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Increasing Q of Waveguide Pulse-Compression Cavities

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Abstract

A limiting factor in microwave pulse compression is the cavity Q. For waveguide cavities of some number of wavelengths in length the skin-effect losses in the conductors is a limiting factor. These can be reduced relative to the power in the cavity by increasing the cross-section dimensions. To avoid unwanted modes, techniques involving symmetry and adding losses to these modes can be used.

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1. Introduction

One of the problems in microwave pulse compression concerns raising the Q of the microwave cavity, as this limits the attainable power multiplication [5]. The skin-effect losses in the conducting cavity walls are a limiting factor. A recent paper [6] considers the losses associated with an iris feeding into the cavity and finds these to be unimportant.

When one switches out the energy in a waveguide resonant cavity one can obtain a pulse whose length (or number of cycles) is proportional to the waveguide length. However, the cavity Q (and potential power multiplication) is inversely proportional to this length [5]. So one will want to make the number of wavelengths in the resonant cavity not too large, but just large enough to obtain the maximum effect, depending on the application.

A commonly used cavity geometry is a rectangular waveguide operated in its fundamental $H_{1,0}$ mode. A rectangular waveguide of width 2a and height has an operating band given by

$$\begin{aligned} &4a \;<\; \lambda \;<\; 8a \\ &\lambda \;\equiv\; \text{wavelength} \\ &f\,\lambda \;=\; c \;=\; \text{speed of light in waveguide medium (here taken as free space)} \\ &f \;=\; \frac{\omega}{2\pi} \;=\; \text{frequency} \end{aligned} \tag{1.1}$$

If we stay in this frequency range then we are limited by the cross-section area $2a^2$ for energy propagation with a circumference of $6a$ on the waveguide walls where skin-effect losses take place. At 1 GHz, copper has a surface resistance of [1]

$$R_s \;\simeq\; 8.3\; m\Omega \tag{1.2}$$

The attenuation constant α (in $e^{\pm\alpha z}$) is proportional to R_s, and the reciprocal of the waveguide-cross-section dimension $2a$ [8]. As one increases a (and decreases the frequency accordingly) and keeps the length of the waveguide proportional to a (for a given number of wavelengths to produce some number of cycles when switched out) the total losses stay the same except for the reduction in R_s (which is proportional to $f^{1/2}$).

If one keeps f fixed (say around a GHz), then one needs to decrease R_s (say by cryogenics), or increase the volume-to-surface ratio of the cavity. (The stored energy is proportional to the volume, while the powerloss is proportional to the surface area of the boundary conductors.) In rectangular waveguide this leads toward overmoded cavities (which introduce their own problems). Here we consider the second possibility. Symmetry [3] and suppression of unwanted modes will play important roles.

Let us now define a figure of merit for rectangular waveguide cavities as

$$\xi \equiv \frac{\text{volume}}{\text{surface}} \text{ for general cavities}$$

$$\equiv \frac{\text{volume}}{\text{perimeter}} \text{ for waveguide cavities} \tag{1.3}$$

For the basic rectangular waveguide of width $2a$ and height a we have

$$\xi_0 \equiv \frac{2a^2}{6a} = \frac{a}{3} \tag{1.4}$$

We can compare various geometries by forming an enhancement ratio

$$\eta \equiv \frac{\xi}{\xi_0} \tag{1.5}$$

2. Doubling Waveguide Height

Figure 2.1 shows a waveguide with doubled height, i.e., $2a$. This still propagates the $H_{1,0}$ made ($\equiv \text{TE}_{1,0}$ mode) with the electric field in the x direction (vertical). Such a waveguide with square cross section, of course, has other modes of propagation depending on our choice of frequency. In particular there is the $H_{0,1}$ mode which is a 90° rotation of the $H_{1,0}$ mode (with the electric field in the y direction).

For this type of waveguide the figure of merit is

$$\xi = \frac{4a^2}{8a} = \frac{a}{2} \tag{2.1}$$

The enhancement is

$$\eta = \frac{3}{2} \tag{2.2}$$

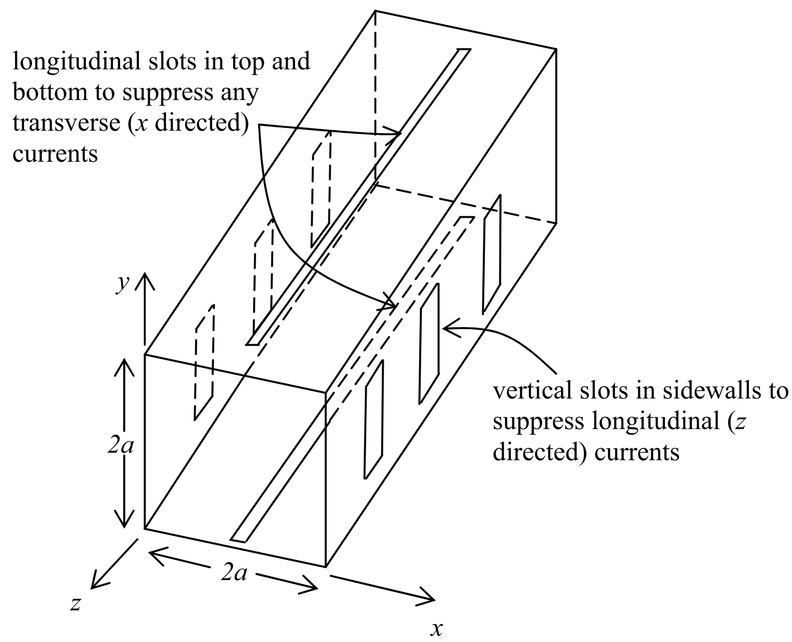


Fig. 2.1 Double-Height Rectangular (Square) W#aveguide for $H_{1,0}$ Mode.

To suppress this $H_{1,0}$ mode we can put slots in the waveguide walls as in Fig. 2.1. These are placed parallel to the surface current density, $\vec{J}_s$, (or equivalently perpendicular to the magnetic field $\vec{H}$ at the walls) so as not to interfere with the $H_{1,0}$ mode. These slots are vertical (y directed) on the side walls. On the top and bottom walls there are single longitudinal (z directed) slots centered in the walls. The $H_{1,0}$ mode then has slots perpendicular to $\vec{J}_s$ (parallel to $\vec{H}$) for suppression (with energy radiated outside the guide).

One could also place vertical slots in the cavity ends, $z = 0$ and $z = -L$. However other things may be occurring there related to feeding in and extracting power.

We need to excite this $H_{1,0}$ mode without exciting the $H_{0,1}$ mode. Here we can use symmetry as indicated in Fig. 2.2. As discussed in [7 (Ch. 1)] electromagnetic fields can be divided into two noninteracting parts, symmetric (sy) and antisymmetric (as), with respect to a symmetry plane. Figure 2.2 has two symmetry planes:

$$x = a \quad , \quad y = a \tag{2.3}$$

The rectangular aperture of height, a, is suited to a feeding rectangular waveguide of width, 2a, and height, a. The fields are symmetric with respect to the $z = a$ plane and antisymmetric with respect to the $y = a$ plane.

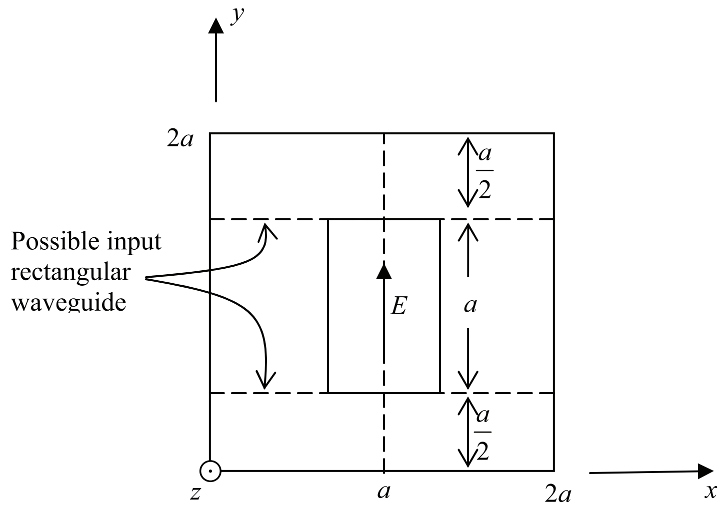


Fig. 2.2 Feeding Square Waveguide With Symmetrically Positioned Rectangular Iris

We still need to extract the energy via a closing switch. If we were to insert a switch directly in the waveguide of Fig. 2.1 we could locate it on the $x = a$ symmetry plane. With the arc closing in the y direction there is a problem maintaining the $y = a$ symmetry plane. One could extend symmetrical electrodes from the $y = 0$ and $y = 2a$ planes so as to place a short arc closely on the $y = a$ plane to minimize the asymmetry when the arc is closing. However, such a short arc limits the power handling capability of this waveguide cavity. This can be improved by enclosing the switch electrodes in a circular cylindrical dielectric tube, pressurized with a gas to raise the switch holdoff voltage.

Another possibility is indicated in Fig. 2.3. With the switch at $\lambda g / 4$ from the shorted end of a standard-height-a waveguide, we can place a quarter-wave-transformer section of waveguide (width $2a$, height $a\sqrt{2}$) [2]. Here we have

$$\lambda_g = \lambda\left[1-\left[\frac{\lambda}{\lambda_c}\right]^2\right]^{-1/2} \equiv \text{guide wavelength}$$

$$\lambda_c = 4a \equiv \text{cutoff wavelength} \tag{2.4}$$

With the switch recessed from the quarter-wave transformer only the $H_{1,0}$ mode can propagate here. Note that the $y = a$ symmetry plane is maintained through the transformer and switching section. While Fig. 2.3 shows the input waveguide with iris feeding in from the left, it could also feed in from the right near the switch.

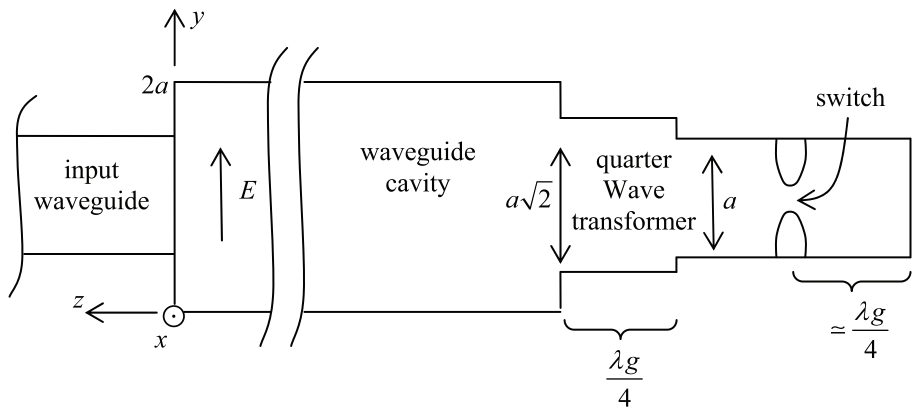


Fig. 2.3 Waveguide Height Reduction Near Switch

After the switch fires, changing the cavity length, one needs an output connection to extract the power. This can be accomplished by connecting a standard waveguide to the sidewall as shown in Fig. 2.4. This is like one part of a magic tee. It is positioned so that during the charging cycle it is centered on a null of the waveguide electric field, giving no propagating mode in the output waveguide. Note the maintaining of the $y = a$ symmetry plane.

As discussed in [4] this output guide should have half the height of the resonant cavity guide to match the impedance of the two waves in the cavity in parallel into the output guide. Since the waveguide cavity is now $2a$ high, this makes a good match to the standard output guide without reducing its height.

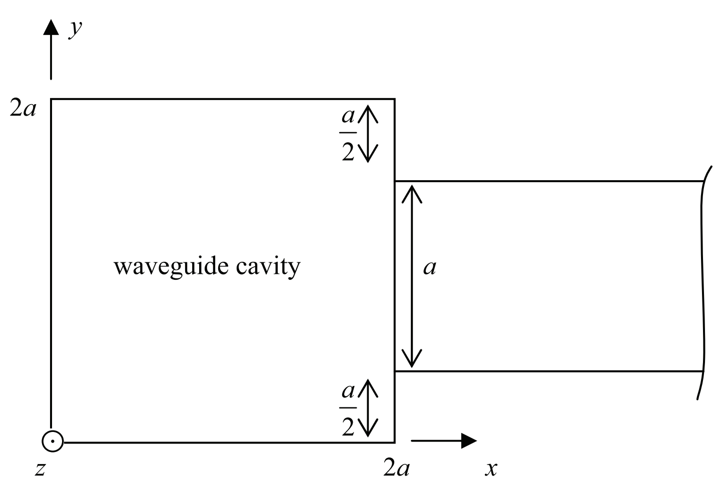


Fig. 2.4 Connection to Output Waveguide

3. Doubling Waveguide Height and Width

Going a step further, let us now consider doubling the width to 4*a*, besides the double height 2*a*. Again we utilize symmetry to select the $H_{1,0}$ mode. Now both the $x = 2a$ and $y = a$ planes are symmetry planes. The figure of merit is now

$$\xi = \frac{8a^2}{12a} = \frac{2a}{3} \tag{3.1}$$

The enhancement is now

$$\eta = 2 \tag{3.2}$$

Note that, with the increased width from 2*a* to 4*a*, the guide wavelength λ_g is also increased for a given free-space wavelength, λ. This will also have some effect on the power in the mode and the losses.

With the guide width doubled the $H_{2,0}$ mode can also propagate. So it is important that the iris in Fig. 3.1 be centered on $x = 2a$, so as not to couple to this mode. Furthermore, the sidewall, *y* directed slots and top- and bottom-wall slots (now centered on $x = 2a$) can still help in suppressing unwanted E modes, but the sidewall slots do not affect the $H_{1,0}$ mode, while the top and bottom slots (due to their position) do still have some effect.

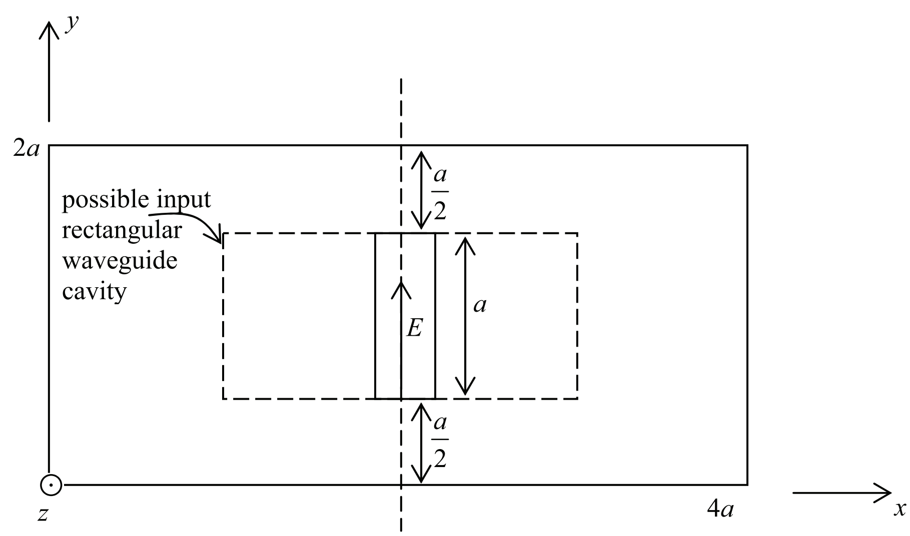


Fig. 3.1 Double-Dimensioned Rectangular Waveguide Cavity

We still need to compress the wave near the switch to avoid introducing other modes there. The switch can lie on the symmetry plane $x = 2a$ (conducting in the y direction) without introducing the $H_{2,0}$ mode or the $H_{0,1}$ mode (as well as the lowest E modes). As discussed in the previous section one can center a short switch arc on $(x, y) = (2a, a)$ to minimize introduction of unwanted modes.

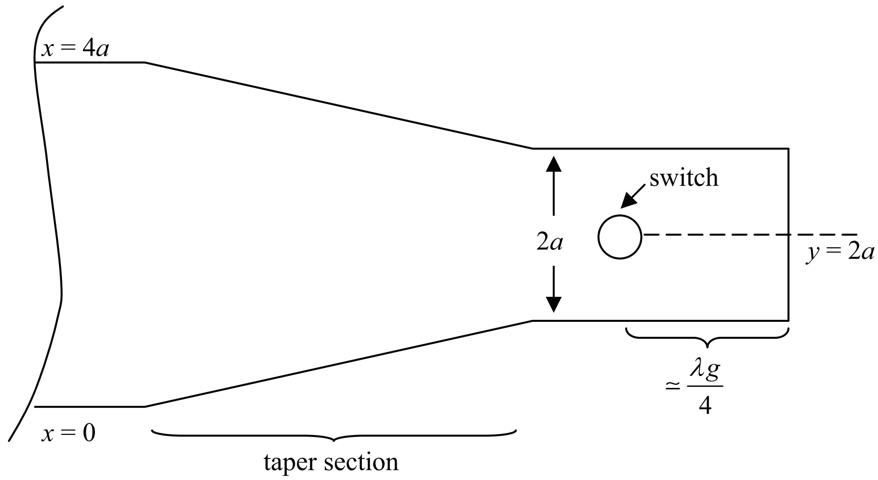
Another approach is to reduce the waveguide-cross-section dimensions near the switch as was done in Fig. 2.3. Now we can reduce both height and width by a taper as in Fig. 3.2, keeping every cross section centered on $(x, y) = (2a, a)$, and thereby maintaining both symmetry planes. Note that λ_g is changing as the wave propagates through the taper. If one wishes to reduce only the height, then the scheme in Fig. 2.3 is applicable.

This leaves the connection to the output waveguides. As illustrated, the scheme in Fig. 2.4 can be generalized to that in Fig. 3.3 with two output waveguides, so as to maintain the $x = 2a$ symmetry plane. The two waveguides can send power to two loads (such as two antennas with proper relative phasing), or the waveguides can rejoin into a single waveguide with an appropriate quarter-wave transformer. Note that the output guides are $2a' \times a'$. Here a' is not necessarily the same as a for impedance matching since the guide wavelength λ_g in the output guide is not in general the same as the λ_g for the $H_{1,0}$ mode in the waveguide cavity.

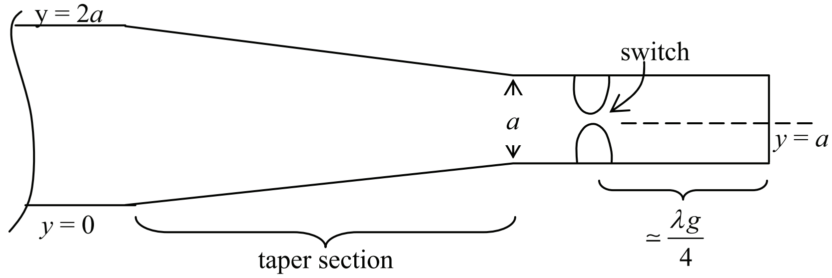
4. Concluding Remarks

Here we have elucidated some techniques for increasing the Q of microwave pulse-compression cavities. Fundamentally, these involve increasing the ratio of the cavity volume to the surface area of the conducting boundaries. For waveguide cavities these become overmoded. So care needs to be taken to avoid exciting and to minimize propagation of unwanted modes. This involves symmetry and providing loss to unwanted modes by interfering with their surface current patterns.

Perhaps these techniques can be extended to obtain even higher Qs of waveguide cavities. There is the low-loss $H_{0,1}$ mode of a circular waveguide which is supported by only-ϕ-directed surface currents. However, this will require special excitation and extraction geometries for such a cavity-mode pattern. One can, in principle, remove the cavity sidewalls to form a Fabry-Perot resonator [8]. However, at frequencies around 1 GHz, such would be quite large and not appropriate for some applications.



A. Top view



B. Side view

Fig. 3.2 Taper to Switch Region

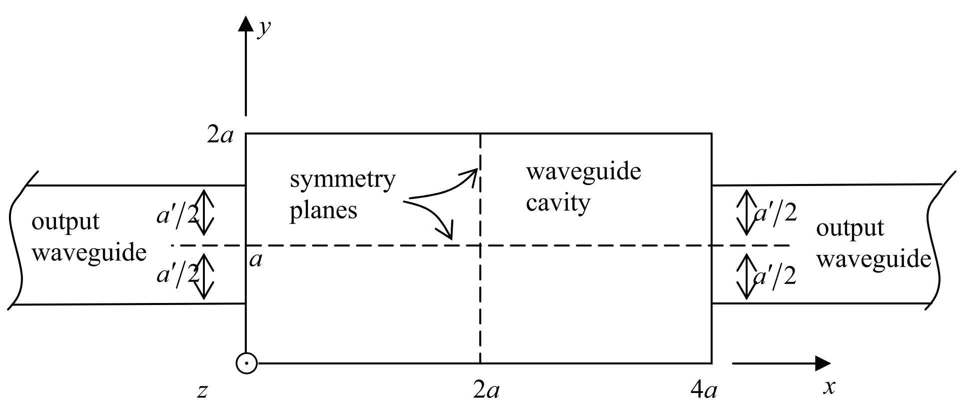


Fig. 3.3 Connection to Output Waveguides

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