ELLIPTICAL CAVITY RESONATORS FOR DUAL-MODE NARROWBAND FILTERS

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I. Abstract

A novel cavity resonator with elliptical cross-section is proposed in order to realize dual-mode narrowband filters without tuning and coupling elements. No discontinuities are required inside the cavities hence significantly enhancing the unloaded Q, the ability to operate with higher power levels, and the ease of manufacturing.
Dual-mode coupling is generated by the step discontinuity between the input rectangular waveguide and an inclined elliptical waveguide; a rigorous full-wave electromagnetic model for this discontinuity has been developed. Proper choice of the ellipticity and of the inclination angle allows us to obtain the desired coupling and tuning actions.
Representative prototypes of elliptical cavities exhibiting various degrees of coupling have been carefully measured; the favorable comparison between experimental and theoretical results proves the accuracy of the model and its applicability for narrowband X/Ku band filters.

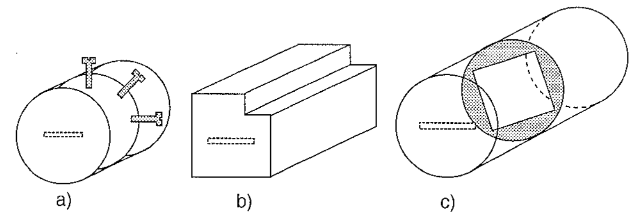

Fig. 1. Some cavities used and proposed for dual-mode filters.

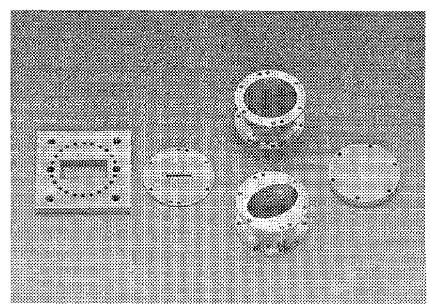

Fig. 2. Photograph of the proposed cavity with elliptical cross-section. From left to right: input rectangular waveguide flange; input iris; two test cavities of elliptical cross-section; short circuit.

II. Introduction

Dual-mode narrowband filters, since their introduction in the early seventies [1], are playing a major role in satellite payloads and are still receiving considerable attention for possible improvements. At first, attention was conveyed to the synthesis of transfer functions or to the tuning of actual filter structures [1]–[3]. More recently, however, investigations have been mainly focused on alternative filters structures, in order to realize the goal of filter manufacturing directly from a set of physical dimensions as obtained from a computer-aided synthesis algorithm, hence avoiding any post-manufacturing adjustments.

Several cavities are currently used for dual-mode filters, some of them being shown in Fig. 1, with relative advantages and disadvantages briefly summarized in the following. The first cavity structure proposed for dual-mode filters [1], Fig. 1(a), is a standard circular cavity with screws for providing the necessary tuning and coupling actions. The high field concentration near the screws, the modest suitability for CAD representation [4], and the necessity of post-manufacturing adjustments, have stimulated alternative arrangements. Following designs have tried to remove the presence of screws altogether; solutions for rectangular [5] and circular [6] cavities have been recently presented and are shown in Fig. 1(b) and (c), respectively. In both cases, however, there are margins for improvements. The computer-aided design of Fig. 1(b) suffers from numerical inefficiencies that, owing to the nonseparable nature of the waveguide cross-section, poses problems when computing a large numbers of modes, as necessary for narrowband filters. The circular cavity of Figure 1(c), though being very suitable for efficient and accurate CAD, presents a discontinuity placed inside the circular cilindrical cavity which causes a degradation of the unloaded Q. Moreover, both solutions [5], [6] exhibit sharp edges within the cavity body, hence reducing power handling capabilities.

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We propose a new cavity, shown in Fig. 2, which is formed by a length of waveguide with elliptical cross-section inclined with respect to the input rectangular waveguide. The proposed cavity has the following advantages:

- higher power handling capability, higher Q
- ease of manufacturing
- suitability for CAD modeling

The first point is achieved since no discontinuities are present inside the cavity. The manufacturing is mainly realized by using milling techniques; finally, efficient and accurate CAD modeling is achieved since we consider a cavity formed by a guide with separable cross-section, i.e. with the spectrum analytically known.

It will be shown in the next Section that, by properly inclining (see Figure 2) an elliptical cavity with respect to the input rectangular guide and by suitably selecting the cavity aspect ratio (defined as a/b, Fig. 3), it is possible to obtain the desired coupling and tuning actions without introducing any element inside the cavity[1]. In Section IV. we present the rigorous description of the step discontinuity between the input rectangular waveguide and the elliptical cavity. Experimental and theoretical results for the proposed cavity filter response are illustrated in Section V..

III. The dual mode elliptical cavity

Starting from the work done in [6], it is apparent that the three independent controls needed in a dual mode cavity (represented by the three screws in Figure 1(a)) are provided, in the case of Figure 1(c), by the aspect ratio of the rectangle, by its inclination, and by the cavity length.

In this Section it is seen that the same result can be achieved by changing the original circular cross-section into a (slightly) elliptic shape. By properly inclining (see Fig. 2) the resulting elliptical cavity with respect to input iris and by selecting suitable values for aspect ratio and length, a new type of dual mode cavity without discontinuities and sharp edges within its body, is obtained. Its nearly optimum shape maximizes the unloaded Q and the capability of handling high power levels.

In order to understand the coupling and tuning properties of the cavity it is convenient to consider a few cases with different inclination angles θ with respect to a vertically polarized field incident on the cavity through a thin horizontal slot, as depicted in Fig. 3. In the following, the reference coordinates are assumed to be those associated with the incident field (and the input iris), regardless of the cavity inclination.

Let us first observe the limiting cases shown in Figure 3 (e) and (a), where the major ellipse's axis is either aligned or in quadrature with the incident field: it is apparent that no cross-coupling takes place due to the symmetry with respect to the y-axis. It is also noted that the aspect ratio of the ellipse only performs a tuning action which increases for larger aspect ratios.

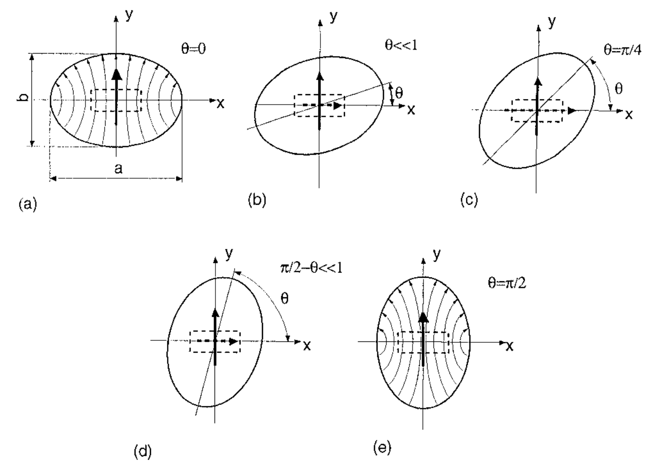

Fig. 3. Step discontinuity between a rectangular waveguide and an elliptical waveguide inclined of an angle θ. The different cases for various inclination angles show the generation of the orthogonal polarization. The vertical arrow (continuous line) represents the field incident from the rectangular waveguide, while the horizontal arrow represents the quadrature component generated inside the elliptical guide as seen from the input guide.

In the case shown in Fig. 3(b), (c) and (d) it is apparent that symmetry with respect to the y-axis is no longer present: as a consequence a superposition of the fields of cases (a) and (e) must be present inside the cavity. Such superposition can be also thought as composed by the sum of a vertically polarized electric field and a horizontal one. It is noted that, while the vertical electric field couples with the incident field through the input iris, the horizontal field is decoupled. The latter is coupled to the vertical one by the cavity inclination. This circumstance justifies the use of the proposed cavity for dual mode filters applications. The above considerations, here heuristically derived, are rigorously confirmed from the full-wave electromagnetic analysis carried out in the next Section.

For a fixed aspect ratio, it is also apparent, see Fig. 3, the increase of coupling from case (a) to (b) and from (e) to (d); maximum coupling is attained for the configuration shown in (c). The coupling value, however, is also dependent on the aspect ratio, increasing for larger aspect ratios, and tending to zero when the ellipse approaches the circular shape. Moreover, case (c), being symmetric with respect to the diagonal bisecting the first and third quadrants, performs no tuning action, since both modes (vertical and horizontal) are subjected to the same boundary conditions.

[1]patent pending

IV. Rigorous analysis of the step discontinuity between a rectangular and an elliptical waveguide

The rigorous full-wave characterization of the step discontinuity between waveguides with rectangular and elliptical cross-sections play a fundamental role in the design of the proposed dual-mode filter cavity. The above step discontinuity problem has not appeared in the literature so far; recently, the step discontinuity between two confocal elliptical waveguides has been considered in [8]. A detailed exposition of the step discontinuity between rectangular and elliptical waveguides would require a quite lengthy discussion; hence we will limit ourselves to mention only the main points relevant for the cavity design.

A. Computation of modal spectra

The spectrum computation of elliptical waveguides has received considerable attention in the past [9], [10]; more recently, interest has raised again [11]–[13]. It is noted, however, that for narrowband filter applications a considerable accuracy is required; moreover, for typical cases, the algorithm should be able to provide a fairly large number of modes (about 400 TE and 400 TM modes for the accurate analysis of the step discontinuity). These facts pose several problems and a new computation scheme has been developed in order to efficiently calculate the modes of elliptical waveguides.

B. Overlapping integrals

Once the cut-off frequencies have been calculated, and the eigenvalues of Mathieu equation have been obtained, it is a relatively easy task to compute the Mathieu functions according to the expansions reported in [9], [10]. The coupling (overlapping) integrals between a rectangular waveguide and an inclined elliptical waveguide are then computed by using Green's identity, i.e. by reducing the surface integrals to contour integrals performed along the boundary of the rectangular waveguide. The latter contour integrals are numerically evaluated and advantage is taken of symmetries in order to reduce the computer effort.

C. S matrix of the discontinuity

After computation of the overlapping integrals we are in a position to apply standard modal analysis as for circular waveguides [7].

It is worthwhile to point out that the overall efficiency of the code for the scattering parameters of the step discontinuity between a rectangular and an elliptical waveguide is fairly good. As an example, the computation of the scattering matrix for a typical discontinuity takes about 3 seconds for each frequency point on an HP K200.

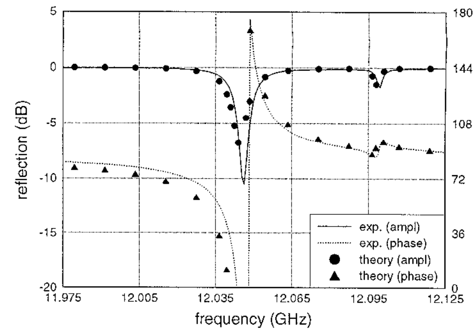

Fig. 4. Measured and computed response of an inclined elliptical cavity with a = 22 mm, b = 21.9 mm, θ = 60 degrees.

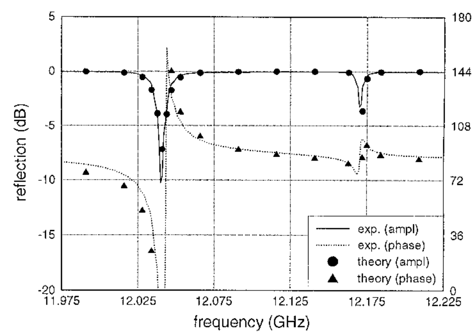

Fig. 5. Measured and computed response of an inclined elliptical cavity with a = 22 mm, b = 21.6 mm, θ = 30 degrees.

V. Experimental and theoretical results

A. Ease of manufacturing

Several prototypes of elliptic cavities with different aspect ratios have been machined out of aluminum. The lack of discontinuities inside the cavities has enabled the use of a numerically controlled milling machine. Electric discharge erosion has been limited to input coupling irises, resulting in a potential cost-reducing technology. In particular, good internal surface finish (which has a direct impact on the cavity loss) can be achieved with a substantial cost reduction with respect to a fabrication involving heavy electric

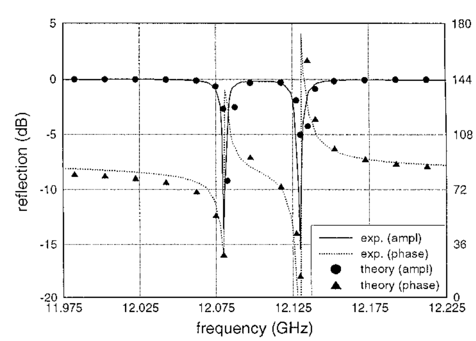

Fig. 6. Measured and computed response of an inclined elliptical cavity with a = 22 mm, b = 21.6 mm, θ = 75 degrees.

discharge steps.

B. Unloaded Q

Also in this case the the cross section uniformity plays an important role. All cavity samples were made using aluminum alloy 7075 T6, which displays a typical conductivity rated at 30-35% that of annealed copper. A simple calculation performed for a circular cavity having the approximately the same cross section, and with a practical efficiency of 58%, deduced from [14], gives an unloaded Q value slightly less than 4000 at 12 GHz. Measured Q's of elliptic cavities are all in the range 3700 - 3800, quite close to the theoretical prediction. Note that these values are nearly 50% higher than those measured in [6], and 25% higher than that of a comparable rectangular cavity.

C. Modeling accuracy

Cavity aspect ratios suitable for a dual mode application are those close to the circular shape, since it is to be expected [6] that a small shrinking of the minor axis of the ellipse is sufficient to produce the desired coupling action.

Two aspect ratios have been, in particular, tested under a moderately large input coupling sufficient to overcouple the resonators in order to get a significant response both in amplitude and in phase. Tested aspect ratios a/b are 1.004566 for cavity 1 (corresponding to a major axis a of 22 mm and a minor axis b of 21.9 mm) and 1.01852 for cavity 2 (corresponding to a major axis a of 22 mm and a minor axis b of 21.6 mm). All cavities have been measured in the range of inclinations from 0 to 90 degrees with a step of 15 degrees; precision alignment pins have been used in order to ensure close control of the setup under measurement. Representative data are reported in Figs. 4 to 6, where measured responses are also compared with mode-matching simulations. In particular, Fig. 4 shows cavity 1 with an inclination of 60 degrees. We may note that a very good agreement is maintained even for this aspect ratio that, being close to the circular shape requires a fairly lengthy and time consuming mode search for the elliptic guide. Cavity 2 is shown for two angular positions of 30 (Fig. 5) and 75 degrees (Figure 6), respectively. Apart from the good agreement between theory and experiment, it is interesting to observe the situation of Figure 6, where the depth of the two resonant peaks is approximately equal.This corresponds to a synchronous tuning of the two resonant modes and further proves the tuning and coupling capability of the new cavity.

VI. Conclusions

A novel cavity structure for dual-mode narrowband filters has been presented which significantly improves the unloaded Q, the ability to operate with high power levels, and the ease of manufacturing. The cavity has elliptical cross-section and no tuning or coupling elements are present in its interior, hence allowing manufacturing by milling techniques.

Appropriate tuning and coupling actions are obtained by suitably selecting the inclination angle with respect to the input rectangular waveguide and the ellipticity of the cavity. A rigorous full-wave electromagnetic model for the step discontinuity between rectangular and elliptical has been developed. Measured and theoretical results for different inclination angles and different values of ellipticity of the cavity have been presented showing the accuracy of the electromagnetic analysis and the validity of the proposed cavity for dual-mode filters applications.

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