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Analysis and Design of Sector Microstrip Multiple Port Power Divider Using Finite Element Method

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Abstract: - In this paper the sector microstrip multiple port power divider is analyzed by using the fullwave finite element method. A new design formula is derived for designing this divider with different geometrical and physical parameters namely the substrate dielectric constant, substrate height and power divider radius. The maximum error in calculating the center frequency of the power divider does not exceed ±4%. 4-way and 5-way sector microstrip power dividers are realized on teflon substrates using thin film technology. Good agreement is found between the experimental and numerical results obtained from both the finite element method and the ready-made software package IE3D.

Keywords: - Sector power dividers, Microstrip lines, FEM, and Fullwave analysis.

1 Introduction

The power divider and power combiner circuits are used extensively at microwave and millimeter-wave frequencies especially the planar (microstrip type) configurations. Two particular circuit types are often used namely the symmetric geometry with radially oriented lines [1] – [2] and the fan out Wilkinson-type geometry [3]. The design and development of 6 and 12 way fork power divider has been demonstrated [4]. These designs may be obtained by using CAD to model multiway microstrip line junctions followed by final experimental tuning. The experimental results have shown high performance fork power dividers.

The use of circular disk planar segments for designing symmetrical power divider circuits were discussed in [5]. Due to their geometrical symmetry, they don't exhibit any imbalance in either the amplitude or the phase of the output signals at any frequency. This property makes them suitable in the design of multielement antenna feed systems, and for replacing the lossy corporate feed structures used in feeding a linear array of antenna element. Also, it can be used as a multiport power combiner to combine multiple oscillators or amplifiers in a single module thus resulting in higher output power capabilities. Ghadha and Gupta [6] derived the Green's functions for the circular and annular sectors in double series format. Abouzahra and Gupta [7] used circular sectors as power dividers/combiners. [8] use single series Green's function for both circular and annular sector to improve the previous solutions. In both papers, an unnecessary constraint is reiterated, that is, the restriction of the sector angle to an integer submultiple of π. This unnecessarily limits the design flexibility, as their formulation is applicable to any sector angle without any modification but leads to using fractional order Bessel functions. This restriction has promoted some researchers to use a more computational methods [8] and boundary element method [9], [10].

This paper analyzes the sector power divider using finite element method in fullwave analysis. This analysis is general and neither restrict the sector angle nor the number of ports. The four-way and the five-way power dividers with 90^o angle have been designed, fabricated, and tested. The measured and calculated scattering parameters are found to be in good agreement.

2 Field Analysis

A generalized schematic diagram of a sector power divider is shown in Fig.1.

The separation between ground plane and the conductor (substrate dielectric thickness) h is arranged to be small w.r.t the wavelength in order to ensure that higher order modes which vary in the z-direction are suppressed. This assumption implies that only the (E_z, H_x, H_y) field components exist.

The E_z field in a planar junction satisfies the Helmholtz scalar wave equation

$$(\nabla_t^2 + K_{eff}^2)E_z = 0 \qquad (1)$$

Where $K_{eff}^2 = \omega^2 \mu_o \mu_r \varepsilon_o \varepsilon_{eff}$ (2)

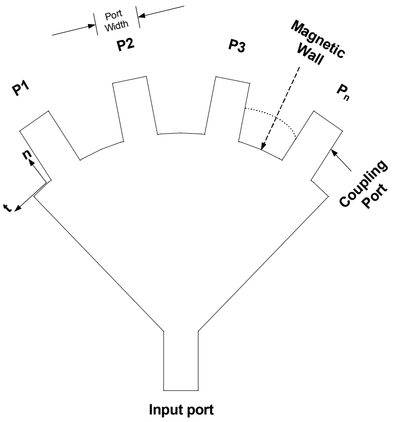

Fig.1 Schematic diagram of four port planar sector power divider

with the boundary condition that the tangential magnetic field vanishes on the boundary

$$\frac{\partial E_z}{\partial n} = 0 \qquad (3a)$$

At the coupling ports, $H_t \neq 0$ and E_z satisfies

$$\frac{\partial E_z}{\partial n} = j\omega \mu_o \mu_r H_t \qquad (3b)$$

In order to solve (1) with (3a-b), it is convient to introduce a Green's function G(r|r_o). The Green's function G(r|r_o) is defined as the solution to differential equation [11]

$$(\nabla_t^2 + K_{eff}^2)\mathrm{G}(\mathrm{r}\,|\,\mathrm{r_o}) = -j\omega\mu_o\mu_r\delta(r - r_o) \qquad (4)$$

Where $\delta(r - r_o)$ is the dirac delta function, and it satisfies the boundary conditions [11]

$$\frac{\partial G(r\,|\,r_o)}{\partial n} = 0 \qquad (5)$$

When a magnetic field $\bar{H}(r_o)$ is located at point r_o, the electric field on the contour of the sector is evaluated as:

$$E_z(r) = \sum_{i=1}^{N} \int_{pi} G(r\,|\,r_o) H_t(r\,|\,r_o) dt_o \qquad (6)$$

Where the integration is carried over the coupling port P_i.

$E_z(r)$: applies at any point in the sector including the interval defined by the coupling ports.

Expanding the Green's function as a series of complex eigenfunction ϕ_a gives [12]

$$G(r\,|\,r_o) = j\omega\mu_o\mu_r \sum_{a=1}^{\infty} \frac{\phi_a(r)\phi^*(r_o)}{K_a^2 - K_{eff}^2} \qquad (7)$$

Where the eigenfunctions ϕ_a and the eigenvalues K_a^2 are the solutions to the differential equation

$$(\nabla_t^2 + K_a^2)\phi_a(r) = 0 \qquad (8)$$

With the boundary conditions imposed on the Green's function in (5). The eigenfunction are orthogonal and normalized.

Assuming that H_t is constant over each coupling port and using Eq.(6) and(7), and assuming that all the coupling ports are of equal width, Z_{ij} is given by [11]

$$Z_{ij} = \frac{jR_e K_{eff}}{W} \sum_{a=1}^{\infty} \frac{1}{K_a^2 - K_{eff}^2} \int_{p_i} \phi_a^*(r)dt \int_{p_i} \phi_a(r_o)dt_o \qquad (9)$$

Where, R_e is the characteristic impedance of a microstrip line of width W and printed onto the substrate of a dielectric constant ε_r.

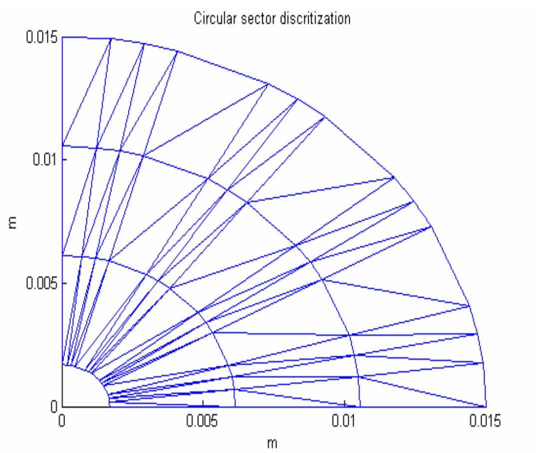

Fig.2 Circular sector power divider discretization

3 Finite Element Method

In this work we have chosen the finite element method. The sector power divider is subdivided into elements as shown in Fig.2. The chosen element is a quadratic triangle element with six nodes in each element. This choice for the discretization process increases the accuracy of the solution and it is suitable for the circular circumference of the sector power divider.

The polynomial eigen function ϕ_a' is introduced to solve the problem numerically. The stored energy in the circuit is minimized by imposing the Rayleigh Ritz condition on the functional, F which is given by [11]

$$F(\phi_a^{'}(r)) = \iint_S (\left|\nabla_t \phi_a^{'}(r)\right|^2 - K_a^2 \left|\phi_a^{'}(r)\right|^2) ds \quad (10)$$

Where r is the position at which E_z field is observed.

The polynomial eigen function $\phi_a^{'}$, that fulfills this minimization satisfies both Helmholtz equation and the boundary conditions for the eigen function ϕ_a ; besides it is an approximation to the exact function ϕ_a and it is expanded as

$$\phi_a^{'}(r) = \sum_{i=1}^{M} C_i N_i \quad (11)$$

Where C_i : The complex expansion coefficients to be determined.

N_i : Real basis functions.

M: The number of the basis function to be considered.

Using Eqs. (10) and (11) then imposing Rayliegh Ritz condition

$$\frac{\partial F(\phi_a^{'}(r))}{\partial c_i^*} = 0 \quad (12)$$

reduces the problem to a set of simultaneous homogenous equations of the form

$$\left[[A] - k_a^2 [B]\right][C] = 0 \quad (13)$$

Which is the generalized eigen value problem. The [A] and [B] are symmetrical matrices and [C] is a column vector defined as

$$C = [c_1, c_2, c_3, \ldots, c_M]^t \qquad \text{(t: transpose)}$$

$$A_{ij} = \iint_S \nabla_t N_i . \nabla_t N_j dS \quad (14)$$

$$B_{ij} = \iint_S N_i . N_j dS \quad (15)$$

A polynomial expansion for eigen function ϕ_a is formed for each element of $(C_i N_i)$. This enables A and B matrices to be calculated. The elements of the matrices are then assembled together to form the complete eigen value problem. A MATLAB program was built using the finite element method and a study was made on the effect of the number of the elements, the number of nodes and the number of modes on the accuracy of the obtained numerical results. It was found that taking the number of elements to be 78, the number of nodes 189 and the number of modes 100, gives sufficient accurate results as compared with other published one. Also, the results were very stable.

Fig.3 shows some modes for electrical field distribution of the sector power divider.

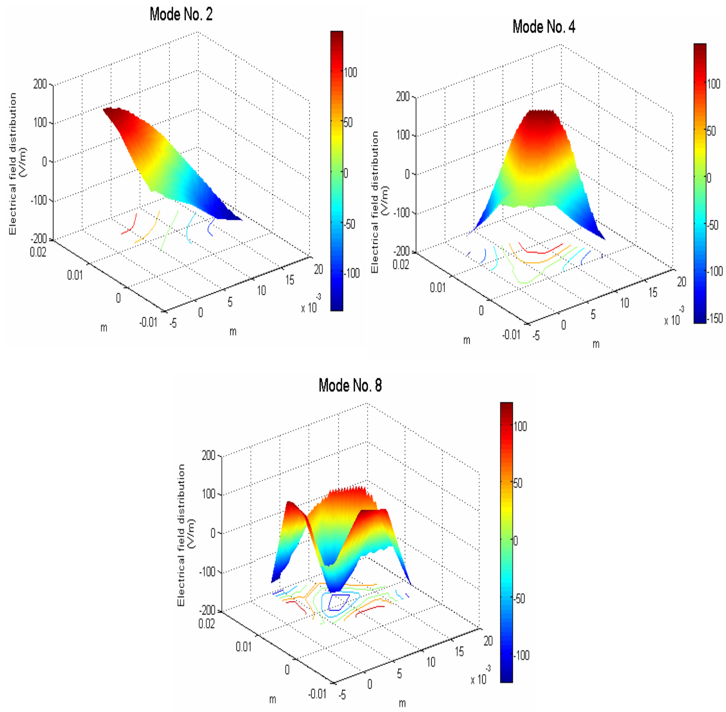

Fig.3 Some modes for electrical field distribution

4 Design Formula

A novel new empirical formula for designing the circular sector power divider was derived by using curve fitting. This formula calculates the center frequency of the power divider as a function of the sector radius, substrate permittivity and substrate thickness. The maximum error in calculating the center frequency of the four port and five port power divider with apex angle $\pi/2$ does not exceed ±4%. This formula is valid in the ranges $1.5 \le \varepsilon_r \le 10$, $0.2mm \le h \le 1.5mm$ and $10mm \le R \le 35mm$. Table (1) gives some of the calculated results.

$$F = [A \cdot R^{(B)}] \cdot \varepsilon_r^{(C+D/R)} \quad (16)$$

Where

$$A = (182 + 60.6h + 374h^2 - 174h^3)$$

$$B = (-0.952 - 0.432h + 0.159h^2 - 0.00544h^3)$$

$$C = (-0.508 + 0.101h - 0.121h^2 + 0.0383h^3)$$

$$D = (0.21 - 2.56h + 0.778h^2 - 0.138h^3)$$

h: substrate thickness

ε_r : Substrate dielectric constant

R: Radius of the sector.

Case No.	ε_r	h	R	No. of output ports	F_z	F_n	F_f	Error %
1	2.2	0.7874	15	4	9.13	9.3	9.36	-2.48
2	2.2	0.7874	15	5	9.25	9.3	9.36	-1.189
3	6.15	0.635	10	4	7.9	7.8	7.585	3.98
4	6.15	0.635	10	5	7.74	7.8	7.585	-1.524
5	2.33	0.635	12	4	10.86	11.25	11.124	-2.39
6	2.33	0.635	12	5	10.825	11.25	11.124	-2.76
7	6.15	0.7874	10	4	7.84	7.95	7.718	1.045
8	6.15	0.7874	10	5	7.83	7.95	7.718	1.43
9	4.7	1.5	20	4	4.518	4.65	4.648	2.7
10	4.7	1.5	20	5	4.473	4.65	4.53	1.32
11	9.8	0.635	17	4	3.52	3.5	3.447	2.07
12	9.8	0.635	17	5	3.5	3.5	3.447	1.51

Table.1 The results of the formula for different values of ε_r , R, h.

Where:
F_z: center frequency obtained by IE3D.
F_n: center frequency obtained by the numerical FEM program.
F_f: calculated ceter frequency of the formula.

5 Numerical and Experimental results

Three different cases of the circular sector power divider (4 and 5 ways with an angle of 90 degree) have been designed, fabricated and their performances were measured using the HP 8719ES vector network analyzer. A photograph of these circuits is shown in Fig.4.

Fig.4 A Photograph of 4-way and 5-way microstrip sector power dividers.

Figs. 5-10 show the scattering matrix parameters of the 4-way sector power divider that were obtained numerically using the finite element method and the experimental results together with the published results [4] and that obtained by using the IE3D ready-made simulator for two different substrate materials. It should be noted that there is a little discrepancy between our numerical and experimental results. This may be attributed to the fact that we didn't take the conductor and dielectric loss into account in addition to the effect of the launchers which can not be detected numerically. These results indicate that the center frequency is around 9 GHz and 8 GHz, where the minimum reflection occurs (S_{11}) and at the same time the power output is divided equally between other ports (-6dB). These figures represent the case of four way-output with apex angle of 90^o and realized either on teflon Duroid 5880 with $\varepsilon_r = 2.2$ and h = 0.031" or Duroid 6006 with $\varepsilon_r = 6.15$ and h = 0.025".

Figs. 11-14 show the case of 5-way power divider that was realized on teflon Duroid substrate 5880 with ε_r = 2.2 and h = 0.031", with an apex angle of 90^o. The output power in each port in this case is -7 dB, while the reflection coefficient at the center frequency is -20 dB. The bandwidth is about 18.75%.

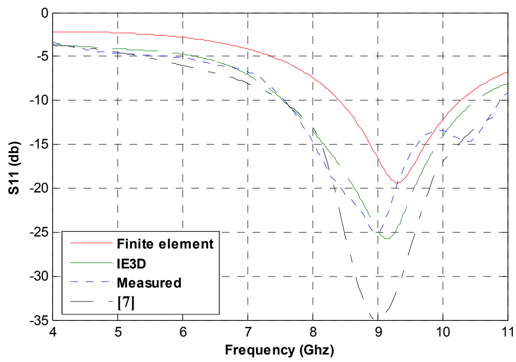

Fig. 5 Reflection coefficient (S_{11}) of a four way 90^o microstrip sector power divider (ε_r=2.2, R=15 mm, h=0.031")

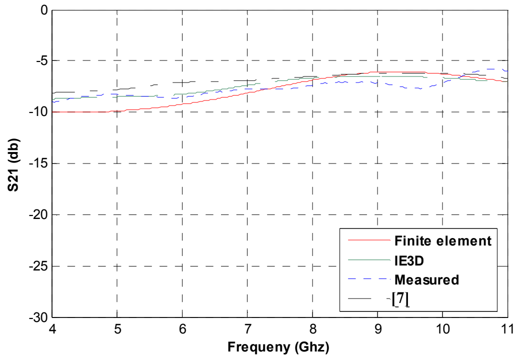

Fig. 6 The scattering parameter (S_{21}) of a four way 90^o microstrip sector power divider (ε_r=2.2, R=15 mm, h=0.031″)

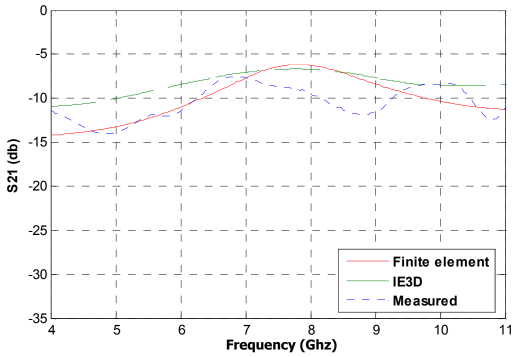

Fig.9 The scattering parameter (S_{21}) of a four way 90^o microstrip sector power divider (ε_r=6.15, R=10 mm, h=0.025″)

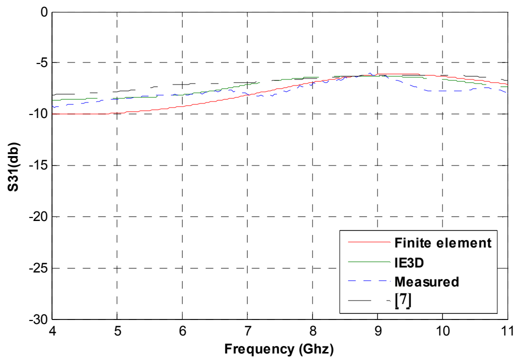

Fig.7 The scattering parameter (S_{31}) of a four way 90^o microstrip sector power divider (ε_r=2.2, R=15 mm, h=0.031″)

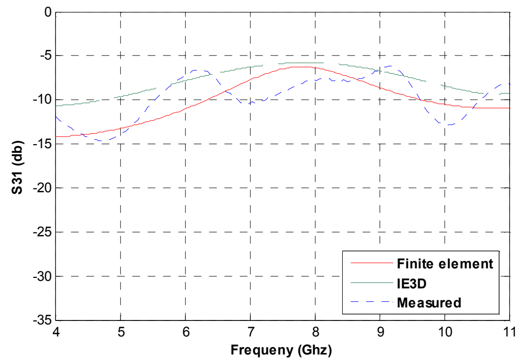

Fig.10 The scattering parameter (S_{31}) of a four way 90^o microstrip sector power divider (ε_r=6.15, R=10 mm, h=0.025″)

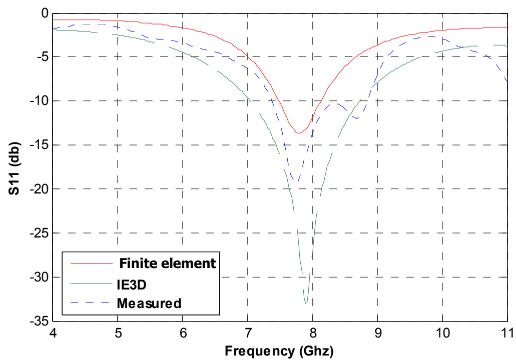

Fig. 8 Reflection coefficient (S_{11}) of a four way 90^o microstrip sector power divider (ε_r=6.15, R=10 mm, h=0.025″)

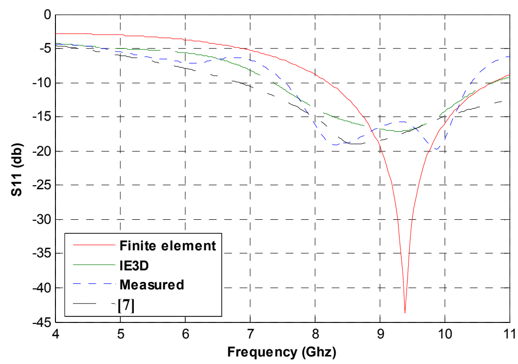

Fig.11 Reflection coefficient (S_{11}) of a five way 90^o microstrip sector power divider (ε_r=2.2, R=15 mm, h=0.031″)

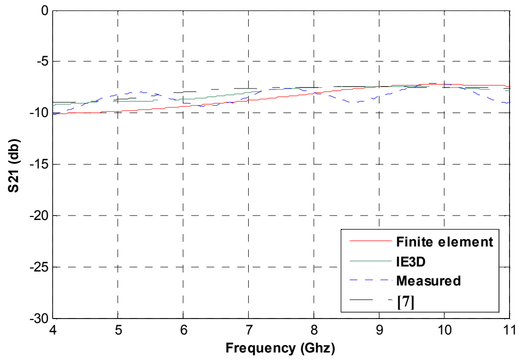

Fig.12 The scattering parameter (S_{21}) of a five way 90° microstrip sector power divider (ε_r=2.2, R=15 mm, h=0.031″)

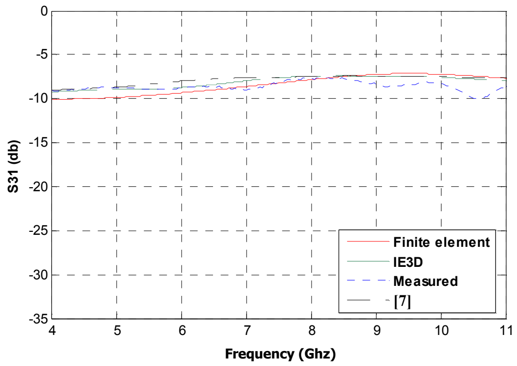

Fig.13 A scattering parameter (S_{31}) of a five way 90° microstrip sector power divider (ε_r=2.2, R=15 mm, h=0.031″)

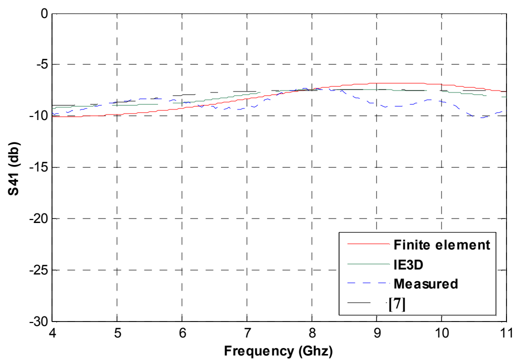

Fig.14 A scattering parameter (S_{41}) of a five way 90° microstrip sector power divider (ε_r=2.2, R=15 mm, h=0.031″)

6 Conclusion

A full wave analysis and a new design formula was developed for the microstrip circular sector power divider (4 and 5-way), which may have many useful applications in the field of MMICs and RF circuits. This type of power dividers is very simple, smaller, and easier in design than common power dividers such as T-junction and Wilkinson power dividers. Finally, the experimental results give very good agreement with the innovated design formula.

References

[1] A.Fathy and D.Kalokitis,"Analysis and Design of a 30-way Radial Combiner for the ku-Band Application", RCA Rev.,vol.47, pp.487-508, Dec.1986.

[2] S.J.Foti, R.P.Flam, and W.J.Scharpf,"60-Way Radial Combiner Uses no Insolators", Microwaves and RF, pp.96-118, July 1984.

[3] A.A.M.Saleh,"Planar Electrically Symmetric N-way Hybrid Power Divider/Combiner", IEEE Trans. Microwave Theory Tech., vol.MTT-28, pp.555-563, June 1980.

[4] N.C.Karmakar and M.E.Bialkowski,"Design of Planar Fork Power Dividers Using Microwave CAD", ASIA Pacific Microwave Conference, pp.120-123, 1999 , sigapore.

[5] M.D.Abouzahra and K.C.Gupta, "Multiple-port Power Divider/Combiner Circuits Using Circular Microstrip Disc Configurations", IEEE Trans. Microwave Theory Tech., vol.MTT-35, pp.1296-1302, Dec. 1987.

[6] R.Ghadha and K.C.Gupta," Green's Function for Circular Sectors, Annular Rings and Annular Sectors in Plannar Microwave Circuits", IEEE Trans. Microwave Theory Tech., vol.MTT-29, pp.68-71, June 1981.

[7] M.D.Abouzahra and K.C.Gupta,"Multiport Power Divider-Combiner Circuits Using Circular Sector-Shaped Planar Components", IEEE Trans. Microwave Theory Tech., vol.MTT-36, pp., June 1988.

[8] S.P.Yeo, et al, "Contour-Integral Analysis of Microstrip Sectorial Power Divider with Arbitrary Sector Angle", IEE Proc. part H, vol.140, no.1, pp.62-64, Feb. 1993.

[9] F.Alhargan and S.R.Judah, "Circular and Annular Sector Planner Components of Arbitrary Angle for N-way Power Dividers / Combiners", IEEE Trans. Microwave Theory Tech., Vol. MTT-42, pp. 1617-1623, September 1994.

[10] M.Miya Zaki, O.Ishida and T.Hashimoto, " A Sector Planner 6-way Hybrid Power Divider with Resistive Slot", Proc. 19th European Microwave Conf., pp. 307-310, Sept. 1989.

[11] R. Lyon, J. Hellszajn, "A Finite Element Analysis of Planar Circulators Using Arbitrary Shaped Resonators ", IEEE Trans. Microwave Theory Tech., vol.MTT-30 ,No. 11, pp. 1964-1974, Nov.1982.

[12] K.C. Gupta, R. Garge, and R. hadha, "Computer Aided Design of Microwave Circuits" Dedharm, MD , Artch House, ch.8, 1981.