LOW-LOSS QUASI-OPTICAL OPEN RESONATOR FILTERS

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ABSTRACT

A novel and efficient coupling method has been devised for the design of a low-loss quasi-optical open resonator filter. The method uses a narrow slot opening in the coupling waveguide. An insertion loss of less than 1 dB was achieved for the passband. The filters should have applications in many millimeter-wave and submillimeter-wave systems.

I. INTRODUCTION

Fabry-Perot or *open* resonators have been used at microwave/millimeter-wave frequencies for diplexers [1], dielectric characterization [2], antennas [3], and power combining [4-7]. Few of these applications have addressed the problem of efficiently coupling power into and out of an open resonator. This paper presents the use of narrow slots for efficient coupling and shows how the slots can be used to make a low-loss filter from an open resonator. The resonators should have many applications in millimeter-wave and submillimeter-wave systems where conventional filters are difficult to fabricate.

Various methods have been used to analyze the Fabry-Perot resonator [8,9]. The most widely used analysis, based on Goubau and Schwering's beamed waveguide transmission theory [10], was summarized by Kogelnik and Li [11]. Their theory assumes large apertures and neglects diffraction, but it provides accurate frequency and field information. The data presented in the fourth section of this paper supports this claim.

For a Fabry-Perot resonator to be made into a useful device, a method of coupling power into and out of the resonator must be devised. Previous methods employed include meshes [1], small apertures [2], waveguide apertures [12], dielectric launchers [5], and microstrip patch antennas [6]. Most of these methods introduce high losses due to poor coupling efficiencies. This paper reports a novel, simple, and low-loss coupling method using narrow slots. This method of coupling comes from a Gaussian beam antenna developed by W.C. Brown for microwave power transmission experiments [13]. The feed for the antenna is a waveguide opening covered by a thin half-wavelength resonant slot. The results show that the slot is a very efficient method for coupling power into and out of an open resonator and that this coupling method can be used to build a low-loss filter.

II. COUPLING DESIGN

The resonant slot is a common antenna in phased-array applications, and design rules for slot antennas are readily available [14]. The slot is simply a narrow aperture in a ground plane. The electrical length of the slot is slightly larger than its physical length, so that its resonant length is slightly shorter than a half-wavelength. The simplest feed for the slot is a waveguide, such as a rectangular waveguide operating in the dominant TE_{10} mode. The slots for these experiments were cut out of copper tape and taped over rectangular waveguide openings in aluminum groundplanes. A reflection measurement made of an X-band slot with an HP8510 network analyzer is shown in Figure 1. As the figure shows, the slot has a sharp resonance at 10.46 GHz. A far-field H-plane pattern of the slot at this frequency made in an anechoic chamber is shown in Figure 2. This pattern looks like that of a dipole. This is expected because the resonant slot is the dual of the half-wavelength dipole.

III. EXPERIMENTAL SETUP

The experimental setup is shown in Figure 3. The resonantor used in all the experiments is *plano-concave*, i.e., it has one flat and one curved reflector. The concave reflector was machined out of solid aluminum to a radius of curvature of 40 inches. Both of the reflectors are 9 inches in diameter, and each has at its center an 0.9 by 0.4 inch X-band rectangular waveguide opening which extends through the thickness of the reflector. The copper tape slot apertures are taped over the waveguide openings. The two reflectors are mounted on an optical rail which allows them to be moved with precision.

Before the two reflectors were aligned to form a resonator, the input characteristics of each slot in the reflector were individually measured. S_{11} and S_{22} measurements of the slots were made using an HP8510 network analyzer. For these measurements, the slots were facing away from each other so that they would not couple. The results are shown in Figure 4. Note that the slots have similar input matching and radiation characteristics. This is important because the device should be reciprocal for maximum efficiency.

IV. MODE MEASUREMENTS

The mode theory presented here comes from Kogelnik [11]. The fundamental modes of a Fabry-Perot resonator have a Gaussian field distribution at every cross-section along the axis of the resonator. As illustrated in Figure 5, most of the power of a fundamental mode is contained in an envelope called the *beam radius* where the field is $1/e$ of its axial value. For efficient coupling to the resonator, the coupling apertures should be located within the beam radii of the reflectors. Additionally, Mink has shown that if an array of apertures is used, the spacing, size, and taper of the array can be adjusted to maximize the coupling to

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the fundamental modes [4]. The phase fronts of the beam match the curvatures of the reflectors. At the *beam waist* between the reflectors, the beam radius is at a minimum, and the phase of the beam is flat. This means that a flat reflector can replace one of the curved reflectors at the beam waist. The higher order modes in cylindrical coordinates are products of Gaussian and Laguerre functions. These modes contain power that is not as tightly concentrated around the axis of the resonator as the power of the fundamental modes. For finite apertures, this means that the fundamental modes will be dominant.

The important dimensions of the resonator are d, the axial distance between the reflectors, and R_1 and R_2, the radii of curvature of the two reflectors. With these parameters, the frequencies of the modes are:

$$f_{plq} = \frac{c}{2d}\left[(q+1) + \frac{1}{\pi}(2p+l+1)\cos^{-1}\sqrt{(1-d/R_1)(1-d/R_2)}\right], \qquad (1)$$

where c is the speed of light. The parameter p describes the variations in higher order radial modes, and l describes the variations in higher order cylindrical modes. Finally, q gives the number of nodes in the field along the axis of the resonator. When $p = l = 0$, q determines different fundamental modes.

If the higher order modes are lumped into a single parameter n, where

$$n = 2p + l, \qquad (2)$$

and if the resonator is made plano concave as in the case of Figure 3 ($R_1 = R, R_2 = \infty$), (1) becomes

$$f_{nq} = \frac{c}{2d}\left[(q+1) + \frac{1}{\pi}(n+1)\cos^{-1}\sqrt{(1-d/R)}\right]. \qquad (3)$$

As an experimental verification of the mode theory, Table I compares the measured and theoretical frequencies obtained from an S_{11} measurement of the resonator. The fundamental is described by $n = 0$. The agreement is very good, with errors less than or equal to 1.1%.

V. FILTER PERFORMANCE

By moving the reflectors closer together than in the previous section, a low-loss filter is formed. Figure 6 shows an S_{21} measurement of the resonator for $d = 1.99$ cm. This is the $q = 0$ fundamental ($n = 0$) mode. The transmission loss at the peak of the resonance is only 0.8 dB, including diffractive, conductive, and mismatch losses. The return loss is about 20 dB. For low-loss, the reflectors must be closely spaced, and the alignment of the reflectors is fairly critical. Q_L, the loaded Q, of this resonance is about 139. Q_U, the unloaded Q, is given by [15]:

$$Q_U = \frac{Q_L}{1 - 10^{-L/20}}, \qquad (4)$$

where L is the insertion loss of the filter in dB. Q_U for this resonance is about 1580.

VI. CONCLUSIONS

An open cavity filter with less than 1 dB of loss has been demonstrated. The resonant slot has been shown to be an efficient means for coupling power into and out of a Fabry-Perot resonator. The slot-fed coupling method also has applications in power combining, diplexing, and resonant cavity antennas.

VII. ACKNOWLEDGEMENTS

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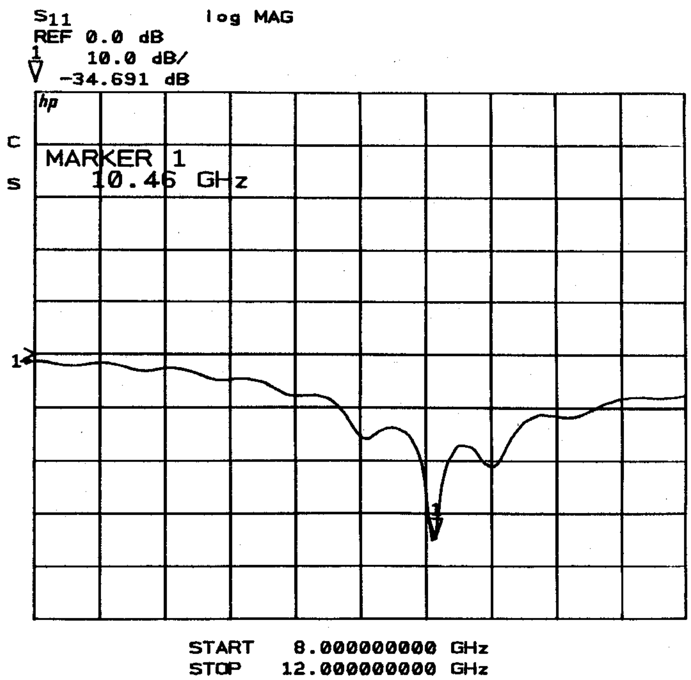

Figure 1: S_{11} for an X-band waveguide fed slot

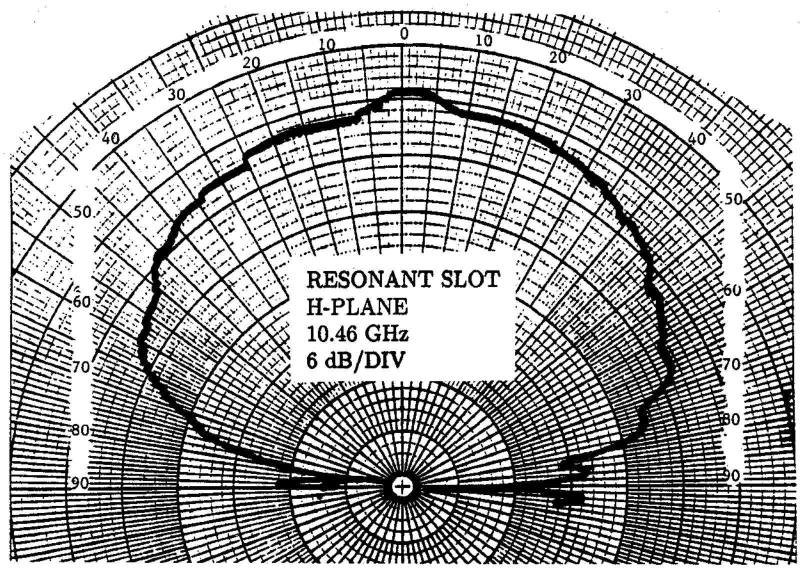

Figure 2: H-plane pattern of the X-band waveguide fed slot

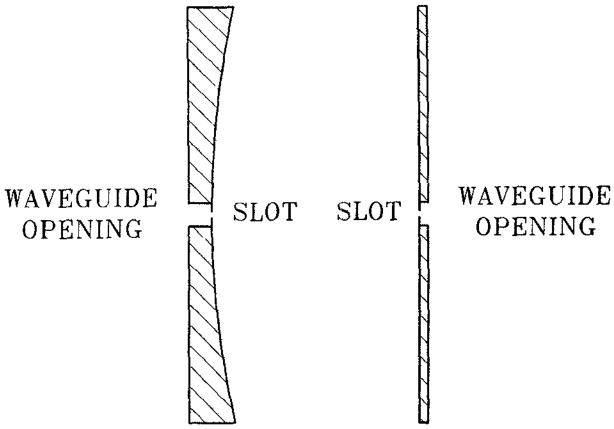

Figure 3: Experimental setup

	$R = 40$ in	$d = 5.29$ cm	$q = 2$
n	measured (GHz)	theoretical (GHz)	error (%)
0	8.74	8.71	0.3
1	8.96	8.92	0.4
2	9.18	9.13	0.5
3	9.38	9.34	0.4
4	9.60	9.54	0.6
5	9.86	9.75	1.1

Table I: Resonant frequencies

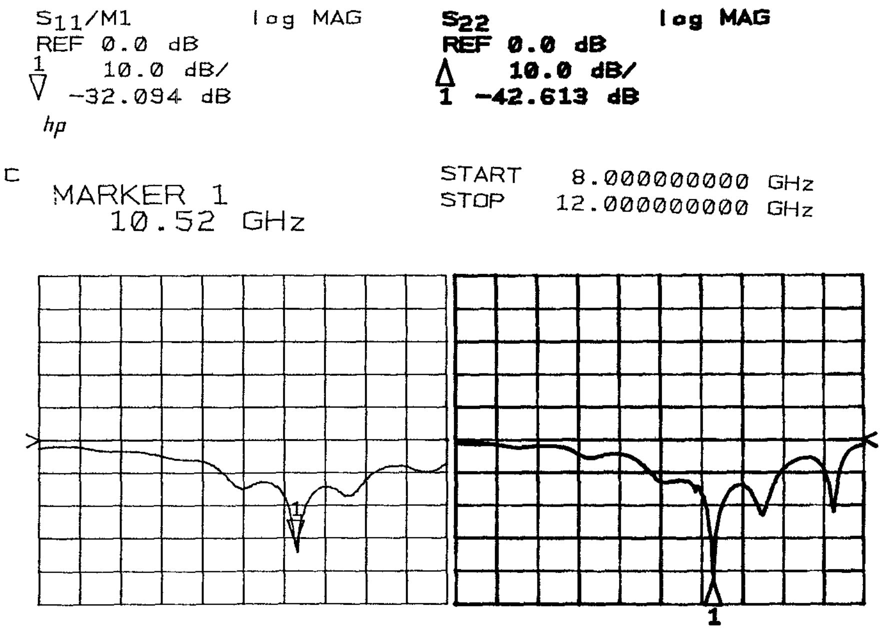

Figure 4: S_{11} and S_{22} for the slots used in the resonator experiments

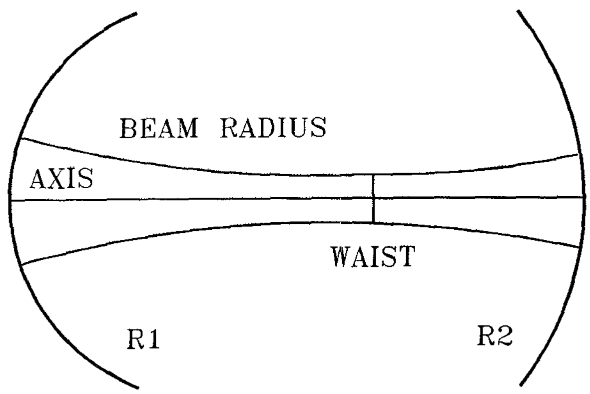

Figure 5: Fundamental mode in a Fabry-Perot resonator

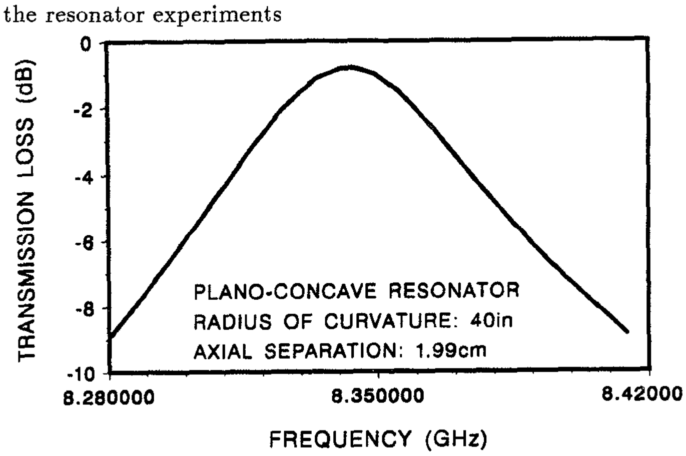

Figure 6: Filter performance