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STACKED TWO-LAYER ELECTROMAGNETICALLY COUPLED CIRCULAR PATCH MICROSTRIP ANTENNAS

Sandhya Mann

Department of Physics, Agra College, Agra-282001 (UP),INDIA

In this paper circular patch microstrip antennas with multidielectric layers have been chosen to yield wide bandwidth because it provides better compromise between bandwidth and surface wave effect, light weight and ease of fabrication. Variation of resonant frequency with various parameters is presented at 10 GHz and 3 GHz of microwave frequency range. Also, the radiation patterns are studied at both the frequency range.

INTRODUCTION

Simple microstrip antennas (MSA) have limited usable frequency bandwidth, being only 2 to 5%. Hence, there is a requirement for increasing the bandwidth of microstrip antennas. The bandwidth can be increased by increasing the substrate thickness or by decreasing the dielectric constant or by combining the above two approaches. However increase in the substrate thickness results in surface wave excitation. When the MSA is fed by a perpendicular coaxial line, the probe introduces a series inductance proportional to substrate thickness. And hence prevent proper matching. In view of the above problems electromagnetic coupling has been used as feed technique for electrically thick MSAs [1-4]. The geometry of the microstrip antenna proposed in this paper is shown in Fig. 1.

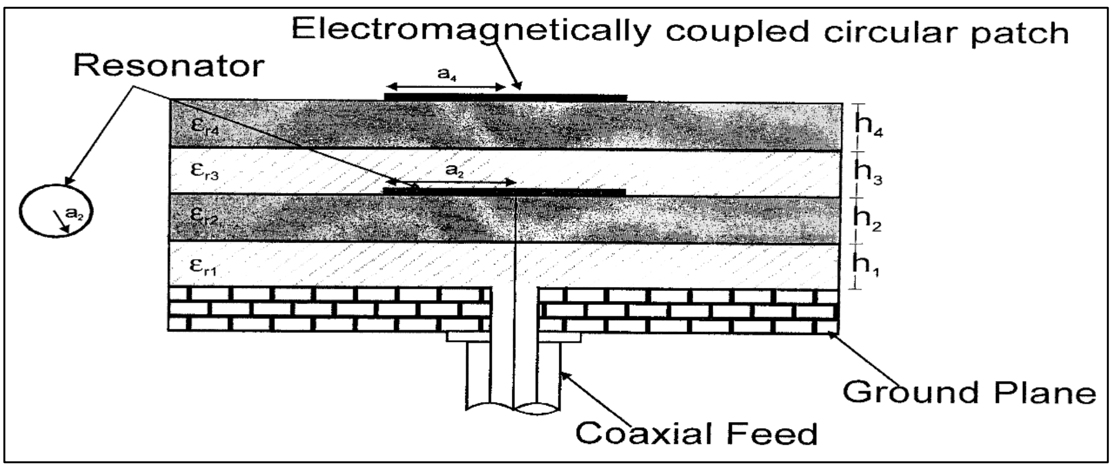

Fig. 1: Configuration of a stacked circular micro-strip patch antenna with electromagnetic coupling.

Formulation

The circular MSA is modelled as a cavity with a magnetic wall along the edge. This is in fact a four-layer cavity. The lowermost layer is of thickness h_1 with relative permittivity ε_{r1} then the second one with thickness h_2 and permittivity ε_{r2}, then the third one with thickness h_3 with relative permittivity ε_{r3} and finally the top layer of thickness h_4 with relative permittivity ε_{r4} respectively.

We use an equivalent single-layer structure of total height $\sum_{i=1}^{4} h_i$ and an effective permittivity [5] expressed by

$$\varepsilon_{re} = \sum_{i=1}^{4} h_i / \sum_{i=1}^{4} \frac{h_i}{\varepsilon_{ri}} \quad ...(1)$$

An analytical formula for resonant frequency of circular MSA for dominant mode is given by [6,7]

$$f_{r,nm} = \frac{\alpha_{nm} c}{2\pi a_{eff}\sqrt{\varepsilon_{r,eff}}} \quad ..(2)$$

$$\varepsilon_{r,eff} = \frac{4\varepsilon_{re}\varepsilon_{r,dyn}}{\left(\sqrt{\varepsilon_{re}}+\sqrt{\varepsilon_{r,dyn}}\right)^2} \quad ...(3)$$

Here, $\varepsilon_{r,dyn}$ is the dynamic permittivity given by

$$\varepsilon_{dyn} = \frac{C_{dyn}(\varepsilon)}{C_{dny}(\varepsilon_0)} \quad ...(4)$$

Where $C_{dyn}(\varepsilon) = C_{0,dyn}(\varepsilon) + C_{e,dyn}(\varepsilon)$ is the total dynamic capacitance expressed as follows for the dominant mode TM_{11}

$$C_{dyn} = \frac{\varepsilon_0\varepsilon_{re}\pi a^2}{h} 2\left[0.352 + \frac{q}{2}\right] \quad ...(5)$$

Where the first term is equal to the dynamic main capacitance $C_{0,dyn}(\varepsilon_0)$ and second is equal to the dynamic fringing capacitance $C_{e,\ dyn}(\varepsilon)$ of the dominant mode. The term q arises due to the fringing field at the edge of the disc capacitor expressed as

$$q = u + v + uv \quad ...(6) \qquad u = \frac{1+\varepsilon_{re}}{\varepsilon_{re}} \frac{4}{a\pi/h} \quad ...(7)$$

$$v = \frac{2}{3t}\frac{\ln(p)}{8+\pi a/h} + \left(\frac{1}{t} - 1\right)/g \quad ...(8) \qquad t = 0.37 + 0.63\varepsilon_{re} \quad ...(9)$$

$$p = \frac{1+0.8(a/h)^2+(0.31a/h)^4}{1+0.9a/h} \quad ...(10) \qquad g = 4 + 2.6\frac{a}{h} + 2.9\frac{h}{a} \quad ...(11)$$

Here, a is the physical radius of the patch and a_{eff} is effective radius of patch defined as

$$a_{eff} = a\sqrt{(1+q)} \quad ...(12)$$

$C_{dyn}(\varepsilon_0)$ is obtained similarly as $C_{dyn}(\varepsilon)$ by replacing ε by ε_0.

Firstly the bottom patch dimensions [8] are calculated for a given operational frequency and hence the resonant frequency f_{r2} of the bottom patch using eqn. (2) (with $h = \sum_{i=1}^{4} h_i$). Then the top patch dimensions approximated assuming the bottom patch to be ground plane for the top patch and actual ground plane to be ground plane for the top patch fringing fields. Finally the resonant frequency f_{r4} of the top patch is calculated using eqn. (2) by exact calculation of the capacitance C between patches [6]

Once the resonant frequencies of the top and bottom patches are determined the band width is enlarged using the center frequency as the matching frequency defined as

$$f_r = \frac{f_{r2}+f_{r4}}{2} \quad ...(13)$$

The bandwidth [9] is usually defined as the frequency range over which the voltage standing wave ratio is less than or equal to some value say S in the frequency range f_1 to f_2 ($f_1<f_2$)

$$BW = \frac{f_2-f_1}{f_r} \quad ...(14)$$

Radiation Patterns

Antenna radiation pattern is defined as a graphical representation of radiation properties of the antenna as a function of space coordinate. In far-zone region, the field are calculated in spherical coordinate system i.e. (r,θ,Φ) the expression for which are as follows [8]:

$$E_\phi = j^n \frac{Vak_0}{2r} e^{-jk_0 r} \cos\theta \sin n\phi \left[J_{n+1}(k_0\, a\sin\theta) + J_{n-1}(k_0\, a\sin\theta)\right] \quad ...(15)$$

$$E_\theta = j^n \frac{Vak_0}{2r} e^{-jk_0 r} \cos n\theta \left[J_{n+1}(k_0\, a\sin\theta) - J_{n-1}(k_0\, a\sin\theta)\right] \quad ...(16)$$

Where E_ϕ and E_θ are components of total electric field vector for EM wave and J_{n+1} and J_{n-1} are $(n+1)^{th}$ and $(n-1)^{th}$ order Bessel's function of first kind respectively.

$V = hE_0 J_n(ka)$ is edge voltage at Φ=0 ...(17)

measured in dB. The directivity is the ratio of maximum radiation intensity to the radiation intensity of an isotropic radiator. And antenna gain Gg is the measure of efficiency times the directivity of the test antenna.

$G_g = \eta D$ and $\eta\% = \frac{G_r}{G_T}\text{x}100$ ...(18)

Results

Each conducting patch is fabricated on an electrically thin substrate of permittivity 2.2 (i.e.,$\varepsilon_{r2} = \varepsilon_{r4} = 2.2$) and of height (i.e.,$h_2 = h_4 = 0.159\, cm$) and separated by a region of air gap (i.e., $\varepsilon_{r3} = 1$) of width h_3. The top element is excited via electromagnetic coupling from the lower element which is located close to the ground plane and fed directly by the feed line.

We have studied the variation of resonant frequencies of top and bottom patch with various parameters like h_1/λ, h_3/λ, a_2, a_4 and ε_{r1}. Here a_2 and a_4 are physical radii of bottom and top patches respectively and λ is wavelength in substrate of permittivity 2.2. Information regarding the resonant frequencies versus different parameters is detailed in Table I and II for two different operating frequencies 10 GHz and 3GHz.

Table I: Resonant frequencies of bottom and top patch versus various different parameters at 10 GHz.

$\frac{h_1}{\lambda}$	$\frac{h_3}{\lambda}$	$h = \sum_{i=1}^{4} h_i$ (cm)	ε_{r1}	a2 (cm)	a4 (cm)	Cx10^{-11} (Farad)	f_{r2} (GHz)	f_{r4} (GHz)	$f_{r2} - f_{r4}$ (MHz)
0.01	0.06	0.459	1	0.59	0.57	0.13	10.35	8.57	1785.2
0.01	0.06	0.459	1	0.59	0.55	0.12	10.35	8.79	1551.8
0.01	0.06	0.459	10.8	0.58	0.55	0.13	10.38	8.57	1816.1
0.03	0.04	0.459	1	0.58	0.58	0.16	10.01	8.39	1623.0
0.03	0.04	0.459	10.8	0.53	0.53	0.17	10.41	8.68	1721.7
0.02	0.06	0.479	1	0.59	0.57	0.10	10.08	8,33	1748.6
0.02	0.06	0.479	10,8	0.56	0.54	0.14	10.33	8.49	1825.9
0.04	0.04	0.479	1	0.58	0.58	0.16	9.87	8.25	1621.1
0.04	0.04	0.479	1	0.58	0.59	0.17	9.87	8.16	1705.1
0.04	0.04	0.479	10.8	0.52	0.52	0.17	10.33	8.62	1719.1

Table II: Resonant frequencies of bottom and top patch versus various different parameters at 3 GHz.

$\frac{h_1}{\lambda}$	$\frac{h_3}{\lambda}$	$h = \sum_{i=1}^{4} h_i$ (cm)	ε_{r1}	a2 (cm)	a4 (cm)	Cx10^{-11} (Farad)	f_{r2} (GHz)	f_{r4} (GHz)	$f_{r2} - f_{r4}$ (MHz)
0.02	0.06	0.857	1	2.34	2.20	0.58	3.07	2.72	351.2
0.02	0.06	0.857	1	2.34	2.15	0.55	3.07	2.77	297.5
0.02	0.06	0.857	10.8	2.15	2.03	0.59	3.20	2.83	377.6
0.04	0.04	0.857	1	2.27	2.27	0.79	3.01	2.66	346.1
0.04	0.04	0.857	10.8	1.87	1.87	0.82	3.30	2.93	372,9
0.04	0.06	0.992	1	2.29	2.24	0.61	2.99	2.61	377.3
0.04	0.06	0.992	1	2.29	2.24	0.62	2.99	2.60	385.5
0.04	0.06	0.992	10.8	1.98	1.92	0.64	3.22	2.80	412.9
0.05	0.05	0.992	1	2.27	2.27	0.71	2.96	2.59	372.9
0.05	0.05	0.992	10.8	1.86	1.86	0.74	3.25	2.85	404.1

From tables I and II, it is found that the frequency separation between bottom and top patches is quite independent of one another. The required frequency separation can be obtained by adjusting the parameters and thickness of the layers. It is also found from the tables I and II that the resonant frequency separation will increase by increasing ε_{r1} and reducing ε_{r3}. Also, for the same height h=$\sum_{i=1}^{4} h_i$; the resonant frequency separation increases by increasing h_3 and reducing h_1. For the same bottom patch radius the frequency separation is directly proportional to the top patch radius. Also, the capacitance between patches C is tabulated in the tables I and II.

Thus, the enlarged bandwidth is obtained through eqn. (13). Using eqn. (1) the fundamental parameters of stacked two layered electromagnetically coupled circular MSAs have been studied in S and X band of microwave frequencies ($\varepsilon_{r1} = \varepsilon_{r3} = 1$, $\varepsilon_{r2} = \varepsilon_{r4} = 2.2$ and, $\varepsilon_{r1} = 10.8$, $\varepsilon_{r2} = \varepsilon_{r4} = 2.2$, $\varepsilon_{r3} = 1$) respectively. The results are detailed in Table III and IV. It is observed that the bandwidth increases with layer thickness. There is an improvement in efficiency as the overall height of antenna increases. The radiation pattern are calculated and carefully plotted in E and H plane for some of the antennas considered above. Fig. 2-5 [10] shows these patterns along with the input parameters considered. The concept presented in this paper can be applied to patches of any arbitrary shape, dual frequency stacked antenna and arrays.

Table III: Fundamental parameters of stacked two layered electromagnetically coupled circular MSA, f= 10 GHz, $\varepsilon_{r2} = \varepsilon_{r4} = 2.2$, $\varepsilon_{r3} = 1$.

$\frac{h_1}{\lambda}$	$\frac{h_3}{\lambda}$	ε_{r1}	a_2 (cm)	a_4 (cm)	B.W (%)	G_g(dB)	D(dB)
0.01	0.06	1	0.594	0.566	12.62	5.39	5.41
0.01	0.06	10.8	0.578	0.552	12.29	5.29	5.31
0.03	0.04	1	0.582	0.576	12.41	5.50	5.51
0.03	0.04	10.8	0.533	0.529	11.35	5.30	5.32
0.02	0.06	1	0.594	0.572	13.30	5.33	5.34
0.02	0.06	10.8	0.563	0.544	12.64	5.21	5.22
0.04	0.04	1	0.582	0.582	13.07	5.48	5.49
0.04	0.04	10.8	0.521	0.521	11.65	5.22	5.23

Table VI: Fundamental parameters of stacked two layered electromagnetically coupled circular MSA, f= 3 GHz, $\varepsilon_{r2} = \varepsilon_{r4} = 2.2$, $\varepsilon_{r3} = 1$.

$\frac{h_1}{\lambda}$	$\frac{h_3}{\lambda}$	ε_{r1}	a_2 (cm)	a_4 (cm)	B.W (%)	G_g(dB)	D(dB)
0.02	0.06	1	2.340	2.204	7.27	6.71	6.73
0.02	0.06	10.8	2.145	2.032	6.84	6.45	6.47
0.04	0.04	1	2.266	2.266	7.07	6.96	6.99
0.04	0.04	10.8	1.874	1.874	6.08	6.39	6.41
0.04	0.06	1	2.298	2.235	8.49	6.65	6.66
0.04	0.06	10.8	1.975	1.929	7.56	6.19	6.20
0.05	0.05	1	2.265	2.265	8.37	6.78	6.79
0.05	0.05	10.8	1.859	1859	7.14	6.17	6.19

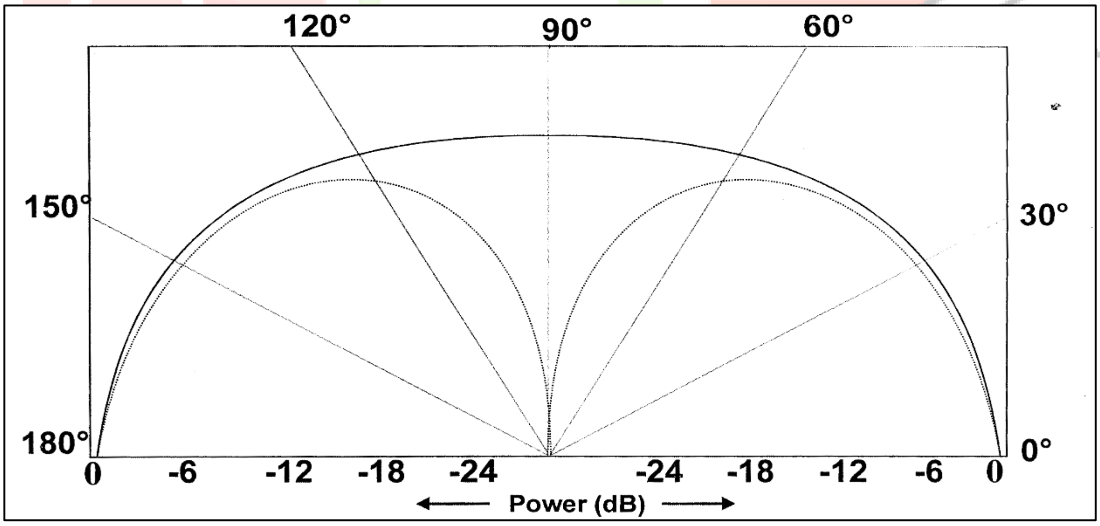

Fig. 2: Field patterns of stacked two layered electromagnetically coupled circular patch MSA. f=10GHz, $h_1=h_3=0.04\lambda$, $h_2=h_4=0.159$cm, $\varepsilon_{r1}=\varepsilon_{r3}=1$, $\varepsilon_{r2}=\varepsilon_{r4}=2.2$ and $a_2=a_4=0.582$cm. —— E-plane pattern ....H-plane pattern

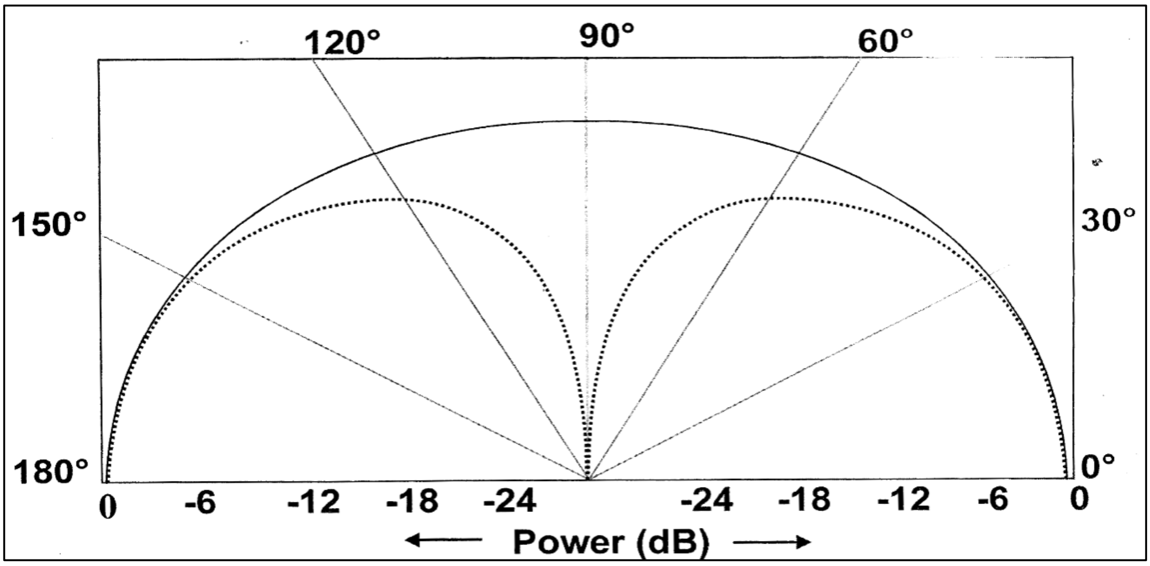

Fig. 3: Field patterns of stacked two layered electromagnetically coupled circular patch MSA. f=10GHz, $h_1=h_3=0.04\lambda$, $h_2=h_4=0.159$cm, $\varepsilon_{r1}= 10.8$, $\varepsilon_{r3} =1$, $\varepsilon_{r2}=\varepsilon_{r4}=2.2$ and $a_2=a_4=0.521$cm. —— E-plane pattern ....H-plane pattern

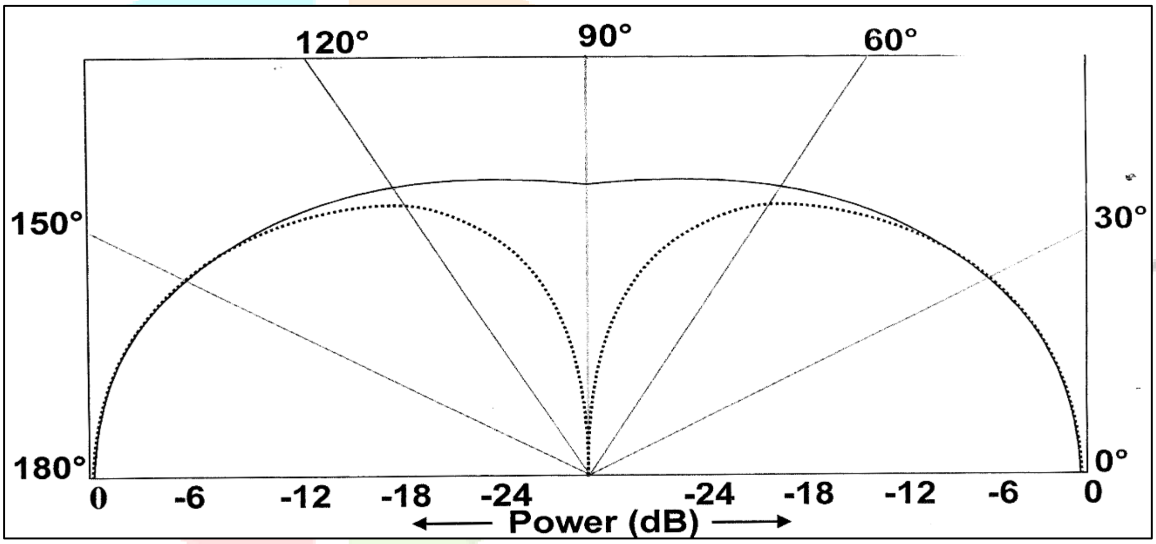

Fig. 4: Field patterns of stacked two layered electromagnetically coupled circular patch MSA. f=3GHz, $h_1=h_3=0.04\lambda$, $h_2=h_4=0.159$cm, $\varepsilon_{r1}=\varepsilon_{r3}=1$, $\varepsilon_{r2}=\varepsilon_{r4}=2.2$ and $a_2=a_4=2.266$cm. —— E-plane pattern ....H-plane pattern

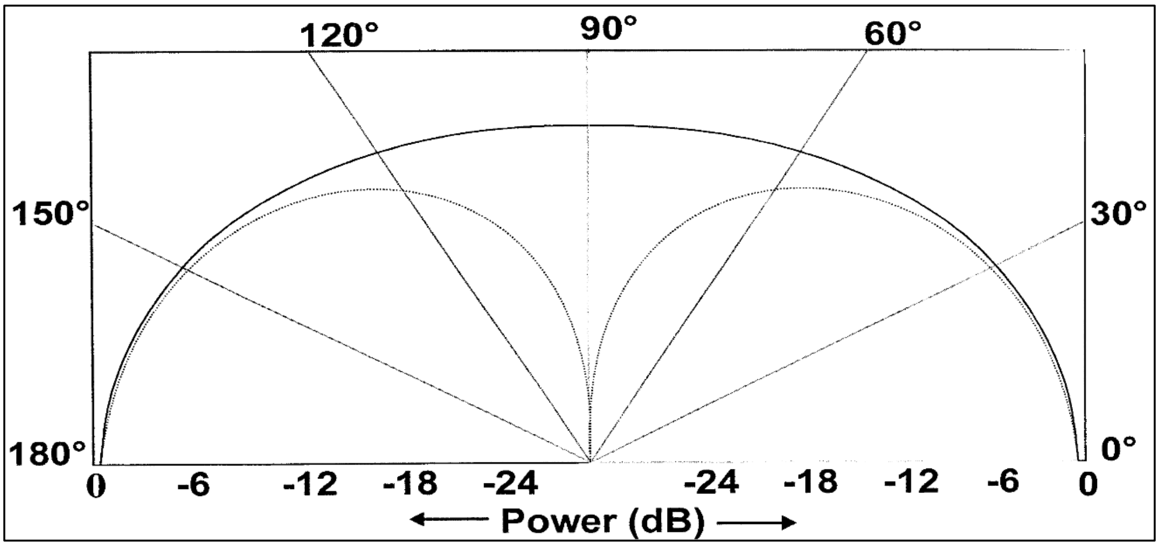

Fig. 5: Field patterns of stacked two layered electromagnetically coupled circular patch MSA. f=3GHz, h_1=h_3=0.04λ, h_2=h_4=0.159cm, ε_{r1}= 10.8, ε_{r3}= 1, ε_{r2}= ε_{r4}=2.2 and a_2=a_4=1.874cm. —— E-plane pattern ....H-plane pattern

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