Theoretical analysis of the radiation fields of parabolic reflector antenna fed by circular shaped microstrip antennas

O. I. Salman, A. S. Tahir &A. A. Al-Hilo

Physics Dept., Science College ,Basra University, Basra, Iraq.

Abstract:

Two theoretical analysis methods; Aperture Field Method (AFM) and Induced Current Method (ICM),have been studied for obtaining the radiation fields of parabolic reflector antenna fed by two types of microstrip antenna.

Calculations have been made of the radiation parameters and patterns of parabolic reflector, when exciting its surface by Circular (CRMA) and outer shorted Annular(ARMA) Ring Microsrtip Antenna. These calculations give the best results, for the aperture diameter (D=20λ) and ratio (f/D) that taken at edge illumination about (-3dB). As a result, both methods are in a complete agreement in studying of radiation patterns in principle planes (E and H) at far-field region.

Keywords: Antenna ; parabolic reflector; microstrip antennas

Introduction:

In general, the Antennas play a very important role in the field of communication system. Some of them are parabolic reflector and patch antenna. The performance and difference in the radiation parameters of parabolic reflector antenna is depending on the type of feed elements that used for exciting its surface (Ghobrial et al., 1989 ;Kooi et al., 1987) .

In other hand, the patch antennas such as microstrip have been receiving much attention due to its many conventional valuable properties like low-profile, light-weight, slim size ,and reasonably cheep to manufacture (Lo et al., 1979 ;Lai et al., 2008) .

In addition, the microstrip antenna that operates as a single element suffer from same drawback like narrow frequency low gain and low radiation efficiency (Kumar et.al. 2006).

Two types of microstrip antenna have been used as feed element of reflector antenna with small (f/D); the first one is Circular Ring Microstrip Antenna and the second is outer

shorted Annular Ring Microstrip Antenna .A CRMA shown in Fig.(1) is characterized by a single parameter, namely it's radius (a) and thickness dielectric (t). Consequently, this study dealt with theoretical analysis of radiation characteristic of parabolic reflector antenna excited by circular and annular microstrip antenna that placed at the reflector focal point. This analysis was carried out by applying AFM and ICM methods.

Analysis of the radiation fields

The theoretical analysis of the radiation pattern of parabolic reflector antenna has been studied by applying two methods (AFM), and (ICM).

1- Aperture Field Method

The first method in analysis is known as the Aperture Filed Method which is based on the knowledge of the tangential field component at aperture plane of the reflector (Obaid, 1985) . The structure diagram which is used in the theoretical analysis study is shown in Fig. (2).It consists of a microstrip antenna with radiating patch has a circular segment of radius (a) and dielectric of thickness (t) and paraboloid reflector with circular aperture. The microstrip is centered at the origin coordinate system(x_f,y_f,z_f) located at focal point of the parabola as a primary feed, while, the paraboloidal reflector is centered at the another origin coordinate system(x_a,y_a,z_a) which is assumed setup in the far-field region of the primary feed CRMA and ARMA. The radiation field components that radiated from exciting sources have been computed by applying the Simple Cavity Model (SCM) (EI-Khamy et al., 1986;Zakaria et al., 2008) ,as the following:

A-Circular Ring Microstrip Antenna

$$E_{\theta_f} = j^n \frac{V_\circ k_\circ a}{2} \frac{e^{-jk_\circ r_f}}{r_f} \cos n\varphi_f \left[J_{n+1}(k_\circ a \sin\theta_f) - J_{n-1}(k_\circ a \sin\theta_f) \right] \quad (1\text{-}a)$$

$$E_{\varphi_f} = j^n \frac{V_\circ k_\circ a}{2} \frac{e^{-jk_\circ r_f}}{r_f} \cos\theta_f \sin n\varphi_f \left[J_{n-1}(k_\circ a \sin\theta_f) + J_{n+1}(k_\circ a \sin\theta_f) \right] \quad (1\text{-}b)$$

Where $V_\circ = t J_n(ka) E_\circ$

$V_\circ$ is the edge voltage at (a, 0),

t is the thickness of dielectric substrate,

J_n is the Bessel function of the first kind of order n,

$k, k_\circ$ is the propagation constant in the dielectric and the free space.

31

The resonant frequency f_{mn} of a CRMA can be expressed as (Lai et al., 2008):-

$$f_{mn} = \frac{x_{mn}c}{2\pi a\sqrt{\varepsilon_r}}$$

Where x_{mn} is the zeros of the derivative of the Bessel function J_n

      C is the speed of light in free space

      ε_r is the relative permittivity

Also for dominant mode TM_{11} $x_{mn} = 1.4811$.

And $t = 1.59mm$, $E_0 = 1$, $\varepsilon_r = 5.3$, $Z_\circ = 120\pi$.

B -Outer Shorted Annular Microstrip Antenna

$$E_{\theta f} = j^n \frac{E_\circ k_\circ t}{2} \frac{e^{-jk_\circ r_f}}{r_f} \cos n(\varphi_f - \varphi_\circ) a\, F_{nm}(a) B_m \qquad (2\text{-}a)$$

$$E_{\varphi f} = -j^n \frac{E_\circ k_\circ t}{2} \frac{e^{-jk_\circ r_f}}{r_f} \sin n(\varphi_f - \varphi_\circ) a\, F_{nm}(a) B_p \qquad (2\text{-}b)$$

Where $F_{nm}(a)$ is defined by

$$F_{nm}(a) = Y_n(kb) J_n(ka) - J_n(kb) Y_n(ka)$$

$$B_m = J_{n-1}(k_\circ a \sin\theta_f) - J_{n+1}(k_\circ a \sin\theta_f)$$

$$B_p = J_{n-1}(k_\circ a \sin\theta_f) + J_{n+1}(k_\circ a \sin\theta_f)$$

Where Y_n is the Bessel function of the second kind of order (n), a and b are the outer and inner radii, and for the dominant mode TM_{11} $K_a = X_{mn} = 3.5133$.

The electric field incident on the reflector surface at point $P(r_f, \theta_f, \varphi_f)$ is given by

$$\bar{E}_i = \hat{\theta} E_{\theta f} + \hat{\varphi} E_{\varphi f}$$

$$\bar{E}_i = \hat{x}_f (E_{\theta f} \cos\theta_f \cos\varphi_f - E_{\varphi f} \sin\varphi_f) + \hat{y}_f (E_{\theta f} \cos\theta_f \sin\varphi_f + E_{\varphi f} \cos\varphi_f)$$

$$+ \hat{z}_f (-E_{\theta_f} \sin\theta_f) \qquad (3)$$

In order to, describe the reflection process for large reflector(D>>λ), the geometric optics principle can be applied and the relation between the incident electric field (E_i) and the reflected electric field (E_r) at point (P) followed to a number of conditions (Stutzman et al., 1981) .

As a result, the reflected electric field with constant amplitude and different phase gives:

$$\vec{E}_r = \hat{x}_f(E_{\theta_f}\cos\varphi_f + E_{\varphi_f}\sin\varphi_f) + \hat{y}_f(-E_{\theta_f}\sin\varphi_f - E_{\varphi_f}\cos\varphi_f) \qquad (4)$$

The tangential electric field $\mathbf{E_t}$ at the point $Q(\rho,\varphi')$ in the aperture plane , after the reflected ray reaches point Q with phase delay ($e^{-jk_\circ PQ}$), is calculated from the reflector surface as :

$$\vec{E}_t = e^{-jk_\circ PQ}[\hat{x}_f(-E_{\theta_f}\cos\varphi_f + E_{\varphi_f}\sin\varphi_f) + \hat{y}_f(-E_{\theta_f}\sin\varphi_f - E_{\varphi_f}\cos\varphi_f)] \qquad (5)$$

It is particularly useful to describe the $\mathbf{E_t}$ at point Q_a which is located at center of the circular aperture by:

$$\vec{E}_t = e^{-jk_\circ PQ}[\hat{x}_a(E_{\theta_f}\cos\varphi' - E_{\varphi_f}\sin\varphi') + \hat{y}_a(-E_{\theta_f}\sin\varphi' + E_{\varphi_f}\cos\varphi')] \qquad (6)$$

$$\vec{E}_t = e^{-jk_\circ PQ}[\hat{x}_a E_{ax} + \hat{y}_a Eay]$$

The electric vector potential ($\vec{F}$) is set up at an observation point $P(r,\theta,\varphi)$ due to the magnetic surface current density ($\vec{M}$), which is associated with ($\vec{E}_t$) on the aperture of parabola, is

$$(7)$$

$$\vec{F} = \frac{e^{-jk_\circ r}}{4\pi r}\int_{sa} M_s \, e^{jk_\circ \rho \sin\theta\cos(\varphi-\varphi')} \, \rho d\rho d\varphi'$$

And $M_s = -\hat{n} \times \vec{E}_t(\rho,\varphi')$

$$\vec{F} = \hat{x}F_x + \hat{y}F_y$$

Where F_x and F_y are defined by

$$F_x = \frac{e^{-jk_\circ r}}{4\pi r}P_x \qquad , \quad F_y = \frac{e^{-jk_\circ r}}{4\pi r}P_y$$

And

$$P_x = \int_0^{2\pi}\int_0^{r_a} E_{ax} \, e^{jk_\circ\rho\sin\theta\cos(\varphi-\varphi')} \, \rho d\rho d\varphi'$$

$$P_y = \int\limits_{0}^{2\pi} \int\limits_{0}^{r_a} E_{ay} \; e^{jk_\circ \rho \sin\theta \cos(\varphi-\varphi')} \; \rho d\rho d\varphi'$$

The scalar radiation electric field in the far-field of parabolic reflector antenna fed by circular and annular microstrip antenna gives

$$E_\theta = -jk_\circ \left(- F_x \; \sin\varphi + F_y \; \cos\varphi \right) \qquad \text{(8-a)}$$

$$E_\varphi = jk_\circ \left(\cos\theta (F_x \; \cos\varphi + F_y \; \sin\varphi) \right) \qquad \text{(8-b)}$$

2-Induced Current method

The second method in this work paper analysis, is known as (ICM), which is based on calculates the radiated field from the electric current induced on the reflector surface due to the primary field of the feed (Hongo et al., 1987). Fig.(3) shows the structure which is used in ICM analysis method .

The electric surface current density (J_s)on the reflector surface of paraboloid reflector antenna is related with the magnetic field (H) by equivalent principle (Stutzman et al., 1981) as :

$$\vec{J}_s = \hat{n} \times \vec{H}_t$$

Where ($\hat{n}$) is the normal unit vector at point on the reflector surface. As a result, the magnetic field set up at the point $P(r_f, \theta_f, \varphi_f)$ is given by

$$\vec{H}_i = \hat{\theta} H_{\theta_f} + \hat{\varphi} H_{\varphi_f}$$

Where ($H_{\theta_f}, H_{\varphi_f}$) are represent the radiation fields component that radiated from microstrip antenna, which are used to excite the parabola surface and associated with (E_θ, E_φ) as :

$$H_{\theta_f} = {E_{\varphi f}}\Big/{Z_\circ} \quad , H_{\varphi f} = {E_{\theta f}}\Big/{Z_\circ}$$

The tangential magnetic field (H_t) at point located at the vertex of the paraboloid (X_s, Y_s, Z_s), yield

$$\vec{H}_{ts} = \hat{x}_s H_{xs} + \hat{y}_s H_{ys} + \hat{z}_s H_{zs} \qquad \text{(9)}$$

Where

$$H_{xs} = \cos\varphi_s \, \cos^2({\theta_f}/{2}) H_{\theta_f} + \sin\varphi_s H_{\varphi_f}$$

$$H_{ys} = \sin\varphi_s \, \cos^2({\theta_f}/{2}) H_{\theta_f} - \cos\varphi_s H_{\varphi_f}$$

$$H_{zs} = \sin({\theta_f}/{2}) \cos({\theta_f}/{2}) H_{\theta_f}$$

Using equivalent principles the electric surface current density on reflector surface is given by:

$$\vec{J}_s = \hat{x}_s J_{xs} + \hat{y}_s J_{ys} + \hat{z}_s J_{zs} \qquad \text{(10)}$$

Where

$$J_{xs} = 2[\sin\varphi_f \ \sin \ (\theta f/2) H_{zs} \ - \cos(\theta f/2) H_{ys}]$$ (11-a)

$$J_{ys} = 2[\cos(\theta f/2) H_{xs} - \cos\varphi_f \ \sin \ (\theta f/2) H_{zs}]$$ (11-b)

$$J_{zs} = 2[\cos\varphi_f \ \sin \ (\theta f/2) H_{ys} - \cos\varphi_f \ \cos(\theta f/2) H_{xs}]$$ (11-c)

components of the induced current density in Eq.(11) are the main source of radiation in an observer point $P(r,\theta,\varphi)$ and source of the magnetic vector potential in the same point which can be written as:

$$\bar{A}_p = \frac{e^{-jk_\circ r}}{2\pi r} \int_S J_s(\rho_s,\varphi_s) \ e^{jk_\circ \ \hat{r}. \ r'} \ da$$ (12)

Where $\hat{r}.r' = \rho_s \ \sin\theta \ \cos(\varphi - \varphi_s) + \rho_s \ \cos\theta \ \cot\alpha$

And $\quad da = \csc^2 \alpha \left[1 + \frac{4F\rho_S \ \cot\alpha}{\rho_s^2 + 16F^2}\right] \rho_s d\rho_s d\varphi_s$

So that, the component of the magnetic vector potential ($\bar{A}_p$) is given by

$$\bar{A}_p = \hat{x}_S A_{xs} + \hat{y}_S A_{ys} + \hat{z}_S A_{zs}$$ (13)

expressing Eq.(13) in spherical coordinate and retaining only (θ and φ) components of $\bar{A}_p$ gives :

$$A_{\theta p} = \cos\theta \cos\varphi \ A_{xs} + \cos\theta \sin\varphi \ A_{ys} - \sin\theta \ A_{zs}$$ (14-a)

$$A_{\varphi p} = -\sin\varphi \ A_{xs} + \cos\varphi \ A_{ys}$$ (14-b)

Consequently, the radiation electric fields in far-field region can be written as :

$$E_\theta = - jk_\circ Z_\circ \left[\cos\theta \cos\varphi \ A_{xs} + \cos\theta \sin\varphi \ A_{ys} - \sin\theta \ A_{zs} \right]$$ (15-a)

$$E_\varphi = -jk_\circ Z_\circ \left[-\sin\varphi \ A_{xs} + \cos\varphi \ A_{ys} \right]$$ (15-b)

Result and discussion

Theoretical results of the radiation field patterns of a paraboloid reflector antenna

operating in (10GHz),excited by Circular Ring and Annular Ring microstrip antenna are operating with TM11 mode, are obtained by numerical evaluation of Eq.(8)   and Eq.(15),which are obtained by the use of AFM and ICM method as a mathematical model.

Fig. (4) and Fig.(5)show the radiation patterns of parabolic reflector with (D=20 λ) and ratio (f/D) were taken at edge illumination (-3dB)and (-6dB), excited by a Circular and outer shorted annular microstrip in the planes E(φ=90)and H(φ=0) also in (co-polar and cr-polar φ=45).These patterns are given a complete agreement between AFM and ICM for both feeders(excited sources).

Fig.(6)and table (1) are show, the comparison between the radiation field patterns and parameters of the paraboloid reflector fed by CRMA and ARMA in principle planes at the best results ,that are chosen at the ratio (f/D) taken at edge illumination (-3dB) and parabola diameters(20 λ).

Conclusions

In conclusion the AFM and ICM methods are more suitable mathematical models to compute the radiation field patterns of paraboloid reflector, that excited by microstrip antennas. Furthermore, choosing the reflector with a small(f/D) ratio and a high directivity is more conventional when circular microstrip antenna is used as a exciting source of the parabolic reflector antenna.
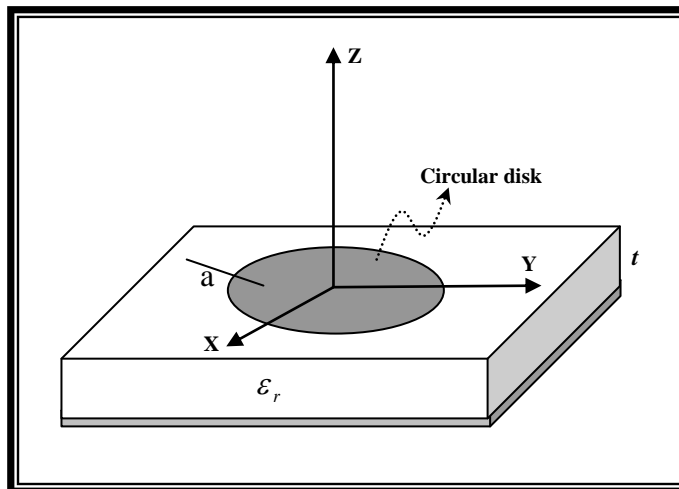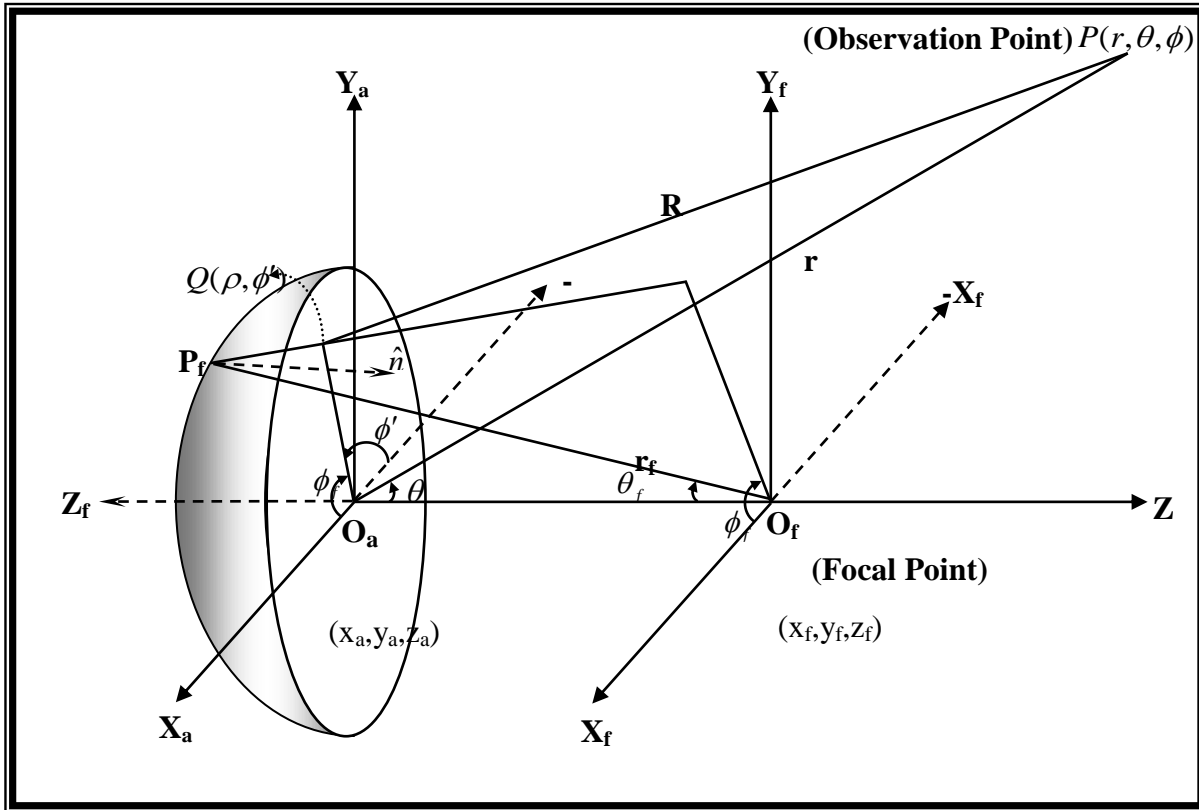

Fig.(1):circular microstrip antenna

Fig.(2):Coordinate system of parabolic reflector antenna ,using (AFM).
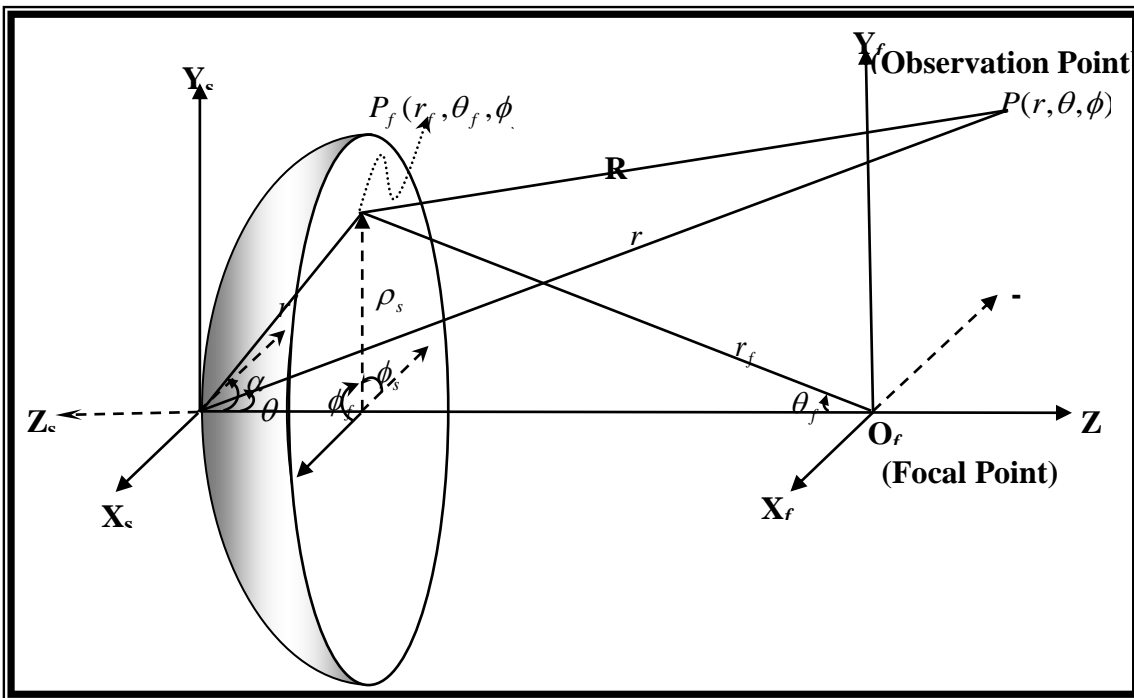

Fig.(3):Coordinate system of parabolic reflector antenna ,using (ICM).

Table (1) The radiation parameters of parabolic reflector antenna fed by CRMA and ARMA with (TM11) mode at frequency (10 GHz)

Ratio f/D	D(λ)	f(λ)	H–plane (φ=0°)				E–plane (φ=90°)				Co–plane (φ=45°)				Cross–Plane (φ=45°)		Directivity
			-3dB BW	-10dB BW	S.L.L dB	Pos. of S.L.L	-3dB BW	-10dB BW	S.L.L dB	Pos. of S.L.L	-3dB BW	-10dB BW	S.L.L dB	Pos. of S.L.L	Xp dB	Pos. of Xp(deg)	
0.263 -3dB CRMA	10	2.6	6.12	10.46	-22.3	10.5	7.96	14	-38.1	18.25	6.8	11.9	-30.6	16	-17.73	6.75	29.0
	15	3.9	4.0	7.0	-23.5	7.25	5.29	9.31	-38.1	12	4.59	7.98	-30.4	10.5	-17.75	4.5	32.6
	20	5.2	3.0	5.21	-22.3	5.25	3.97	6.98	-38.1	9.0	3.4	5.98	-30.49	7.75	-17.76	3.5	35
0.14 -6dB CRMA	10	1.44	6.0	10.33	-21	15.25	14.18	21.36	-60	-	8.37	15.39	-24.5	15.5	-9.55	7.25	28.3
	15	2.1	4.0	6.87	-20.6	10	9.76	14.4	-27.2	14.5	5.6	10.4	-24.3	10.5	-9.22	4.75	31.86
	20	2.8	3.0	5.0	-20.6	7.5	7.31	10.81	-27.9	11	4.24	7.8	-24.7	8.0	-9.23	3.5	34.3
0.344 -3dB ARMA	10	3.4	6.94	12.12	-31.0	15.75	7.09	12.36	-32.8	16.25	7.01	12.24	-32.11	16	-41.56	5.75	28.91
	15	5.1	4.63	8.0	-30.8	10.5	4.71	8.22	-32.8	10.75	4.67	8.15	-32	10.5	-42.1	4	32.45
	20	6.1	3.47	6.0	-30.7	7.75	3.5	6.16	-32.8	8.0	3.5	6.11	-32	8.0	-42.3	3	34.96
0.18 -6dB ARMA	10	1.8	7.66	14.45	16.96	14.5	12.51	19.98	-27.87	20	9.58	17.93	-27.97	18	-16.47	6.5	26.86
	15	2.7	5.11	9.64	-17.0	9.75	8.33	13.27	-27.83	13.5	6.39	11.94	-28.2	12	-16.51	4.5	30.39
	20	3.6	3.83	7.23	-16.87	7.25	6.25	9.95	-27.82	10	4.79	8.95	-28.29	9	-16.52	3.25	32.88
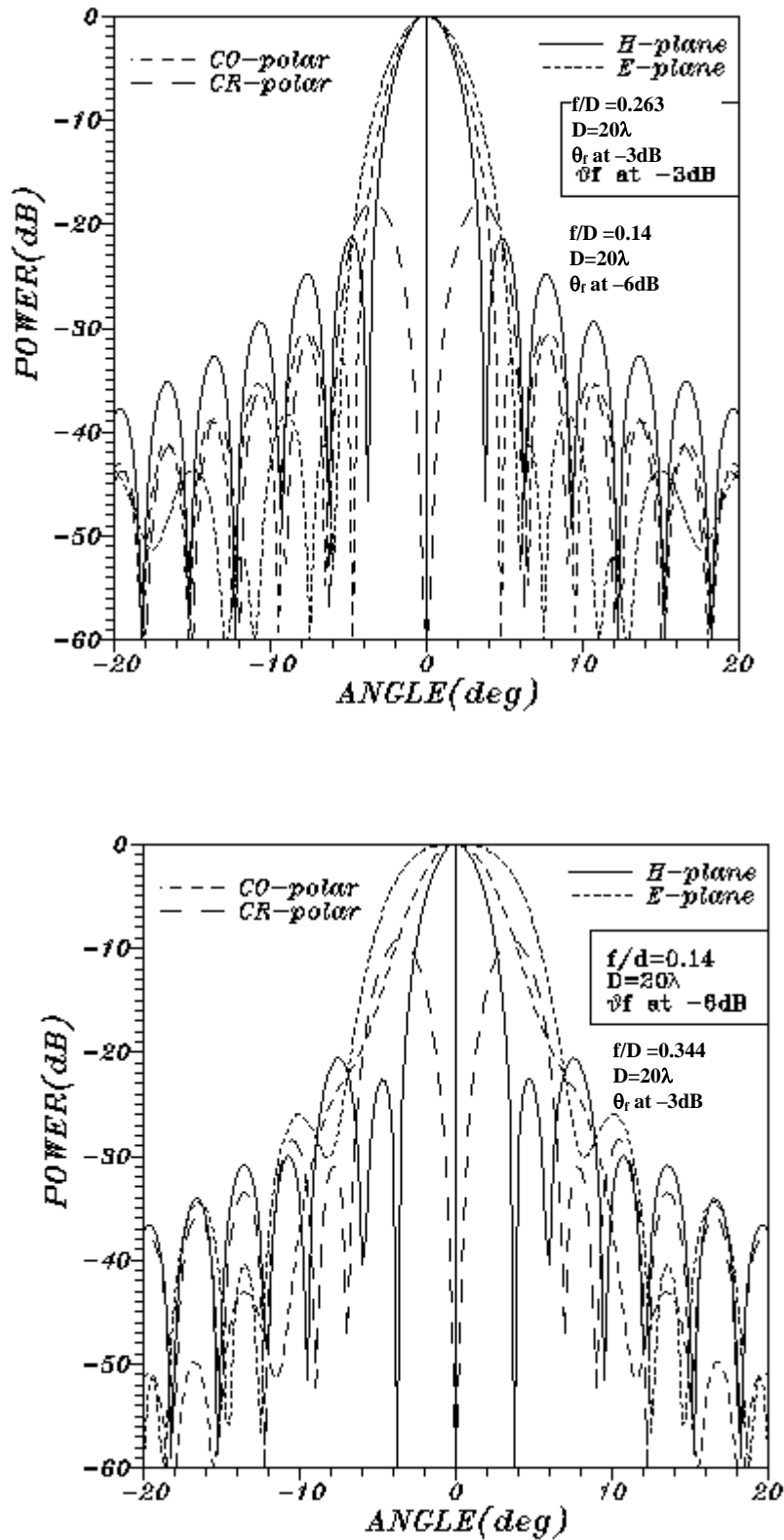
Fig(4): Radiation patterns of parabolic reflector antenna, with (f/D) taken at edge illumination (-3 dB) and (-6 dB), fed by circular microstrip antenna CRMA in principle planes by using AFM and ICM methods.
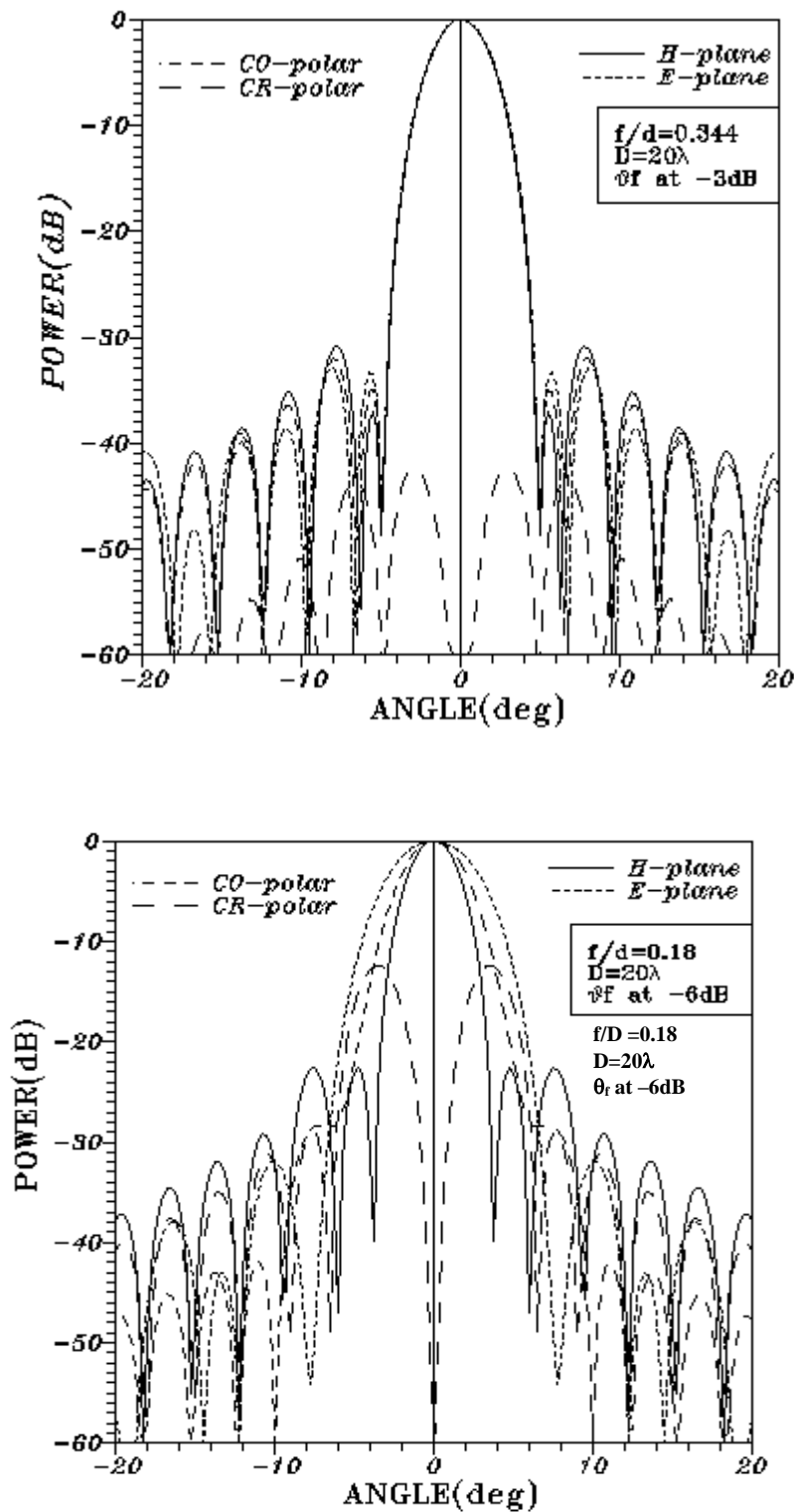
Fig(5): Radiation patterns of parabolic reflector antenna, with (f/D) taken at edge illumination (-3 dB) and (-6 dB), fed by outer shorted annular microstrip antenna ARMA in principle planes by using AFM and ICM methods.
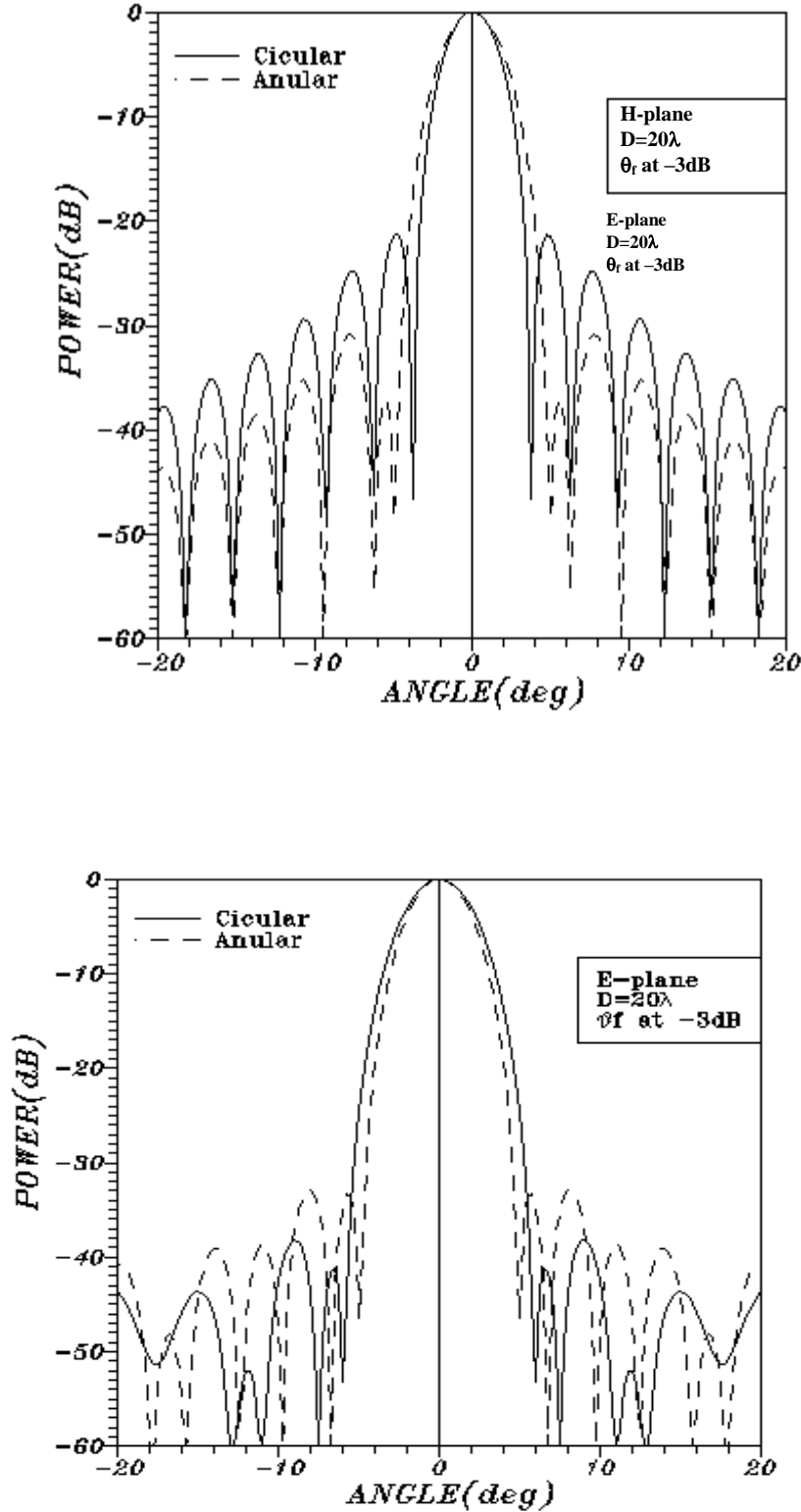
Fig(6): Comparison between radiation patterns of parabolic reflector antenna in H-and E-planes fed by CRMA and ARMA

Reference

Ali A.S. Obaid ,"propagation and radiation characteristics of rectangular corrugated wave guide", Ph.D. Thesis ,university of Birmingham ,Jan. 1985.

EI-Khamy S.E.&R.M.EI-Awadi," Simple analysis and design of annular ring microstrip antenna ", IEE proceeding ,Vol. 132,pt. h, No. 6,pp. 384-390, 1986.

Ghobrial,S.I. and H.R. Sharobim " Radiation pattern of a paraboloidal reflector fed by a pyramidal horn with lossy wall", IEEE Trans. On Antennas and Propagation , Vol . 37, No. 10, Oct. 1989.

Hongo,K. and H. Matsuura, "comparison of Induced current and aperture field Integration for an offset parabolic reflector ", IEEE Trans. On Antennas and Propagation , Vol . AP-35, No. 1, Jan. 1987.

Kooi, P.S. and M.S.leong and Chandra "Radiation characteristics of a waveguide-excited short backfire –fed parabolic reflector operating in Q-band ",Electron Lett., Vol. 24, No. 11,pp. 653-654, may 1987.

Lo.Y.T.,D.Solomon and W.F.Richards," Theory and experiment on microstrip antennas ",IEEE Trans. On Antennas and Propagation , Vol . AP-27, No. 2, PP.137-146, 1979.

N.A.Zakaria , A.A. Sulaiman and M.A.A. Latip," Design of a Circular Microstrip Antenna ",IEEE International RF and Microwave conference proceedings ,December 2008.

Stutzman,W.L.and G.A. Thiele," Antenna theory and design ",New York, John Wiley and Sons,1981.

T.F.Lai,Wan Nor Liza Mahadi, Nohayati Soin ," Circular patch Microstrip Array Antenna for KU-band", proceedings of World Academy of Science ,Engineering and Technology ,Vol. 36,December 2008.

Vijay Kumar Tiwari, Aradhana Kimothi, D Bhatnagar, J S Saini &V K Saxena ," Theoretical and experimental investigation of circular sector microstrip antenna",Indian Journal of Radio &Space Physics ,Vol. 35,pp.206-211,June 2006.

التحليل النظري لمجالات الإشعاع لهوائي القطع المكافئ مغذى بالهوائيات الشريطية دائرية الشكل

عون عيسى سلمان و عقيل سامي طاهر و علاء عبدالحليم هاشم
قسم الفيزياء ، كلية العلوم ، جامعة البصرة ، البصرة ، العراق

الخلاصة

يتناول البحث طريقتين في التحليل النظري ، طريقة مجالات الفتحة (AFM)وطريقة التيارات المحتثه (ICM) تم استخدامها لتحديد مجالات الإشعاع لهوائي قطع مكافئ مغذى بنوعين من الهوائيات الشريطية .

حسابات هياكل ومعاملات الإشعاع لهوائي القطع المكافئ عندما يثار سطحه العاكس بهوائي شريطي دائري (CRMA) وهوائي شريطي حلقي مغلق من الخارج(ARMA)،أعطت أفضل نتائج عند اختيار قطر العاكس (D=20λ)وبنسبة (f/D) مأخوذة عند حافة إضاءة بحدود (3dB-).

وبالنتيجة، فأن كلا الطريقتين أعطت توافق تام لهياكل المجالات الإشعاعية في المستويات الأساسية في منطقة المجال البعيد للإشعاع.

الكلمات المفتاحية : هوائي ،عاكس قطع مكافيء ،هوائي مايكروسترب .