An Optimal Circular-Waveguide Dual-Mode Filter Without Tuning Screws

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***Abstract*— A novel circular-waveguide dual-mode (CWDM) filter structure[1] is proposed. The coupling between the degenerate modes in the same cavity is provided by an off-centered circular iris built in at the middle of the resonant cavities. Considering the facts of: 1) simplicity of mechanical process; 2) a potentially high Q; 3) a wide spurious-free frequency band; and 4) the effectiveness of electromagnetic (EM) modeling, the structure can be considered as an optimal coupling structure for CWDM filters when a precise EM design is required. A rigorous mathematical proof is given for explaining its working mechanism. The detailed formulations for designing the new coupling structure is also discussed. To validate the new structure, a narrow-bandwidth four-pole *Ku*-band elliptic filter is designed, manufactured and tested. Very good agreement is obtained between the calculated and measured responses.**

***Index Terms*— Circular waveguides, dual mode filters, electromagnetic modal analysis, microwave filters, mode matching, tuning screws.**

I. Introduction

RECENTLY there has been a tendency for the structures of traditional microwave components or devices, which used to rely heavily on imprecise design and manual tuning, to be modified. The electrical performance of the modified devices can be easily, accurately, and efficiently simulated using advanced electromagnetic (EM) modeling tools. With an appropriate optimization routine and advanced mechanical manufacturing facilities, these new devices can be precisely designed and manufactured without (or with very minor) tuning. In particular, this situation is true for the circular-waveguide dual-mode (CWDM) filters.

The CWDM filters are widely employed as a narrow-bandwidth bandpass channel filters in communication satellite output multiplexers [1] due to their unique merits such as high unloaded Q in a relative compact volume. Intensive research has been carried out on EM modeling and design of the CWDM filters. There are four major reasons to have precise EM designs of the filters:

1) to reduce the risks of passive intermodulation (PIM) and multipaction, which are likely caused by the tuning screw gaps and contamination on the surface of the screws;
2) to predict and remove the spurious modes from the frequency band of interest;
3) to minimize the conductor surface loss and PIM caused by the imperfect contact between the tuning screws and threaded holes;
4) to reduce the manufacture cycle time of a flight hardware.

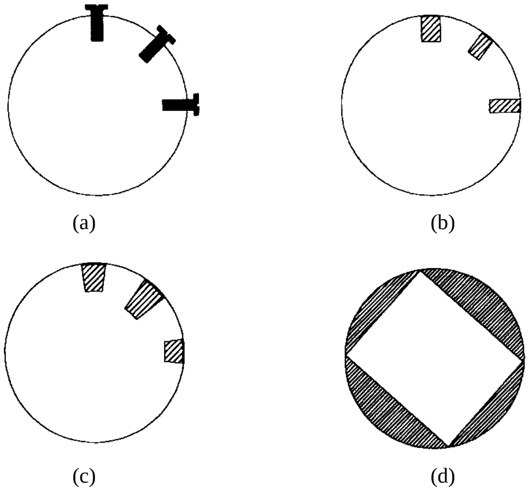

Fig. 1. Various coupling structures for CWDM filters.

The conventional cavity structures of a CWDM filter is shown in Fig. 1(a), where a typical three-screw arrangement is used to provide a desired coupling and phase balance. The most straightforward way is to replace the tuning screws by short rectangular posts standing out of the cavities [2], [3] [see Fig. 1(b)], for which a pure numerical finite-element method (FEM) analysis has been applied to obtain the eigenmodes of the first few TE and TM modes. Afterwards, the tuning rectangular post structure has been deformed as a circular ridged waveguide (CRW) [4] [see Fig. 1(c)] in order to determine the TE and TM modes more easily. Since the boundary contour of the CRW structure can fit into cylindrical coordinates, a relatively efficient semianalytical method of lines (MoL) has been utilized to compute the cutoff frequencies and eigenmodes functions. Conceptually, all these modifications still remain in the realm of traditional notion: the degenerate modes in a cavity have to be coupled by a perturbation of a screw-like conducting object. On the other hand, due to the narrow-band nature of the dual-mode filters, it is difficult to ensure the accuracy and efficiency of the eigenmode solutions provided by any numerical approaches.

More recently, a significant innovation on the modification of the CWDM tuning section has been reported [5]. The new structure employs inclined short sections of rectangular

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waveguides in the middle of the resonant cavities, as shown in Fig. 1(d), by which the coupling and tuning functions are obtained by the rotation angle, aspect ratio of the rectangular waveguide, and thickness of the sections. Since the eigenmodes are analytically available both in circular and rectangular waveguides, the structure can be analyzed accurately and efficiently using the mode-matching method. Although the new structure provides tremendous advantages over the previous modifications, in terms of manufacturing simplicity and computational effectiveness, it still requires sophisticated mechanical processes, such as electro-discharge machining (EDM), to ensure the sharp right-angle corners of the rectangular waveguide sections. If the sharp-corner assumption is made in the EM design, the round corners produced by conventional milling will not be tolerable, especially for high-frequency applications. On the other hand, since the minimum ratio of remaining conductor surface area on the coupling sections over the cavity cross section is as large as $(\pi - 2)/\pi$, the conductor loss on the remaining surface will decrease the unloaded Q of the filter, which is very critical to a narrow-band filter for space applications. Moreover, a short section of cutoff coupling waveguide may increase the risk of having spurious modes in a TE_{113}-mode circular cavity.

In this paper, a novel coupling structure for the CWDM filter is introduced. The proposed structure uses off-centered circular irises to replace the three-screw coupling arrangement in circular waveguide cavities. Coupling and phase balancing can be controlled by adjusting the inclination of the off-centered circular aperture, the radius of the aperture, amount of off-center distance, and the thickness of the section. Since the modal eigenfunctions are analytically available for the circular waveguide, the structure can be analyzed rigorously without any numerical integration. In fact, the circular aperture is the easiest geometry to machine. The proposed coupling structure can be very easily built into a circular cavity using conventional milling machines. Considering the facts that: 1) the rectangular and circular coupling structures are the only configurations which are most suitable for rigorous EM design without numerical manipulation; 2) the remaining conductor surface in the new circular coupling structure is much less than that of the rectangular aperture structure and, consequently, provides a much better unloaded Q and a wide spurious-free frequency band; and 3) a circular aperture is much easier to manufacture than any other shapes, it can be seen that the proposed off-centered circular iris coupling structure can be considered as an optimal solution for CWDM filters when a precise EM design is required.

To provide a deep insight of the new off-centered circular coupling structure, its working mechanism is explained mathematically without any assumptions. Detailed formulations for converting the field parameters obtained from the EM analysis into the filter circuit parameters are discussed to provide a design guideline. In order to demonstrate the feasibility of the proposed structure, a four-pole narrow-band CWDM filter at *Ku*-band has been designed, fabricated, and measured. Very good agreement is obtained between the designed and measured responses. Special attentions have been paid on the spurious-mode behavior and the unloaded Q. Experimental results reveal that the performance of the new structure is not inferior to that of the conventional three-screw coupling configuration.

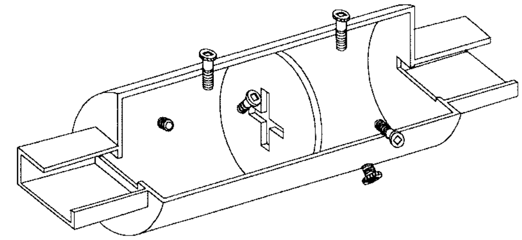

Fig. 2. A conventional four-pole CWDM filter.

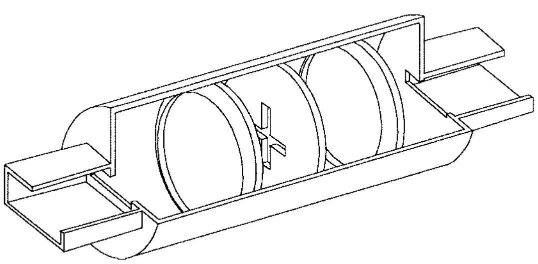

Fig. 3. A four-pole CWDM filter with the proposed new coupling structure.

II. Working Mechanism of the New Coupling Structure

A. Conventional Coupling Structure

As depicted in Fig. 2, a conventional CWDM filter uses a typical three-screw coupling and balancing structure. The vertically polarized mode in the first cavity is excited by the TE_{10} mode in the input rectangular waveguide through the horizontal slot of the input iris. The energy in the horizontal mode of the cavity is coupled by the coupling screw, which is usually inclined at 45°, with respect to the horizontal slot. The horizontal and vertical modes are coupled to the adjacent cavity through a thin cross-shaped iris or a thick rectangular inter-cavity iris. To balance the phase of the two modes in the same cavity, vertically and horizontally placed tuning screws are needed. A recursive tuning process of the three screws provides nonindependent control of coupling, phase for the vertical mode, and phase for the horizontal mode.

B. New Coupling Structure

In the proposed new coupling structure, the three-screw structure is replaced by an off-centered circular iris, as shown in Figs. 3 and 4. Coupling between the two degenerate modes, as well as the phase balance, is controlled by the radius of the circular aperture, amount of the center offset, inclination, and the thickness of the iris. For the narrow-bandwidth application, where a very weak coupling is required, $R1$ is usually very close to $R2$. Therefore, the remaining conductor surface on the coupling iris can be minimized. Since it is a circular-shaped aperture, a cavity with built-in coupling iris can be easily fabricated with conventional machines.

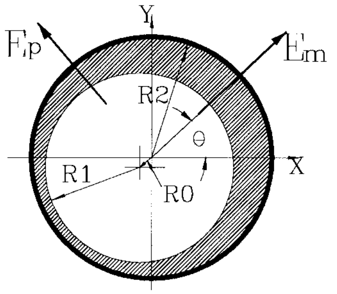

Fig. 4. The proposed coupling structure employing an off-centered circular to circular waveguide iris and two major polarization field components E_m and E_p.

Since the radius of the coupling aperture is very close to that of the circular cavity, the resonance mode chart for the new cavity structure will not have noticeable difference as compared with the conventional three-screw coupling arrangement. It is very important to ensure that no more spurious modes will be introduced in the new structure. This has been verified by a wide-band simulation and measurement results, which will be discussed in Section IV.

C. Mathematical Interpretations of the Coupling Structure

The working mechanism of the coupling structure can be explained through the mathematical expression derived in this section, particularly (3). It needs to be mentioned that the equations used in this section are for interpretation purposes only. The design formulation will be given in the following section.

In a circular-waveguide cavity having an off-centered circular iris with the inclination angle θ, two major polarization field components can be considered: field E_m parallel to the inclination axis and field E_p perpendicular to the inclination axis, as shown in Fig. 4. Incident and reflected fields of the major field components on both sides of the coupling iris can be described by the following scattering matrices:

$$\begin{Bmatrix} b_m^1 \\ b_m^2 \end{Bmatrix} = \begin{bmatrix} s_m^1 & s_m^2 \\ s_m^2 & s_m^1 \end{bmatrix} \begin{Bmatrix} a_m^1 \\ a_m^2 \end{Bmatrix}$$

and

$$\begin{Bmatrix} b_p^1 \\ b_p^2 \end{Bmatrix} = \begin{bmatrix} s_p^1 & s_p^2 \\ s_p^2 & s_p^1 \end{bmatrix} \begin{Bmatrix} a_p^1 \\ a_p^2 \end{Bmatrix} \tag{1}$$

where $\{a_m^1, a_m^2\}^T$ and $\{b_m^1, b_m^2\}^T$ are the field magnitudes of incident and reflected waves of the E_m field component, and $\{a_p^1, a_p^2\}^T$ and $\{b_p^1, b_p^2\}^T$ are the field magnitudes of incident and reflected waves of the E_p field component, at ports 1 and 2. Since the coupling structure is a symmetric two-port network, $s_{11} = s_{22} = s^1$ and $s_{12} = s_{21} = s^2$ in the two scattering matrices. Generally speaking, the scattering matrices for the two field components are not equal.

Considering the projection relations of (m, p) field components and (x, y) field components, which are the field components of interest in dual-mode filter design

$$a_m^i = a_x^i \cos\theta + a_y^i \sin\theta$$
$$b_m^i = b_x^i \cos\theta + b_y^i \sin\theta$$

and

$$a_p^i = -a_x^i \sin\theta + a_y^i \cos\theta$$
$$b_p^i = -b_x^i \sin\theta + b_y^i \cos\theta$$

where $i = 1$ or 2, the two matrices in (1) can be combined into one matrix equation in terms of the field coefficient of horizontal mode (x-component) and the vertical mode (y-component) in the same cavity as follows:

$$\begin{bmatrix} c & s & 0 & 0 \\ 0 & 0 & c & s \\ -s & c & 0 & 0 \\ 0 & 0-s & c & \end{bmatrix} \begin{Bmatrix} b_x^1 \\ b_y^1 \\ b_x^2 \\ b_y^2 \end{Bmatrix} = \begin{bmatrix} s_m^1 & s_m^2 & 0 & 0 \\ s_m^2 & s_m^1 & 0 & 0 \\ 0 & 0 & s_p^1 & s_p^2 \\ 0 & 0 & s_p^2 & s_p^1 \end{bmatrix} \begin{bmatrix} c & s & 0 & 0 \\ 0 & 0 & c & s \\ -s & c & 0 & 0 \\ 0 & 0 & -s & c \end{bmatrix} \begin{Bmatrix} a_x^1 \\ a_y^1 \\ a_x^2 \\ a_y^2 \end{Bmatrix} \tag{2}$$

where $c = \cos(\theta)$ and $s = \sin(\theta)$.

Since the matrix on the left-hand side of (2) is an orthogonal matrix, it is straightforward to have the following equation, which reveals the relation between the vertical and horizontal modes, shown in (3), at the bottom of this page.

From (3), following characteristics of the coupling structure can be observed.

1) When $\theta = 0°$ or $\theta = 90°$, there is no coupling between the vertical mode and horizontal modes, independent from the offset displacement $R0$ and the aperture size.
2) The coupling between the modes is proportional to the differences of s_m^1 and s_p^1, or s_m^2 and s_p^2. When the offset displacement $R0$ is zero, there are $s_m^1 = s_p^1$ and $s_m^2 = s_p^2$; therefore, there is no coupling between the vertical and horizontal modes. For a given cavity radius, reducing $R1$ will increase the coupling between the two degenerate modes.
3) The variation of the coupling versus the inclination angle follows exactly the function of $\sin(2\theta)$; therefore, the maximum coupling occurs at $\theta = 45°$.
4) Since $R1$ is very close to $R2$, the resonant modes supported in the circular cavities are above cutoff of the waveguide section with radius of $R1$. Therefore, the parameters of s_m^1, s_p^1, s_m^2, and s_p^2 (consequently, the

$$\begin{Bmatrix} b_x^1 \\ b_y^1 \\ b_x^2 \\ b_y^2 \end{Bmatrix} = \begin{bmatrix} c^2 s_m^1 + s^2 s_p^1 & c \cdot s(s_m^1 - s_p^1) & c^2 s_m^2 + s^2 s_p^2 & c \cdot s(s_m^2 - s_p^2) \\ c \cdot s(s_m^1 - s_p^1) & s^2 s_m^1 + c^2 s_p^1 & c \cdot s(s_m^2 - s_p^2) & s^2 s_m^2 + c^2 s_p^2 \\ c^2 s_m^2 + s^2 s_p^2 & c \cdot s(s_m^2 - s_p^2) & c^2 s_m^1 + s^2 s_p^1 & c \cdot s(s_m^1 - s_p^1) \\ c \cdot s(s_m^2 - s_p^2) & s^2 s_m^2 + c^2 s_p^2 & c \cdot s(s_m^1 - s_p^1) & s^2 s_m^1 + c^2 s_p^1 \end{bmatrix} \begin{Bmatrix} a_x^1 \\ a_y^1 \\ a_x^2 \\ a_y^2 \end{Bmatrix} \tag{3}$$

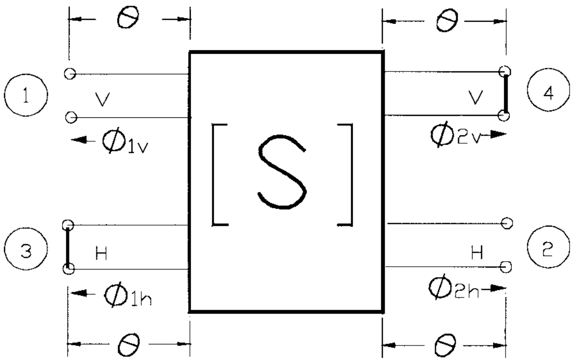

Fig. 5. The conversion of a loaded four-port network representing a dual-mode waveguide resonator to a two-port network.

coupling between the vertical and the horizontal modes) are less sensitive to the iris thickness.

III. Design Formula and Full-Wave EM Modeling

The coupling structure can be considered as an impedance inverter, which couples energy from the vertical mode to the horizontal mode or vice versa. Actually, if the coupling iris was sited in a piece of circular waveguide with matched ends, it can be represented by a four-port network described in (3). However, in a dual-mode cavity, only two opposite modes are considered to be matched at center frequency. The other two modes are loaded by the end irises with small aperture. Since, in most of the applications, the magnitude of the loading effects can be ignored in designing the cavity dimensions, only phase contributions from the end irises are taken into account. The structure connected to the coupling iris can be equivalent to a piece of shorting stub with electric length θ. As shown in Fig. 5, where the coupling from vertical mode in port 1 to horizontal mode in port 2 is considered, the loaded four-port network can be converted to a matched two-port network by terminating the other two ports with shorting stubs. The $[S]$ matrix of the four-port network is given by (3) and the electric length θ of the shorting stubs are determined from the phase balance equations for a dual-mode resonant cavity

$$\phi_{1h}+\theta+\angle S_{12}^{hh}+\theta+\phi_{2h}=n\pi \tag{4a}$$

$$\phi_{1v}+\theta+\angle S_{12}^{vv}+\theta+\phi_{2v}=n\pi \tag{4b}$$

where ϕ_{1h} and ϕ_{2h} are the phase loading for horizontal modes at ports 3 and 2, ϕ_{1v} and ϕ_{2v} are the phase loading for vertical modes at ports 1 and 4, and $\angle S_{12}^{hh}$ and $\angle S_{12}^{vv}$ are the phase shift of the horizontal and vertical modes across the coupling iris, respectively. It can be seen that unlike the case of a single-mode cavity, the coupling in a dual-mode cavity strongly depends on the loading effects from the end irises. Once the two-port network is found, the impedance inverter can be determined in the same fashion as that for single-mode filters.

The impedance inverter can be described using an equivalent T circuit having a shunt reactance Xp and a series reactance Xs on each arm. From a practical design point-of-view, it is important to have a relation between the field parameters obtained from EM analysis and the circuit parameters used in filter prototype design. Referring to the matched two-port network, shown in Fig. 5, the relation can be easily found as

$$jX_s=\frac{1-S_{12}+S_{11}}{1-S_{11}+S_{12}} \tag{5a}$$

$$jX_p=\frac{2S_{12}}{(1-S_{11})^2-(S_{12})^2} \tag{5b}$$

where S_{12} and S_{11} are the transmission and reflection coefficients of the two-port network, respectively. By having these circuit parameters converted from the field parameters, the filter parameters, such as the insertion phase ϕ, impedance inverter K, and the coupling value $M_{v,h}$ between the vertical and horizontal modes can be easily determined [9], [11] as follows:

$$\phi=-\tan^{-1}(2X_p+X_s)-\tan^{-1}X_s \tag{6}$$

$$K=|\tan(\phi/2+\tan^{-1}X_s)| \tag{7}$$

and

$$M_{v,h}=\frac{2}{\pi}(\lambda/\lambda_g)^2\cdot \mathrm{BW}\cdot K \tag{8}$$

where λ_g is the waveguide wavelength in the circular cavity, λ is the free-space wavelength and BW is the fractional bandwidth of the filter.

As shown in Fig. 3, the considered new CWDM filter structure is composed of four types of waveguide junctions. Each of them can be rigorously analyzed using existing analytical modal analysis modules. The rectangular-to-rectangular junction has been addressed in [10] as a "classical" problem. The rectangular-to-circular junction and cross-to-circular junction have been solved analytically [6], [7] using the newly developed "plane-wave expansion of cylindrical modal functions." Furthermore, the analytical modal analysis of the off-centered circular iris has also been recently reported in [8]. The generalized scattering matrix (GSM) for each of these junctions can be calculated accurately. This feature is very important to attain the accuracy of the design. By cascading the GSM of each junction modules in an appropriate sequence, the overall GSM for a complete CWDM filter can be obtained.

IV. Numerical Results and a Design Example

With the formulations discussed above, the coupling value M and insertion phase of the coupling inverter for balancing the two modes in the same cavity can be accurately calculated. By adjusting the inclination angle θ, the radius of the coupling aperture $R1$, and the thickness of the coupling iris, the physical dimensions can be synthesized for a desired filter response. Fig. 6 shows the calculated coupling value versus inclination for a typical coupling iris. The curve of $M_0\cdot\sin(2\theta)$ is also superposed, where M_0 is the coupling value at 45°. It can be seen that the variation of the coupling value versus the inclination follows exactly the function of $\sin(2\theta)$, as is expected from (3). There is no coupling when the inclination is 0° or 90°. Fig. 7 presents the coupling value versus the radius of the coupling aperture for the same waveguide cavity as that of Fig. 6. As explained in Section II, the larger the radius, the smaller the coupling. It is also interesting to see

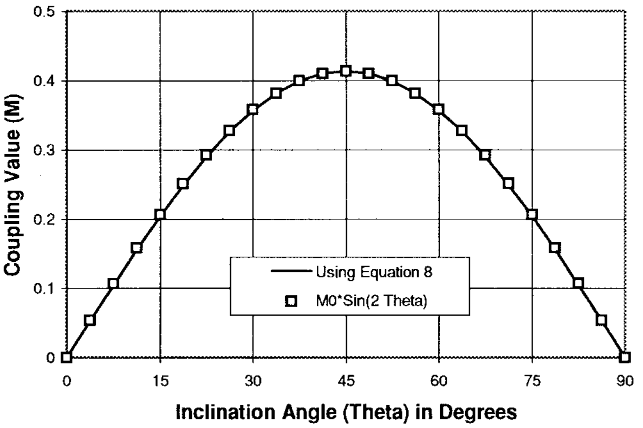

Fig. 6. Calculated coupling value of TE_{111} mode versus the inclination angle (theta) with $R2 = 0.3$, $R0 = 0.99R2 - R1$, thickness of coupling iris $= 0.099$, $f0 = 14.05$ GHz, bandwidth = 600 MHz, $\phi 1\nu = -20.77^\circ$. $\phi 2\nu = -3.412^\circ$, $\phi 1h = -13.17^\circ$, $\phi 2h = -12.36^\circ$.

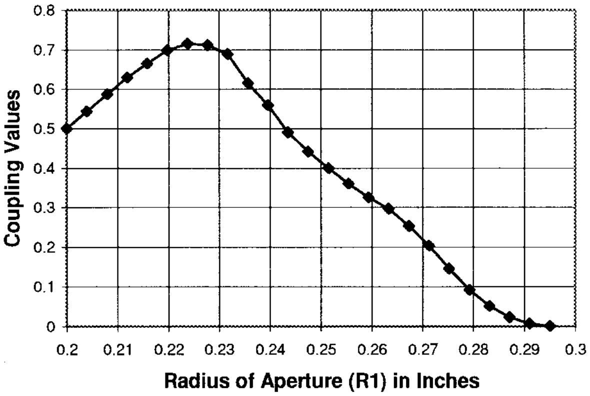

Fig. 7. Calculated coupling value of TE_{111} mode versus the radius of the coupling iris with inclination angle $= 45^\circ$. The rest of parameters are the same as those in Fig. 6.

that there is maximum coupling with the change of the radius. This maximum coupling value changes with the iris thickness and cavity radius.

To demonstrate the feasibility of the proposed new structure, a four-pole equiripple elliptic filter using TE_{113} mode, with bandwidth of 36 MHz and center frequency of 12.6 GHz, is designed using complete full-wave EM modal analysis. The coupling matrix for the desired filter response is listed as follows:

$$[M] = \begin{bmatrix} 0.04 & 1.053 & 0.0 & -0.2218 \\ 1.053 & 0.04 & 0.8883 & 0.0 \\ 0.0 & 0.8883 & 0.04 & 1.053 \\ -0.2218 & 0.0 & 1.053 & 0.04 \end{bmatrix},$$

$$\text{with termination } R1 = R2 = 1.3998.$$

A prototype filter hardware has been fabricated where the two cavities with built-in coupling iris were manufactured using a conventional lathe machine. In this example, the remaining conductor area of the coupling iris is about 16% of the cavity cross-section area and the iris thickness is 0.019-in thick. As shown in Fig. 8 for the passband response and in Fig. 9 for wide-band response, the measured responses are in very good agreement with the full EM designed responses.

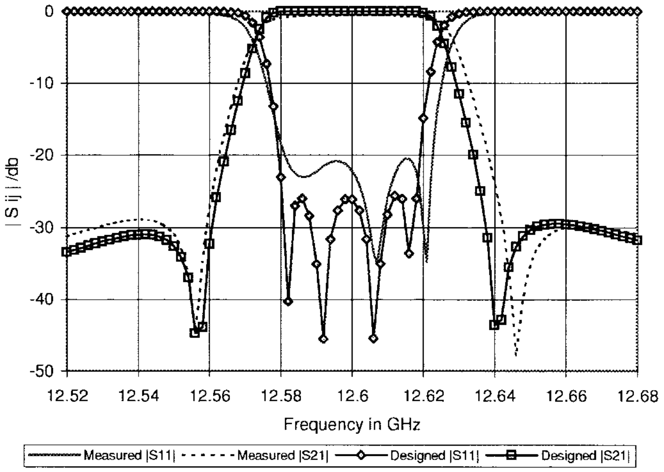

Fig. 8. The designed and measured passband responses of the prototype four-pole elliptic filter.

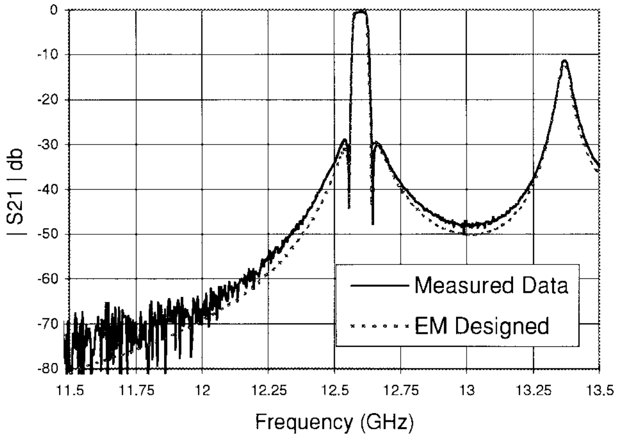

Fig. 9. The designed and measured wide-band responses of the prototype four-pole elliptic filter.

Since this is a very narrow-bandwidth filter, any imperceptible mechanical imperfection will easily deteriorate the bandwidth by a few percent.

It is worth mentioning that the measured unloaded Q of the filter is about 14 000–15 000, which means that the same quality factor as that of the conventional dual-mode circular-waveguide filter for space application has been achieved. It can also be observed from Fig. 9 that the resonance of TE_{212} mode occurs at about 13.3 GHz, the same location as that of conventional three-screw structure if the same cavity radius is used. This observation proves the postulate that circular cavities with the proposed coupling structure will have the same spurious mode performance as that of a conventional one.

V. CONCLUSIONS

A novel CWDM filter structure has been proposed and demonstrated. A rigorous mathematical proof has been provided to explain its working mechanism. It can be seen that the new coupling structure has the features of easy and cost-effective manufacturing, high power-handling capability, and potentially high Q. A very important and attractive feature is that its electric performance can be analytically modeled using modal analysis. The latter enables the complete EM modeling of the entire CWDM filter (even an entire waveguide multiplexer) in conjunction with existing modal analysis modules. Considering the facts of: 1) simplicity of mechanical process; 2) potentially high Q; 3) wide spurious-free frequency band; and 4) effectiveness of EM modeling and designing, the new structure is considered as an optimal coupling structure for CWDM filters when a precise EM design is required.

To provide a design guideline, a formulation, which converts the equivalent four-port network to a two-port network and calculates the circuit parameters from the field parameters, is also discussed since a practical design work still needs to start from an equivalent-circuit model. With the formulations discussed, a four-pole elliptic CWDM filter using the new coupling structure was designed, fabricated, and tested. Very good agreement between the design and measurement results was obtained.

The idea embedded in the coupling structure has been extended to other junctions of the CWDM filter and the filter structure employing more than two degenerate modes. For example, the input iris and the inter-cavity iris can be realized using off-centered circular apertures. The detailed implementation will be reported in the near future.

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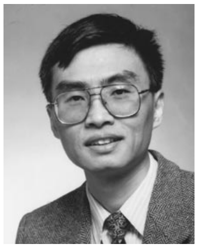

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