THE ROTARY SLOT ATTENUATOR

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ABSTRACT

A new precision waveguide attenuator is presented which is the dual of the rotary vane attenuator. The device consists of rectangular to circular waveguide transitions coupled to a section of circular waveguide containing a pair of longitudinal slots. The entire circular section may be rotated so as to couple varying amounts of microwave energy into external loads. The attenuation produced varies as 20 log $\cos^2\theta$ where θ is angle of the slots with respect to the incident electric field. Since the absorbing material is external to the circular guide, this device is suitable for high power applications. The theoretical analysis is based on the equivalence of rectangular and circular waveguides insofar as slot coupling is concerned. The attenuation per unit length is derived and compared to the experimental results. A unit has been constructed which dissipates 10 KW average power and 100 KW peak power in the 2.6 - 3.95 GHz frequency band. The input VSWR was less than 1.15 through all values of attenuation and the insertion loss was less than 0.1 dB. The maximum value of attenuation was greater than 50 dB. Other units are described which were designed in the X-Band and Ku-Band frequency ranges.

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NOTES

I. INTRODUCTION

The rotary slot attenuator consists of a section of circular waveguide, slotted longitudinally, which rotates in a manner similar to a rotary vane attenuator. Energy is coupled out of the slot into an external load. Thus, the unit can dissipate much more power than a rotary-vane attenuator. Rectangular-to-circular transitions couple energy from the circular section and from the circular section to the output guide. Attenuation produced by rotation of the slot is the same as in rotary-vane attenuators:

$$A = 20 \log \mathrm{Cos}^2 \theta$$

where θ is the angle of the slot with respect to the incident electric field.

In systems applications, it is sometimes desirable to vary transmitter output power over a wide range. This can be troublesome because the output of high-power klystrons and TWTs is regulated by adjusting drive voltage. By varying the input drive, however, the output signal-to-noise ratio may be changed considerably since the noise produced by the tube is essentially constant. Thus, the resulting output signal-to-noise ratio varies as a function of the output power. But, with the rotary-slot attenuator, drive voltage need not be adjusted and the signal-to-noise ratio can remain constant at its maximum value.

Power monitoring of a transmitter output with large dynamic range also presents difficulties. In the past, several complex systems have been developed to switch output power monitors from one range to another and to protect measuring elements. Inserting the rotary-slot attenuator can simplify the monitoring and protection system.

The rotary-slot attenuator also can be used as a precision device since it can be made electrically as good as rotary-vane attenuators. It does not suffer from dielectric loading, warping of the resistive element or contact of the vane to the waveguide walls. It has the same properties of phase shift independency on attenuation as the rotary-vane attenuator.

II. THEORETICAL ANALYSIS

There are many similarities between the rotary-slot attenuator and the rotary-vane attenuator because indeed they are duals. The vane interacts with the electric fields and the slot interacts with the magnetic fields. The analysis is greatly simplified if incident fields are broken up into two orthogonal modes - one whose electric field is along the vane or perpendicular to the slot and the orthogonal component. One of these modes is greatly affected by the slot or vane and the other essentially passes through unaffected. The end transitions to rectangular waveguide play an important role in absorbing the energy which is in the rectangular TE_{01} mode.

Figure 1 shows the cross sectional views of the major parts of the rotary slot attenuator and the corresponding parts of the rotary vane attenuator with the electric field vectors of the dominate modes.

The input wave is designated by E, travels from rectangular to circular waveguide with an absorbing slot or vane which has no effect on the incident wave. It then enters the rotary section and is decomposed into two orthogonal components of magnitude E Sin θ and E Cos θ, where θ is the angle of the slot. The E Sin θ component is attenuated by the slot and the other component, E Cos θ, travels through the rotary slot section virtually unattenuated. This wave E Cos θ is further decomposed into two waves, $E \cos^2\theta$ and E Cos θ Sin θ, when it enters the fixed slot. The E Cos θ Sin θ wave is absorbed leaving the component $E \cos^2\theta$ at the output. The resulting attenuation produced is

$$A = 20 \log \cos^2\theta.$$

The attenuation formula $A = -20 \log \cos^2\theta$ is accurate only if the slot absorbs all of the power. For high values of attenuation or short length slots all of the power is not absorbed by the slot and some couples to the output. Due to the different propagation characteristics of the orthogonal modes, they may combine with variable phase at the output. This may cause some unwanted frequency response and marked departure from the simple attenuation formula.

Assume as in Figure 2 an incident wave E which is decomposed into two orthogonal components, E Cos θ and E Sin θ. Choosing a suitable reference point at the end of the slot, whose length is L, we have E Cos θ and $E\epsilon^{-\gamma L} \sin\theta$ where $\epsilon^{-\gamma L} = \epsilon^{-\alpha L - j\Delta\beta}$ and α is the attenuation per unit length of the slot and $\Delta\beta$ is the difference of the phase factors between the two orthogonal waves. At the output only, the Cos θ component of the wave transforms to the TE_{10} mode of the rectangular guide.

For maximum departure from $\cos^2\theta$ attenuation dependence we have,

$$\cos^2\theta \pm \epsilon^{-\alpha L} \sin^2\theta$$

the resulting attenuation is

$$L = 20 \log (\cos^2\theta \pm \epsilon^{-\alpha L} \sin^2\theta)$$

For a slot that only has a 30 dB attenuation the departure is shown in Figure 3.

For very accurate attenuation measurements it is necessary to have a very large slot attenuation. If, however, there is no attenuation in the slot, only the phase term is present and depending upon the propagation velocity a quarter or half wave plate phenomenon exists.

For high power application it is of interest to calculate the power dissipated in the various elements. The input transition from rectangular to circular waveguide with a slot on the top and bottom ideally dissipates no power - it is only there to stop some reflections from the rotary slot discontinuity and to prevent resonance build up.

The slot dissipates under ideal conditions of infinite slot loss - $E^2\sin^2\theta$ as shown in Figure 1. The output power is $E^2\cos^4\theta$ so that the end slot in the circular to rectangular transition dissipates a power equal to $E^2(1 - \cos^4\theta - \sin^2\theta)$. Figure 4 shows the fractional amount of power lost in each section as a function of angle. The end slot dissipates 1/4 of the incident power when $\theta = \pi/4$.

Since circular geometries with rectangular slots are inconvenient to handle mathematically, the circular guide operating in the TE_{11} mode is transformed to an equivalent rectangular guide operating in the TE_{10} mode. (The magnetic field in the region of the slot is the same if the slot is narrow.) The dimensions of the rectangular guide are chosen so that the two guides have the same cutoff frequency and the same power transmitted down the guide. The condition of equal cutoff wavelength, λ_c, required $2a_o = \lambda_c = 3.41\, a$, where a_o is the width of the rectangular guide and a is the radius of the circular guide.

The condition for equivalent power flow is satisfied by setting the power flow equal for the two modes and calculating the appropriate b_o in terms of a.

After the relationship between the two guides is established, we can then concern ourselves with calculating the power lost into the slot and therefore the attenuation per unit length of the slot section. By decomposing the TE_{10} mode into two waves, one traveling down the guide and the other transversed to the guide, one can compute the energy lost in the slotted section. The results of this analysis show that the attenuation per unit length

$$\alpha = \frac{8.54\, b_2 \lambda_g}{a^3} \left(\frac{1}{\cos^2 \beta L + b_2^2/b_1^2 \sin^2 \beta L}\right)$$

where λ_g is the guide wavelength in the TE_{11} mode of circular waveguide of radius a with a slot width of b_1 and a load width of b_2. The thickness of the slot is L, $\beta = 2\pi / \lambda_o$.

Figure 5 shows the total attenuation of an 8" section of slot in the X-Band region as a function of frequency.

III. EXPERIMENTAL RESULTS

Several units have been constructed. An X-Band unit is shown in Figure 6 which has an input VSWR of less than 1.15 and an insertion loss of less than .15 dB. The maximum value of attenuation is greater than 50 dB. It has a maximum value of attenuation versus frequency dependence similar to that shown in Figure 4. It was found to operate satisfactorily with 10 KW peak power and 1 KW average power.

A water cooled unit has been constructed in the 2.6 - 3.95 GHz frequency band. This unit dissipates 10 KW average power and 100 KW peak with an input VSWR less than 1.15 and an insertion loss of less than 0.1 dB.

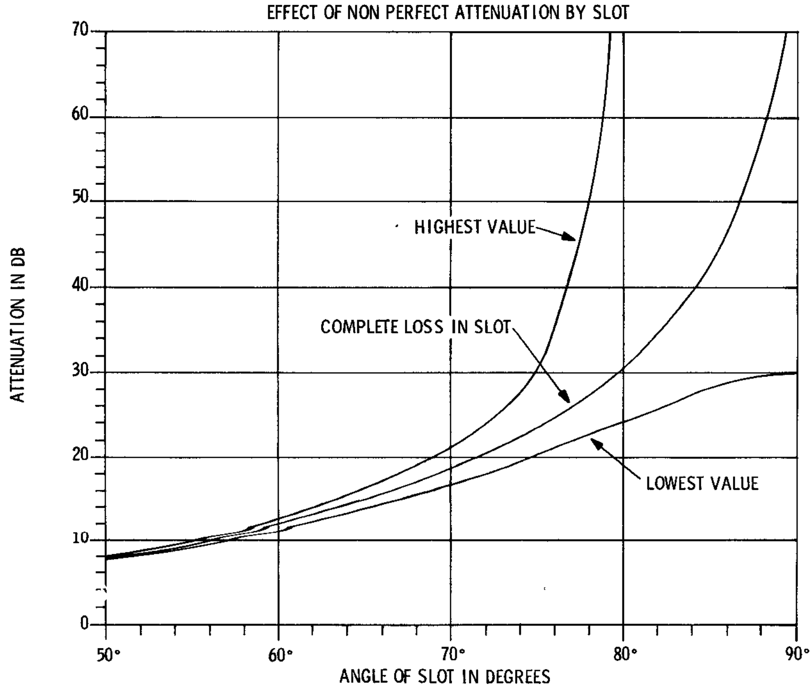


FIGURE 3
EFFECT OF NON PERFECT ATTENUATION BY SLOT

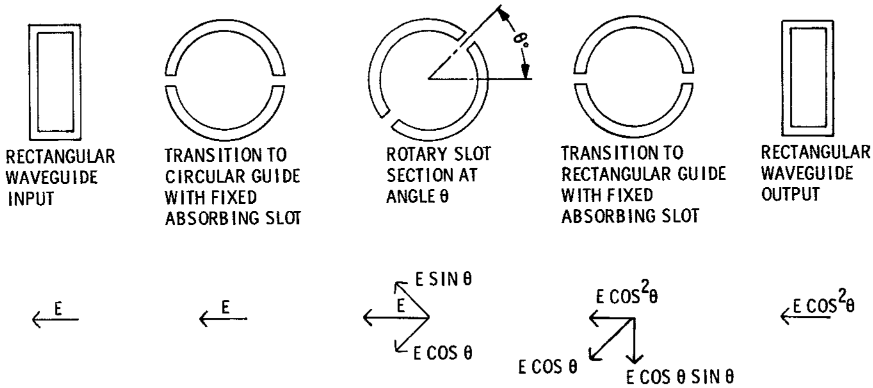


FIGURE 1A CROSS SECTIONAL VIEWS OF ROTARY SLOT ATTENUATOR AND ASSOCIATED ELECTRIC FIELDS

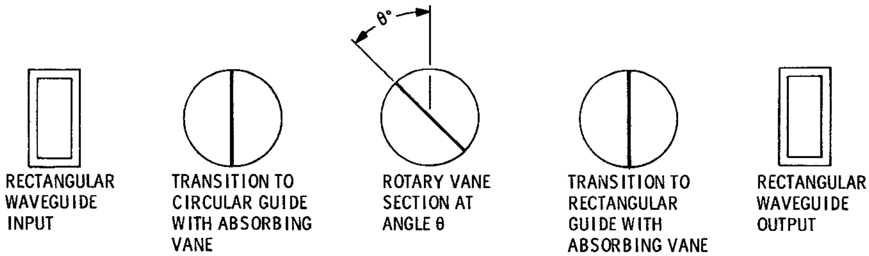


FIGURE 1B CORRESPONDING PARTS OF ROTARY VANE ATTENUATOR

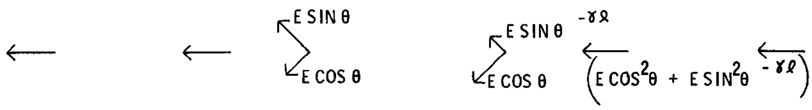


FIGURE 2 EFFECTS OF FINITE ATTENUATION BY THE SLOT OR VANE

FIGURE 4
FRACTIONAL POWER LOST AS FUNCTION OF ANGLE

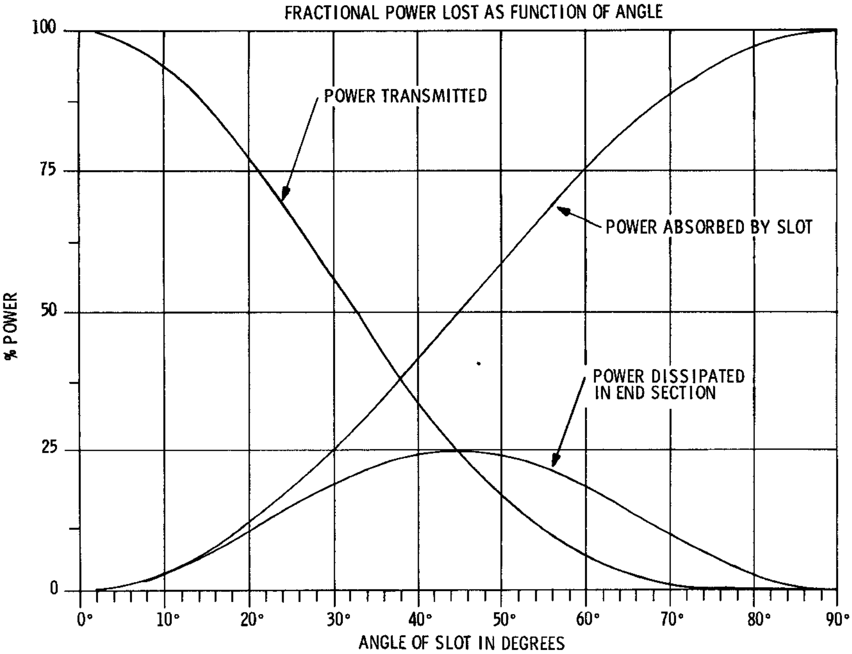
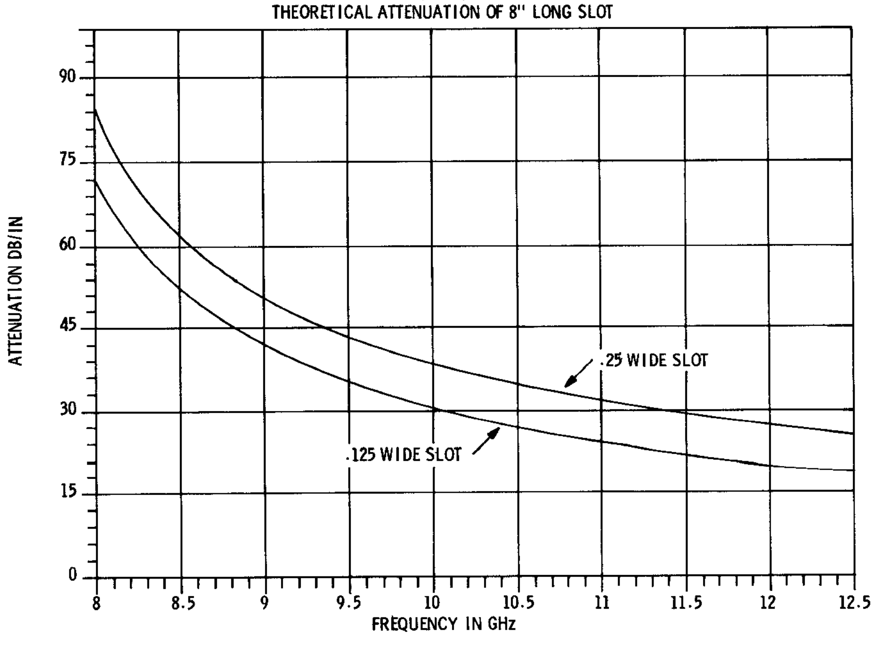


FIGURE 5
THEORETICAL ATTENUATION OF 8" LONG SLOT



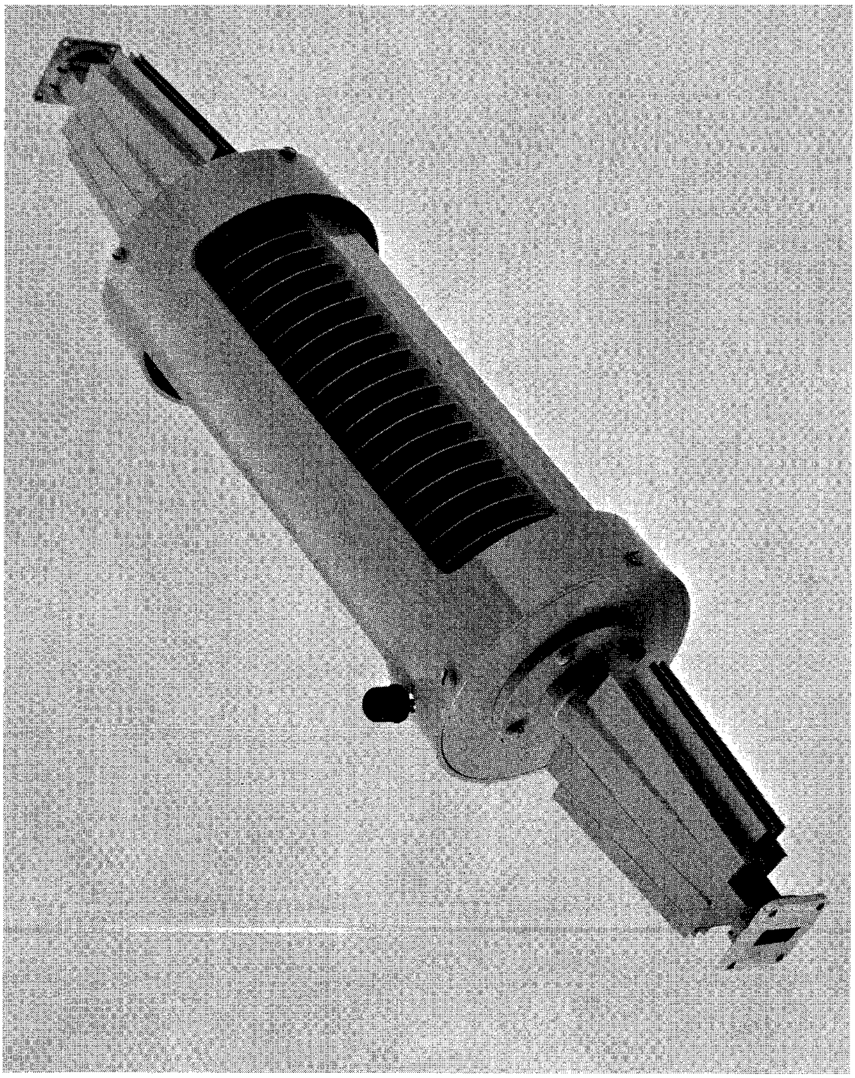


FIGURE 6 - COMPLETED ROTARY SLOT ATTENUATOR