LOW LOSS FLEXIBLE HELIX WAVEGUIDE

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ABSTRACT

We have found the optimum wall structure of small inner diameter flexible helix waveguides which scarcely cause TE_{01} mode conversion despite a bending or elliptical deformations. TE_{01} mode loss is below 0.25dB for a wide millimeter wave range. The attenuation is lower than that of a single corner waveguide which has been generally used at the severe curved segment of waveguide line. Moreover, there is no generation of unwanted higher order TE_{0n} modes. These low loss flexible helix waveguides will be useful for the wide frequency range of the millimetric waveguide communication systems.

Introduction

In order to realize the millimetric waveguide communication systems in Japan, it is necessary for the waveguide line to have many severe curved sections. Though we are able to construct severe curved segments using corner waveguides with sufficient mechanical strength, they cause higher order unwanted TE_{0n} modes which damage the transmission characteristics of the waveguides. [1]

We have found that small inner diameter flexible helix waveguides can be used to construct a curved segment with low loss by achieving a smooth bend of the waveguide axis. For the first time, a measurement method of wall impedance was studied, and the optimum wall structure for low loss flexible helix waveguides which scarcely cause any mode conversion loss even by a curvature and an elliptical deformation was obtained.

Among the good properties are;

1. Attenuation of TE_{01} mode is low compared with the corner waveguide which is used in a curved segment.
2. There is no generation of unwanted higher order TE_{0n} modes.
3. It is possible to use the flexible helix waveguide with complex curvature.

Theoretical Analysis

Wall Impedance

In a circular waveguide, mode coupling between TE_{01} and another mode is caused by curvature or elliptical deformation of the waveguide. In the following section, we call every mode except TE_{0n} (n=1,2, 3, ---) "i" modes.

The structure of the flexible helix waveguide is shown in Figure 1-(a). The wall structure is resembled to the conventional helix waveguides. It is composed of spaced wound helix wire, low loss dielectric layer by fiber reinforced plastics (F.R.P.), electro magnetic shield by metal and reinforcement layer by F.R.P..

These mode couplings are changed by the axial wall impedance of the flexible helix waveguide. The relation between axial wall impedance "Zz" and cut off wave number "χ_i" is given by the following characteristic equation of helix waveguide. [2]

$$j\omega\varepsilon a Z_z - \frac{\chi_i\, J_p(\chi_i)\, J_p'(\chi_i)}{\dfrac{P^2}{\chi_i^2}\dfrac{\gamma_i^2}{k^2} J_p^2(\chi_i) + J_p'^2(\chi_i)} = 0 \qquad (1)$$

$$(\chi_i/a)^2 = k^2+\gamma_i^2 \ , \quad k^2 = \omega^2\mu\varepsilon \qquad (2)$$

where "ω" is the angular frequency, "μ","ε" are the permeability and permittivity of the waveguide interior, "γ_i" is the propagation constant and "$J_p(\chi_i)$" is the Bessel function of the first kind. When the matching layer "t" of the figure has no loss, the propagation constant is purely imaginary, and characteristic equation is solved easily.

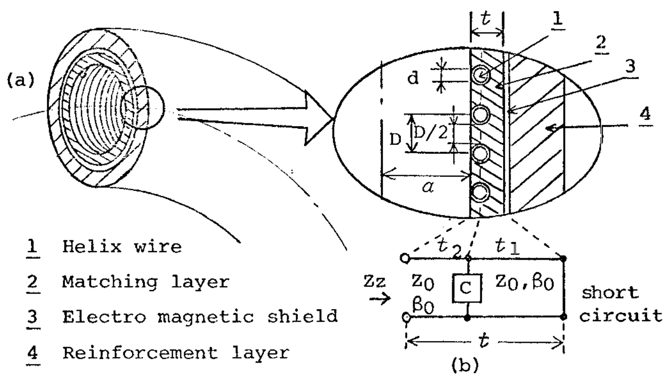

Figure 1. Wall structure of flexible helix waveguide and equivalent circuit of wall impedance.

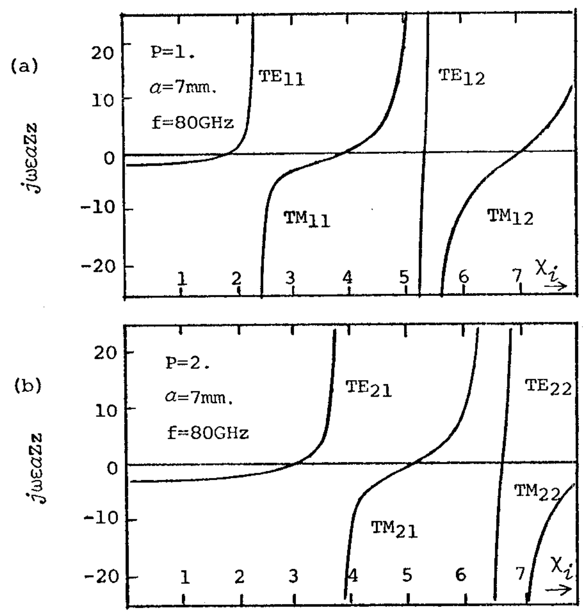

Figure 2. Relation between "$j\omega\varepsilon a Z_z$" versus "χ_i" where P=1. and P=2., waveguide radius "a" is 7mm., and frequency "f" is 80GHz.

Figure 2-(a) shows the relation between "$j\omega\varepsilon a Z_z$" and "χ_i" in the case of the curved helix waveguide. (p =1) Figure 2-(b) shows the relation between "$j\omega\varepsilon a Z_z$" and "χ_i" in the case of elliptical deformed helix waveguide. (p=2)

The axial wall impedance of a helix waveguide is a function of the capacitance of the helix wire and the impedance of the matching layer. The total thickness of matching layer "t" is composed of the ammount of "t_1" and "t_2". The equivalent circuit of the axial wall impedance of the flexible helix waveguide is shown in Figure 1-(b), and the value is calculated by;

$$Z_z = jZ_0 \frac{Z_0\omega C \sin(\beta_0 t_1)\sin(\beta_0 t_2) - \sin\beta_0(t_1+t_2)}{Z_0\omega C \sin(\beta_0 t_1)\cos(\beta_0 t_2) - \cos\beta_0(t_1+t_2)} \qquad (3)$$

with [3]
$$C/\text{square} = \varepsilon_0\varepsilon_s d\left(\frac{d}{D-d} - \frac{\ln 4}{\pi}\right) \qquad (4)$$
$$\beta_0 = \omega\sqrt{\mu\varepsilon}\sqrt{\varepsilon_s - 1}\,, \quad Z_0 = \sqrt{\mu/\varepsilon}\sqrt{\varepsilon_s-1}/\varepsilon_s$$
$$t = t_1 + t_2$$

The value of "$j\omega\varepsilon a Z_z$" is calculated as in Figure 3 where waveguide radius "a" is 7mm., diameter of the helix conductor "d" is 0.12mm., wound pitch of the helix wire "D" is 0.3mm., permittivity of matching layer "ε_s" is 4 and thickness of matching layer "t" as a parameter.

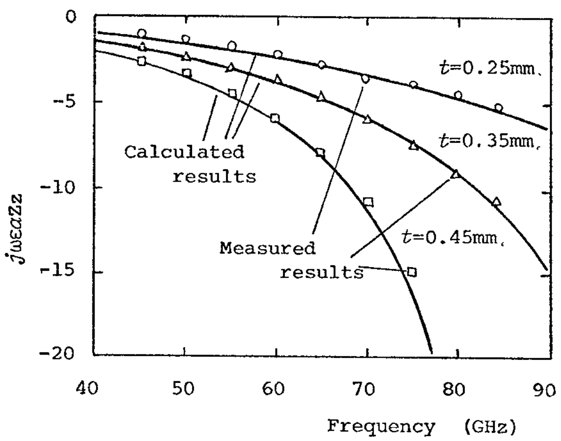

Figure 3. Calculated and measured results of "$j\omega\varepsilon a Z_z$" versus frequency where "a" is 7mm., "d" is 0.12mm., "D" is 0.3mm., "ε_s" is 4 and thickness of matching layer as a parameter.

Mode Conversion Loss

In the case of a uniform bend radius "R" and an elliptical deformation "δ", the mode conversion loss $\Gamma_i(l)$ by these deformation is obtained from equation 5.

$$\Gamma_i(l) = \left[\left(\frac{C_i}{\Delta\beta}\right)^2\{\Delta\alpha l + 1 - \exp(-\Delta\alpha l)\cos(\Delta\beta l)\}\right] \qquad (5)$$ [4]

Where "C_i" is the coupling coefficient between TE_{01} and "i" mode, "l" is the length of curvature section, $\Delta\alpha$ and $\Delta\beta$ are the differences of attenuation and phase constant between TE_{01} and "i" mode respectively. From equation 5, it is clear that mode conversion loss for TE_{01} proportional to $(1/\Delta\beta)^2$. In order to reduce $\Gamma_i(l)$, therefore, $(C_i/\Delta\beta)^2$ and $\Delta\alpha$ must be reduced, and it is generally desirable to make $\Delta\beta$ increase. Typical calculated results of $\Gamma_i(l)$ is shown in Figure 4.

The closer the wall impedance reaches to the metallic wall, the larger the mode coupling between TE_{01} and TM_{11} mode. Conversely, the further the wall impedance separates from the metallic wall, the larger the mode couplings between TE_{01} and elliptical TE_{21} and TM_{21} mode. Therefore, it is necessary to keep the wall impedance at a suitable value as the mode coupling between TE_{01} and "i" mode becomes small.

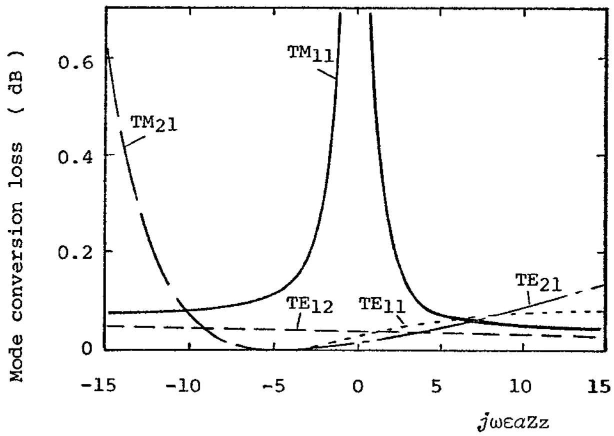

Figure 4. Typical mode conversion loss versus "$j\omega\varepsilon a Z_z$" where "a" is 7mm., "f" is 90GHz, "l" is 1.8m., "R" is 1.0m. and elliptical deformation "δ" is 0.5%.

Total Attenuation

Attenuation of curved flexible helix waveguide is calculated as the sum of $\Gamma_i(l)$ and heat loss. The loss factors of the flexible helix waveguides are composed of heat loss, mode conversion loss caused by the curvature and the elliptical deformation. As these three loss factors are dependent each other, the optimum wall structure must be designed to reduce the sum of these loss factors.

Figure 5 shows the total attenuation for TE_{01} mode versus waveguide radius where curvature radius of one meter and a 90 degree bend. From this figure, optimum waveguide radius is determined. Here we have a design for extremely low loss flexible helix waveguides.

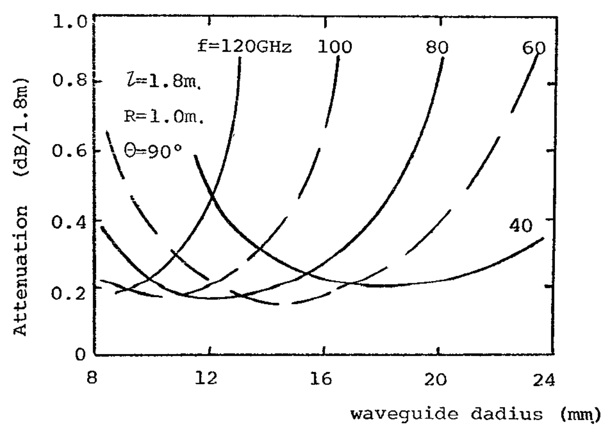

Figure 5. Total attenuation for TE_{01} mode versus waveguide radius where "t" is 0.25mm. and frequency as a parameter.

Experimental Results

Measurement of Axial Wall Impedance

The measurement method of the axial wall impedance of a flexible helix waveguide is shown in Fighre 6. Its principle is an extention of the well known single pulse method. One of "i" modes is superposed with a circular TE_{01} mode, and they are guided into a sample of the flexible helix waveguide. The movable shutter which is remotely controlled from the measuring end is moved along the axis. From the measurement of the beat wavelength which caused by mode conversion-reconversion between TE_{01} and "i" mode, the propagation constant of "i" mode in the flexible helix waveguides were obtained.

Measurement results which are dotted in Figure 3 are in agreement with the calculated results.

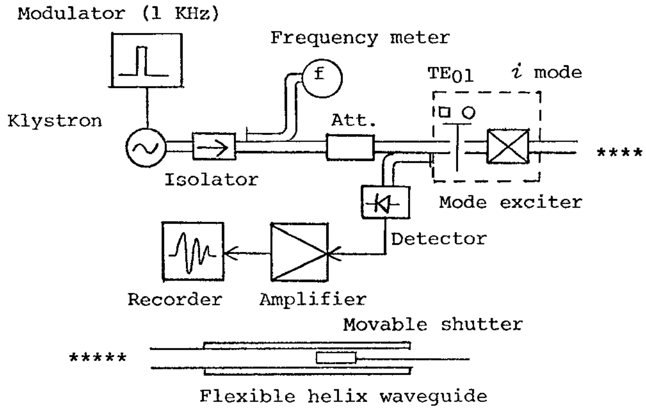

Figure 6. Axial wall impedance measurement setup.

Transmission Characteristics

Figure 7 shows the calculated and measured results of the low loss flexible helix waveguides with the optimum wall structure for different inner diameters.

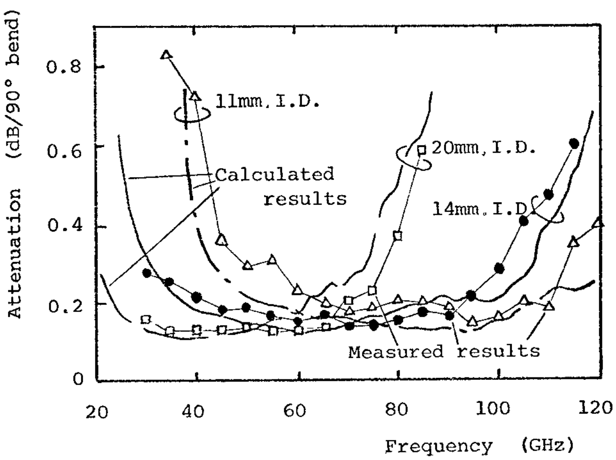

Figure 7. Calculated and measured results of the low loss flexible helix waveguide with the optimum wall structure, inner diameter as a parameter.

Measurement results are in agreement with the calculated value, assuming that the mode coupling coefficient "C_i" is "$0.7C_i$". Mode conversion losses caused by curvature and wlliptical deformation are below 0.25dB.

Table 1 shows the optimum structure and bending condition of the typical low loss flexible helix waveguides.

Waveguide inner diameter (mm.)	20	14	11
Bend radius (m.)	1.0	0.7	0.5
Waveguide length (m.)	1.8	1.3	1.0
Bend angle (deg.)	90		
Thickness of (mm.) matching layer	0.35	0.25	0.25
Attenuation (dB)	less than 0.25dB		
Freq. band (GHz)	(30)-75	35-100	50-110

Table 1. The optimum structure and bending condition of the low loss flexible helix waveguides.

Mechanical Strength

After a 50 times temperature cycling test of -20°C and +60°C, and after a 50 times bend test with one meter radius bend over a 90 degree bend, the electrical and the mechanical characteristics were very stable.

Conclusion

We have achieved the theoretical and experimental investigation on small inner diameter millimetric flexible helix waveguides, and they have realized the low loss transmission characteristics. Measurement results of attenuation and wall impedance are in agreement with the theoretical value. Total attenuation for the TE_{01} mode is below 0.25dB for a wide millimeter wave range. The attenuation is lower than that of a single corner waveguide which has been generally used at the severe curved segment of waveguides. Moreover, there is no generation of unwanted higher order TE_{0n} modes. These low loss flexible helix waveguide will be useful for the millimetric waveguide communication systems.

References

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