A New Family of All-Inductive Dual-Mode Filters

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***Abstract*—In this paper, we describe a new family of dual-mode filters that is based on the use of simple inductive discontinuities in a rectangular waveguide environment. The proposed filter structure can be analyzed and optimized very efficiently using multimode equivalent network representations, thus leading to a simple and rapid development procedure. In addition to theory, the measured performance of a number of filter structures is also presented, thereby fully validating the proposed filter concept.**

***Index Terms*—Dual-mode filters, EM simulation, inductive filters.**

I. Introduction

DUAL-MODE filters in circular waveguide are commonly used in the input/output networks of communication satellites, and their basic features are now well understood (see, e.g., [1] and [2]). In the classical industrial implementation, a dual-mode filter uses cross-shaped irises for the inter-resonator couplings and will, in general, have a minimum of three tuning screws per cavity that need to be adjusted manually. Furthermore, due to the interactions between the coupling irises and tuning screws, a significant experimental characterization effort may be required for the correct dimensioning of the coupling irises.

To reduce (or eliminate) manual tuning, and experimental characterization, what is generally required is an efficient software tool for the full-wave electromagnetic (EM) simulation of the complete filter structure. Recently, several contributions have been made in this area proposing, for instance, the use of a square waveguide [3], [4], or alternative filter geometries (see, e.g., [5]–[8]). Furthermore, an attempt was also made to model tuning screws using, for instance, a circular-ridge waveguide together with a finite-element procedure [9], [10]. More recently, a very accurate and efficient software tool was demonstrated, which can indeed be used for the design and optimization of the complete filter structure, including the effects of tuning screws [11] to [13].

Although all of the results mentioned above have indeed very significantly advanced the state-of-the-art in this area, the manufacturing of satellite output multiplexers based on dual-mode filters in circular waveguide still requires very significant time and cost. This is mainly due to two aspects of the design and manufacturing processes. The first is that even though the computer-aided design (CAD) tools developed are indeed practical for single filter designs, they are not fully adequate for the design of complete multiplexers with many channels (typically from 10 to 20 are required). The second is that the geometry that is required can have very complex shapes and it is, therefore, very difficult to realize mechanically with the required precision (usually better than 2 μm or less).

The objective of this paper is to introduce a new family of dual-mode filters, which is based on the use of simple inductive discontinuities in rectangular waveguide environment (patent pending). The major features of this new family of filter implementations are essentially three. The first is that since they only use inductive discontinuities in rectangular waveguides, they can be analyzed and optimized much more accurately and efficiently than the standard circular waveguide implementations, even for complex multichannel implementations. The second is that they are ideal for low-loss high-power applications. The third is that the required filter structure is extremely simple and very well suited for low-cost high-precision machining so that the total development and manufacturing effort is very significantly reduced.

In the remainder of this paper, we first describe in detail the basic concept of the new filter family. We then describe a filter design procedure and discuss a number of specific filter design examples covering symmetric and asymmetric, tuned and tuning-less implementations, both wide- and narrow-band. Finally, in addition to simulations, measured data are also presented, thereby fully validating the concepts proposed.

II. Dual-Mode Filters in Rectangular Waveguide

The basic dual-mode filter in a circular waveguide resonator is based on the use of the two degenerate TE_{11n} modes with electric fields rotated 90° with respect to each other. Using this two modes, a single resonator can provide two independent electrical resonances. By connecting in series two such resonators, one can then introduce cross-couplings between the four independent resonances, thereby obtaining complex filtering functions.

The coupling between the two independent resonances within each resonator is introduced with a tuning screw at 45° with respect to the electric fields of the two resonances; the inter resonator coupling and the input output couplings are introduced with coupling irises. The tuning of the individual resonances is achieved with additional screws parallel to the electric field of the specific mode being tuned. All of these elements represent discontinuities in the resonator environment, which excite both TE and TM higher order modes. The presence of these higher order modes is what makes the EM analysis of this type of structure a very demanding task.

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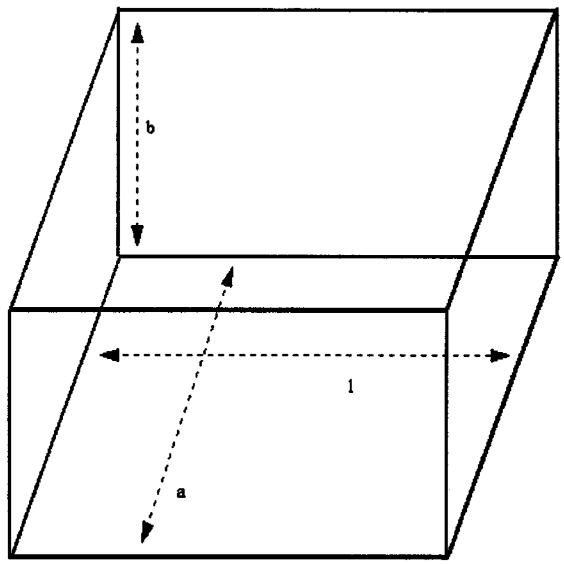

Fig. 1. Basic rectangular resonator.

The new family of dual-mode filters proposed in this paper is based on the use of a pair of resonant modes of a *single family* of modes of a rectangular resonator. The use of higher order modes in rectangular waveguide filters is not new in itself and many contributions can be found in the technical literature exploiting the various possible modal interactions (see, e.g., [14]–[19]). All of the above contributions, however, basically describe single-mode filters structures in which each resonator provides one transmission pole, and where the higher order mode interactions are used to implement transmission zeros to increase the filter selectivity. The novelty introduced in this paper is in that each cavity of the structures proposed produces two transmission poles and one transmission zero, thereby allowing the implementation of simple "planar" dual-mode filter structures.

Following the concept described in this paper, many choices are indeed possible, all of which share the same basic features. To find the modal combinations which are possible in a rectangular resonator of sides a, b, and l (Fig. 1), we first impose that the eigenvalue relative to the dimension b is equal to zero. Next, we impose the condition that both modes resonate at the same frequency, namely,

$$\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{l}\right)^2 = \left(\frac{p\pi}{a}\right)^2 + \left(\frac{q\pi}{l}\right)^2 \quad (1)$$

where the subscripts m, n refer to the first mode and p, q refer to the second. Equation (1) leads to the following expression for the initial choice of the ratio a/l in relation to the chosen mode pair:

$$\frac{a}{l} = \sqrt{\frac{m^2 - p^2}{q^2 - n^2}}. \quad (2)$$

The resonance wavenumber is instead given by

$$k_o = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{l}\right)^2}. \quad (3)$$

The only additional constraint that must be imposed in order to obtain a dual-mode operation is that the modal indexes m and p (and n and q) must be different. By imposing this last condition, one ensures, in fact, that on each side of the resonator, the field distributions of the chosen resonant modes are orthogonal, thereby allowing for the dual-mode operation.

It is important to note that in all of the above equations, the wavenumber relative to the b dimension has been set equal to zero. As a consequence, one obtains very simple filter structures containing only *inductive* discontinuities, which are at the same time easy to analyze and easy to fabricate with high mechanical accuracy.

Another important feature of this new dual-mode filter implementation is that the quality factor Q of the structure can be adjusted by simply changing the height of the resonator so that very reduced insertion losses can be achieved. Furthermore, since the height of all the coupling apertures is equal to the full height of the filter, no multipaction problems are encountered and high-power performance can be easily achieved without any problems.

III. Filter Design

The numerical efficiency of the EM analysis of all of the structures described in this paper has a very important consequence: the design and optimization of the filters can be simply carried out by using an efficient full-wave simulator. For all of the examples discussed in this paper, the design procedure has been as follows. The first step is to use (2) and (3) to obtain the ideal dimensions of a resonant cavity at the frequency of interest. The next step is to analyze a single cavity structure with an efficient EM simulator. In this paper, we used the package WIND developed at the European Space Research and Technology Centre (ESTEC), Noordwijk, The Netherlands. This software package is based on the multimode impedance network representation of an inductive step in a rectangular waveguide environment [20, p. 213].

The optimization of a single-cavity filter requires only the adjustment of three parameters, namely, the input/output apertures and the length and width of the resonator. To start, the offset can be chosen to be zero. Using, for example, the TE_{102} and TE_{201} resonances at 11 GHz, we obtain a resonator size of about 30 mm. Using a coupling aperture 10-mm wide and 2-mm thick, with zero offset, we obtain the result shown in Fig. 2 (input/output waveguide WR75). The basic dual-mode behavior is clearly evident. One important feature of the results obtained is the presence of a transmission zero on the right-hand side of the passband. This zero is due to the fact that the input output apertures couple to both the TE_{102} and TE_{201} modes [21]. However, since the TE_{102} resonance changes sign to the field going from the input to the output, a destructive interference is produced, thus creating a transmission zero. The position of the transmission zero can be easily moved to the left-hand side of the bandpass by simply changing the ratio of cavity length to cavity width. Changing the width of the resonator to 31 mm, we obtain, for instance, the result shown in Fig. 3.

These two basic structures can then be used as starting points for the optimization of more complex filters composed of cas-

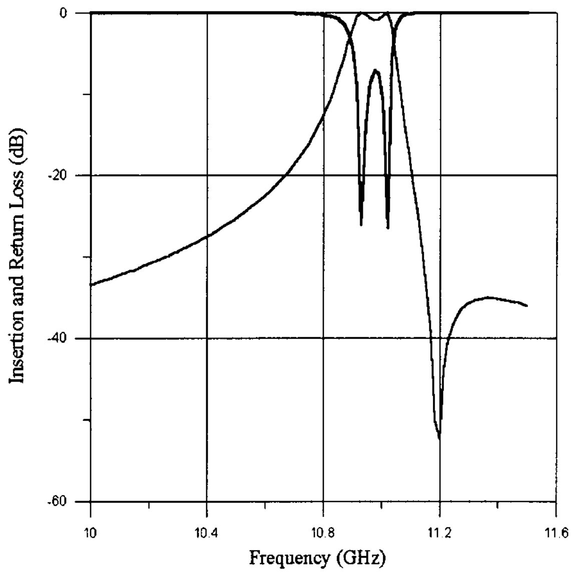

Fig. 2. Basic response of a dual-mode resonator with one transmission zero to the right-hand side of the passband.

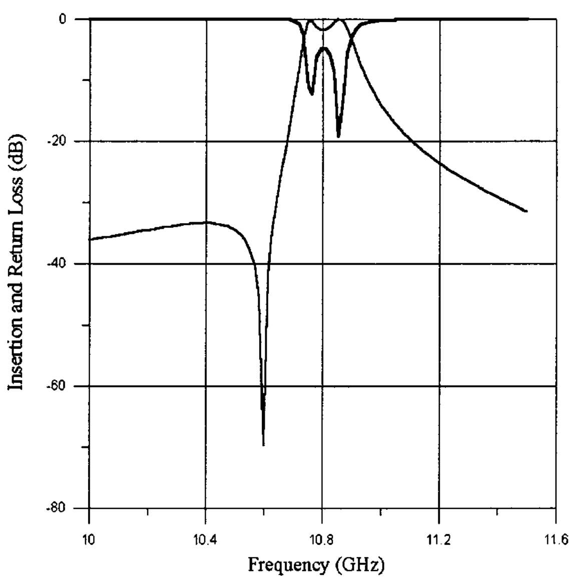

Fig. 3. Basic response of a dual-mode resonator with one transmission zero to the left-hand side of the passband.

caded resonators using directly as a target function the final desired electrical behavior [22]. The position of the transmission zeros can be adjusted by changing the value of the offset in the input and output aperture of each resonator.

IV. Application Examples

As a first example, we consider in Fig. 4 a single dual-mode resonator fed by a standard rectangular waveguide. The modes chosen for this case are TE_{102} and TE_{301}. The simulated and measured response for this filter is shown in Fig. 5. As we can see, very good agreement between theory and measurements has indeed been achieved.

As a second example, we discuss the Ku-band filter structure in Fig. 6. For this example, we have used the TE_{102} and TE_{201}

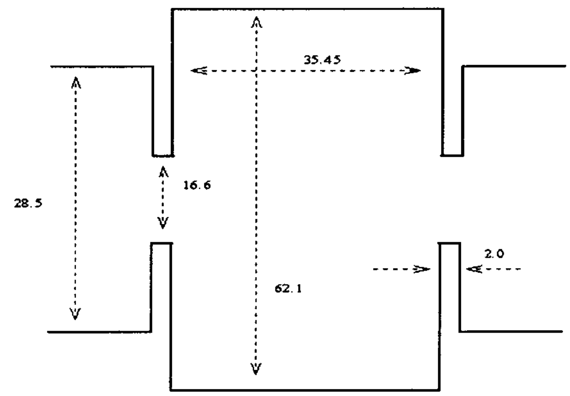

Fig. 4. Single dual-mode cavity (dimensions in millimeters).

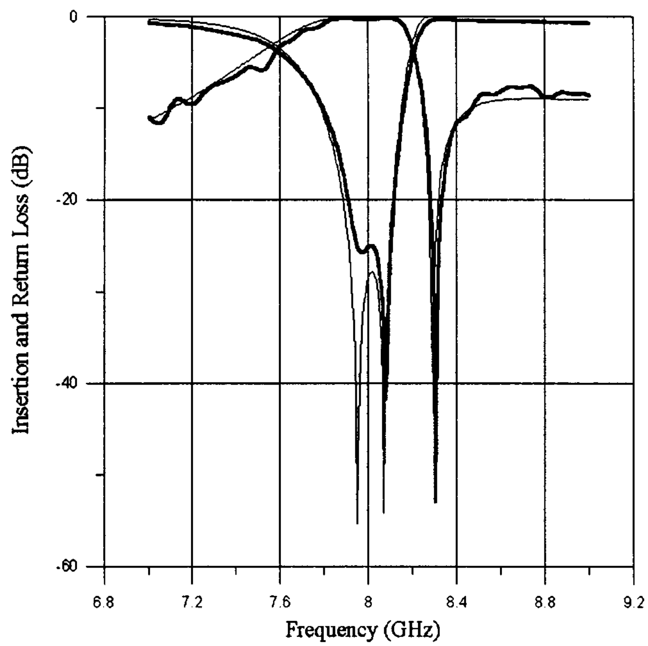

Fig. 5. Measured (thick) and simulated response of the single dual-mode cavity in Fig. 4.

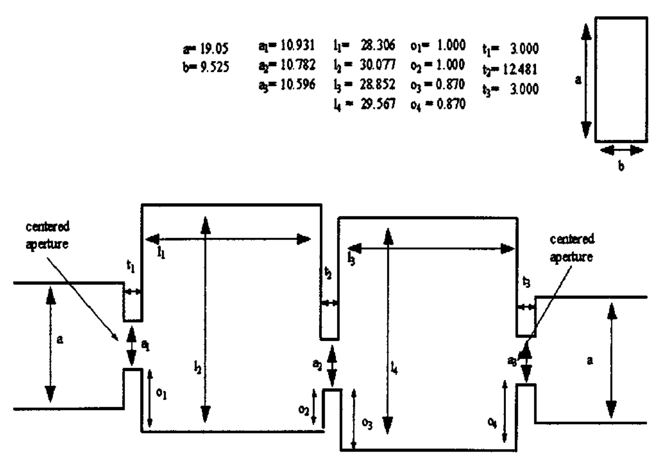

Fig. 6. Four-pole dual mode filter in the Ku-band.

resonant modes corresponding to an even and an odd field distribution, respectively, on each side of the resonators. The simulated and measured in-band performance is shown in Fig. 7,

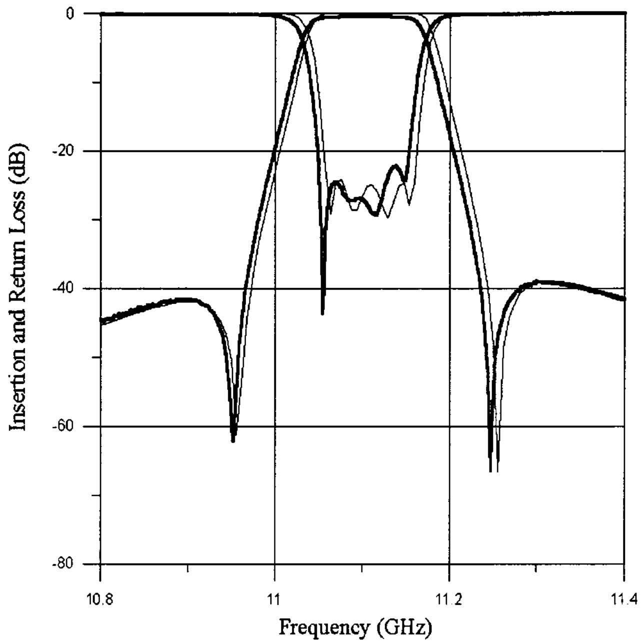

Fig. 7. Measured (thick) and simulated in-band response of the filter in Fig. 6.

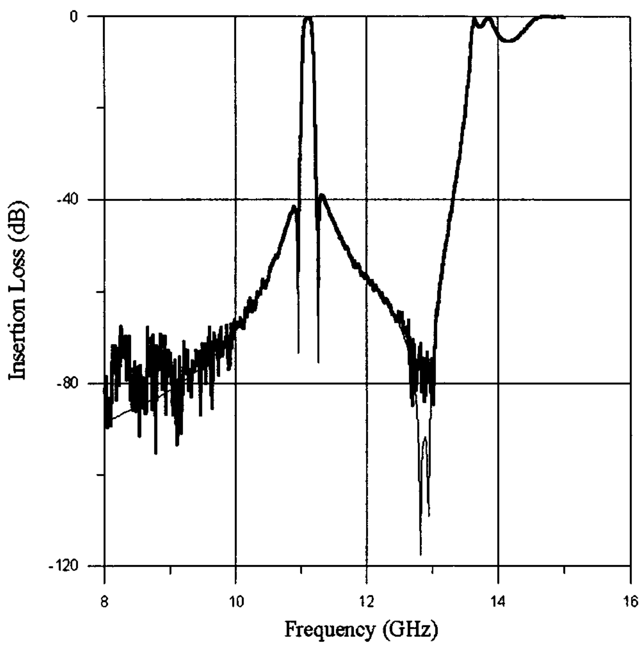

Fig. 8. Measured (thick) and simulated wide-band response of the filter in Fig. 6.

while the out-of-band performance is shown in Fig. 8. As we can see, the agreement is very good, especially if we consider that no tuning screws have been used. The out-of-band response of the filter in Fig. 8 is acceptable only up to about 13.5 GHz. If a significant rejection value is desired above this frequency, an additional low-pass structure is required.

Using two coupled dual-mode cavities, we have been able to obtain two transmission zeros, one on each side of the passband. This last configuration is particularly interesting because it lends itself to manual tunability. This feature is essential for narrow-band applications. This is because even though the optimization performed using WIND does provide very accurate di-

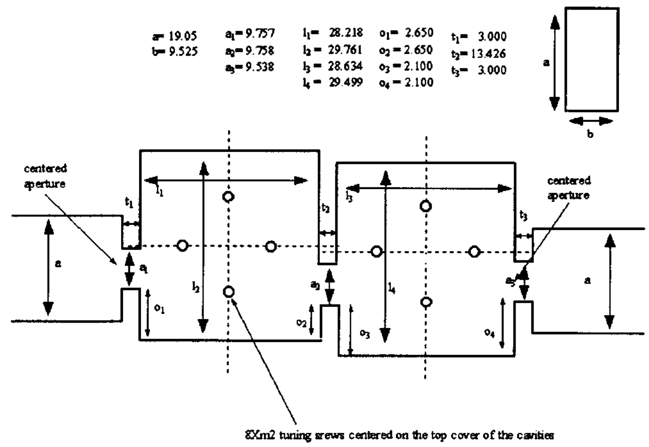

Fig. 9. Tunable in-line configuration.

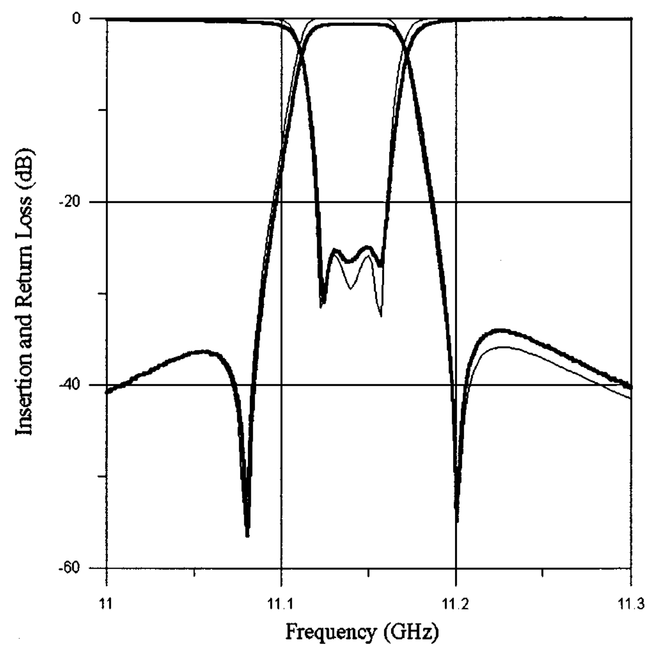

Fig. 10. Measured (thick) and simulated in-band response of the filter in Fig. 9.

mensions, the required mechanical accuracy for tuning-less implementations is not easily achievable. Fig. 9 shows the structure of a Ku-band filter of narrow bandwidth where tuning screws are used. The simulated (without tuning) and measured results for this filter are shown in Fig. 10. As we can see, also in this case, very good agreement has been achieved. It is important to note that the tuning screws in this case have only been introduced to compensate for the errors in resonant frequency due to the mechanical realization. Their presence has, therefore, been ignored during the filter optimization process. The specific transfer function implemented in this last example is a *chained function* implementation using as seeds a first- and third-order polynomial [23]. As discussed in detail in [23], this particular type of transfer function exhibits the desirable feature of reduced sensitivity to manufacturing errors. The result shown in Fig. 10 have, in fact, been obtaining tuning only the resonant frequencies. The coupling apertures have not been tuned.

The use of tuning screws reduces the need for high mechanical accuracy, but may not be desirable for high-volume produc-

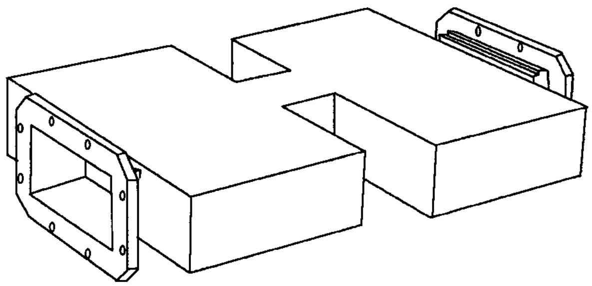

Fig. 11. C-band electroformed filter.

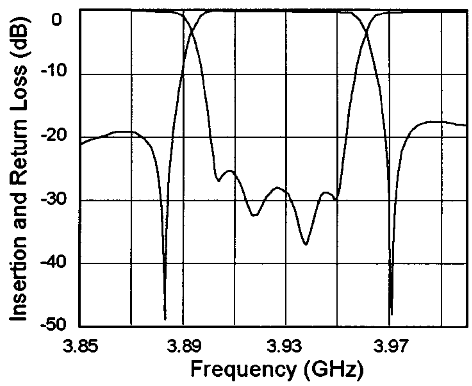

Fig. 12. Measured in-band response of the filter in Fig. 11.

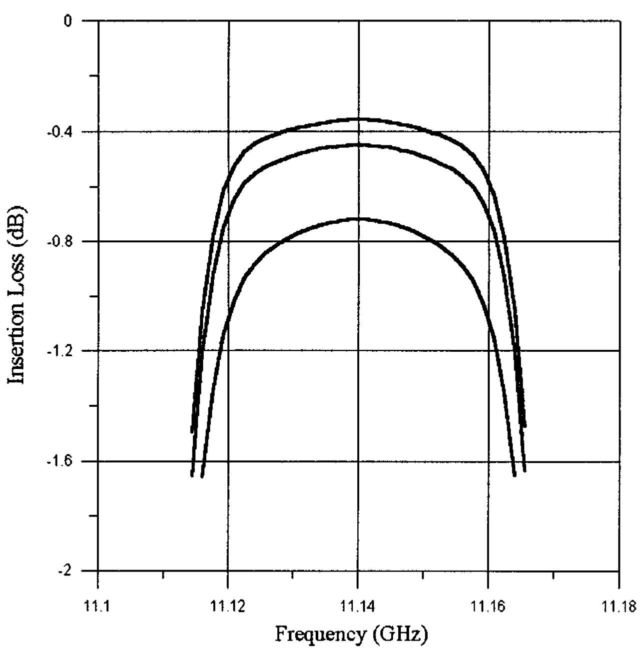

Fig. 13. Simulated in-band response of the filter in Fig. 9 with different waveguide heights.

tion. Fig. 11 shows the sketch of a four-pole tuning-less filter with two transmission zeros realized with electroforming technology. The filter has a center frequency of 3.925 GHz and a bandwidth of only 49 MHz. The measured response is shown in Fig. 12. As we can see, a very good performance has indeed been obtained.

Another important feature of the family of filters described in this paper is that the unloaded quality factor Q_u of the basic resonator can be effectively increased by simply changing the height of the whole filter structure. To illustrate this point, we show in Fig. 13 three simulated results obtained including the losses in the EM simulation. The curve with the highest insertion loss has been obtained using the standard waveguide height (9.525 mm) and using a surface resistivity value to give approximately 0.71 dB of insertion loss (the result obtained in Fig. 10). The next curve has been obtained keeping constant the surface-resistivity value and changing the height of the waveguide to 19.05 mm (square waveguide). The minimum insertion loss obtained in this case is 0.45 dB. Increasing the height of the filter structure to 28.575 mm (inverted rectangular), we obtain the result with the lowest insertion loss, namely, 0.35 dB. This last value is comparable to the values normally obtained with standard dual-mode filters in circular waveguide.

V. Conclusion

In this paper, we have introduced a new family of dual-mode filters based on the use of TE_{m0n}-mode family in a rectangular resonator environment. The major features of this new family of filters are three. The first is that they are extremely easy to simulate and optimize since they only employ inductive discontinuities. The second is that they are amenable to a very low-cost high-precision manufacturing process. The third is that they are ideally suited for low-loss high-power applications. A number of different filter structures have been demonstrated, also including measured results, thereby fully validating the new filter concept.

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