A NEW FORM OF MOVABLE WAVEGUIDE SHORT-CIRCUIT

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***Abstract-* This paper describes a new type of movable waveguide short-circuit which avoids the rather complicated choke arrangement of the familiar 'non-contact' short-circuit, and therefore should be easier to manufacture. Calculation shows that the new short-circuit is likely to have as satisfactory a perfomance over the normal waveguide bandwidth as the usual choke type.**

THE BASIC THEORY

Consider a short-circuited rectangular waveguide supporting the TE_{01} mode. The magnetic field vector has the following components:

$$H_x = H_0 \sin\left(\frac{\pi x}{a}\right)\cos\left(\frac{2\pi z}{\lambda_g}\right) \qquad (1a)$$

$$H_z = -\frac{\lambda_g}{2a} H_0 \cos\left(\frac{\pi x}{a}\right)\sin\left(\frac{2\pi z}{\lambda_g}\right) \qquad (1b)$$

The magnetic field lines are found by integrating the equation below:

$$\frac{dx}{dz} = \frac{H_x}{H_z}$$

The current flow lines in the broad face of the guide are everywhere orthogonal to the magnetic vector and so are given by:

$$\frac{dx}{dz} = -\frac{H_z}{H_x} = \frac{\lambda_g}{2a}\cot\left(\frac{\pi x}{a}\right)\tan\left(\frac{2\pi z}{\lambda_g}\right) \qquad (2)$$

Integrating leads to:

$$\ln\left|\cos\left(\frac{\pi x}{a}\right)\right| - \left(\frac{\lambda_g}{2a}\right)^2 \ln\left|\cos\left(\frac{2\pi z}{\lambda_g}\right)\right| = K \qquad (3)$$

Write $K = \ln K'$, and then, after rearranging:

$$z = \frac{\lambda_g}{2\pi}\arccos\left\{K'\left[\cos\left(\frac{\pi x}{a}\right)\right]^{\left(\frac{2a}{\lambda_g}\right)^2}\right\} \qquad (4)$$

for $0 \leqslant x \leqslant a/2$.

There is a special case in which a particularly simple solution of (4) exists; this is when:

$$\lambda_g = 2a = \sqrt{2}\lambda \qquad (5a)$$

$$\lambda = \frac{2a}{\sqrt{2}} = \frac{\lambda_c}{\sqrt{2}} \qquad (5b)$$

Then (4) is satisfied if $K'=1$ and:

$$\frac{2\pi z}{\lambda_g} = \pm\frac{\pi x}{a} + n\pi$$

or

$$z = \pm x + na$$

The relevant solutions are:

$$z = x \quad \text{and} \quad z = a - x \qquad (6)$$

These straight lines are lines of current flow, so no current crosses them. They are shown in Fig 1.

THE MOVABLE SHORT CIRCUIT

Fig. 2 shows the general scheme. The triangular edges of the short-circuit lie along current flow lines, and so, ideally, no current crosses the moving contact on the broad faces of the guide.

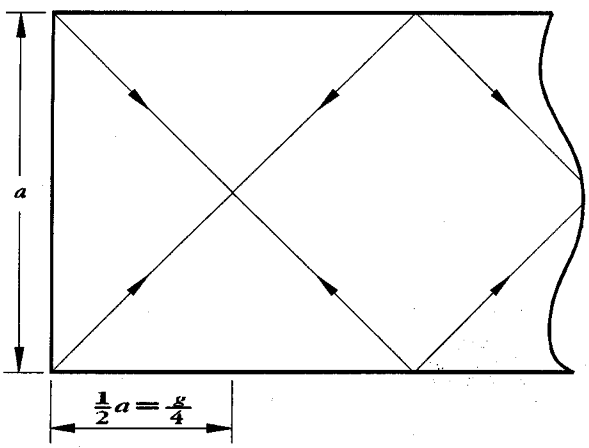

Fig. 1 - Lines of current flow for the case $\lambda_g = 2a$

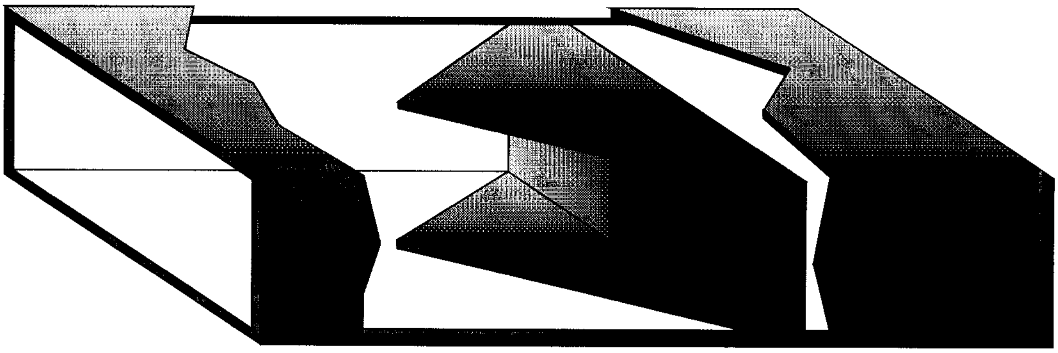

Fig. 2 - Cut-away sketch of the movable short-circuit

On the narrow faces, the current flow lines are again parallel to the edges of the movable conductor. This last remark is true at all frequencies. However, the triangular shape is only valid at the frequency for which (5) holds. At any other frequency, the correct edge profile is no longer linear, but has a more complicated shape given by (4), and is specific to the chosen frequency. (It may be noted, in passing, that the usual choke type of movable short-circuit is only theoretically perfect at the frequency at which the choke length is one quarter of a guide wavelength.) Whilst there are a number of important single-frequency applications, for example industrial heating, it is often necessary to work over a band of frequencies.

In that case, it is desirable to examine the effect of finite contact resistance on the bandwidth.

In the next section, the special edge profiles for other frequencies, and the bandwidth available with linear profiles will both be discussed.

BANDWIDTH

Consider the edge OA of one of the triangular plates of the movable short-circuit, as shown in Fig 3. From (1), the current crossing the line element Δs is:

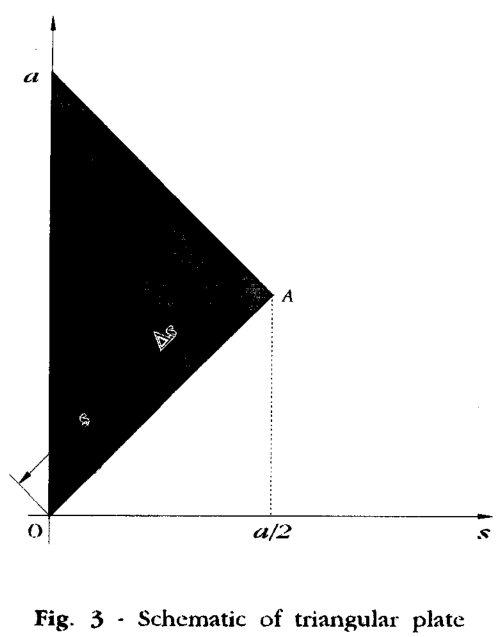

Fig. 3 - Schematic of triangular plate

$$i = J_S \Delta s = \frac{1}{\sqrt{2}}(H_x + H_z)\Delta s \tag{7}$$

In detail:

$$J_S = \frac{H_0}{\sqrt{2}}\left(\sin k_c x \cos \beta z - \frac{\lambda_g}{2a}\cos k_c x \sin \beta z\right) \tag{8}$$

where:

$$k_c = \frac{\pi}{a}, \quad \beta = \frac{2\pi}{\lambda_g} \tag{9}$$

On OA:

$$x = z = \frac{s}{\sqrt{2}} \tag{10}$$

Put:

$$k'_c = \frac{k_c}{\sqrt{2}}, \quad \beta' = \frac{\beta}{\sqrt{2}} \tag{11}$$

Then:

$$i = \frac{H_0}{\sqrt{2}}\left(\sin k'_c s \cos \beta' s - \frac{\lambda_g}{2a}\cos k'_c s \sin \beta' s\right) \tag{12}$$

The contact resistance r of the element Δs is inversely proportional to Δs. Let:

$$r = \frac{R}{\Delta s} \tag{13}$$

where R is the 'resistivity' of the contact Ωm.

The losses in the triangular plates and in the waveguide inself itself are assumed to be negligible.

The power dissipated in the length Δs is then:

$$\Delta P = \frac{1}{2}(J_S \Delta s)^2 \frac{R}{\Delta s} = \frac{1}{2} J_S^2 R \Delta s \tag{14}$$

Substituting from (8) and proceeding to the limit, the total power P_t dissipated in the length OA is:

$$P_t = \frac{1}{4} R H_0^2 \int_0^L \left(\sin k'_c s \cos \beta' s - \frac{\lambda_g}{2a}\cos k'_c s \sin \beta' s\right)^2 ds$$

or

$$P_t = \frac{1}{4} R H_0^2 I_L \tag{15}$$

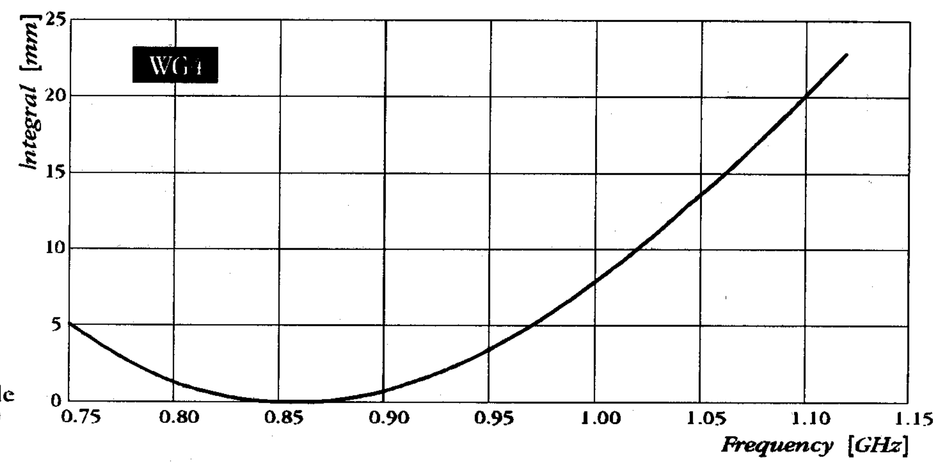

Fig.4 - Loss integral for movable short-circuit **WG4**, 9.750"×4.875"

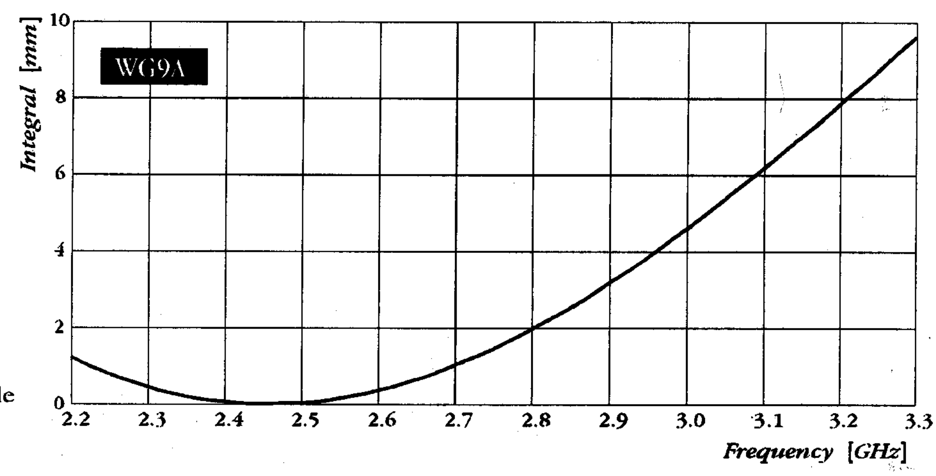

Fig.5 - Loss integral for movable short-circuit **WG9A**, 3.40"×1.70"

Carrying out the integration gives:

$$\begin{aligned} I_L = & \frac{1}{4}\left(1+q^2\right)L \\ & -\frac{1}{4}\left(1-q^2\right)\frac{\sin 2k_c' L}{qk_c'} + \frac{1}{4}\left(1-q^2\right)\frac{\sin 2\beta' L}{q\beta'} \\ & -\frac{1}{8}\left(1-2q+q^2\right)\frac{\sin q\,(k_c'-\beta')L}{q\,(k_c'+\beta')} \\ & -\frac{1}{8}\left(1+2q+q^2\right)\frac{\sin q\,(k_c'-\beta')L}{q\,(k_c'-\beta')} \end{aligned} \quad (16)$$

where $L=a/\sqrt{2}$, $q=\lambda_g/2a$.

In Figs 4 and 5, I_L is evaluated as a function of frequency for waveguides **WG4** and **WG9A**. It is interesting to note that for **WG4** and **WG9A**, the minimum value of I_L (zero), and therefore the minimum contact resistance resistance loss, occurs close to the specified industrial heating frequencies of 0.896 GHz and 2.45 GHz respectively. From a practical point of view, it is the reflection coefficient of the short-circuit which is of prime importance. Since there are four edges, from (15) the total power lost in contact resistance is:

$$P_l = R H_0^2 I_L \quad (17)$$

H_0 is the total magnetic field at a maximum of the standing wave, so the incident magnetic field is $H_0/2$. Thus, the incident power is:

$$P_i = \frac{1}{q}\left(\frac{1}{2}H_0^2\right)\left(\frac{\mu_0}{\varepsilon_0}\right)^{1/2}\frac{\lambda_g}{\lambda}\frac{ab}{2} \quad (18)$$

The power reflection coefficient is given by:

$$|\Gamma|^2 = \frac{P_i - P_l}{P_i} \quad (19)$$

or

$$|\Gamma|^2 = 1 - \frac{R I_L}{\left(\frac{ab}{16}\right)\left(\frac{\mu_0}{\varepsilon_0}\right)^{1/2}\frac{\lambda_g}{\lambda}} \quad (20)$$

$$|\Gamma| \approx 1 - \frac{R I_L}{\left(\frac{ab}{8}\right)\left(\frac{\mu_0}{\varepsilon_0}\right)^{1/2}\frac{\lambda_g}{\lambda}} \quad (21)$$

Estimating R is difficult. The total resistance of one edge of length $a/\sqrt{2}$ is $R_t = R/\left(a/\sqrt{2}\right)$. For **WG4**, $a/\sqrt{2} = 175\,mm$. Suppose the total contact resistance is R_t = 10 Ω. (It is unlikely to be so high; this is intended to be very conservative estimate.) Then R = 1750 *Ωmm*. Consider operation at 0.896 GHz. The loss integral then has the value 0.6477 *mm*, and so $RI_L = 1133\Omega mm^2$. At 0.896GHz, λ_g/λ = 1.36; also $ab/8 = 3833\ mm^2$, and $(\mu_0/\varepsilon_0)^{1/2}$ = 377 Ω. Substituting in (21) gives:

$$|\Gamma| = 1 - \left(5.76 \times 10^{4}\right)$$

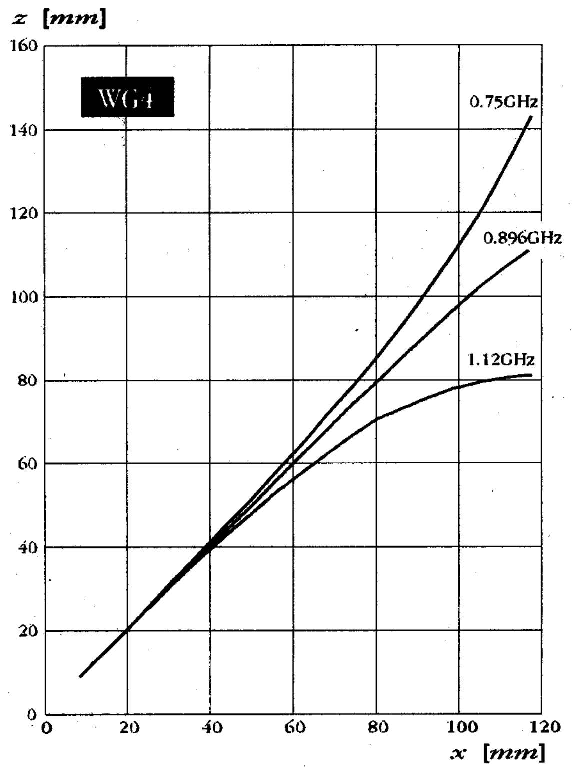

Fig. 6 - Edge profiles **WG4**, 9.750"×4.875"

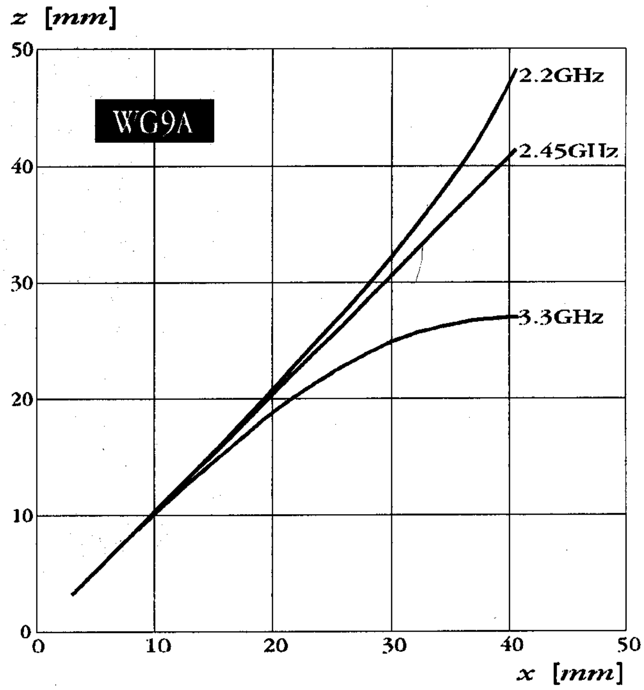

Fig. 7 - Edge profiles **WG9A**, 3.400"×1.700"

from which the return loss is 0.005 *dB*, and for most purposes this will be negligible.

IDEAL EDGE PROFILE

Equation (4) gives the ideal edge profile for a given frequency. These ideal profiles are plotted in Figs 6 and 7 for waveguides **WG4** and **WG9A**. Note that the profiles for 0.896 GHz and 2.45 GHz are very nearly straight lines, thus explaining from another point of view the excellent performance of straight line profiles for **WG4** at 0.896 GHz and of waveguide **WG9A** at 2.45 GHz.

CONCLUSIONS

It has been shown theoretically that there is good reason to suppose that the proposed sliding short-circuit could provide a simpler and cheaper alternative to the familiar quarter-wave choke design. It also seems possible that the power-handling capacity may be better. But experimental verification at low and high power is necessary before either of these potential advantages can be claimed as proven.