マイクロストリップアンテナ回想録

----- マイクロストリップアンテナ・ミニハンドブック -----

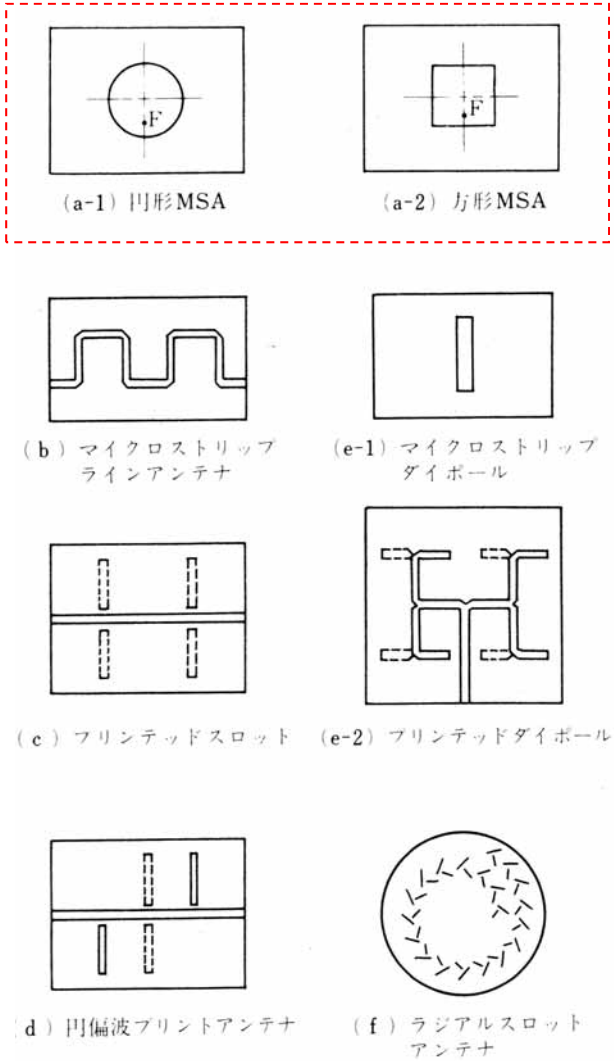
アンテナ伝搬研究会(函館)

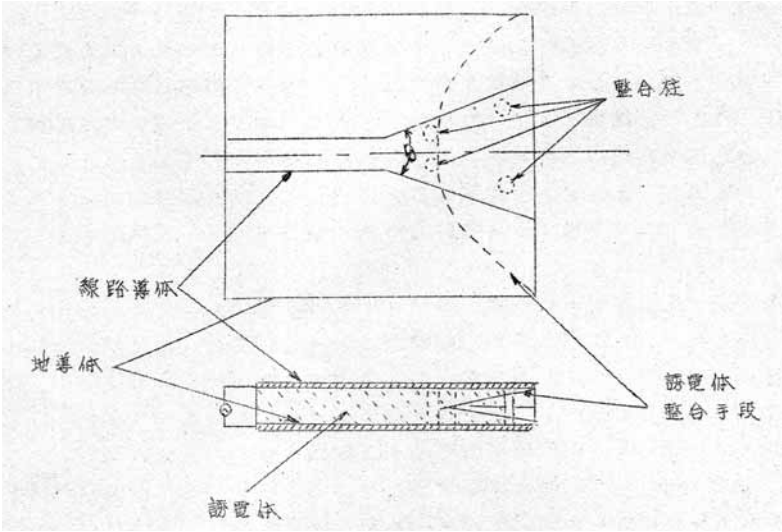
2013年7月24

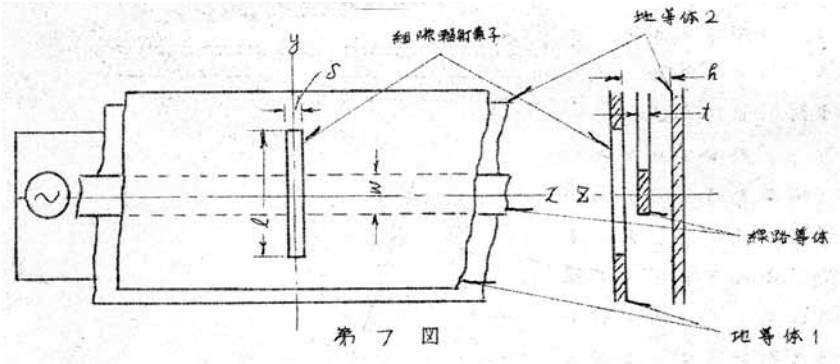
東京農工大学
鈴木　康夫

はじめに(1/2)

マイクロストリップ(平面)アンテナの分類







第7図

ここでは、Patch タイプの MSAを取り上げます。

はじめに(2/2)

MSA の長所

①Low-Profileで、曲率をもったボディへの適合性が良い
②量産化に適している
③二次元であり設計上の自由度が大きい
④半導体や他のマイクロ波素子との適合性が良い

MSA の特徴

①一点給電での円偏波励振が容易
②偏波切り換えが容易
③マルチモード対応が容易
④インピーダンス整合が容易

MSA の課題

①広帯域化

ここでは、一点給電円偏波励振と広帯域化を主な対象とします。

マイクロストリップアンテナ進展の主な経緯

年	内 容
1951	[1] R. M. Barrett et al, “Microwave printed circuits,”
1952	[2] D. D. Grieg et al, “Microstrip – A New Transmission Technique for the Kilomegacycle Range,”
1953	[3] G. Deschamps, “Microstrip Microwave Antennas,”
1969	[4] R. Collings, “U. S. Patent Application,”
1970	[5] E. V. Byron, “A new flush-mounted antenna element for phased array application,”
1971	
1972	[6] R. E. Munson, “Microstrip Phased Array Antennas,” [7] J. Q. Howel , “Microstrip Antennas,” [8] 三好、大越, “マイクロ波平面回路の解析的取扱い,”
1973	[9] H. D. Weinschel, “Progress report on development of microstrip cylindrical arrays for sounding rockets,”
1974	[10] R. E. Munson, “Conformal Microstrip Antennas and Microstrip Phased Arrays,” [11] 許　他, “マイクロ波平面回路の固有モードによる解析,” [12] 小林、田辺、田中, “平衡形円板共振器の固有値の計算機解析,”

年	内 容
1975	[13] J. Q. Howel , “Microstrip Antennas,” [14] **大越, 三好, “”平面回路,”** [15] G. Sanford et al., “Development and test of a conformal microstrip airborne phased array for use with the ATS-6 satellite,” [16] H. D. Weinschel, "A Cylindrical Array of Circularly Polarized Microstrip Antenna,"
1976	[17] H. D. Weinschel and K. R. Carver, “A medium-gain circularly polarized microstrip UHF antenna for marine DCP communication to the GOES satellite system,” [18] A. G. Derneryd, "Linearly Polarized Microstrip Antennas,”
1977	[19] J. L. Kerr, “Other Microstrip Antenna Applications,” [20] H. S. Jones et al., “A Conformal, Dielectric-Filled Edge –Slot Antenna for Bodies of Revolution,” [21] Y. T. Lo et al., “Study of microstrip antennas, microstrip phased arrays, and microstrip feed networks,”
1978	[22] A. G. Brejcha et al., “The Seasat-A Synthetic Aperture Radar Antenna,” [23] J. L. Kerr, “Terminated Microstrip Antenaa,” [24] J. L. Kerr, “Microstrip Polarization Techniques,” [25] J. P. Montbomery, “A Microstrip Reflectarray Antenna Element,” [26] Y. T. Lo et al., “Theory and Experiment on Microstrip Antennas,”

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1979	[27] K. R. Carver and E. L. Coffey, “Theoretical Investigation of the Micrstrip Antenna,” [28] S. A. Long and M. D. Walton, “A dual-frequency stacked circular-disc antenna,” [29] 多賀, 三島, 兼堀, ”UHF帯マイクロストリップアンテナの広帯域化,” [30] K. R. Carver, “A Modal Expansion Theory for the Microstrip Antenna,” [31] W. F. Richards et al., “An Improved Theory for Microstrip Antennas and Applications,” [32] W. F. Richards et al., “Design and Theory of Circularly Polarized Microstrip Antennas,” [33] H. S. Jones et al., “Dual-Frequency Piggyback Antenna,” [34] L. R. Murphy, “SEASAT and SIR-A microstrip antennas,” [35] J. L. Kerr, “Microstrip Antenna Developments,” [36] Proc. Workshop, “Special Issue on Printed Circuit Antenna Tech.,”
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1981	[43] IEEE Trans. On Antennas and Propagation, “Special Issue on Microstrip Antennas,” [44] D. H. Schaubert et al., “Microstrip Antennas with Frequency Agility and Polarization Diversity,” [45] K. Araki et al., “Hankel Transform Domain Analysis of Open Circular Microstrip Radiating Structures,” [46] W. F. Richards et al., "An Improved Theory for Microstrip Antennas and Applications,“ [47] S. A. Long et al., “An Experimental Study of the Circular-Polarized Elliptical Printed-Circuit Antenna,” [48] D. H. Schaubert et al., “Post- Tuned Microstrip Antennas for Frequency-Agile and Polarization-Diverse Applications,” [49] 羽石　他, “一点給電による方形円偏波MSAの一設計法,” [50] Y. Suzuki et al., “Expanding The Frequency Bandwidth of a Microstrip Antenna,” [51] J. R. James, P. S. Hall, and C. Wood, "Microstrip Antenna Theory and Design,”
1982	[52] T. Chiba et al., “Suppression of Higher Modes and Cross Polarized Component for Microstrip Antenna,” [53] T. Chiba et al., “A Phased Array Antenna Using Microstrip Patch Antennas,”
1983	[54] 徳丸　他, “ポスト装荷マイクロストリップ円偏波アンテナ,” [55] 秋葉、小川、伊藤, “円形マイクロストリップアンテナを用いた太陽発電衛星受電用レクテナモジュールに関する研究,” [56] D. A. Paschen, “Broadband Microstrip Matching Techniques,”

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1984	[57] Y. Suzuki et al., “Computer Analysis Method for Arbitrarily Shaped Microstrip Antenna with Multiterminls,” [58] C. H. Chen et al., “Broadband Two-Layer Microstrip Antenna,” [59] Y. T. Lo et al., “Circularly Polarized Microstrip Antennas,” [60] Y. Suzuki et al., “Designign Method of Microstrip antenna Considering the Bandwidth,”
1985	[61] Y. Suzuki et al., “Improved Theory for a Singly Fed Circularly Polarized Microstrip Antenna,” [62] 堀、中嶋, “広帯域同一面給電円偏波マイクロストリップアレーアンテナ,” [63] T. Teshirogi et al., “Wideband circularly polarized array with sequential rotation,” [64] D. H. Schaubert et al., “Antenna Elements for Integrated Phased Arrays,” 1985
1986	[65] 金田、桜井、後藤, “円環アンテナの共振モードと指向性,” [66] P. L. Sullivan et al., “Analysis of an aperture coupled microstrip antenna,” [67] D. R. Tanner, “Wide-band Double-Tuned Microstrip Elements,” [68] D. A. Paschen, “Practical Examples of Integral Broadband Matching of Microstrip Antenna Elements,” [69] D. H. Schaubert et al., “Aperture Coupled Patch Antennas and Arrays,” [70] K. Araki, “Numerical Analysis of Circular Disk Microstrip Antenna with Parastic Elements,” [71] D. M. Pozar, “A Reciprocity Method of Analysis for Printed Slot and Slot-Coupled Microstrip Antennas,”

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1987	[72] Y. Suzuki et al., “Circularly Polarized Radiation from Singly-Fed Equilateral-Triangular Microstrip Antenna,”
1988	[73] **柏, 小池, 吉田, 深井**, “Bergeron**法によるパッチアンテナの3次元解析**,” [74] Y. T. Lo et al., “Simple Design Formulas For Circularly Polarised Microstrip Antennas,” [75] W. F. Richards, “Microstrip Antennas,”
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1991	[81] H. Iwasaki et al., “A Circular Microstrip Antenna with a Cross Slot for Circular Polarization,”
1992	[82] K. Hirasawa, et al., ”Analysis, Design, and Measurement of Small and Low-Profile Antenna,”
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1994	[84] N. I. Herscovici et al., “A Microstrip Array Fed by a New Type of Multilayer Feeding Network,”

年	内 容
1995	[85] D. Pozar et al., “Microstrip Antenna,”
1996	[86] 羽石、平沢、鈴木, “小形・平面アンテナ”
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2012	[92] 山本, “プリントアンテナの基礎と設計,” AP研・二種研WS

Deschampsの論文の検証(1/8)

論文と検証内容

[3] G. A. Deschamps, "Microstrip Microwave Antennas," presented at the 3rd USAF Symp. On Antennas, 1953.

- **本当にMSAの概念を示した最初の論文か？**

- **共著者の有無？**

[A] J. T. Bernhard et al, “A commemoration of Deschamps’ and Sichak’s “Microstrip Microwave antennas””: Years of development, divergence, and new direction,” Proc. of the 2003 Antenna Applications Symposium, pp.17-19, Sept. 2003.

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MICROSTRIP MICROWAVE ANTENNA

W. Sichak

By Georges Deschamps and
Federal Telecommunication Laboratories

Contract AF33(038)-13289

INTRODUCTION

The problem was to obtain a high resolution, X-band antenna with shaped vertical-pattern and a horizontal beamwidth of less than one degree. The usual solution of using a long linear array feeding a cylindrical reflector was adopted and it remained to design the linear array, which in the present case was to be 300 wavelength long.

Methods for obtaining such an array are: 1) The pillbox or sectoral lens, 2) The end fed slot array, 3) The linear array where all elements are fed through equal lengths of waveguide. With the second solution the pattern varies with frequency and the design is complicated by mutual effects between slots. The first and third solutions avoid this difficulty and are essentially similar; in (1) the power distribution is done continuously by spreading of the wave and bending by refraction or reflection, in (2) it occurs at the junctions along the feed system.

Deschampsの論文の検証(2/8)　共著者の有無

・W. Sichak の共著者追加申請に対する文献 [A] による見解

発端

1953年に開催された
USAF Antenna Research and Development Program のThird Symposiumにおいて、FTL(Federal Telecommunications Laboratory)のG. A. Deschamps は共著者無しで “Microstrip Microwave Antennas” を発表した。

↓

しかし

・Illinois 大学のElectromagnetics Laboratory に所蔵されているProceedingsのコピーにはW. Sichakが共著者になっている。
・ W. Sichakは、後にIRE Fellowになっており、当時はFTLでG. A. Deschampsと一緒に仕事をしている。

↓

従って

論文に対する W. Sichak の貢献は疑う余地がない。

論文の主旨

目的 ： 水平面 (H 面) 内指向性の狭ビーム化による
X-band レーダの高解像度化
ただし、垂直面 (E 面) 内はシリンドリカルリフレクタ等による
成形ビーム (例えばコセカント二乗パターン)

実現手段 ： シリンドリカルリフレクタの一次放射器を 300 λ 程度の
一次元アレーで構成 し、水平面内で狭ビームを合成

課題 ： 一次放射器の給電回路を導波管で構成したら
バルキーになってしまう

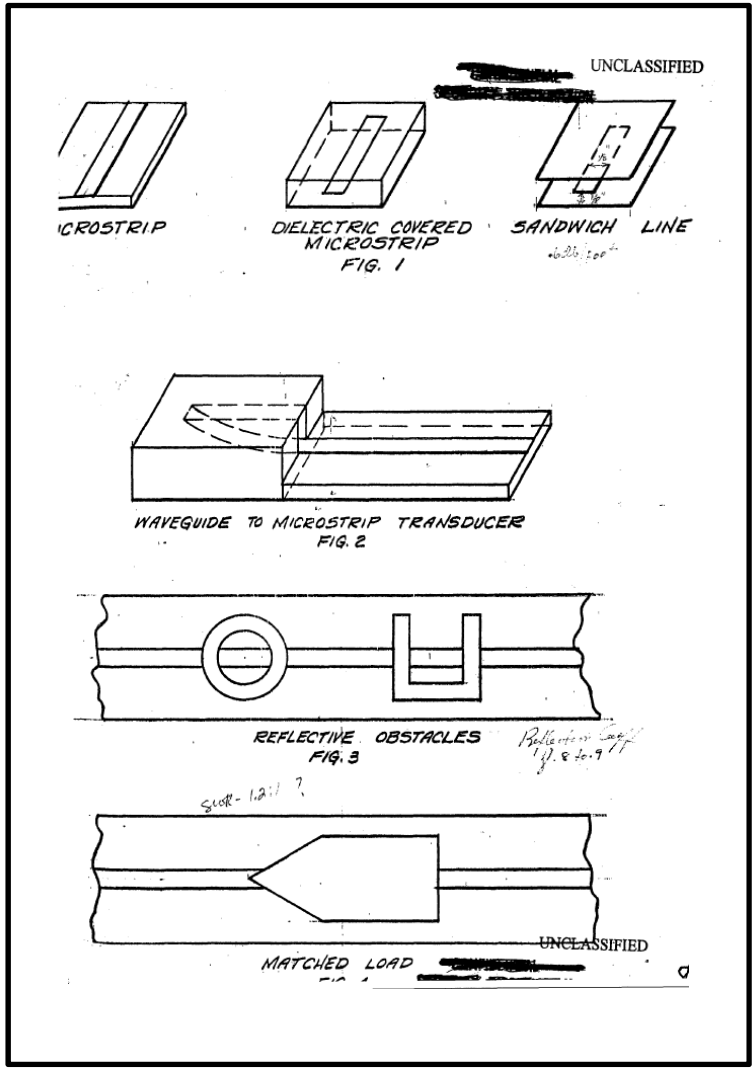
解決策 ： 給電回路をマイクロストリップ線路で構成する

これが論文の主旨

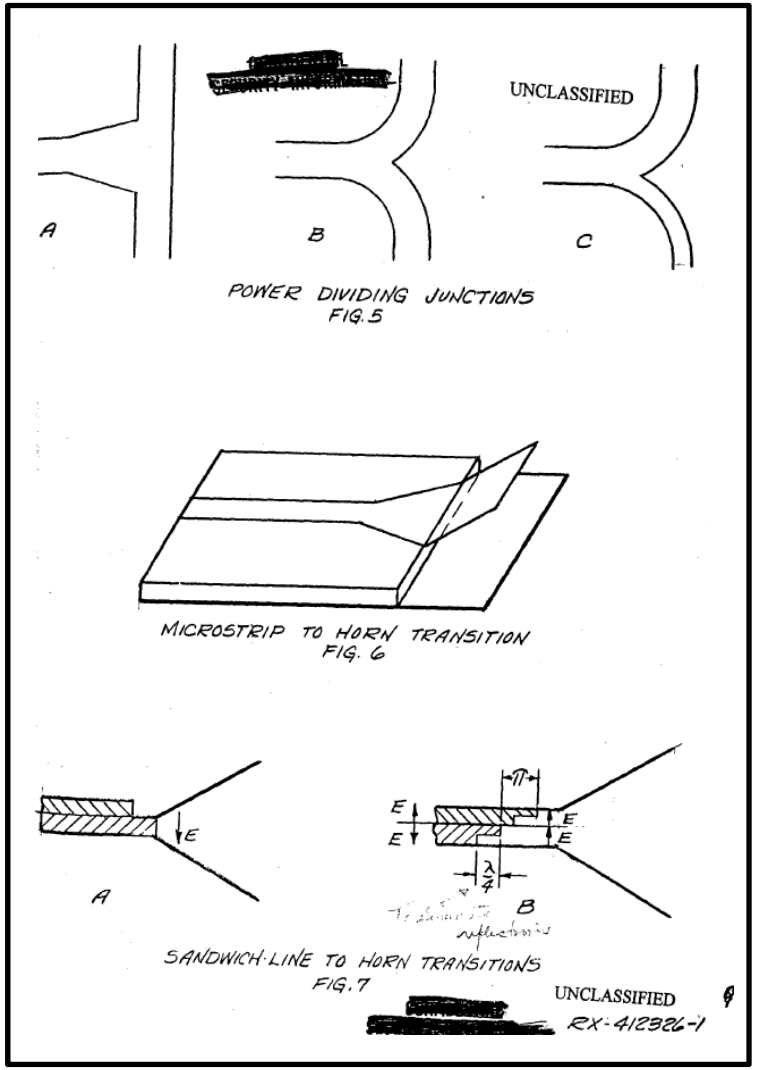
Deschampsの論文の検証(4/8)　論文の内容(1/4)

給電回路の構成要素に関する考察

給電回路の構成要素



電力分配器と放射素子(ホーン)



アレーアンテナの試作と考察(Ⅰ)

ホーンアンテナによる 32 素子アレーアンテナのエッチングパターン

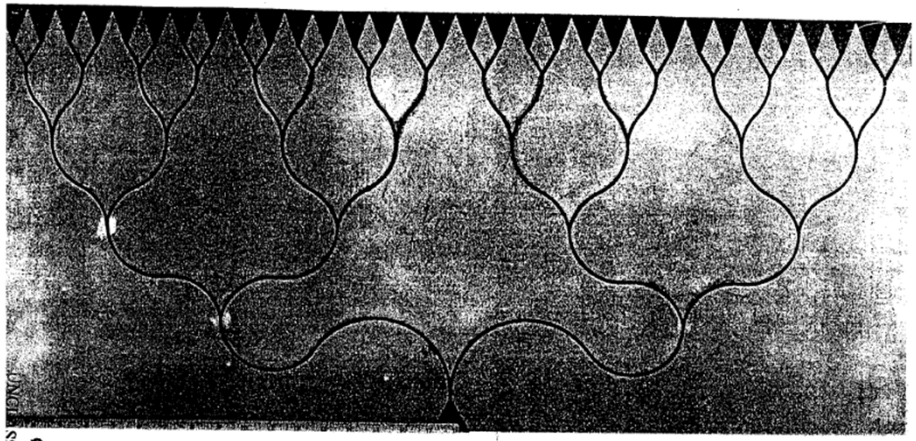


FIGURE 8

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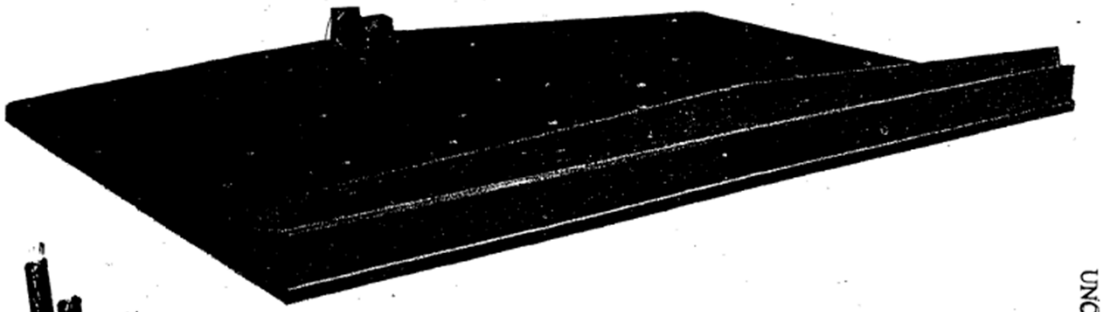
給電回路をマイクロストリップ線路で
構成することにより
小型･軽量化を達成

不平衡型給電による 32 素子アレーアンテナの外観



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アレーアンテナの試作と考察(II)

レンズアンテナによる 4 素子アレーアンテナのエッチングパターン(不平衡型給電を想定)

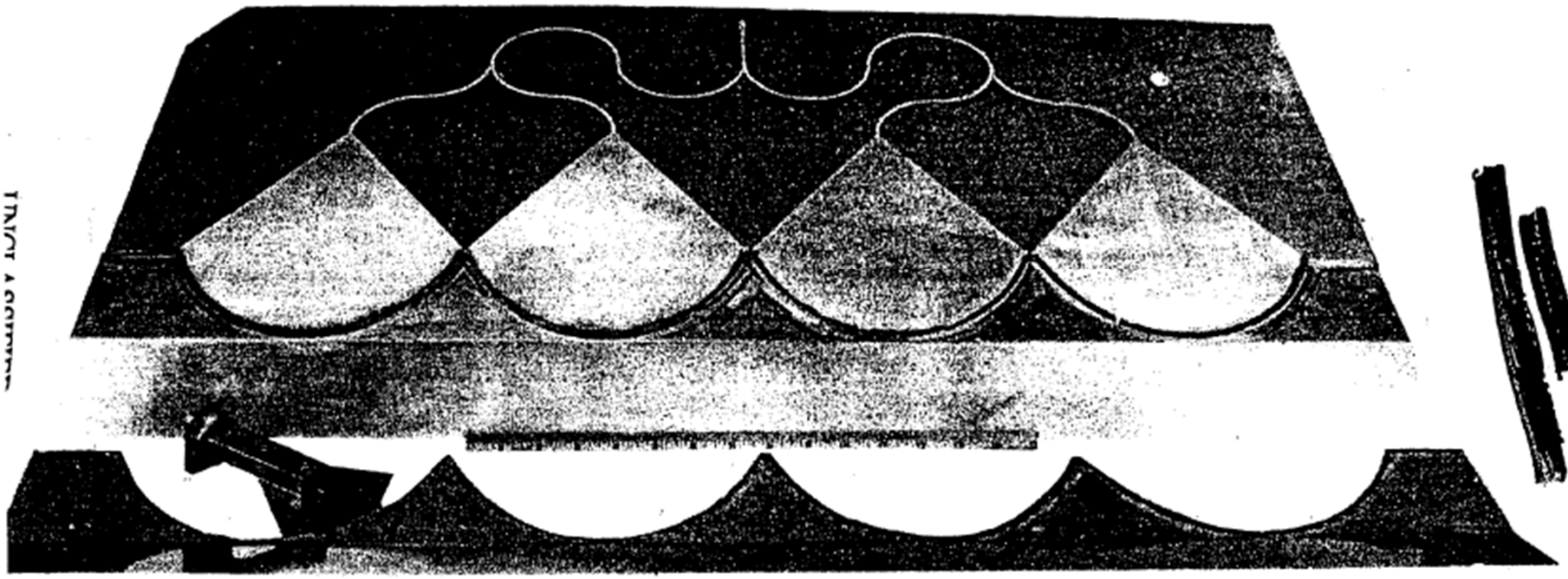

FIGURE 13

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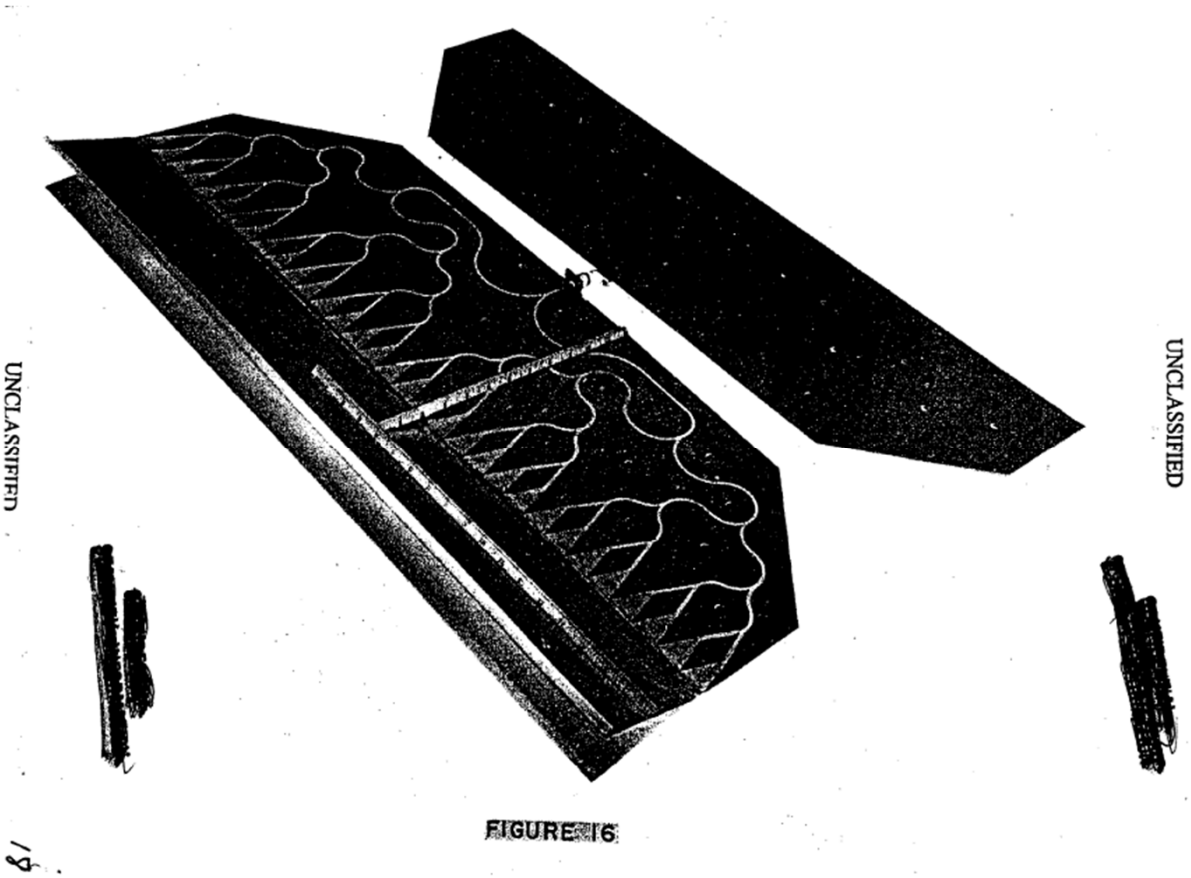
アレーアンテナの試作と考察(III)

不平衡型の給電回路では
放射損が大きいことを指摘

給電回路を平衡型とすることで
低損失化を実現

これを契機に、
マイクロストリップ線路からの放射を
積極的に利用するタイプのアンテナの
研究が活発化。
ただし、パッチアンテナではない。

平衡型給電による32 素子アレーアンテナの外観



Deschampsの論文の検証(8/8)　パッチタイプのMSA との関係

★ マイクロストリップアンテナ(MSA)の概念を示した最初の論文か否か？

・小型・軽量化のために、給電回路を導波管に代わって、
マイクロストリップで線路で構成。
ただし、論文の中には、パッチタイプのMSAは出てこない。
・試作アレーアンテナとその測定結果が示されており、
各コンポーネント(導波管-マイクロストリップ線路変換器、電力分配器、放射素子)
が開発課題と述べている。
ただし、放射素子はマイクロストリップ線路またはレンズを三次元的に広げた
ホーンアンテナを対象にしている。

文献[A] でも

・現在知られているようなMSAが広く知られるようになったのは
1970年のByron[5]、Munson[6,10]、Howell[7,13]の論文による。→本当か?
・Deschamps (とSichak) の論文が成したことは、
給電回路にマイクロストリップ線路を使用することを通して、
寸法、重量、価格を考慮したアンテナシステムの新しい考え方を示唆したこと。

と言っている。

[4] Collingsの特許(1969)　出願アンテナの概要

最初に MSA を具現化したのはMunson[6] とされているが、それより前に、Collingsが、MSA とは異なる発想で、以下の特許出願している。

直線偏波励振

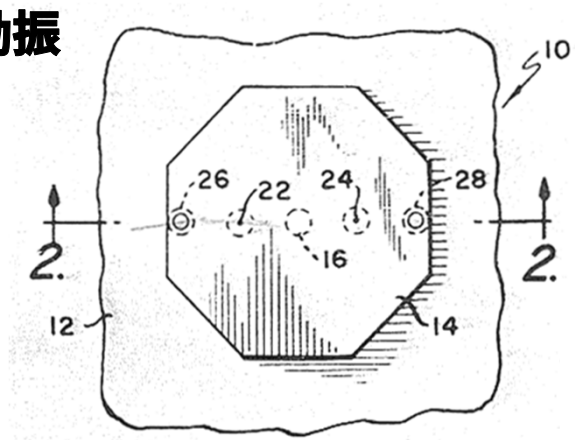


FIG. 1.

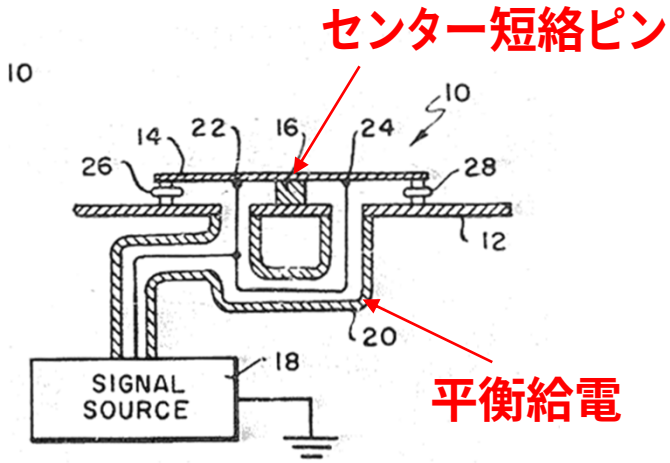
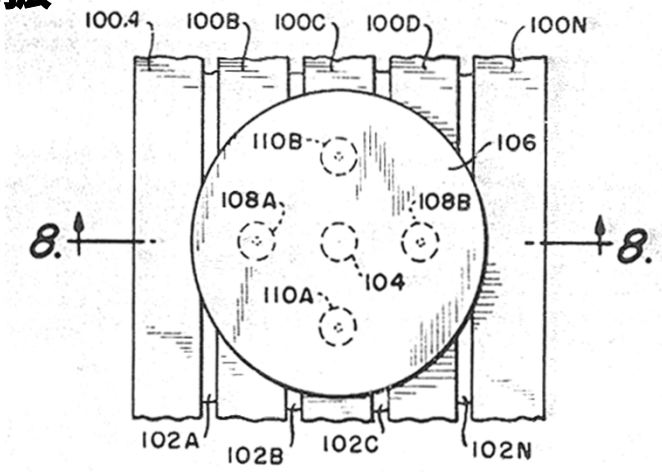
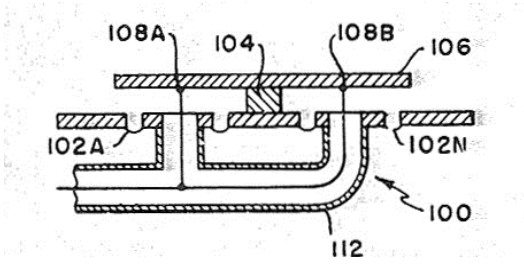


FIG. 2.

円偏波励振

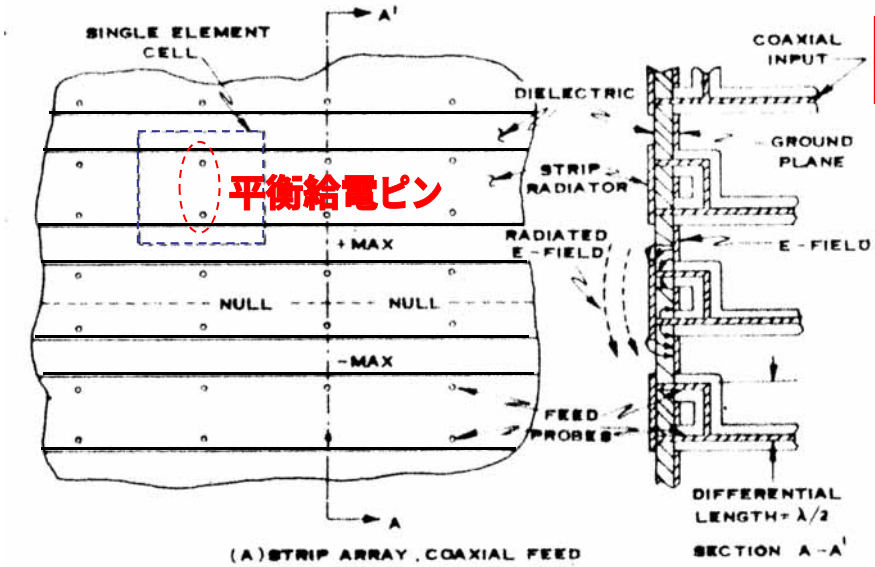




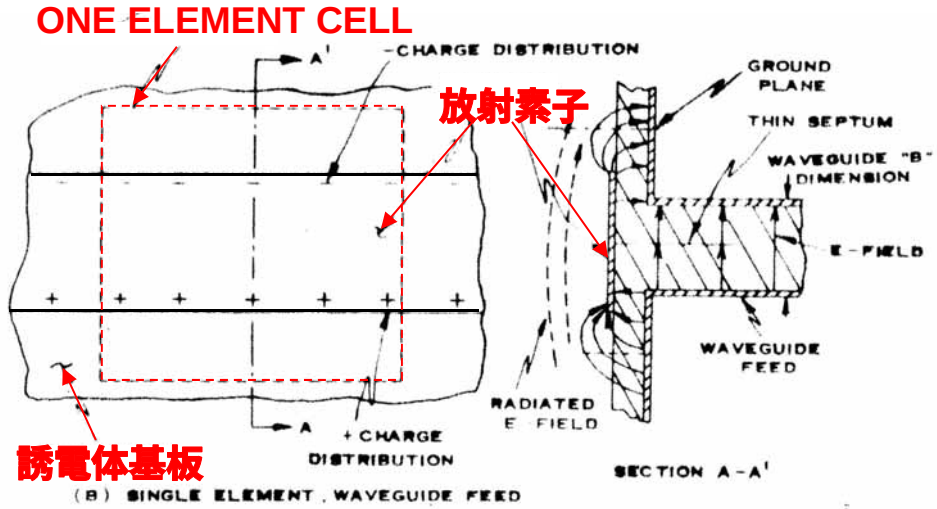
[5] Byronの論文(1970)

提案アンテナの概要

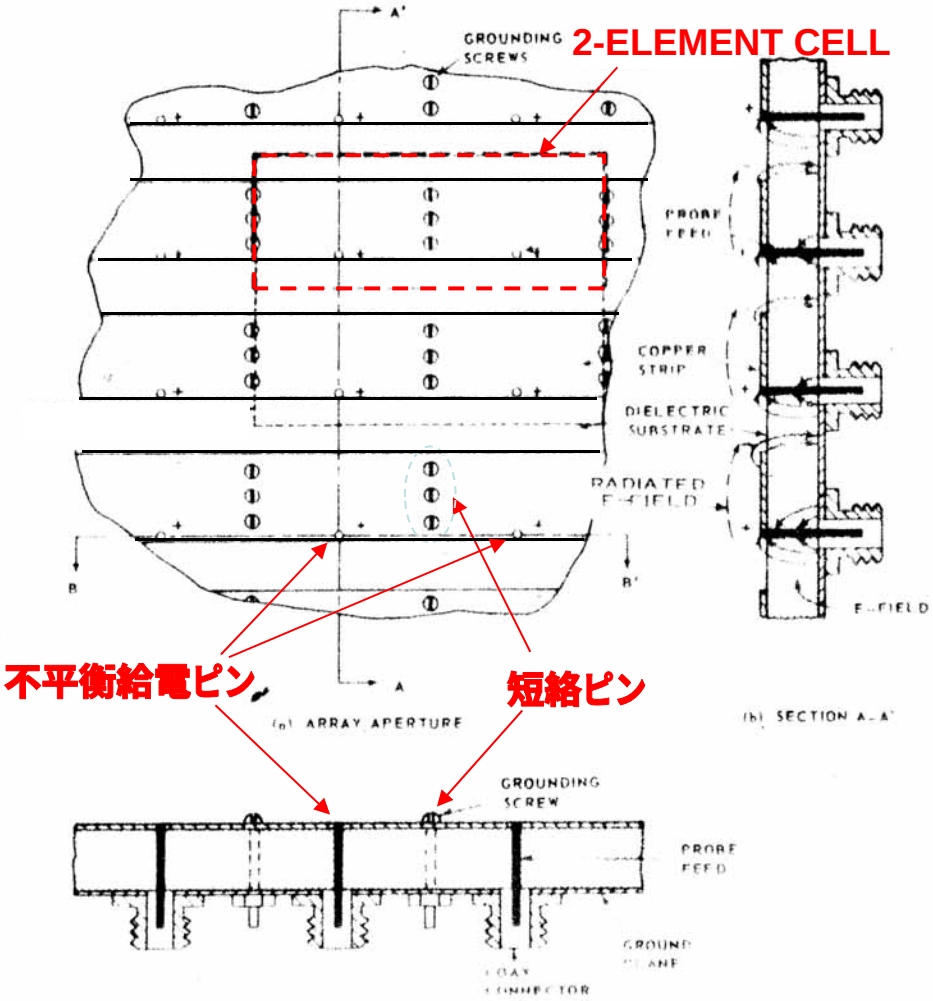
ミサイル搭載電子走査アンテナの開発



(a) Uバランによる平衡給電



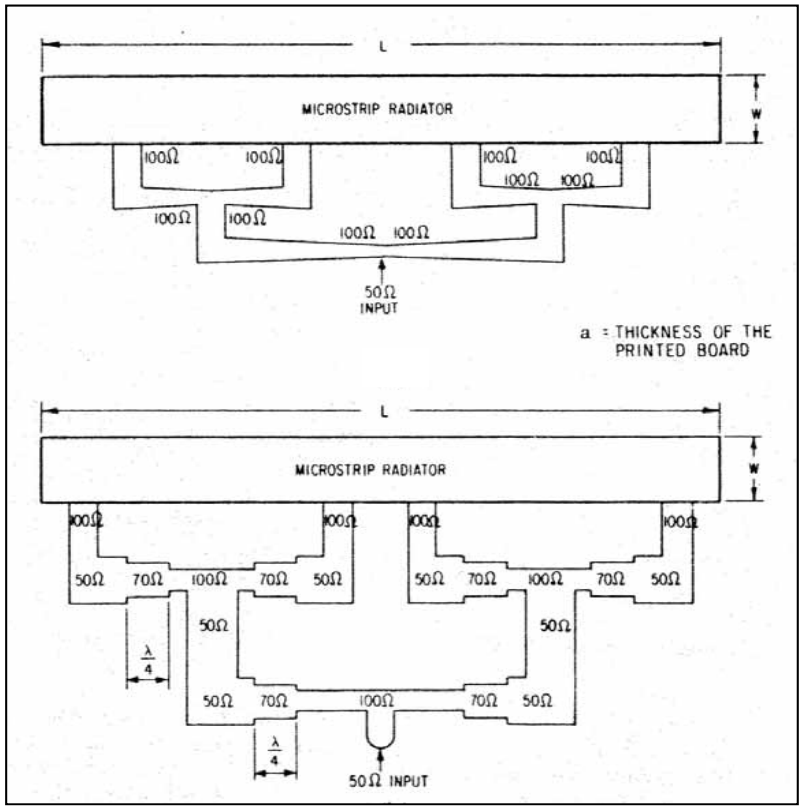
(b) 導波管による平衡給電



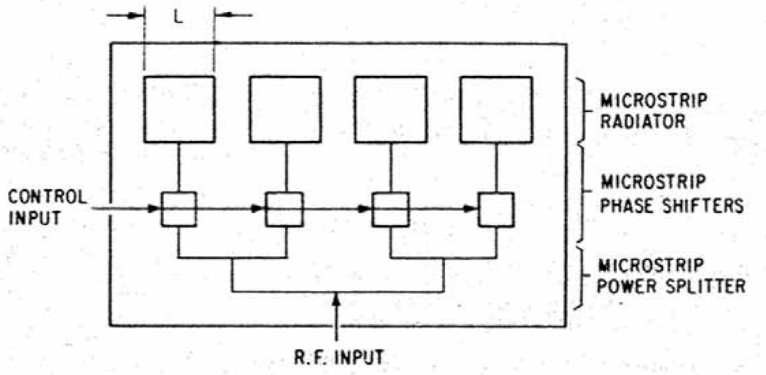
(c) 同軸線路による不平衡給電

[6] Munsonの論文(1972)　論文の概要

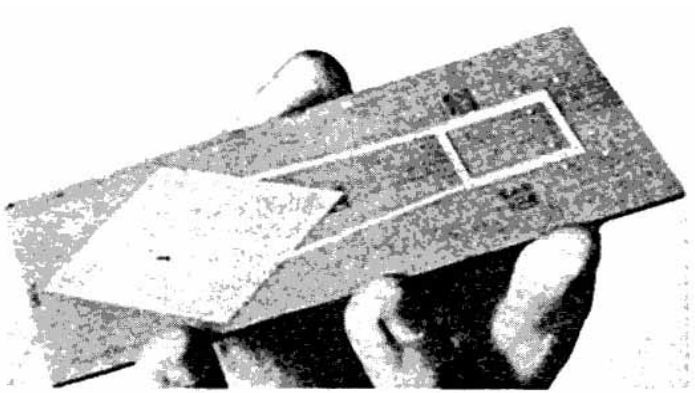
ミサイル搭載用共平面給電 MSA と円偏波 MSA の試作



(a) 共平面給電 Strip Radiator



(b) Microstrip Phased Array

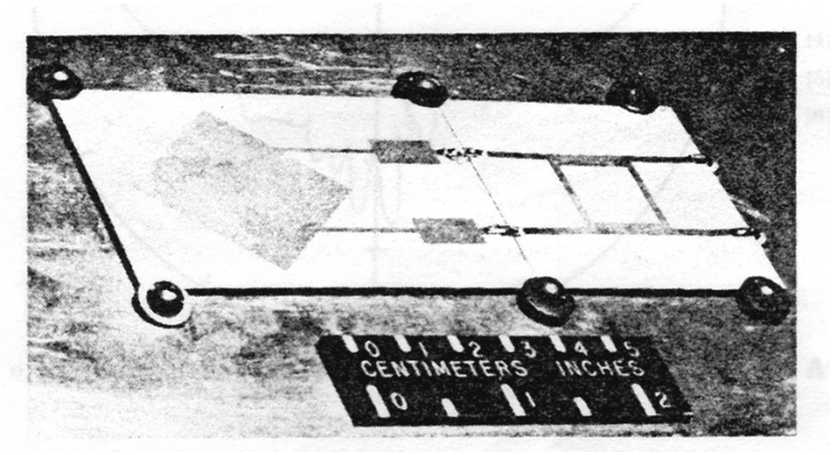


(c) 円偏波矩形マイクロストリップアンテナ

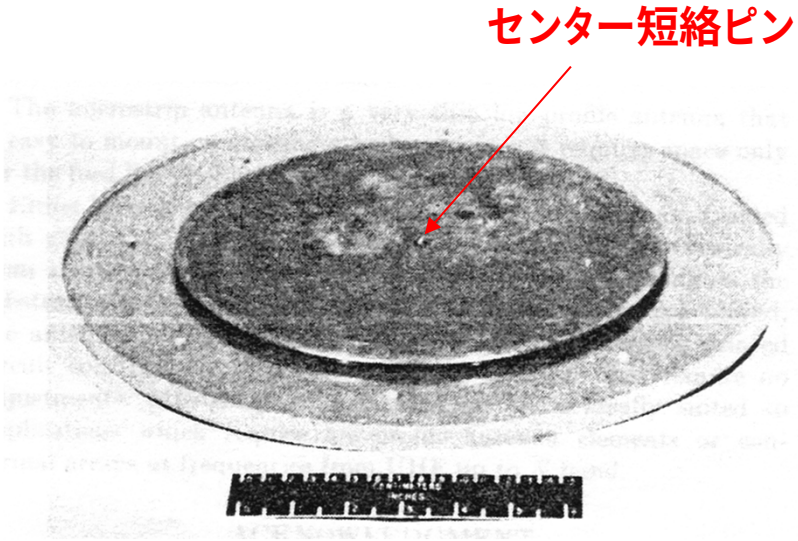
図(c) の円偏波アンテナについては、1972年のHowell の論文[7]より数か月先行している。

[7] Howell の論文(1972)　提案アンテナの構造と論文の要点

MSA による円偏波励振



(a) 共平面給電円偏波矩形MSA



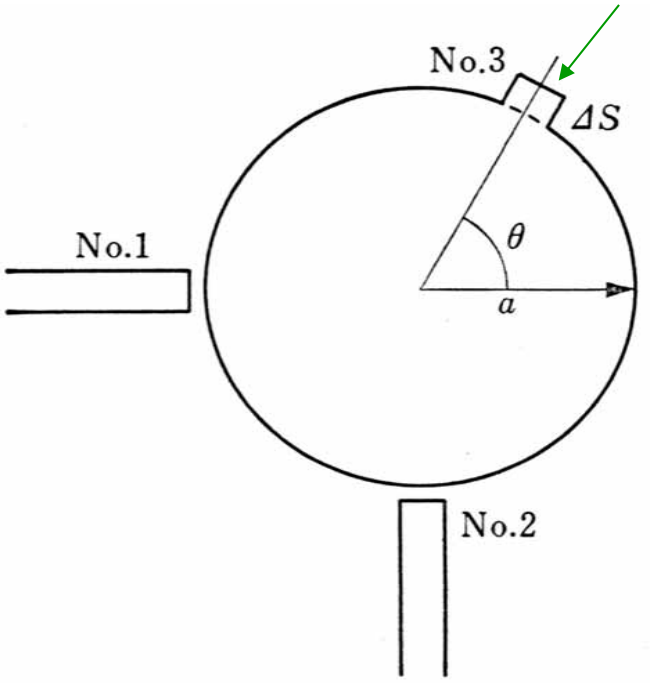
(b) 背面給電円偏波円形MSA

Munson の論文[6] より数か月遅れて発表、
しかし、Howell がこの論文の内容とそれに関連した発表をまとめた
1975年の論文[13]は、**パッチアンテナの最初の論文**としてリファーされることが多い。

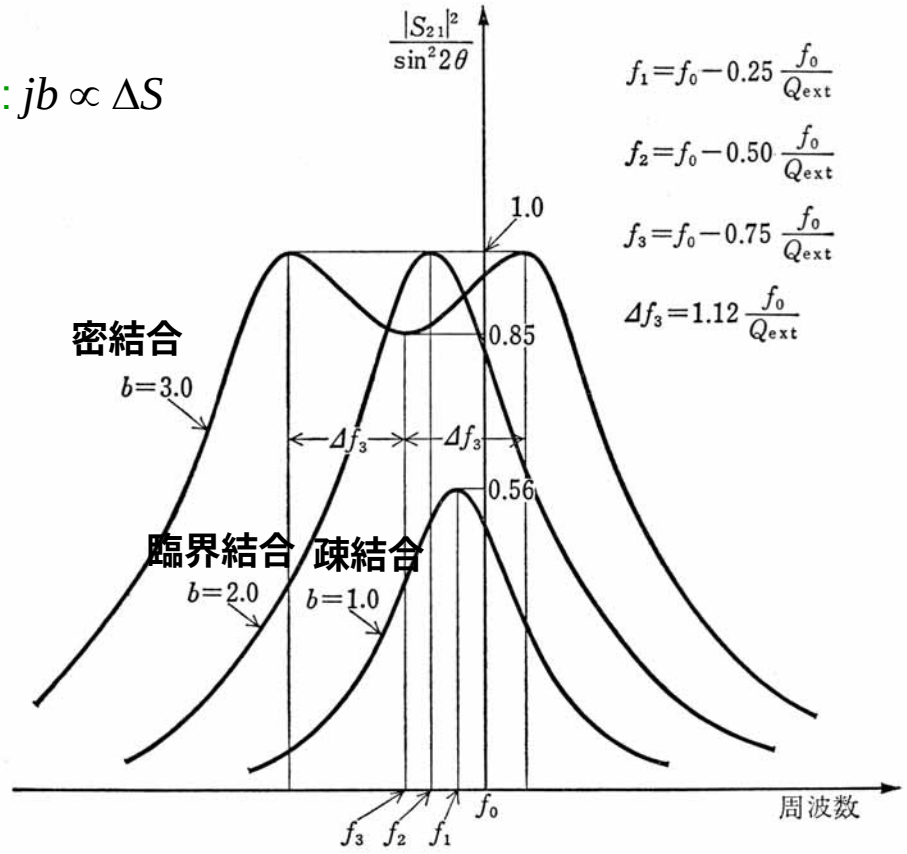
[8] 三好の論文(1972)

論文の概要

縮退分離したモード間の結合を利用した平面回路フィルタを開発



（ a ） 回路パターン



第 12・11 図　モード結合フィルタの透過特性（$Q_{ext}=Z_0'\omega_0 C$）

一点給電円偏波 MSA の動作原理の解明に貢献

[12] 小林の論文(1974)　論文の概要

平衡型円板共振器の固有値の厳密解を用いた複素誘電率の測定法を提案

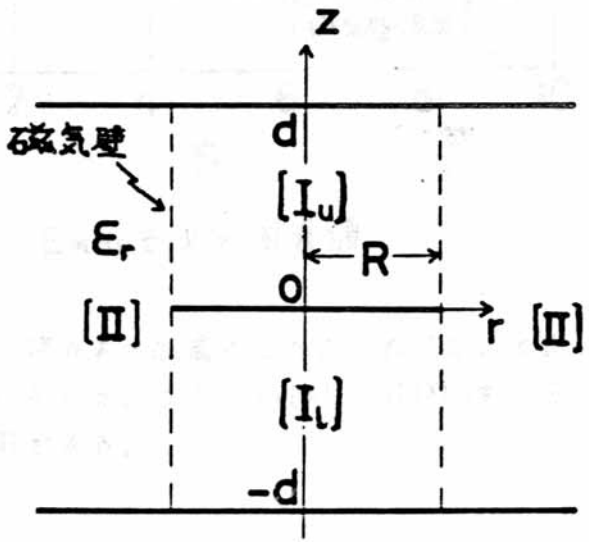


図1 平衡形円板共振器の側面図

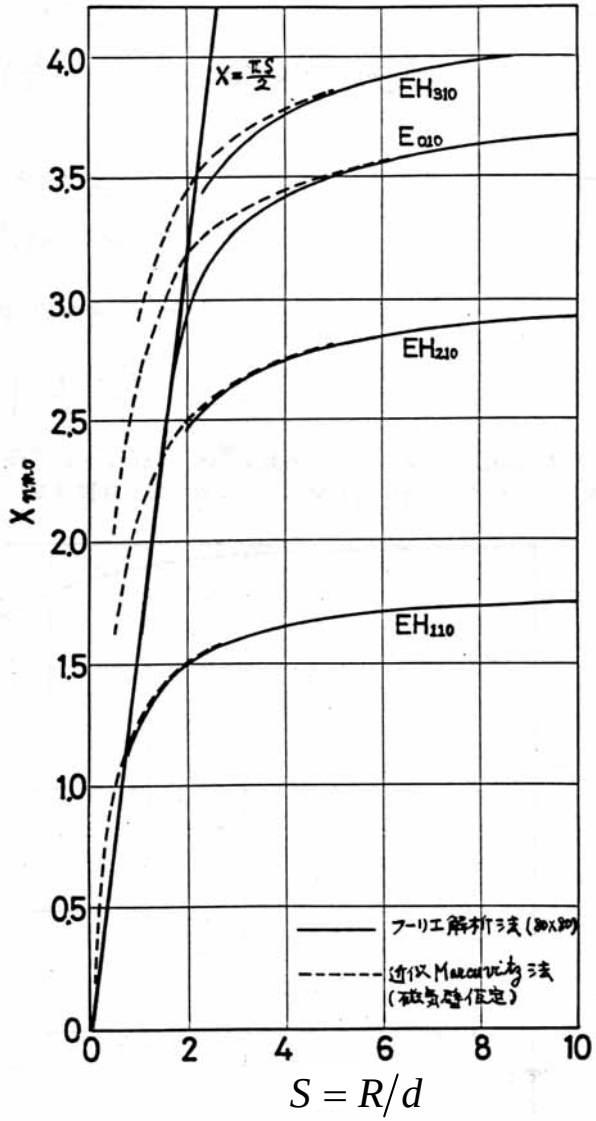


図2 Enm0モードの固有値

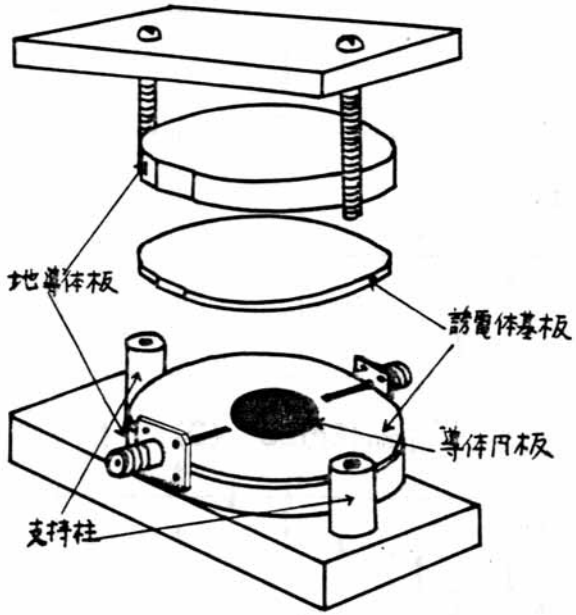


図5 平衡形円板共振器の測定装置

MSA のモード展開法による解析に貢献

比誘電率と tanδ の測定

$$\varepsilon_r = \left[\frac{\lambda_0}{2\pi R} x_{nm0}(S) \right]^2$$

$$\tan\delta = \frac{1}{Q_0} - \frac{1}{Q_c}$$

[16] Weinschelの論文(1975)

論文の概要

五角形 MSA から
一点給電で円偏波を励振

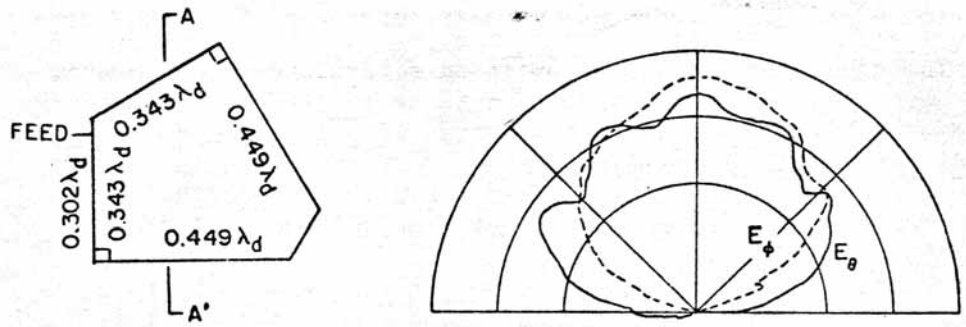


Fig. 1 and 2 Sketch and pattern of the unit element in the A-A' plane

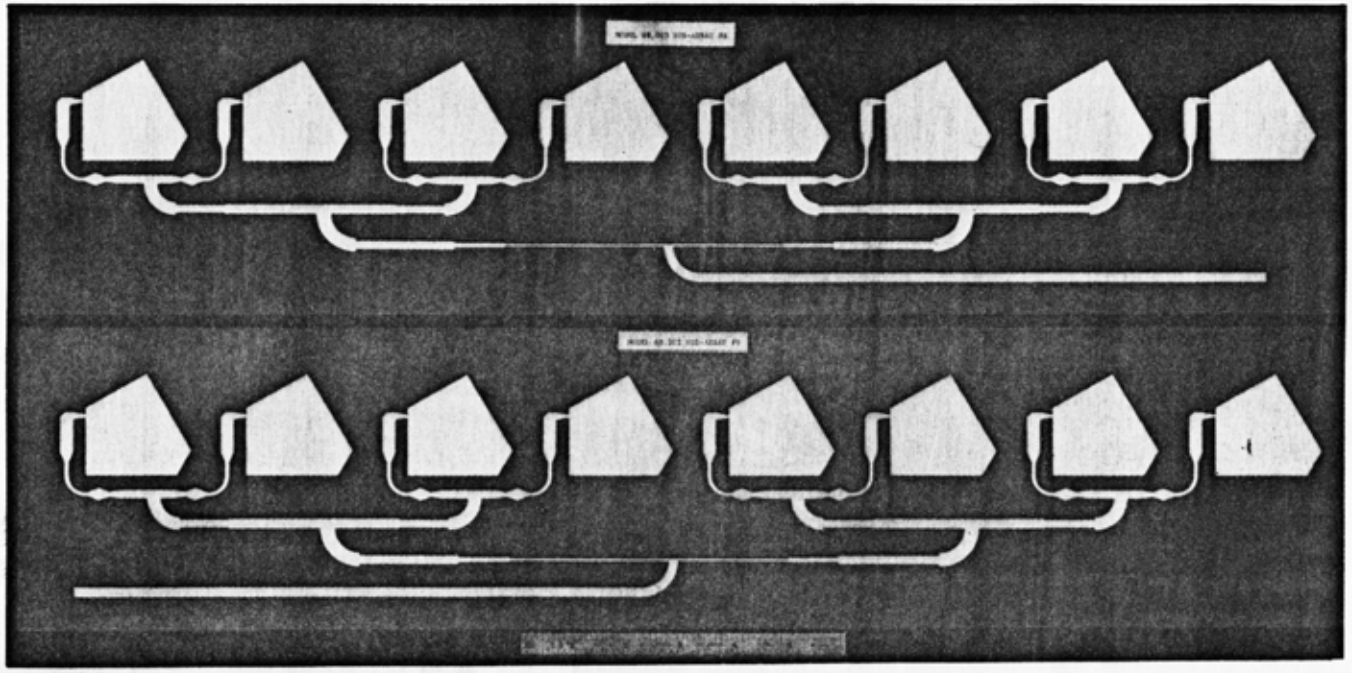


Fig. 6 Circularly Polarized S-Band Microstrip Array

[18] Derneryd の論文(1976) | 論文の概要(1/2)

伝送線路モデルにより矩形 MSA を解析

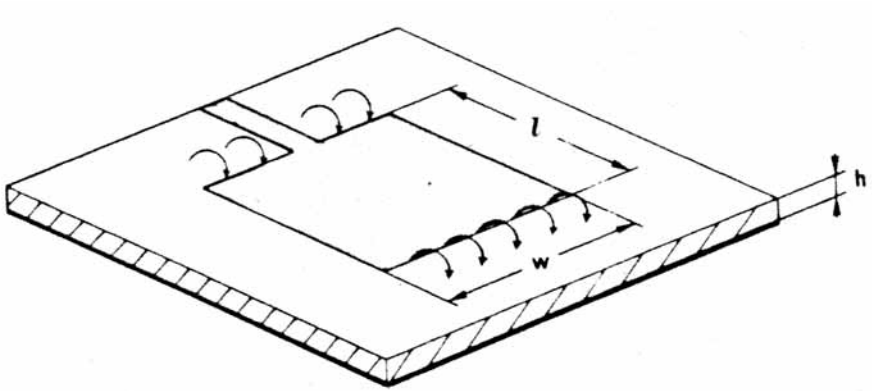


Fig. 1. Linearly polarized microstrip radiating element.

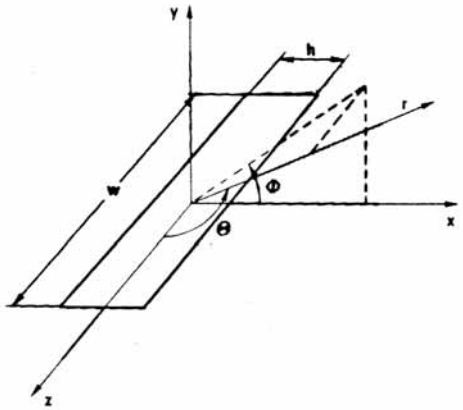


Fig. 2. Geometry of radiating slot.

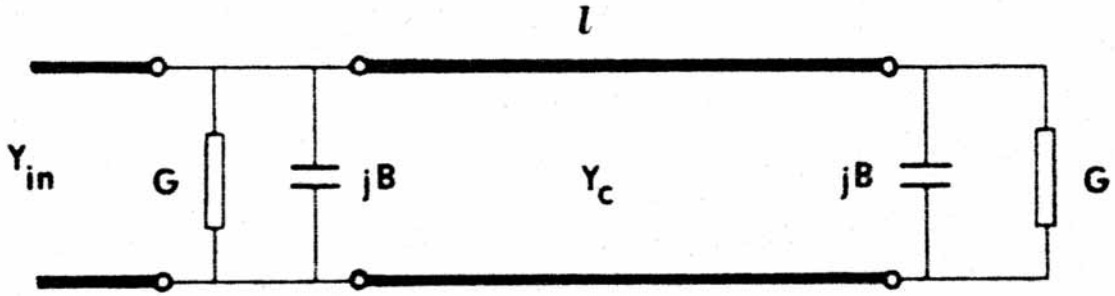


Fig. 5. Equivalent network of microstrip radiating element.

[18] Derneryd の論文(1976)　論文の概要(2/2)

伝送線路モデルにより矩形 MSA アレーを解析

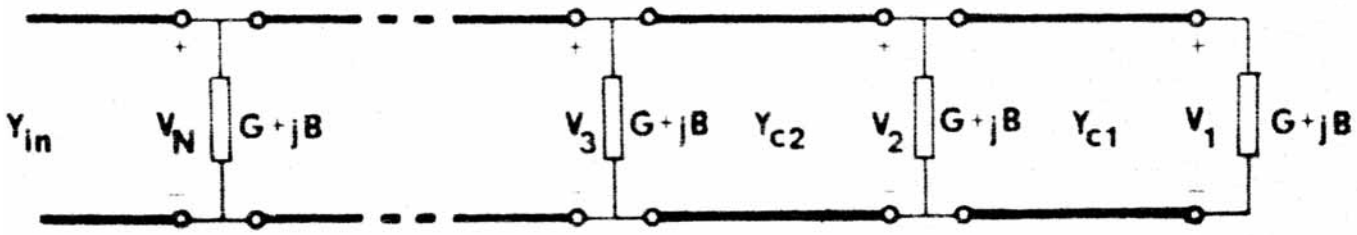


Fig. 9. Equivalent network of linear microstrip array.

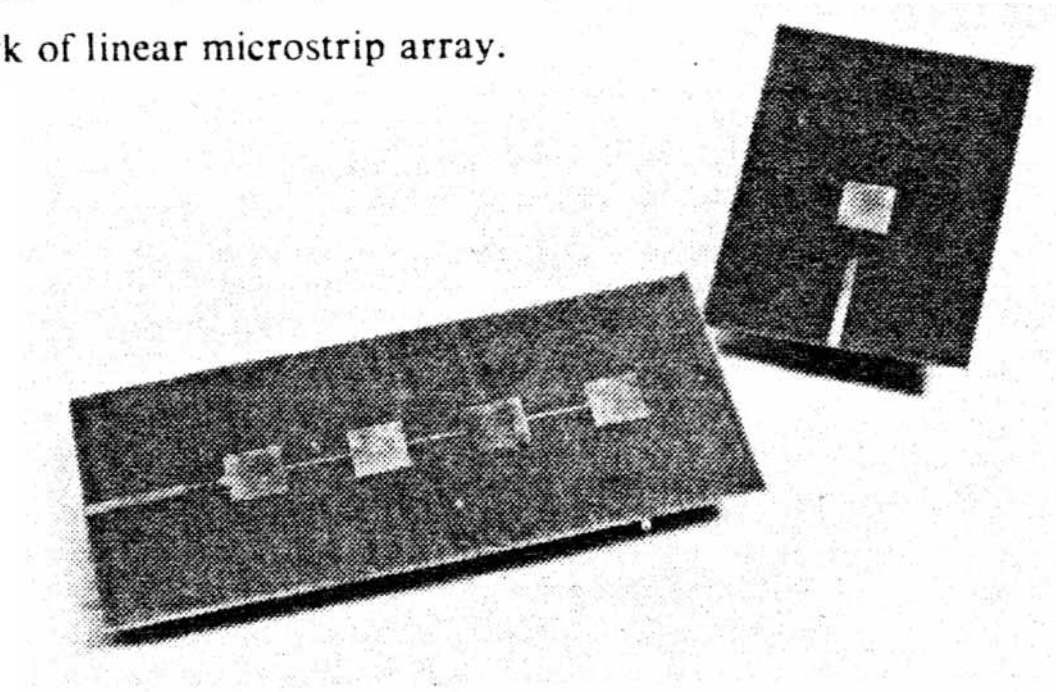


Fig. 10. Microstrip antennas for X band.

[21] Y. T. Lo の論文(1977)

論文の要点

[21] Y. T. Lo, D. D Harrison, D. Solomon, G. A. Deschamps and F. R. Ore, “Study of microstrip antennas, microstrip phased arrays, and microstrip feed networks,” Rome Air Development Center, Tech. Rep. TR-77-406, Oct. 1977.

MSA をcavity model に基づき変数分離法で解析

- [26]では、変数分離法で解析可能な種々の形状のMSAを取り上げている。
- また、開放境界 cavity model に基づく円偏波励振の話については、W. Richardsが[32]にまとめている。

なお、

- 1974年に Howellは、既にMSA と開放境界 cavity model の類似性を指摘しているが、
- Lo と彼の学生による共同研究が生き残る形となった。

また、

- 1978年には、J. P. Montgomery が “full wave annalists” の提案を行っている[25]が、
- Lo 等による開放境界 cavity model についての展開に先を越され、その有用性を発揮するまで長い時間を要することになった。

[22] Breichaの論文(1978)

論文の概要

Seasat-A Synthetic Aperture Radar Antenna への展開

ハニカム基板の採用

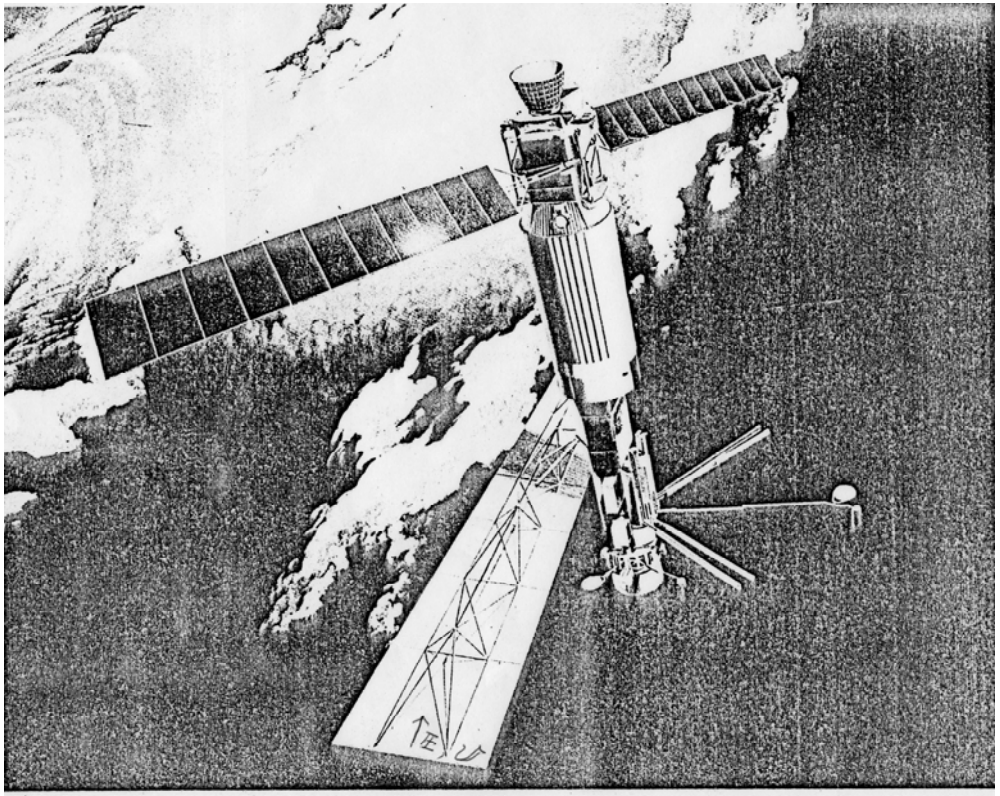


Figure 1. Seasat-A

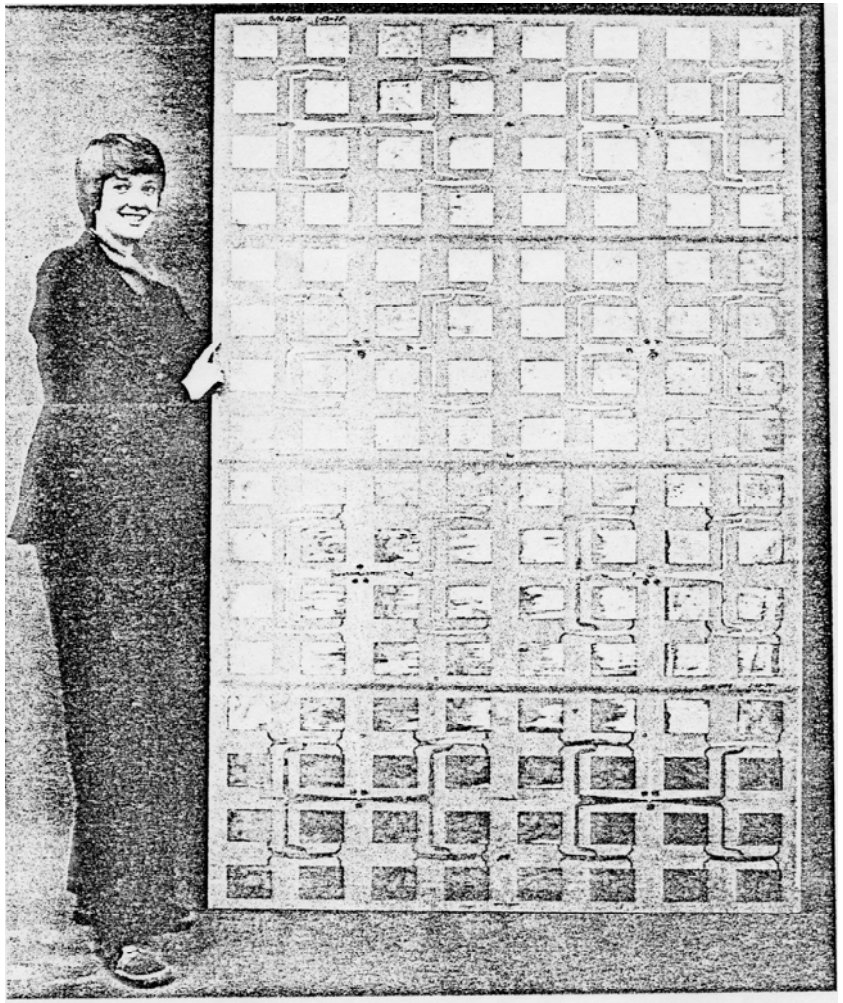
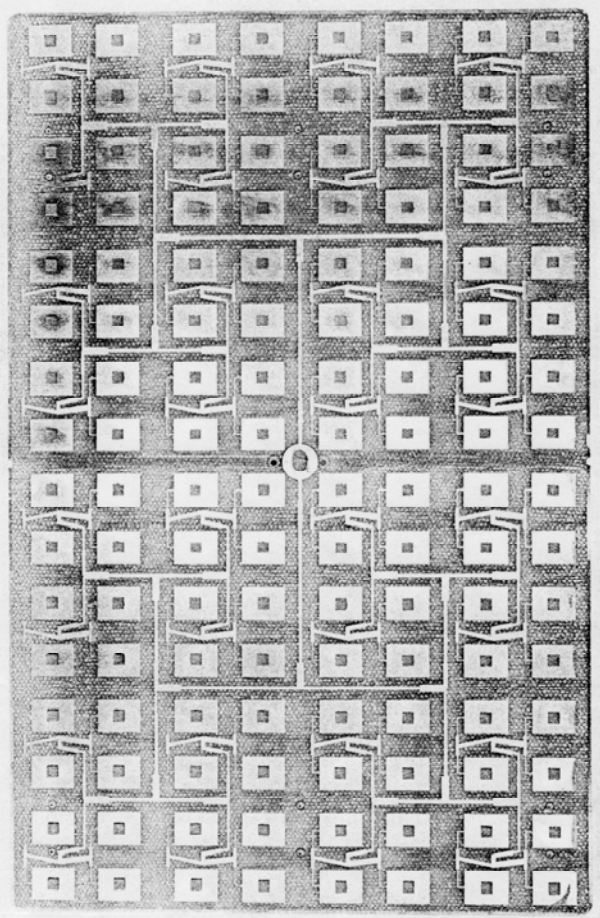


Fig. 7. SAR Antenna Panel

[34] Murphyの論文(1979)　論文の要点

SIR-A と Seasat の比較

SIR-A (共平面給電)



Shuttle Imaging Rader Panel

Ball Aerospace Systems が開発

Seasat (共平面+背面同軸給電)

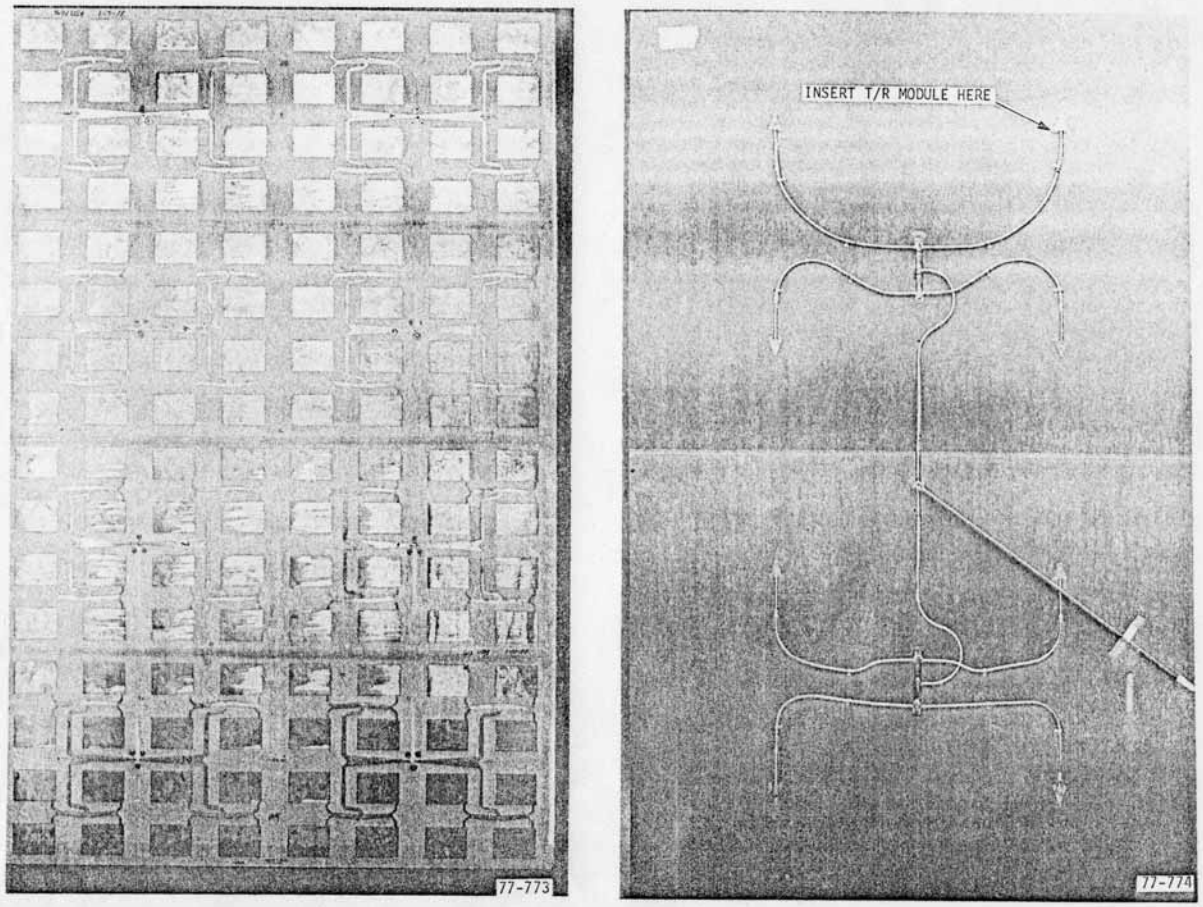


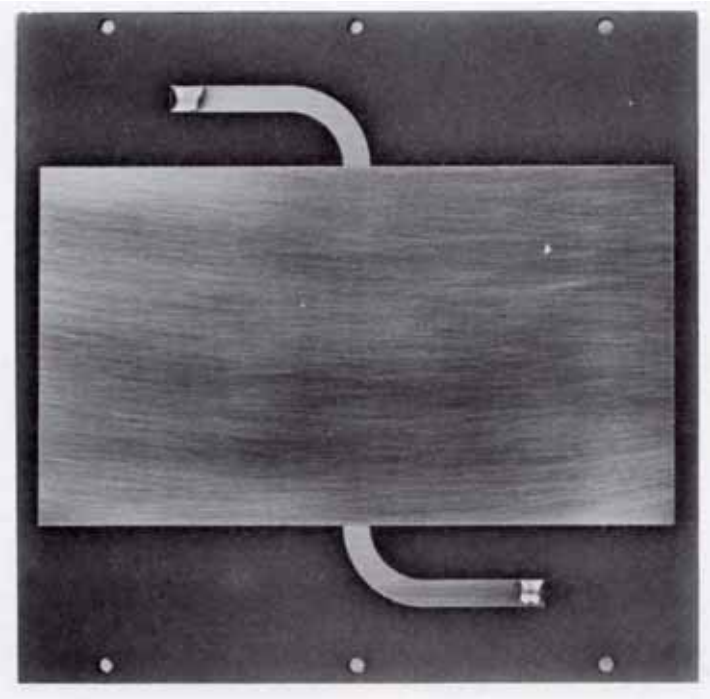
Figure 6 SEASAT Antenna Panel

Jet Propulsion Lab. と Ball Brothers Research Corp. の共同開発

[23] J. L. Kerr の論文(1978)

論文の概要

リアクタンスを装荷することで、動作周波数の調整や、インピーダンス整合のための調整ができることを示す。



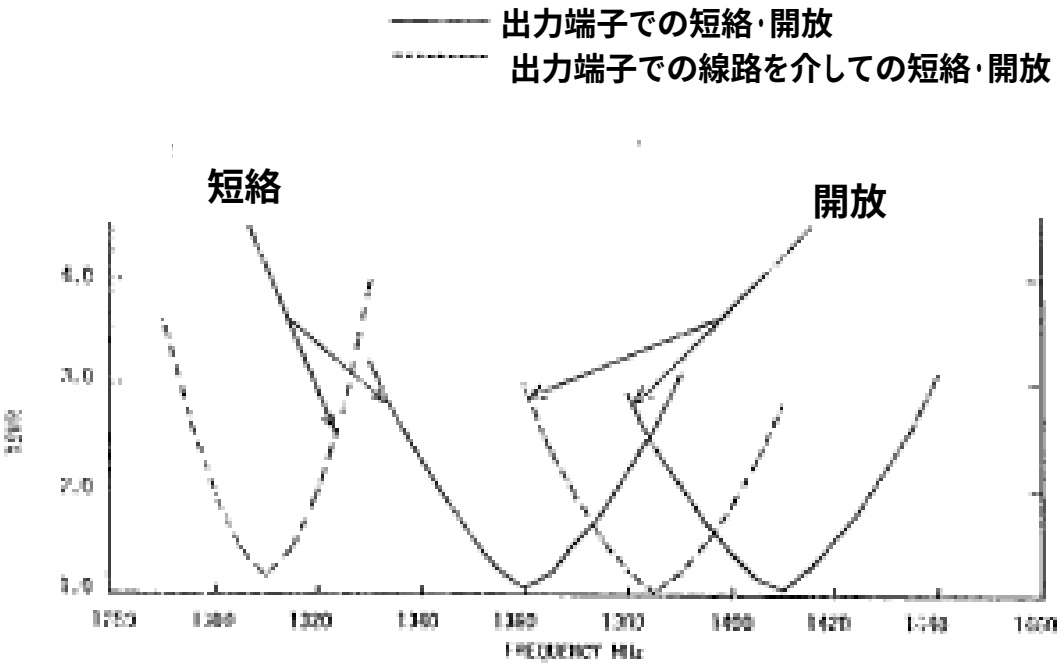


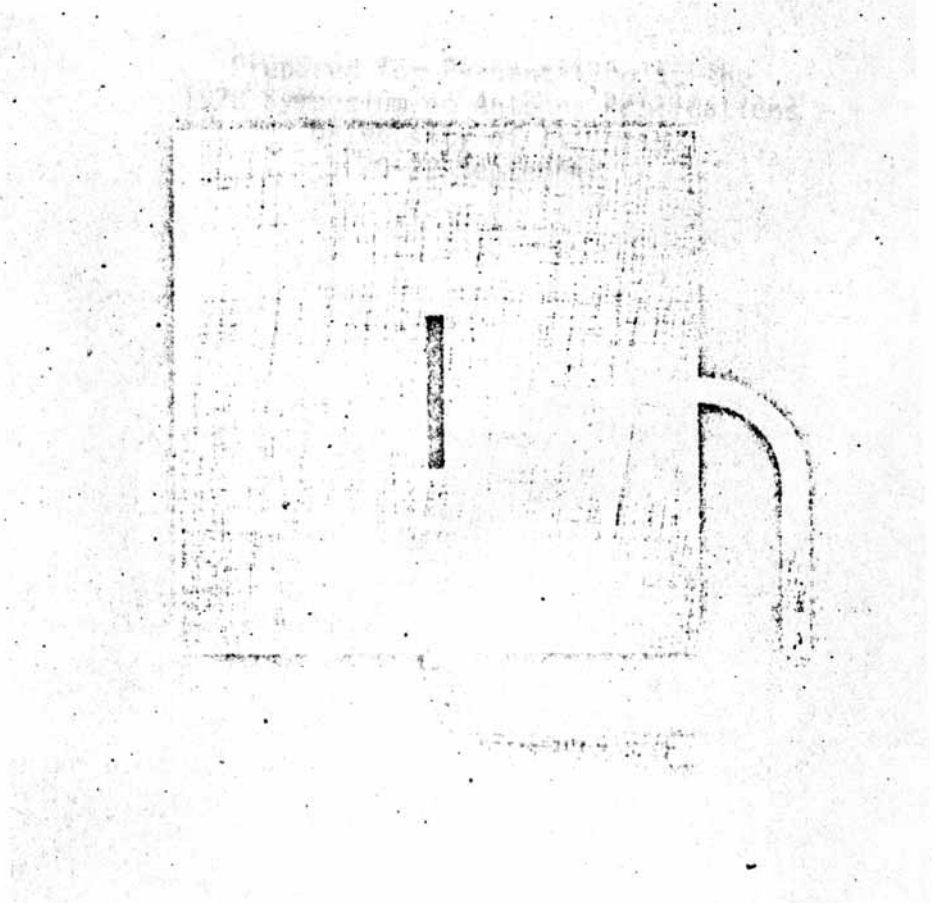
Fig. 3. Kerr's results for frequency tuning by open-circuit and short- circuit loads at two locations.

付加マイクロストリップ線路の先端を開放した場合と短絡した場合の線路の長さをパラメータとしたときのVSWR特性の実測例

しかし、この方法で強引にマッチングを取っても、放射指向性は良好なものにならないことも指摘。

[24] J. L. Kerr の論文(1978) | 論文の概要(1/3)

MSA に下図のようにスロットを切ることで共振周波数が下かることを示す



DUAL-FREQUENCY
ORTHOGONALLY POLARIZED RADIATOR

FIGURE 14

[24] J. L. Kerr の論文(1978)

論文の概要(2/3)

MSA に下図のようにスロットを切ることで一点給電で円偏波が励振でることを示す

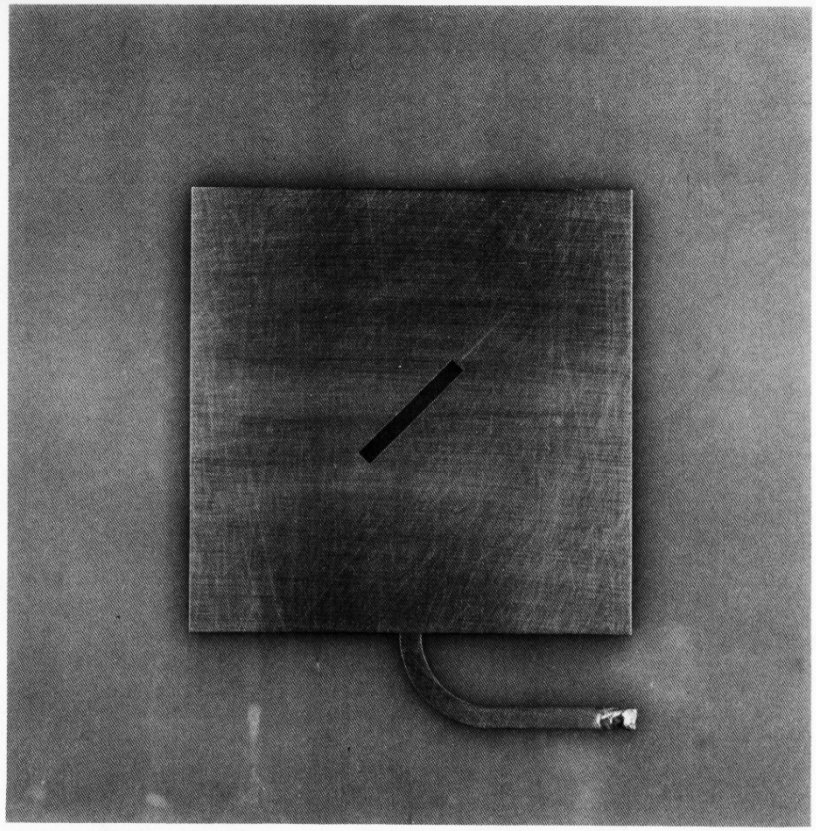
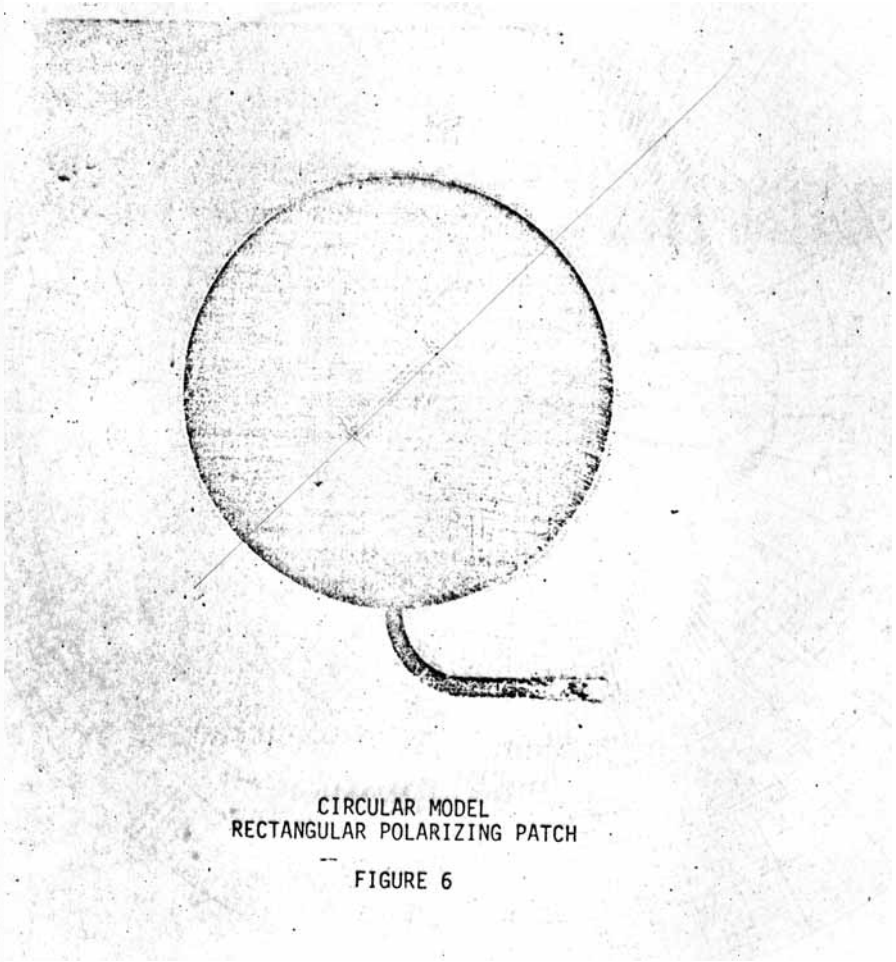


Figure 8. CP Square Microstrip Radiator



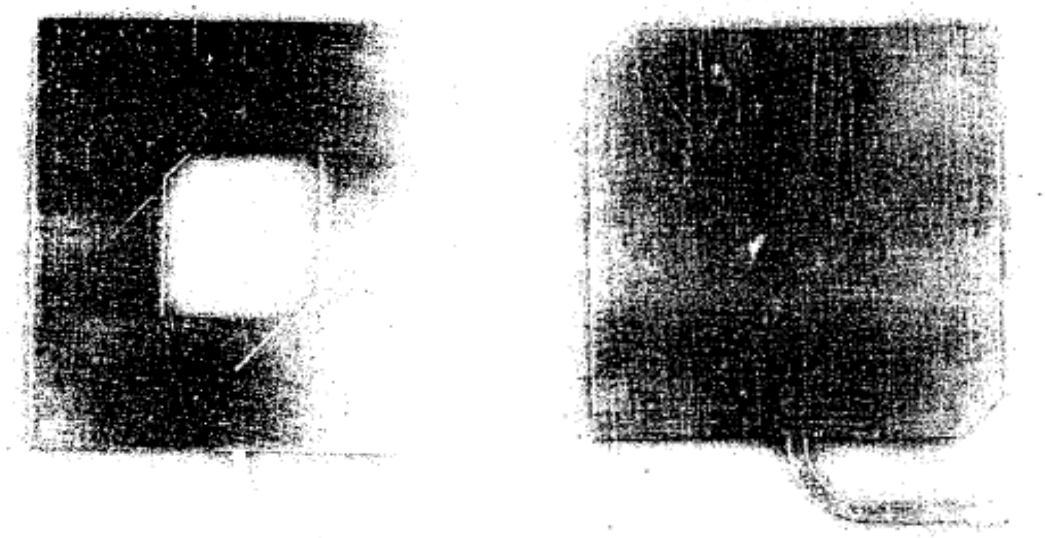
CIRCULAR MODEL
RECTANGULAR POLARIZING PATCH

FIGURE 6

[24] J. L. Kerr の論文(1978)　論文の概要(3/3)

種々の一点給電円偏波 MSA を提案

Fig. 4. Corner-fed square patch antenna with horizontal slot to lower vertically polarized resonance slightly, resulting in circularly polarized antenna.



(a)　(b)

Fig. 7. Two patches produce circular polarization.
(a) Square patch with square central hole that has opposite corners clipped.
(b) Square patch with opposite corner clipped. .

この論文と以下の論文は、その後の MSA の発展に大きな影響を及ぼすことになる

[19] J. L. Kerr, “Other Microstrip Antenna Applications,” Proc. of the 1977 Antenna Applications Symposium, April 27-29, 1977.

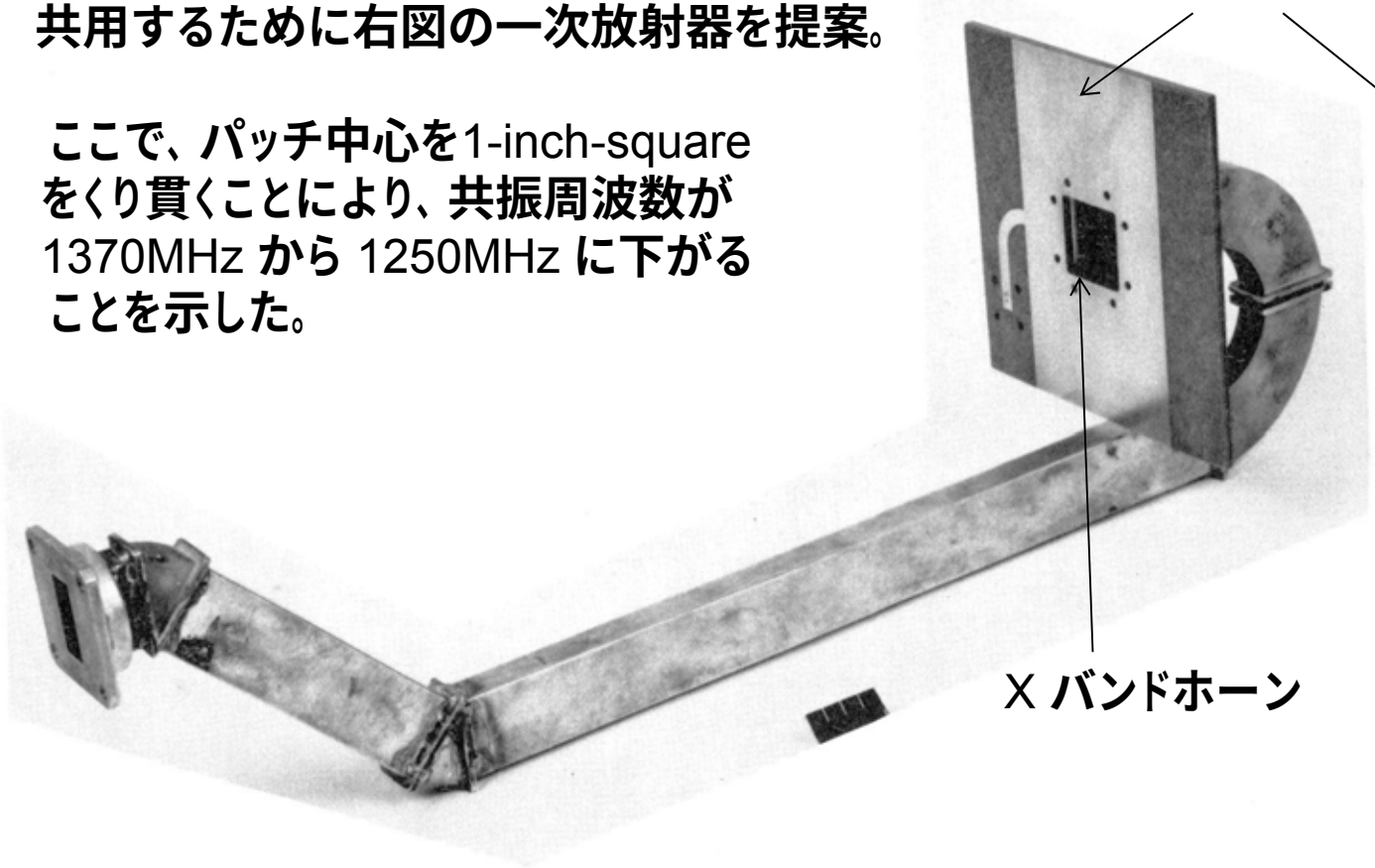
[23] J. L. Kerr, “Terminted Microstrip Antenna,” Proc. of the 1978 Antenna Applications Symposium, September 20-22, 1978.

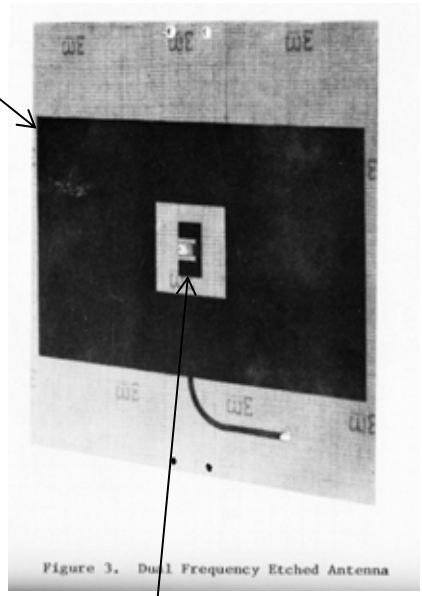
[35] J. L. Kerr の論文(1979)　論文の概要

種々の周波数共用 MSA を開発

・X バンドの既存のリフレクタを L バンドと共用するために右図の一次放射器を提案。

ここで、パッチ中心を1-inch-square をくり貫くことにより、共振周波数が 1370MHz から 1250MHz に下がることを示した。





L バンド MSA

X バンドホーン

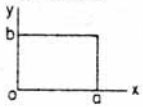
X バンド MSA

[26] Y. T. Lo の論文(1979)　論文の概要

変数分離法で解析できる形状の種々の MSA を列挙

TABLE I

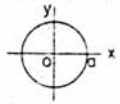
RECTANGLE



$$\psi_{mn} = \cos\frac{m\pi}{a}x \quad \cos\frac{n\pi}{b}y$$

$$k_{mn} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$$

CIRCLE (DISK)



$$\psi_{mn} = J_n(k_{mn}\rho)e^{jn\phi}$$

$$J_n'(k_{mn}a) = 0$$

CIRCULAR SEGMENT

$$\psi_{m\nu} = J_\nu(k_{m\nu}\rho)\cos\nu\phi$$

$$\nu = n\pi/\alpha, \quad J_\nu'(k_{m\nu}a) = 0$$

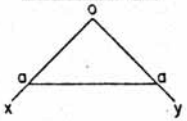
DISK WITH SLOT

$$\psi_{mn} = J_{n/2}(k_{mn}\rho)\cos n\phi/2$$

$$J_{n/2}'(k_{mn}a) = 0$$

$$\alpha \approx 2\pi, \quad \nu = n/2$$

RIGHT ISOSCELES



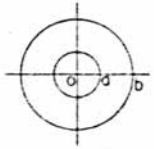
(a) $\psi_m = \cos\frac{m\pi}{a}x - \cos\frac{m\pi}{a}y$

$k_m = \sqrt{2}\,\frac{m\pi}{a}$

(b) $\psi_m = \cos\frac{m\pi}{a}x \quad \cos\frac{m\pi}{a}y$

$k_m = \sqrt{2}\,\frac{m\pi}{a}$

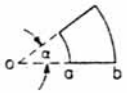
CIRCULAR RING



$$\psi_{mn} = \left[N_n'(k_{mn}a)\,J_n(k_{mn}\rho) - J_n'(k_{mn}a)\,N_n(k_{mn}\rho)\right]e^{jn\phi}$$

$$\frac{J_n'(k_{mn}a)}{N_n'(k_{mn}a)} = \frac{J_n'(k_{mn}b)}{N_n'(k_{mn}b)}$$

CIRCULAR RING SEGMENT

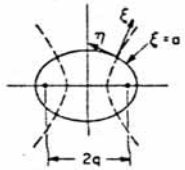


$$\psi_{mn} = \left[N_\nu'(k_{m\nu}a)\,J_\nu(k_{m\nu}\rho) - J_\nu'(k_{m\nu}a)\,N_\nu(k_{m\nu}\rho)\right]\cos\nu\phi$$

$$\nu = n\pi/\alpha$$

$$\frac{J_\nu'(k_{m\nu}a)}{N_\nu'(k_{m\nu}a)} = \frac{J_\nu'(k_{m\nu}b)}{N_\nu'(k_{m\nu}b)}$$

ELLIPSE



EVEN-MODES:

$$\psi_{mn} = Re_m(\xi, \chi e_n)\,Se_m(\eta, \chi e_n)$$

$$Re_m(\alpha, \chi e_n) = 0, \quad \chi e_n = kq$$

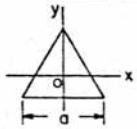
major axis $= 2q\cosh\alpha$

minor axis $= 2q\sinh\alpha$

ODD-MODES:

Replacing e by o in the above.

EQUILATERAL TRIANGLE



$$\psi_{mn} = \cos\frac{2\pi L}{3b}\left(\frac{u}{2}+b\right)\cos\frac{\pi(m+n)(v-w)}{9b} + \cos\frac{2\pi m}{3b}\left(\frac{u}{2}+b\right)\cos\frac{\pi(n-L)(v-w)}{9b} + \cos\frac{2\pi n}{3b}\left(\frac{u}{2}+b\right)\cos\frac{\pi(L-m)(v-w)}{9b}$$

$$L = -(m+n), \quad u = \frac{\sqrt{3}}{2}x + \frac{1}{2}y,$$

$$v - w = -\frac{\sqrt{3}}{2}x + \frac{3}{2}y, \quad b = a/2\sqrt{3},$$

$$k_{mn}^2 = \left(\frac{4\pi}{3a}\right)^2(m^2 + n^2 + mn)$$

おそらく、シェルクノフの原本も間違っている

[28] S. A. Long の論文(1979)　論文の概要

非励振素子装荷による複共振化 $(a_1 < a_2)$

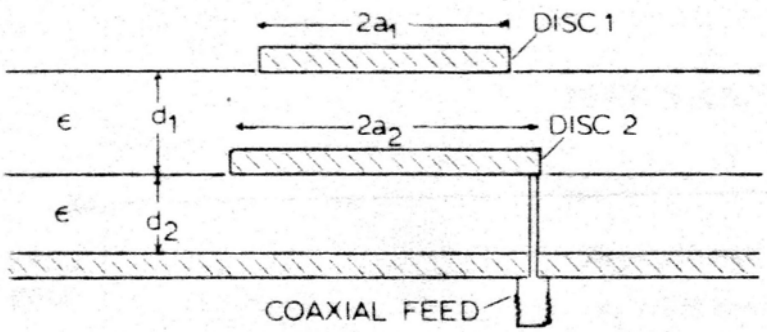


Fig. 1. Stacked circular-disc antenna structure.

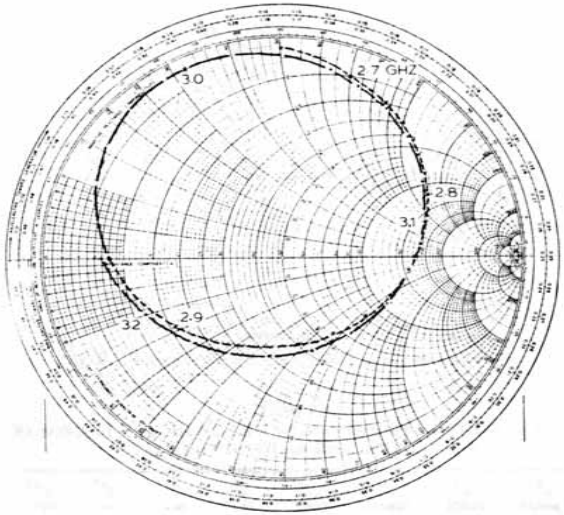


Fig. 2. Smith chart impedance of stacked structure.

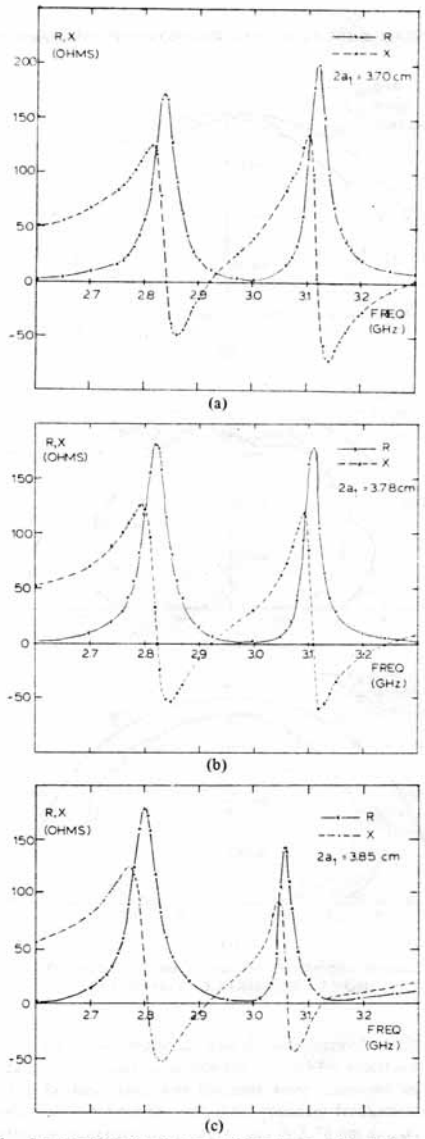


Fig. 3. Real and imaginary parts of impedance of stacked structure. (a) $2a_1$ = 3.70 cm. (b) $2a_1$ = 3.78 cm. (c) $2a_1$ = 3.85 cm.

[29] 多賀 の論文(1979)　論文の概要

非励振素子装荷による広帯域化 $(b > a)$

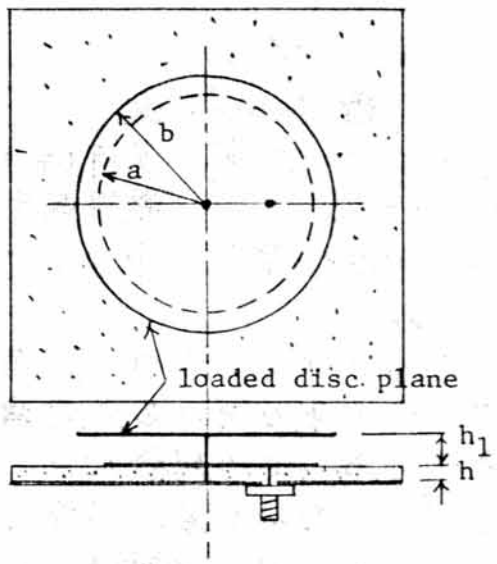


図5. 円板を装荷した Microstrip Antenna

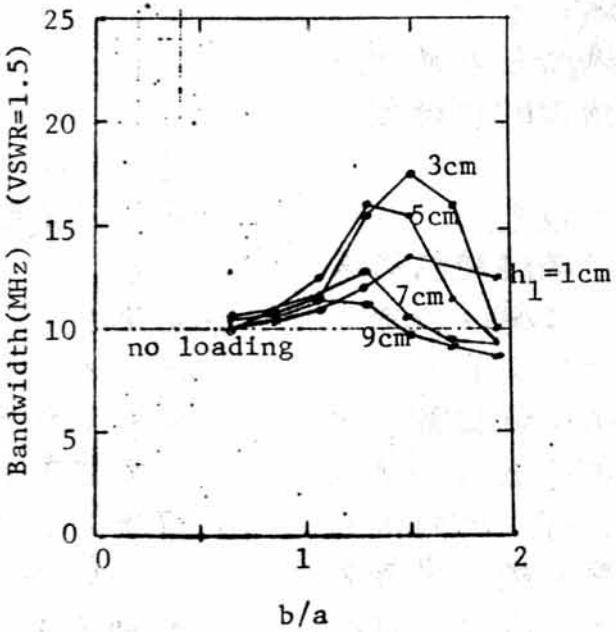


図6. 半径と帯域幅（実験値）

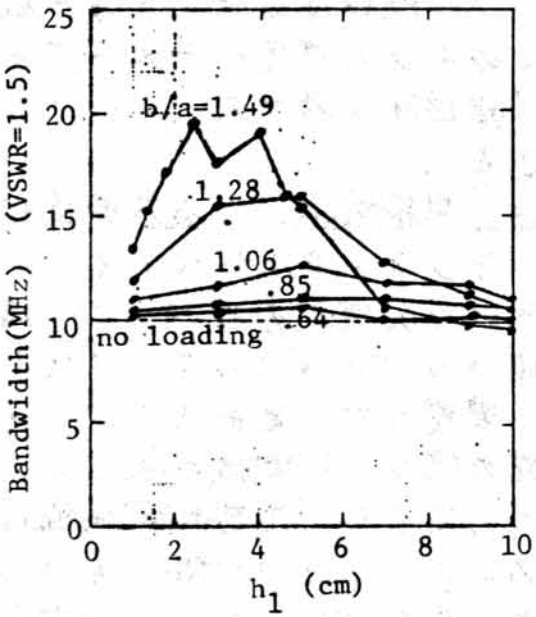


図7. 高さと帯域幅（実験値）

[30] Carverの論文(1979)

論文の概要

Modal Expansion Theory により矩形 MSA を解析

The input impedance to a coaxial probe-fed rectangular patch may be found from the modal expansion to be

$$Z_{in} = j X_L - j \frac{t\,\omega}{\varepsilon ab} \sum_m \sum_n \frac{X_{mn}^2 \cos^2 \frac{m\pi y_o}{b} \cos^2 \frac{n\pi x_o}{a}}{\omega^2 - \omega_{mn}^2 \left(1 + \frac{j}{Q_{mn}}\right)} \qquad (2)$$

放射損と導体損のモード依存を考慮？

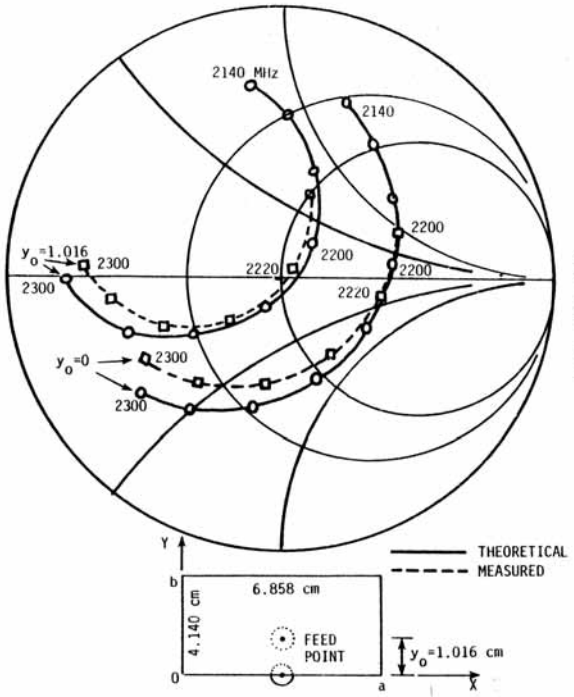
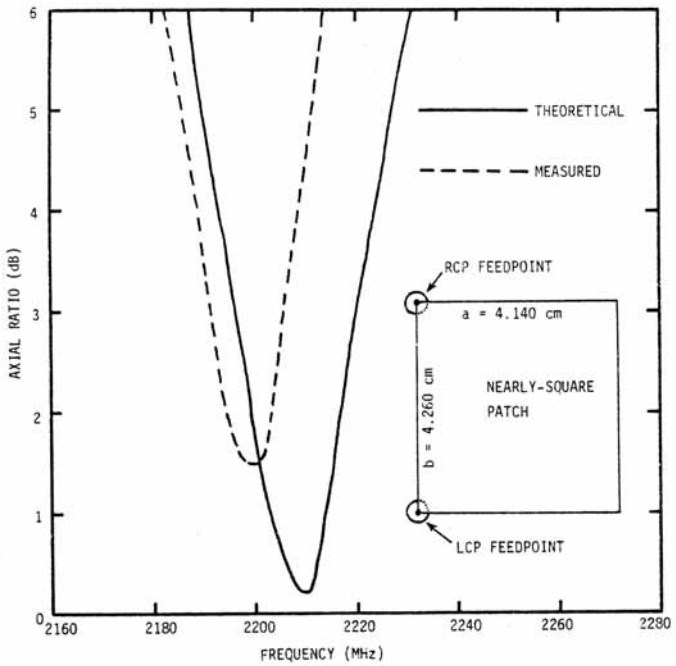


Fig. 1. Theoretical & measured input impedances to rectangular microstrip patch antenna fed by coaxial probe at two locations.



一点給電円偏波励振時の軸比特性

Fig. 2. Theoretical & measured on-axis axial ratio vs. frequency for S-band nearly-square corner-fed microstrip patch.

[31] Richardsの論文(1979) | 論文の概要(1/2)

Cavity Model に基づく 変数分離法 により矩形と円形 MSA を解析

x-y plane is considered. The electric field in the cavity can be written as

ストリップ線路による共平面給電

誘電体損のみを考慮？

$$\mathbf{E} = \hat{\mathbf{z}} j k_0 \eta_0 \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{\phi_{mn}(x,y)\phi_{mn}(x',y')}{k^2 - k_{mn}^2} j_0\left(\frac{m\pi d}{2a}\right) \tag{1}$$

where $k^2 = \epsilon_r(1-j\delta)k_0^2$, $k_0 = 2\pi f/v$, f = frequency, v = speed of light, ϵ_r = relative dielectric constant, δ = loss tangent of dielectric, $\eta_0 = 377\Omega$, $k_{mn}^2 = (m\pi/a)^2 + (n\pi/b)^2$, $j_0(x) = \sin(x)/x$, $\phi_{mn}(x,y) = \left(\frac{\epsilon_{0m}\epsilon_{0n}}{ab}\right)^{1/2} \cos(m\pi x/a)\cos(n\pi y/b)$, $\epsilon_{0m} = 1$ for $m=0$ and 2 for $m \neq 0$, and d is the "effective width" of a uniform strip of z directed source current of one amp at (x',y'). The inner series in (1) can be summed in closed form. This is equivalent to

Thus, Z_{11} and Z_{22} are computed in precisely the same way as was the input impedance for the one port discussed earlier. The mutual impedance, Z_{12}, is computed using

$$Z_{12} = -j\omega\mu_0 t \sum_{m,n} \frac{\phi_{mn}(x_1,y_1)\phi_{mn}(x_2,y_2)}{k^2 - k_{mn}^2} j_0^2\left(\frac{m\pi d}{2a}\right)$$

From the Z parameters, the S parameters can be easily computed and compared with measured results as shown in Fig. 3 for the case of a rectangular microstrip. It is seen that the agreement is excellent.

[31] Richardsの論文(1979)

論文の概要(2/2)

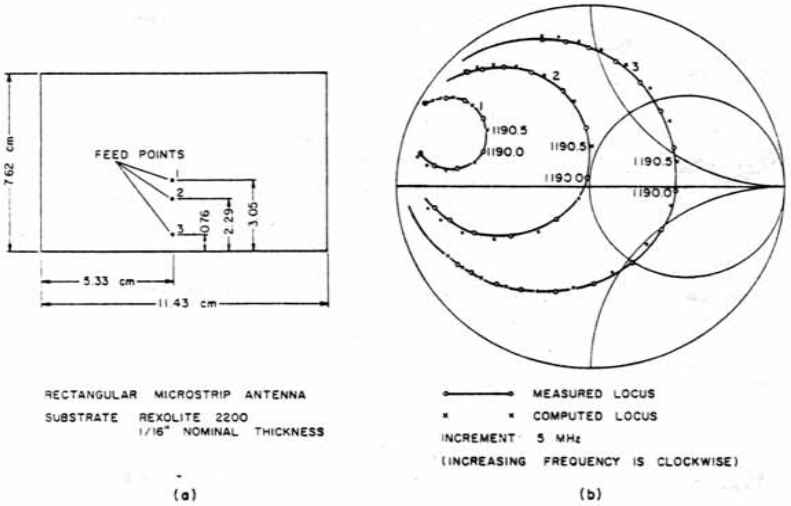


Fig. 1 (a) Dimensions and feed locations of rectangular microstrip antenna.
(b) Measured and computed impedance loci.

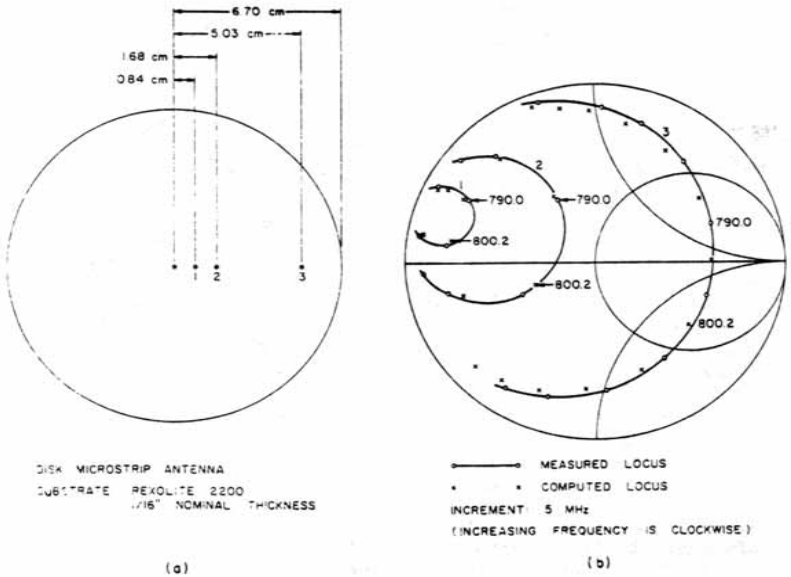


Fig. 2 (a) Dimensions and feed locations of circular disk microstrip antenna. (b) Measured and computed impedance loci.

[32] Richardsの論文(1979) | 論文の概要(1/2)

一点給電円偏波矩形 MSA の円偏波励振条件を導出

$$\frac{E_y}{E_x} \approx A\frac{k^2 - k_{10}^2}{k^2 - k_{01}^2} \approx A\frac{k - k_{10}}{k - k_{01}}. \tag{2}$$

It is particularly illuminating to plot k, k_{01}, and k_{10} in the complex k plane as was done in Fig. 2. For E_y/E_x to be $e^{j\pi/2}$, equation (2) requires that

$$\Delta k = k_{01} - k_{10} = L(A + \frac{1}{A}). \tag{3}$$

But

$$\frac{L}{\bar{k}} \approx \frac{1}{2}\delta_{\text{eff}} = \frac{1}{2Q}, \tag{4a}$$

$$k_{01} - k_{10} = \frac{\pi}{b} - \frac{\pi}{a} = \frac{\pi}{b} - \frac{\pi}{b+c} \approx \frac{\pi c}{b^2}, \tag{4b}$$

$$\bar{k}b \approx \pi. \tag{4c}$$

(The parameters $\bar{k}$ and L are defined in Fig. 2.) Thus, combining (3) with (4),

$$\frac{\Delta k}{\bar{k}} = \frac{k_{01} - k_{10}}{\bar{k}} \approx \frac{c}{b} \approx \frac{A + \frac{1}{A}}{2Q}.$$

For the case of the feed point taken on the diagonal of the microstrip, $A=1$ and therefore

$$\boxed{\frac{a}{b} = 1 + \frac{1}{Q}.}$$ **：円偏波励振条件**

The sense of rotation of the CP wave produced by the antenna fed at point 2 will be left hand circularly polarized. By simply feeding at point 4 instead, the sense is reversed.

[32] Richardsの論文(1979) | 論文の要点(2/2)

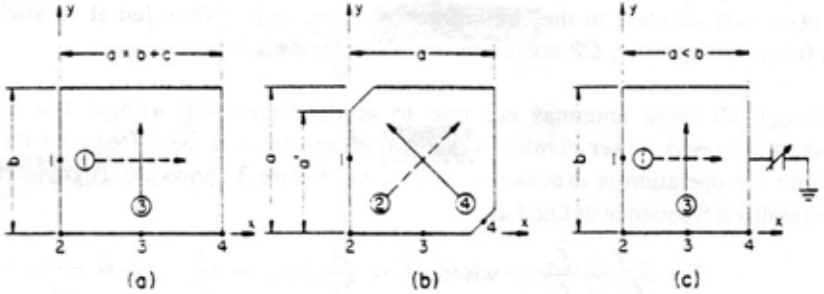


Fig. 1. CP antenna configurations. (Arrows on patches indicate polarization of far field at zenith when fed at numbered feed)

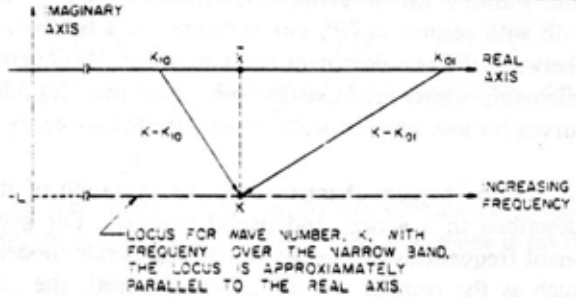


Fig. 2. Poles and locus of k in complex k plane.

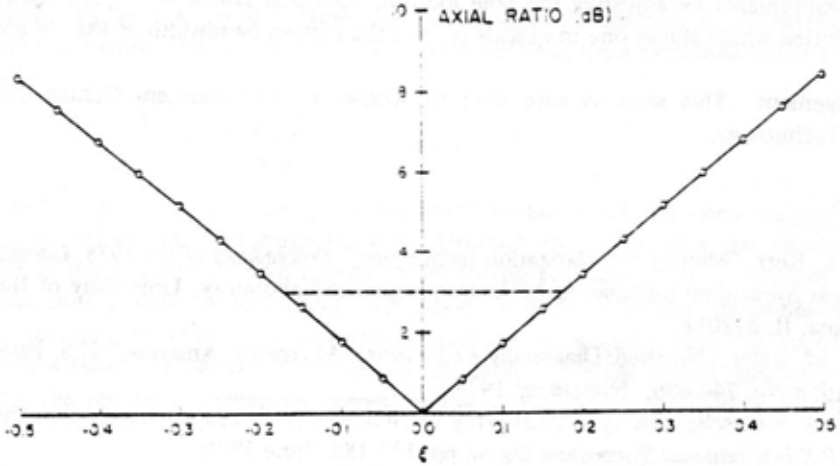


Fig. 3. Axial ratio of CP antennas vs normalized frequency.

[38] 羽石の論文(1980)

論文の概要

等価回路モデルに基づく一点給電円偏波円形 MSA の円偏波励振条件を導出

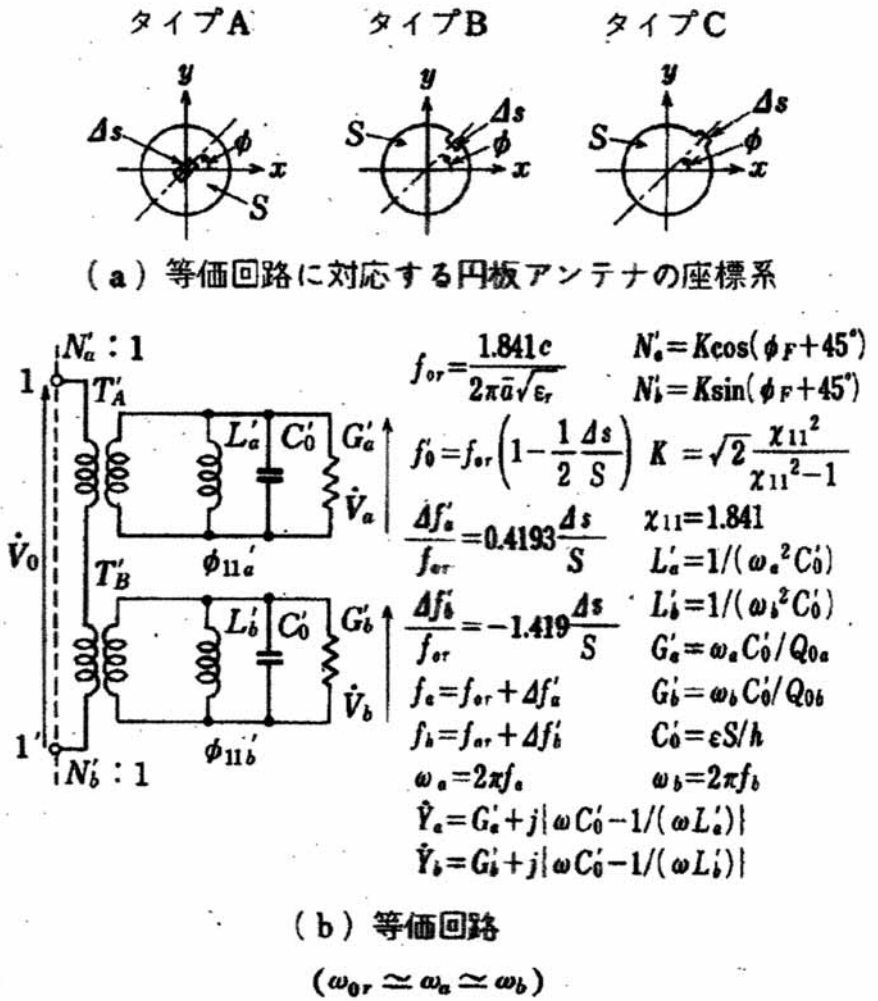


図 11　摂動後の円板アンテナの等価回路

Fig.11–Equivalent circuits of microstrip disk antenna after perturbation.

$$\left|\frac{\dot{V}_b}{\dot{V}_a}\right|=1,\qquad \arg\left(\frac{\dot{V}_b}{\dot{V}_a}\right)=\pm 90^\circ$$

$$\frac{\Delta s}{S}=0.03$$

円偏波励振条件

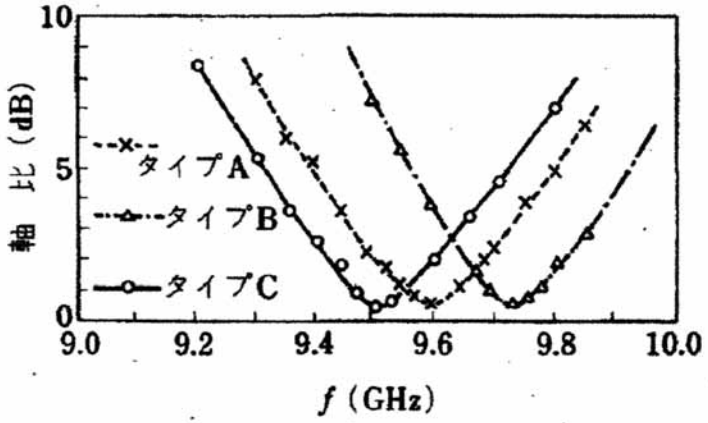


図 8　軸比の周波数特性

Fig.8–Frequency characteristics of axial ratio.

[39] 稲垣の論文(1980)　論文の概要

境界要素法 + モーメント法による 任意形状 MSA の解析

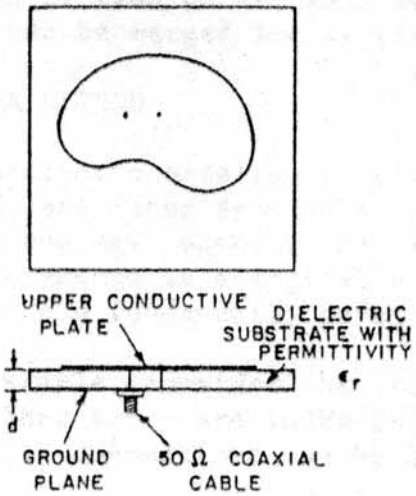


Figure 1. Structure of a micro-strip antenna.

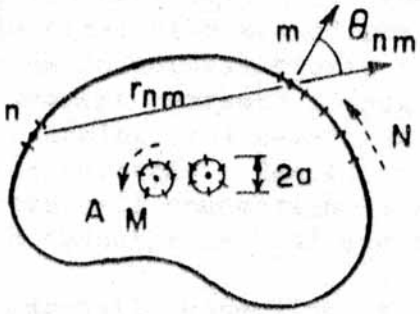


Figure 2. Subdivision of the boundary and definition of variables.

★ 境界要素法(内部電磁界の関係)

$$V = U^{-1} H I$$

$$\begin{bmatrix} V_t \\ V_a \end{bmatrix} = \begin{bmatrix} Z_{tt} & Z_{ta} \\ Z_{at} & Z_{aa} \end{bmatrix} \begin{bmatrix} I_t \\ I_a \end{bmatrix}$$

$$\because \; V = \begin{bmatrix} V_t \\ V_a \end{bmatrix}$$

$$\because \; I = \begin{bmatrix} I_t \\ I_a \end{bmatrix}$$

★ モーメント法(外部電磁界の関係)

$$I_a = Y_m V_a$$

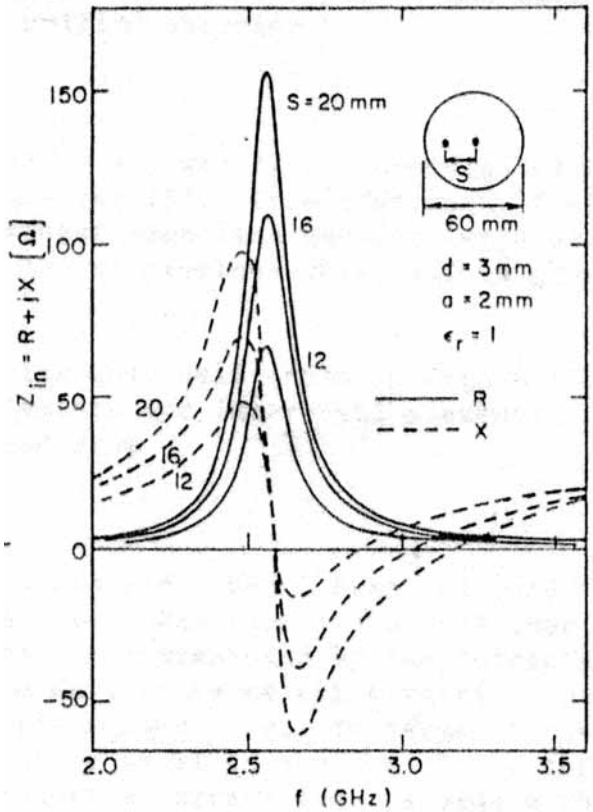


Figure 3. Calculated input impedance of a circular micro-strip antenna (N=40, M=10).

[40] Schaubert の論文(1980)　論文の概要

ショートピンを装荷することにより共振周波数が高域に移動することを示す

1977年に、円筒ポディにマウントされた edge-slot antenna の動作周波数がビアによってチューニングできることを示していた[20]。

さらに、Kerr の発表[19, 23] を聞き、図(a)の Shorting Posts による Tunable patch antenna を提案した。

図の shorting Posts は動作周波数を高くする効果がある。

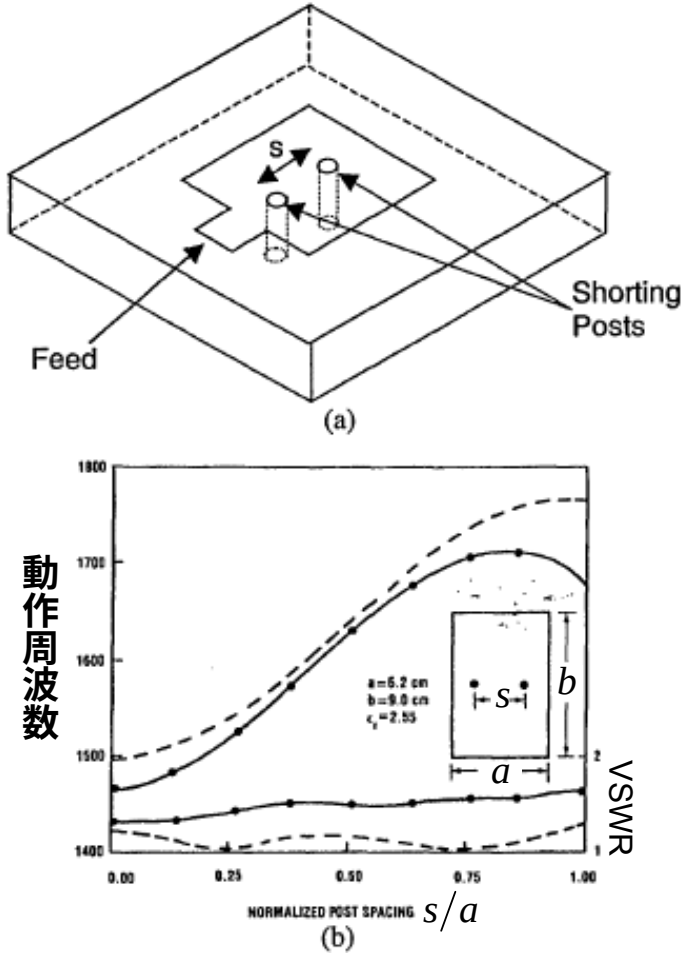
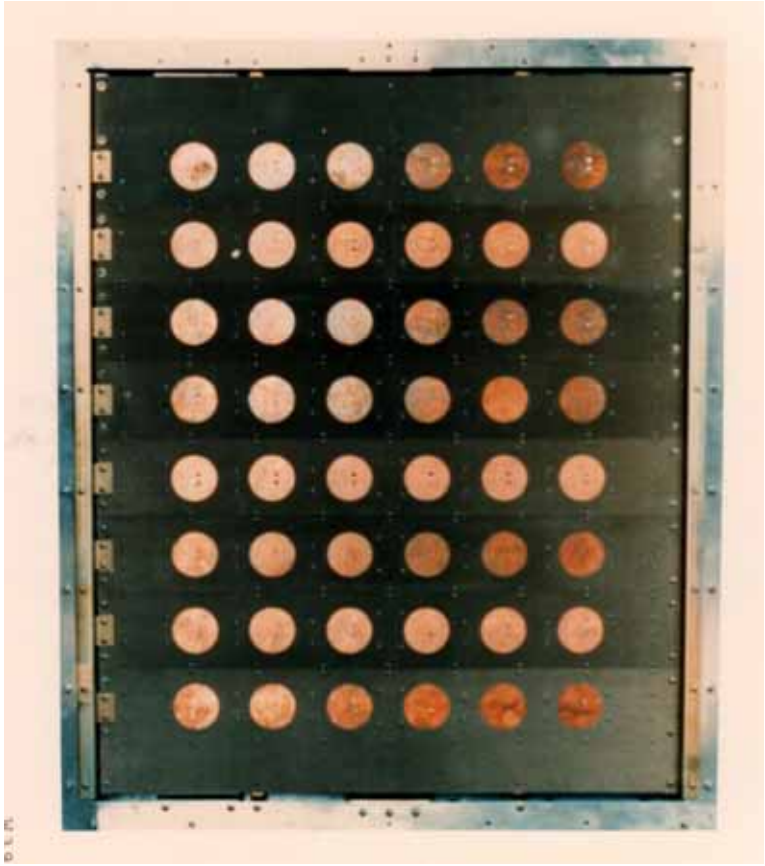


Fig.8 Post-tuned microstrip patch antenna inspired by work in [19],[20] and [23].
(a) Antenna with pair of posts separated by distance s.
(b) Frequency tuning and VSWR of post-tuned antenna.

[41] 大森　他の論文論文(1980)

論文の概要

MSA による成形ビームアンテナの開発



相互結合が小さい特徴を利用

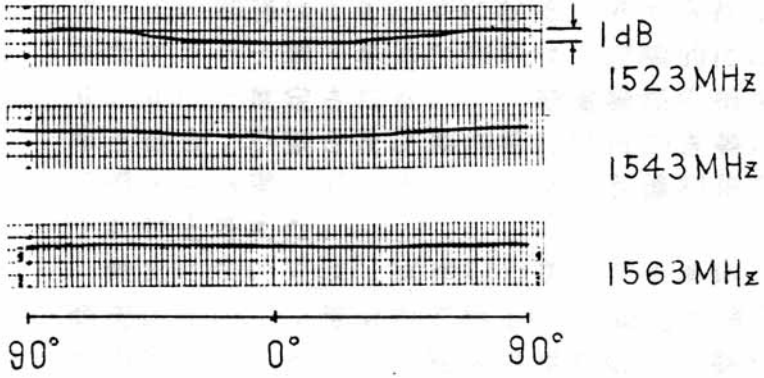
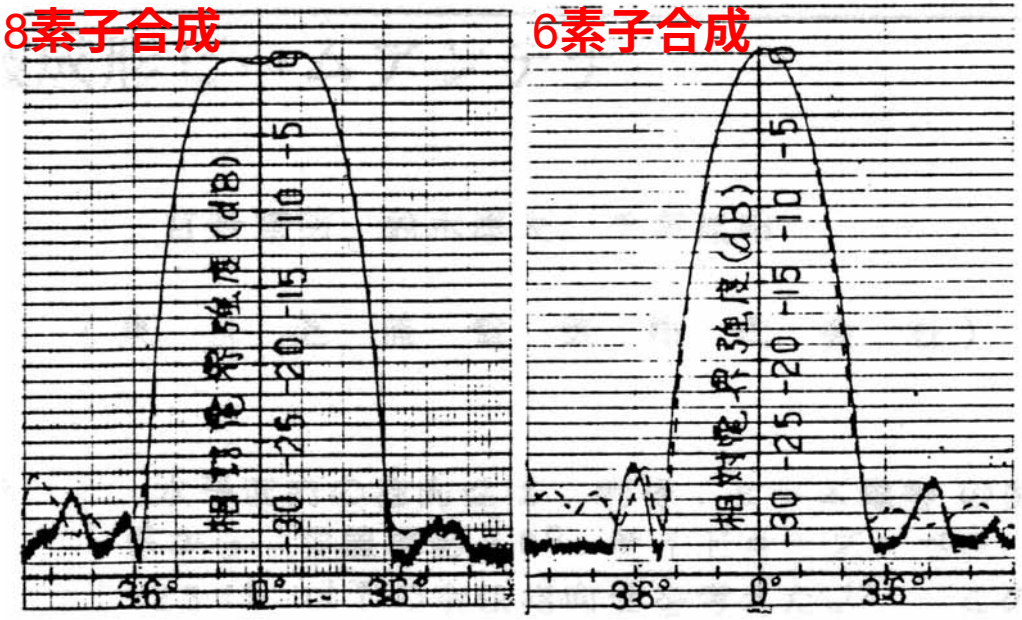


図5　軸　比　特　性

8素子合成　　**6素子合成**



----水平偏波 ——— 垂直偏波　　1543MHz

図3　垂直面内パターン　　図4　水平面内パターン

[44] Schaubert の論文(1981) | 論文の概要(1/2)

ショートポストの装荷と放射素子の切欠きによる Tunable MSA を提案

予め、Patch の一部を切欠くことにより、動作周波数を下げておき、Tuning Posts を挿入することにより動作周波数を上げることにより、広帯域に渡り、放射指向性も含めて良好に動作することを示した[48]。

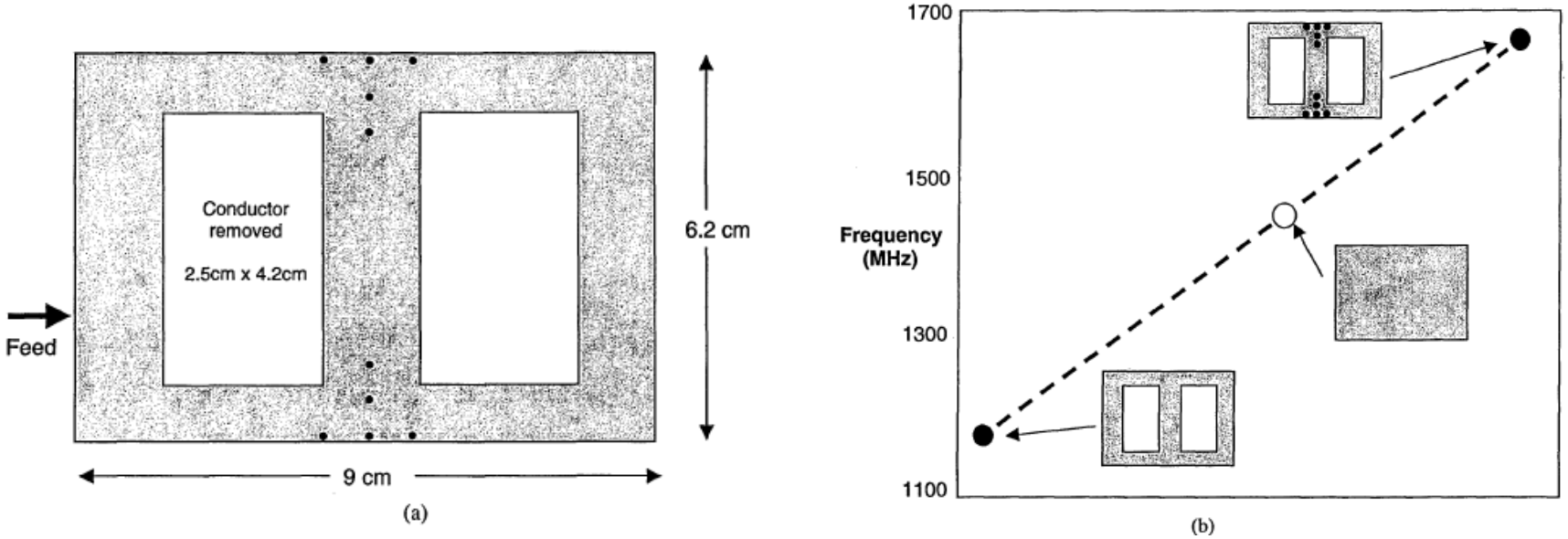


Fig. 9 (a) Patch antenna with metallization removed to lower basic operating frequency and posts added to then raise it.
(b) Typical tuning range of patch antenna.
Standard patch antenna of same size operates at 1465 MHz. After [48].

Kerr と Jones et al. の仕事の長所を取り入れた新たな MSA の提案

[44] Schaubert の論文(1981)

論文の概要(2/2)

Shorting Posts の選択による 4 偏波切り換え MSA の提案

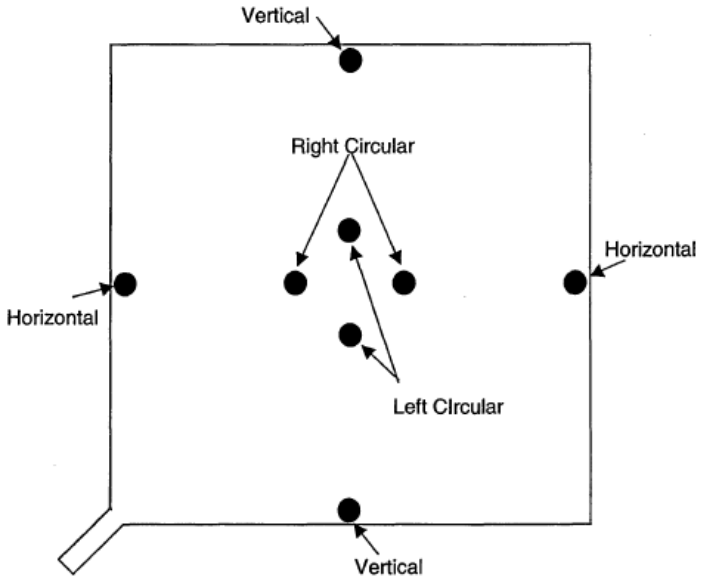


Fig. 10. Switchable shorting posts provide polarization diversity of a corner-fed patch antenna.

上 図のように short posts を挿入し、
適当にpost を選択することで、
4 種類の偏波に切り替え可能。
ただし、
post を挿入すると動作周波数が 高くなるので、
patch のサイズが大きくなる点に要注意。

スロットとShorting Posts による マルチモード MSA の提案

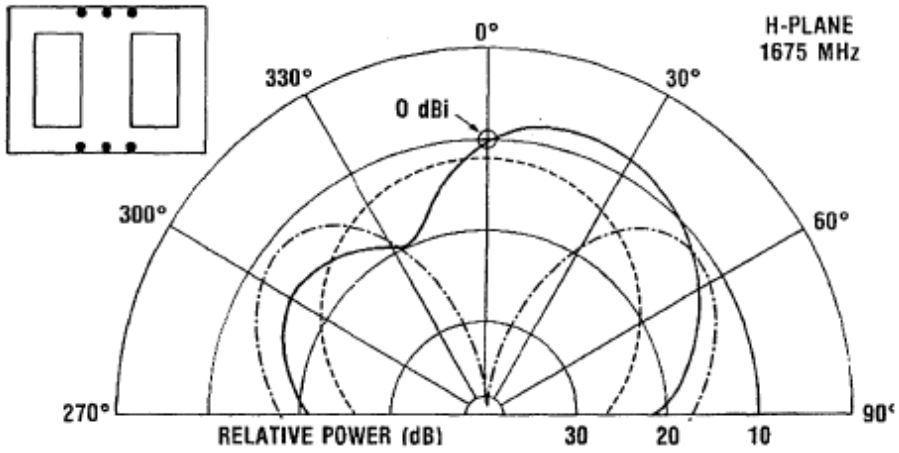


Fig. 11. Combining holes in metallization and posts can force two modes of the patch to share a common resonant frequency. The patterns of the individual modes are indicated by the dashed lines sketched onto the plot. The solid curve is the measured radiation pattern of the 6.2-cm × 9-cm antenna at 1675 MHz. From [48].

複数のモードを利用することにより、
上図のような指向性が実現できる
ことを示した。

[45] 荒木の論文(1981)　論文の概要

ハンケル変換による円形 MSA の Full wave 解析

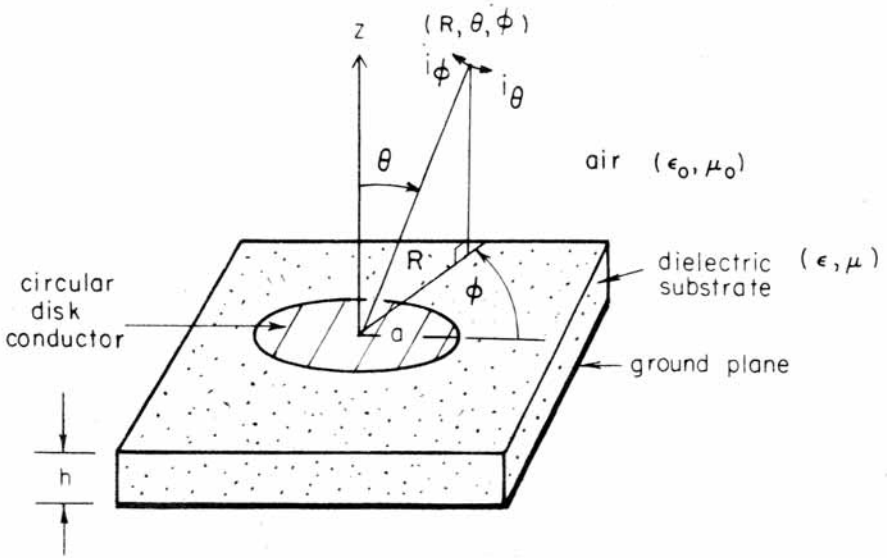


Fig. 1. Structure of circular printed antenna and coordinate system.

A. Substrate Region $(0 < z < h)$

The axial field components H_z and E_z satisfying the Helmholtz equations can be written as follows:

$$H_z(r, \phi, z) = e^{jn\phi} \int_0^\infty \tilde{H}_z(\alpha) J_n(\alpha r) \sin \beta z \alpha \, d\alpha \qquad (1)$$

$$E_z(r, \phi, z) = e^{jn\phi} \int_0^\infty \tilde{E}_z(\alpha) J_n(\alpha r) \cos \beta z \alpha \, d\alpha \qquad (2)$$

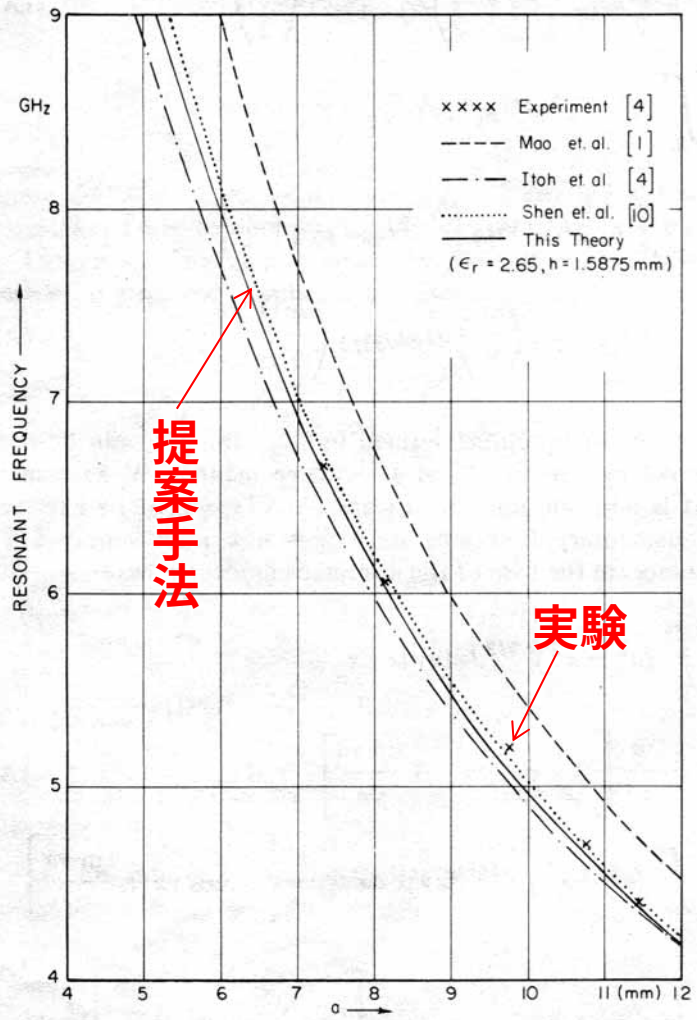


Fig. 2. Comparison with experimental and calculated results of resonant frequency.

[47] S. A. Longの論文(1981)

論文の概要

楕円 MSA による一点給電円偏波励振

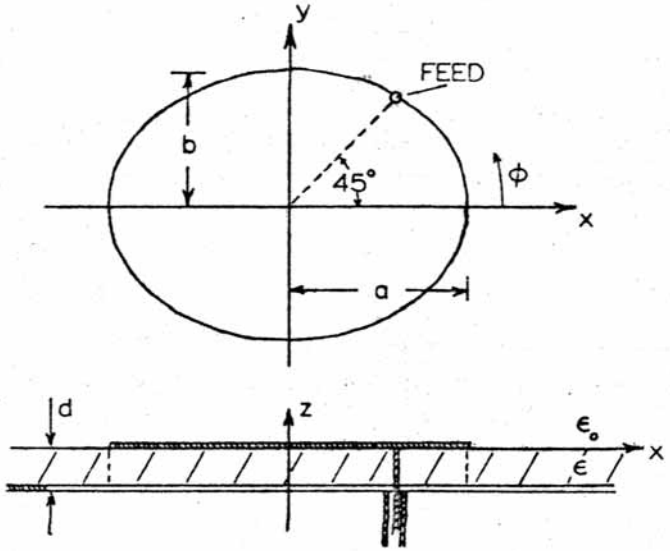


Fig. 1. Geometry of elliptical printed-circuit antenna.

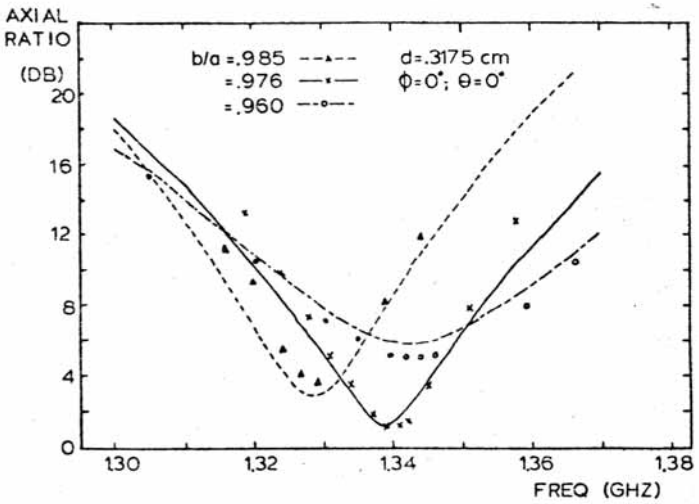
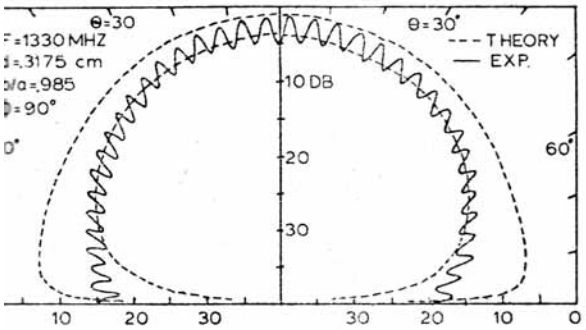
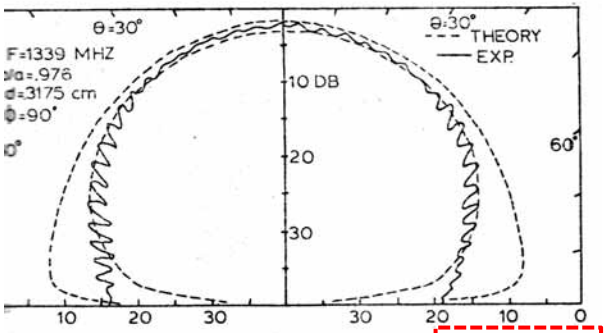


Fig. 14. Axial ratio versus frequency (d = 0.3175 cm).



ig. 11. Radiation pattern (d = 0.3175 cm; b/a = 0.985).



ig. 12. Radiation pattern (d = 0.3175 cm; b/a = 0.976).

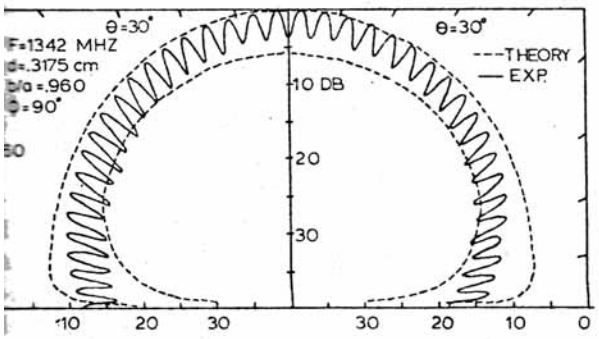


Fig. 13. Radiation pattern (d = 0.3175 cm; b/a = 0.960).

[49] 羽石の論文(1981)

論文の要点(1/2)

等価回路モデルに基づく一点給電円偏波円形 MSA の円偏波励振条件を導出

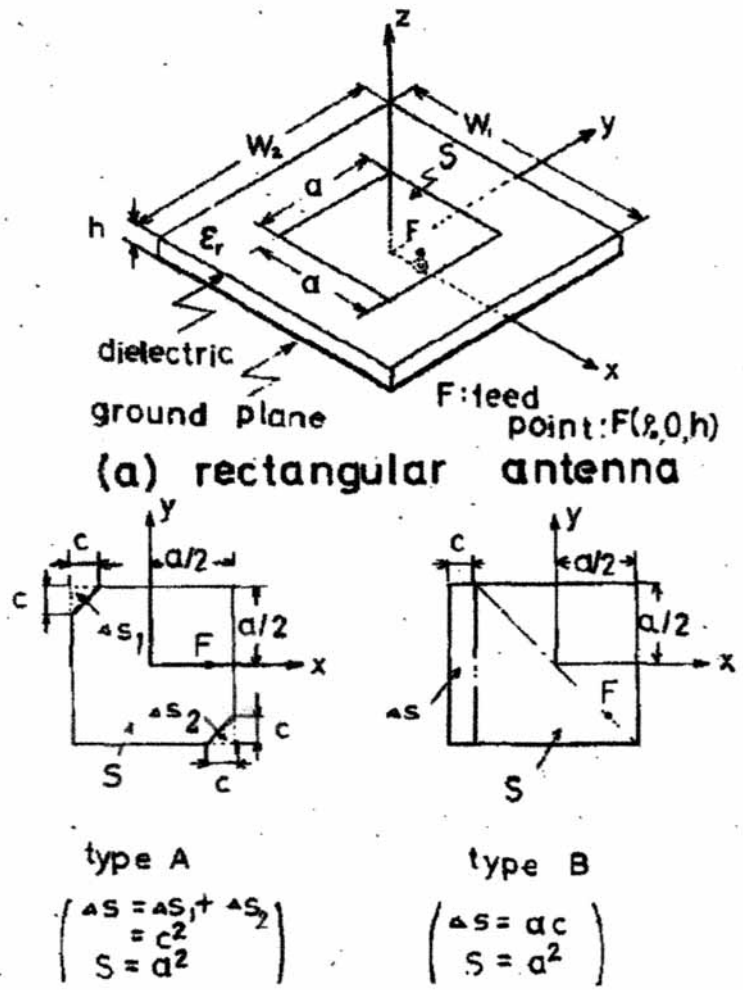


図1　1点給電方形アンテナ†

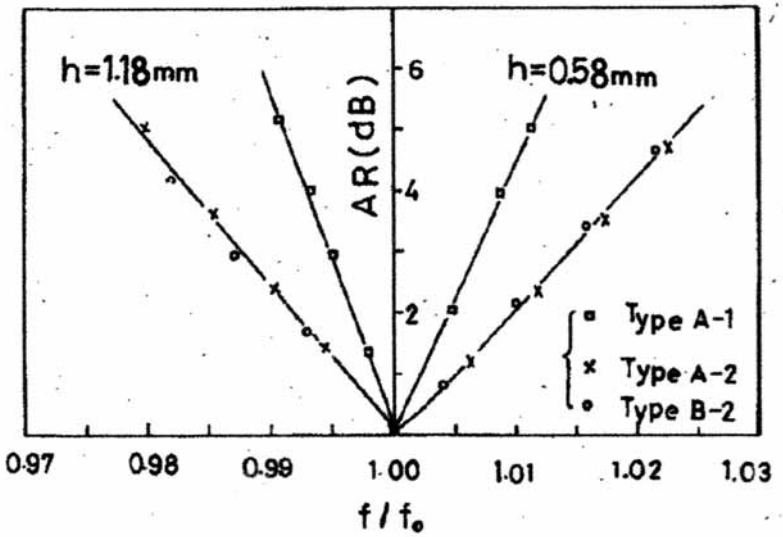


図8　軸比の周波数特性

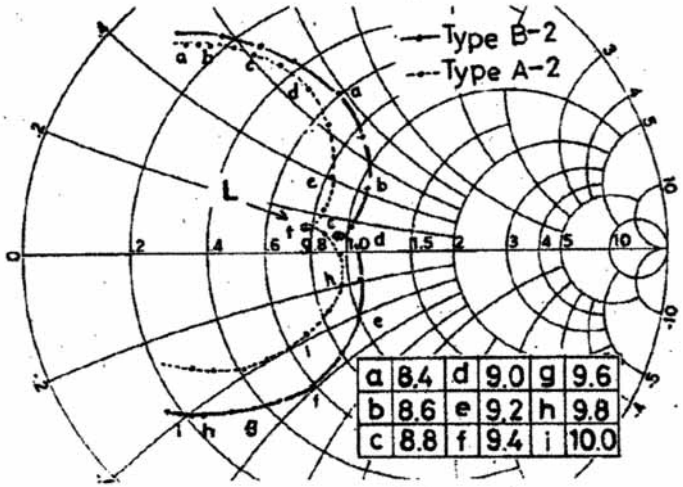


図9　インピーダンス特性（素子単体）

[49] 羽石の論文(1981)

論文の要点(2/2)

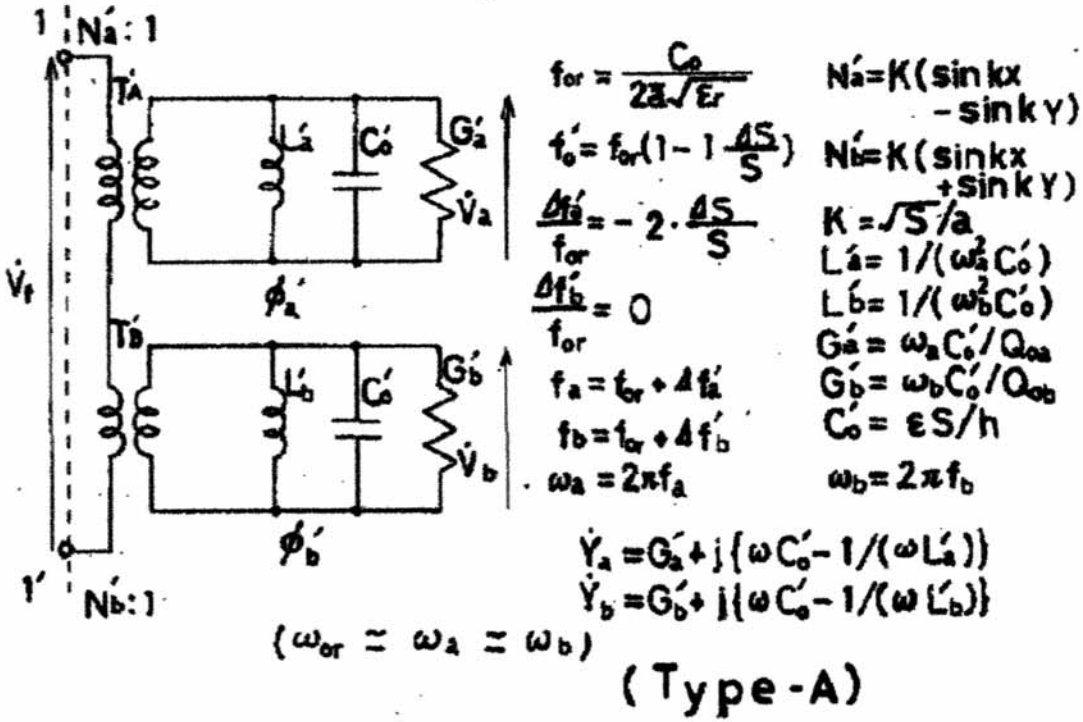


図 4　摂動後の 1 点給電方形アンテナの等価回路
Fig.4 - Equivalent circuits of rectangular microstrip antenna after perturbation.

$$\left|\frac{\dot{V}_b}{\dot{V}_a}\right| = 1, \qquad \arg\left(\frac{\dot{V}_b}{\dot{V}_a}\right) = \pm 90^\circ$$

$$\left|\frac{\Delta s}{S}\right| = \begin{cases} \dfrac{1}{2Q_0} & \text{type A} \\ \dfrac{1}{Q_0} & \text{type B} \end{cases}$$

円偏波励振条件

[53] 千葉 の論文(1982)　論文の要点(1/2)

広帯域化に伴う高次モードの抑圧と電子走査アンテナの試作

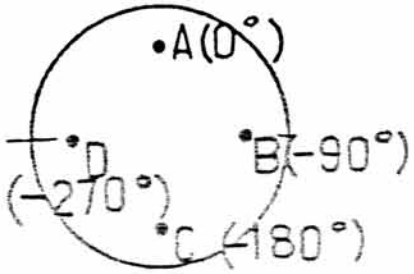


Fig. 7 Feeding method for obtaining circular polarization (for supressing higher modes)

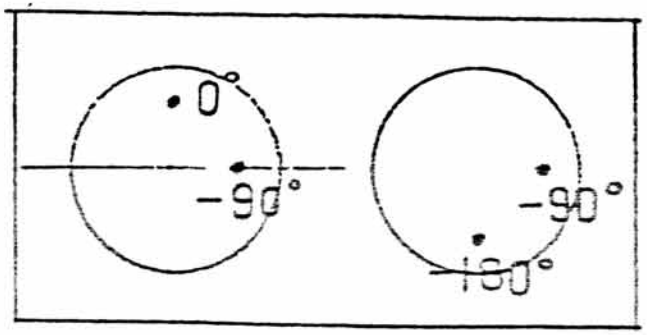


Fig. 9 Feeding method for improving the axial ratio

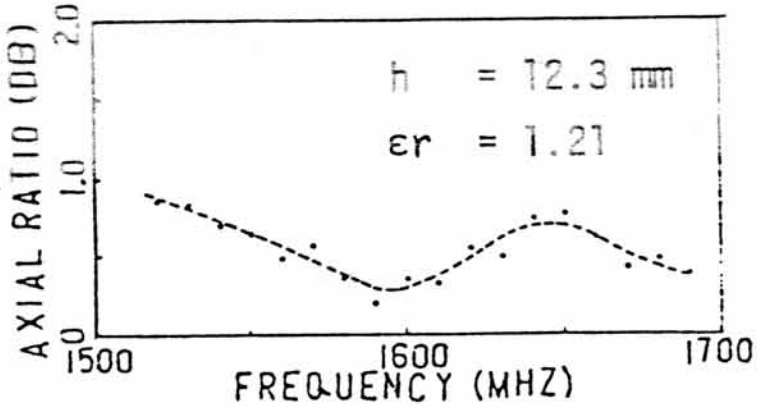


Fig. 8 Boresight axial ratio vs frequency (4-point feeding)

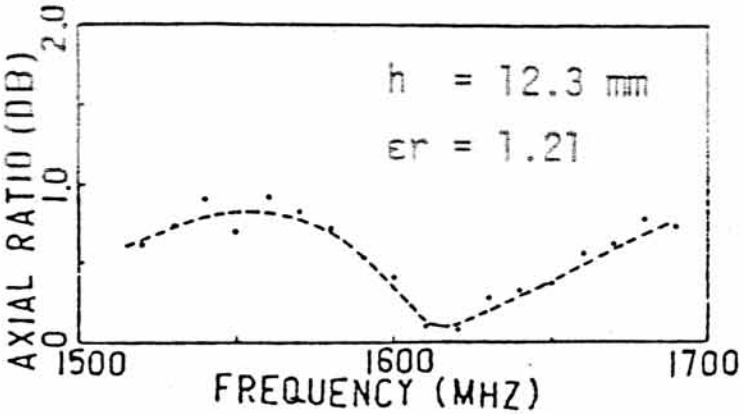
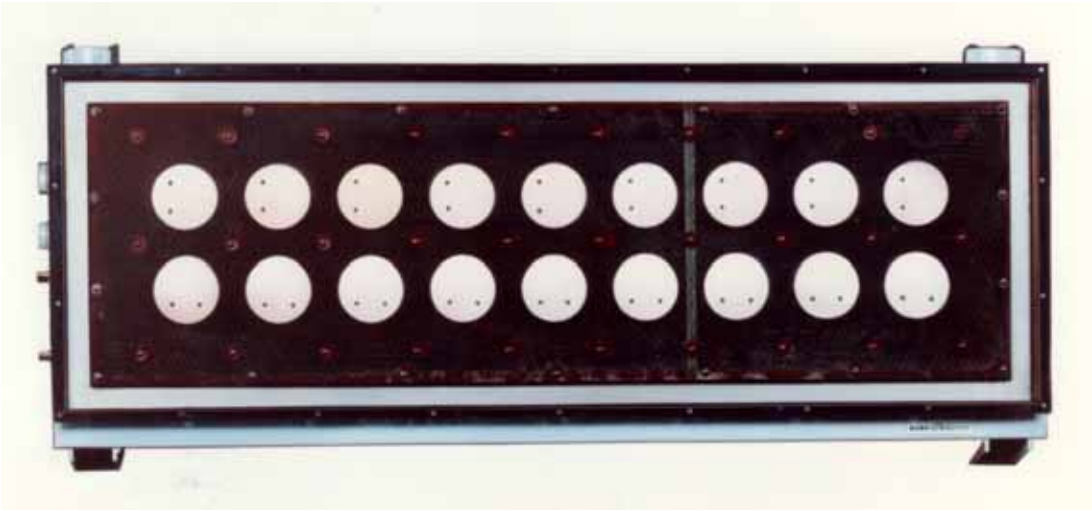


Fig. 10

Boresight axial ratio vs frequency (improved pair of MSA)

[53] 千葉 の論文(1982)

論文の概要(2/2)



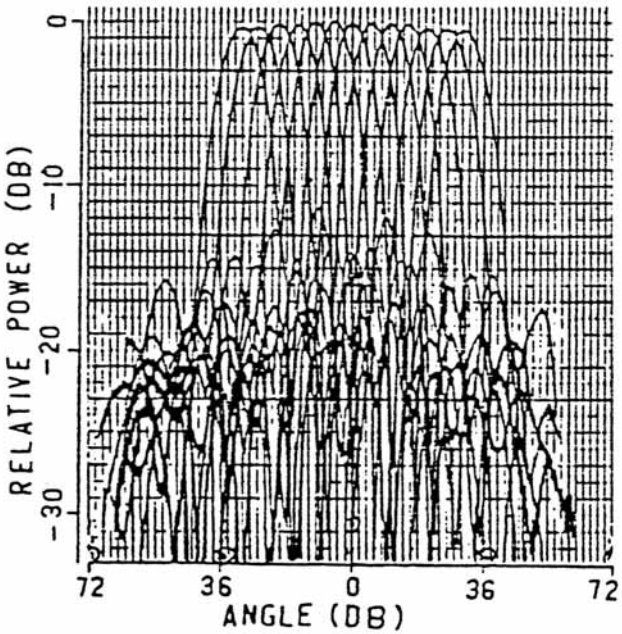


Fig. 12 Scanned radiation pattern

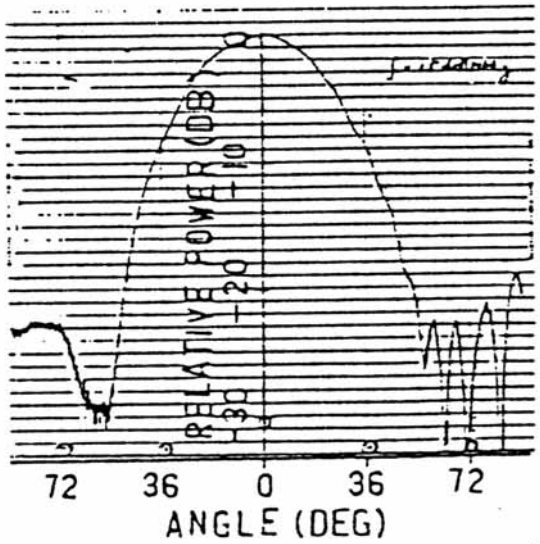


Fig. 13 Radiation pattern in non-scanned plane

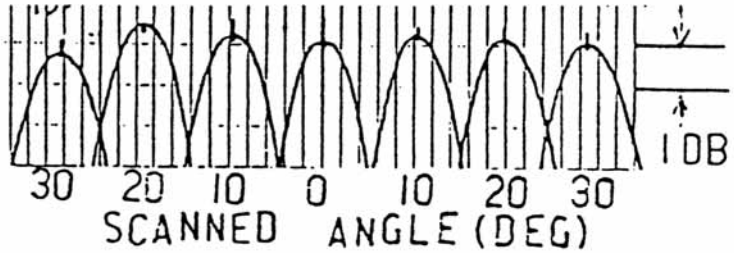


Fig. 14 Axial ratio at the beam nose

[54] 徳丸 の論文(1983)　論文の概要

短絡ポスト装荷円形 MSA による一点給電円偏波励振

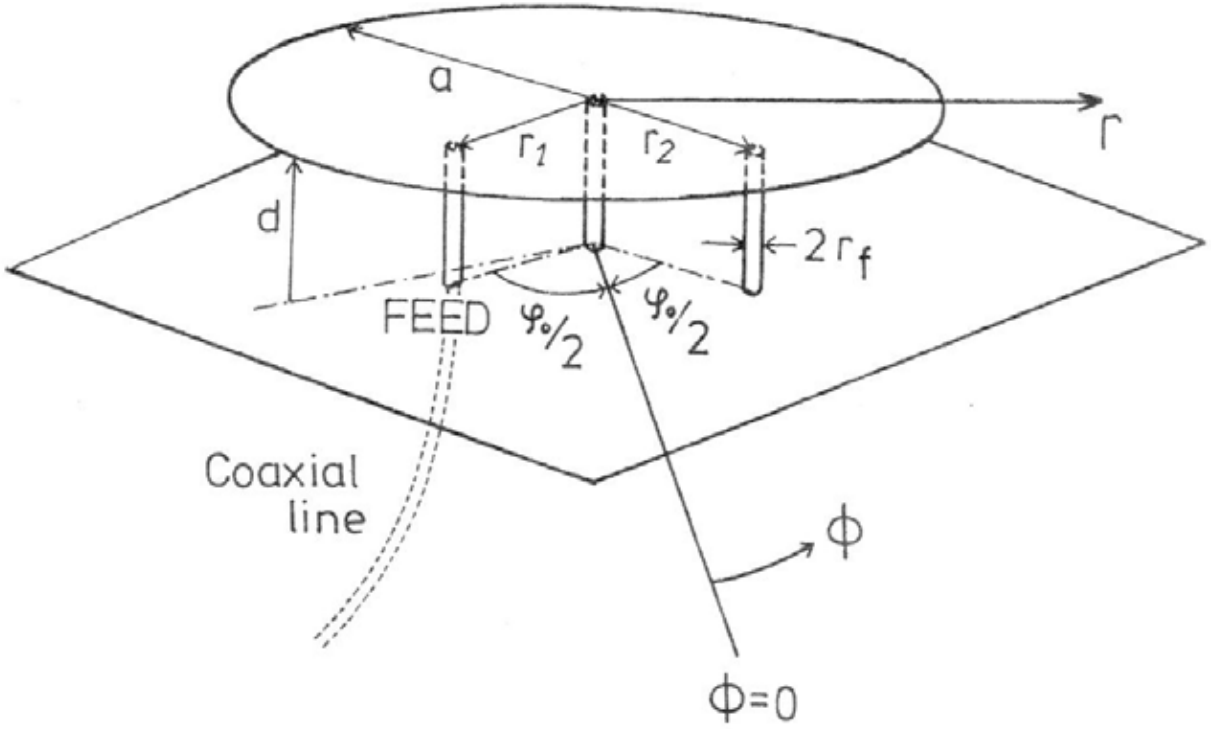


Fig.−1　アンテナの構造と座標系

[55] 秋葉の論文(1983)　論文の要点

円形MSAの高次モードの共振周波数の非周期性を利用したレクテナ素子の開発

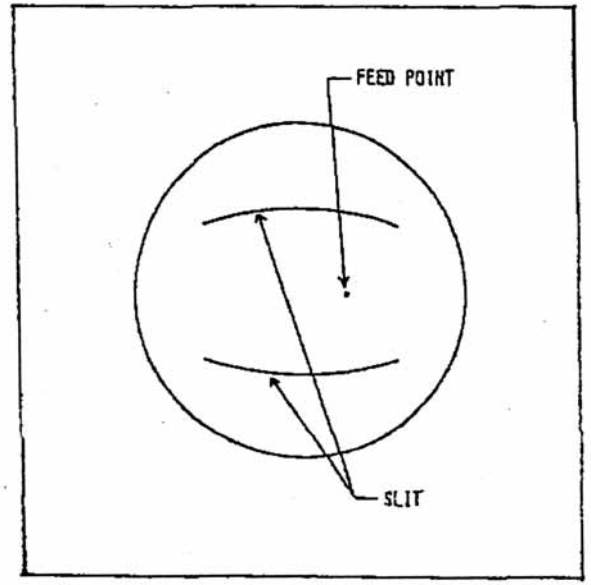


Fig.1　スリット入り CMSA

スリットは、高次モード対策？

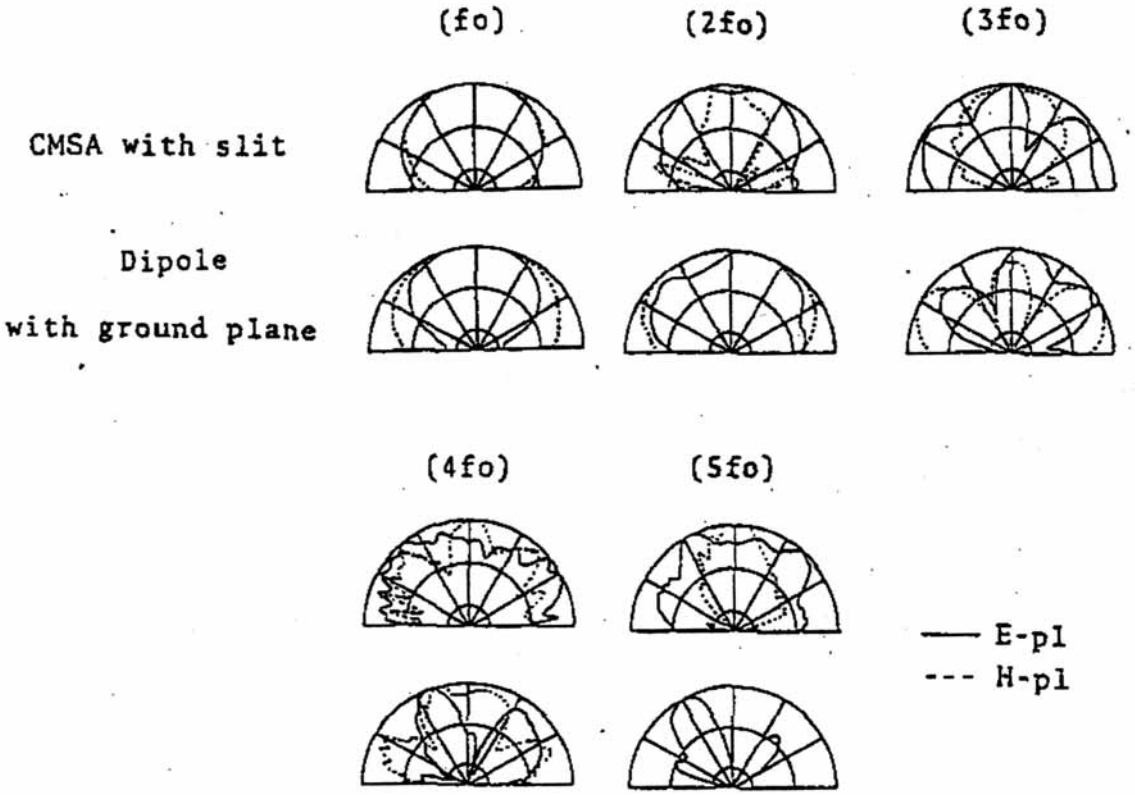


Fig.4　スリット入りCMSA と反射板付ダイポールの放射パターン（測定値）

[57] 鈴木 の論文(1984)

論文の概要(1/2)

平面回路法よる Weinschel の一点給電円偏波 MSAを解析

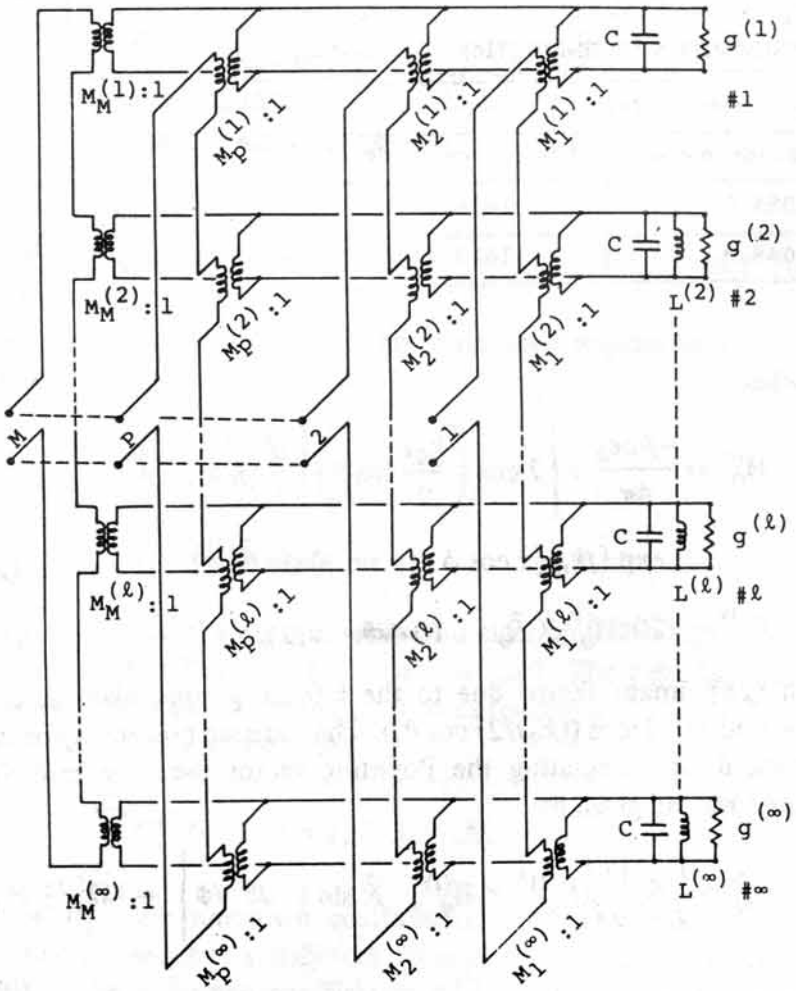


Fig. 3. Network model for a multiterminal microstrip antenna.

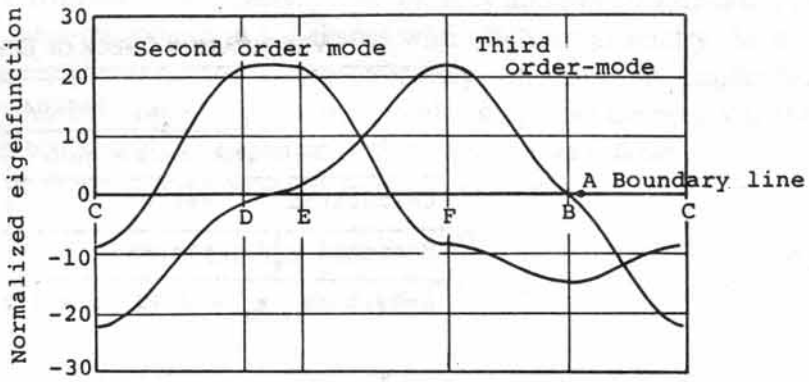


Fig. 4. Second- and third-order eigenfunction distributions on the boundary.

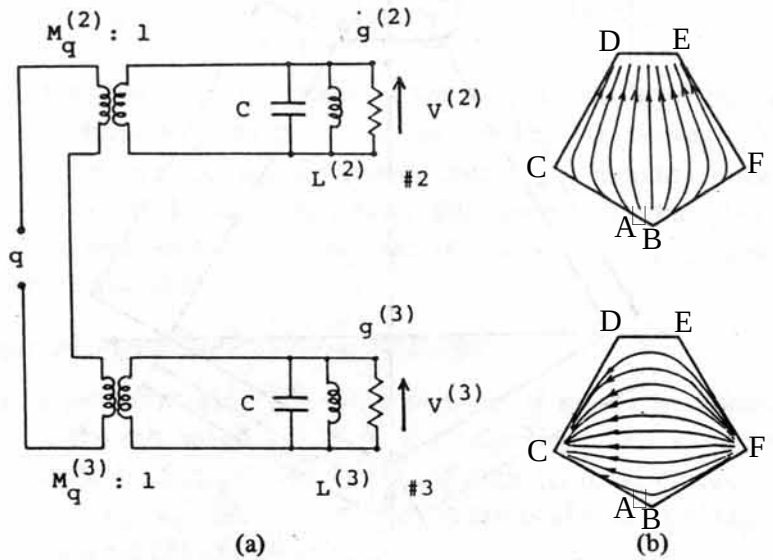


Fig. 5. Network model for a pentagonal microstrip antenna for a slightly narrow-band operation, selecting A as feeding point.

[57] 鈴木 の論文(1984)

論文の概要(2/2)

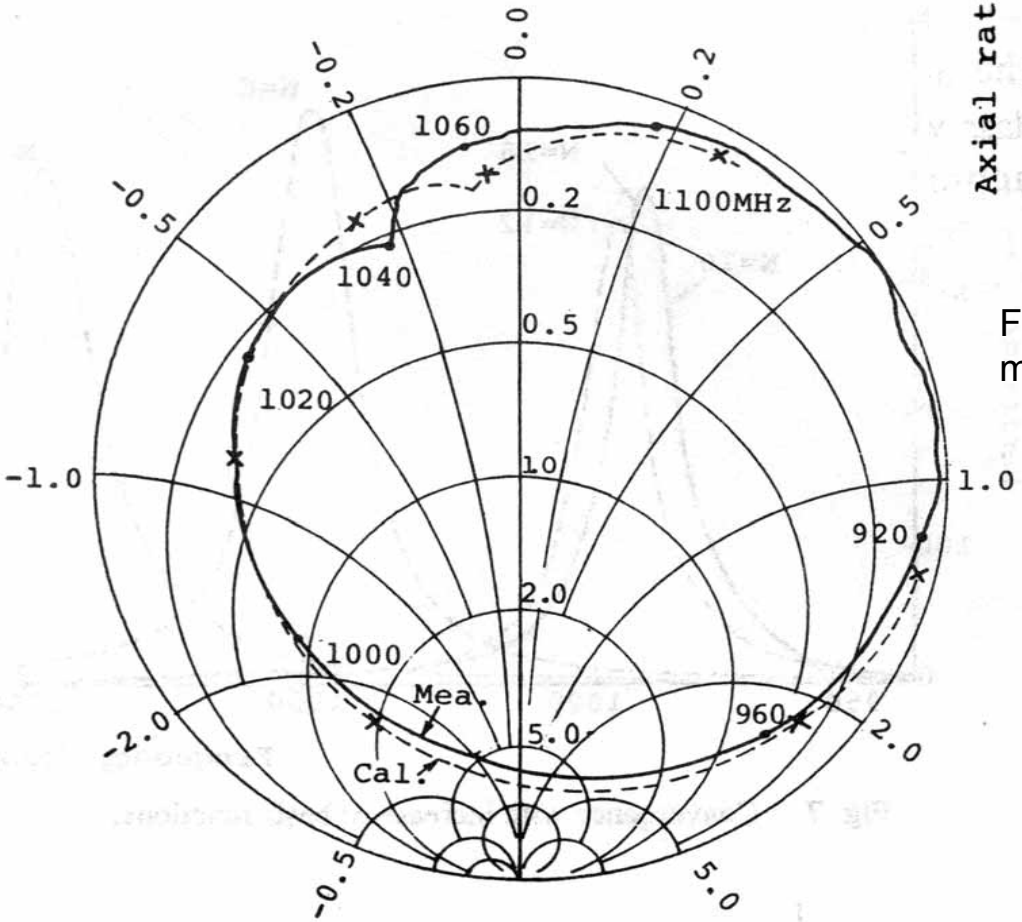


Fig. 6. Input impedance characteristic for a pentagonal microstrip antenna with point A as feeding point.

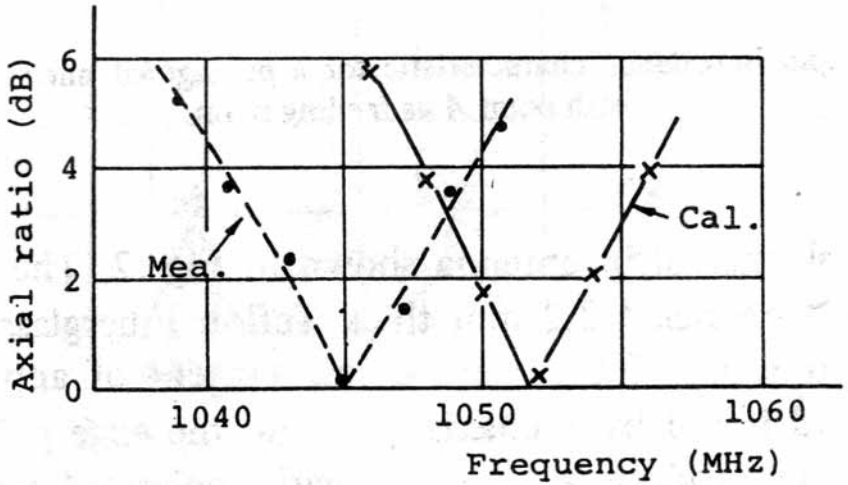


Fig. 8. Boresight axial ratio for a pentagonal microstrip antenna, with point A as feeding point.

[58] Chen の論文(1984)

論文の概要

非励振素子装荷による広帯域化と円偏波特性の改善

EMCP (electromagnetically coupled patch)

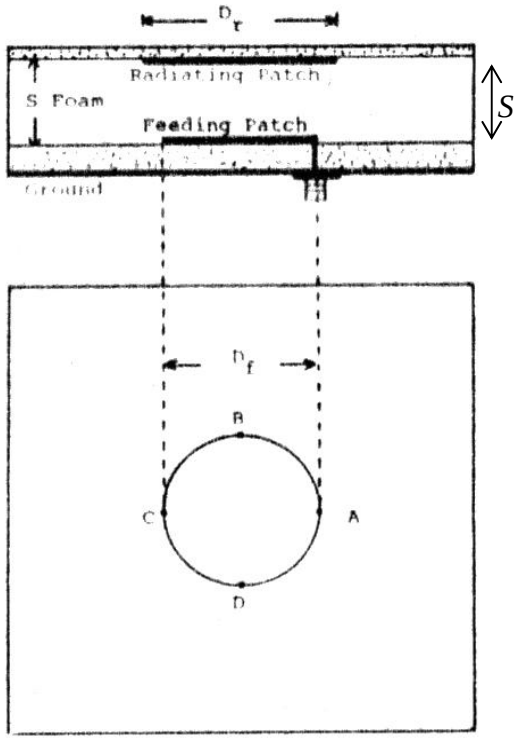


Figure 1. Antenna Element Structure

EMCP の広帯域特性

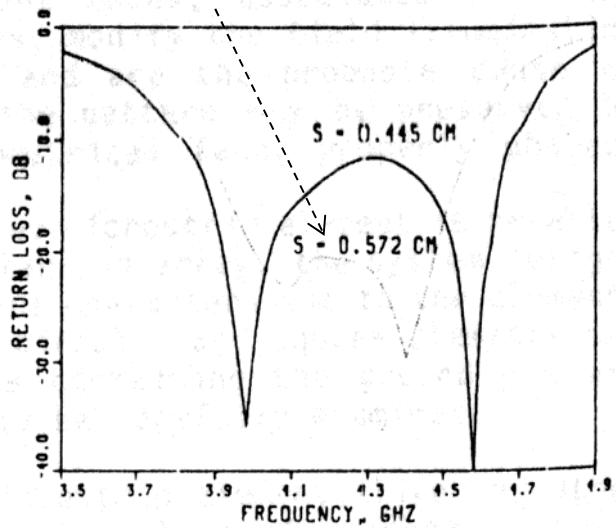


Figure 2. Measured Return Loss

シーケンシャルか？

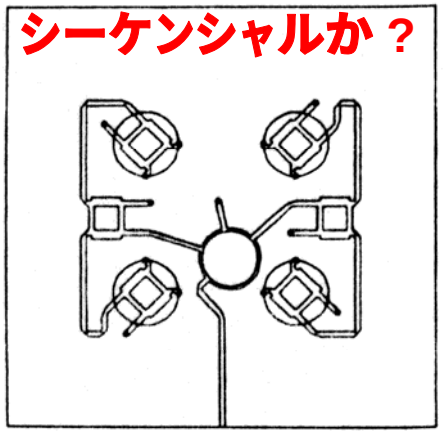


Figure 6. Circularly Polarized EMCP Array

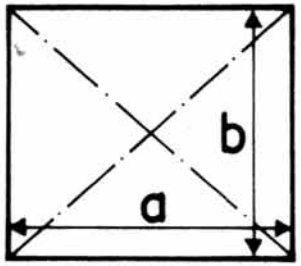
★ 円偏波特性の改善法

(1) Two feed points (A and B) with unequal excitation.
(2) Four feed points (A, B, C, D) with equal excitation.
(3) Symmetrical deployment of the radiation elements, which are equally excited at two points

[61] 鈴木 の論文(1985)　論文の発端(1/2)

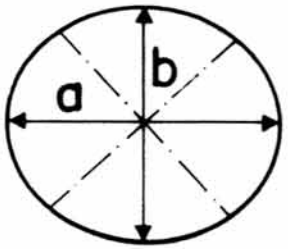
従来の一 点給電円偏波 MSA の形状と励振点には一般性がない

給電点の位置が「一点鎖線上にある」ことに違和感

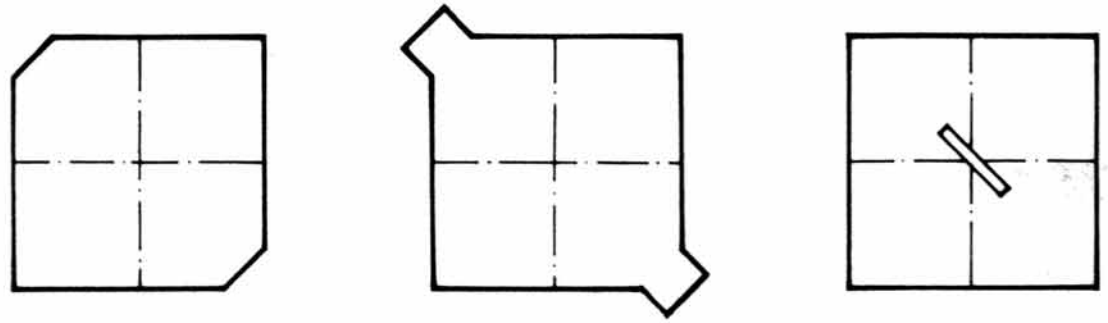


$$\frac{a}{b} = 1.029 \quad [27]$$

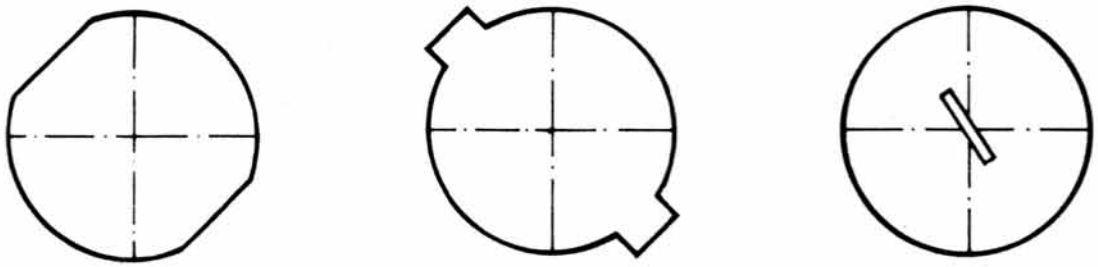
$$= 1 + \frac{1}{Q_0} \quad [46]$$



$$\frac{b}{a} = 0.976 \quad [47]$$



$$\frac{\Delta S}{S} = \frac{1}{2Q_0} \quad [49]$$

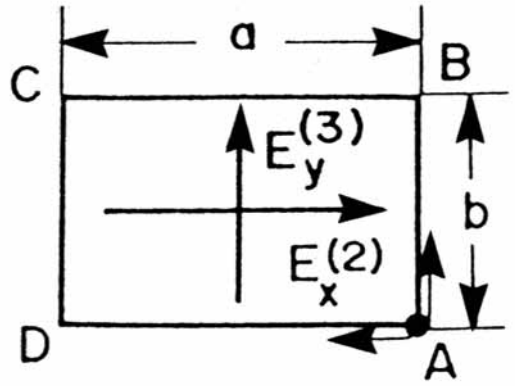


$$\frac{\Delta S}{S} = \frac{1}{1.841Q_0} \quad [38]$$

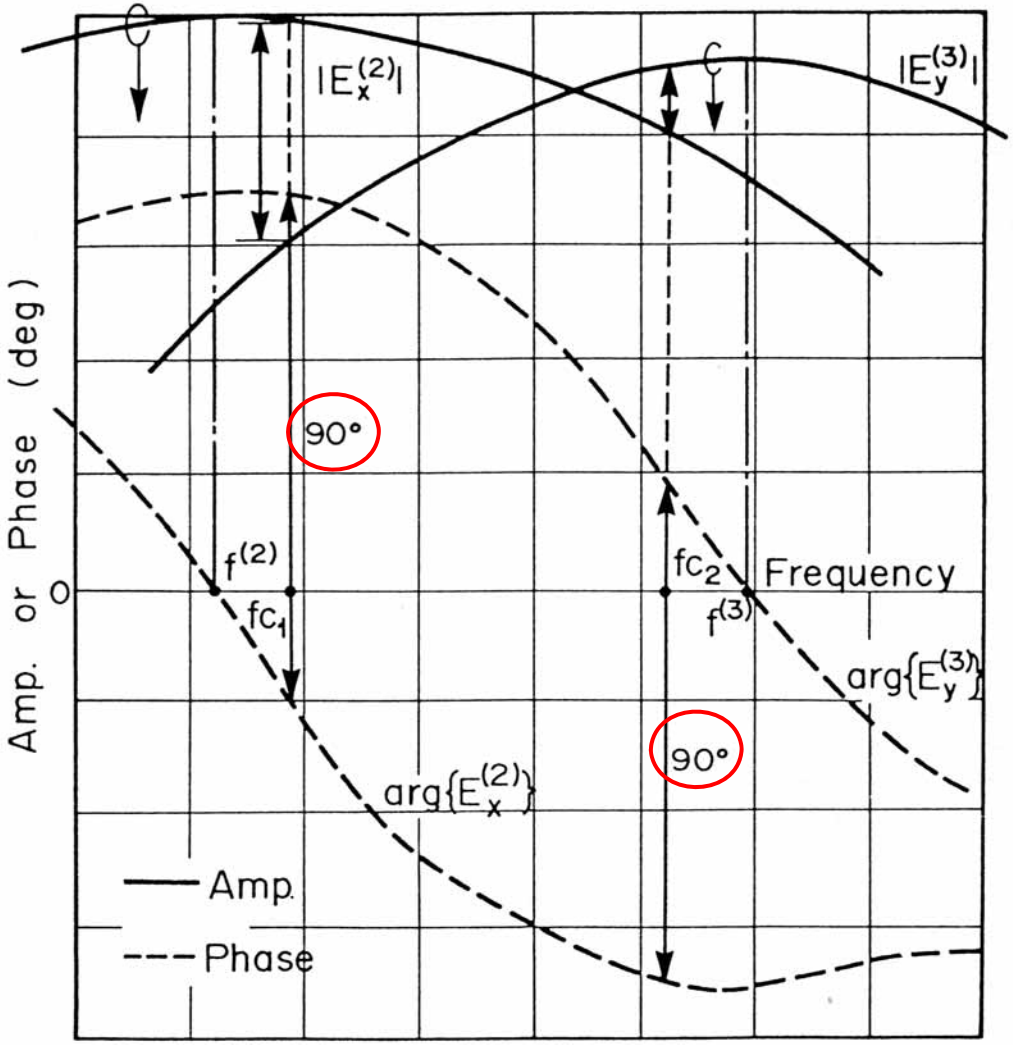
「励振条件が摂動を与える場所に依存しないのはおかしい」ことに着目

[61] 鈴木 の論文(1985)　論文の発端(2/2)

2 周波で 一 点給電円偏波励振が可能なハズ



励振振幅は給電点の位置を変えることで調整可能



一般に、縮退を解かれたモード間の位相素が90度になる周波数が2波存在する

[61] 鈴木 の論文(1985)

論文の概要(1/2)

矩形 MSA が 2 つの周波数で
一点給電円偏波励振が可能であることを示す

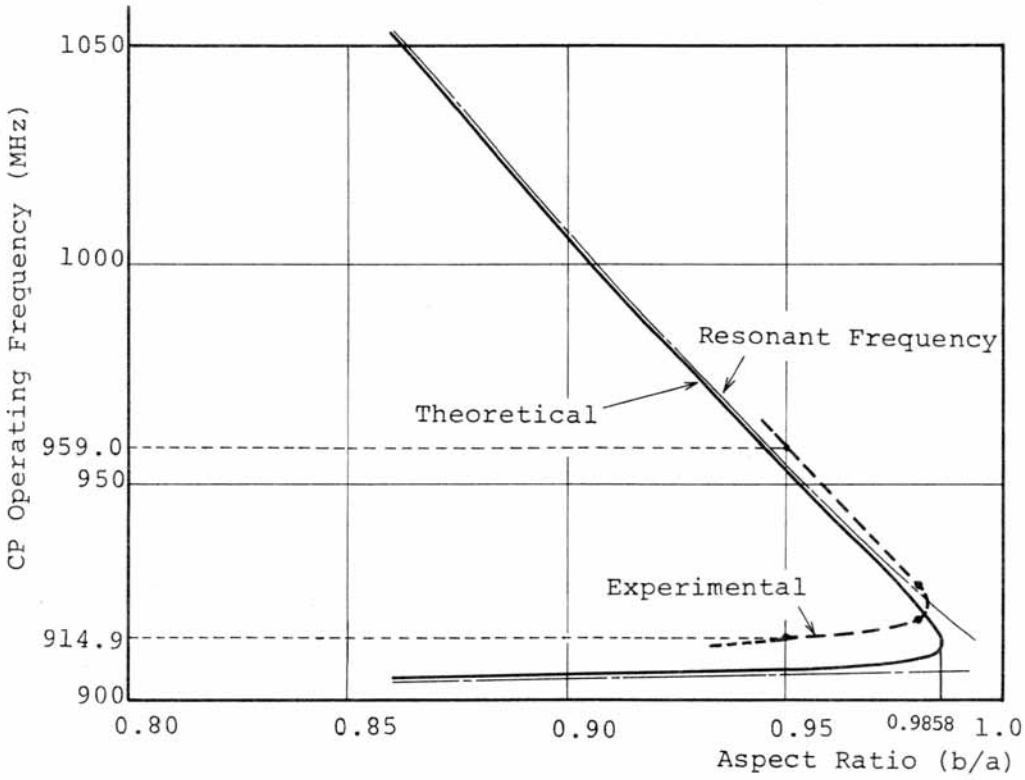


Fig. 2 CP operating frequency vs. aspect ratio for a nearly square microstrip antenna with $a=100$ mm, $t=3.2$ mm, $\varepsilon_r=2.55$, and $\tan\delta=0.0018$.

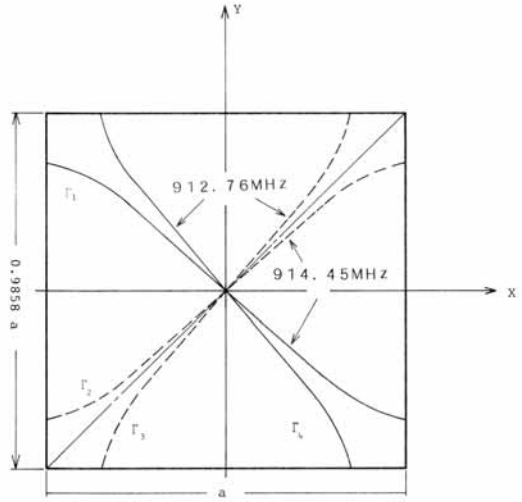


Fig. 4 Feed location loci for a nearly square microstrip antenna with $b/a=0.9858$, $a=100$ mm, $t=3.2$ mm, $\varepsilon_r=2.55$, $\tan\delta=0.0018$. (RHCP ———, LHCP - - - - - -)

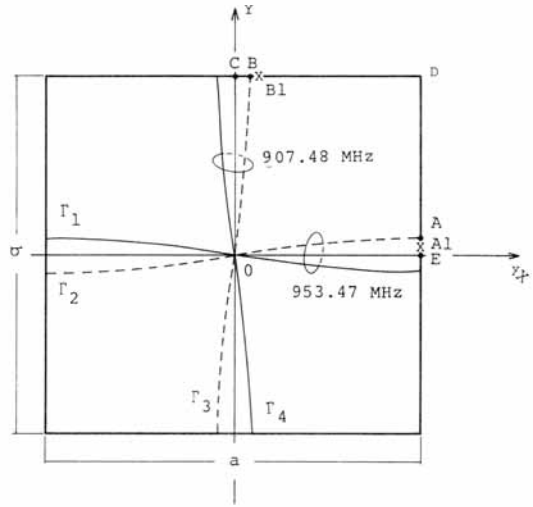


Fig. 3 Feed location loci for a nearly square microstrip antenna with $b/a=0.95$, $a=100$ mm, $t=3.2$ mm, $\varepsilon_r=2.55$, $\tan\delta=0.0018$. (RHCP ———, LHCP - - - - - - -)

[61] 鈴木 の論文(1985)

論文の概要(2/2)

五角形 MSA でも 2 つの周波数で一点給電円偏波励振が可能であることを示す

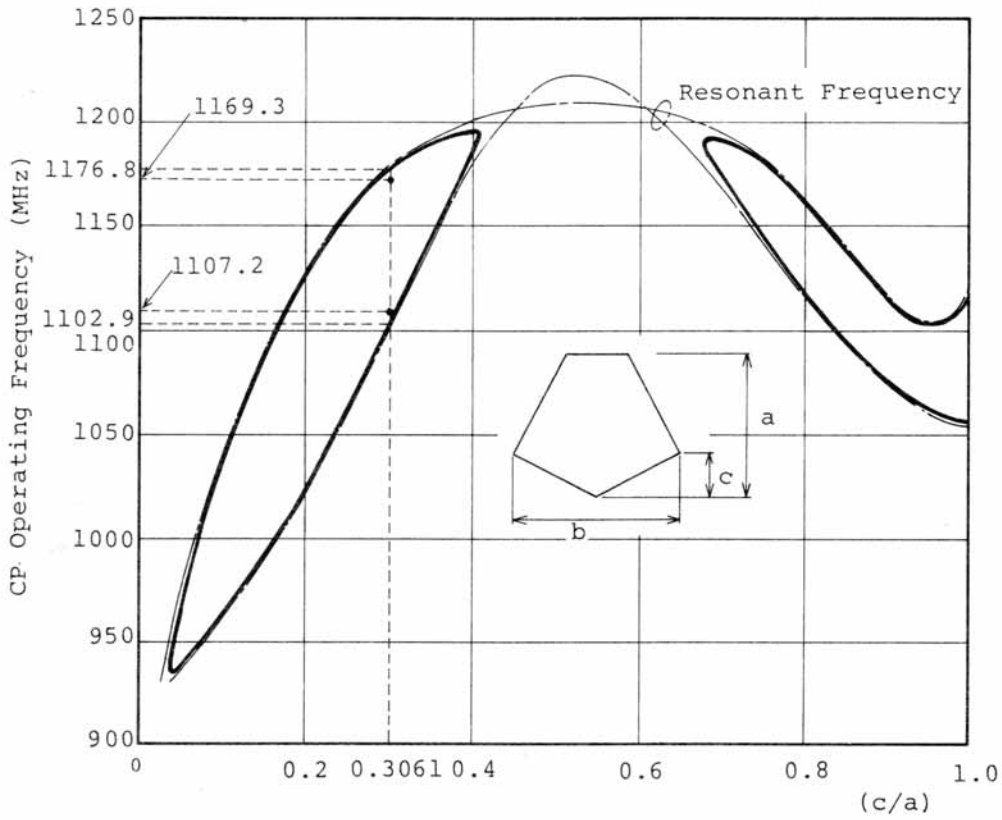
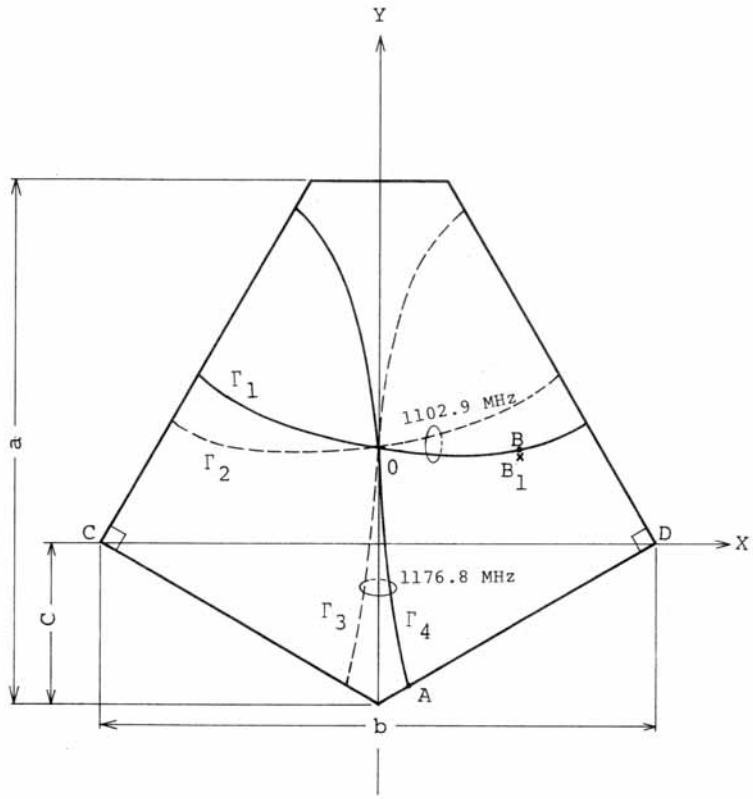


Fig. 7 CP operating frequency vs. aspect ratio (c/a) for a pentagonal microstrip antenna with $b/a=1.0603$, $a=100$ mm, $t=3.2$ mm, $\varepsilon_r=2.55$, and $\tan\delta=0.0018$.
(Theoretical ———————— , Experimental ●)



[62] 堀 の論文(1985)

論文の概要

非励振素子装荷 MSA の広帯域化の改善
(実験による最適条件の導出)

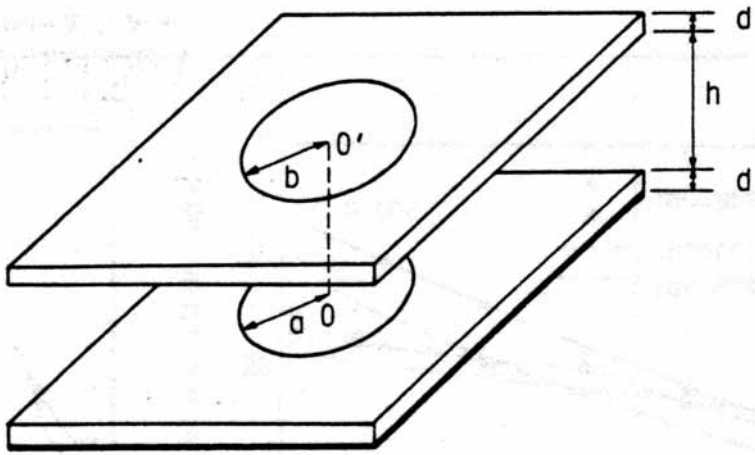


図 1　無給電素子を用いた円形マイクロストリップアンテナの構造

Fig.1　Microstrip disk antenna with a parasitic element.

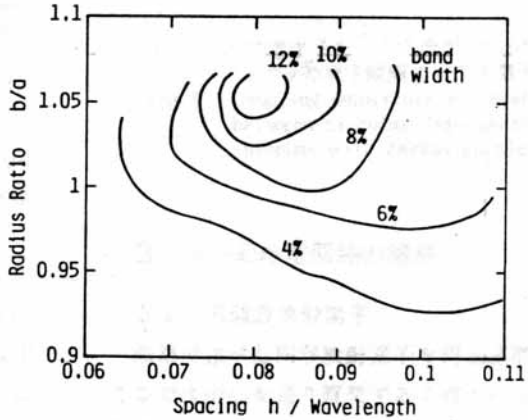


図 2　円形素子の間隔および半径比に対する比帯域幅の変化〔実測値〕

Fig.2　Relative bandwidth variation against element spacing and radius ratio of circular disk elements (Measured).

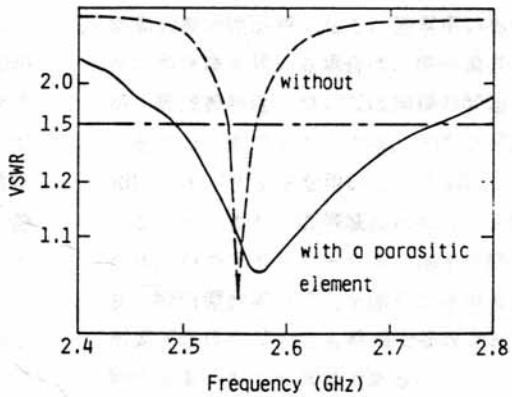
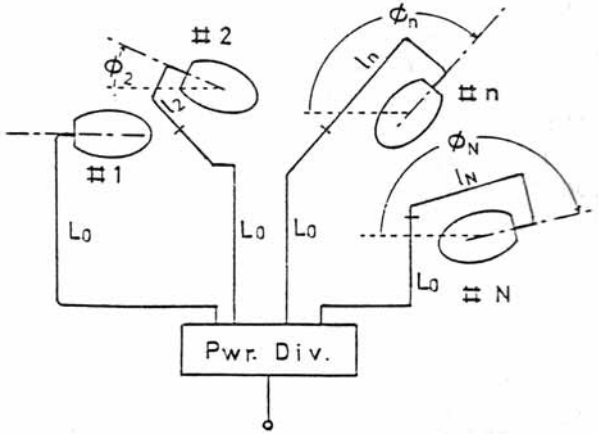


図 3　無給電素子の有無に対するVSWR特性の変化〔実測値〕

Fig.3　Frequency dependence of measured VSWR of a radiating element with or without a parasitic element.

[63] 手代木 の論文(1985)　論文の概要

シーケンシャル配列による円偏波特性の広帯域化の定式化

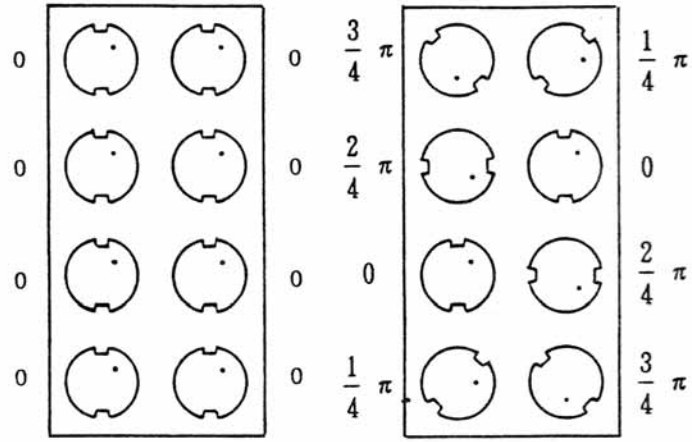


$$L_n = L_0 + \ell_n$$

$$k_0 \ell_n = \phi_n = (n-1)p\pi / N$$

$$k_0 = 2\pi f_0 \sqrt{\varepsilon \mu}$$

Fig.1. Configuration of a sequential array



(1) Conventional array　(2) Sequential array

Fig.4. Arrangement of elements for two test arrays

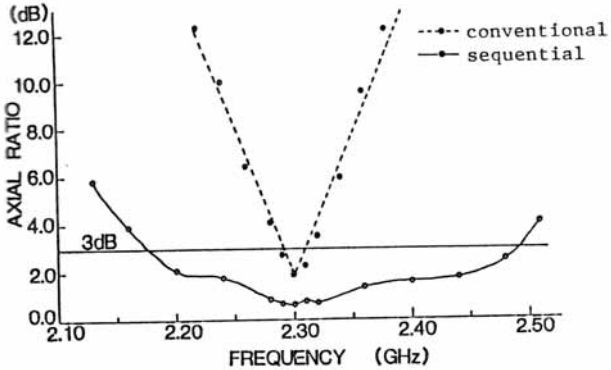


Fig.5. Measured axial ratio vs. frequency

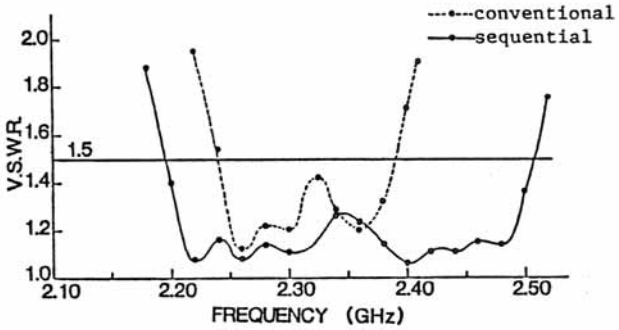


Fig.6. Measured V.S.W.R. vs. frequency

[65] 金田の論文(1986)　論文の概要

Self diplexing antenna のための同軸構造 MSA の提案

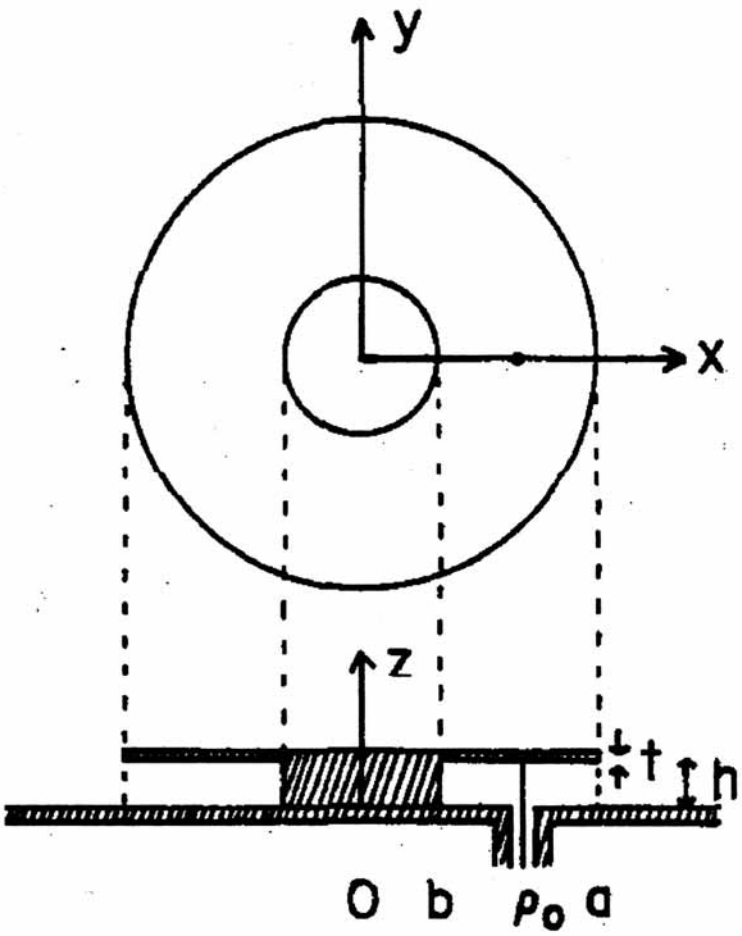


図 1　円環アンテナ

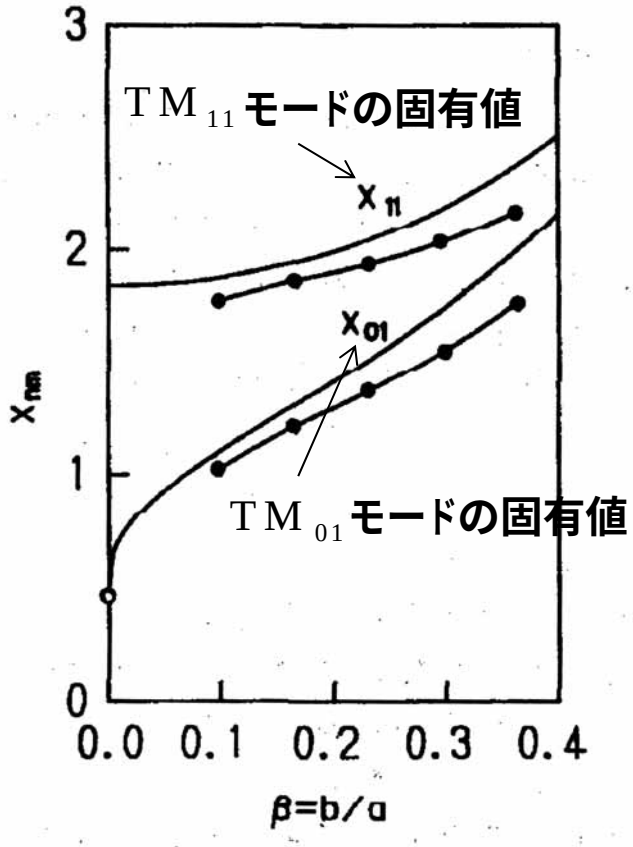


図 3　x_{11}, x_{01} の計算値および測定値
——：計算値、—●—：測定値

[65] 金田の論文(1986)

論文の概要

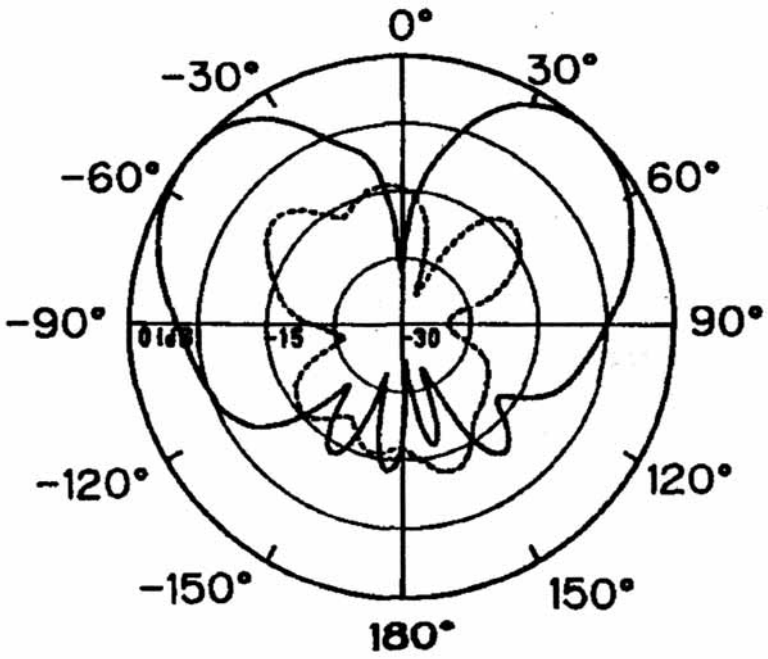


図７　TM_{01}モードの指向性パターン
———：主偏波、- - - -：交差偏波
f=2.596 GHz,　β=0.363

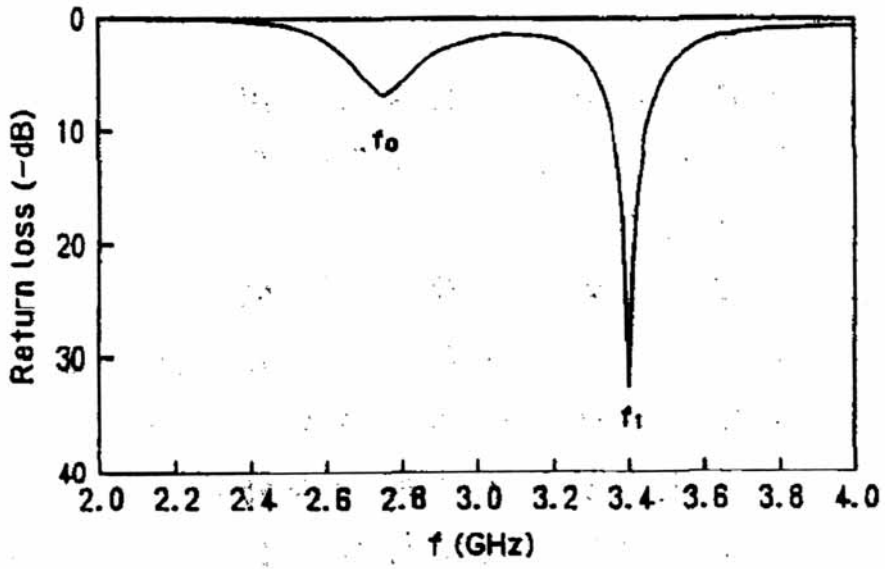
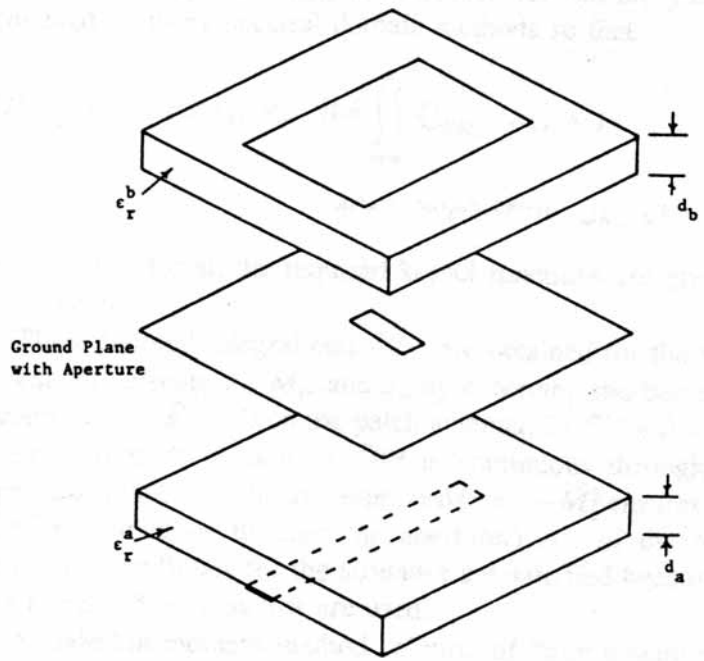


図５　共振特性
f_0=2.767 GHz, f_1=3.410 GHz

[66] Sullivan の論文(1986)　論文の概要

電磁結合 MSA を Full Wave 解析



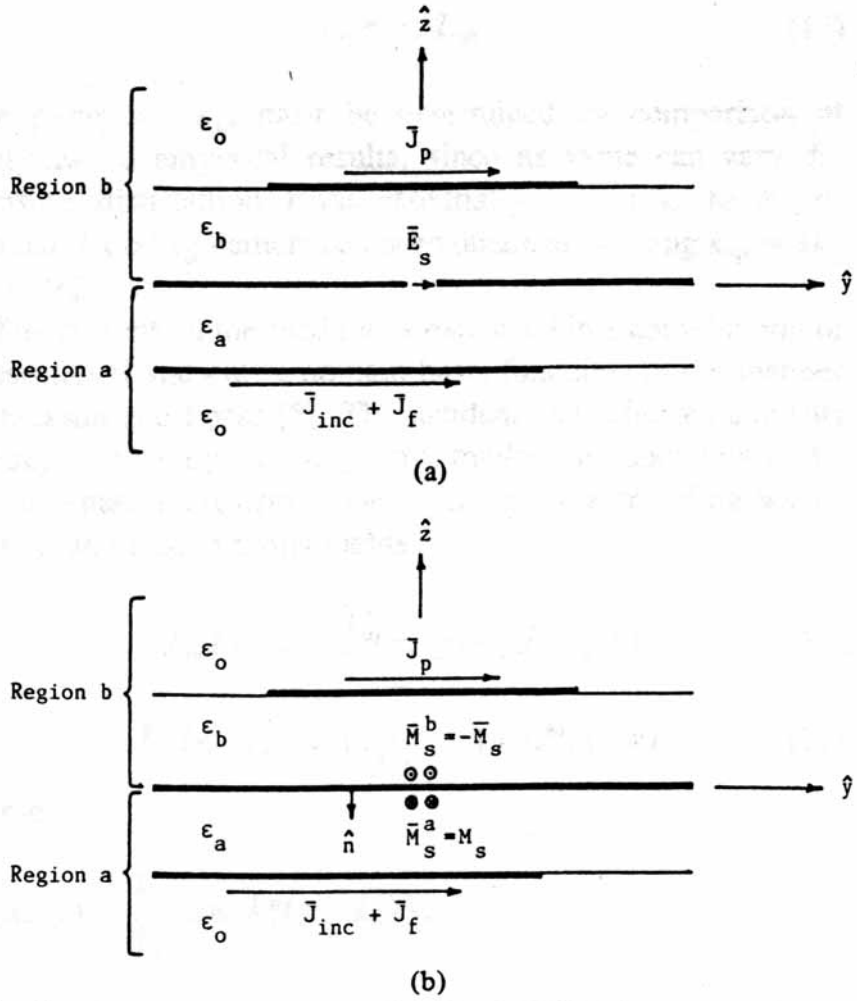


Fig. 2. Antenna and feed with incident and induced currents. (a) Original problem. (b) Equivalent problem.

パッチ上の電流分布：

$$\boldsymbol{J}_p(x,y) = \sum_{n=1}^{N_b} I_n^b \boldsymbol{J}_n^b(x,y)$$

$$\because \quad \boldsymbol{J}_n^b(x,y) = \frac{1}{W_p} \frac{\sin k_e^b \left(h^b - |y - y_n|\right)}{\sin k_e^b h^b} \hat{y}$$

[68] Paschen の論文(1986)

論文の概要

MSA のフィルタ理論に基づく広帯域化

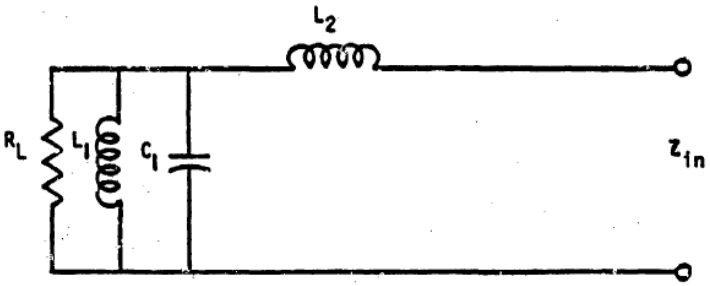


Fig.1 Microstrip Patch Model

Fig.8 Direct Fed Patch

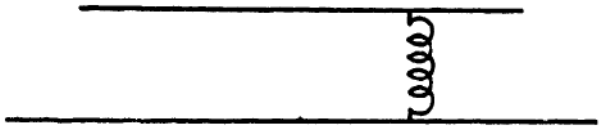


Fig.9 Increase Inductance

広帯域化

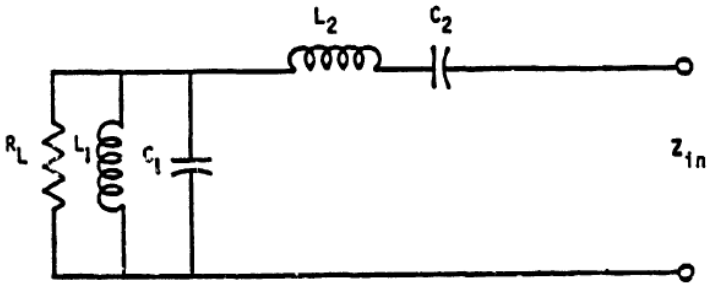


Fig. 2 Bandpass Filter (N-2)

Parallel - Plate

Cylindrical

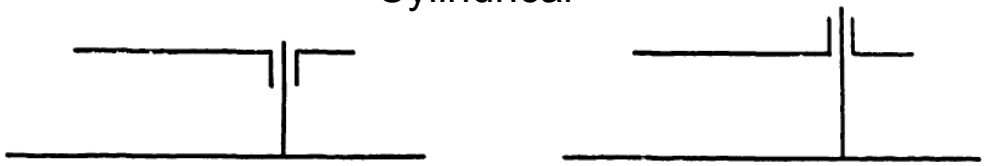


Fig.10 Four Methods of Integral Series Capacitance

[70] 荒木の論文(1986)

論文の概要

ハンケル変換による非励振素子装荷円形 MSA の解析

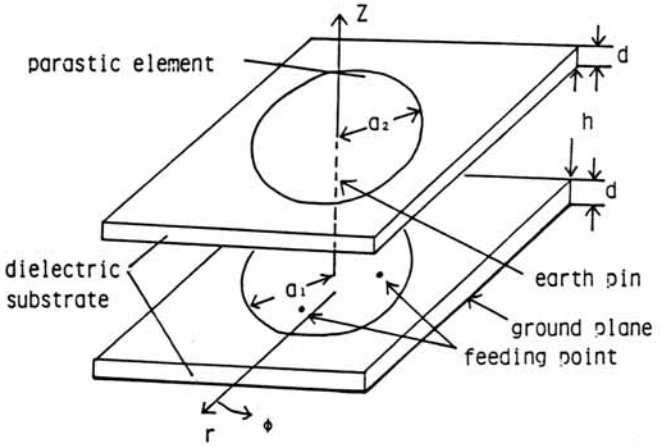


Fig. 1. Structure of circular double tuned microstrip antenna and coordinate system.

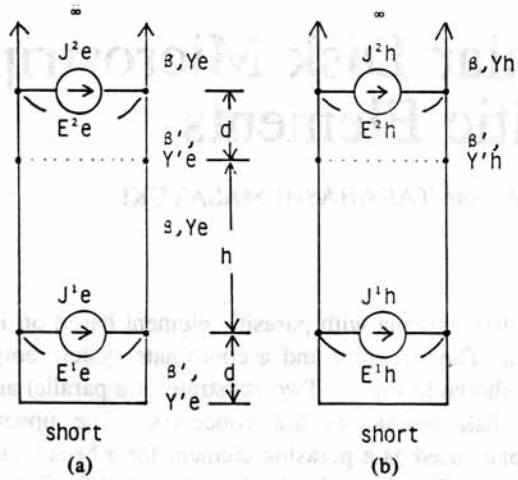


Fig. 2. Equivalent transmission lines for TE and TM components. (a) *E*-wave. (b) *H*-wave.

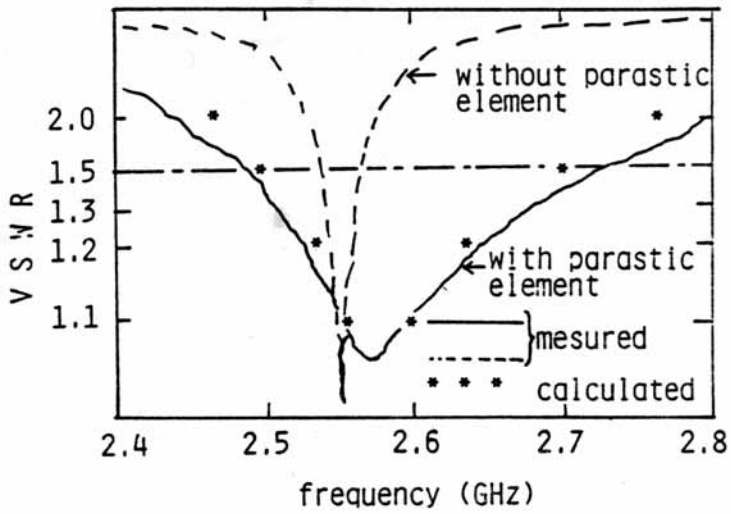


Fig. 6. Calculated and measured VSWR characteristics (h = 10.0 mm, a_1 = 20.8 mm, a_2 = 21.0 mm, d = 1.6 mm, $\epsilon = 2.55\epsilon_0$).

[71] Pozar の論文(1986)

論文の概要

電磁結合 MSA を Full Wave 解析

[66] より精度が良い(パッチ上の電流分布の仮定の違い)

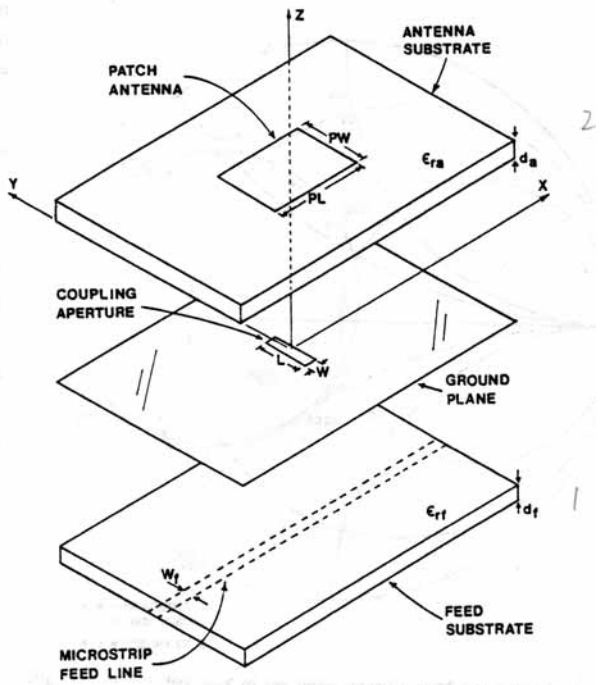


Fig. 6. Geometry of an aperture coupled microstrip patch antenna.

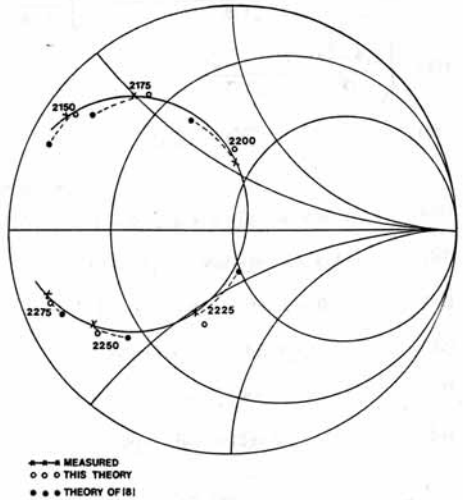


Fig. 7. Smith chart plot of the input impedance of a stub-tuned aperture coupled patch antenna. $\epsilon_{ra} = 2.54$, $d_a = 0.16$ cm, PL = 4.0 cm, PW = 3.0 cm, $\epsilon_{rf} = 2.54$, $d_f = 0.16$ cm, $L = 1.12$ cm, $W = 0.155$ cm, $W_f = 0.442$ cm, $L_s = 2.0$ cm.

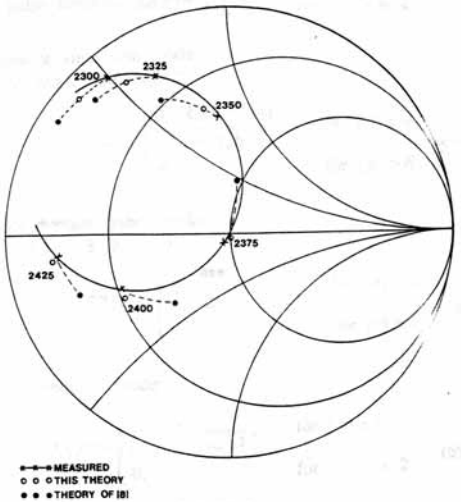


Fig. 8. Smith chart plot of the input impedance of a stub-tuned aperture coupled patch antenna. $\epsilon_{ra} = 2.22$, $d_a = 0.16$ cm, PL = 4.0 cm, PW = 3.0 cm, $\epsilon_{rf} = 10.2$, $d_f = 0.127$ cm, $L = 1.0$ cm, $W = 0.11$ cm, $W_f = 0.116$ cm, $L_s = 1.1$ cm.

パッチ上の電流分布：

$$J_{sx} = \frac{1}{W}\sum_{n=1}^{N} I_n f_s^n(x)$$

$$\because \quad f_s^n(x) = \sin\frac{m\pi}{2a}(x+a) \quad for \quad |x| < a$$

[72] 鈴木 の論文(1987)

論文の概要(1/2)

三角形 MSA でも 2 つの周波数で一点給電円偏波励振が可能であることを示す

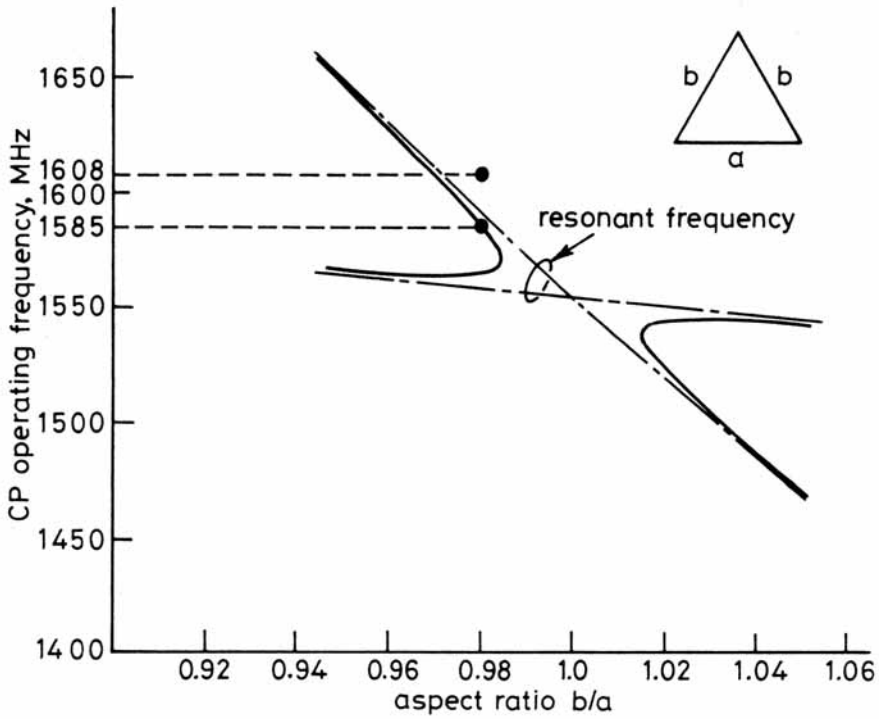


Fig. 2 *Relationship between CP operating frequency and aspect ratio for equilateral-triangular microstrip antenna*

——— theoretical

· experimental

$a = 76$ mm; $\varepsilon_r = 2.55$; $t = 3.2$ mm; $\tan\delta = 0.0018$

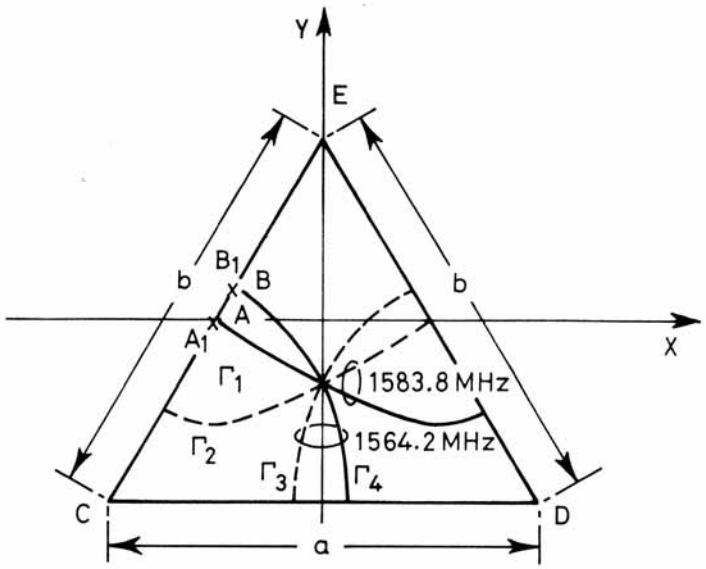


Fig. 3 *Feed-location loci for equilateral-triangular microstrip antenna*

$b/a = 0.98$; $a = 76$ mm; $t = 3.2$ mm; $\varepsilon_r = 2.55$: $\tan\delta = 0.0018$

——— RHCP

– – – – LHCP

[72] 鈴木 の論文(1987)

論文の概要(2/2)

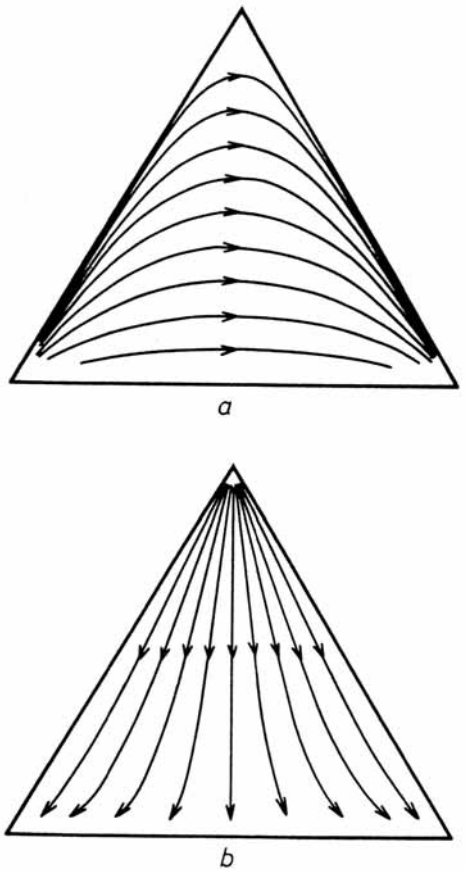


Fig. 4 *Current flows on inner surface of equilateral-triangular patch with point A as a feed point*

a Current flow for 2nd-order mode
b Current flow for 3rd-order mode

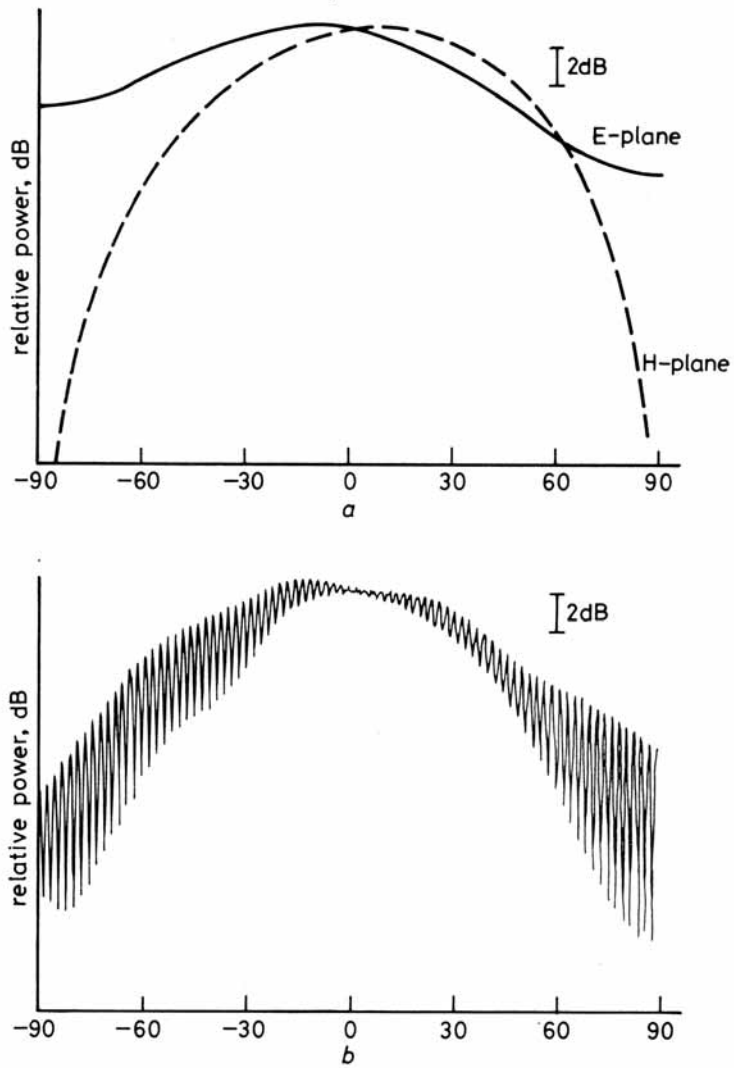


Fig. 7 *Radiation patterns in xz-plane for equilateral-triangular microstrip antenna*

a Calculated result at 1583.8 MHz; selecting A as a feed point
b Measured result at 1608 MHz; selecting A_1 as a feed point

[73] 柏 の論文(1988)

論文の概要

空間回路網法により MSA を解析

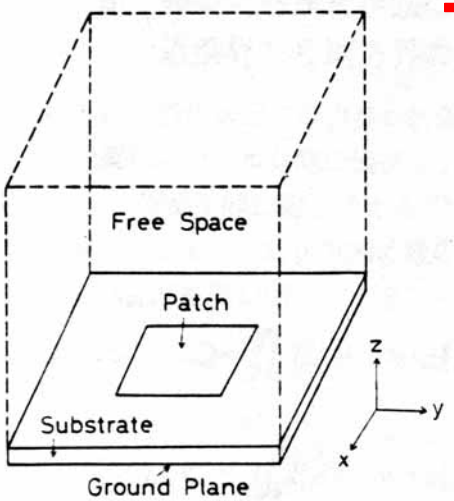


図 1　方形パッチアンテナの解析モデル

Fig. 1　Analyzed model of the rectangular patch antenna

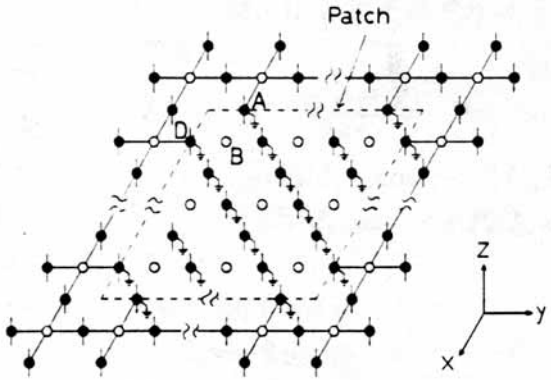


図 2　パッチ部の等価回路

Fig. 2　Equivalent circuit of the patch.

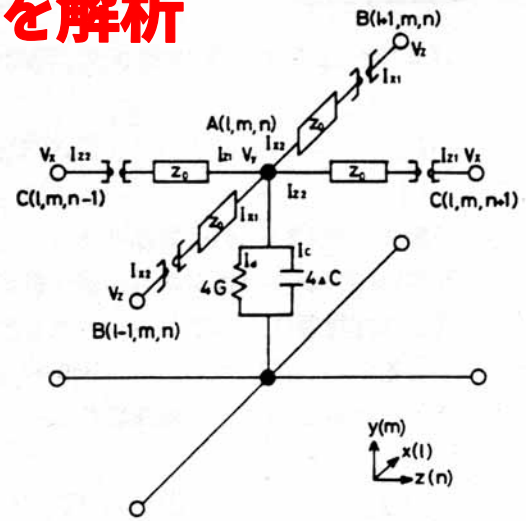


図 3　$A(l, m, n)$ 点での媒質条件を含む等価回路

Fig. 3　Equivalent circuit of node $A(l, m, n)$ with medium condition.

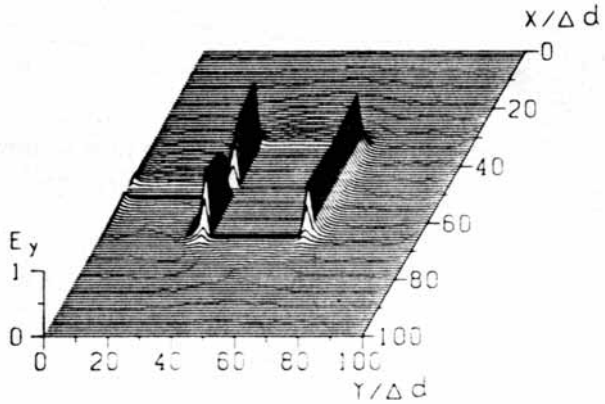


図 7　パッチを含む水平面での電界成分 E_y の分布（直線偏波）

Fig. 7　Distribution of the electric field E_y in the plane including the patch (Linear polarization).

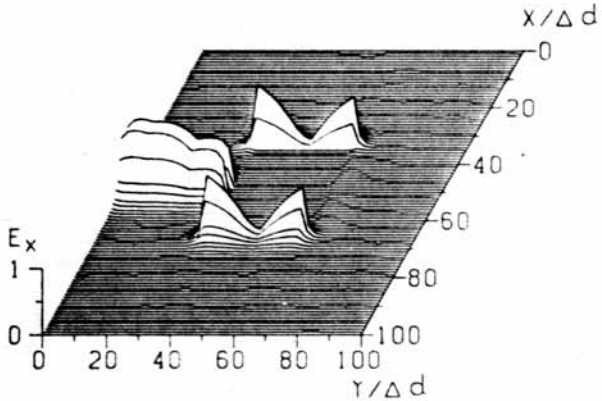


図 8　パッチを含む水平面での電界成分 E_x の分布（直線偏波）

Fig. 8　Distribution of the Electric Field E_x in the plane including the patch. (Linear polarization).

[74] Y. T. Lo の論文(1988)　論文の概要

矩形 MSA が 2 つの周波数で一点給電円偏波励振が可能であることを示す

$$\frac{E_y}{E_x} \simeq A\,\frac{k-k_{10}}{k-k_{01}} = \pm j \qquad (4)$$

where

$$A = \frac{\cos(\pi y'/b)}{\cos(\pi x'/a)} \qquad (5)$$

The $\pm$ sign in eqn. 4 designates the left-hand (LH) and the right-hand (RH) CP waves, respectively. One way to determine the feed position (x', y') for given a and b is by examining eqn. 4 in the complex k-plane, as shown in Fig. 1, which states that the phasors $(k - k_{10})$ and $(k$

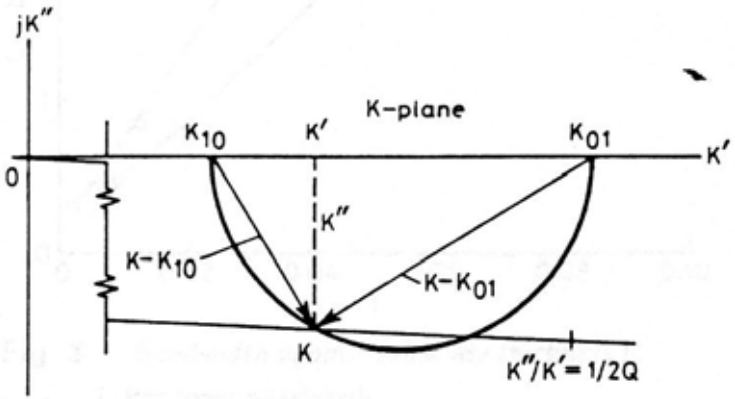


Fig. 1 *Geometric relations of phasors k_{10}, k_{01}, and k in k-plane for CP operation*

$k = k' - jk''$

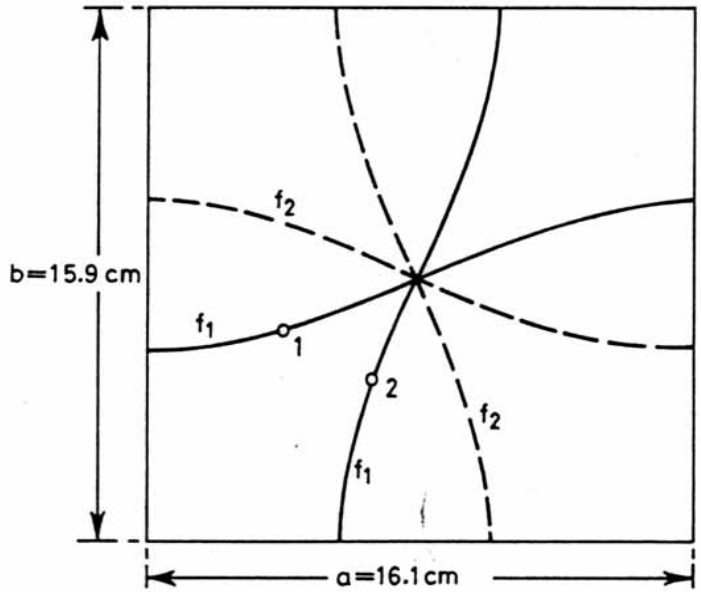


Fig. 2 *Feed loci for a rectangular CP microstrip antenna*

Substrate thickness 0.32 cm; $\varepsilon_r = 2.62$

○ feed point

——— LHCP

- - - - RHCP

文献[61]の完全な後追い

[77] Reineix の論文(1989)　論文の概要

FDTD 法により Stacked rectangular MSA を解析

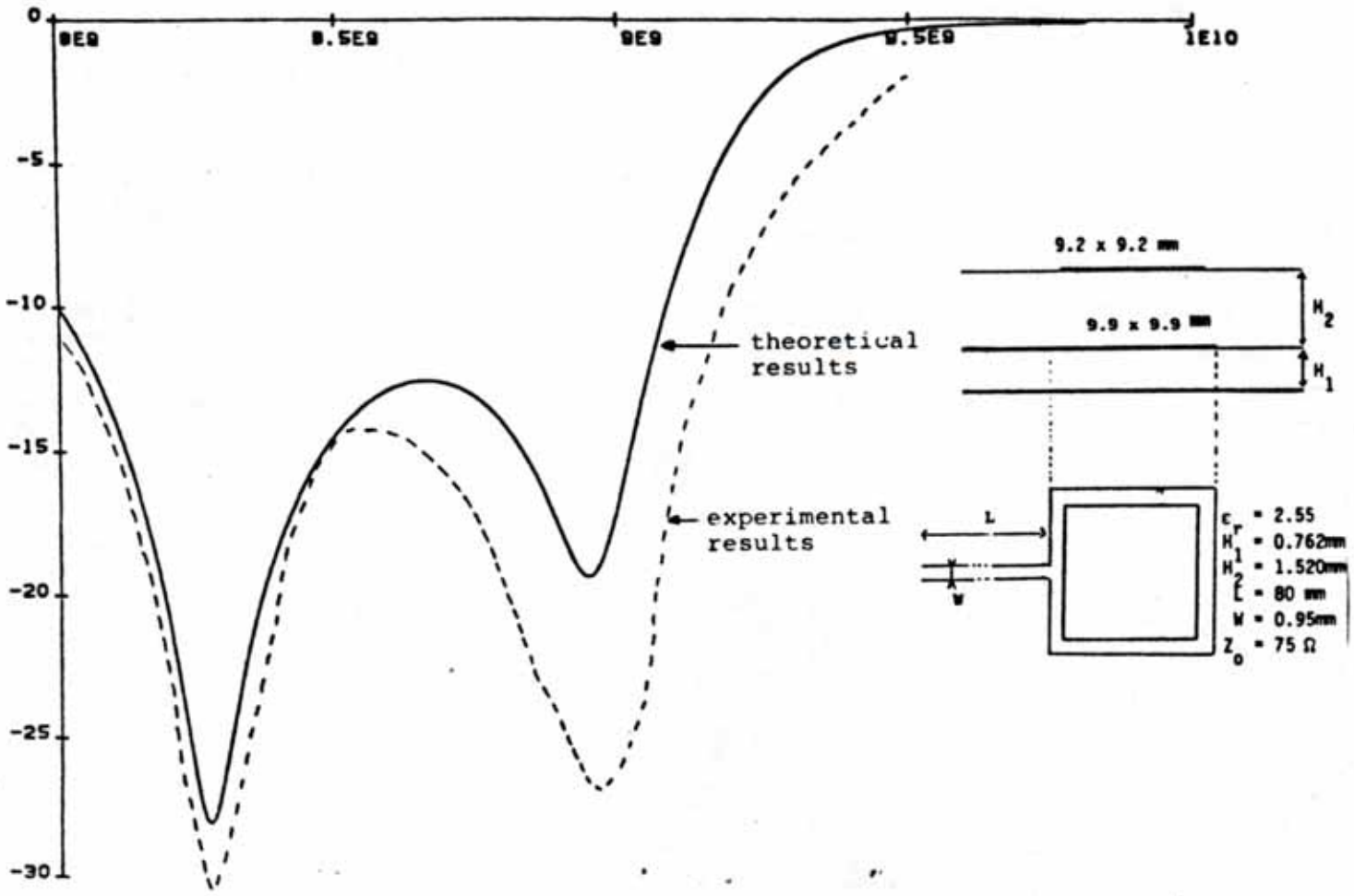


Fig. 18. Reflection coefficient of a microstripline fed stacked antenna (Fig. 17).

[78] Pues の論文(1989)

論文の概要

マッチング回路により広帯域化を実現

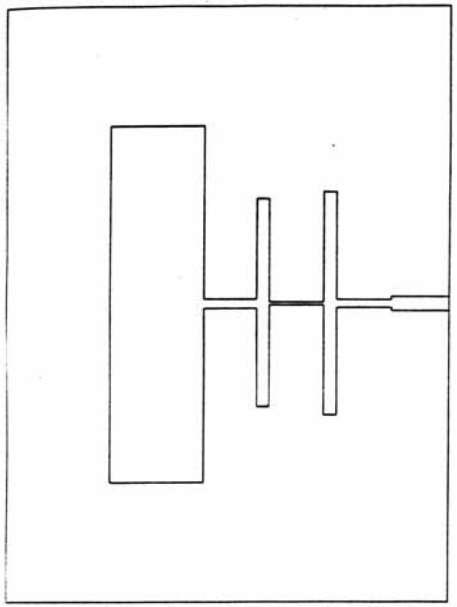


Fig. 6. Layout of rectangular impedance-matched antenna (antenna #1).

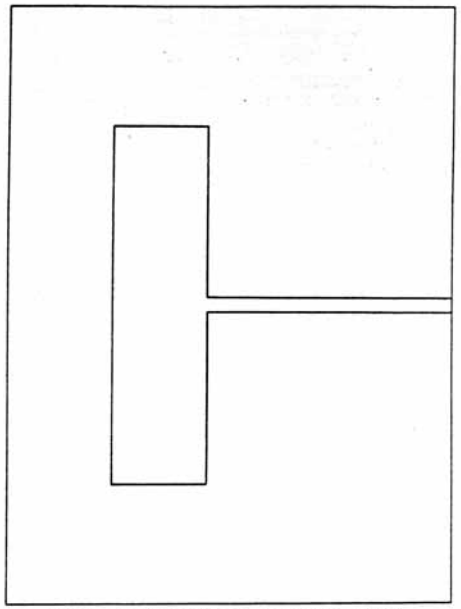


Fig. 7. Layout of reference antenna (antenna #2).

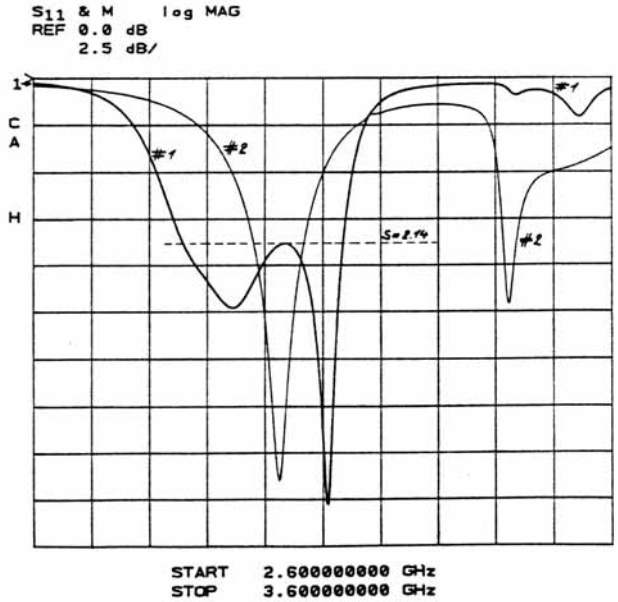


Fig. 8. Return loss versus frequency of antennas #1 and #2.

[80] N. Miyanoの論文(1990)　論文の概要(1/2)

MSA のSSR モード S 用電子走査アンテナへの展開

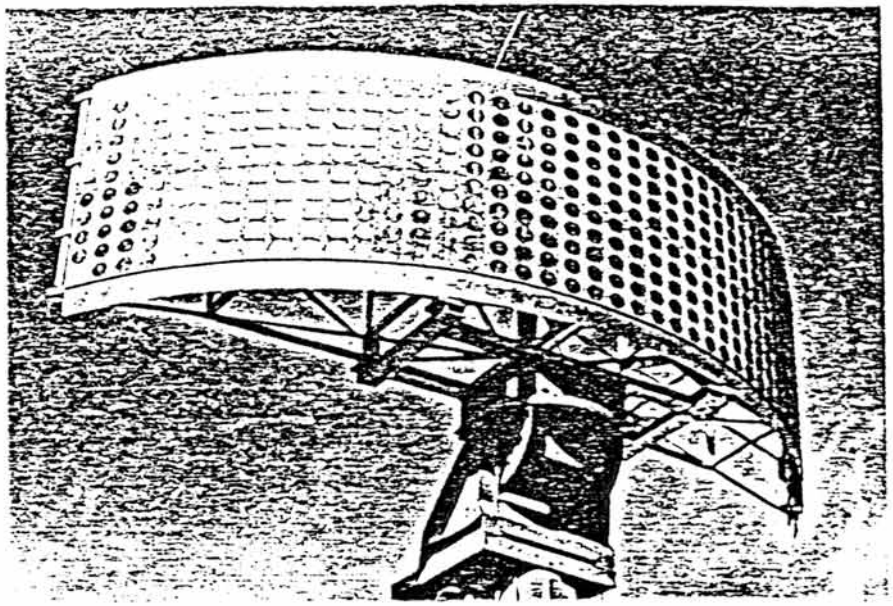


Fig.1 OUTSIDE VIEW

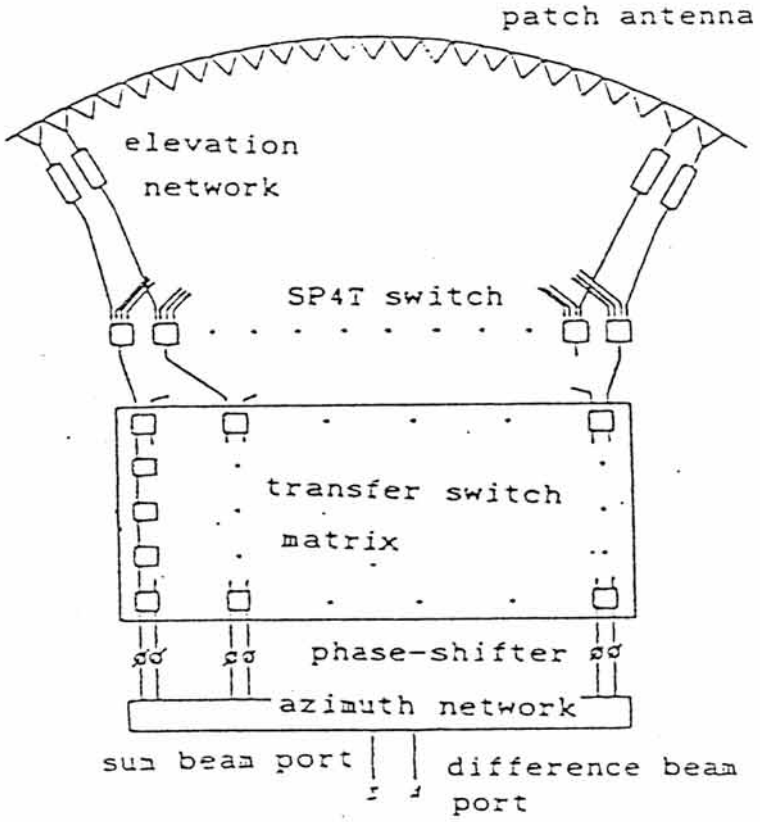


Fig.2 RF BLOCKDIAGRAM

[80] N. Miyanoの論文(1990)

論文の概要(2/2)

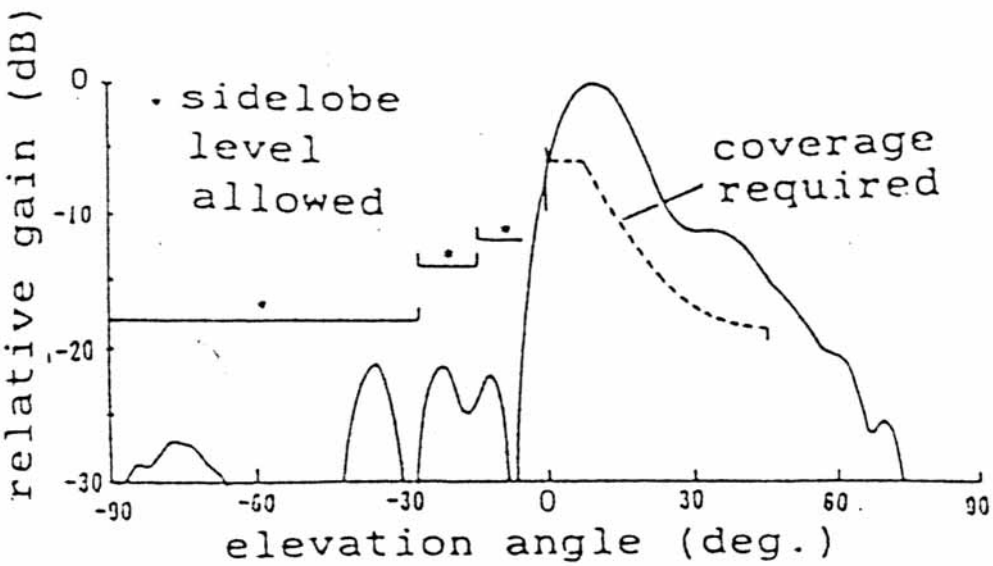


Fig.5 ELEVATION PATTERN

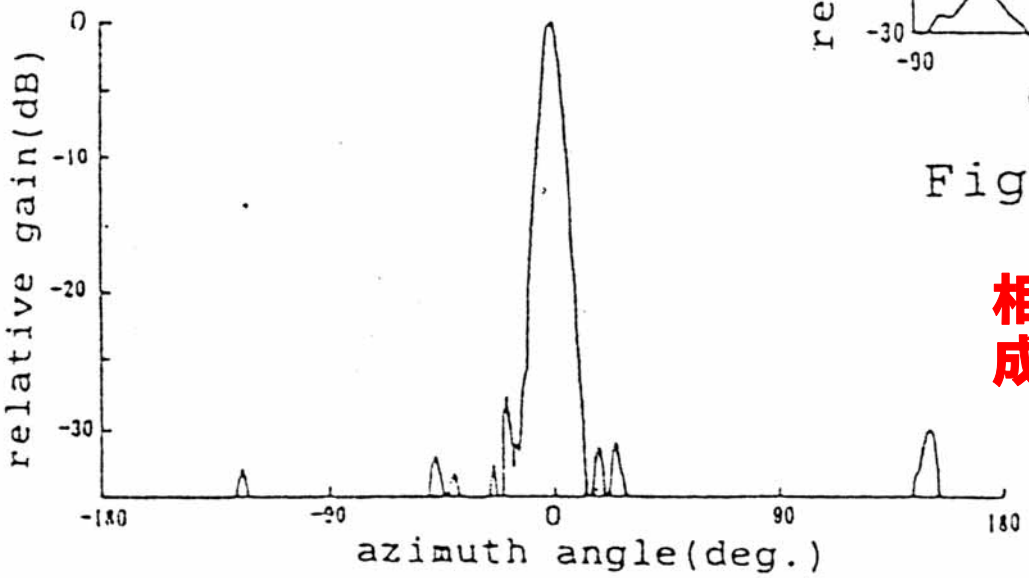


Fig.7 AZIMUTH PATTERN

相互結合が小さいことに着目した成形ビームの合成

[81] H. Iwasakiの論文(1991)　論文の概要(1/2)

十字スロット結合による1点給電円偏波アンテナ

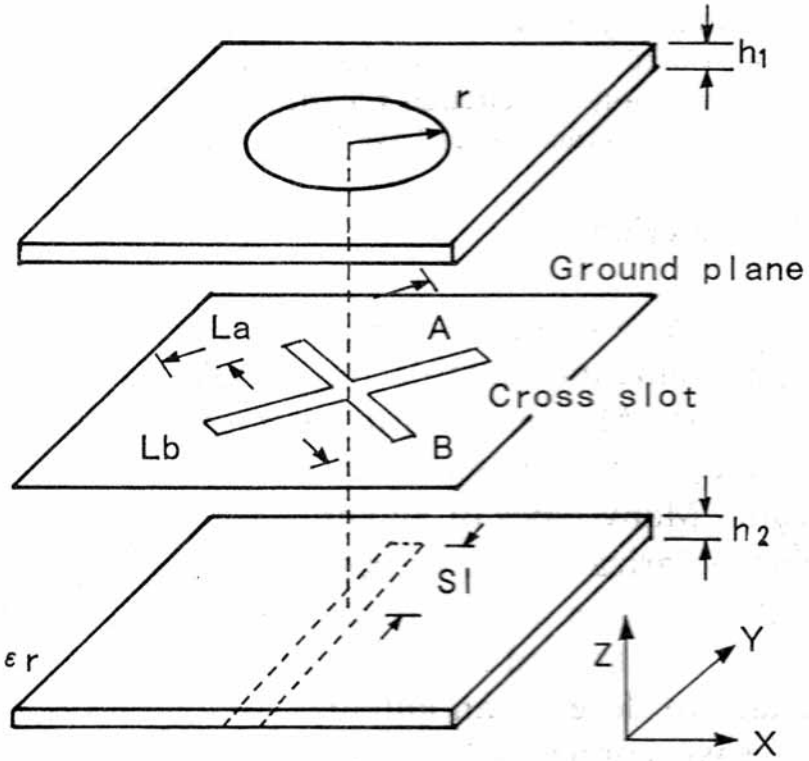


Fig. 3　Patch antenna fed by a slot using a microstrip line.

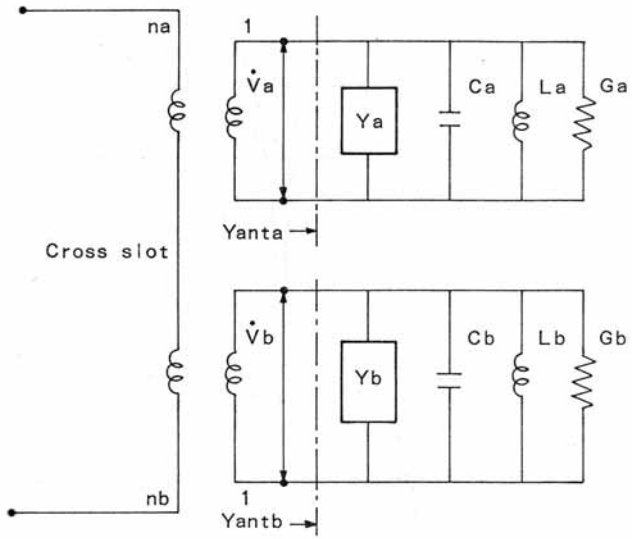


Fig. 4　Equivalent circuit of a patch antenna with a cross slot.

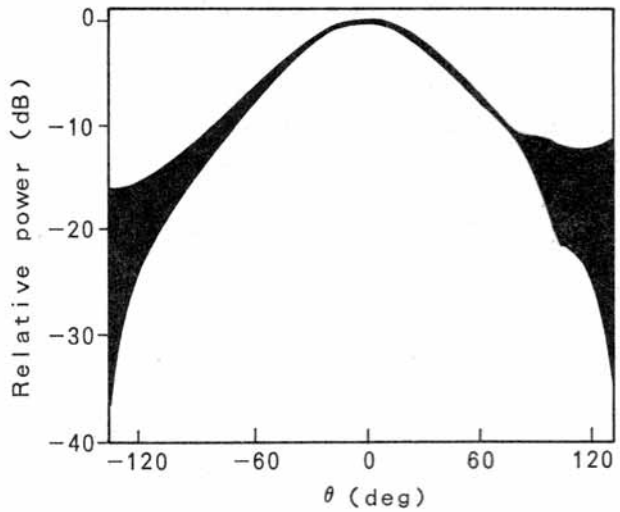


Fig. 8　Measured radiation pattern.　Frequency=1.6 GHz, S_R=1.3.　x-z plane.

終わりに

ここで紹介させて頂いた論文以外にも
まだまだ重要な論文があるとは思いますが、

時間と紙面の都合により、
特に印象に残っている論文を
回想録としてご紹介させて頂きました。

今回ご紹介できなかった論文については、
ご容赦のほどお願い致します。