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Research Article

EFFECT OF SHIFTING THE AXIS OF TWIST ON PROPAGATION OF ELECTROMAGNETIC WAVES IN TWISTED RECTANGULAR WAVEGUIDE

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ABSTRACT
Rectangular waveguide twist components are required in many communication applications, especially in satellite communications. While designing twisted waveguides it is necessary to take care about exact location and angle of twist for proper distribution of electric and magnetic fields. So that electromagnetic waves can propagate through waveguide in the desired manner. The problem of propagation of dominant TE mode in twisted waveguide of rectangular cross section with shift in axis of twist is analyzed up to 12^{th} order perturbation terms. The helical coordinate system is used for mathematical formulation of the problem and perturbation technique is used in obtaining the solution. It is shown that the effect of shifting the axis of twist cannot be observed up to second order terms. The contribution of higher order terms cannot be neglected for accuracy of results. The information about the percentage contribution of higher order terms is worked out. This is useful in deciding the number of terms to be included for the expected accuracy and fixing the position of axis of twist of waveguide for propagation of electromagnetic waves without loss.

Key Words: *Rectangular Waveguide, Twisted Waveguide, Perturbation Technique*

INTRODUCTION
Waveguide is normally rigid and therefore it is often necessary to direct the waveguide in a particular direction. Waveguide bends and twists are very useful in building a waveguide system. Using waveguide bends and twists it is possible to arrange the waveguide into the positions required. Regular straight hollow waveguides have phase velocities greater than the free-space speed of light for propagating electromagnetic waves. Conventional slow wave structures used for accelerating charged particles and other applications employ reactive loadings in hollow straight waveguides to reduce the phase velocity of electromagnetic fields in the specific mode to be used. Waveguide twists are also useful in many applications to ensure the polarization is correct.

Lewin (1955) investigated the propagation in curved and twisted rectangular waveguides by putting the wave equation in a form in which the co-ordinates in a waveguide cross-section are also the independent variables in the differential equation. Lewin and Ruehle (1978) obtained the solution for degenerate mode in twisted rectangular waveguide, with emphasis on the square waveguide.

Twisted waveguide sections have been implemented in waveguide circuits for simple plumbing purposes with no attention to their phase properties. It has been found that the twisted hollow waveguides may support slow-wave waveguide modes. The twisted waveguide structures have been modeled and simulated using MAFIA (1997) and Agilent HFSS codes, the 3-D electromagnetic solvers, to show the slow-wave properties.

With an optimum shape of the cross section and pitch angle, a twisted waveguide can have the desired phase velocity of a specific mode. Bornemann (1995) designed rectangular waveguides of 90^0 twist ideally suited for application in satellite communication. Reutskiy (2008) investigated the methods of external excitation for analysis of arbitrarily-shaped Hollow Conducting Waveguides. Mazar Qureshi (2010) discussed processes of designing the twist of various angles. Hatsuo Yabe *et al.*, (1984) studied theoretically the reflection characteristics of straight rectangular waveguide. They used a perturbation method and a modal analysis is applied to the hybrid mode field inside the twisted waveguide. He also reported that the rectangular input and output ports can be of different cross-sections, thus eliminating the need for additional impedance transformers.

Wilson *et al.*, (2008) studied twisted waveguides for particle accelerator applications and also discussed the advantages of using twisted guides over conventional RF accelerating cavities. They

also claimed that the existing perturbation theory methods yield adequate results for slowly twisted structures.
A twisted waveguide maintains a uniform cross section at any location on the beam axis except the bearing angle. If a simple rectangular waveguide is twisted, both electric and magnetic fields in the waveguide will be twisted along the guide to satisfy the boundary conditions.
When using waveguide bends and waveguide twists, it is necessary to ensure the bending and twisting is accomplished in the correct manner otherwise the electric and magnetic fields will be unduly distorted and the signal will not propagate in the required manner, causing loss and reflections. Accordingly waveguide bend and waveguide twist sections are manufactured specifically to allow the waveguide direction to be altered without unduly destroying the field patterns and introducing loss. In this paper we discussed the effect of shifting the axis twist of rectangular waveguide on propagation of electromagnetic waves. For this we used perturbation technique and obtained the solutions for higher order terms up to twelfth order to obtain the sufficient accuracy.

MATHMATICAL FORMULATION

The problem of effect of higher order perturbation terms on propagation of wave in twisted rectangular waveguide with the axis of twist at its centre was worked out by Chaudhari and Patil (1994). Now the problem of effect of shifting the axis of twist has solved.

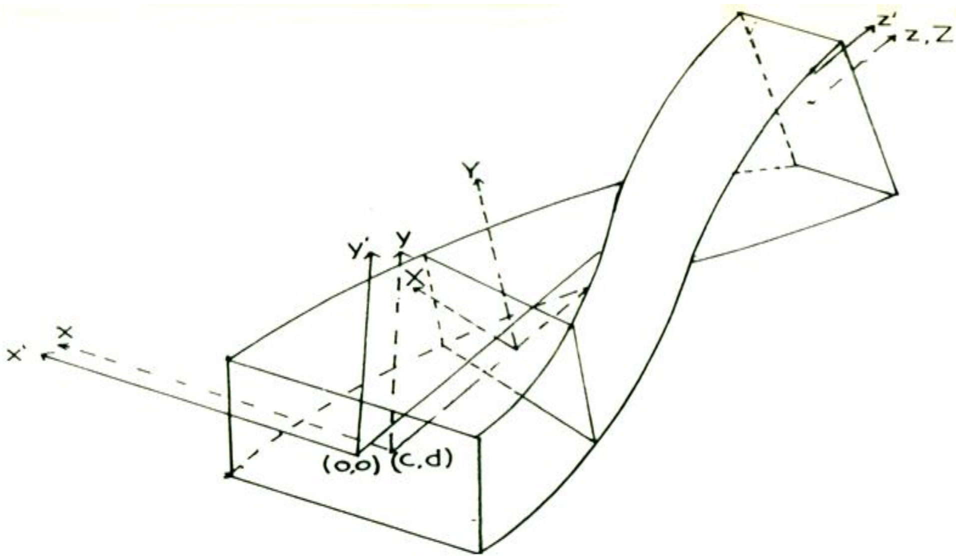

Figure 1: Twisted Rectangular Waveguide (With Shift in Axis of Twist)

Figure 1 shows rectangular waveguide twisted about an axis shifted to point (c, d) with respect to origin (centre of the waveguide), and (x, y, z) represent co-ordinates of twisted co-ordinate system. The transformation equations are

$$\left.\begin{aligned} X &= (x + c)\cos(pz) + (y+d)\sin(pz) \\ Y &= (y+ d)\cos(pz) - (x+c)\sin(pz) \\ Z &= z \end{aligned}\right\} \qquad \ldots\ldots\ldots\ldots 1$$

Where $P = \frac{2\pi}{L}$, L is the distance in which twisted guide makes one complete rotation.

The wave equation in fixed co-ordinate system is

$$\frac{\partial^2\Psi}{\partial x^2} + \frac{\partial^2\Psi}{\partial y^2} + \frac{\partial^2\Psi}{\partial z^2} + k^2\Psi = 0 \qquad \ldots\ldots\ldots\ldots 2$$

Where $k = \frac{2\pi}{\lambda}$ and λ = free space wavelength.

The boundary conditions are

$$\left.\begin{array}{lll} E_x = \frac{\partial \Psi}{\partial Y} = 0 & \ldots\ldots\ldots \begin{cases} \text{at } Y = (b/2) - d \\ \text{at } Y = (-b/2) - d \end{cases} \\ E_y = \frac{\partial \Psi}{\partial X} = 0 & \ldots\ldots\ldots \begin{cases} \text{at } X = (b/2) - c \\ \text{at } X = (-a/2) - c \end{cases} \\ E_z = 0 & \ldots\ldots\ldots\ \text{On the guide surface.} \end{array}\right\} \quad \ldots\ldots\ldots 3$$

The zeroth order, first order and second order perturbation equations are same as that for waveguide twisted about z-axis at its centre. The corresponding general solutions assumed are

$$\Psi_0 = \sin\left(\frac{(\pi\ (x+c)}{a}\right) \quad \ldots\ldots\ldots 4$$

$$\Psi_0 = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} A_{mn} \left\{cos\left[\left(x - \frac{a}{2} + c\right)\frac{m\pi}{a}\right].\cos\left[\left(Y - \frac{b}{2} + d\right)\frac{n\pi}{b}\right]\right\} \quad \ldots\ldots\ldots 5$$

And

$$\Psi_2 = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} B_{mn} \left\{cos\left[\left(x - \frac{a}{2} + c\right)\frac{m\pi}{a}\right].\cos\left[\left(Y - \frac{b}{2} + d\right)\frac{n\pi}{b}\right]\right\} \quad \ldots\ldots\ldots 6$$

By assuming these solutions, the calculations for A_1, A_2 A*mn* and B*mn* are carried out with the process used in the calculations for waveguide twisted about Z-axis at its centre (Chaudhari and Patil, 1994). It is observed that the values of A_1, A_2 A*mn* and B*mn* are same as that for waveguide twisted about Z-axis at its centre. In other words, the effect of shifting the axis of twist cannot be observed up to second order terms.In order to see the effect of shifting the axis of twist it is necessary to obtain the solutions for higher order equations.

Third order Solution

The general solution for third order perturbation equation satisfying boundary conditions in eq.3 is

$$\Psi_3 = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} C_{mn} \left\{cos\left[\left(x - \frac{a}{2} + c\right)\frac{m\pi}{a}\right].\cos\left[\left(Y - \frac{b}{2} + d\right)\frac{n\pi}{b}\right]\right\} \quad \ldots\ldots\ldots 7$$

After carrying out calculations as in section (2.2C), the values of A_3 and C'*mn* obtained are

$$A'_3 = 0 \quad \ldots\ldots\ldots 8$$

and

$$C'_{mn} = A'_{mn} \cdot \frac{\left\{ab\left[\left(\frac{\pi}{a}\right)^2 A_{2-} \frac{n\pi^2}{b}\left(\frac{a^3}{12}ac^2 + \frac{1}{2}\frac{a^3}{m\pi^2}\right) - \left(\frac{m\pi}{a}\right)^2\left(\frac{m\pi}{a}\right)^2\left(\frac{b^3}{12}bd^2 + \frac{1}{2}\frac{b^3}{n\pi^2}\right)\right\}}{\left\{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 - \left(\frac{\pi}{a}\right)^2\right\}ab} \quad \ldots\ldots 9$$

Fourth order Solution:

The general solution for fourth order perturbation equation satisfying boundary conditions in eq.3 is

$$\Psi_4 = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} D'_{mn} \left\{cos\left[\left(x - \frac{a}{2} + c\right)\frac{m\pi}{a}\right].\cos\left[\left(Y - \frac{b}{2} + d\right)\frac{n\pi}{b}\right]\right\} \quad \ldots\ldots\ldots 10$$

With usual process of determining coefficients as in section 2.2d, the values of A'$_4$ and D' mn are

$$A'_4 = \sum_{m=0}^{\infty}\sum_{n=1}^{\infty}\frac{2jk'}{b}\left\{m\left(\frac{b}{n\pi}\right)^2 - \left(\frac{a}{\pi}\right)^2\right\}.\left\{\frac{2a}{\pi^2}C'_{mn} - \frac{A_2}{ak'^2}A_{mn}\right\}[(1 + \cos m\pi)\ (1 - \cos n\pi)] \quad \ldots\ldots\ldots 11$$

and

$D'_{mn} = 0.$ 12

Fifth order Solution

The general solution for fifth order perturbation equation satisfying boundary conditions in eq.3 is

$$\Psi_5 = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} E'_{mn} \left\{cos\left[\left(x-\frac{a}{2}+c\right)\frac{m\pi}{a}\right].\cos[\left(Y-\frac{b}{2}+d\right)\frac{n\pi}{b}]\right\} \quad \ldots\ldots\ldots 13$$

With the process of determining coefficients as in the section (2.2e), we get

$A'_5 = 0$ 14

and

$E'_{mn} = \left\{\left(\frac{\pi}{a}\right)^2 (A_2 \ C'_{mn} + A'_4 A'_{mn} - \frac{3}{2} C'_{mn} - C'_{mn} (\frac{n\pi}{b})^2 \left[\frac{a}{12}^2 + c^2 + \frac{1}{2} \left(\frac{a}{m\pi}\right)^2\right] - \right.$

C'mnmπa2+b212+ d2+12−bnπ2 x 1mπa2+nπb2−πa2 ..…..……15

A similar method is used for calculations of higher order equations upto 12th order.
The expressions for the respective coefficient and constant are given below.

Sixth order Solution

$$A'_6 = j\left(\frac{4a}{b\pi^4}\right)\sum_{m=0}^{\infty}{}'\sum_{n=1}^{\infty}\left(\frac{mb^2}{n^2}-a^2\right)\left\{k'E'_{mn} - \frac{\pi^2}{2a^2K,}\left(A'_4A_{mn} + A_2C'_{mn}\right)\right.$$
$$\left. - \frac{\pi^4}{Ba^4K'^3} A_2^2A_{mn}\right\}\{(1+cosm\pi)(1-cosn\pi)\} \quad \ldots\ldots\ldots 16$$

and

$F'_{mn} = 0$ 17

Seventh order Solution

$A'_7 = 0$ 18

and

$$G'_{mn} = \left\{\left(\frac{\pi}{a}\right)^2 \left(A_2 E_{mn} + A'_4C'_{mn} + A'_6A_{mn}\right) - \frac{3}{2} E'_{mn}\right.$$
$$- E'_{mn}\left[\left(\frac{n\pi}{b}\right)^2\left(\frac{a^2}{12}+c^2+\frac{1}{2}\left(\frac{a}{m\pi}\right)^2\right) + \left(\frac{m\pi}{a}\right)^2\left(\frac{b^2}{12}\right) + d^2\right.$$
$$\left.\left. + \frac{1}{2}\left(\frac{b}{n\pi}\right)^2\right]\right\} x \ \frac{1}{\left\{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 - \left(\frac{\pi}{a}\right)^2\right\}} \quad \ldots\ldots\ldots 19$$

Eight order Solution

$$A'_7 = j\left(\frac{4a}{b\pi^4}\right)\sum_{m=0}^{\infty}{}'\sum_{n=1}^{\infty}\left(\frac{mb^2}{n^2}-a^2\right)\left\{k'G'_{mn} - \frac{\pi^2}{2a^2K,}\left[A'_6A_{mn} + A'_4C'_{mn} + A_2E'_{mn}\right]\right.$$
$$- \frac{\pi^4}{8a^4K'^3}\left[2A_2A'_4A_{mn} + A_2^2C'_{mn}\right]$$
$$\left. - \frac{\pi^6}{16a^6K'^5} A_2^3A_{mn}\right\}\{(1+Cosm\pi)(1-cosn\pi)\} \quad \ldots\ldots\ldots 20$$

and

$H'_{mn} = 0$ ..……..21

Ninth order Solution

$A'_9 = 0$ ..……..22

and

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$$I'_{mn} = \left\{\left(\frac{\pi}{a}\right)^2 \left(A_2\, G_{mn} + A'_4 E'_{mn} + A'_6 C_{mn} + A'_8 A_{mn}\right) - \frac{3}{2}\, G'_{mn} - G_{mn}\left[\left(\frac{n\pi}{b}\right)^2 \left[\frac{a^2}{12} + c^2 + \frac{1}{2} + \left(\frac{a}{m\pi}\right)^2\right] + \left(\frac{m\pi}{a}\right)^2 \left(\frac{b^2}{12}\right) + d^2 + \left(\frac{b}{n\pi}\right)^2\right]\right\} x \,\frac{1}{\left\{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 - \left(\frac{\pi}{a}\right)^2\right\}} \quad \ldots\ldots\ldots 23$$

Tenth order Solution

$$A'_{10} = j\left(\frac{4a}{b\pi^4}\right) \sum_{m=0}^{\infty}{}' \sum_{n=1}^{\infty} \left(\frac{mb^2}{n^2} - a^2\right) \left\{k' I'_{mn} - \frac{\pi^2}{2a^2 K,} \quad [A'_8 A_{mn} + A'_6 C'_{mn} + A_4 E'_{mn} + A_2 G'_{mn}] - \frac{\pi^4}{8a^4 K'^3}\left[\left(2A_2 A'_6 + A'^2_4\right) A_{mn} + 2A_2 A'_4 C'_{mn} + A_2^2 E'_{mn}\right] - \frac{\pi^6}{16a^6 K'^5}\; 3A_2^3 A'_4 A_{mn}\right\}\{(1 + Cosm\pi)(1 - cosn\pi)\} \quad \ldots\ldots\ldots 24$$

and

$$J'_{mn} = 0 \qquad \ldots\ldots\ldots 25$$

Eleventh order Solution

$$A'_{11} = 0 \qquad \ldots\ldots\ldots 26$$

and

$$K'_{mn} = \left\{\left(\frac{\pi}{a}\right)^2 \left(A_2\, I_{mn} + A'_4 G'_{mn} + A'_6 E_{mn} + A'_8 C_{mn} + A'_{10} A_{mn}\right) - \frac{3}{2}\, I'_{mn} - I_{mn}\left(\frac{n\pi}{b}\right)^2 \left(\frac{n\pi}{b}\right)^2 \frac{a^2}{12} + c^2 + \left(\frac{a}{m\pi}\right)^2 + \left(\frac{m\pi}{a}\right)^2 \left(\frac{b^2}{12}\right) + d^2 + \left(\frac{b}{n\pi}\right)^2\right\} x \,\frac{1}{\left\{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 - \left(\frac{\pi}{a}\right)^2\right\}} \quad \ldots\ldots\ldots 27$$

Twelfth order Solution

$$A'_{12} = j\left(\frac{4a}{b\pi^4}\right) \sum_{m=0}^{\infty}{}' \sum_{n=1}^{\infty} \left(\frac{mb^2}{n^2} - a^2\right) \left\{k' k'_{mn} - \frac{\pi^2}{2a^2 K,}\left[A'_{10} A_{mn} + A'_8 C'_{mn} + A_6 E'_{mn} + A_4 G'_{mn} + A_2 I'_{mn}\right] - \frac{\pi^4}{8a^4 K'^3}\left[2\left(A_2 A'_8 + A'_4 A'_6\right) A_{mn} + \left(2A_2 A'_6 + {A'_4}^2\right) C'_{mn} + 2A_2 A'_4 E'_{mn} + {A_2}^2 G'_{mn}\right] - \frac{\pi^6}{16a^6 K'^5}\left[3\left({A_2}^2 A'_6 + {A'_4}^2 A_2\right) A_{mn} + 3{A_2}^2 A'_4 C'_{mn} + {A_2}^3 E'_{mn}\right]\right\}.\{(1 + Cosm\pi)(1 - cosn\pi)\} \quad \ldots\ldots\ldots 28$$

and

$$L'_{mn} = 0 \qquad \ldots\ldots\ldots 29$$

Evaluation of Propagation Constant Square

With constants $A'_1 \quad A'_2 \quad A'_3 \ldots\ldots A''_{12}$ the propagation constant square is

$$\beta_s^2 = K^2 - \left(\frac{\pi}{a}\right)^2 (1 + A'_1 P^2 + A'_3 P^3 + \ldots\ldots A'_{12} P^{12}) \qquad \ldots\ldots\ldots 30$$

(In this formula $A'_1 = A'_1 \;\; and \;\; A'_2 = A''_2$)

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After substituting the values of constants $A'_1 \ \ A'_2 \ \ A'_3 \ldots\ldots A'_{12}$ from respective equations we obtain the value of propagation constant of a wave propagating through a rectangular waveguide twisted about an axis shifted to point (c, d) with respect to centre.

NUMERICAL CALCULATIONS:

Now we used theoretically derived formula

$$\beta_s^2 = K^2 - \left(\frac{\pi}{a}\right)^2 (1 + A'_2P^2 + A'_4P^4 + \ \ldots\ldots + A'_{12}P^{12})$$

For obtaining the values of β_s^2 under different shift in the axis of twist and find quantitative effect of the shift. These calculations are carried out on PCAT with mathematical co-processor 80287. The constants a'2, A'4, A'6 . . . . A'_{12} required in the above formula are evaluated by program 'RWCD'. The process adopted for the determination of coefficients A_{mn}, C'_{mn}, E'_{mn}, I'_{mn} and constants A'_2, A'_4, A'_6 . . . . A'_{12}, is same as that for calculations for waveguide twisted at its centre. Here also the program subroutines 'RWA2CD', 'RWA4CD', 'RWA6CD', 'RWA8CD', RWA10CD'and 'RWA12CD' are developed for determination of constants A'_2, A'_4, A'_6, A'_8, A'_{10} and A'_{12} respectively. The program is compiled till the convergence is obtained.

In order to see the effect of shifting the axis of twist, the relative departure of β_s^2 from propagation constant square with axis of twist at centre of the guide with respect to β_0^2 i.e. $(\beta_s^2 - \beta_0^2)/\beta_0^2$ is calculated. The shift of axis of twist is carried along X-axis and Y-axis and diagonal. The propagation constant square with shift along X-axis, Y-axis and diagonal are represented by $\beta_C^2, \beta_D^2, \beta_{CD}^2$ respectively.

The relative departure of β_D^2 form β_0^2 with respect to β_0^2 i.e. $(\beta_D^2 - \beta_0^2)/\beta_0^2$ is calculated for fixed length L = 110mm and its percentage variation is plotted against shift of axis of twist along Y-axis from 0.0 to 0.5b for λ = 28mm, 30mm and 32mm in figure 2.

The relative departure of β_C^2 from β_0^2 with respect to i.e. β_0^2 i.e. $(\beta_C^2 - \beta_0^2)/\beta_0^2$ is calculated for fixed length L = 110mm and its percentage variation is plotted against shift of axis of twist along X-axis from 0.0 to 0.5a for λ =28mm, 30mm and 32mm in figure 3.While figure 4 shows percentage variation of $(\beta_{CD}^2 - \beta_0^2)/\beta_0^2$ against shift along diagonal at L = 110mm and for λ = 28mm, 30mm and 32mm.

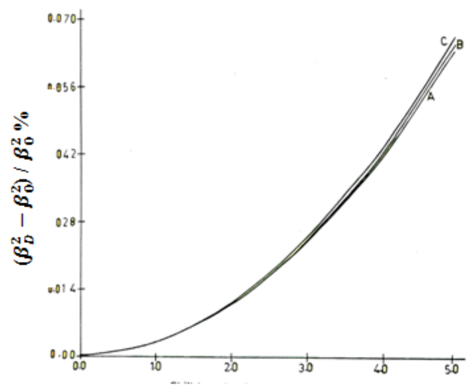

Figure 2

Variation of $(\beta_D^2 - \beta_0^2)/\beta_0^2$ % against Shift in Axis of twist along y-axis at L = 110 mm. (Curves A, B and C are for λ =28, 30 and 32 mm respectively)

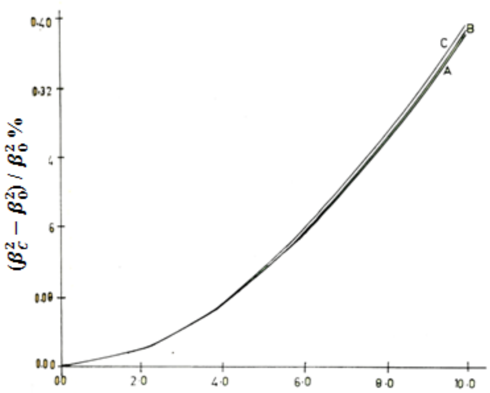

Figure 3

Variation of $(\beta_C^2 - \beta_0^2)/\beta_0^2$ % against Shift in Axis of twist along X-axis at L = 110 mm. (Curves A, B and C are for λ =28, 30 and 32mm respectively)

In general program 'RWCD' is used for calculations of shifting the axis along diagonal. With C=0, this program gives calculations for the shift of axis along Y-axis while with d=0, it gives calculations for the shift of axis along X-axis. For plotting graphs in figures 2, 3 and 4 program 'PRWCD' is developed.

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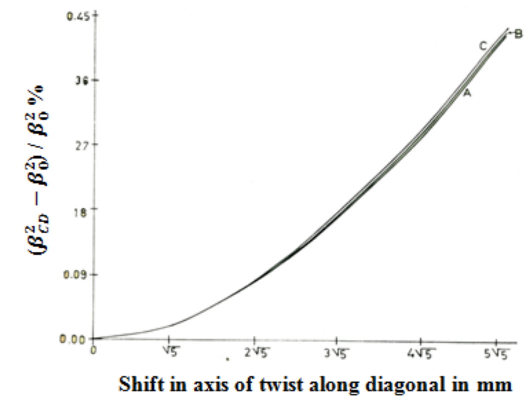

Figure 4
Variation of $(\beta_{CD}^2 - \beta_0^2) / \beta_0^2$ % against Shift in axis of twist along diagonal at L = 110 mm. (Curves A, B and C are for λ =28, 30 and 32 mm respectively)

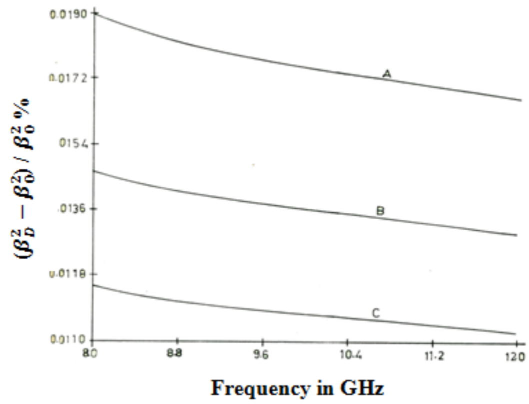

Figure 5
Variation of $(\beta_D^2 - \beta_0^2) / \beta_0^2$ % against frequency with axis of twist at (0, 0.4*b) for different twist lengths L (Curves A, B and C are for L =140, 150 and 160 mm respectively)

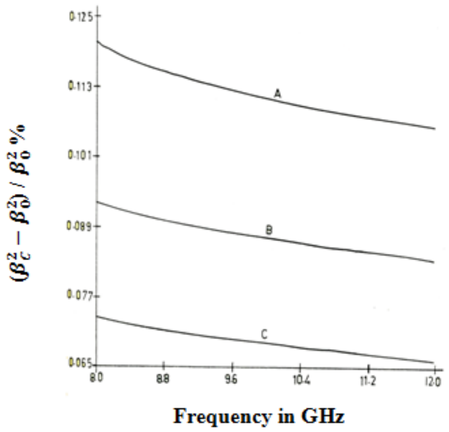

Figure 6
Variation of $(\beta_C^2 - \beta_0^2) / \beta_0^2$ % against frequency with axis of twist at (0, 0.4*a, 0) for different twist lengths L. (Curves A, B and C are for L =140, 150 and 160 mm respectively)

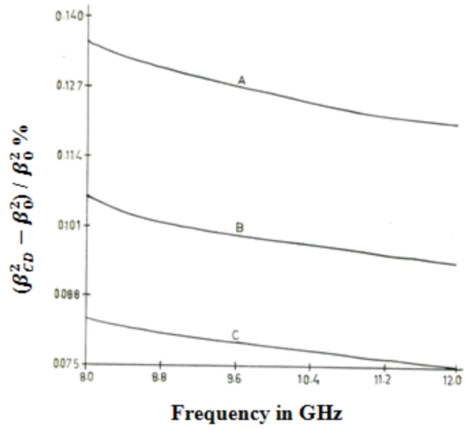

Figure 7
Variation of $(\beta_{CD}^2 - \beta_0^2) / \beta_0^2$ % against frequency with axis of twist at (0, 0.4*a, 0.4*b) for different twist lengths L. (Curves A, B and C are for L =140, 150 and 160 mm respectively)

The calculations are also carried out for the relative departures$(\beta_D^2 - \beta_0^2)/\beta_0^2$, $(\beta_C^2 - \beta_0^2)/\beta_0^2$ and $(\beta_{CD}^2 - \beta_0^2)/\beta_0^2$ at fixed length (angle of twist) and different frequencies. Figures 5, 6 and 7 show the percentage variation of $(\beta_D^2 - \beta_0^2)/\beta_0^2$, $(\beta_C^2 - \beta_0^2)/\beta_0^2$ and $(\beta_{CD}^2 - \beta_0^2)/\beta_0^2$ respectively, for L = 140mm, 150mm and 160mm against frequency ranging from 8 GHz to 12 GHz.

CONCLUSION

From the graphs plotted for to see the effect of shifting axis of twist of the waveguide, we observed the following conclusions.

From figure 2 we conclude that the relative departure of β_D^2 from β_0^2 with respect to β_0^2 increases as we shift the axis of twist along Y-axis from centre of the guide towards the broader wall.

Similarly the relative departure of β_C^2 from β_0^2 with respect to β_0^2 increases as the axis of twist is shifted along X-axis from centre of the guide towards narrower wall, as shown in figure 3. But the magnitude of this departure is greater than the departure for shift in the axis of twist along Y-axis. The same trend is observed in figure 4, where the shift is along both axis to the same fraction of respective side (i.e. along the diagonal).

The relative departure along the diagonal is approximately equal to the addition of relative departure along X-axis and relative departure along Y-axis.
From figures 5, 6 and 7 we conclude that for given twist and given shift of the axis of twist,$(\beta_s^2 - \beta02/\beta02$, decreases as frequency increases. Here $\beta s2$ may be $\beta C2$ or $\beta D2$ or $\beta CD2$.

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