmetry, the ripples in the measured pattern mask this behavior. However, it is evident that the contributions from the short end segments of the folded element are very small, which is an important finding. For longer monopoles, the patterns remain essentially omnidirectional; the asymmetry does, however, change direction as the height of the folded element above the ground plane is changed.

b) $\phi = 90^\circ$; $-90^\circ < \theta < 90^\circ$: This radiation pattern is also similar to that of a monopole. Typical computed and

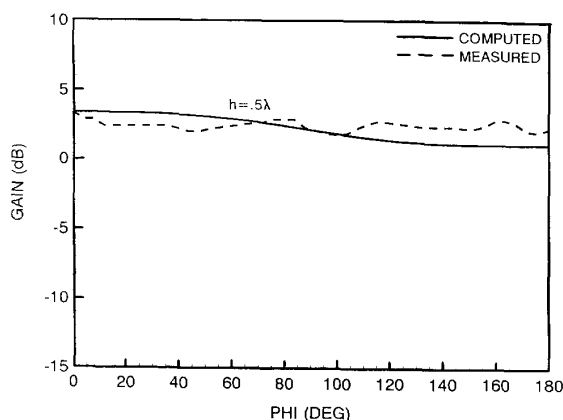


Fig. 5. Computed and measured E_θ component radiation patterns of loaded monopole, $\theta = 90^\circ$, $0^\circ < \phi < 180^\circ$, $h = 0.5\lambda$.

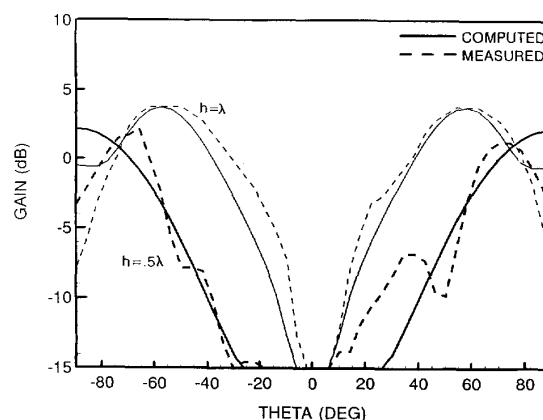


Fig. 6. Computed and measured E_θ component radiation patterns of loaded monopole, $\phi = 90^\circ$, $-90^\circ < \theta < 90^\circ$, $h = 0.5\lambda, 1.0\lambda$.

measured patterns for half lengths of 0.5 and 1.0λ are shown in Fig. 6. These patterns are symmetrical since the $\phi = 90^\circ$ cut is in a neutral plane with regard to the short segments of the folded element. Aside from the discrepancies noted earlier, the agreement between measured and computed results is very good.

c) $\phi = 0^\circ$; $-90^\circ < \theta < 90^\circ$: This set of patterns is by far the most complex and the most interesting since it has contributions from all elements of the antenna; in addition it is significantly affected by the distance of the folded element above the ground plane.

The characteristics of these radiation patterns are best illustrated by observing the systematic change in the patterns as the monopole half length is increased, as is shown in parts (a)–(d) of Fig. 7. For $h = 0.375\lambda$ the pattern is almost omnidirectional. As the monopole height is increased the pattern becomes less symmetrical and a null appears at an angle of $\theta = 58^\circ$. When the monopole has a height of 0.75λ an additional null appears near $\theta = 0^\circ$. This null is not exactly at 0° because the lower and upper sections of the folded element are not exactly 0.5λ above the ground plane; thus the image currents do not completely cancel out the unbalanced currents on these elements and an asymmetrical pattern results. As the height is further increased the pattern tends to become omnidirectional once again and for a half length of 1.0λ nulls begin to appear at angles of $\theta = 34^\circ$ and 80° . If the half length is further increased these nulls deepen and a third null appears near $\theta = 0^\circ$. Still longer monopoles have multilobed patterns similar to those of a traveling-wave monopole. Note the excellent agreement between the measured and computed results, even though the directional properties are very asymmetrical. Utilizing a computer code to obtain the radiation pattern of an antenna is often risky. These results showed that NEC can be used with confidence for this type antenna.

2) E_θ Component:

a) $\phi = 90^\circ$; $-90^\circ < \theta < 90^\circ$: This set of patterns is similar to that of a horizontal dipole over a ground plane since it is only the folded element that is radiating. Typical

patterns are shown in Fig. 8 for half lengths of 0.5 , 0.75 , and 1.0λ respectively. For $h = 0.5\lambda$ the pattern is almost omnidirectional, as is expected. When $h = 0.75\lambda$ the folded element is one-half wavelength above the ground plane and a null appears at $\theta = 0^\circ$. Once again the fact that the upper and lower segments of the folded element are not exactly a half wavelength above the ground plane prevents the null from being deeper.

As the height of the monopole is further increased, the pattern becomes multilobed, consistent with that of a two-element array with widely spaced elements. For these particular cuts the agreement between measured and computed results is almost perfect.

b) $\theta = 70^\circ$; $0^\circ < \phi < 180^\circ$: Since the E_ϕ field approaches zero as θ approaches 90° , this field must be computed and measured for an angle less than 90° . Patterns for a $\theta = 70^\circ$ cut are shown in Fig. 9 for a half length of 0.5λ . For longer folded monopoles the directional properties remain the same; however the magnitude changes because of the multilobed behavior in the θ plane.

IV. CONCLUSIONS

It has been shown that by inserting a modified folded dipole one-quarter wavelength from the end of a monopole it is possible to produce a traveling wave distribution of current on the monopole, up to the folded element. Input impedances, current distributions, and radiation patterns were computed for this antenna as a function of half length; input impedances and radiation patterns were also measured and were found to be in good agreement with the computed results. In general, the E_ϕ patterns are similar to those of a horizontal dipole over a ground plane, and the E_θ patterns in a plane orthogonal to the folded element are similar to those of a monopole over a ground plane. In addition, we also obtain coverage in the zenith direction in the $\phi = 0^\circ$ plane from the folded element, as long as it is not an integral number of half wavelengths above the ground plane. We also note that we can control peaks and nulls in this pattern by adjusting the monopole height accordingly and that it is possible to approach near hemispherical coverage.

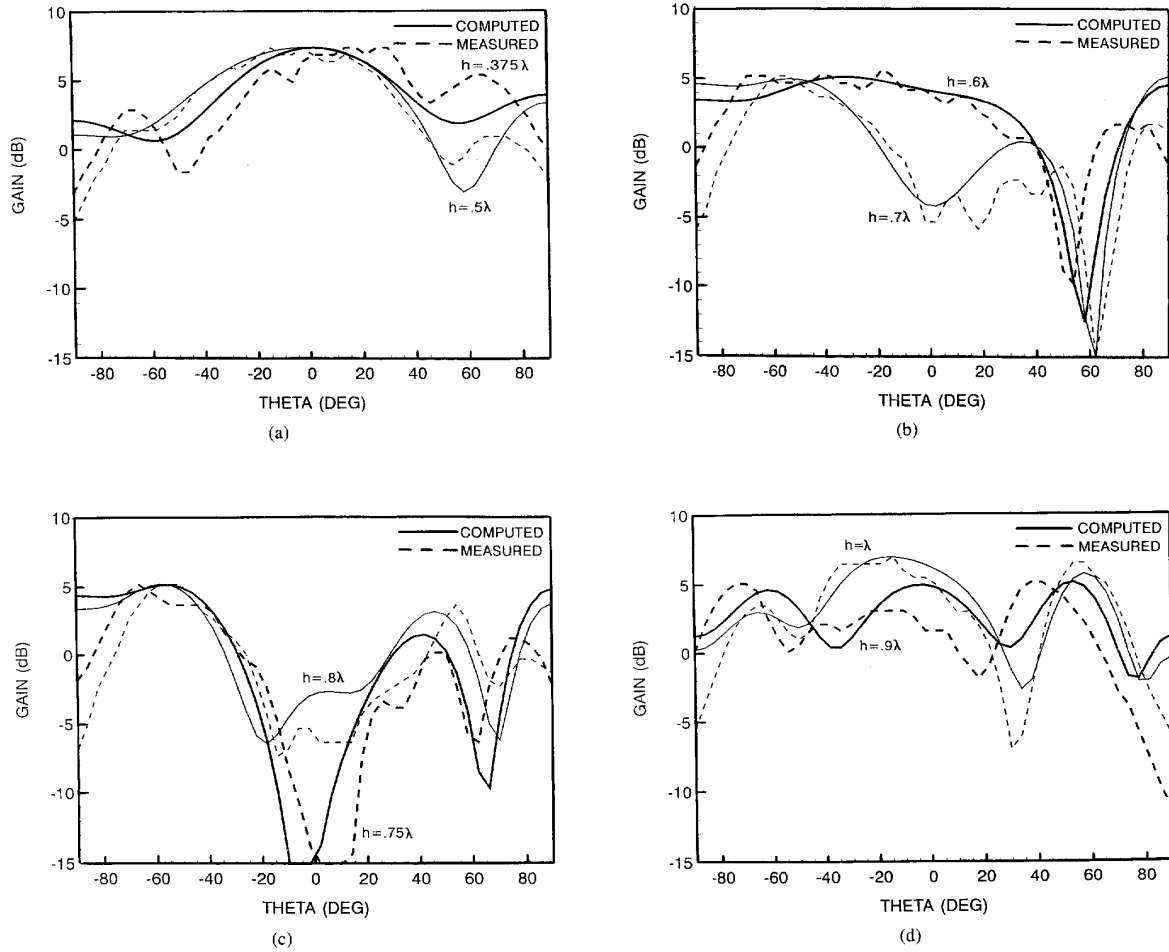


Fig. 7. Computed and measured E_θ component radiation patterns of loaded monopole, $\phi = 0^\circ$, $-90^\circ < \theta < 90^\circ$: (a) $h = 0.375\lambda$, 0.5λ ; (b) $h = 0.6\lambda$, 0.7λ ; (c) $h = 0.75\lambda$, 0.8λ ; (d) $h = 0.9\lambda$, 1.0λ .

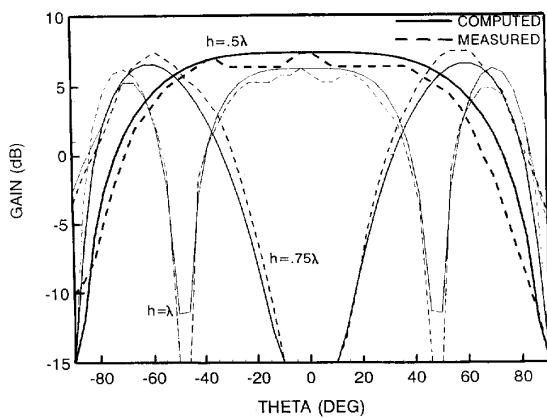


Fig. 8. Computed and measured E_ϕ component radiation patterns of loaded monopole, $\phi = 90^\circ$, $-90^\circ < \theta < 90^\circ$, $h = 0.5\lambda$, 0.75λ , 1.0λ .

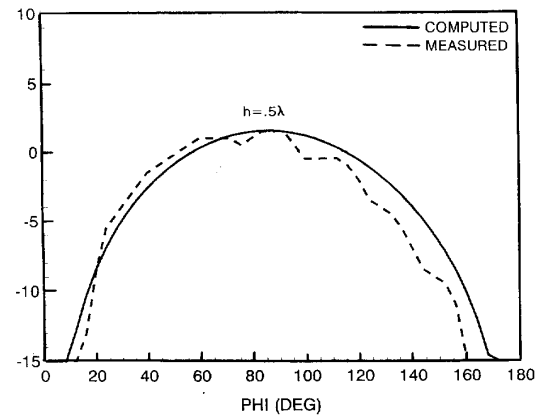


Fig. 9. Computed and measured E_ϕ radiation patterns of loaded monopole, $\theta = 70^\circ$, $0^\circ < \phi < 180^\circ$, $h = 0.5\lambda$.

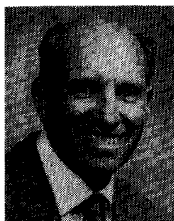
In this paper we have presented only preliminary results of this new type of antenna. Other types of inserted antenna elements are also being investigated.

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REFERENCES

- [1] E. E. Altshuler, "The traveling-wave linear antenna," *IRE Trans. Antennas Propagat.*, vol. 9, pp. 324-329, July 1961.
- [2] E. E. Altshuler, "Self- and mutual impedances of traveling-wave linear antennas," *IEEE Trans. Antennas Propagat.*, vol. 37, pp. 1312-1316, Oct. 1989.
- [3] R. W. P. King, "The wave antenna for transmission and reception," *IEEE Trans. Antennas Propagat.*, vol. 31, pp. 956-965, Nov. 1983.
- [4] G. J. Burke and A. J. Poggio, "Numerical Electromagnetics Code (NEC)—Method of Moments," Rep. UCID18834, Lawrence Livermore Lab. CA, Jan. 1981.
- [5] R. W. P. King, *The Theory of Linear Antennas*. Cambridge, MA: Harvard University Press, 1956.



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