A NEW CLASS OF COPHASAL ANTENNA ARRAYS WITH SIMPLE COMPACT FEEDS

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Abstract – *To reduce the number of driven elements in a broadside colinear antenna array, in narrowband applications COCO (coaxial colinear) antennas have been used since relatively recently, either as isolated elements, or as parts of antenna arrays. COCO antennas have a single actual port, but the driving voltage is transmitted to several other ports via transposed segments of a coaxial cable of which the antenna is made, resulting in approximately cophasal currents along the COCO antenna segments. This paper is aimed at demonstrating that COCO antennas are a special case of a new wide class of one-port, multiply-excited antennas ("OPOMEX" antennas), which can be in a variety of forms, including printed versions. The design of OPOMEX antennas is significantly more flexible than that of COCO antennas, since they have more parameters that in practical realizations can be varied easily. The paper describes two approximate methods for the analysis of OPOMEX antennas, and presents numerical and experimental results for a number of such printed-strip antennas. Numerical results are found to be in reasonable agreement with experiment.*

1. INTRODUCTION

For a vertical rod antenna, it is frequently of interest to increase the antenna gain in the horizontal plane. This can be done by making a colinear array of vertical dipoles driven in phase. Not infrequently, narrowband operation only is required for such arrays. For example, wind-profiling low-frequency radars (UHF range) operate in such a narrow frequency band. There are numerous other applications where smaller or larger linear arrays are needed for essentially single-frequency operation. To simplify the feed system, in such cases coaxial colinear (COCO) antennas have sometimes been used. The basic COCO-antenna element consists of transposed sections of a coaxial line and is excited at a single point. COCO antennas have been used both as single elements (Wheeler, 1956; Balsley and Ecklund, 1972; Judasz *et al.*, 1987; Judasz and Balsley, 1989), and as elements in large linear-antenna arrays (Ochs, 1965; Balsley *et al.*, 1980). The interest for these inherently narrowband antennas has been increasing, so that commercial whip COCO antennas have been available for some time (Sinclair Radio Labs).

The paper first discusses briefly the physical basis of operation of COCO antennas. It next proposes a new class of antennas, which have similar properties as COCO antennas, but are much more flexible and can be of diverse forms, including printed versions. Since such antennas are excited at a single port, but behave as

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if excited at a number of ports, the acronym "OPOMEX" (One-POrt-Multiply-EXcited) antennas seems appropriate.

Many forms of OPOMEX antennas are possible. Some forms need wires or strips of widely differing radii, namely widths, but some can be produced even of a single-gauge wire. A number of forms of OPOMEX antennas, including narrow-strip versions, possibly printed on a thin dielectric substrate, can be analysed approximately by wire-antenna computer programs, e.g. *WireZeus* (Popović, 1991). One such printed form is considered in the paper in more detail, and parallel results for this type of OPOMEX antenna and the corresponding COCO antenna are presented. The results show that the properties of this simple form of OPOMEX antennas are quite similar to those of a COCO antenna, which, however, cannot be produced in a printed version.

The paper presents also numerical and experimental results for a number of strip and printed-strip OPOMEX antennas. It is shown that OPOMEX antennas can have properties which cannot be achieved with COCO antennas. For example, numerical optimum of sidelobe levels for a 2 × 5 element free-space COCO antenna appears to be at the most −14 dB. A 2 × 5 element OPOMEX antenna is described in the paper, obtained by numerical optimization, for which all sidelobes are suppressed for more than −25 dB. As another example, it is possible to design OPOMEX antennas having very high and approximately real impedance (over 1 kΩ), which does not appear possible with COCO antennas. Such high values of impedances are of interest when feeding in parallel several OPOMEX antennas.

2. PHYSICAL BASIS OF OPERATION OF OPOMEX ANTENNAS

Consider first the classical COCO antenna. It consists of a sequence of colinear, closely spaced coaxial-line segments. The inner and outer conductors from one segment to the next are transposed, as in Fig.1. The inner conductor of the last segment is connected with the outer line conductor at a distance of about a quarter-wavelength (along the line) from the interconnection with the preceding segment. The last "port" then sees an open circuit in that direction. If the lengths of the segments are approximately half a wavelength along the line, this high impedance as seen by the line towards the ends of the antenna arms will be transmitted to the generator. As seen from Fig.1, all the secondary "ports" between adjacent segments of the antenna then have a voltage of amplitude and phase (with respect to the indicated reference direction) close to the antenna driving voltage. Approximately cophasal current distribution along the outer surface of the coaxial segments (the antenna radiating current) should therefore be expected. Of course, the same effect can be obtained if the last segment is half a wavelength long (along the line), and open-circuited.

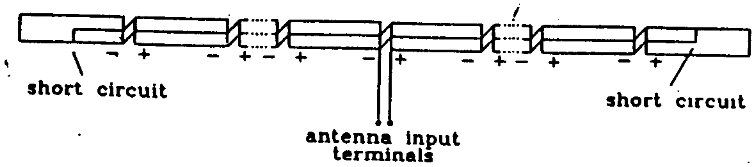


FIGURE 1. Sketch of a symmetrical COCO antenna.

Referring to Fig.1, let us ask a simple question: why a COCO antenna radiates at all? For, it consists, in fact, of two antennas, one within the other (the inner and outer coaxial-line conductor), connected to the same source in such a way that the currents in them are practically equal and opposite (see Fig.1). Transposition of the coaxial-line conductors at certain intervals does not change the propagation along the line. It is intended to produce proper voltages across the gaps between adjacent line segments.

It is a simple matter to conclude that, if the characteristic impedance of the coaxial-line sections were made to approach zero (i.e., the radius of the inner conductor to approach that of the outer conductor), the COCO antenna would not radiate any more. This indicates that the COCO antenna radiates because the two parallel antennas which make it have different current magnitudes at the input COCO antenna port, as a result of different radii (and thus impedances) of these two antennas at that port (see Fig.1).

Consequently, antennas of the form shown in Fig.2(a) and Fig.2(b), made of close segments of wires of different radii, should have properties similar to those of a COCO antenna. Indeed, the antenna in Fig.2(a) can be considered as obtained from that in Fig.1 by "pulling out" the inner line conductors and putting them outside the outer conductors, parallel to them. Voltages will therefore appear between the two thicker (and two thinner) conductors at places where the "inverse connections" are made. The antenna will behave as if excited not only by the actual generator, but also by concentrated voltage generators at these points of "inverse connections", as in the case of the classical COCO antennas.

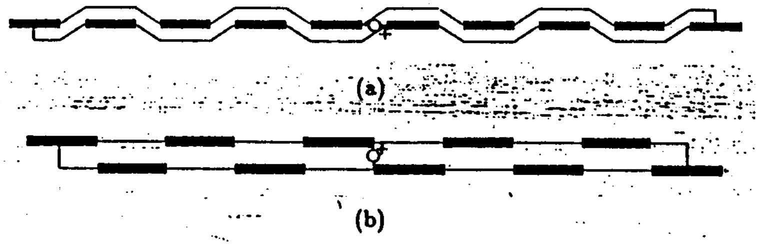


FIGURE 2. Two possible forms of the OPOMEX antenna. Both forms (a) and (b) are constructed of segments of two-wire lines with conductors of different radii or with strips of different widths.

This is quite an unexpected conclusion. It means that the OPOMEX antennas can be constructed in a multitude of forms, which only must comply with the general philosophy mentioned. For example, another antenna of this type, constructed entirely of the same wire, is sketched in Fig.3. The antennas sketched in Fig.2 and Fig.3 can be analyzed approximately by means of computer programs for the analysis of wire-antennas. *WireZeus* has been extended to handle automatically both the analysis of COCO antennas and the two forms of OPOMEX antennas sketched in Fig.2(a) and Fig.2(b).

With the OPOMEX antennas we have a number of relatively easily adjustable parameters. For example, if the conductors in Fig.2 or Fig.3 are wires, there is a wide range of available wire radii, and we can choose the distance between them in a relatively wide range. Further, the OPOMEX-antenna conductors need not be

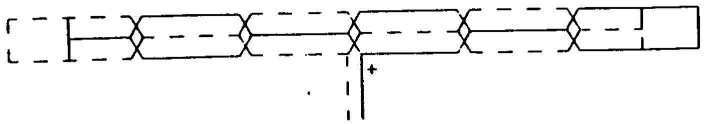


FIGURE 3. Another possible form of the OPOMEX antenna. The antenna is constructed of wire segments of the same radius. The planes of the two antenna parts (indicated in solid and in dashed lines) are separated for a small distance.

round wires. For example, one conductor may be tubular (of any cross-section, not necessarily circular), and the other a thin wire running parallel to the tube, outside it or inside it. If placed inside the tube, it need not run along the tube axis, as it does in COCO antennas. The two conductors may also be strips of different width, which is very simple to obtain. The strips can be glued onto a styrofoam support, on the same side or on the opposite support sides. In that case the propagation coefficient of the equivalent line will be very nearly as that for air. Alternatively, they can be printed on a thin dielectric substrate, in which case the propagation coefficient may also be a parameter. The strips can be printed on the same side, or on the opposite sides, of the substrate; in the latter case, the strips need not be staggered, but may be one above the other. Many other forms of the OPOMEX antennas with associated easily adjustable parameters can be imagined. Of course, any antenna of this wide family can be enclosed by a tubular radome.

3. METHODS FOR ANALYSIS OF OPOMEX ANTENNAS

In principle, OPOMEX antennas of the form shown in Figs.2 and 3 can be analysed as wire structures. However, one should be aware of the fact that most wire-antenna analysis programs, including *WireZeus*, assume uniform current distribution around wire circumference. For OPOMEX antennas this certainly is not true, since the thick and thin wire of any OPOMEX segment are quite close (axis-to-axis distance on the order of the diameter of the thick wire). In addition, we have interconnections of wires with greatly differing radii, which is extremely difficult to take into account accurately. Finally, radius of the short segment with the generator influences significantly the antenna susceptance, i.e., its. impedance. Consequently, although such programs can be used for approximate analysis of OPOMEX antennas, one cannot expect very accurate results, in particular for the antenna impedance.

On the other hand, we can reason as follows. The thick and thin wire make an (asymmetrical) transmission line. Both in Fig.2 and Fig.3 we can consider the points of the wire transposition as additional ports, with unknown voltages. We can next use the principle of superposition. Let one component of the current in thick wires be equal to the current in the adjacent thin wire, but in the opposite direction. The other component is the difference of the total current in thick wires and the first component. Since the first component is a transmission-line current, and the line conductors are very close, it practically does not radiate. Therefore the second component is the actual radiating current.

The transmission-line component of current exists in a line of characteristic impedance which for round wires can be calculated easily. Note that the transposition of the conductors has no effect on the propagation along the line. Note also that

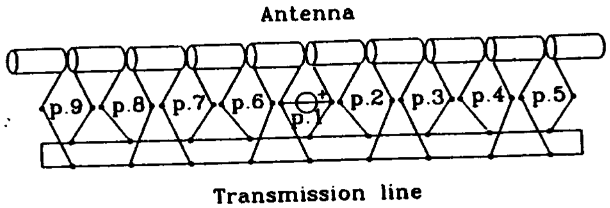


FIGURE 4. The OPOMEX antenna represented as a parallel connection of two multiport networks, with common ports p.1, p.2,..., p.7 in the case shown. If this combination is considered as an equivalent multiport network, all ports of the equivalent network except port 1 are open circuited.

the (unknown) voltages at the additional ports are connected between the antenna segments (i.e., thick-wire segments) on one hand, and between the line conductors on the other hand. This is sketched in Fig.4. The transmission-line assembly and the antenna assembly of generalized OPOMEX antennas can be considered as two multiport networks connected in parallel. This parallel connection can, it turn, be considered as an equivalent multiport network. It is evident from Fig.4 that in the ports of the equivalent network there is current only in the actual port (labeled 1), while the other (additional) ports of the equivalent multiport network are open circuited.

Based on this reasoning, it is possible to develop another approximate method for the analysis of OPOMEX antennas (which can also be used for the analysis of COCO antennas). Briefly, the currents at the transmission-line multiport-network assembly can be represented as

$$[I_{\text{line}}] = [Y_{\text{line}}][V]. \tag{1}$$

In this equation, the $n \times n$ admittance matrix $[Y_{\text{line}}]$ (n is the number of ports) is the transmission-line admittance matrix. The elements of this matrix can be calculated with relative ease from the transmission-line equations. The left-hand side of the equation is an one-column matrix of currents at the transmission-line n ports, and $[V]$ is the matrix of voltages at these ports.

The currents at the ports of the antenna-multiport network can likewise be expressed as

$$[I_{\text{antenna}}] = [Y_{\text{antenna}}][V]. \tag{2}$$

The matrix of the antenna-multiport network, $[Y_{\text{antenna}}]$, can be obtained only numerically, and requires full numerical analysis of the antenna. The evaluation of $[Y_{\text{antenna}}]$ can, however, be incorporated in any wire-antenna analysis program, as has been done in *WireZeus*.

Referring to Fig.4, the current in the generator is obtained from the matrix equation

$$[I] = ([Y_{\text{line}}] + [Y_{\text{antenna}}])[V]. \tag{3}$$

The sum of two admittance matrices represents the admittance matrix of the multiport network obtained as the parallel connection of the transmission-line and the antenna multiport networks. As explained, all ports except port 1 of this equivalent multiport network are open-circuited, so that all the elements of the column matrix $[I]$ are zero except the first, I_1. We can assume any current I_1 in port 1, and solve for voltages $V_1, V_2, \ldots, V_n$. The OPOMEX-antenna impedance is then obtained as

$$Z_{\mathrm{OPOMEX}} = \frac{V_1}{I_1}. \tag{4}$$

Note that this impedance is, in fact, the impedance of the antenna proper and the transmission-line assembly connected in parallel. *This is, however, the impedance observed by the generator.*

Knowing the relative port voltages, we actually know the voltages which drive the antenna proper. We can assume any voltage at the input antenna port, scale the other voltages accordingly, calculate the antenna current distribution, and hence the antenna radiation field. Note that the impedance of the antenna proper so calculated is *not* the impedance of the OPOMEX antenna in eq.(4).

The only remaining problem is the determination of the antenna-assembly equivalent radius. It is not difficult to conclude that, by decomposing the total current into the transmission-line current and the antenna current, we were left with the thick-wire assembly as the antenna. Therefore, the equivalent radius of the antenna should be taken to be the radius of the thick wire.

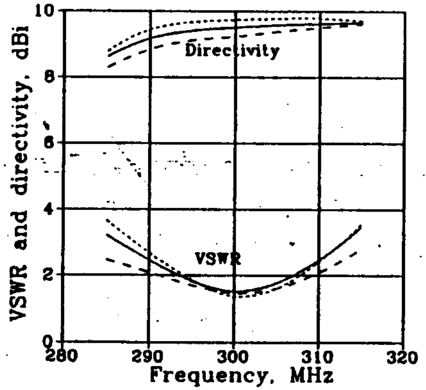


FIGURE 5. Directivity and VSWR (with respect to 200 Ω), of the 300 MHz OPOMEX antenna described in the text, obtained by the direct method (solid lines) and by the multiport-network method (dashed lines). Also shown are directivity and VSWR (with respect to 50 Ω) for approximately equivalent COCO antenna, made of commercial coaxial-line segments and described in Subsection 4.2 (dotted lines).

Finally, let us make a qualitative comparison between the two proposed methods for the analysis of OPOMEX antennas. Note that the excitation zone in the two models is quite different. In the direct method (direct use of *WireZeus*), a delta-function generator is connected at the starting point of a short segment of the *thin* wire. This segment, in turn, is connected in a complex way to the adjacent thin and thick antenna segments. In the multiport-network approach, the antenna proper is excited between two thick wire segments by a delta-function generator.

The excitation mechanisms being so different, we cannot expect good agreement in the antenna impedance obtained by the two methods. We can expect, however, relatively good agreement of the radiation patterns. We can also expect that both methods should predict the antenna operating frequency with reasonable accuracy.

4. NUMERICAL AND EXPERIMENTAL RESULTS

4.1. Comparison of Two Analysis Methods

To check the difference in the results for the two methods for the analysis of OPOMEX antennas, an antenna of the form shown in Fig.2(b) was analysed by *WireZeus* using both methods. The antenna had 2 × 5 segments, radius of the thick wire was 0.9 cm, and of the thin wire 0.5 mm, with the distance between the wire axes 2 cm. The characteristic impedance of the two-wire-line segments was about 255 Ω. The design aim was to obtain an antenna for 300 MHz with a high gain in the transverse direction, but simultaneously well matched to 200 Ω.

Interactive optimization was used, and the segment lengths (including that of the last, short-circuited line segment) were the parameters. The optimal antennas obtained by the two methods were of somewhat different sizes. The direct method (analysis by means of *WireZeus*) resulted in first four segment lengths of 48.5 cm, the length of the last segment 42 cm and the length of the short-circuited line segment 20 cm. The indirect method (the use of multiport-network approach) resulted in these segment lengths of 45 cm, 45 cm and 24 cm, respectively. Note that the characteristic impedance of the line was 255 Ω, which in no circumstances can be obtained with a coaxial line. The results are summarized in Fig.5. It is seen that the two antennas have similar VSWR's and gains. This indicates that both methods should be used in the CAD of OPOMEX antennas, to get an insight into possible errors in both methods.

Radiation pattern of the OPOMEX antenna obtained by the direct analysis method is shown in Fig.6. Note that the second sidelobe is about −13 dB below the main lobe.

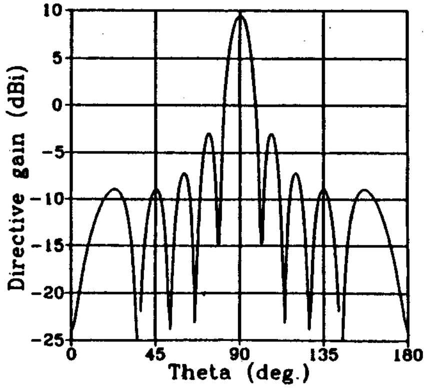


FIGURE 6. Radiation pattern in the plane containing the long axis of the 300 MHz OPOMEX antenna described in the text, calculated by the direct analysis method.

4.2. Comparison of OPOMEX and COCO Antenna

It was of considerable interest to compare the results of the preceding example with those for a true COCO antenna (made of sections of a realistic coaxial line). Note that the results of the multiport-network method in the preceding example correspond to those for a COCO antenna made of line segments with a characteristic impedance $Z_c = 255\ \Omega$ situated in air. This can, in principle, be also a coaxial line. However, such a high characteristic impedance is obtained for the ratio of radii of outer and inner coaxial-line conductor of about 70, which is not commercially available and is quite difficult to realize.

The idea was to design a COCO antenna made of sections of an available coaxial line. Therefore the following coaxial-line parameters were adopted: $Z_c = 75\ \Omega$, $v/c = 0.67$, and the line attenuation constant $\alpha = 0.03\,\text{dB/m}$.

Naturally, since the wavelength along this coaxial line is only 0.67 that in free space (assumed in the preceding example), to obtain approximately the same gain it was necessary to adopt the length of COCO to be about the same as before, i.e. about $2 \times 5 \times 45 = 450\,\text{cm}$. Therefore the COCO antenna was adopted with 2×7 segments, each 33.5 cm long (i.e., half a wavelength along the line at 300 MHz), making a total length of 469 cm. The length of the short-circuited line segments was adopted to be half this length (16.7 cm).

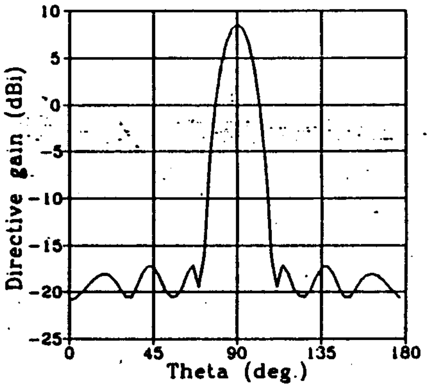


FIGURE 7. Directive gain of the 3 GHz printed OPOMEX antenna optimized for low sidelobe levels, calculated by direct method.

The computed VSWR (with respect to 50 Ω) and gain of this antenna are shown in Fig.5 in dotted lines. It is seen that this approximately equivalent COCO antenna has very nearly the same properties as the OPOMEX antenna. This conclusion was found to be true in many other cases of parallel analysis of COCO and OPOMEX antennas. However, OPOMEX antennas not only can be made of lines having a high characteristic impedance, but this impedance can also be varied very easily if desired. For example, this is a valuable tool for controlling sidelobe levels, as the next example will demonstrate.

4.3. OPOMEX Antenna with Minimized Sidelobes

As explained, the OPOMEX antenna in Fig.2(a) and (b) will practically not radiate if made of conductors of the same radius; a difference in radii of the line conductors is essential for the OPOMEX-antenna operation. One can expect, therefore, that the antenna current component along the OPOMEX antenna can be tapered if the difference in the conductor radii (or in strip widths) is decreased towards the antenna ends. The following numerical example will show theoretically that this is indeed true. In Subsection 4.5 a fabricated printed OPOMEX antenna of this type will be described and it will be shown that the measured results also confirm this reasoning.

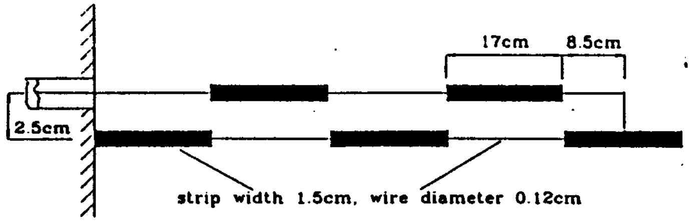


FIGURE 8. Sketch of half of the OPOMEX antenna in Fig.2(b), mounted on a ground plane.

A printed antenna for 3 GHz was considered using the direct method, with the aim to design an antenna with minimized sidelobes. The array shown in Fig.2(b) can also be considered to be made of strips printed on a thin dielectric substrate. This type of the OPOMEX printed antenna was optimized interactively using *WireZeus*, in order to obtain the best possible match (possibly with added matching network) and as low sidelobes as possible. The antenna was assumed to be printed on a 0.508 mm substrate with $\epsilon_r = 2.17$, having 2×5 sections. The distance of the axes of the printed strips was adopted to be 5 mm, and their length (except that of the last segment) 44 mm. The distance of the short circuit from the last interconnection was 22.2 mm, and the distance from the short circuit to the array end 24 mm. The width of all the narrow strips (including that with the generator) was 0.3 mm. The optimization of the widths of the wider strips, counted from the generator away, resulted in widths of 3 mm, 2.8 mm, 2.3 mm, 1.5 mm and 0.5 mm. The antenna matching network was simultaneously optimized, with the aim that at 3 GHz the antenna is well matched to 50 Ω.

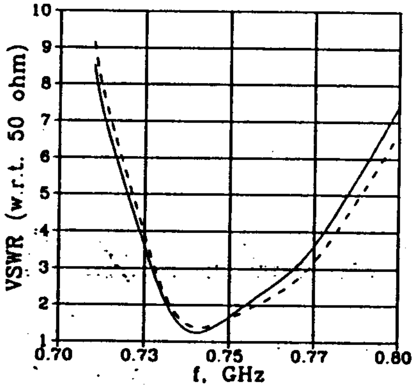
The optimized antenna radiation pattern in the plain containing the long antenna axis is shown in Fig.7. Compare the sidelobe levels in Figs.6 and 7. The sidelobes in Fig.7 are for more than −25 dB below the main beam, while in Fig.6 they are only for about −13 dB below the main beam. Note that the latter result corresponds approximately to that for the classical COCO antenna, where it is practically impossible to suppress the sidelobes for more than about −14 dB.

The compensated optimal antenna VSWR was about 1.14 at 3 GHz, and below 2.2 in the frequency range (3.00 ± 0.02) GHz.

4.4. A Quasi OPOMEX Strip-Antenna

In order to check accuracy of the direct method, half of the OPOMEX antenna shown in Fig.2(b) was manufactured from thin wires and thin metal rectangles. It was supported by a styrofoam support, and the thin-wire conductor was connected to the inner coaxial line conductor protruding through the ground plane. The structure is sketched in Fig.8, with indicated dimensions. Note that this is not an OPOMEX antenna, since the image of the wide conductor in the ground plane is also a wide (instead of a narrow) conductor, and the image of the thin conductor is also a thin (instead of a wide) conductor. However, this configuration enable measurement of the impedance for a structure which is very similar to the OPOMEX antenna.

Fig.9 shows theoretical and measured VSWR of the antenna, with respect to 50 Ω. The theoretical results were obtained using the direct method, and were corrected for estimated difference in capacitance between the generator model (delta-unction generator), and the actual N-connector used in measurements. Good agreement of the two sets of results can be observed.



IGURE 9. Experimental (solid) and theoretical (dashed) VSWR, with respect to 0 Ω, of the antenna sketched in Fig.8, versus frequency.

.5. Printed OPOMEX Antenna

3 GHz antenna of the form shown in Fig.2(b), with the number of segments nd their lengths as described in Subsection 4.3, was fabricated on a substrate of ickness $t = 0.508$ mm and relative permittivity $\epsilon_r = 2.17$ (produced by "Arlon"). ue to lack of precision of the etching means available, the minimum strip width hich could be obtained was about 0.7 mm. Therefore the strip widths differed om those in Subsection 4.3. The thin strip width was about 0.7 mm (instead of 3 mm), and the widths of the wider strips, from the feeding point towards the ntenna arm ends, were 4.0 mm, 3.0 mm, 2.5 mm and 1.0 mm, respectively (instead 3.0 mm, 2.8 mm, 2.3 mm, 1.5 mm and 0.5 mm, respectively). The antenna was atched to the 50 Ω feeder by a 200 Ω two-wire line matching section (approximately required by the matching-network design in *WireZeus*), and a coaxial balun. Note

that, although the difference in desired and actual strip widths was relatively large, the strip-width tapering rate in the two cases was kept relatively close.

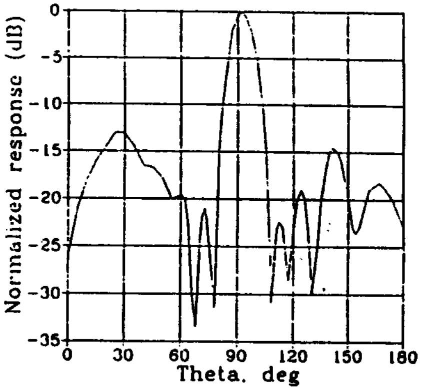


FIGURE 10. Normalized measured copolar power pattern of the experimental 3 GHz printed OPOMEX antenna described in the text.

Fig.10 shows the normalized measured antenna copolar power pattern (the crosspolar pattern for all angles was at the most −16 dB with respect to the main lobe). Note the suppression of the first sidelobe for about −21 dB, in spite of relatively crude experimental model when compared with the mathematical model (different printed-strip widths). The measurements were performed in a small anechoic chamber of the University of Colorado at Boulder.

Finally, Fig.11 shows the measured reflection coefficient of the antenna with its matching network. Note excellent match of the antenna to 50 Ω at about 2.92 GHz (the reflection coefficient is only −31 dB). Theoretically, it should have the reflection coefficient of 0.064 (i.e., −24 dB) at 3.0 GHz. The difference in frequency is hence very small (less than three per cent).

5. CONCLUSIONS

The paper describes a new class of antennas, having a single port, but behaving as if excited at a number of ports. This is achieved by making the antenna arms in the form of segments of asymmetrical two-conductor lines, with exchanged places of the conductors at certain (regular or irregular) intervals. So-called coaxial colinear (COCO) antenna is a special case of this new antenna class. Since these antennas are one port, but multiply excited, the acronym 'OPOMEX' seemed appropriate.

The OPOMEX antennas are much more flexible than COCO antennas, which have been made only of segments of coaxial lines. In contrast, the OPOMEX antennas can be made in a wide variety of forms, using segments of any two-conductor transmission line with conductors of different equivalent electrical radii. For example, a strip line with strips of different width, a two-wire line with wires of different radii and two strips of different width on the two sides of a dielectric substrate are possible building-blocks for an OPOMEX antenna. Finally, the OPOMEX antenna can be made of successive segments of different lines, resulting in a further possibility to modify current distribution along the antenna.

The paper proposes two methods for the analysis of OPOMEX antennas. According to one method, OPOMEX antennas are analysed as wire antennas. The other method uses the principle of superposition and the basics of the multiport-network theory, combined with numerical analysis of wire antennas.

Numerical and experimental results are presented for several OPOMEX antennas, and are shown to be in reasonable agreement.

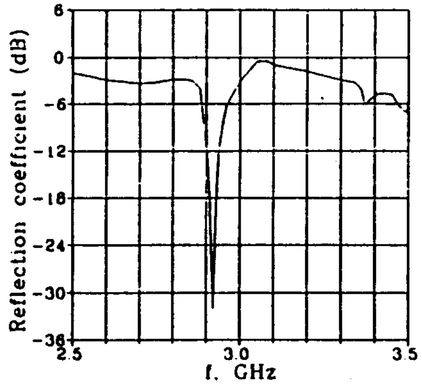


FIGURE 11. Measured reflection coefficient of the experimental 3 GHz printed OPOMEX antenna described in the text.

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