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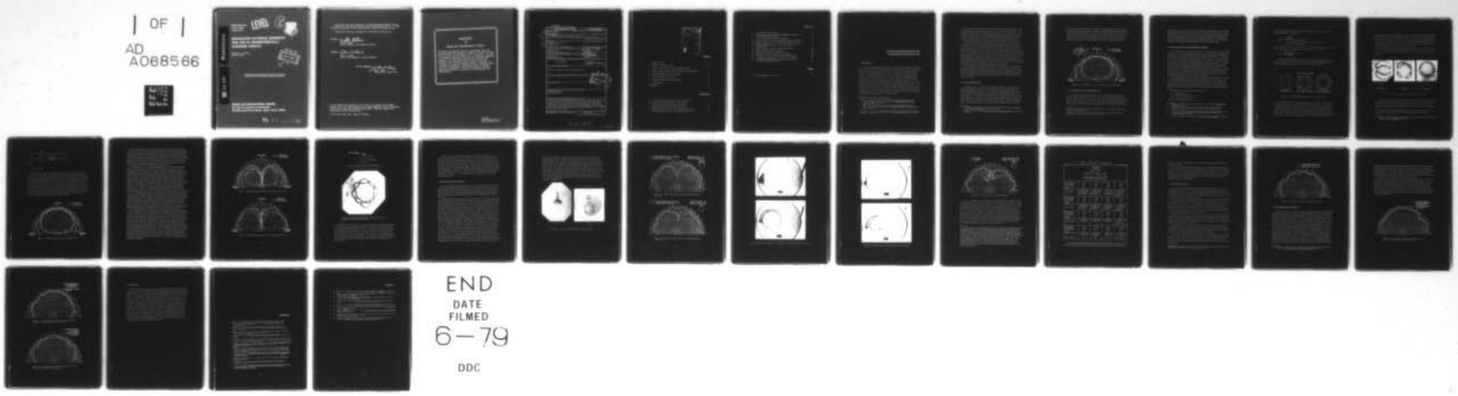

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RADC-TR-79-43
In-House Report
February 1979

MICROSTRIP ANTENNA ELEMENTS FOR USE IN HEMISPHERICALLY SCANNED ARRAYS

Nicholas P. Kernweis
John McIlvenna

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This report is an experimental study of various modifications that affect the radiation pattern of a circular disc microstrip element. The objective is to produce an element pattern with enhanced performance in the angular regions well away from broadside. The study includes the effect of higher order modes, an investigation of circumferential loading, the use of shorting pins at the element edge, and the pattern changes produced by mutual coupling in a closely spaced array.

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1. INTRODUCTION

A microstrip antenna element consists of a conducting metal patch on a large dielectric sheet with a ground plane backing. Recent reports show that even a simple, open end microstrip line radiates from its end and can serve as a basic antenna element.[1,2] More typical, however, is a microstrip line, broadened to form a circular or rectangular shaped patch element. Patches can be arranged singly or in arrays and are currently used as low profile, conformal, rugged antennas in missile, satellite, and aircraft communication and control systems.* The advantages of the microstrip patch antenna lies in the fact that when arrayed, only one feed point is required, since circuitry such as phase shifters, power dividers, corporate feed structures, and so on, can be contained in the same plane as the radiating element. If a microstrip array antenna is used as a conformal antenna on an aircraft fuselage, only a small access hole is required to feed the array as opposed to the large opening required for a slot array antenna.

(Received for publication 13 February 1979)

1. James, J.R., and Wilson, G.J. (1977) Microstrip antennas and arrays, Pt 1 - Fundamental action and limitations, Microwaves, Optics, and Acoustics, 1(No. 5):165-174.
2. James, J.R., and Hall, P.S. (1977) Microstrip antennas and arrays, Pt 2 - New array design techniques, Microwaves, Optics, and Acoustics, 1(No. 5):175-181.

*The reader is referred to RADC-TR-78-46 Design of Microstrip Patch Antenna Elements, A. Derneryd, Jan 1978, for a partial bibliography of pertinent papers.

Antenna arrays, conformally mounted to an aircraft or satellite surface, suffer various degrees of scanning loss as the main beam is tilted from broadside.[3] Proposed aircraft-to-satellite communication links place two or more arrays in various locations to provide coverage over the upper hemisphere centered on the aircraft. A single conformal array, mounted on top of the aircraft and capable of scanning electronically down to either horizon is an attractive but elusive alternative.

Good performance from a scanning array in the horizon or end-fire directions is difficult.[3] Added to all the scanning losses that are beyond the control of the antenna designer, is the fact that most array elements have radiation patterns that exhibit significant power fall-off in the end-fire regions. Arraying techniques cannot overcome this basic element limitation. Microstrip elements in particular have an end-fire pattern fall-off that is almost twice as great as comparably sized elements such as slots. Microstrip patch elements are inherently poor radiators (or receivers) of electromagnetic energy in the vicinity of the plane of the patch because the far field radiation characteristics are those produced by a horizontally polarized source above a ground plane. Because of the direction of the current and its image there is a resultant null in the radiation pattern in the end-fire direction.

The investigation in this report is focused on modifications to microstrip elements that improve their end-fire performance. The investigation is primarily experimental and deals exclusively with the circular disc microstrip element. Topics considered include the use of higher order modes, shape perturbations, internal shorts in the element, and the improvement of element end-fire performance in an array environment.

2. SLOT IN A GROUND PLANE

The ideal element for use in an aircraft phased array has a radiation pattern that is hemispherically isotropic. Real elements, however, have patterns significantly different from this ideal. In order to have a quantitative comparison of the far field radiation patterns of various shaped microstrip elements and to determine the effects of modifications on these elements, a narrow slot in a large ground plane was used as a standard. Figure 1 shows the measured far field E_θ and E_ϕ power patterns for a narrow ($W < \lambda/10$) slot, $0.34\ \lambda$ long in a large ($L > 6\lambda$) ground plane. Theoretical patterns are also shown, plotted as dotted lines.[4] Note that

3. Mailloux, R. J. (1977) Phased array aircraft antennas for satellite communications, Microwave Journal, Oct 1977, pp 38-44.

4. Harrington, R. F. (1961) Time Harmonic Electromagnetic Fields, McGraw-Hill p 139.

the finite ground plane introduces a ripple in the measured patterns, causes the E_ϕ component null at end-fire to fill in and the E_θ component at end-fire to be about 4 dB below the predicted value. Note also that the element pattern levels at end-fire show losses of about 7 dB for E_θ and about 19 dB for E_ϕ (compared to the largest pattern values). The goal in the following sections is to create a modified microstrip element that has an end-fire performance equal to or better than the slot.

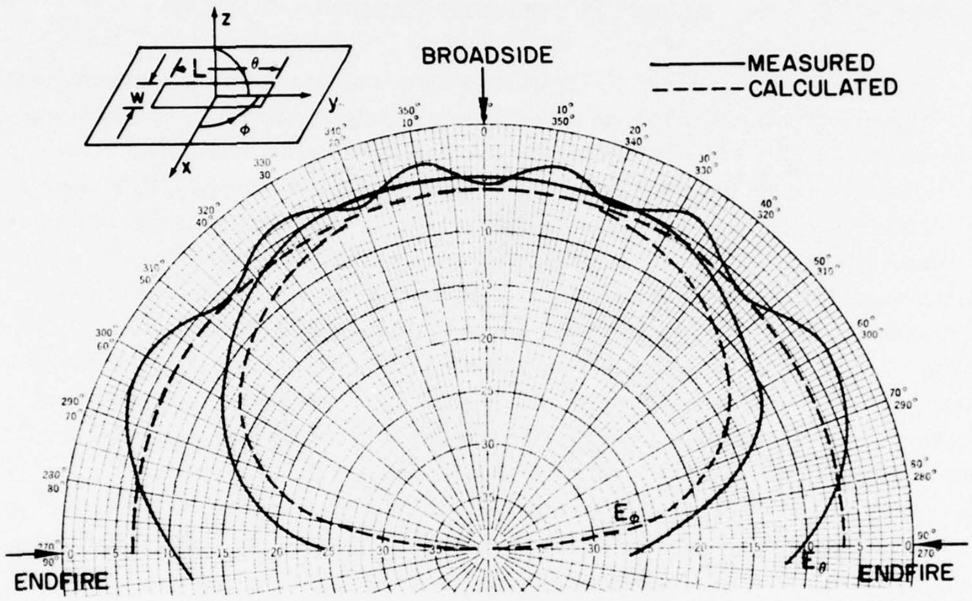


Figure 1. Power Patterns of Narrow Slot in Large Ground Plane

3. USE OF LIQUID CRYSTALS AS DIAGNOSTIC AIDS*

The use of liquid crystal detectors in microstrip antenna design has been reported in detail elsewhere.[5,6,7,8] Suffice it to say that in the laboratory, they allow the designer to see the structure of and monitor changes in the electromagnetic fields on the microstrip patches and associated feed and power divider networks. Liquid crystal detectors also make comparison between individual elements in an

*The liquid crystal detectors were supplied by Mr. James Sethares, RADC/EEA, Hanscom AFB, Bedford, MA.

(Because of the number of references cited above, they will not be listed here. See Reference Page 27, for References 5 through 8.)

array a simple matter. The detection of fabrication or excitation flaws is as simple as comparing the crystal display from element to element. In a sense, the crystal detectors provide, in a single integrated view, all the amplitude or power information picked up sequentially by a very wideband near-field probe. Throughout this report, photographs and sketches of liquid crystal displays will be used to supplement the more traditional radiation pattern and network analyzer plots.

4. MODE STRUCTURES ON CIRCULAR MICROSTRIP ELEMENTS

The disc element, like other patch elements, can be excited in a variety of mode structures, each of which has its own particular radiation pattern. Expressions for the modes of a circular microstrip disc are available in the literature.[9] The analysis is based on modeling the disc as a thin, dielectric loaded cavity. This same type of analysis was recently used to characterize the disc element in terms of its radiation conductance, Q-factor, radiation efficiency, bandwidth and losses.[10] A generalization of this approach has also been reported and handles a variety of patch shapes in terms of the magnetic wall current at the edge of the elements.[11] In an earlier report, the authors used liquid crystal detectors to show that the modes predicted by theory are in fact present on a disc antenna but that the feed location, a parameter not included in the cavity theory, controls which modes are excited.[5] Not all modes can be excited from a single feed location.

Earlier experimental work on the disc radiator claimed that higher order modes were associated with radiation pattern lobes in the plane of the disc, that is, the end-fire plane.[12] The intent in this part of the investigation was, therefore, to catalog the modes and associated radiation patterns for a disc antenna whose feed location and frequency of operation had been properly adjusted to excite the various modes.

All the modes of a dielectric cavity are given by[9]

$$\begin{aligned} E_r &= E_\theta = H_z = 0, \\ E_z &= k^2 J_n(kr) \cos(n\theta + \phi), \\ H_r &= j\,\omega\,\epsilon\, n/r\, J_n(kr) \sin(n\theta + \phi), \\ H_\theta &= j\,\omega\epsilon\, J_n'(kr) \cos(n\theta + \phi), \end{aligned} \qquad (1)$$

9. Watkins, J. (1969) Circular resonant structures in microstrip, Electronics Letters 5:524-525.

10. Derneryd, A. (1977) Analysis of the Microstrip Disk Antenna Element, RADC-TR-77-353.

11. Lo, Y.T. et al (1977) Study of Microstrip Antennas, Microstrip Phased Arrays and Microstrip Feed Networks, RADC-TR-77-406, Final Report on Contract F19628-76-C-0140.

12. Howell, J. (1975) Microstrip antennas, IEEE Trans. AP, AP-23(No. 1):90-93.

where ϕ is a reference angle and is completely arbitrary, and r and θ are the standard cylindrical coordinates,

k	=	$\omega\sqrt{\mu_r \epsilon_r}$,
$J_n(kr)$	=	Bessel function of order n ,
r	=	radial distance out from center of circular element,
R	=	radius of circular element.

Since H_θ must be zero at r = R for all n, t and ϕ, $J_n'(kR) \equiv 0$ and thus, once a value of R is selected, the frequencies at which the modes occur are given by

$$f_{n,m} = \frac{(m^{th} \text{ zero of } J_n')\, c}{2\pi R\sqrt{\mu_r \epsilon_r}} . \tag{2}$$

Figure 2 shows the field geometry for the dominant and next two higher order modes. The feed locations that actually excite the modes at the frequencies $f_{n,m}$ were determined empirically with the aid of liquid crystal detectors.

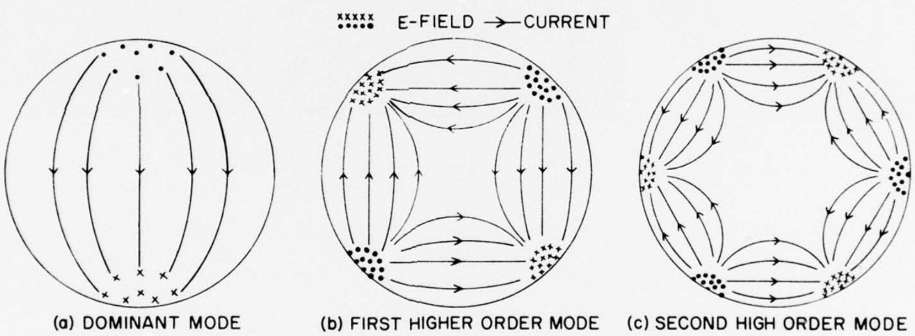


Figure 2. Theoretical Mode Structures on a Circular Disc

The dominant mode of a circular microstrip disc is defined as that mode for which the resonant radius is a minimum for any given frequency. From Eq. (2), the minimum radius is obtained when m, n = 1. The value of $J_1(kr)$ equals zero at the origin, and from Eq. (1), $E_z = 0$. To ensure that E_z is actually zero at the origin, a shorting pin is usually inserted through the circular disc and dielectric at the center. The frequencies for the dominant, first and second order modes, for a disc of radius 1.84 cm are found from Eq. (2) to be 2.99, 4.9 and 6.8 GHz respectively. More accurate formulas for the mode frequencies have recently been reported.[10, 11, 13] Calculations based on these lead to mode frequencies of 2.86, 4.74, and 6.52 GHz for a 1.84 cm radius disc. A disc of this radius was fabricated from 1/16-in. teflon-fiberglas board, $\epsilon_r = 2.55$, with a center shorting pin (0.20 in. diameter). The feed was placed on the back of the board at a 50 Ω point, determined by experiment to be 0.57 cm from the center of the disc.

It was necessary to relocate the feed to 0.28 cm from the center to excite the second order mode.[5] Liquid crystal displays of the first three modes are shown in Figure 3. The actual measured frequencies of the modes were 2.88, 4.82, and 6.80 GHz

(a) Dominant Mode

(b) First Higher Order Mode

(c) Second Higher Order Mode

Figure 3. Liquid Crystal Detector Displays of Disc Modes

Derneryd[10] has provided an expression for the input impedance of a disc element as a function of mode number and radial location of the feed. The variation of Z_{in} from zero (caused by the center shorting pin) to a few hundred ohms, allows the element to be well matched to almost any feed line simply by a choice of feed position.

Expressions for the radiation patterns of a microstrip disc, excited in any of its modes, have been derived.[10, 11] The field components are given by

13. Shen, L.C. (1977) Resonant frequency of a circular disk printed circuit antenna, IEEE Trans. AP, AP-25(No. 4):595-596.

$$E_\theta = -j^n \frac{e^{-jk_o r}}{r} k_o V_o R J_n' (k_o R \sin\theta) \cos n\phi$$

$$E_\phi = j^n \frac{e^{-jk_o r}}{r} n V_o \frac{J_n(k_o R \sin\theta)}{\sin\theta} \cos\theta \sin n\phi$$

where

$$V_o = nE_o J_n (kR) .$$

Figure 4 compares plots of these equations to the measured patterns of the 1.84 cm radius disc mounted on a flat ground plane, excited in the dominant mode ($n = 1$) at f = 2.88 GHz. The agreement is generally good except near end-fire where the effects of the finite ground plane are evident. It can be expected that mounting the same microstrip element on a curved ground plane would bring the measured E_θ at end-fire about 3 dB closer to the theoretical value.[3] Figure 4 shows that the microstrip element performs worse at end-fire than the equally sized slot of Figure 1. (The measurements of the two elements were performed on the same ground plane.) The fall-off for the microstrip disc between maximum and end-fire is about 13 dB on average in E_θ, compared to about 7 dB for the slot. Between maximum and 80°, the disc falls off 9 dB and the slot about 3.5 dB.

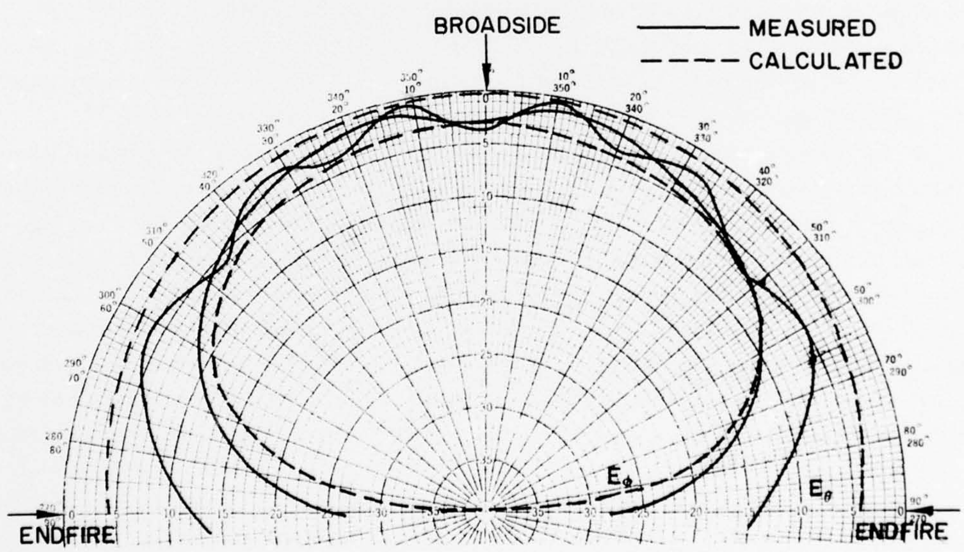


Figure 4. Radiation Patterns of Disc in Dominant Mode

Figure 5 compares theory and measurement for the first higher order mode pattern (n = 2) on the 1.84 cm radius disc, excited at 4.82 GHz. The pattern equations show that all modes higher than the dominant mode have broadside nulls.[10] In spite of this objection, note that agreement between calculated and experimental E_θ is good and that pattern dropoff is about 3 dB at 80° and 6 dB at 90°, an improvement over the dominant mode. Agreement between calculated and measured E_θ patterns is much worse, although it is true that the disc actually performs much better in E_ϕ at end-fire than predicted by the calculations.

Calculations for the n = 3 hexagon shaped mode[5] at 6.8 GHz shows that the maximum value of E_θ occurs in the end-fire direction as indicated in earlier investigations.[11] Measurements in Figure 6 confirm this behavior but also show significant difference between theory and experiment in the broadside sector. The null fill in at broadside was attributed to asymmetries in the mode structure excited on the disc. In an effort to improve mode symmetry, the liquid crystal detector display of this mode was used to monitor changes produced by feed displacements, removal of the center shorting pin and various circumferential loading schemes. Of the approaches tried, removing the center pin and relocating the feed to 0.8 cm from the center produced the most symmetrical hexagon shaped mode structure. However, the measured patterns still did not show the deep broadside nulls predicted by theory. The conclusion reached, after similar results for the n = 4 octagon shaped mode, was that even using the crystal detector display as a guide to producing the required mode geometry, phase difference and perhaps contamination by other non-resonant modes makes use of the discs at these higher order modes difficult. The difficulty is not that the discs perform poorly (their end-fire behavior and broadside null fill-in are desirable features) but that the pattern results do not conform to expectations. This behavior of the disc at the higher modes seems to be in contrast to results reported for the rectangular patch,[8] although somewhat similar results have been reported in edge-fed discs.[11]

An interesting effect noted in these mode investigations was that a small disc (washer, metal piece, and so on) placed on the circumference of the disc as shown in Figure 7 could be used to excite almost any mode desired simply by changing the circumferential location and overlap with the main disc. This technique eliminates the need to physically change the feed location as various modes are excited. Placement of the small disc is facilitated by using the liquid crystal detectors. Figure 8 shows the crystal display for an octagonal (n = 4) shaped mode excited by a circumferential load as described above. Radiation pattern comparison showed no measureable difference between the two ways of exciting the higher order modes. It was also noted that the small disc load could be used to alter the dominant and higher order mode frequencies. Since the small tab appeared quite effective in changing the high frequency behavior of the plain microstrip disc, bigger loads could be expected to alter the dominant mode behavior. Some of these experiments are discussed in Section 5.

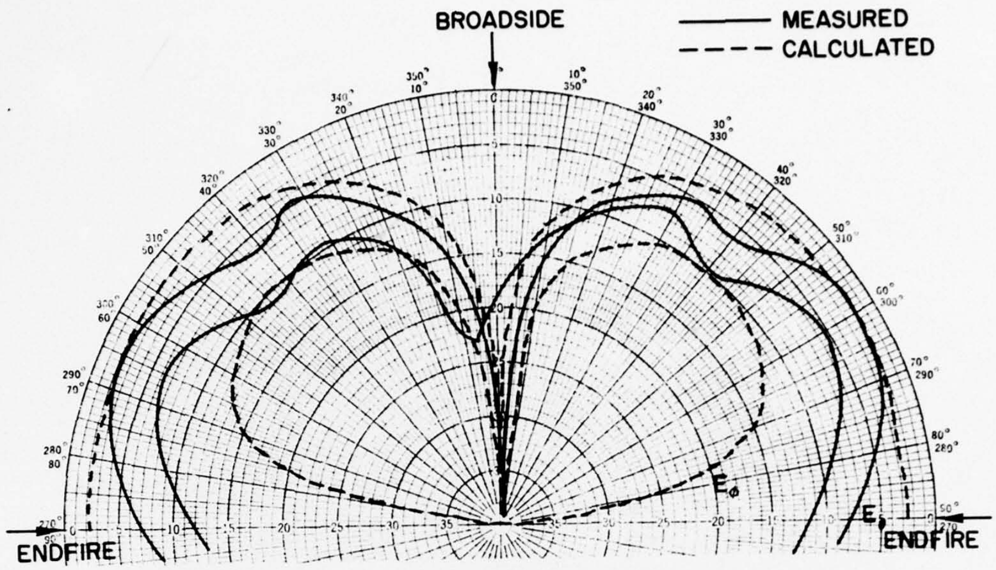


Figure 5. Radiation Patterns of Disc in First Higher Order Mode

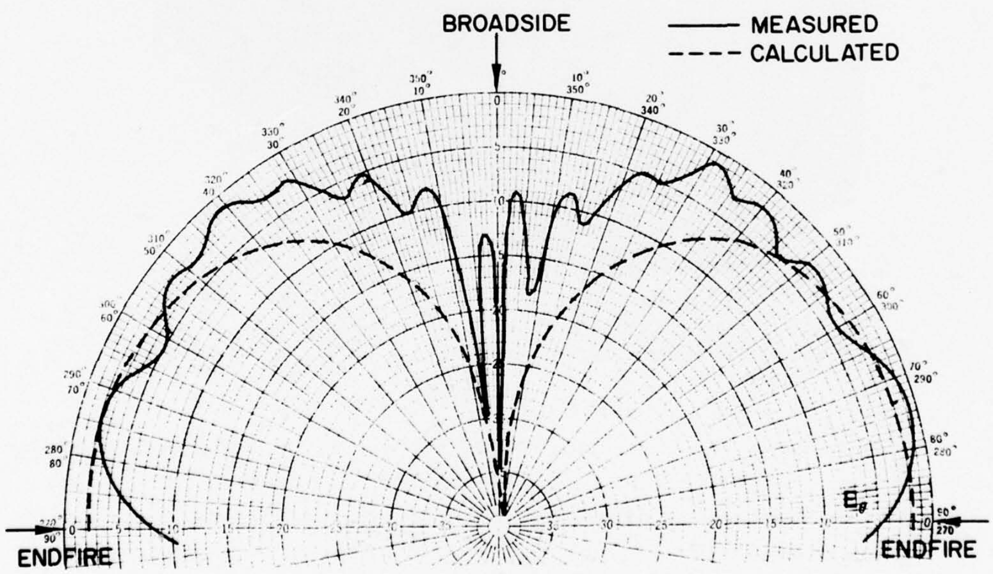


Figure 6. Radiation Patterns of Disc in Second Higher Order Mode

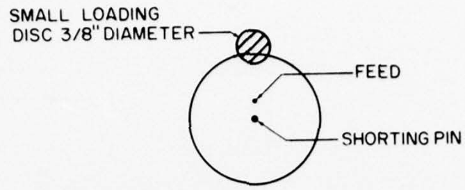


Figure 7. Edge Loading of Disc Antennas

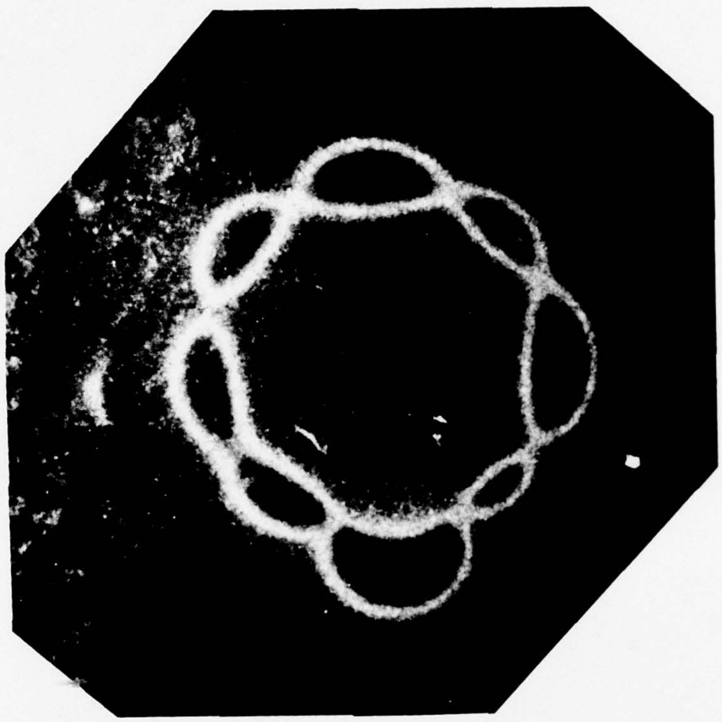


Figure 8. Liquid Crystal Display of Octagon Shaped Mode, Excited by Circumferential Loading

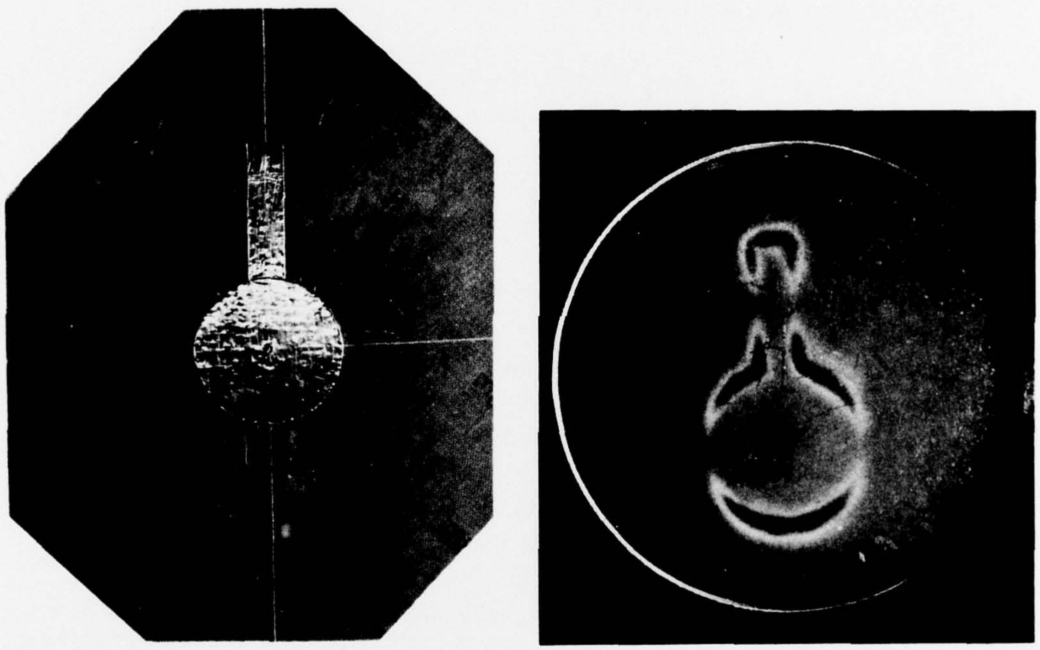
As frequency was varied over the 2 to 10 GHz range, the liquid crystal display showed that the plain disc exhibited not only the predicted mode structures, but a variety of other field configurations as well. In contrast to the typical symmetric mode structures predicted by theory and shown in Figure 3, some of these non-modal resonances were quite asymmetric. Each of these was investigated to see if they offered any pattern improvements. End-fire performance was not improved and most of these non-modal fields radiated inefficiently when compared to the dominant mode.

In summary, microstrip disc antennas in the dominant mode perform worse in the end-fire region than do slots. In theory, the higher modes of a dielectric disc cavity all have broadside nulls and maximum values in the end-fire direction. In practice, the nulls of the disc antenna are filled in and the end-fire performance is a few dB better than the dominant mode. Use of liquid crystal detectors to monitor the modes shows that exciting symmetric higher order modes is difficult and the resulting patterns are sensitive to small variations in feed location. In order to get a microstrip disk to perform as well at end-fire as a slot, some modification of the element is necessary. Some attempts at such modification are presented in the following section.

5. STRIP LOADING FOR DISC ELEMENTS

The liquid crystal detectors showed that the small tabs on the circumference of the disc antenna produced large changes in the field structure on the disc. It appeared to be not only a way to easily excite the disc modes, but also a convenient method to alter the frequency and the basic radiating properties of the plain disc. The small tabs, however, produced no significant improvement in end-fire performance.

The geometry of the circular disc was then modified in a systematic manner by replacing the small tabs with radial conducting strips of various lengths and widths. This modification also perturbs the disc surface currents and thus alters the radiation characteristics of the original element. A strip loaded patch element and a typical liquid crystal display are shown in Figure 9. The strong fields on the strip are evident. Measurements showed that almost any length and width strip could provide improved end-fire performance in the E_θ pattern. The E_ϕ pattern was not greatly affected by the strip loading. The end-fire improvement was obtained however, only as one of a series of changes in the element behavior. Strip loading caused resonant frequency changes, changes in VSWR, and pattern variations in the angular regions about broadside. Strips ranging in length from $\lambda\epsilon/2$ to $\lambda\epsilon/8$ (where λ_ϵ is the wavelength in dielectric of the plain disc dominant mode) and in width, from $\lambda\epsilon/2$ to $\lambda\epsilon/16$ were placed on the edge of the disc, in line with the center pin and feed. Generally speaking, the long wide strips caused least frequency shift, improved end-fire performance but produced patterns with deep broadside nulls (see Figure 10). (Frequency shift is measured by comparing the resonant frequencies at VSWR = 1 with and without the strip.) The pattern nulls could, however, be eliminated by decreasing the width of the loading strip. Short narrow strips also improved end-fire performance and provided a good VSWR but introduced large frequency shifts and undulations in the pattern (see Figure 11). It is also true that like the small circular tab, the short strips produce significant changes in the network analyzer trace. Figure 12 shows a typical trace for a short, narrow loading strip, $\lambda\epsilon/8 \times \lambda\epsilon/8$ over the 2 to 8 GHz range. (Figure 13 shows the trace for a plain disc as a comparison.) Whereas the plain disc had mode frequencies of 2.88, 4.82, and 6.8 GHz, the strip loaded disc had frequencies of 2.57, 5.62, and 6.78 GHz. The radiation patterns (at these three latter frequencies) for the strip loaded disc do not differ drastically from the radiation patterns corresponding to the modes of the plain disc shown in Figures 5, 6, and 7. Even though the network analyzer shows that the strip disc is equally well matched at 5.62 and 6.78 GHz, this dual frequency behavior is not exemplified by the corresponding patterns (see Figure 14).



(a) (b)

Figure 9. Strip Loaded Disc and Liquid Crystal Display

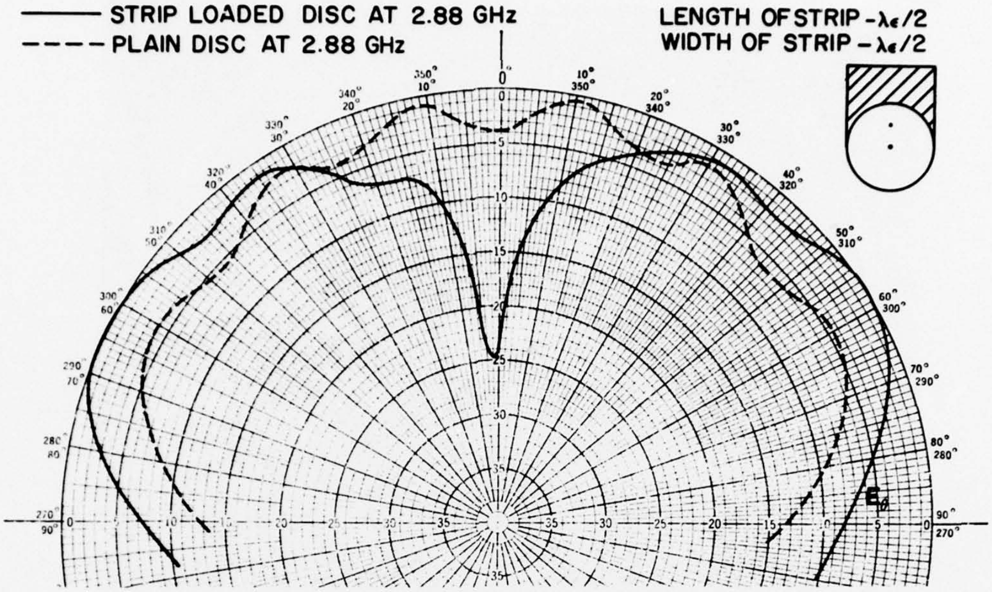


Figure 10. Typical E_θ Pattern of a Disc Loaded With a Long, Wide Strip

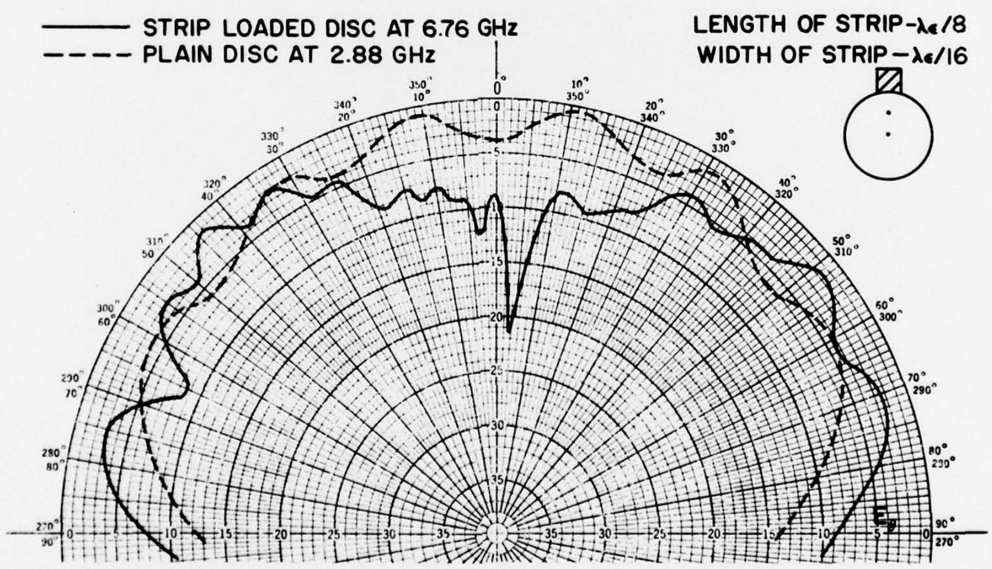
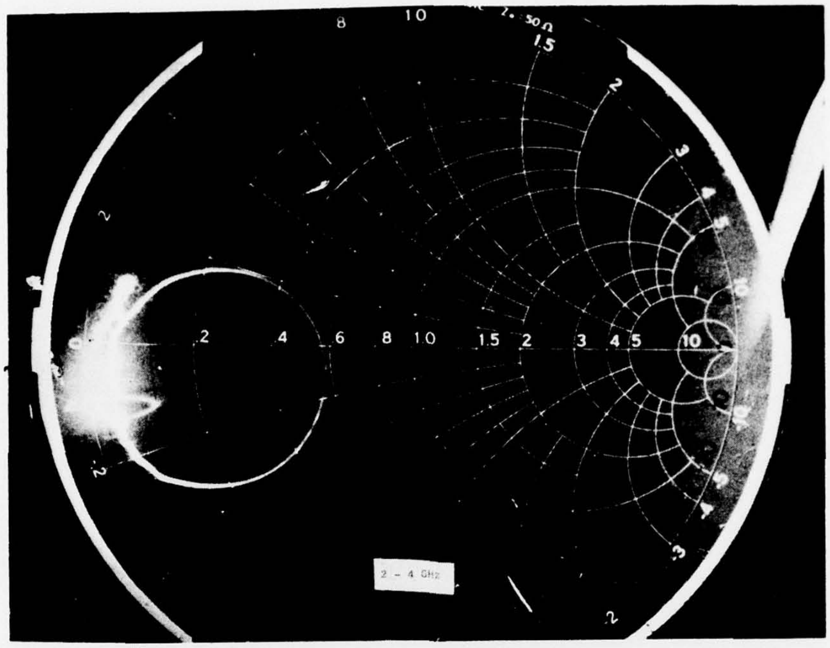
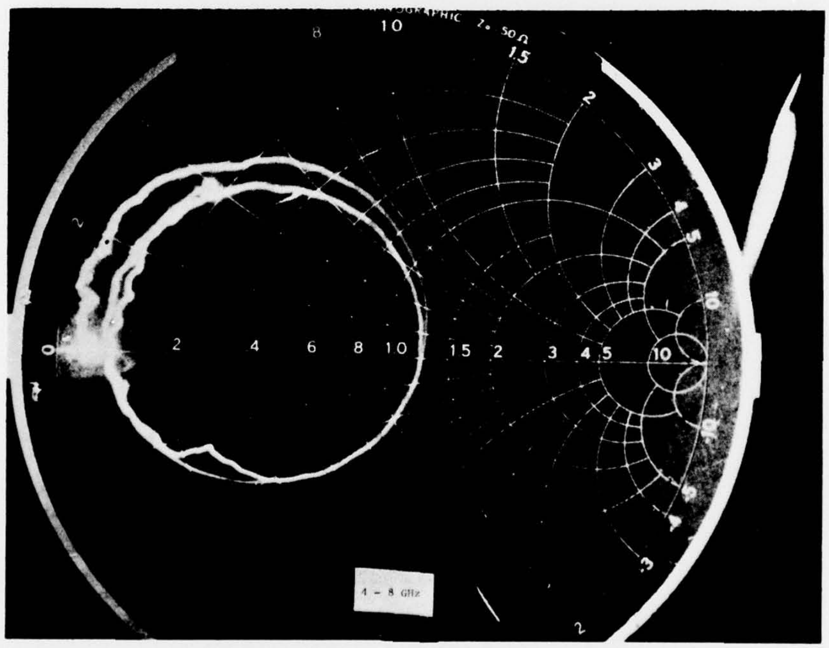


Figure 11. Typical E_θ Pattern of a Disc Loaded With a Short, Narrow Strip

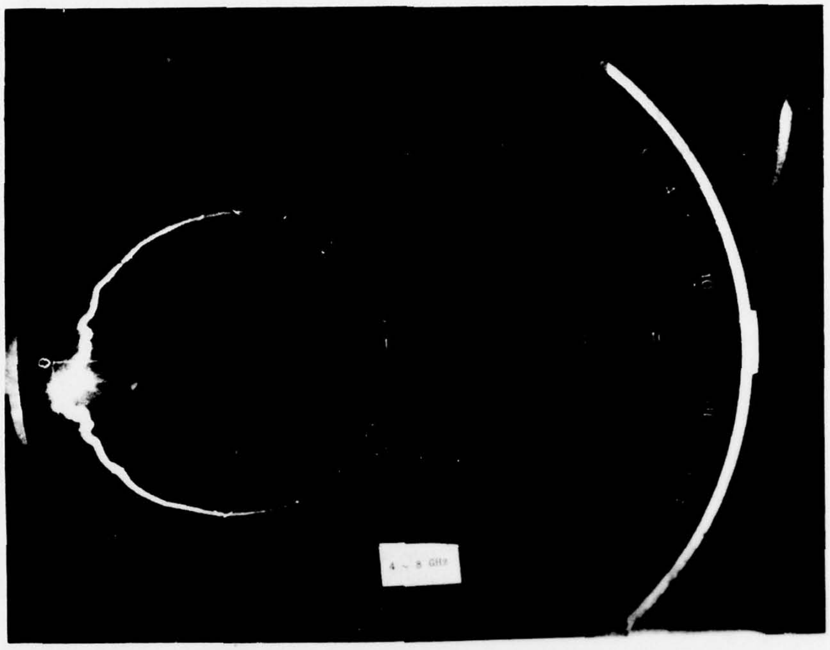


(a)



(b)

Figure 12. Network Analyzer Trace for a Disc Loaded With a Short Narrow Strip



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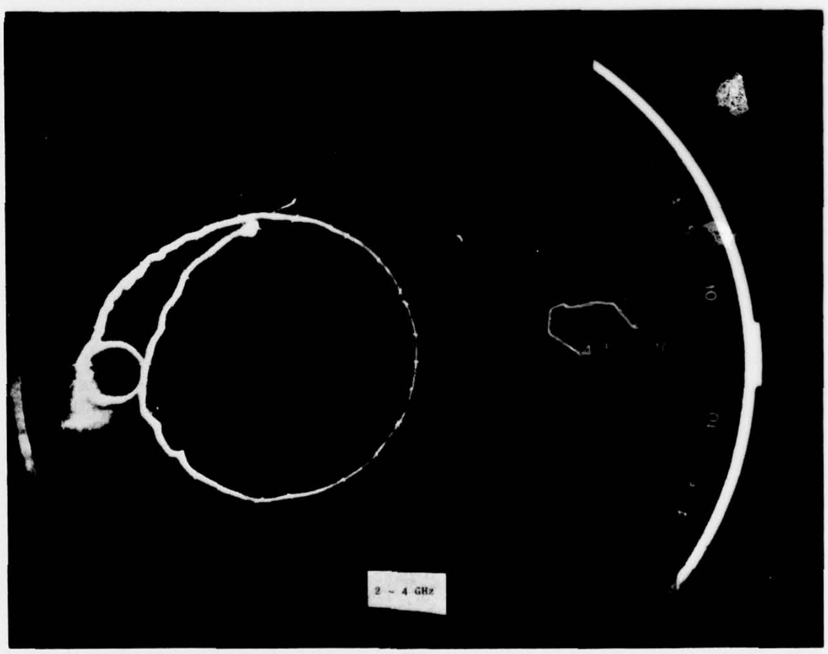

(b)

Figure 13. Network Analyzer Trace for a Plain Disc Element

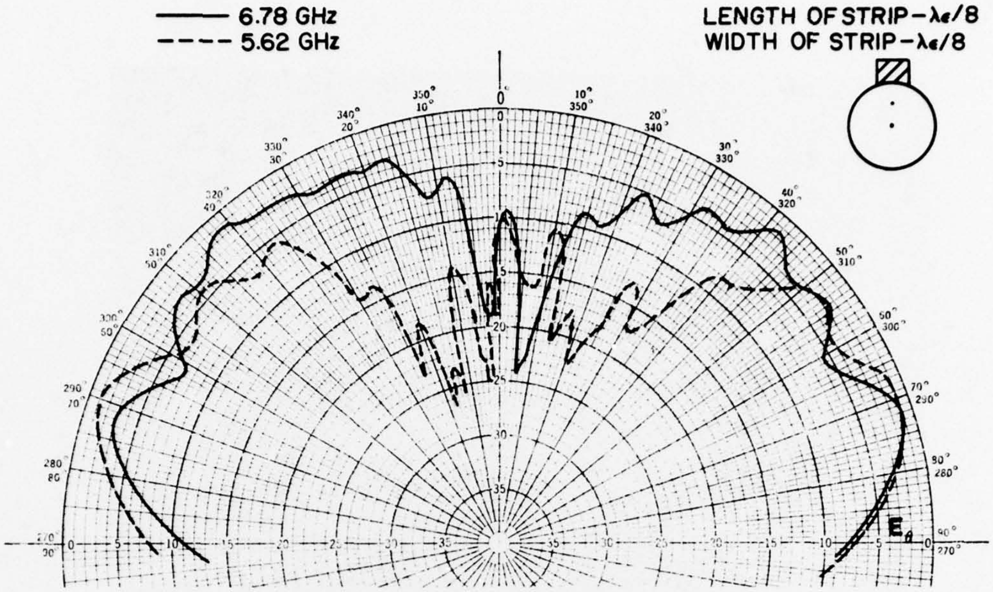

Figure 14. Strip Loaded Disc Radiation Patterns

Table 1 summarizes the data collected on the strip loaded disc elements at the resonant frequency closest to a VSWR of 1.0. Note that for a given width, a change in length of the strip can produce an octave or more variation in frequency.* Generally speaking, most of the strips improve end-fire performance (in E_θ) by about 4 or 5 dB compared to the plain disc. The strip loaded disc is therefore about as good as a slot. Pattern ripple, the difference in dB between the highest and lowest pattern values in the sector from broadside to ± 60°, increases as the strips get smaller and becomes excessive for the strips associated with the greatest shift in frequency. Note that for strips intermediate in length and width, that is, lengths of $\lambda\epsilon/4$ to $\lambda\epsilon/2$ and widths of $\lambda\epsilon/16$ to $\lambda\epsilon/8$, end-fire improvement can be obtained with acceptable changes in frequency, VSWR, and pattern.

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*Small strips cause a partial fill-in of the broadside null in the higher order resonant frequency patterns. As the strip length increases, the lowest resonant frequency shifts below 2 GHz and a poor VSWR indicates that this mode is no longer usable without a change in feed position. The first higher order resonance however, continues to alter its pattern as it shifts downward in frequency, completely filling in the broadside null, and becoming for all practical purposes a replacement dominant mode pattern. As the strip gets even larger, that is, $\lambda\epsilon/2 \times \lambda\epsilon/2$, so that the size and shape of the disc is substantially altered, the first higher order mode of the original plain disc has become the dominant mode of the altered disc. The first three columns of Table 1 summarize this behavior. For the very short strips, that is, $\lambda\epsilon/8$, in the last column of Table 1, one has a choice between the modes available. We have chosen what is effectively the second higher order mode on the strip disc.

Table 1. Strip Loaded Disc Performance

<table>
<tr><td colspan="5">Plain Disc
f_o = 2.88 GHz
VSWR at f_o = 1.0
Pattern Fall-off at 80° - 10 dB
90° - 13 dB
Maximum Pattern Ripple- 3.5 dB
in ± 60° Sector about Broadside</td></tr>
<tr><td>Strip Length
Strip Width
Δf_o (percent)
VSWR
Pattern Fall-off

Comments:</td><td>$\lambda\epsilon/2$
$\lambda\epsilon/2$
0%
1.0
4-6 dB at 80°
7-8 dB at 90°
25 dB Null at Broadside</td><td>3/8 $\lambda\epsilon$
$\lambda\epsilon/2$
+13%
1.2
3-4 dB at 80°
8 dB at 90°
19 dB Null at Broadside</td><td>$\lambda\epsilon/4$
$\lambda\epsilon/2$
+25%
1.1
4 dB at 80°
9 dB at 90°
27 dB Null at Broadside</td><td>$\lambda\epsilon/8$
$\lambda\epsilon/2$
+93%
1.3
3-4 dB at 80°
8-10 dB at 90°
No Null but 13 dB max Ripple</td></tr>
<tr><td>Strip Length
Strip Width
Δf_o (percent)
VSWR
Pattern Fall-off

Comments:</td><td>$\lambda\epsilon/2$
$\lambda\epsilon/4$
+2%
1.0
4-6 dB at 80°
7-9 dB at 90°
9 dB Null at Broadside</td><td>3/8 $\lambda\epsilon$
$\lambda\epsilon/4$
+12%
1.5
3-4 dB at 80°
7-8 dB at 90°
9 dB Null at Broadside</td><td>$\lambda\epsilon/4$
$\lambda\epsilon/4$
+24%
1.6
4-5 dB at 80°
8 dB at 90°
7 dB Null at Broadside</td><td>$\lambda\epsilon/8$
$\lambda\epsilon/4$
+99%
1.2
3 dB at 80°
8 dB at 90°
No Null but 13 dB max Ripple</td></tr>
<tr><td>Strip Length
Strip Width
Δf_o (percent)
VSWR
Pattern Fall-off

Pattern Ripple</td><td>$\lambda\epsilon/2$
$\lambda\epsilon/8$
+3%
1.0
4-5 dB at 80°
8 dB at 90°
5.5 dB</td><td>3/8 $\lambda\epsilon$
$\lambda\epsilon/8$
+10%
1.6
4-6 dB at 80°
8 dB at 90°
4.5 dB</td><td>$\lambda\epsilon/4$
$\lambda\epsilon/8$
+21%
1.7
3-4 dB at 80°
7-8 dB at 90°
5.5 dB</td><td>$\lambda\epsilon/8$
$\lambda\epsilon/8$
+92%
1.1
1-2 dB at 80°
6-7 dB at 90°
18 dB Null at 20°</td></tr>
<tr><td>Strip Length
Strip Width
Δf_o (percent)
VSWR
Pattern Fall-off

Pattern Ripple</td><td>$\lambda\epsilon/2$
$\lambda\epsilon/16$
+3%
1.0
5.5 dB at 80°
8 dB at 90°
3.5 dB</td><td>3/8 $\lambda\epsilon$
$\lambda\epsilon/16$
+8%
1.6
5-6 dB at 80°
8.5-10 dB at 90°
3 dB</td><td>$\lambda\epsilon/4$
$\lambda\epsilon/16$
+19%
1.5
4 dB at 80°
8 dB at 90°
4.5 dB</td><td>$\lambda\epsilon/8$
$\lambda\epsilon/16$
+135%
1.3
3.5 dB at 80°
7.5 dB at 90°
20 dB dip at 5°</td></tr>
</table>

Tests showed that the loading strip could be moved to other circumferential locations. Relocations about ± 40° from the line of the center pin and feed provided patterns that fell off about 8 dB at 90°, that is, end-fire performance was as good as the in-line strip load.

In summary, strip loading on the edge of a microstrip element offers frequency shift, end-fire pattern improvement, good VSWR, the possibility of multi-frequency operation, and a simple means for placing nulls in the element pattern. It appears that most any type of modification to the plain element edges can produce a variety of interesting effects,[14] and offers the means to tailor the microstrip element pattern to a variety of applications.

6. THE PINNED DISC ELEMENT

The literature reports the use of metal pins to short out one entire edge of a rectangular element.[15, 16, 17] This improves the end-fire radiation capability. The use of individual shorting pins at various locations at the edges and within the element itself has also been reported.[14, 18] These latter experiments, however, were not aimed directly at end-fire improvement.

The rectangular microstrip element is often modeled as two edge slots separated by a transmission line.[8, 12, 19] Shorting out one edge should give an element pattern similar to a single slot. The same procedure can be applied to a disc element by placing shorting pins (20 pins were used) around one half of the element edge. The liquid crystal display shows that, as expected, only one of the two field regions shown in Figure 3a is present. The pins cause a downward frequency shift of about 19 percent and a change in VSWR from 1.0 to 4.5.

The pattern shows about a 2 dB improvement over the plain element at end-fire. When the feed is repositioned to improve the impedance match (moved closer to the center of the element) the VSWR is about 2.5 to 1, the frequency shift downward is about 22 percent (compared to the plain element) and the pattern shows about a 4 dB end-fire improvement (see Figure 15).

Placing one or a small number of pins, that is, less than 6, symmetrically about the center line connecting the shorting pin and the feed, caused no changes in the end-fire radiation. Resonant frequency was shifted upward, however, by about 35 percent, the amount dependent on the number of pins used.

In summary, the pinned disc, like the pinned rectangular element, can provide improved element patterns in the end-fire sector. Large changes in VSWR, caused by the pin emplacement, can be reduced by proper location of the feed. Small numbers of pins can provide frequency shift and patterns not much changed from the plain element.

(Because of the large number of references cited above, they will not be listed here. See Reference Page 27, for References 14 through 19.)

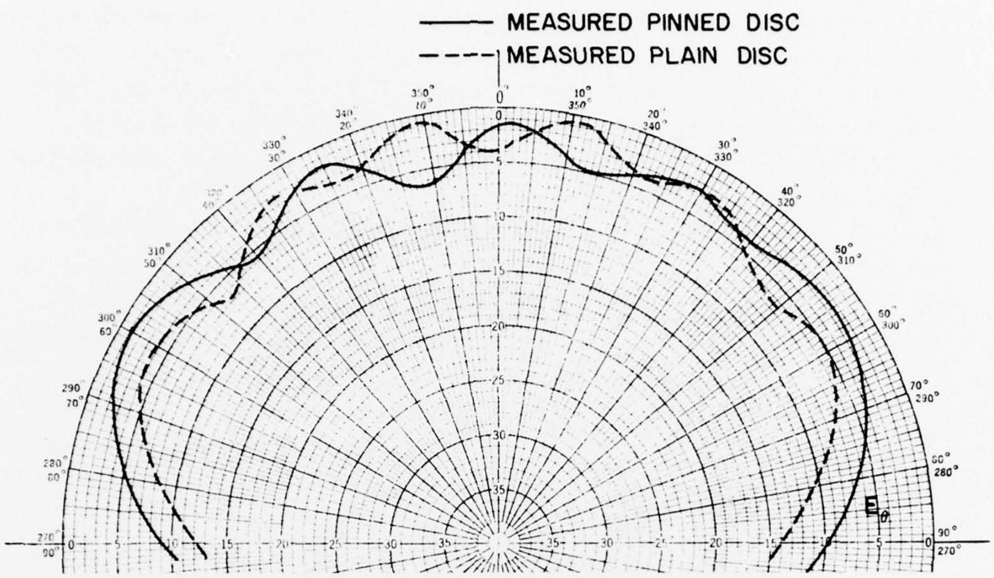

Figure 15. Radiation Pattern for a Pinned Disc Element

7. END-FIRE IMPROVEMENT IN ARRAYS

Scanning the beam of an array to angles well off broadside requires interelement spacings of less than 0.5λ, if one is to avoid grating lobes. Such close spacings emphasize mutual coupling problems. Studies of mutual coupling in microstrip elements have been reported.[8, 11, 16, 20] The emphasis in this section is, however, to determine whether mutuals have any serious effects on end-fire patterns. Four and eight plain disc elements, linearly arrayed with center-to-center separations $0.4\ \lambda_o$ were measured. (λ_o is the free space wavelength of the frequency corresponding to the lowest resonance in the elements. If resonant frequency changed from element to element, the average frequency was calculated and used for radiation pattern measurements.) Network analyzer traces of each element, with the other elements terminated in 50 Ω, showed small changes in VSWR and resonant frequency from element to element. The VSWR was less than 1.2 and frequency variation was 3 percent or less in an 8-element array. The largest frequency changes occurred in the end elements. Comparison of the individual element pattern in the 4- and 8-element arrays with the isolated element pattern (exemplified

20. Parks, F., and Bailey, M. (1976) Mutual coupling between microstrip disc antennas, IEEE AP-URSI Meeting Symposium Digest, p 399.

by Figure 5) indicated that arraying at close distances actually improved the end-fire performance of the pattern in the 80 to 90° angular sector. Figure 16 shows a center element pattern in such an array. Figure 17 shows an end element pattern in the same array. Note that the center element is about 5 dB better than the isolated element in the 80° to 90° sector while the end element shows less improvement, but is still a few dB better than the isolated element.

This behavior was verified in a three-element test array, where the outer two elements were displaced from the center element by 0.38 λ_o to 0.8 λ_o. Figure 18 shows the center element patterns for the two extreme cases of outer element separation. VSWR and resonant frequency of the center element showed little change as the outer two elements were moved. At the close spacing, the center element pattern became more symmetric in the end-fire regions. It appears that simply arraying plain disc elements closely can add a few dB end-fire improvement in the element patterns.

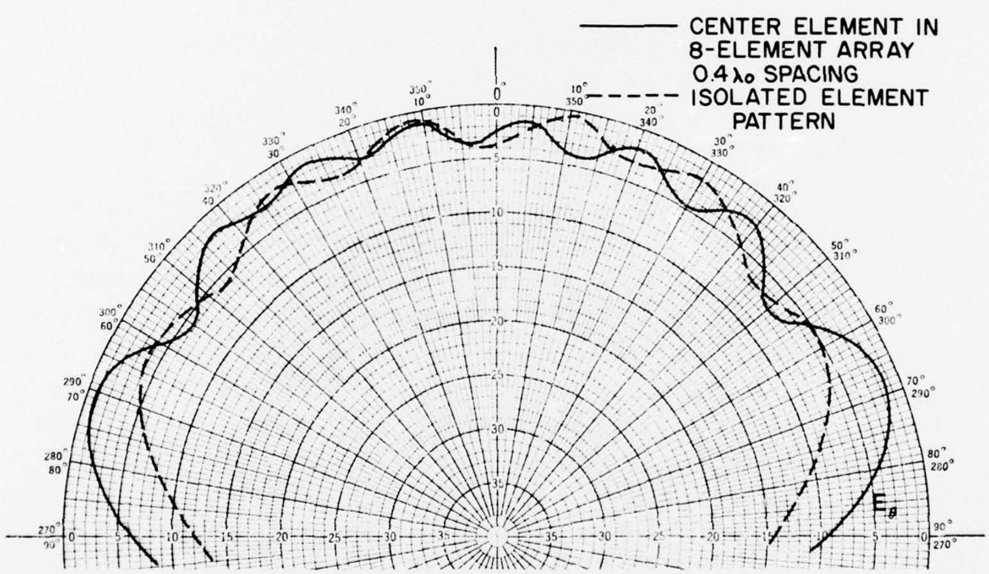

Figure 16. Comparison of Isolated Element With Arrayed Element. Element Separation in Array 0.4 λ_o

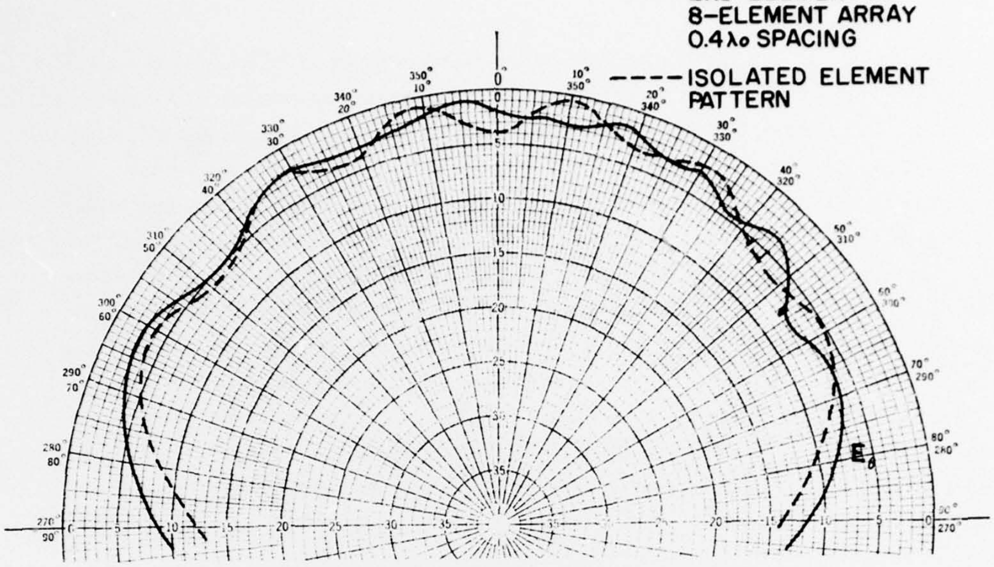

Figure 17. Comparison of Isolated Element With Arrayed Element. Element Separation in Array 0.4 λ_o

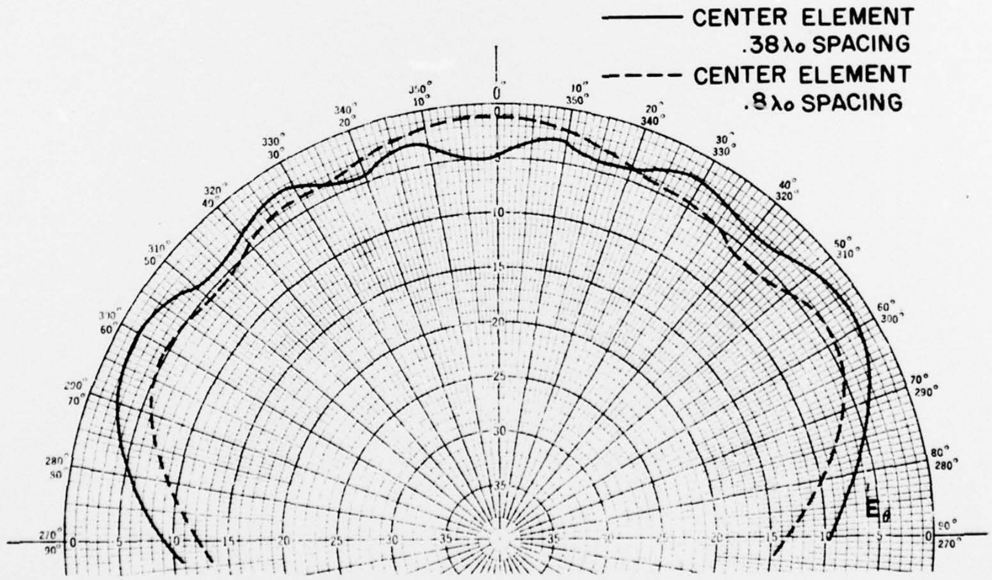

Figure 18. Comparison of Center Element Pattern in Three Element Arrays With Different Spacings

8. CONCLUSIONS

The report has discussed several experiments aimed at improving the end-fire response of the microstrip disc element. The E_ϕ radiation pattern has a deep null at end-fire and none of the modifications discussed had any significant effect on this pattern. The E_θ pattern, however, could be changed in the end-fire sector. The best of the modifications discussed brought the disc response close to that of a slot in a ground plane. Improvement in the end-fire sector was usually obtained only with other modifications in the element characteristics, some of which were not desirable. Exciting the disc in higher order modes increased end-fire radiation levels but introduced broadside nulls. Circumferential loading was a promising method that also produced multi-frequency loops in the network analyzer trace of the element. A great variety of pattern effects were obtained by varying the size, shape and location of the edge load. Shorting pins at the element edge produced frequency shifts and, depending on the number used, end-fire improvement. It also appears that mutual coupling effects in closely spaced arrays cause an end-fire sector improvement in the element patterns.

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