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Analysis of S-X Band Slot Coupled Wave Guide Junction

*P. Ujjvala Kanthi Prabha, **G.S.N. Raju, ***V.K.Varma Gottumukkala

*Department of ECE, MVGR college of Engineering,Vizianagaram-535005, India (*kanthiprabha@rediffmail.com)*
** Andhra university, Visakhapatnam-530003, India (*profrajugsn@gmail.com)*
***Qualcomm, USA (Gvk_v@yahoo.com)

Abstract:

H-plane Tee junction is formed by coupling primary wave guide to secondary wave guide through a longitudinal slot or an inclined slot. Such junctions are commonly used in power division application and as a radiator with vertical polarization. In the present work, wave guides of two different bands are coupled i.e., S-band wave guide coupled to X-band wave guide through an inclined slot in the narrow wall of primary wave guide. No literature is available on such type of H-plane Tee junctions.

The analysis involves evaluation of conductance, susceptance, coupling and VSWR (voltage standing wave ratio) as a function of frequency. By varying slot width and slot inclination the numerically evaluated values on admittance, coupling and VSWR are compared with that of experimental results. The analysis is carried out by using the concepts of self-reaction and discontinuity in modal current. The knowledge of variation of real and imaginary parts of admittance of this new coupler provides additional design parameters for the array designer.

Key Words: H-plane Tee junction, inclined slot, self-reaction, discontinuity in modal current

1. Introduction:

In high directive radar applications, a slot cut in one of the walls of rectangular wave guide are used due their compactness. The power radiated in a specified direction is controlled by slot parameters, slot geometry and dimensions of waveguide. An inclined slot makes an angle θ with the vertical axis to produce radiation, as the vertical slot does not radiate.

The wave guide junctions are used to split the waves from one wave guide to other wave guide. By connecting a secondary arm to the primary arm either in broad wall or narrow wall, a three pot junction is formed. H-plane Tee junction is formed by connecting secondary arm to the primary arm in narrow wall. H-plane Tee is an electrical equivalent of connecting secondary in parallel or shunt. The circulating magnetic field in secondary arm divides the power into two arms of the primary wave guide equally at the junction. If input is given at the third port, then port1 and 2 are in shunt. Hence third port is also known as shunt port.

Different type slot in the rectangular wave guides are presented by several researchers [1-3]. The concepts of Rumsey [4] and Marcuvitz and Schwinger [5] are made to simplify the formulations in electromagnetic theory for the slots of present interest. Marcuvitz et al [5] has presented the representation of electric and magnetic fields produced by currents and discontinuities of waveguides. The results are valid for both thin and thick slots. The slots which are entirely in the narrow wall having resonant length for a given inclination are only considered in order to make them suitable for planar arrays. By considering inclined slots in the narrow wall of rectangular waveguide admittance characteristics and resonant length of slot are formulated using self-reaction and discontinuity in modal current approach by Das [6]. The analysis of electromagnetic energy through the common broad wall between two rectangular waveguides using variational method was reported by Sangster [7]. Oliner et al. [8] has carried out analysis to obtain equivalent impedance parameters as seen from primary waveguide. Here, Variational approach and power stored in the wave guide are considered. Pandharipande et al. [9] obtained the equivalent circuits of a narrow wall waveguide slot coupler and impedance characteristics are presented. Das et al [10] has Analyzed T-Junction different from conventional H plane T-Junction in which T arm is rotated by 90^0 and coupling is through inclined slot in the narrow wall of rectangular waveguides. Hsu et al. [11] obtained some admittance properties of the inclined slots in the narrow wall and investigated on the possible resonant length. The internal power storage in evanescent modes in the waveguides is included in the analysis. Das et al [12] designed a wave guide array for desired radiation pattern by suppressing cross polarization. Young et al. [13] reported analysis of a rectangular wave guide, edge slot array with finite wall thickness. He obtained the fields in the slots which are calculated from hybrid finite element boundary integral equation method. This method is a hybrid method where the effect of an external waveguide structure is rigorously included through the use of a spectral domain moment method. Neto et al. [14] has carried out theoretical investigations on ultra-wide band slot arrays. Closed form expressions are obtained for active impedance and radiation pattern. Homayoon et al. [15] reported a new method for design and optimization of standing and traveling wave fed centered inclined slot arrays, cut on the broad wall of rectangular waveguides, based on the method of least squares. Devarapalli et al. [16] proposed a configuration for a narrow band rugged high power antenna with a horizontally polarized fan beam radiation pattern. Slot coupled planar antennas are used for dual polarization and they are found to exhibit wide bandwidth.

2.Formulation:

As show in fig.1, the primary wave guide with broad wall dimensions a_1=3.48cm and narrow wall dimensions b_1=7.24 cm and secondary wave guide with broad wall dimensions a_2=1.016cm and narrow wall dimensions b_2=2.28cm are coupled through an inclined slot with an angle θ, in the narrow wall of primary wave guide. The length of the slot is 2L and the width of the slot is 2W. Using self-reaction and discontinuity in modal current concepts the slots admittance characteristics are analyzed.

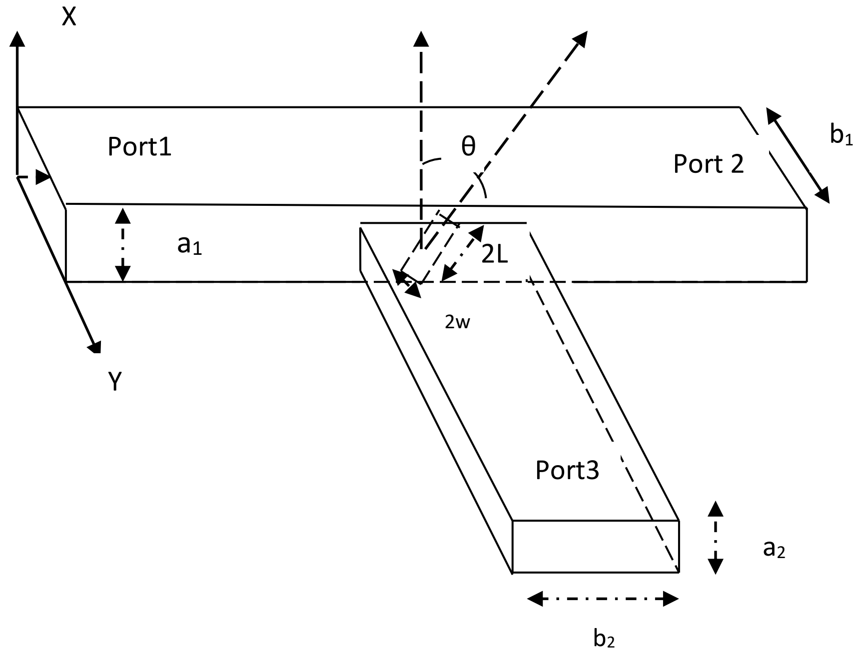


Fig.1.S-X band wave guides H-plane Tee junction coupled through inclined slot in the narrow wall

2.1Self-reaction equations in H plane Tee junction coupled through inclined slot:

The Electric field in aperture plane of slot is replaced by an equivalent magnetic current. the total self-reaction <r,r> of this magnetic current, with magnetic fields produced by this magnetic currents. The admittance seen by primary guide can be expressed as

$Y_T = -\frac{(I_s I_s)}{<r,r>}$, where I_s is discontinuity in modal current. (1)

Expression for self- reaction is given by [3]

$$< r,r > \; = -\int \overline{H_S}.\overline{M_S}\, dv. \quad (2)$$

where $\overline{H_S}$ is magnetic field and $\overline{M}_S$ is magnetic current. V is the coupled volume.

The equivalent network parameter is given by [10] the expression of the form [5]. In present work Self-reaction <r,r> is determined separately for the two guides. The self -reaction $\langle r,r\rangle_l$ in primary guide is longitudinal component of magnetic current, the self-reaction $\langle r,r\rangle_v$ in primary guide is transverse component of magnetic current, the self-reaction $\langle r,r\rangle_s$ in secondary guide, obtained from the modal expansion of the magnetic field in the coupled guide, is given by [14]. The shunt impedance loading on the primary guide due to the slot coupled shunt Tee can be expressed as the total self-reaction is equal to the sum of self-reactance $\langle r,r\rangle_l$, $\langle r,r\rangle_v$ and $\langle r,r\rangle_s$.

Hence, the equivalent network parameter will be

$<r,r> = \langle r,r\rangle_l + \langle r,r\rangle_v + \langle r,r\rangle_s$

The expression for shunt impedance loading on the primary guide due to slot coupled matched terminated Tee arm will be

$$Z_T = -\frac{\langle r,r\rangle}{I_s I_s} = -\frac{\langle r,r\rangle_l}{I_s I_s} - \frac{\langle r,r\rangle_v}{I_s I_s} - \frac{\langle r,r\rangle_s}{I_s I_s} \quad (3)$$

$$Z_T = Z_1 + Z_2 + Z_3$$

2.2 Self-reaction due to longitudinal component of magnetic current in primary wave guide $\langle \mathbf{r},\mathbf{r}\rangle_L$:

The Electric field $\overline{E_S}$ in aperture plane of slot of fig 1 is related to equivalent magnetic Current $\overline{M_S}$ by the relation

$$\overline{M_S} = \overline{E_S\, X a_n} \quad (4)$$

Where $\bar{a}_n$ is unit vector normal to the aperture plane

The field distribution in the slot is assumed to be of form given by [6]

$$\overline{E_S} = \overline{a_x} E_m \, sink(L - |z'|) \tag{5}$$

For $\frac{a_1}{2} - W \leq |x'| \leq \frac{a_1}{2} + W$ and $-L \leq |z'| \leq L$

where E_m is maximum Electric field, $\overline{a_x}$ is unit vector along x dire ction and K=2π/λ. λ is wave length. 2L is length of the slot and 2W is width of the slot.

From the fig.1 that $\overline{a_n} = \overline{a_y}$. Hence the magnetic current due to slot is in z direction. From the knowledge of magnetic field and magnetic current, it is possible to evaluate self -reaction required for obtaining expression for equivalent network. The self -reaction has been defined in (2) in the form of volume integral. Since magnetic current is distributed over the surface, the volume integral in the self–reaction reduced to surface integral. Taking the image in the wall y=b into account, the expression for self-reaction

Takes the form $< r, r >_l = -\int \overline{H}_S . \overline{2M}_S \, ds$

By integrating and simplifying the above expression,

$$< r, r >_l$$
$$= \sum_m^{\infty} \sum_n^{\infty} U E_m^2 \, 2w \cos^2 m\pi \cos \frac{n\pi}{2} \frac{\sin\left(\frac{n\pi\omega}{a_1}\right)}{\frac{n\pi\omega}{a_1}} \int_{\frac{\pi}{2}-w}^{\frac{\pi}{2}+w} \cos\left(\frac{n\pi x}{a_1}\right) dx \left[\cos \int_{-L}^{L} e^{-\gamma_{mn}} |z| sink(L\right.$$
$$\left. - |z'|) dz - e^{-\gamma_{mn}} |z| \int_{-L}^{L} \cosh \gamma_{mn} \, sink(L - |z'|)\right]$$

where $U = \frac{\epsilon_m \epsilon_n \lambda}{j40 \gamma_{mn} a_1 b_1 \pi^2}$ and $\epsilon_m = \epsilon_n = 1 \; for$ m=0, n=0, $\epsilon_m = \epsilon_n = 2 \; for$ m= n=1,2..,..,

By further Simplifying the expression for self -reaction for the longitudinal component of the slot magnetic current in primary wave guide will be reduced to

$$\langle r,r\rangle_l = R\sum_{m=0}^{\infty}\sum_{n=1}^{\infty}\frac{\epsilon_m \epsilon_n}{\gamma_{mn}(k^2+\gamma_{mn}{}^2)}cos^2 m\pi . cos^2\frac{n\pi}{2}\left[\frac{\sin(nP)}{(nP)}\right]^2$$

$$\left[0.5\left(1+e^{-2\gamma_{mn}L\sin\theta}\right)-\cos(kLsin\theta)\left\langle 2e^{-\gamma_{mn}L\sin\theta}-\cos(kL\sin\theta)+\frac{\gamma_{mn}}{k}\sin(kL\sin\theta)\right\rangle\right] \quad (6)$$

where $P = \frac{\pi W\sin\theta}{a_1}$ and $R = \frac{jV^2 sin^4\theta}{15\omega a_1 b_1 \ \lambda}$, for m=0, n=1.((In the above expression summation is done for except m=0,n=0 and m=1,n=0.) and $\gamma_{mn} = \left[\left(\frac{m\pi}{b_1}\right)^2+\left(\frac{n\pi}{a_1}\right)^2-(k)^2\right]^{\frac{1}{2}}$

2.3 Self-reaction due to transverse component of magnetic current in primary wave guide $< r,r >_v$:

The field distribution in the slot is assumed having length $2L_t$ and width $2W_t$ given by

$$\overline{E_S} = \overline{a_z}E_m \, sink(L_t - |x'|) \quad (7)$$

For $-W_t \le |z'| \le W_t$ and $\frac{a_1}{2} - L_t \le |x'| \le \frac{a_1}{2} + L_t$

where E_m is maximum Electric field, $\overline{a_z}$ is unit vector and K=2π/λ . λ is wave length. a and b are narrow wall and broad wall dimensions of feed guide.L_t =Lcos θ, W_t= Wcos θ with respect to x-component of magnetic current. Corresponding magnetic current is $\overline{M_S}$

$$\overline{M_S} = \overline{E_S}\, X\overline{a_n} \quad (8)$$

The magnetic current is along x-direction in present case

$$\overline{M_S} = \overline{a_n}X\,\overline{a_z}E_M \, sink(L_t - |x'|)$$

For $-W_t \le |z'| \le W_t$ and $\frac{a_1}{2} - L_t \le |x'| \le \frac{a_1}{2} + L_t$

By using self-reaction expressions given by [4]

$$< r,r >_v = -\iiint \bar{\mathrm{H}}.\bar{\mathrm{M}}\, \mathrm{dv}$$

As the magnetic current distributed over the surface, the volume integral reduces to surface integral

$$< r,r >_v = -\int \bar{\bar{H}}_s.\bar{\bar{M}}_s\, ds \tag{9}$$

By integrating and simplifying the expression for Self-reaction given by [9]

$$\langle r,r\rangle_v =$$

$$T\sum_m^\infty \sum_n^\infty O\left[k^2-\left(\frac{n\pi}{a_1}\right)^2\right] cos^2\ m\pi sin^2\frac{n\pi}{2}\left[\frac{2k}{k^2-\left(\frac{n\pi}{a_1}\right)^2}\right]^2\left[\cos\frac{n\pi L_t}{a_1}-\cos kL_t\right]^2\left[\frac{4W_t\gamma_{mn2e}{}^{-2\gamma_{mn}W_t}-2}{\gamma_{mn}W_t^2}\right] \tag{10}$$

where $T = \frac{j\lambda}{240\pi^2}$ and $O = \frac{E_m^2\,\epsilon_m W_t^2}{a_1 b_1 \gamma_{mn}^2}$

It should be noted that the integral $-\int \bar{\bar{H}}_s.\bar{\bar{M}}_s\, ds$ is performed at y=b plane

Because the magnetic current M_s is the surface current and extended in x direction from $\frac{a_1}{2}-L_t$ to $\frac{a_1}{2}+L_t$ and in z direction $-W_t$ to W_t. Self-reaction of magnetic current along to x-Component of magnetic current can be obtained by replacing L_t by Lcos θ,W_t by Wcosθ and E_m by Vcos θ.

With modification Self-reaction due to transverse component of magnetic current in primary wave guide

$$< r,r >_v = -\int \bar{\bar{H}}_s.\bar{\bar{M}}_s\, ds \tag{11}$$

$\langle r, r \rangle_v =$

$Q \sum_{m=0}^{\infty} \sum_{n=1}^{\infty} \frac{\epsilon_m}{(\gamma_{01}{}^2)} cos^2 m\pi . sin^2 \frac{n\pi}{2} \left[\frac{1}{k^2 - \left(\frac{n\pi}{a_1}\right)^2} \right]^2 \left[cos\left(\frac{n\pi L cos\theta}{a_1}\right) - \cos(kLsin\theta) \right]^2 \left[2cos\theta + \frac{e^{-2\gamma w cos\theta}}{\gamma_{mn} w} - \frac{1}{\gamma_{mn} w} \right]$ (12)

where Q $= \frac{jV^2 cos^2\theta}{60\pi a_1 b_1}$

In similar way, the self- reaction $\langle r, r \rangle_s$ is reduced to

2.4 Self-reaction in coupled/ secondary wave guide $\langle \mathbf{r}, \mathbf{r} \rangle_s$:

$$\langle r, r \rangle_s = 2 \sum_{m=0}^{\infty} \sum_{n=1}^{\infty} (Y_0)_{mn}^e \, (V_{mn}^e)^2 + 2 \sum_{m=0}^{\infty} \sum_{n=1}^{\infty} (Y_0)_{mn}^m \, (V_{mn}^m)^2 \quad (13)$$

where $(Y_0)_{mn}^e = \frac{\gamma_{mn}}{j\omega\mu_0}$; $(Y_0)_{mn}^m = \frac{j\omega\epsilon}{\gamma_{mn}}$ and $\gamma_{mn} = \left[\left(\frac{m\pi}{b_2}\right)^2 + \left(\frac{n\pi}{a_2}\right)^2 - (k)^2 \right]^{\frac{1}{2}}$

And modal voltages are given by [4]

$$V_{mn}^e = \frac{V}{2\pi} \left[\frac{a_2 b_2 \in_m \in_n}{m a_2{}^2 + n b_2{}^2} \right]^{\frac{1}{2}} \left[\left(\frac{m\pi}{b_2} cos\theta + \frac{n\pi}{a_2} sin\theta \right) (coskL - cosAL) \frac{2k}{k^2 - A^2} \frac{sinBw}{Bw} sin\overline{m+n} \frac{\pi}{2} + \left(\frac{m\pi}{b_2} cos\theta - \frac{n\pi}{a_2} sin\theta \right) (coskL - cosCL) \frac{2k}{k^2 - C^2} \frac{sinDw}{Dw} sin\overline{m-n} \frac{\pi}{2} \right]$$

$$V_{mn}^m = \frac{-V}{\pi} \left[\frac{a_2 b_2}{m a_2{}^2 + n b_2{}^2} \right]^{\frac{1}{2}} \left[\left(\frac{n\pi}{a_2} cos\theta - \frac{m\pi}{b_2} sin\theta \right) (coskL - cosAL) \frac{2k}{k^2 - A^2} \frac{sinBw}{Bw} sin\overline{m+n} \frac{\pi}{2} + \left(\frac{n\pi}{a_2} cos\theta + \frac{m\pi}{b_2} sin\theta \right) (coskL - cosCL) \frac{2k}{k^2 - C^2} \frac{sinDw}{Dw} sin\overline{m-n} \frac{\pi}{2} \right]$$

where $A = \frac{m\pi}{b_2} cos\theta + \frac{n\pi}{a_2} sin\theta$

B$= \frac{n\pi}{a_2} sin\theta - \frac{m\pi}{b_2} cos\theta$

C $= \frac{n\pi}{a_2} cos\theta - \frac{m\pi}{b_2} sin\theta$

$$D = \frac{n\pi}{a_2} sin\theta + \frac{m\pi}{b_2} cos\theta$$

2.5 Expression for discontinuity in modal current I_s:

The expression for discontinuity in modal current [9] reduces to the form

$$I_S = -2jY_{01} V\left(\frac{2}{a_1 b_1}\right)^{1/2} \frac{2\pi^2}{b_1 \beta_{01} \lambda} \frac{1}{\beta_{01}^2 - k^2}\left(\cos\beta_{01}\frac{L}{2} - \cos k\frac{L}{2}\right)\frac{\sin\beta_{01} w/2}{\beta_{01} w/2} \tag{14}$$

where $Y_{01} = \frac{\beta_{01}}{\omega\mu_{01}}$ and $\beta_{01} = \sqrt{k^2 - \left(\frac{\pi}{b_1}\right)^2}$; V=2$E_m$W

2.6 Expression for admittance loading:

The normalized shunt admittance is related to normalized impedance by the relation and can be calculated from the knowledge of self-reaction and discontinuity in modal current

$$Y_T = g_n + jb_n = \frac{1}{z_T} = \frac{1}{r + jx} \tag{15}$$

where g_n the normalized conductance and $\mathbf{b_n}$ is the normalized susceptance

2.7 Expression for Coupling and VSWR (voltage standing wave ratio):

It has been possible to represent the radiation of present interest by the equivalent circuit which consists of admittance parameters.

The reflection coefficient ρ in terms of load admittance is

$$\rho = \frac{1 - Y_L}{1 + Y_L} \quad \text{where} \quad Y_L = 1 + Y_T$$

Using power balanced condition the radiated power coupled to free space is given by[9]

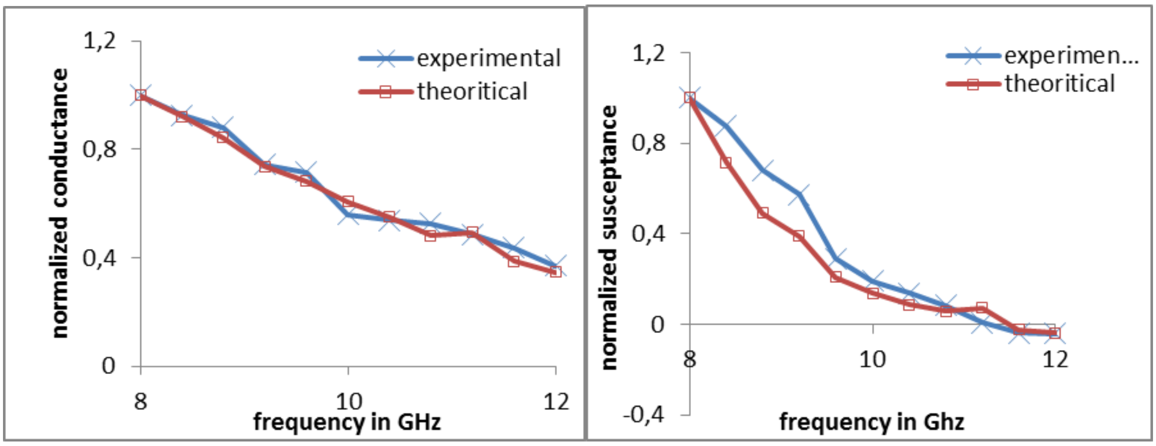
$$C = 4g_n^2/[(2+g_n)^2 + b_n^2] \qquad (16)$$

The VSWR in terms of reflection coefficient is given by [9]

$$VSWR = \frac{1+|\rho|}{1-|\rho|} \qquad (17)$$

2 Results:

From the obtained resonant length, normalized conductance, normalized susceptance, coupling and VSWR are numerically computed as a function of frequency, from expressions Eq.(14), Eq .(15) ,Eq.(16)and Eq .(17).for a_1=3.48cm, b_1=7.24cm, a_2=1.016 cm, b_2=2.286 cm, for slot length 2L=1.6cm,shown in Fig.2 are the Results for slot width 2W= 0.1cm, for slot inclination $\theta = 30^0$, Fig.3.for, for slot width 2W= 0.1cm, for slot inclination $\theta = 40^0$. Fig.4. for slot width 2W= 0.2cm, for slot inclination $\theta = 35^0$. Fig.5. for slot width 2W= 0.2cm, for slot inclination $\theta=45^0$.



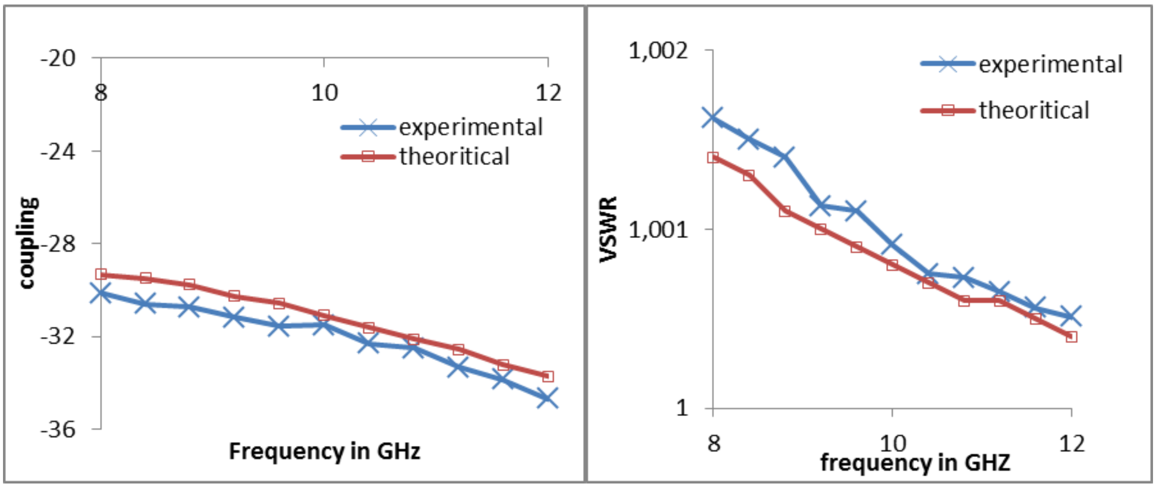


Fig.2.Variation in conductance, susceptance, coupling and VSWR as a function of frequency for slot length =1.6cm, slot width=0.1cm and slot inclination θ=30^0

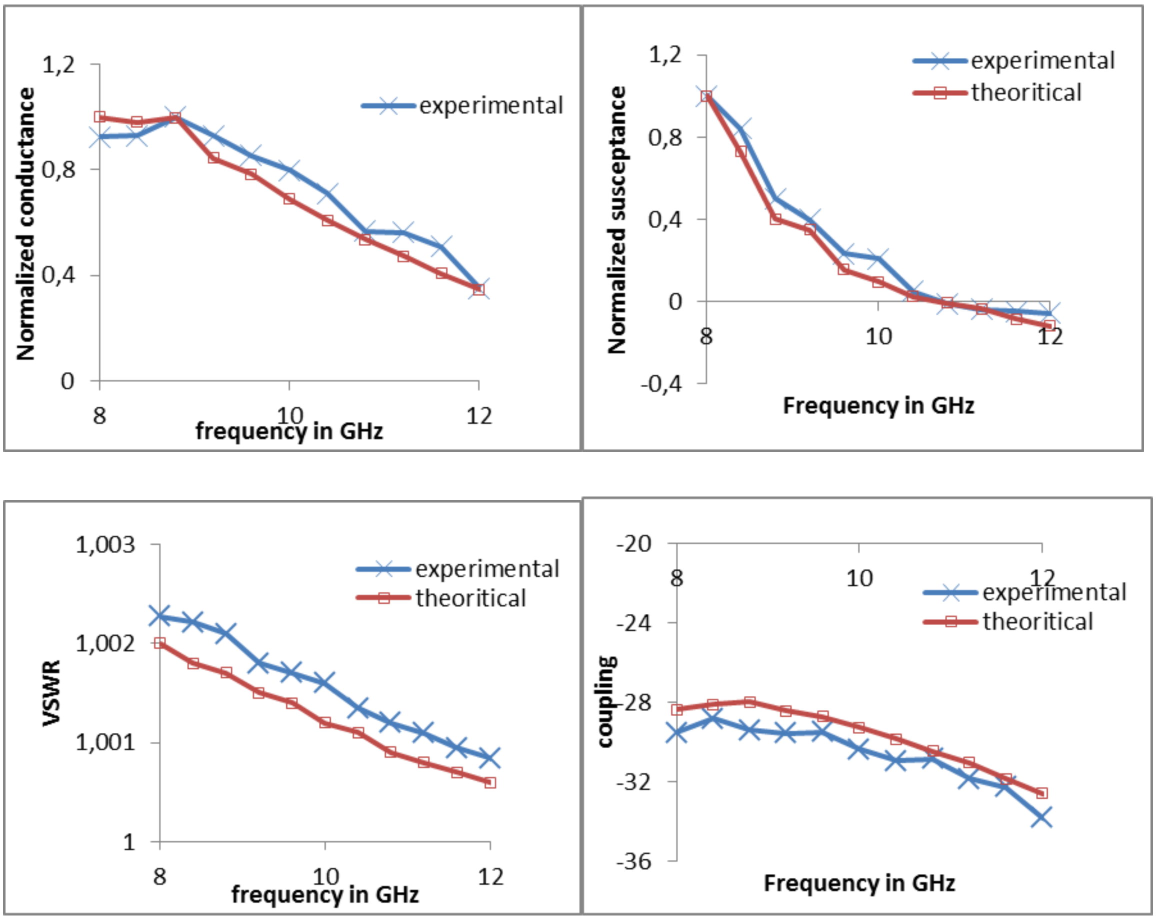


Fig.3.Variation in conductance, susceptance, coupling and VSWR as a function of frequency for slot length =1.6cm, slot width=0.1cm and slot inclination θ=40^0

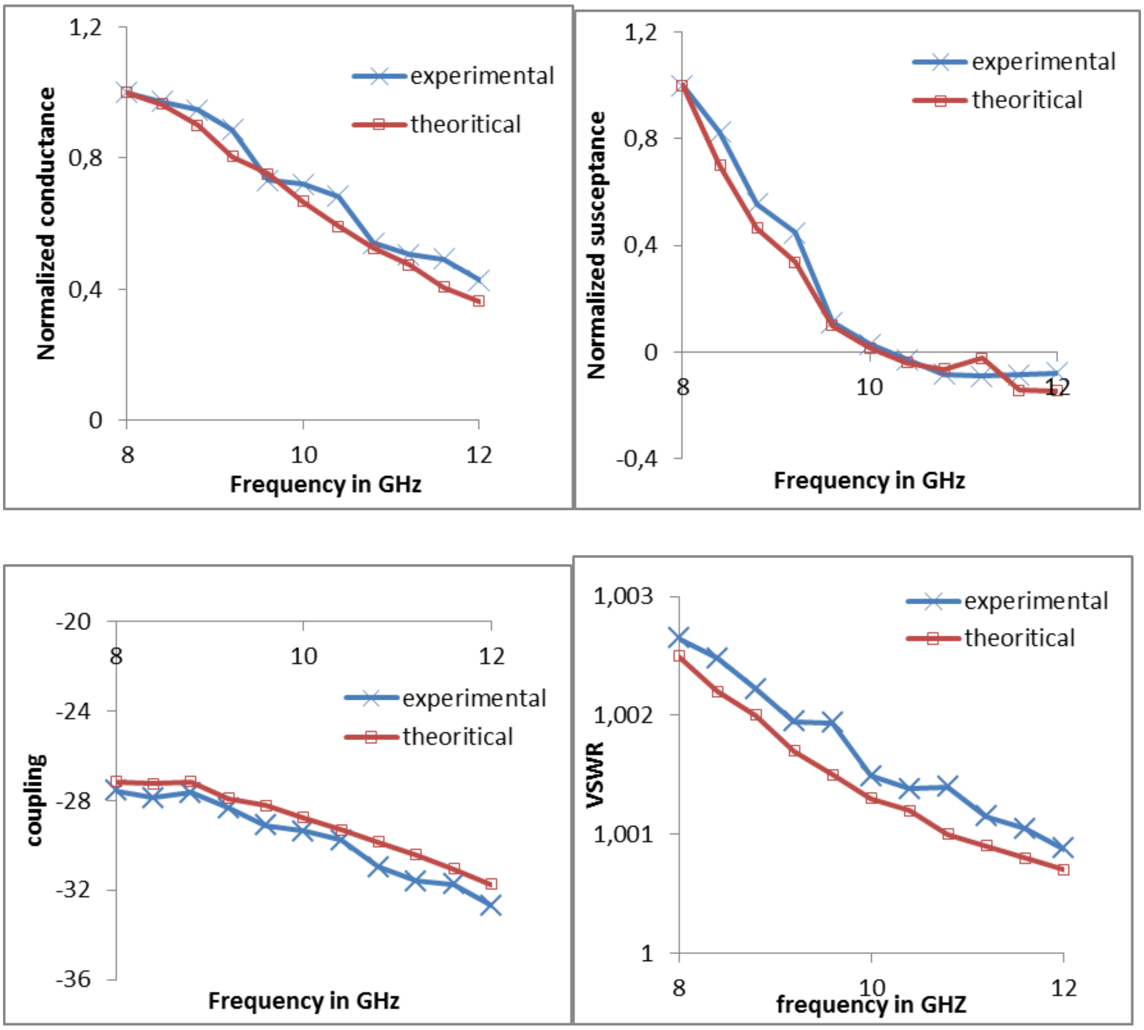


Fig.4.Variation in conductance, susceptance, coupling and VSWR as a function of frequency for slot length =1.6cm, slot width=0.2cm and slot inclination θ= 45^0

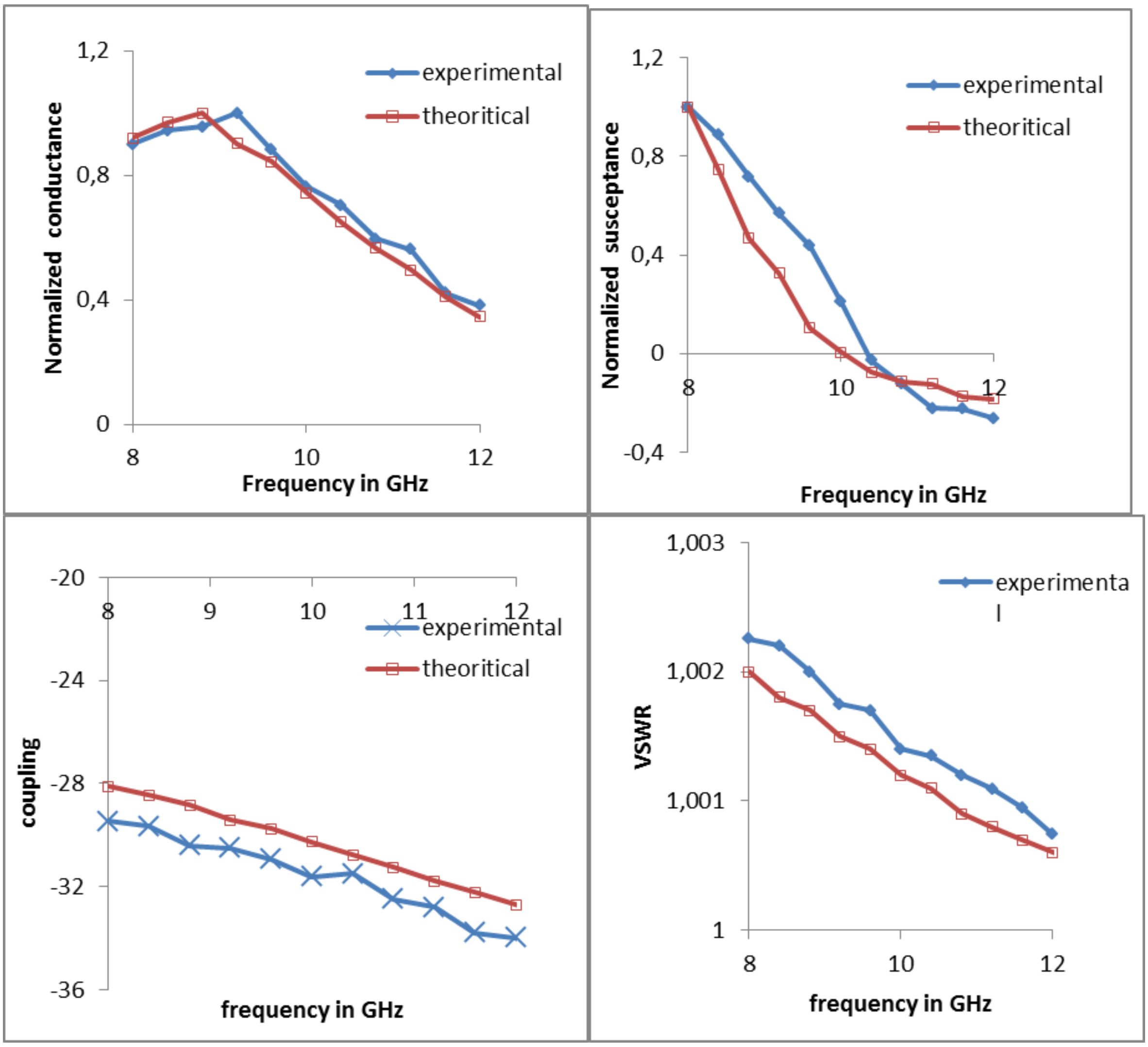


Fig.5.Variation in conductance, susceptance, coupling and VSWR as a function of frequency for slot length =1.6cm, slot width=0.2cm and slot inclination θ= 35^0

4 Conclusion:

H plane junction considered in the paper is unique, as it is a junction formed by one S-band and another X-band. The two wave guides primary and secondary have different dimensions. In order to obtain analysis, the concept of self-reaction and discontinuity modal current is applied. This methodology is found to provide suitable convergence of infinite series. It is evident from the results that expression for admittance loading consists of double infinite summation in primary and secondary guides. The convergence has been successfully tested and admittance parameters are evaluated. From the data so obtained coupling in dB and VSWR are also evaluated.

For the sake of comparison, the slot coupled junction considered and measurements are carried out on $g_{n,,}$ b_n, coupling and VSWR. The difference between theoretical and experimental results is very marginal. The junction presented is not only useful as a coupler, but also useful as radiator with vertical polarization. This information is required for the array designer for the design of arrays.

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