ANALYSIS AND APPLICATION OF A NEW WAVEGUIDE STRUCTURE WITH DIELECTRIC LOADING

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ABSTRACT

A new waveguide structure has been proposed for the design of a distributed constant circuit elements at a lower microwave frequency band. Theoretical and experimental analysis of the structure has been carried out, and it was applied to the design of a compact 850 MHz band radio frequency filter.

The equivalent permittivity of the waveguide (ϵ_{eff}) is about half the permittivity of the medium dielectric material (ϵ_r). The amount of coupling between quarter wavelength resonators (the diameter of the dielectric rod is 15 mm and ϵ_r = 20) within the cutoff waveguide (15 mm x 31 mm) is approximately 3×10^{-2} for spacing of 2 mm.

Unloaded Q (Qu) of the resonator is about 1,600 using the dielectric material of which tan δ is about 1.4×10^{-4} at 6.3 GHz.

Introduction

Recently several new vehicular communication technologies have been developped at lower microwave frequency bands below 2 GHz.

One of the existing difficulties to present a compact and an economical radio telephone transceiver is the realization of a small and low loss radio frequency filter unit.

A conventional dielectric-filled coaxial waveguide structure has been first introduced into r.f resonators of a filter.

A new waveguide structure is presented in this paper to be constructed with a dielectric rod having a central thin metal conductor inserted between two parallel conductor plates without gaps. The new waveguide has the characteristics of high unloaded Q (Qu) at the lower microwave frequency band and the simple cross sectional structure to yield a sufficient amount of coupling between parallel waveguides.

Theoretical and experimental analysis of the structure has first been carried out.

The relaxation method is used for theoretical analysis of the electromagnetic field in the waveguide. The pure TEM mode is assumed. The results obtained by numerical calculation have been examined by experiments at a lower microwave frequency band. Calculated values of the impedance, amount of coupling and equivalent permittivity of the waveguide showed good coincidence with the results of experiments. At the higher microwave frequency band, a coupled mode between the TEM mode and a surface wave TM_{01} mode is assumed. The mode coupling constant obtained from a resonant mode experiment was used to calculate wavelength constant β of the waveguide. The theoretical and experimental results for the coupled mode wavelength constant β showed also relatively good coincidence.

The lowest higher order mode was proved to exist between twice and three times of the designed center frequency.

The new structural filter is approved to have a smaller volume in size than a conventional coaxial filter filled with dielectric ceramics, and it was also approved to reduce the cost enough for the quantity production.

Theoretical analysis by the relaxation method

Theoretical

The basic configuration of the new waveguide is shown in Fig. 1 (a). A thin inner conductor with the diameter of 2b is inserted at the center of a dielectric rod with the diameter of 2a which is held between two parallel conductor plates with the spacing of W. In this thesis, W equals 2a as no gap is assumed.

Fig. 1 (b) shows the cross sectional view of the waveguide. Infinitely long lines are assumed repetitive at cycles of L. The pure TEM mode has been considered for basic analysis.

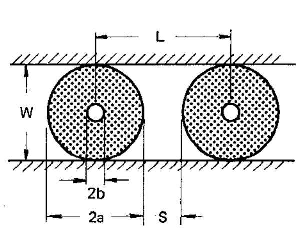


Fig. 1 (a) The basic configuration of the new waveguide structure

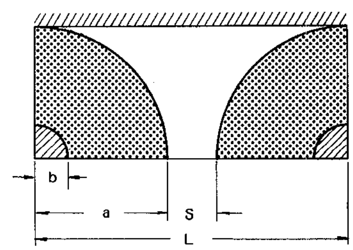


Fig. 1 (b) The cross sectional view of the waveguide for numerical analysis

(1) The potentials of the point group in homogeneous medium

The pure TEM mode potential is obtained for each grid point to minimize the residual R_0 specified by the following:

$$R_0 = \phi_0 - \frac{1}{4}(\phi_1 + \phi_2 + \phi_3 + \phi_4) \qquad (1)$$

The potentials $\phi_0 \sim \phi_4$ are specified to meet the two-dimensional.

Laplace equation corresponding to the points of square grid with a spacing h on the uniform and homogeneous plane.

(2) The potentials of the point group with a boundary

The axial system is shown in Fig. 2.

When the grid point group includes a boundary between a metal, air and a dielectric material, the pseudopotential of each point is introduced into the equation (1) instead of the real potentials.

Under the limited condition of the objective waveguide, the cases of the grid point group are specified by three shown in the Table 1.

The pseudopotential in each case can be derived out with the consideration of the boundary conditions in the Maxwell equation. They are listed in the table.

In the Table 1, the angle θ_r is chosen $\theta_r > \pi/4$ radian. When the angle θ_r below $\pi/4$ rad., $(\theta_r - \pi/4)$ should be applied instead of the angle θ_r.

(3) Impedance, Effective permittivity, Coupling coefficient

The wave impedance Z_0 is following in homogeneous medium:

$$Z_0 = \frac{1}{C\nu}\ (\Omega) \qquad (2)$$

where $\nu = \nu_0/\sqrt{\epsilon_r}$ is the phase velocity in the medium, ν_0 is the optical

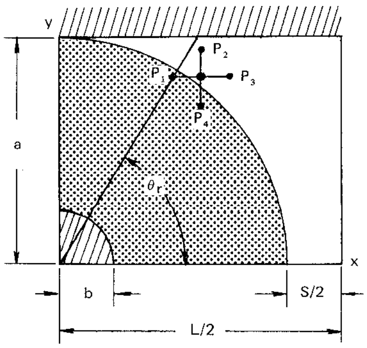
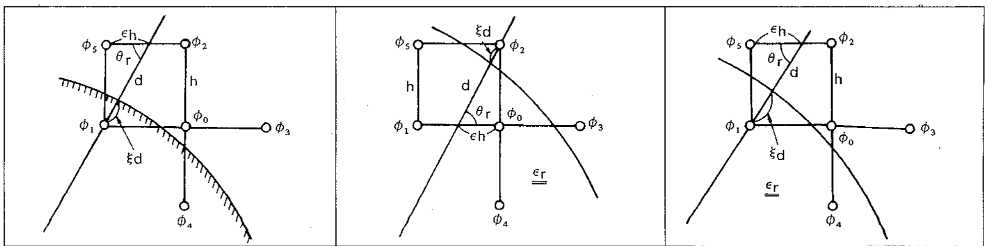


Fig. 2 Axial system for the numerical calculation



$\phi_1' = \dfrac{1-\{\phi_5+\epsilon(\phi_2-\phi_5)\}\cdot\xi}{1-\xi}$ $\epsilon = h\cdot\cot\theta$	$\phi_2' = \phi_0 - \epsilon(\phi_0-\phi_1) + \dfrac{\phi_2 - \{\phi_0-\epsilon(\phi_0-\phi_1)\}}{\epsilon_r\xi + (1-\xi)}$	$\phi_1' = \phi_5+\epsilon(\phi_2-\phi_5) + \dfrac{\phi_1 - \{\phi_5+\epsilon(\phi_2-\phi_5)\}}{\frac{1}{\epsilon_r}\xi+(1-\xi)}$

Table 1 The classification of the grid point group including a boundary

velocity in free space and ϵ_r is the permittivity of the medium. C is the waveguide capacity per unit length. The wave impedance Z in inhomogeneous medium is the following;

$$Z = \frac{1}{\nu_0\sqrt{Ci\cdot C_0}}\ (\Omega) \tag{3}$$

where Ci and C_0 is the waveguide capacity per unit length with and without medium dielectrics respectively.

The effective permittivity of the waveguide is;

$$\epsilon_{eff} = \sqrt{Ci/C_0}$$

The coupling coefficient between two parallel waveguides is the following;

$$k = (Z_{even} - Z_{odd})/(Z_{even} + Z_{odd}) \tag{4}$$

where Z_{even} and Z_{odd} corresponds to the even and odd potential specified among two waveguides respectively.

(4) The attenuation constant of the waveguide

The attenuation constant due to the cupper loss is calculated by the following:

$$\alpha_C = \frac{\frac{1}{2}Rm\frac{\epsilon_0}{\mu_0}\int_{\ell_1+\ell_2}\epsilon_r\left(\frac{\partial\phi}{\partial n}\right)^2 d\ell}{\nu\int_{\ell_2}\epsilon_0\,\epsilon_r\left(\frac{\partial\phi}{\partial n}\right)d\ell}\quad \text{(neper/meter)} \tag{5}$$

Where Rm is the surface resistance, ℓ_1 and ℓ_2 is the integrating path along the outer and the inner conductor respectively.

The attenuation constant of the waveguide due to the medium dielectric loss factor is obtained by the following:

$$\alpha_d = \frac{\frac{1}{2}\omega\,\epsilon_0\epsilon_r\tan\delta\iint_S\left[\left(\frac{\partial\phi}{\partial x}\right)^2+\left(\frac{\partial\phi}{\partial y}\right)^2\right]ds}{\nu\int_{\ell_2}\epsilon_0\,\epsilon_r\left(\frac{\partial\phi}{\partial n}\right)d\ell}\quad \text{(neper/meter)} \tag{6}$$

where ω is the angular frequency, $\tan\delta$ is the tangential factor of the complex permittivity and S is the cross sectional area of the waveguide for integration.

The total attenuation constant is

$$\alpha = \alpha_C + \alpha_d \quad \text{(neper/meter)} \tag{7}$$

and the Q-factor of the waveguide is obtained by the following:

$$Q = \frac{27.3}{\alpha_\lambda},\quad \alpha_\lambda = 8.686\cdot\alpha\cdot\lambda_g,\quad \lambda_g = \lambda_0/\sqrt{\epsilon_{eff}} \tag{8}$$

Calculation and Measurement of TEM Mode Parameters

The electromagnetic field is classified into even mode and odd mode, and the equipotential distribution is obtained for each of these modes, as shown in Fig. 3 (a) and (b) respectively.

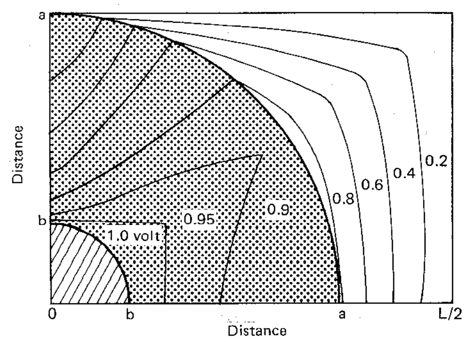


Fig. 3 (a) Equipotential distribution in case of odd mode 2a = 15 mm, 2b = 4 mm, S = 6 mm and ϵ_r = 20

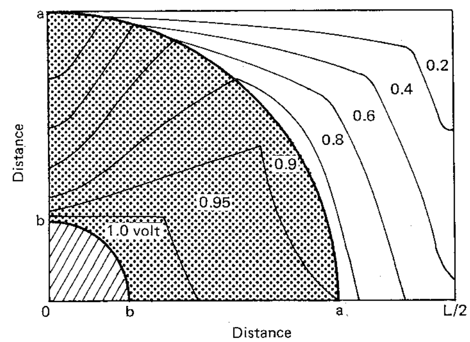


Fig. 3 (b) Equipotential distribution in case of even mode 2a = 15 mm, 2b = 4 mm, S = 6 mm and ϵ_r = 20

The impedance for each mode [equation (9)] and coupling constant k [equation (4)] were obtained by integration around each conductor along the path of integration ℓ_2.

$$Z_{even} = \frac{1}{\nu_0\sqrt{Cie\cdot C_0}},\qquad Z_{odd} = \frac{1}{\nu_0\sqrt{Cio\cdot C_0}} \tag{9}$$

where, Cie, Cio : Even and odd mode capacitance, respectively

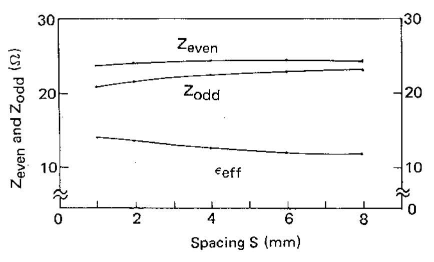


Fig. 4 Theoretical impedance for each of even mode and odd mode

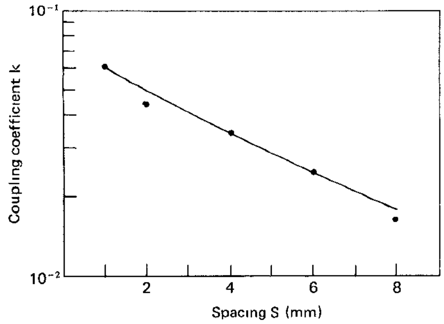


Fig. 5 Coupling coefficient k

The solid line is theoretical, dotted points show measured values.

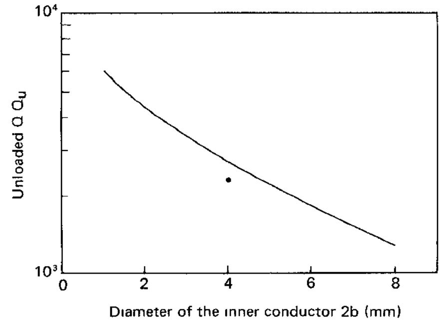


Fig. 6 Unloaded Q of transmission line

The solid line is theoretical, dotted points show measured values.

Modal analysis by the theory of mode coupling

Wavelength constant of the surface TM_{01} mode

In this thesis, W equals 2a as no gap is assumed, so the TEM mode is prospective as the principal mode. If W is greater than 2a, the surface TM_{01} mode is also prospective as the principal mode. The authors have been studying it as an attractive waveguide at the higher microwave frequency band.

Frequency dispersion of wavelength constant of TM_{01} mode has been obtained by the analysis of the following characteristic equation.

$$\frac{K_1(kr2a)}{kr2K_0(kr2a)} = \frac{\epsilon r}{kr1} \cdot \frac{J_0(kr1b)N_1(kr1a) - J_1(kr1a)N_0(kr1b)}{J_0(kr1a)N_0(kr1b) - J_0(kr1b)N_0(kr1a)} \quad (10)$$

where

$$kr1^2 = k_1^2 - \beta^2$$
$$kr2^2 = \beta^2 - k_0^2$$
$$k_0^2 = \omega^2 \epsilon_0 \mu_0$$
$$k_1^2 = \omega^2 \epsilon_0 \epsilon r \mu_0$$
$$kr1^2 + kr2^2 = k_0^2(\epsilon r - 1)$$
$$\beta = \frac{2\pi}{\lambda g}$$

The calculation is performed on the conditions; 2a = 15, 2b = 4 mm, and $\epsilon r = 20$.

As for TM_{01} mode, $W = \infty$ is assumed to simplify the analysis. The effect of limited W can be approximately estimated by the theory of perturbation. Fig. 7 (a) shows the calculated wavelength constant β of the mode by dotted line curve TM_{01} ($\epsilon r = 20$).

Calculation and Measurement of the Coupled Mode Wavelength Constant

The wavelength constant β of the waveguide was calculated assuming that the modes TEM and TM_{01} are coupled by the coupling constant κ.

Wavelength constant βc_0 and βc_1 of two modes resulting from mode coupling between TEM and TM_{01} are calculated as follows.

$$\frac{\beta c_0}{\beta c_1} = \frac{\beta_0 + \beta_1}{2} \pm \sqrt{|\kappa|^2 + \frac{1}{4}(\beta_0 - \beta_1)^2} \quad (11)$$

where, κ indicates the coupling coefficient between two modes. βc_0 and βc_1, when $\kappa = 0.1 \sim 0.3$, are shown by two curves covered by $\kappa = 0.1$ and $\kappa = 0.3$ in Fig. 7 (a), respectively.

Fig. 7 (a) and Fig. 7 (b) show the calculated wavelength constant β and the measured one, respectively. These results agreed relatively well. The mode coupling constant ($\kappa = 0.1 \sim 0.3$) obtained by experimental result in Fig. 7 (b) and used in calculation for Fig 7 (a) can be regarded as reasonable as compared with the result reported in the past[1].

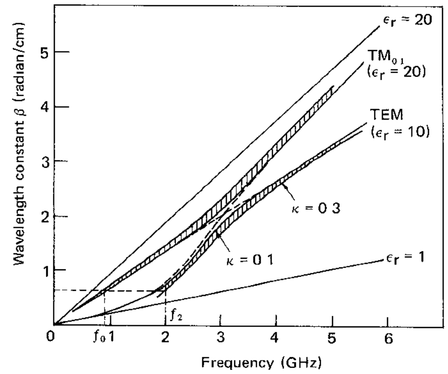


Fig. 7 (a) Wavelength constant of the guide with mode coupling between TEM and TM_{01} [Theoretical]

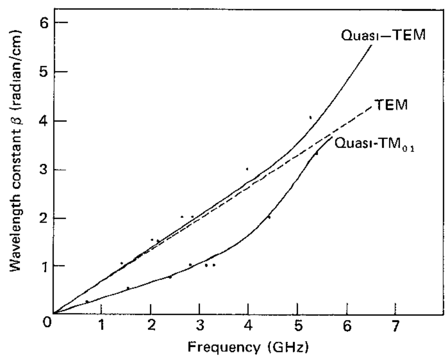


Fig. 7 (b) Wavelength constant of the waveguide with mode coupling between TEM and TM_{01} [Measured]

Application

A 7-element Chebishev-performance filter unit was designed and fabricated based on the requirements of:

1) 835 MHz transmitting frequency (f_{0T})
2) 880 MHz receiving frequency (f_{0R})
3) 20 MHz bandwidth of 0.5 dB down flat response
4) 60 dB selectivity at both edges of passband
5) 1 dB insertion loss
6) lowest spurious response $f_1 \gg 2$ (f_{0T} and f_{0R})

The volume of the quarter wavelength resonator filter that satisfied the above requirements was 68 cubic centimeters and the weight was 270 grams.[2] The lowest spurious response is calculated to be at 2 GHz and was found at 2.1 ~ 2.3 GHz.

REFERENCES

1. T.G. Bryant and J.A. Weiss, "Normal mode impedance of a coupled pair of microstrip transmission lines", GMTT International Symposium, pp.110-116, May 1968.
2. A Fukasawa, et al., "Miniaturized dielectric radio frequency filter for 850 MHz band mobile radio", IEEE VTC-26, pp.181-186, March 1979.