United States Patent [19]

Inada

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[45] **Oct. 28, 1975**

[54] **CIRCULAR TE_{0N} MODE FILTER**

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[21] Appl. No.: **452,357**

[30] **Foreign Application Priority Data**

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May 18, 1973	Japan	48-56003
June 18, 1973	Japan	48-68529

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[51] **Int. Cl.²**..... **H01P 3/12;** H01P 3/13; H01P 1/16
[58] **Field of Search**... 333/98 M, 98 R, 21 R, 21 A, 333/31 R, 31 A, 95 R

[56] **References Cited**

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Primary Examiner—James W. Lawrence
Assistant Examiner—Marvin Nussbaum
Attorney, Agent, or Firm—Armstrong, Nikaido & Wegner

[57] **ABSTRACT**

A circular arc polygonal type waveguide provides an excellent TE_{on} mode filter. In a circular waveguide and/or a helix waveguide for transmission of millimeter-wave energy, the electromagnetic field of the fundamental TE_{01} mode converts easily to that of undesirable higher order TE_{on} modes. This conversion is undesirable for the transmission of millimeter-wave energy. According to the invention, the undesirable TE_{on} mode is converted purposely to a higher order TE_{pq} mode by the present mode filter, the profile of which is slightly deformed from as compared to the perfectly accurate circular one, and said converted TE_{pq} mode is absorbed in a conventional helix waveguide. Thus, the fundamental TE_{01} mode is transmitted in a waveguide without distortion.

10 Claims, 28 Drawing Figures

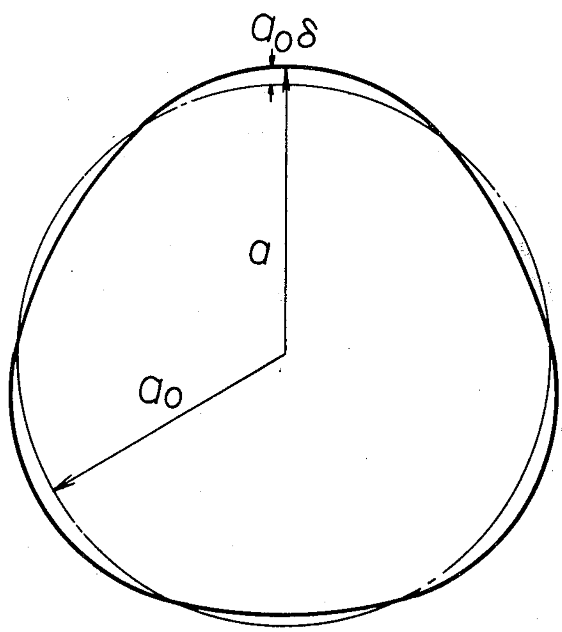


Fig. 1

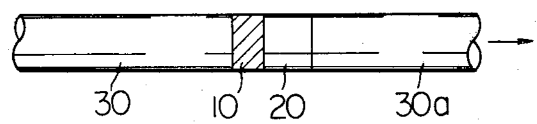


Fig. 2

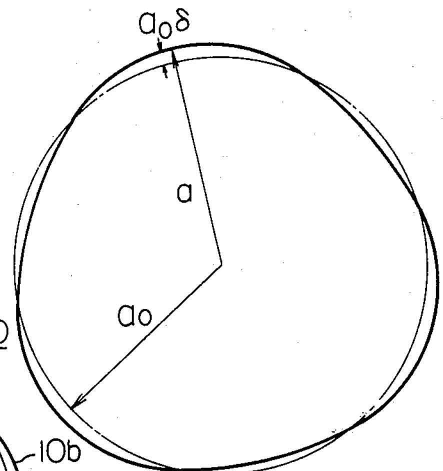


Fig. 3

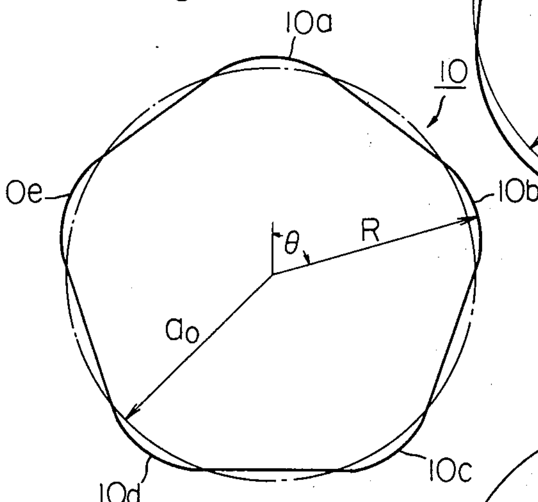
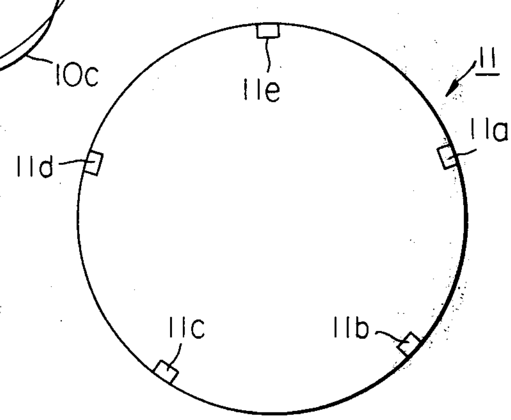


Fig. 4



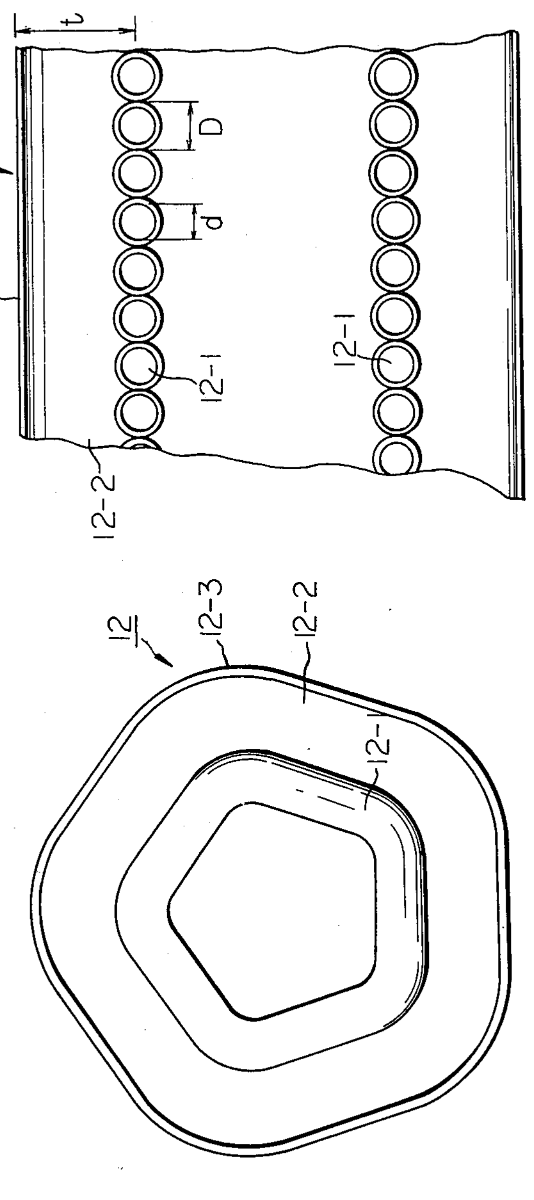


Fig. 5

Fig. 6A

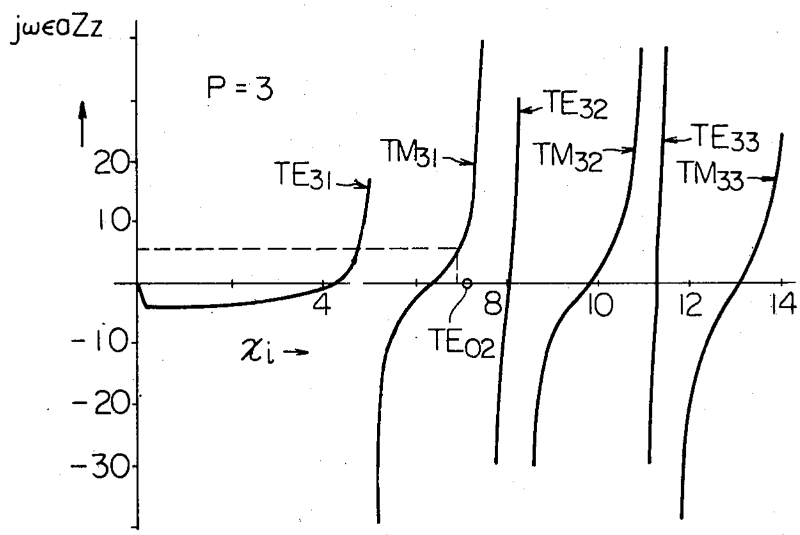

jωεaZz
P = 3
20
10
-10
-20
-30
TE31
TM31
TE32
TM32
TE33
TM33
TE02
4
8
10
12
14
x_i →

Fig 6B

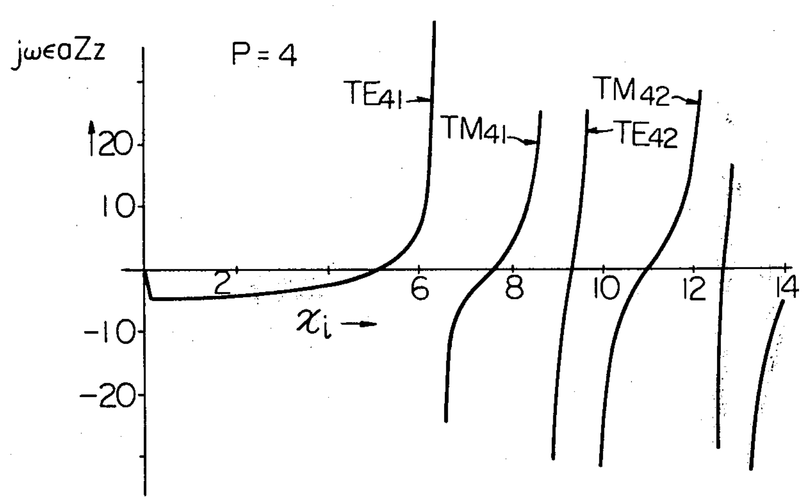

jωεaZz
P = 4
20
10
-10
-20
TE41
TM41
TM42
TE42
2
6
8
10
12
14
x_i →

Fig. 6C

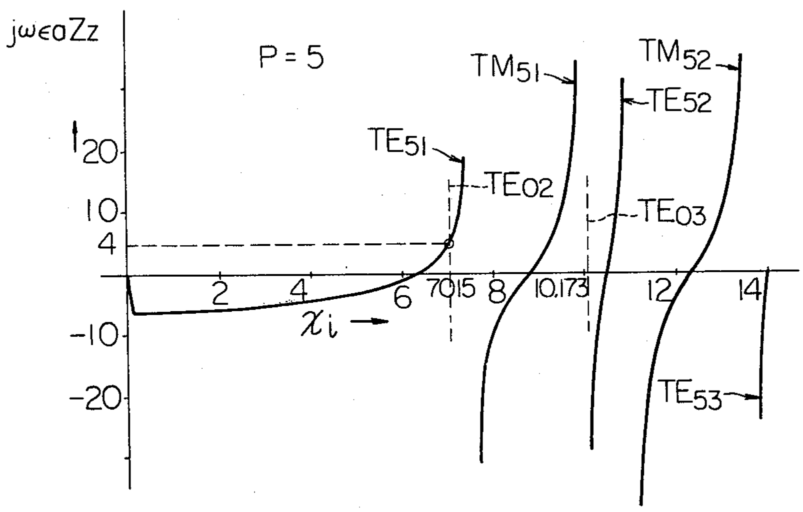

jωεaZz
P = 5
20
10
4
-10
-20
2
4
6
7.015
8
10.173
12
14
x_i
TE51
TE02
TM51
TM52
TE52
TE03
TE53

Fig. 6D

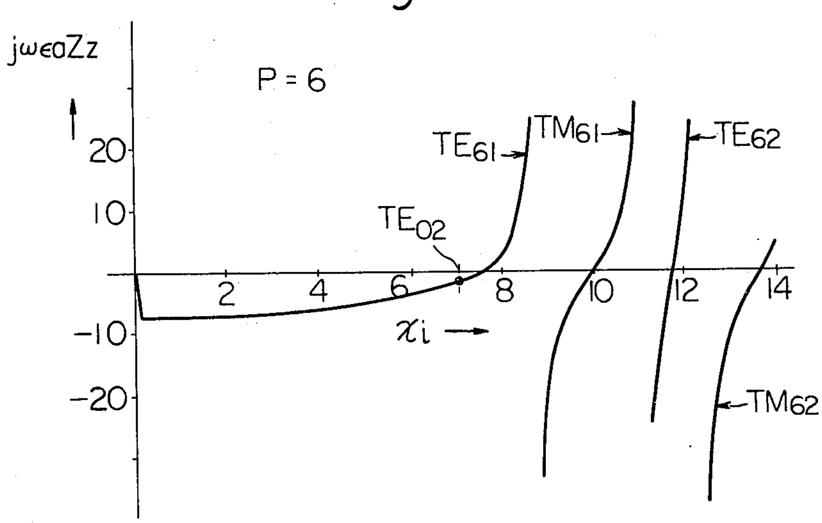

jωεaZz
P = 6
20
10
-10
-20
2
4
6
8
10
12
14
x_i
TE61
TM61
TE62
TE02
TM62

Fig. 6E

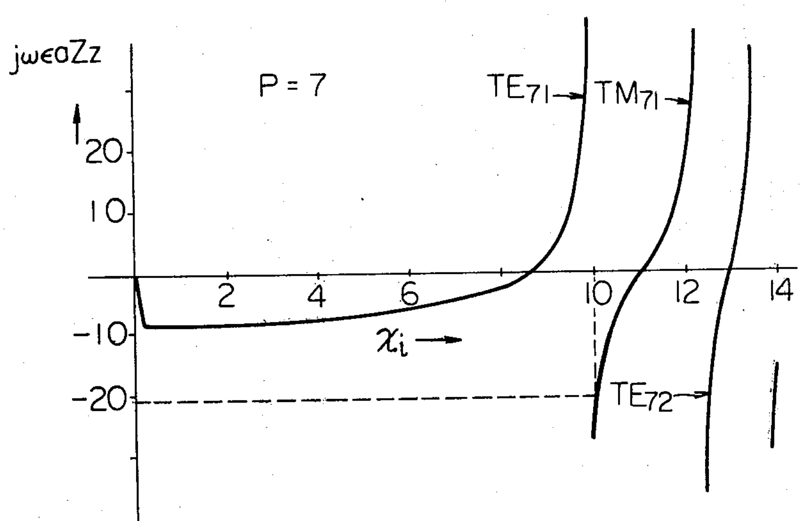

jωεoZz
P = 7
20
10
-10
-20
2
4
6
10
12
14
TE71
TM71
TE72
x_i

Fig. 6F

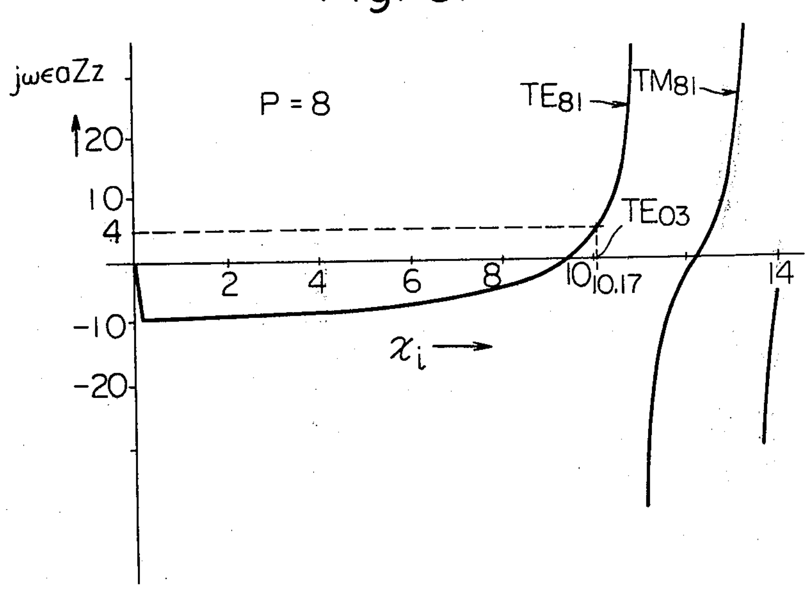

jωεoZz
P = 8
20
10
4
-10
-20
2
4
6
8
10
10.17
14
TE81
TM81
TE03
x_i

Fig. 7A

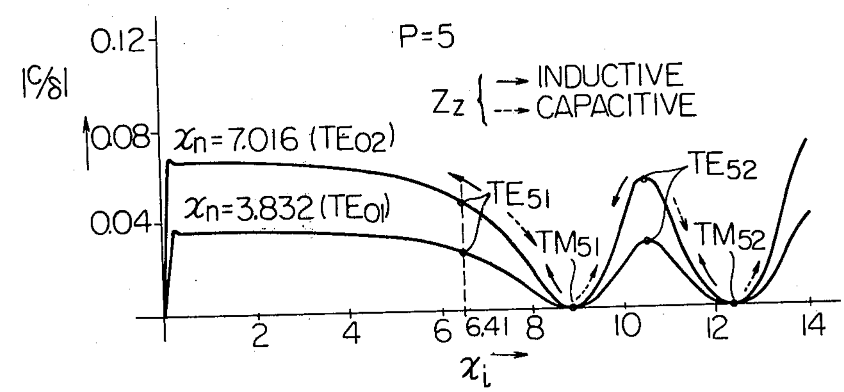

P=5
Zz { → INDUCTIVE
--→ CAPACITIVE
|C/δ|
0.12
0.08
0.04
xn=7.016 (TE02)
xn=3.832 (TE01)
TE51
TM51
TE52
TM52
2
4
6
6.41
8
10
12
14
xi →

Fig. 7B

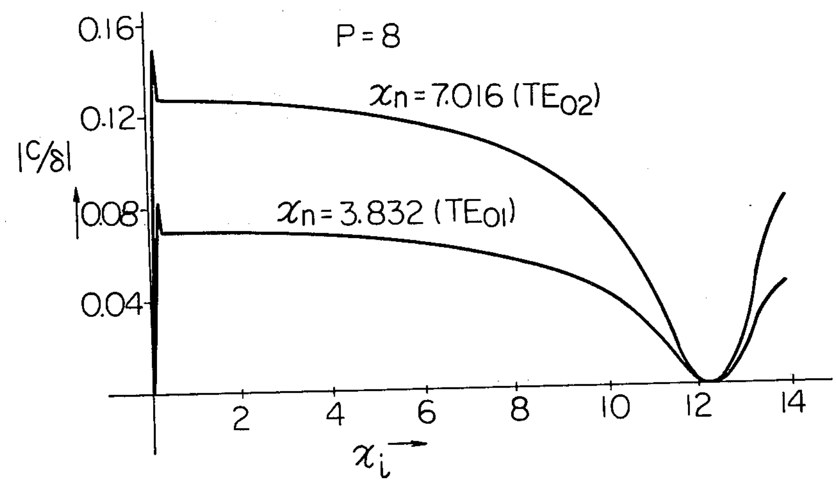

P=8
|C/δ|
0.16
0.12
0.08
0.04
xn=7.016 (TE02)
xn=3.832 (TE01)
2
4
6
8
10
12
14
xi →

Fig. 8

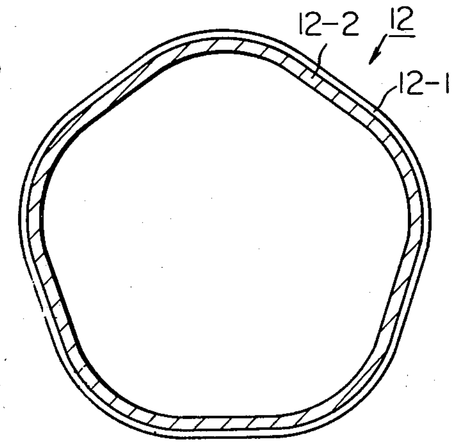

12-2
12
12-1

Fig 9

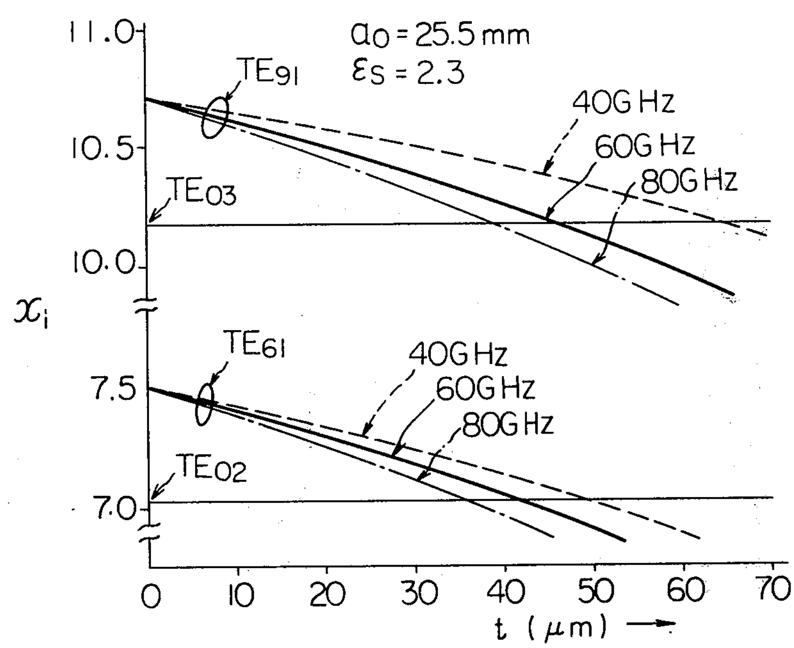

11.0
10.5
10.0
7.5
7.0
x_i
a_0 = 25.5 mm
ε_s = 2.3
TE_{91}
TE_{03}
TE_{61}
TE_{02}
40GHz
60GHz
80GHz
40GHz
60GHz
80GHz
0
10
20
30
40
50
60
70
t (μm) →

Fig. 10

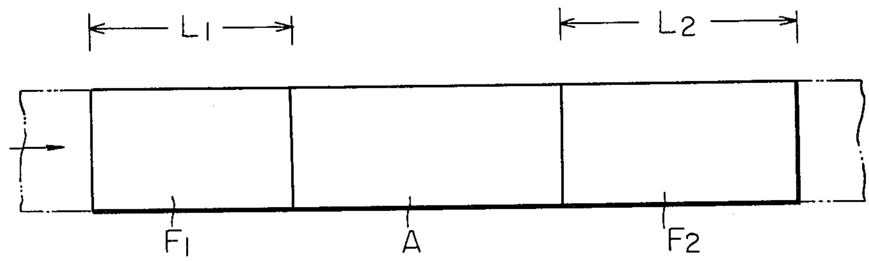


Fig. 11

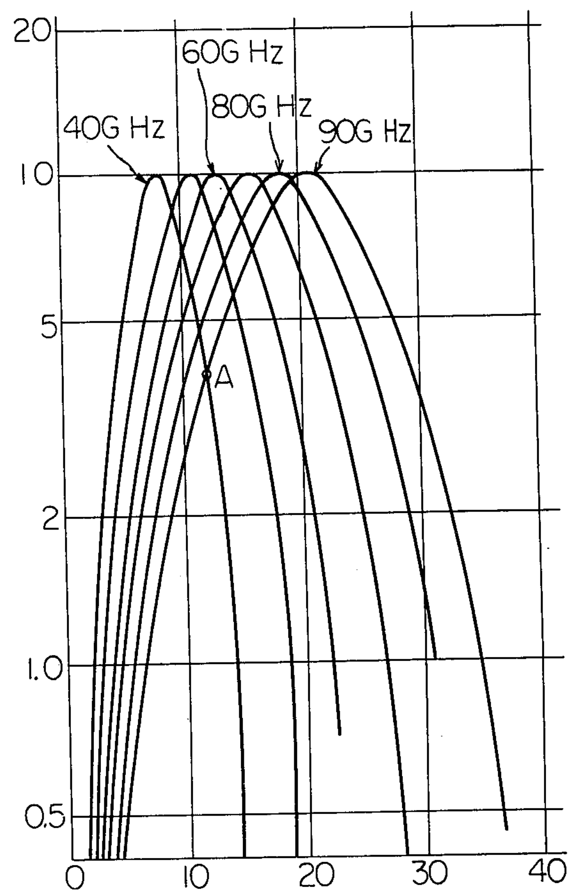


Fig. 12

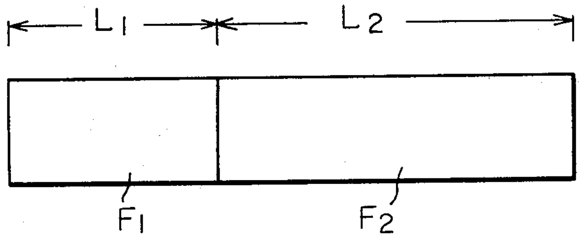


Fig. 13

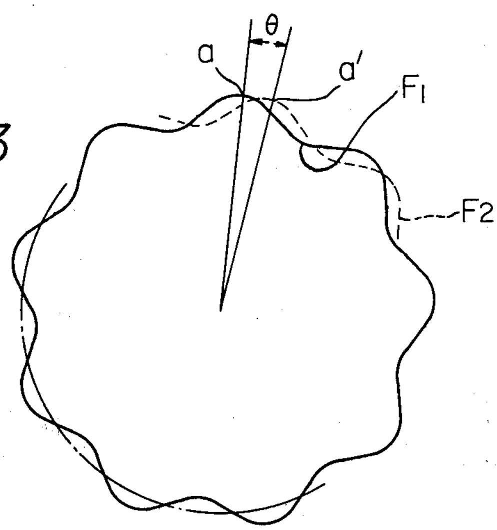


Fig. 14(A)

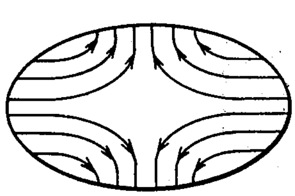


Fig. 14(B)

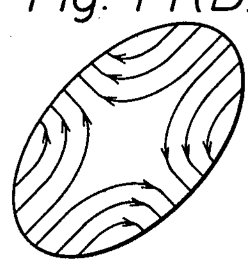


Fig. 15

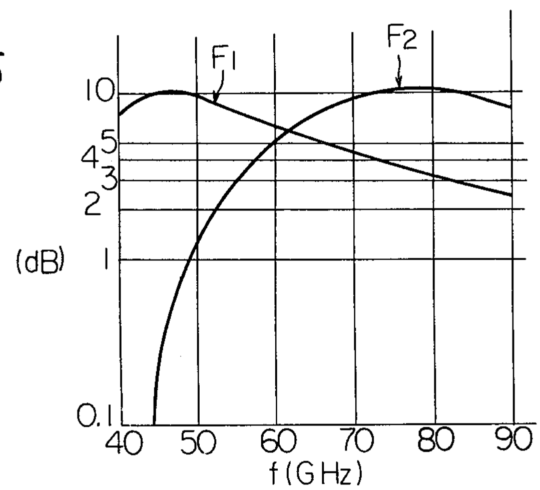

F1
F2
10
5
4
3
2
(dB)
1
0.1
40
50
60
70
80
90
f (GHz)

Fig. 16

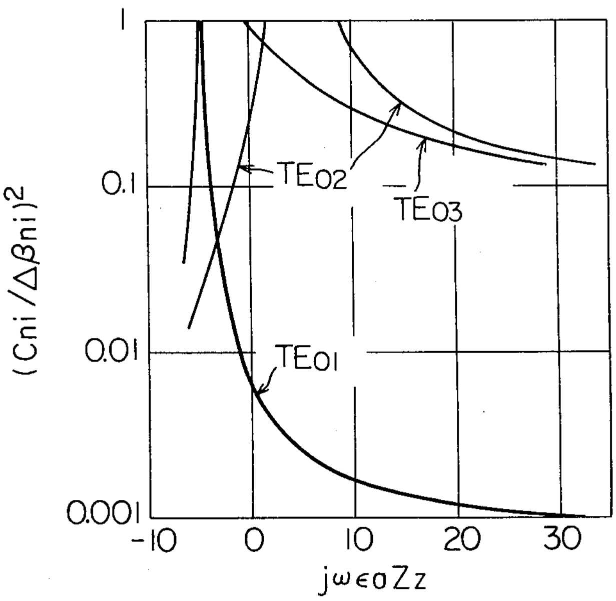

1
0.1
0.01
0.001
$(Cni/\Delta\beta ni)^2$
TE02
TE03
TE01
-10
0
10
20
30
jωεaZz

Fig. 17

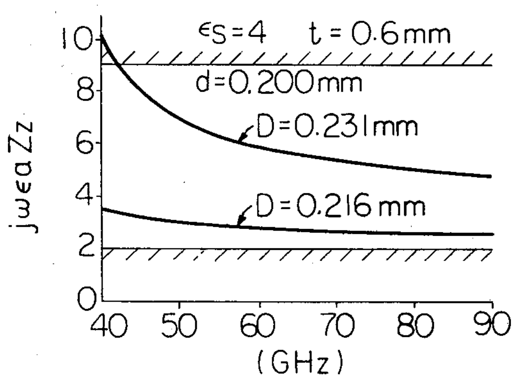

εs=4 t=0.6mm
d=0.200mm
D=0.231mm
D=0.216mm
jωεaZz
10
8
6
4
2
0
40 50 60 70 80 90
(GHz)

Fig. 18

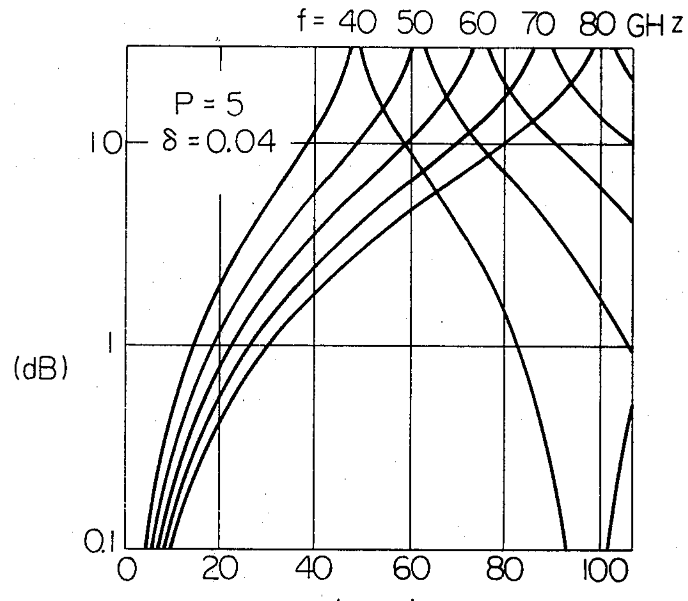
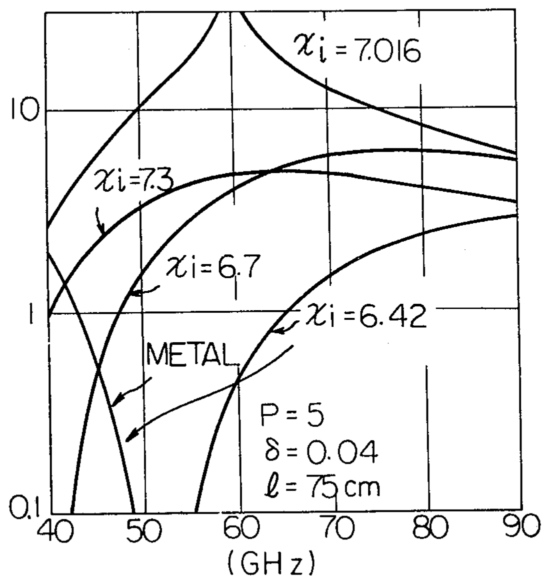
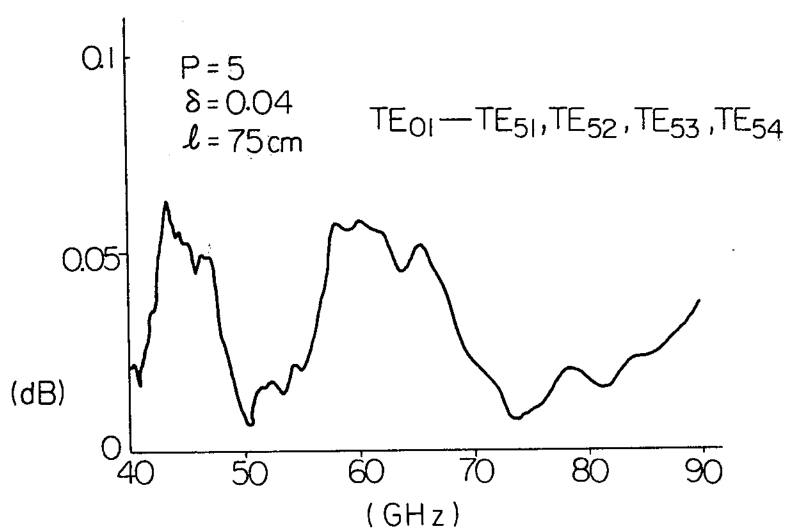

f= 40 50 60 70 80 GHz
P=5
δ=0.04
10
1
0.1
(dB)
0 20 40 60 80 100
(cm)

Fig. 19



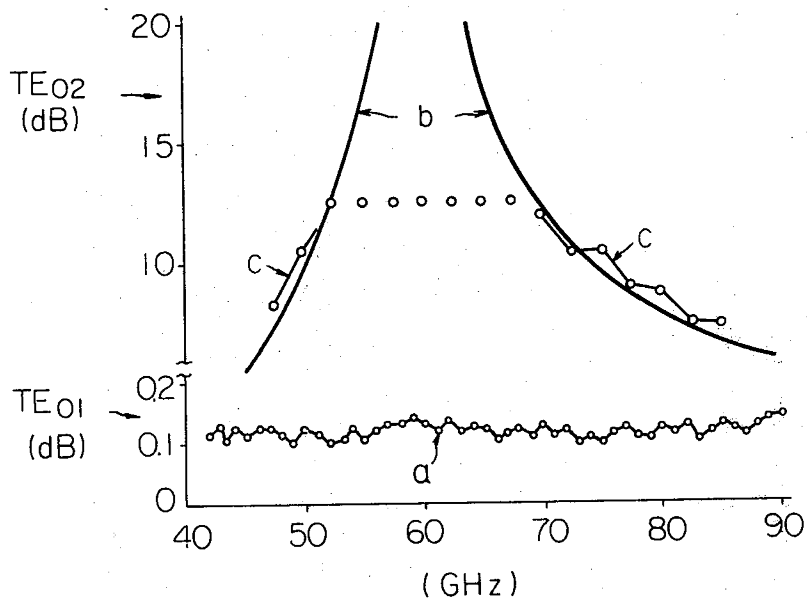
x_i = 7.016
10
x_i=7.3
x_i=6.7
1
x_i =6.42
METAL
(dB)
P = 5
δ = 0.04
ℓ = 75 cm
0.1
40
50
60
70
80
90
(GHz)

Fig. 20



0.1
P = 5
δ = 0.04
ℓ = 75cm
TE01 — TE51, TE52, TE53, TE54
0.05
(dB)
0
40
50
60
70
80
90
(GHz)

Fig 21



CIRCULAR TE_{ON} MODE FILTER

BACKGROUND OF THE INVENTION

The present invention relates to a mode filter or a suppressor for an undesired mode for a circular waveguide for transmission of millimeter-wave energy, which involves very small loss of the TE_{01} mode and very large loss for higher modes.

The TE_{01} mode is generally utilized for the transmission of millimeter-wave energy with millimeter wavelengths (for instance 40 – 100 GHz) since the transmission loss of the TE_{01} mode is very small in that frequency band. In a circular waveguide with a diameter several times larger than the wavelength of the energy to be transmitted many higher modes other than the TE_{01} mode appear, since the TE_{01} mode is not a dominant or principle mode for a waveguide of the above size. A slight deformity of the circular waveguide, a corner waveguide at bend portions and/or an elastic or expansion waveguide are triggers for generation of higher TE_{on} modes. These undesirable higher TE_{on} modes should be absorbed for the TE_{01} mode transmission.

It is very difficult to eliminate unwanted TE_{on} modes since the electromagnetic field of the higher TE_{on} modes are closely similar to that of the fundamental TE_{01} mode.

Various types of TE mode filters which absorb these TE_{on} modes have been proposed. Some of them are a distribution coupling type filter, a long slit type filter, a resonant slit type filter and a phase reverse type filter. But these types of prior mode filters have the following disadvantages: (i) Their structures are very complex, requiring high degree of manufacturing accuracy and thus are very expensive: (ii) It is difficult to obtain large inner diameters such as **51** mm and so, tapered waveguides are needed to mate and these tapers may generate other TE_{on} modes. (iii) TE_{01} mode loss is relatively large. (iv) The structures of the filters are very complicated and different from that of the waveguide line.

SUMMARY OF THE INVENTION

The object of the present invention is to provide a TE_{on} mode filter which overcomes the above-mentioned drawbacks.

Another object of the present invention is to provide a mode filter of simple structure which is similar to the structure of a circular or helix waveguide.

Still another object of the present invention is to provide a mode filter of short length, with a very wide frequency band.

The above and other objects are attained by a mode filter comprising a circular waveguide of a predetermined length, the cross-section of said waveguide being almost circular but being slightly deformed by the existence of a plurality of ridges on the periphery of the waveguide, whereby the mode conversion loss in said waveguide from TE_{on} mode ($n \geqq 2$) to TE_{pm} mode is much greater than that from TE_{01} mode to another modes.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and attendant advantages of the invention will be appreciated as they become better understood by the accompanying drawings wherein;

FIG. **1** shows a section of a whole transmission line using the mode filter according to the present invention;

FIG. **2** and FIG. **3** show two cross sections of mode filter according to the present invention;

FIG. **4** shows a modified cross section of a mode filter according to the present invention;

FIG. **5** shows another embodiment of a structure of a mode filter according to the present invention;

FIGS. **6**A through **6**F show calculated curves of the characteristics of the mode filter of FIG. **5**;

FIGS. **7**A and **7**B also show calculated curves of the characteristics of a mode filter according to the present invention;

FIG. **8** shows another cross section of a mode filter according to the present invention;

FIG. **9** shows a calculated curves for the practical design of the mode filter of FIG. **8**;

FIG. **10** shows a longitudinal cross section of another embodiment of a mode filter system according to the present invention;

FIG. **11** shows calculated curves of the frequency characteristics of a mode filter according to the present invention;

FIG. **12** shows a longitudinal cross section of another mode filter system according to the present invention;

FIG. **13** shows a cross section of a mode filter system of FIG. **12**;

FIG. **14**(A) and FIG. **14**(B) indicate electric fields of a mode filter system similar to that of FIG. **12**;

FIG. **15** shows curves of attenuated characteristics of TE_{02} mode by a mode filter system of FIG. **12**;

FIG. **16** through FIG. **20** show calculated curves for the practical design of a mode filter according to the present invention, and

FIG. **21** shows an experimental measured curve of a mode filter according to the present invention.

PREFERRED EMBODIMENTS

FIG. **1** shows a section of a whole transmission line using the mode filter according to the present invention. In FIG. **1** reference number **10** indicates a mode filter according to the present invention, **20** indicates a helix waveguide, **30** and **30***a* indicate ordinary circular waveguides. The TE_{01} mode propagates in the waveguide system of FIG. **1** in the direction of the arrow, and in the waveguide **30,** some undesirable modes are generated. TE_{02}, TE_{03} and another higher TE_{on} modes are converted in the mode filter **10** into TE_{mn} (where $n \neq 0$) modes which are absorbed in the helix waveguide **20.** Accordingly, pure TE_{01} mode is provided in the succeeding circular waveguide **30**a.

Since the helix waveguide **20** and circular waveguide **30** or **30***a* are well known in the art, the main purpose of the present invention is to provide a mode filter **10** as shown in FIG. **1.**

The first embodiment of the present invention, that is, a mode filter with conductive metal walls, is described below with reference to FIGS. **2, 3** and **4.**

Generally speaking, a circular waveguide with metal walls whose outline is not a perfect circle but is deformed, generates undesirable higher TE_{pm} modes, from the fundamental desirable TE_{01} mode where P 0. For instance, FIG. **2** shows a cross section of a circular waveguide which is almost circular but is deformed by the existence of three mounds or ridges on its inner periphery, and is made of metal with small wall impedance. In that case, an electromagnetic field of TE_{3m} (where $m = 1, 2, 3, \ldots$) is generated. Mathematically, the TE_{on} mode couples with the TE_{pm} mode in the event that there are P mounds or ridges on the inner periphery of a waveguide and the instant radius between the center of the waveguide and the inner surface of the waveguide a is

$a = a_o(1 + \delta \cos p\zeta)$. In that case, the coupling coefficient $C_{[on][pm]}$ between TE_{on} and TE_{pm} is expressed below.

$$C_{[on][pm]} = D_{[on][pm]} \cdot (\beta_{[on]} - \beta_{[pm]})\,\delta \quad (1)$$

where

$$D_{[on][pm]} = \frac{\chi_{[on]}(\chi_{[pm]})^2}{\sqrt{2}\sqrt{(\chi_{[pm]})^2 - P^2}\,\{(\chi_{[pm]} - (\chi_{[on]})^2\}} \cdot \frac{\beta_{[on]} + \beta_{[pm]}}{\sqrt{\beta_{[on]} \cdot \beta_{[pm]}}}$$

β[on]; a phase constant of TE_{on} mode;

β[pm]; a phase constant of TE_{pm} mode;

χ[on]; the n'th radix of the differentiated Bessel function $J'o(\chi) = 0$

χ[pm]; the p'th radix of the differentiated Bessel function $J'p(\chi) = 0$

Supposing that the TE_{on} mode of unit amplitude enters into said deformed waveguide, the amplitude $E_{[on]}(l)$ of the TE_{on} mode at distance l decreases due to the mode conversion and is expressed below.

$$E_{[on]}(l) = 1 - j \sum_m \frac{(C_{[on][pm]})^2}{(\beta_{[on]} - \beta_{[pm]})^2} \cdot$$

$$\times [(\beta_{[on]} - \beta_{[pm]})l + j(e^{jl}\ [(\beta_{[on]} - \beta_{[pm]})l\ ] \ldots (2)$$

Accordingly, on the condition that the desirable values of p and l are chosen, it is possible that $E_{[on]}(l)$ (n 2) is considerably smaller than $E_{[01]}(l)$, and the attenuation of TE_{02} and/or TE_{03} is extremely greater than that of TE_{01}.

The mode filter according to the present invention is based on the above principle, the cross-section of the mode filter being almost circular but slightly deformed, and the length of the mode filter being optional.

The explanation of a mode filter for the TE_{02} mode using metal wall circular waveguide is presented below.

The mode conversion loss for the TE_{on} mode is obtained from the formula (3) as follows;

$$\chi_{[on]}(l) = \sum_m \frac{(C_{[on][pm]})^2}{(\beta_{[on]} - \beta_{[pm]})^2} \cdot \{1 - \cos(\beta_{[on]} - \beta_{[pm]})l\}\ \text{(nepa)} \quad (3)$$

Accordingly, in order to obtain an effective TE_{02} mode filter,

$$\{1 - \cos(\beta_{[02]} - \beta_{[pm]}\, l\} \quad (4)$$

$$\frac{(C_{[02][pm]})^2}{(\beta_{[02]} - \beta_{[pm]})^2} \quad (5)$$

should be as large as possible, and

$$\{1 - \cos(\beta_{[13\ 01]} - \beta_{[pm]})l\} \quad (6)$$

and

$$\frac{(C_{[01][pm]})^2}{(\beta_{[01]} - \beta_{[pm]})^2} \quad (7)$$

should be are, small as possible.

optimum value of p, which represents the number of mounds or ridges on the periphery of a waveguide, is determined to satisfy the above conditions. The maximum values of formulas (4) and (6) are, mathematically 2.

Further, values of $\beta_{[02]}$ and $\beta_{[pm]}$ are expressed as follows.

$$\left.\begin{aligned} \beta_{[02]} &= \sqrt{\left(\frac{2\pi}{\lambda}\right)^2 - \left(\frac{\lambda_{[02]}}{a_o}\right)^2} \\ \beta_{[pm]} &= \sqrt{\left(\frac{2\pi}{\lambda}\right)^2 - \left(\frac{\lambda_{[pm]}}{a_o}\right)^2} \end{aligned}\right\} \quad (8)$$

where a_o indicates the radius of a waveguide, and λ the wavelength of the transmitted wave. Accordingly, in order to obtain the maximum value of formula (5), the value $(\beta_{[02]} - \beta_{[pm]})$ should be as small as possible. That is to say, the difference between $\chi_{[02]}$ and $\chi_{[pm]}$ should be as small as possible. The reason for this and the relationship between χ and β will be apparent from formula (10) and its explanation. The values of $\chi_{[mn]}$ for TE modes are the same as radix of the differentiated bessel function, and are shown in the following Table 1.

Table 1

Mode	χ(mn)	Mode	χ(mn)
TE 1-1	1.841184	TE 3-2	8.015237
TE 2-1	3.054237	TE 1-3	8.536316
TE 0-1	3.831706	TE 7-1	8.577836
TE 3-1	4.201189	TE 4-2	9.282396
TE 4-1	5.317553	TE 8-1	9.647422
TE 1-2	5.331443	TE 2-3	9.969468
TE 5-1	6.415616	TE 0-3	10.173468
TE 2-2	6.706133	TE 5-2	10.519861
TE 0-2	7.015587	TE 9-1	10.711434
TE 6-1	7.501266	TE 3-3	11.345924
TE 1-4	11.706005	TE11-1	12.826491
TE 6-2	11.734936	TE 7-2	12.932386
TE10-1	11.770877	TE 2-4	13.170371
TE 4-3	12.681908		

Further, the calculated value of

$$\frac{(C[on][pm])^2}{(\beta[on] - \beta[pm])^2}$$

is shown in Table 2, where the frequency f is 80 GHz (wavelength λ is 3.75 mm), the radius of a waveguide a_o is 25.5 mm and δ, which is the deformation rate, is 0.1.

Table 2

p	TE_{pm} \ TE_{on}	TE_{01}	TE_{02}	TE_{03}
	TE_{21}	0.167	0.010	0.004
2	TE_{22}	0.016	2.694	0.030
	TE_{23}	0.004	0.041	12.690
	TE_{24}	0.002	0.011	0.075
	TE_{31}	1.202	0.036	0.010
3	TE_{32}	0.009	0.326	0.100
	TE_{33}	0.003	0.022	0.447
	TE_{41}	0.104	0.146	0.024
4	TE_{42}	0.006	0.080	0.651
	TE_{43}	0.002	0.014	0.112
	TE_{51}	0.044	1.589	0.056
5	TE_{52}	0.005	0.037	5.756
	TE_{53}	0.002	0.010	0.055
	TE_{61}	0.027	3.093	0.145

Table 2-Continued

p	TE_{pm} TE_{on}	TE_{01}	TE_{02}	TE_{03}
6				
	TE_{62}	0.004	0.023	0.330
	TE_{71}	0.019	0.365	0.509
7				
	TE_{72}	0.003	0.017	0.121
	TE_{81}	0.014	0.153	5.664
8				
	TE_{82}	0.003	0.013	0.066
9	TE_{91}	0.012	0.090	6.411
10	TE_{101}	0.010	0.062	0.840
11	TE_{111}	0.001	0.046	0.346

The attenuation of TE_{01}, TE_{02}, TE_{03} . . . modes is calculated from the above formula (3), using Tables 1 and 2. When $p = 2$, the attenuation of the TE_{02} mode can be more than ten times as large as that of the TE_{01} mode, and the attenuation of the TE_{03} mode can be more than sixty times as large as that of the TE_{01} mode, therefore, a mode filter with two ridges on the periphery of the waveguide ($p = 2$) is very beneficial. When $p = 3$ or $p = 4$, the attenuations of TE_{01}, TE_{02} and TE_{03} are almost the same, and a mode filter of $p = 3$ is not effective. When $p = 5$, the attenuations of TE_{02} and TE_{03} modes are more than 30 and 110 times, respectively, as large as that of the TE_{01} mode, and a mode filter of $p = 5$ is more effective than that of $p = 2$. When $p = 6$, the attenuations of the TE_{02} and TE_{03} modes are more than 100 and 15 times, respectively, as large as that of the TE_{01} mode. When p is greater than seven, the difference of attenuation between the TE_{01} mode and higher TE_{on} modes is considerably large and a mode filter with p greater than seven is considered effective.

On the other hand, the length l of deformed mode filter is determined to obtain the maximum value of

$$1 - \cos\{(\beta_{[on]} - \beta_{[pm]})l\}$$

Since the mathematical maximum value of the above formula is **2**, the length l should be determined to ensure that the value of that formula is **2**.

For instance, supposing that $p = 5$, $a = 25.5$ mm, and $f = 80$ GHz, then

$$\beta[02] - \beta[51] = \sqrt{(\frac{2\pi}{3.75})^2 - (\frac{7.0156}{25.5})^2} - \sqrt{(\frac{2\pi}{3.75})^2 - (\frac{6.4156}{25.5})^2} = -0.00374/\text{mm}.$$

Accordingly, the length l for the largest attenuation of the TE_{02} mode is

$$l = 839 \text{ mm}$$

Said length l is obtained by the formula

$$\cos(\beta_{[02]} - \beta_{[51]})\, l = -1$$

FIG. **3** shows the cross section of a mode filter **10** for the TE_{02} mode according to the presnet invention. Said mode filter **10** has five ridges **10***a* – **10***e* ($p = 5$ and $\delta = 0.05$) and with a length of 840 mm the attenuation for the TE_{02} mode in 80 GHz is thirty times as large as that for the fundamental TE_{01} mode.

A post of conductive material can be used instead of a mound or a ridge on the periphery of a mode filter. FIG. **4** shows a cross-section of a post type mode filter **11**, in which there is a plurality of posts **11***a* – **11***e* inside the wall. The function of these posts **11***a* – **11***e* is the same as the ridges **10***a* – 10*e* of FIG. **3**.

The second embodiment of the present mode filter **10** (FIG. **1**) is described below. The second mode filter is substantially a helix waveguide, whose cross section is almost circular but is deformed by the existence of some mounds or ridges on its inner periphery.

FIG. **5** shows a structure of a helix type mode filter **12** which has an insulated helix wire **12-1**, a dielectric layer **12-2** of thickness t covering the outer portion of the wire **12-1** and a shield layer **12-3** shielding the outer portion of the dielectric layer **12-2**. The diameters of the conductor and the insulator of the wire **12-1**, are *d* and D, respectively. The important feature of the second embodiment of the present mode filter is that the almost circular inner surface of the wire **12-1** is deformed by the existence of some mounds or ridges. Therefore, the cross-section of the inner surface of the present helix type mode filter is similar to that of FIG. **2** or FIG. **3**. The wall impedance of the helix type mode filter is designed so that the TE_{on} ($n \geqq 2$) mode is converted perfectly to the TE_{pm} mode but the TE_{01} mode propagates without conversion.

Generally, the characteristic formula or equation for the particular mode in a helix waveguide or a helix mode filter is the one shown below.

$$j\omega\epsilon a Zz - \frac{\chi_i J_p(\chi_i) J'_p(\chi_i)}{\frac{p^2}{\chi_i^2} \cdot \frac{\gamma_i^2}{k^2} J_p^2(\chi_i) + J'^2_p(\chi_i)} = 0 \qquad (9)$$

$$(X_i/a)^2 = k^2 + \gamma_i^2,\ k^2 = \omega^2\mu\epsilon \qquad (10)$$

wherein ϵ and μ represents space dielectric constant and magnetic space permeability, respectively, γi is a propagation constant for the *i* mode and is expressed as $\gamma i = \alpha i + j\beta i$, Zz is a wall impedance, a is an inner radius of the helix waveguide, p is a number of ridges, χi is constant α is attenuation constant and β is phase constant.

From equations (9) and (10), when ω, ϵ, a and Zz are determined, the value of χi which satisfies the above equations can be calculated easily. FIGS. **6A** through **6F** show the curves of the relationship between χi and $j\omega\epsilon a Zz$, where the radius a of a helix waveguide is 25.5 mm, and wavelength λ is 3.75 mm. Thevalue of χi obtained from these figures The value a value of the propagation constant γi through said equation (10) since a and k are constant in a particular case. In order to obtain an excellent mode filter, the difference of phase constant β between the undesirable mode TE_{on} and the TE_{qm} mode to be generated, sould be much smaller than the difference of the phase constant between the TE_{pm} mode and the TE_{01} mode. The reason for this will be explained in detail later.

Since propagation constant γi is equal to $\alpha i + j\beta i$ and if loss factor αi is very small, the analysis of βi can be substituted by the analysis of γi. Further, γi and χi are connected by the equation (10), where values of a and k are constant in each particular case. Accordingly, the difference of βi's depends upon the difference of χi's. That is to say, it is satisfactory that the difference of χi between the undesirable mode TE_{on} and the TE_{pq} mode to be generated is much smaller than the difference of χi between the TE_pq mode and the TE_{01} mode.

Some typical cases are presented with reference to FIGS. 6A through 6F.

a. $p = 3$ in FIG. 6A.

When the wall impedance Zz is designed so that $j\omega\epsilon a$-Zz is 6 (Zz is capacitive), the value of χi of the TM_{31} mode is 7.0 from FIG. 6A. And the value χi of the TE_{02} mode is 7.0 from Table 1. A helix waveguide with 3 ridges can be a TE_{02} mode filter.

b. $p = 4$ in FIG. 6B.

The TE_{03} mode ($\chi i = 10.17$ in Table 1) and TE_{42} mode can degenerate. Thus, a helix waveguide with 4 ridges can be the TE_{03} mode filter. That is to say, the loss of the TE_{03} mode is much larger than that of the TE_{01} mode.

c. $p = 5$ in FIG. 6C.

When the wall impedance Zz is designed so that $j\omega\epsilon a$Zz is 4 (Zz is capacitive), the value of χi of the TE_{51} mode is the same as that of the TE_{02} mode and is equal to 7.0. Since the value of χi of the TE_{01} mode (= 3.8) is sufficiently different from the value of χi of TE_{51} mode (= 7.0) the mode conversion loss of the TE_{01} mode is very small. A mode filter with five ridges is the most preferable for a TE_{02} mode filter.

d. $p = 6$ in FIG. 6D.

Though the TE_{03} mode and the TM_{61} mode degenerate with $j\omega\epsilon a$Zz being equal to 1, the TE_{03} mode does not couple with the TM_{61} mode in the case that the wall impedance Zz is very small such as, one. Therefore, a TE_{03} mode filter with six ridges is not practical.

e. $p = 7$ in FIGS. 6E.

When the wall impedance Zz is large so that the value of $j\omega\epsilon a$Zz is sufficiently inductive negative, the value of χi of the TM_{71} mode can be equal to that of the TE_{03} mode and is equal to 10.17. Therefore, a helix waveguide with seven ridges may be a TE_{03} mode filter.

f. $p = 8$ in FIG. 6F

When the value of $j\omega\epsilon a$Zz is 4 (Zz is capacitive), the value of χi of the TE_{81} mode is equal to that of TE_{03} mode, and is equal to 10.17. Therefore, the TE_{03} mode is completely converted to the TE_{81} mode. A mode filter with eight ridges is the most preferable TE_{03} mode filter.

The mathematical analysis of the helix type mode filter according to the present invention is given below.

First, the amplitude of coupling coefficient Cni between the TE_{on} mode and the i mode is illustrated by the following formula.

$$Cni = \frac{\sqrt{\pi}}{2} N_i \sqrt{\frac{\gamma_i}{\gamma_n}} \frac{\chi_n \cdot \chi_i^2}{\omega \sqrt{\mu\epsilon a^2}} p J_p(\chi_i) Y_i \delta \quad (11)$$

where

$$Y_i = \frac{J_p(\chi_i)}{\chi_i J_p'(\chi_i)}$$

$$N_i = \frac{\sqrt{2}}{\sqrt{\pi} J_p(\chi_i)} \left[\frac{p^2 \gamma_i^2}{\omega^2 \epsilon\mu} (p^2 - \chi_i^2) Y_i^2 + \frac{1}{Y_i^2} + \chi_i^2 \left(1 - \frac{p^2}{\omega^2 \epsilon\mu a^2}\right) + 2 \left(\frac{1}{Y_i^2} - p^2 Y_i\right) \right]^{-1/2}$$

γn: represents the propagation constant of TE_{on} mode;

δ: the deformation rate

FIGS. 7A and 7B shows two examples of the solution of formula (11) and are curves of Cni/δ of the i mode (vertical axis) versus χi. Cni is represented as |Cni/δ| along the vertical axis since the value of δ is constant in this particular case. FIG. 7A shows the value of |Cni/δ| between the TE_{01} or TE_{02} mode, and the i mode when $p = 5$, and FIG. 7B shows the value of |Cni/δ| between TE_{01} or TE_{02}, and the i mode when $p = 8$. Further, in FIGS. 7A and 7B, the values of radius a and wavelength λ are 25.5 mm and 3.75 mm, respectively. In FIG. 6C, when the wall impedance Zz changes from zero to the inductive direction or capacitive direction (in this figure the area above the horizontal axis is capacitive and the area under the horizontal axis is inductive), the value of χi changes to the right or left direction. Therefore, the coupling coefficient Cni changes in the direction of the arrow (inductive or capacitive) in FIG. 7A, depending upon changes of the value of χi. For instance, when the wall impedance Zz changes from zero (metal wall) to capacitive impedance in FIG. 6C, the value of χi of the TE_{51} mode approaches close to the value of χi of the TE_{02} mode (which is 7.016). Then, as in FIG. 7A, the coupling coefficients between TE_{02} and TE_{51} becomes small.

The amplitude $a_i(z)$ of the i mode and the amplitude $a_{01}(z)$ of TE_{01} mode in this mode filter is obtained from the following equations.

$$a_i(Z) = \frac{1}{2p}[2Cnia_{on}(O) + (p + \Delta\beta ni)a_i(O)]e^{-\gamma_1 z} - \frac{1}{2p}[2Cnia_{on}(O) - (p - \Delta\beta ni)a_i(O)]e^{-\gamma_2 z} \quad (12)$$

$$a_{on}(Z) = \frac{1}{2p}[(p - \Delta\beta ni)a_{on}(O) + 2Cnia_i(O)]e^{-\gamma_1 z} + \frac{1}{2p}[(p + \Delta\beta ni)a_{on}(O) - 2Cnia_i(O)]e^{-\gamma_2 z} \quad (13)$$

with

$\gamma_2 = j(\beta \pm p/2)$, $\beta = (\beta on + \beta i)/2$, $\Delta\beta ni = \beta on - \beta i$, $p = \sqrt{(\Delta\beta ni^2 + \Delta Cni^2)}$

where $a_{01}(\mathbf{0})$ and $a_i(\mathbf{0})$ are the amplitudes of a_{01} and a_i with Z = zero. In the case of $\Delta\beta oi >> Coi^2$, from (12) with $a_i(0) = 0$, we get the next equation.

$$\left|\frac{a_{on}(Z)}{a_{on}(O)}\right| = 1 - \left(\frac{Cni}{\Delta\beta ni}\right)^2 \sin^2 \frac{\Delta\beta ni}{2} Z = 1 - \left(\frac{Cni}{\Delta\beta ni}\right)^2 (1 - \cos\Delta\beta ni Z) \quad (14)$$

When the deviation from roundness is independent of distance along the waveguide, mode conversion of the TE_{on} mode is represented by a periodic function including the term (1 - cos ΔβniL) and the maximum of α(L) becomes $2\,\Sigma(Cni/\Delta\beta ni)^2$. When Zz is determined, we can get the mode conversion losses of the TE_{on} mode by calculating the relation between $(Cni/\Delta\beta ni)^2$ and Zz. In order to increase $(Cni/\Delta\beta ni)^2$, Δβni must be kept as small as possible. In other words, the propagation constants of the TE_{on} mode and the i mode should be kept as close as possible. In this case, Δβni >> Cni is not satisfied, so equations from (12) to 15) are already not correct. When Δβni = 0, $E_{on(z)}$ becomes as follows.

$$E_{on}(Z) = e^{-j\beta_{on} z} \cos C_{ni} Z \qquad (15)$$

When Zz is set to satisfy Cni Z $= \pi/2$, the TE_{on} mode is completely transformed into some other i mode. This i mode is absorbed easily in a conventional helix waveguide and consequently TE_{on} mode attenuations become very large.

The following describes the practical design of a helix type mode filter with five ridges ($p = 5$) according to the present invention. In the design of a helix type mode filter, (a) the height of ridges (= the value of δ), (b) the length of mode filter, and (c) the structure of the wall, should be decided. Concerning the value of δ, the larger it is, the larger the coupling coefficient Cni between TE_{01} and TE_{51} becomes. That is to say, when the value of δ is large, the loss of the fundamental mode TE_{01} itself is large, thus, the upper limit of δ is determined by the permissible attenuation of the TE_{01} mode. Concerning the length l of the mode filter, the optimum length l is $l = \pi/2 \,.\, 1/\mathrm{Cni}$. When the coupling coefficient Cni is large, the length l can be short. However a large coupling coefficient Cni requires a large value of δ, and results in an increased attenuation of the TE_{01} mode.

Of course, a mode filter with l less than $\pi/2 \,.\, 1/\mathrm{Cni}$ is possible, in which case, attenuation of TE_{02} mode is reduced a little relative to the short length l.

A typical numerical example of a helix type mode filter shown in FIG. **5**, where the center frequency is 80GHz, the radius of a waveguide is Ao = **25.5** mm, the tolerable attenuation of the TE_{01} mode is 0.005 nepa, is shown below.

$\delta = 0.040$
$l = 1000$ mm
$t = 0.5$ mm
$d = 0.18$ mm
D = 0.20 mm
$\epsilon s = 4$ (ϵs = (ϵs is the relative dielectric constant of dielectric layer **12–2** in FIG. **5**)

If the frequency band of the mode filter is 40 – 80 GHz the length l should be 750 mm. With the above numerical embodiment, the value of $j\omega\epsilon a Zz$ holds about **5** in the whole frequency band.

Some modifications of a helix type mode filter are possible to make by those skilled in the art. For instance, a plurality of conductive paste disposed on the inner surface of a helix waveguide function in the same manner as mounds or ridges of the mode filter of FIG. **5**. The helix type mode filter is, of course, used in the waveguide system shown in FIG. **1**, together with an ordinary circular metal wall waveguide and an ordinary helix waveguide.

The third embodiment of the present invention concerns a dielectric lined type mode filter, the cross section of which is shown in FIG. **8**. A dielectric lined type mode filter **12** comprises the deformed metal wall **12-1** and the dielectric layer **12-2** lined on the inner surface of the metal wall **12-1**. The structure of dielectric lined type mode filter is the same as that of the metal wall type mode filter in FIGS. **2** and **3** except that the dielectric lined type mode filter has the dielectric layer **12-2**.

The deviation of the phase constants $\Delta\beta_{[pm]}$ and $\Delta\beta_{[on]}$ for the TE_{pm} mode and the TE_{on} mode, by the addition of the dielectric layer **12-2** to the metal wall are shown below.

$$\Delta\beta_{[pm]} = \frac{p^2}{\chi^2_{[pm]} - p^2} \cdot \frac{\epsilon_s - 1}{\epsilon} \cdot \frac{t}{a_o} \cdot \beta_{[pm]}$$

$$\Delta\beta_{[on]} = \frac{\chi^2_{[on]}}{3} (\epsilon_s - 1) \left(\frac{t}{a_o}\right)^3 \beta_{[on]}$$

where t is the thickness of the dielectric layer **12-2.** Generally, (t/a_o) is sufficiently small, and $\Delta\beta_{[on]}$ is much smaller than $\Delta\beta_{[pm]}$. Therefore, an appropriate value of (t/a_o) provides the extremely small value of $(\beta_{[on]} - \beta_{[pm]})$, and the larger value of formula (5) (where $n = 2$) is obtained.

FIG. **9** shows the calculated curves of the relationship between the thickness t of the dielectric layer (horizontal axis) and the value of χ_i (vertical axis) for the TE_{61} mode and TE_{91} mode where $a_o = 25.5$ mm and $\epsilon_s = 2.3$. It should be noted from FIG. **7** that the appropriate thickness of the dielectric layer provides the same phase constant of the TE_{61} mode as that of the TE_{02} mode, and the same phase constant of the TE_{91} mode as that of the TE_{03} mode.

The fourth embodiment of the present mode filter is described below.

FIG. **10** shows a part of a mode filter system, which comprises a first mode filter F_1, an ordinary helix waveguide A and a second mode filter F_2. An alternate arrangement of a mode filter F_1 or F_2 and an ordinary helix waveguide A shown in FIG. **8,** provides a mode filter system which covers a very wide frequency band. For instance, if the first mode filter F_1 covers a low frequency band, such as 40 – 60 GHz, and the second mode filter covers a high frequency band, such as 60 – 80 GHz, then the whole filter system including both filters F_1 and F_2 covers wide frequency band 40 – 80 GHz. Each component filter F_1 or F_2 can be a helix type mode filter as illustrated by FIG. **5.** The typical numerical design of a combination mode filter system shown in FIG. **10** is as follows:

Number of ridges; five ($p = 5$)
Tolerable attenuation of TE_{01} mode; 0.005 nepa
Ratio of ridges; 0.04 (δ= 0.04)
Radius of helix waveguide; $a_o = 25.5$ mm
Frequency band; 40 – 80 GHz
Length of first filter; $L_1 = 625$ mm (Center frequency is 50 GHz)
Length of second filter; $L_2 = 875$ mm (Center frequency is 70 GHz)
Length of helix waveguide A; 1000 mm
Structure of helix wall in FIG. **5**
Relative dielectric constant of dielectric layer; $\epsilon_s = 4$
Thickness of dielectric layer; t 32 0.5 mm
Diameter of coil; D = 0.129 mm and $d = 0.12$ mm

With the above numerical design, the value of $j\omega a Zz$ of both filters F_1 and F_2 is about four.

In the combination mode filter system of FIG. **10,** the micro-wave energy propagates in the direction of the arrow, and undesirable TE_{02} mode included in the low frequency band is converted by the first filter F_1 to the TE_{51} mode, which is absorbed by the helix waveguide A. Further, undesirable TE_{02} mode included in the high frequency band is converted by the second filter F_2 to the TE_{51} mode, which is absorbed by a succeeding helix waveguide (not shown). Some modifications of FIG. **10** are, of course, possible. For instance, a metal wall type mode filter or dielectric lined type mode filter can be used as a component of a combination filter system, instead of the helix type mode filter.

With regard to the fifth embodiment of the present mode filter, FIG. **11** shows the relationship between the length (horizontal axis; cm) and the mode conversion loss of the TE_{03} mode (vertical axis; dB), with parameters of some frequencies, where radius $a_o = 25.5$ mm, number of ridges $p = 9$, deformation rate $\delta = 0.06$, and the attenuation of TE_{01} mode is less than 0.1 dB. On the condition that the frequency band from 40 GHz to 90 GHz should be covered by a single mode filter, the length of that filter is determined to be 12 cm from Point A in FIG. **11**, and the loss of the upper limit frequency (90 GHz) is the same as that of the lower limit of frequency (40 GHz). However, with the length of 12 cm, any significant loss at both higher and lower frequencies is not satisfactory. The fourth embodiment described above with reference to FIG. **10**, overcomes that disadvantage, but the mode filter in said fourth embodiment is too large in size.

Therefore, the fifth embodiment provides a wide band mode filter of a small size.

FIG. **12** and FIG. **13** show the longitudinal view and cross sectional view, respectively, of a filter system of the fifth embodiment, which comprises a first filter F_1 and second filter F_2. The second filter F_2 is connected to the first filter F_1 along a common longitudinal axis, however, corresponding points on the periphery of filters F_1 and F_2, for instance *a* on F_1 and a' on F_2 in FIG. **13**, are separated from each other by angle θ. Said angle θ is determined as $\theta = 2\pi/4p$. Accordingly to the structures in FIGS. **12** and **13**, since an ordinary helix waveguide between two filters like those of FIG. **10** is unnecessary, the entire length of the filter system is shortened.

The operational principle of the filter system in FIGS. **12** and **13** is explained with a simple example (p 32 2), shown in FIGS. **14**(A) and **14**(B). When the TE_{on} mode propagates in a waveguide with two ridges ($p = 2$) shown in FIG. **14**(A), said TE_{on} mode is converted to the TE_{21} mode, whose field is shown in FIG. **14**(A).

On the other hand, when two filters are connected directly on the condition that first one (FIG. **14**(A)) is turned by angle θ ($\theta = 2\pi/4p = 45°$) to the second one (FIG. **14**(B)), the electrical fields in FIG. **14**(A) and FIG. **14**(B) are in the relationship of a sine mode to a cosine mode, and those fields do not couple with each other. Accordingly, two filters of FIG. **14**(A) and FIG. **14**(B) operate independently and it seems as if two mode filters are provided. Therefore, an ordinary helix waveguide between two filters can be omitted.

Numerical design of the fifth embodiment is shown below.

Type of waveguide; metallic wall waveguide
Number of ridges; nine ($p = 9$)
Inner radius; $a_o = 25.5$ mm
Length of first filter; L_1 10 cm
Length of second filter; $L_2 = 18$ cm
Angle θ; $\theta = 2\pi/4p = 2\pi/4 \times 9 = 10°$
Deformation rate; $\delta = 0.06$

The characteristics of the fifth embodiment with the above numerical data are shown in FIG. **15**, where the horizontal axis denotes frequency in GHz and the vertical axis denotes loss of TE_{03} mode in dB, curve F_1 relates to the loss by first filter F_1 and curve F_2 relates to the loss by second filter F_2. As apparent from FIG. **15**, the total loss ($= F_1 + F_2$) is almost constant between wide frequency bands.

The second numerical design of the fifth embodiment is shown below.

Type of waveguide; helix waveguide
Number of ridges; $p = 5$
Deformation rate; $\delta = 0.04$
Radius; $a_o = 25.5$ mm
Value of $j\omega\epsilon aZz$; 4
Specific inductivity; $\epsilon_s = 4$
Thickness of dielectric layer; $t = 0.5$ mm
Diameters of coil; D = 0.129 mm, $d = 0.12$ mm
Length of first filter; $L_1 = 625$ mm
Length of second filter: $L_2 = 875$ mm
Angle θ; $\theta = 2\pi/4p = 2\pi/4 \times 5 = 18°$

The mode filter described in FIG. **8** is also applicable to the filter system of the fifth embodiment.

The coupling portion of first filter F_1 and second filter F_2 should be covered by a metallic cover in practical use.

Next, some useful calculated data for the design of the mode filter according to the present invention are presented below.

FIG. **16** shows the relationship between $j\omega\ aZz$ along the horizontal axis and loss factor

$$\left(\frac{C_{ni}}{\Delta\beta ni}\right)^2$$

along the vertical axis on the condition that $p = 5$, $a_o = 25.5$ mm and $\delta = 0.04$. These curves are calculated from formulae (9), (10) and (11).

FIG. **17** shows the curves of the frequency in GHz along the horizontal axis versus the value of $J\omega\epsilon aZ/zon$ the condition that $a_o = 25.5$ mm, $\epsilon_s = 4$, $t = 0.6$ mm and $d = 0.2$ mm.

FIG. **18** shows the relationship between the length of a mode filter in cm along the horizontal axis and the loss of TE_{02} mode in dB along the vertical axis with a parameter of frequencies (GHz), on the condition that $p = 5$ and $\delta = 0.04$. Mathematically speaking, the length l of a mode filter is determined to satisfy the formula

$$l = \frac{\pi}{2} \cdot \frac{1}{C_{ni}}$$

However, in the practical design in which the mode filter is used for the wide frequency band, the length l should be designed from FIG. **18** so that the losses at the highest and lowest frequencies are the same.

FIG. **19** shows the frequency characteristics of the loss of TE_{02} mode with parameters of wall impedance. In FIG. **19**, the horizontal axis shows the frequency in GHz and the vertical axis shows the loss of TE_{02} mode in dB. The condition of FIG. **19** is that $p = 5$, $\delta = 0.04$ and $l = 75$ cm.

FIG. **20** shows the relationship between the frequency in GHz along the horizontal axis and the loss of the fundamental TE_{01} mode in dB along the vertical axis on the condition that $p = 5$, $\delta = 0.04$ and $l = 75$ cm. The curve of FIG. **20** shows a total conversion loss where TE_{01} mode is converted to TE_{51}, TE_{52}, TE_{53} and

TE_{54}. It should be noted that the loss or attenuation of the TE_{01} mode in the mode filter is extremely small.

Further, it is simply calculated that the heat loss of the TE_{01} mode by the outer dielectric layer of a helix type mode filter is negligibly small on the condition that the frequency is less than 100 GHz and the thickness of the dielectric layer is (0.3 mm $<t<$ 0.8 mm).

Finally, the experimental result of the TE_{02} mode filter according to the present invention is shown in FIG. **21.** The mode filter of FIG. **21** is a helix type filter, and its dimensions are $p=5$, $l=75$ cm, and the center frequency is 60 GHz. In FIG. **21,** the horizontal axis shows the frequency in GHz, and the vertical axis of the upper part shows the loss of TE_{02} mode in dB, and that of the lower part shows the loss of TE_{01} mode in dB. In FIG. **21,** the curve *a* shows the experimental measured loss of the TE_{01} mode, the curve *b* shows the calculated loss of the TE_{02} mode, and the dotted curve *c* shows the measured loss of the TE_{02} mode. It should be noted from FIG. **21** that the measured data coincides very well with the corresponding calculated data.

It should be noted, further, that tapered waveguide between the mode filter according to the present invention and an ordinary circular waveguide is unnecessary, since the coupling loss at the coupling point is very small.

From the foregoing, it will now be apparent that a new and improved mode filter has been found. It should be understood, of course, that the embodiments disclosed are merely illustrations and are not intended to limit the scope of the invention. Reference should be made to the following claims, rather than the specification, as indicative of the scope of the invention.

What is claimed is:

1. A mode filter comprising a circular waveguide of a predetermined longitudinal length, characterized in that the cross section of said waveguide wall is almost circular but is slightly deformed by the existence of a plurality of ridges formed in the wall per se, whereby the mode conversion loss in said waveguide from the TE_{on} mode ($n \geqq 2$) to the TE_{pm} mode is much greater than that from the TE_{01} mode to other modes.

2. A mode filter according to claim **1,** further comprising a thin dielectric layer inscribed on the inner surface of said deformed waveguide.

3. A mode filter according to claim **1,** wherein the number of said ridges is six.

4. A mode filter according to claim **1,** wherein the number of said ridges is nine.

5. A mode filter according to claim **1,** wherein the number of said ridges is eight.

6. A mode filter comprising a circular helix waveguide of a predetermined longitudinal length having at least a helix wire and a thin dielectricl layer covering said wire, characterized in that the cross section of said helix waveguide is almost circular but is slightly deformed by the existence of a plurality of ridges on the periphery of the waveguide, and that by the design of the wall impedance of said helix waveguide the difference of phase constants between the TE_{on} mode ($n \geqq 2$) and the converted modes from said TE_{on} mode is smaller than the difference of phase constants between the TE_{01} mode and said converted modes.

7. A mode filter according to claim **6,** wherein the number of said ridges is five.

8. A mode filter according to claim **6,** wherein the nimber of said ridges is eight.

9. A mode filter system comprising at least;

a. a first helix waveguide having at least a helix wire and a thin dielectric layer covering said wire, the cross section of said helix waveguide is almost circular but is slightly deformed by the existence of a plurality of ridges on the periphery of the waveguide, the wall impedance of said waveguide being so designed that the difference of phase constants between the TE_{on} mode ($n \geqq 2$) and the converted modes from said TE_{on} is smaller than the difference of phase constants between the TE_{01} mode and said converted modes, the approximate length l of said helix waveguide being designated as

$$l = \pi/2 \,.\, 1/C_{ni},$$

where C_{ni} is the coupling coefficient between TE_{on} mode and i mode, and the frequency characteristics of said waveguide being almost flat in the lower frequency band,

b. an ordinary helix waveguide connected to said first helix waveguide, and

c. a second helix waveguide connected to said ordinary helix waveguide, said second helix waveguide being similar to said first helix waveguide except that the frequency characteristics of said second helix waveguide are almost flat in the higher frequency band.

10. A mode filter system comprising at least two circular waveguides, their cross-sections being almost circular but being slightly deformed by the existence of a plurality of ridges on the periphery of the waveguides, whereby the mode conversion loss in said waveguides from the TE_{on} mode to the TE_{pm} mode are much greater than that from the TE_{01} mode to other modes, characterized in that said two circular waveguides operate as a mode filter in lower and higher frequency bands, respectively, and that said two circular waveguides are connected along a common axis so that the corresponding points on the periphery of the two circular waveguides are separated from each other by an angle $\theta = 2\pi/4p$radian, where p is the number of said ridges along the periphery of the circular waveguides.

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