Application of Dual TM Modes to Triple- and Quadruple-Mode Filters

RENE R. BONETTI, SENIOR MEMBER, IEEE, AND ALBERT E. WILLIAMS, FELLOW, IEEE

Abstract —The cylindrical cavity dual orthogonal transverse magnetic (TM) mode is introduced as a basic building block for the realization of microwave multiple-coupled-cavity bandpass filters. This concept is shown to offer significant advantages in the design of triple-mode filters and permits the design of the new quadruple-mode filter. Experimental verification is provided by the realization of a triple-mode, six-pole elliptic function bandpass filter with dual TM_{110} and single TE_{211} (transverse electric) modes and a quadruple-mode, eight-pole bandpass filter with dual TM_{110} and dual TE_{112} mode cavities. All units exhibit good agreement between theory and experiment.

I. Introduction

The DEVELOPMENT of the dual orthogonal TE_{11n} cylindrical modes [1], [2] and their application to narrow-band, coupled-cavity microwave filters and equalizers have revolutionized satellite transponder design [3]. When compared to single-mode cavity filters, this design results in weight and volume reductions of 50 percent. Further, the introduction of nonadjacent couplings creates additional savings by permitting optimum filter responses to be generated.

The use of triple resonant degeneracies yields further savings of weight and volume and allows the designer a wider range of filter geometries, which may become increasingly attractive in the millimeter-wave range. Single-cavity multiple-mode filters were first introduced by Lin in 1951 [4], and Atia and Williams in 1971 [2] extended this idea to multicoupled cavities, describing a six-pole elliptic function bandpass filter using the degeneracy of the dual TE_{111} and the single TM_{010} modes. In 1983, Tang and Chaudhuri [5] continued this work and introduced an iris structure that permitted full control of each coupling. Additional work describing the use of the dual TE_{113} and TM_{012} mode as a triple degeneracy in a multiplexer filter design was presented by Pley and Tang in 1985 [6].

This paper extends these concepts by exploiting the degeneracies of the dual TM and single and/or dual TE modes for the realization of generalized coupled-resonator filter transfer functions. These mode combinations allow new geometries for triple-mode filters and, in particular, the introduction of the quadruple-mode filter. Normalized design data for representative mode degeneracies are presented, and different realizations are compared in terms of spurious frequency separations, cavity Q's, and volumes.

Experimental verification of these degeneracies is provided by the realization of two new filter types: a triple degeneracy, two-cavity, 12-GHz, six-pole, elliptic function bandpass filter, and a two-cavity, quadruple degeneracy, eight-pole, 12-GHz, quasi-elliptic function bandpass filter. Both units show good correlation with the predicted performance.

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The authors are with COMSAT Laboratories, Communication Satellite Corporation, Clarksburg, MD 20871.

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II. Dual Orthogonal TM Mode

The dual orthogonal TE_{11n} cylindrical cavity modes have been extensively used in multiple-coupled-cavity filter designs. The existence of a pair of solutions with angular variations, $\sin\theta$ and $\cos\theta$, allows two orthogonally polarized modes to be independently tuned and coupled by a set of screws located at the cavity's side wall (Fig. 1(a)). Adjacent mode separations compatible with most practical channelizing applications can be achieved for the modes with $n = 1$, 2, 3, and 4.[1]

In an analogous manner, the TM_{1m0} modes form a dual set of orthogonal modes where the electric fields are only mathematically orthogonal (instead of mathematically and geometrically orthogonal, as in the TE dual case). Nevertheless, these modes can still be conveniently tuned by perturbing the longitudinal electric field component E_z with screws located at the end of the cavity (Fig. 1(b)).

Table I shows a representative set of properties for some of the dual TE and dual TM modes: the normalized spurious free frequency windows ($\Delta f/f_0$) at the lower ($-$) and higher ($+$) sides of the center frequency (f_0), the normalized theoretical Q ($Q\sqrt{f}$) for silver-plated cavities, and the normalized volume (V/V_0) as a function of the cavity diameter/length (D/L) ratio. It is evident from these data that the TM dual-mode sets do not introduce any specific advantages when compared to the dual TE modes; rather, their importance lies in their combination with the TE modes to form triple- and quadruple-mode sets. Fig. 2 illustrates the coupling screw configuration for independently tuning and coupling dual TM to dual or single TE modes. Corner screws 12 and 34 provide the

[1] The higher order dual modes such as TE_{12n} and TE_{13n} do not yield practical filters due to the proximity of the TE_{41n} and TE_{71n} modes, respectively.

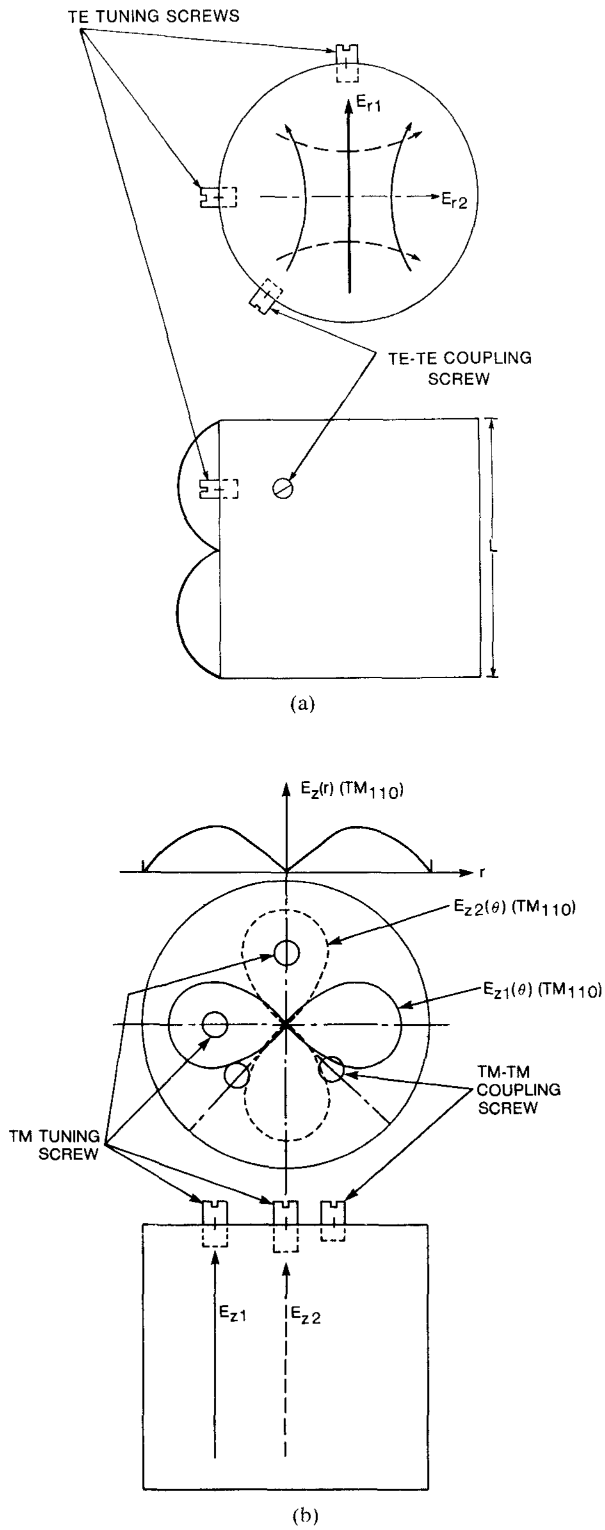

Fig. 1. Tuning and coupling screw configurations for dual TE and dual TM modes. (a) TE_{112} mode. (b) TM_{110} mode.

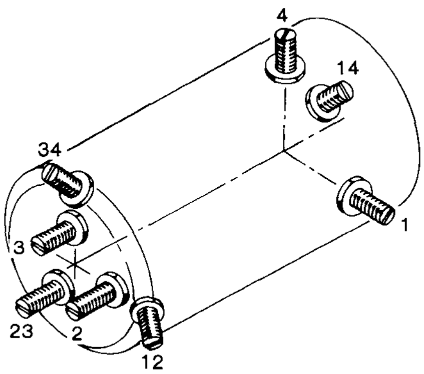

Fig. 2. Triple/quadruple-mode cavity.

TABLE I
TYPICAL DUAL-MODE SOLUTIONS

Sol. No.	Mode	D/L	Δf/fo (%) −	Δf/fo (%) +	Q √f (K) (f in GHz)	V/Vo*
1	TE111	0.50	100.0	20.1	34.9	1.16
2	TE111	1.35	14.5	14.5	40.6	1.18
3	TE112	0.74	9.9	10.2	55.1	2.55
4	TE112	1.14	4.8	5.0	61.7	4.14
5	TE113	0.51	4.5	4.3	64.0	3.93
6	TE113	0.62	7.2	4.9	70.6	4.71
7	TE114	0.50	5.7	5.2	81.5	6.98
8	TE114	0.73	3.2	3.9	97.7	11.96
9	TE115	0.57	2.8	3.0	107.9	14.40
10	TM110	1.18	6.8	6.8	56.4	3.45
11	TM110	1.70	6.2	5.9	48.5	2.39
12	TM120	2.36	5.2	5.2	75.5	10.60
13	TM130	2.88	2.0	1.5	97.7	26.40

*The normalizing volume V_0 is the minimum volume of a cylindrical cavity resonating in the TE_{111} mode. This occurs at $D/L = 0.83$.

TABLE II
TYPICAL TRIPLE- AND QUADRUPLE-MODE SOLUTIONS*

Sol. No.	TM 1 M 0	TE L M N	D/L	Δf/fo (%) −	Δf/fo (%) +	Q √f (f in GHz) (K) TE	Q √f (f in GHz) (K) TM	V/Vo**
1		1 1 1	2.140	37.2	7.8	39.1	43.4	1.90
2		1 1 2	1.070	9.0	7.8	61.0	58.5	3.80
3		1 1 4	0.535	9.0	2.4	84.6	70.8	7.61
4	M=1	2 1 1	1.474	12.9	16.8	46.7	51.7	2.76
5		2 1 2	0.737	12.9	2.6	54.2	65.6	5.52
6		2 1 3	0.491	6.2	2.0	57.4	72.1	8.28
7		1 1 1	4.310	9.1	2.4	36.5	52.1	5.79
8		1 1 2	2.155	7.7	2.4	65.9	79.1	11.59
9	M=2	2 1 1	4.021	3.7	5.3	39.1	54.6	6.21
10		3 1 1	3.577	3.1	8.2	44.5	58 9	6.98
11	M=3	3 2 1	3.989	2.3	3.1	103 8	79 6	19.09

*For degeneracies with $|\Delta f/f_0| \geqslant 2$ percent.
**Normalizing volume V_0, as defined for Table I.

TE–TM coupling. Some of the useful mode combinations for which the spurious mode frequency windows are greater than 2.0 percent are presented in Table II[2] along with normalized cavity Q's and normalized volumes. All these solutions have potential application to two-cavity filters: the triple degeneracies to six-pole and the quadruple degeneracies to eight-pole filter realizations. The usefulness of any one mode set for filter design lies in the basic requirement of independent mode tuning and intermode coupling.

III. TRIPLE- AND QUADRUPLE-MODE CAVITY FILTER DESIGN

The optimum coupled-cavity low-pass filter transfer function $T(s)$ is given by

$$T(s) = C \cdot N(s)/D(s) \tag{1}$$

[2] The dual TM_{1mn} modes which are degenerate with the TE_{0mn} modes for all D/L ratios are not included in this table.

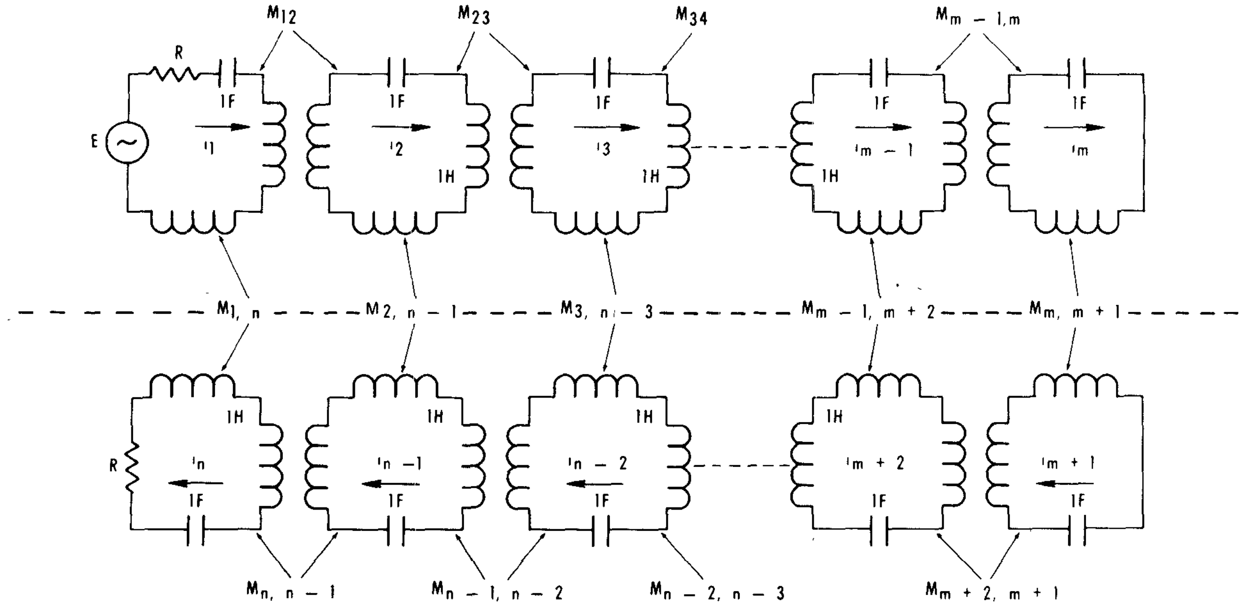

Fig. 3. Canonical nth-order coupling matrix equivalent circuit.

where

s = jw (w is the low-pass frequency),
N an even polynomial in s,
D a Hurwitz polynomial with order at least two greater than $N(s)$,
C a constant normally related to the band edge ripple value.

Synthesis of $T(s)$ in the form of a coupled resonator bandpass filter results in the basic canonical matrix [7] structure shown in Fig. 3. The elements $M_{i,i+1}$ are known as the series couplings, while the elements $M_{i,n+1-i}$ are known as the shunt couplings.

Since the shunt elements are, in general, smaller than the series couplings, the most natural way to realize six-pole triple- and eight-pole quadruple-mode filters is to divide the circuit along the symmetry dotted line shown in Fig. 3 and to realize each side in separate identical cavities. This distribution allows the input and output ports to be located in different physical cavities and consequently permits good out-of-band rejection to be achieved.

To achieve independent mode coupling across the intercavity iris, the correct geometrical pattern of coupling slots can be determined from the radial and angular variation of the magnetic and electric fields of each mode. The coupling factors (K) between each set of field components have the following form:

H_θ to H_θ:

$$K_M \propto M' \cdot \left[\frac{J_l(x'_{lm} 2r/D)}{(x'_{lm} 2r/D)} \right]^2 \cdot \sin^2 l\theta$$

H_r to H_r:

$$K_M \propto M' \cdot \left[J_l'(x'_{lm} 2r/D) \right]^2 \cdot \cos^2 l\theta$$

for the TE_{lmn} modes, and

H_θ to H_θ:

$$K_M \propto M' \cdot \left[J_1'(x_{1m} 2r/D) \right]^2 \cdot \sin^2 \theta$$

H_r to H_r:

$$K_M \propto M' \cdot \left[\frac{J_1(x_{1m} 2r/D)}{(x_{1m} 2r/D)} \right]^2 \cos^2 \theta$$

E_z to E_z:

$$K_E \propto P' \left[J_1(x_{1m} 2r/D) \right]^2 \cdot \sin^2 \theta$$

for the TM_{1m0} modes, where x'_{lm} and x_{1m} are the appropriate Bessel function solutions and M' and P' are the corrected magnetic and electric polarizabilities [8], respectively.

As a general rule, it is important that the degenerate modes be chosen to have dissimilar field patterns at the iris and, in particular, that at least one of the modes have magnetic field zeros at some location. This is generally satisfied as a function of the angular variable θ and at the positions along the radius where the Bessel functions go to zero.

IV. Experimental Filters

A. Six-Pole Triple-Mode Filter

The triple-mode combinations whose solution are given in Table II can be directly implemented in a canonical matrix form and the intercavity iris couplings generated separately using the magnetic field patterns of TE_{l1n} ($l \geqslant 1$) and TM_{1m0} modes. Fig. 4 depicts a practical iris geometry and sketches of the tangential magnetic field components for the TM_{110} and TE_{21n} modes, illustrating how dis-

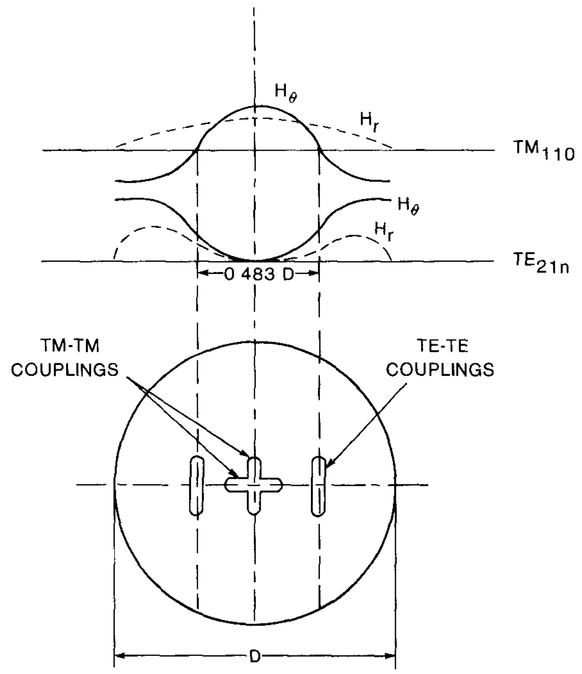

Fig. 4. Iris geometry and tangential magnetic field variation for triple-mode filter.

crimination between the mode couplings can be achieved. A pair of conventional cross slots located at the center of the iris will independently couple two pairs of dual TM modes in separate cavities through the radial magnetic field component (H_r). Another slot (or a set of two or four for symmetry) located at the null position of the TM mode angular magnetic field (H_θ) will provide independent TE mode coupling between the two different cavities. All the remaining couplings can be realized by coupling screws.

Three structures that realize the canonical matrix in the manner described above are shown in Fig. 5. The most advantageous is the combination depicted in Fig. 5(b), which allows the center slots to be small compared to the offset slot, thereby minimizing the possibility of spurious couplings between the TE modes in one cavity and the TM modes in the second cavity.

To illustrate these principles, a six-pole elliptic bandpass filter was designed for a center frequency of 12 GHz, a 75-MHz, 0.01-dB equiripple bandwidth; and a selectivity of 0.75. The synthesized canonical coupling matrix was obtained as

$$[M] = \begin{bmatrix} 0 & 0.978 & 0 & 0 & 0 & 0.081 \\ 0.978 & 0 & 0.592 & 0 & -0.312 & 0 \\ 0 & 0.592 & 0 & 0.819 & 0 & 0 \\ 0 & 0 & 0.819 & 0 & 0.592 & 0 \\ 0 & -0.312 & 0 & 0.592 & 0 & 0.978 \\ 0.081 & 0 & 0 & 0 & 0.978 & 0 \end{bmatrix}$$

with the normalized termination $R = 1.372$. The negative sign for coupling M_{25} is provided simply by locating the two coupling screws in an antisymmetric position in the two different cavities.

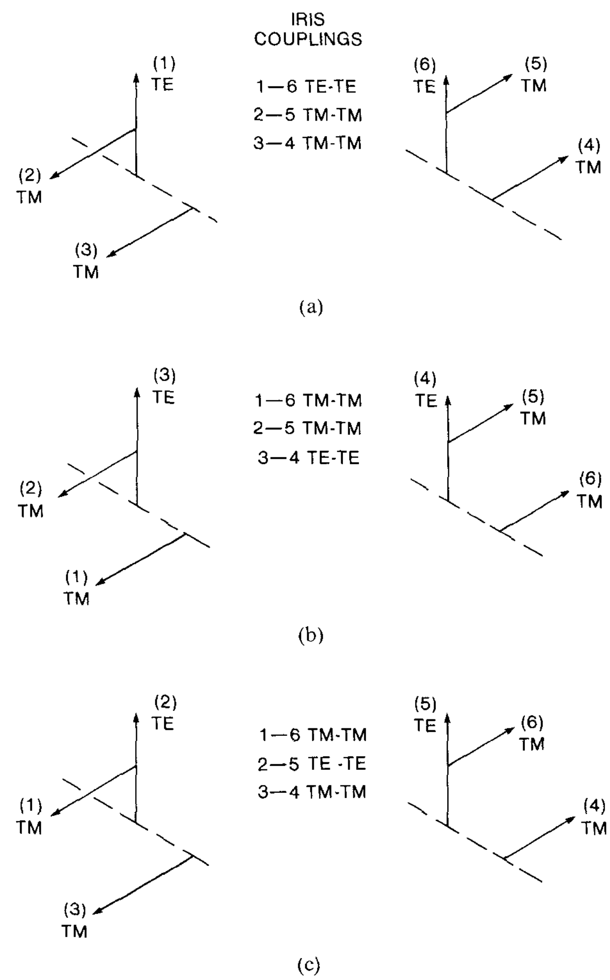

Fig. 5. Different configurations of triple-mode six-pole canonical filters.

The semiautomatic procedure described in [9] was used to tune the filter by aligning each individual cavity separately. The measured swept narrow-band and wide-band responses, shown in Fig. 6(a) and (b), respectively, exhibit good agreement with the desired performance. The small deviation of the spurious passbands with respect to the lower and higher mode frequencies is due to the perturbations introduced by the tuning screws. The resulting unloaded Q, derived from a center frequency loss of 0.35 dB, is 10,500, which translates into a Q efficiency of 73 percent.

B. Eight-Pole Quadruple-Mode Filters

The natural application of the quadruple-mode sets is a two-cavity eight-pole filter. By using the TE and TM dual orthogonal mode degeneracy and with the basic assumption that input and output ports should be in different physical cavities,[3] the two mode-coupling arrangements shown in Fig. 7(a) and (b) directly satisfy the canonical geometry. The only difference between these geometries is that, in the one case, the input and output ports are

[3] A four-pole elliptic function can be realized from a single quadruple degeneracy [10]. However, since the input and output ports must lie in the same physical cavity, the out-of-band isolation is limited

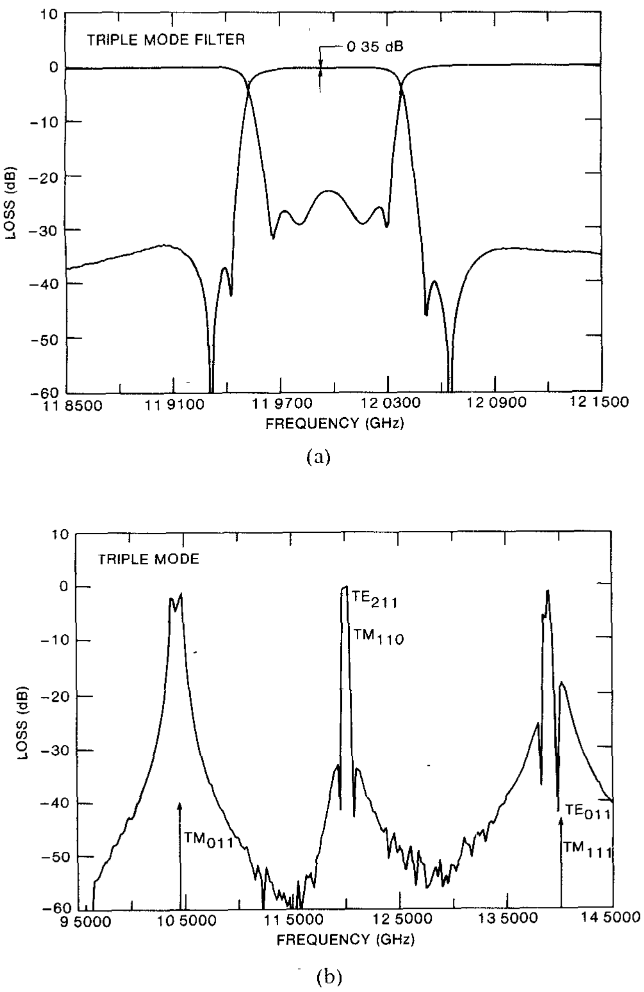

Fig. 6. Measured responses of triple-mode, six-pole elliptic function filter. (a) In-band. (b) Wide-band.

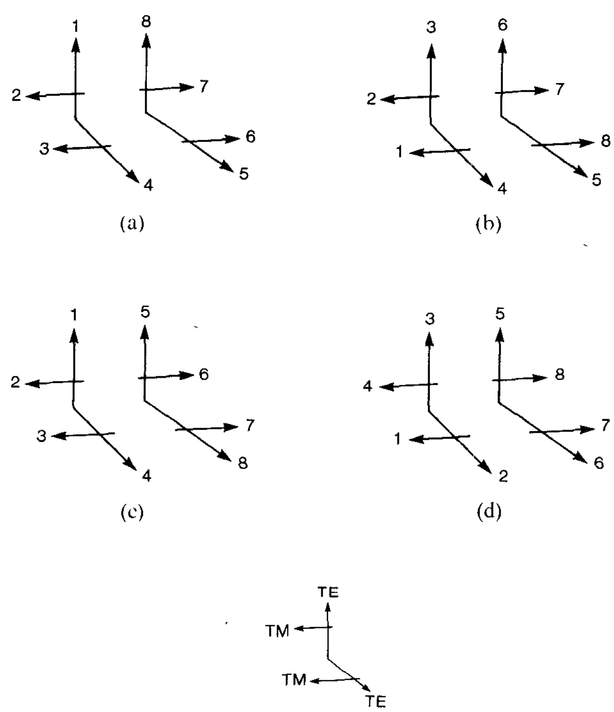

Fig. 7. Different configurations of quadruple-mode eight-pole filters.

	M_{12}		M_{14}				M_{18}
M_{12}		M_{23}				M_{27}	
	M_{23}		M_{34}		M_{36}		
M_{14}		M_{34}		M_{45}			
			M_{45}		M_{56}		M_{58}
		M_{36}		M_{56}		M_{67}	
	M_{27}				M_{67}		M_{78}
M_{18}				M_{58}		M_{78}	

(a)

	M_{12}		M_{14}				M_{18}
M_{12}		M_{23}				0	
	M_{23}		M_{34}		M_{36}		
M_{14}		M_{34}		M_{45}			
			M_{45}		M_{56}		M_{58}
		M_{36}		M_{56}		M_{67}	
	0				M_{67}		M_{78}
M_{18}				M_{58}		M_{78}	

(b)

	M_{12}		M_{14}				M_{18}
M_{12}		M_{23}				M_{27}	
	M_{23}		M_{34}		0		
M_{14}		M_{34}		M_{45}			
			M_{45}		M_{56}		M_{58}
		0		M_{56}		M_{67}	
	M_{27}				M_{67}		M_{78}
M_{18}				M_{58}		M_{78}	

(c)

Fig. 8. Eight-pole filter coupling matrix configurations. (a) Canonical with added M_{14} and M_{58} couplings. (b) With $M_{27}=0$. (c) With $M_{36}=0$.

coupled by parallel TE modes, while in the other case they are coupled by parallel TM modes.[4]

These geometries allow the basic canonical coupling elements to be generated and also yield two additional couplings, M_{14} and M_{58} (see Fig. 8(a)). This allows a certain amount of flexibility in the realization of an eight-pole filter, since the couplings across the intercavity iris can be reduced from a maximum of four to three by forcing either M_{27} or M_{36} to be equal to zero (see Fig. 8(b) and 8(c)) [2]. Additional zeros are obtained if the degree of

[4] The other two geometries shown in Fig. 7(c) and 7(d) can be derived by interchanging the coupling matrix rows and columns. Note that the input/output ports are now perpendicular; in certain applications, this may be a preferred arrangement

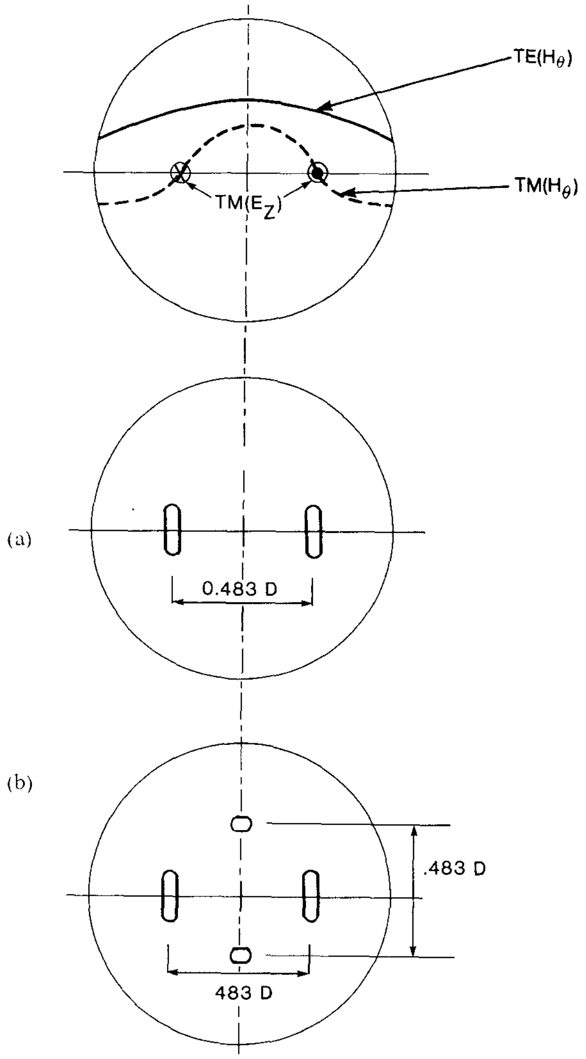

Fig. 9. Quadruple-mode filter iris geometry and tangential magnetic field variation. (a) For quasi-elliptic response. (b) For elliptic response.

the numerator is less than 6. For example, for a quasi-elliptic function response where the order of $N(s)=4$, couplings M_{18} and M_{36} are also zero.

To illustrate these concepts, the quadruple degeneracy of the TM_{110} and TE_{112} dual modes (solution 2 in Table II) was chosen to realize a two-cavity eight-pole filter.

Using the geometry of Fig. 7(a), a quasi-elliptic bandpass response was designed with a 1.18 selectivity; a 50-MHz, 0.01-dB equiripple bandwidth; and a center frequency of 12 GHz. The resulting normalized coupling matrix is

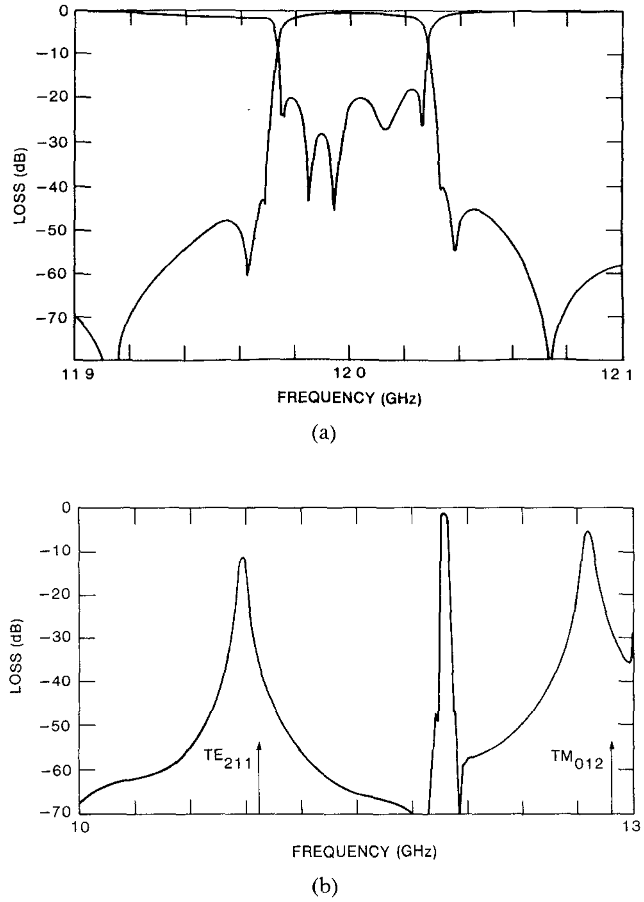

Fig. 10. Measured response of eight-pole quadruple-mode filter. (a) In-band. (b) Wide-band.

with $R=1.312$. As in the six-pole filter, the fields at the iris are different for each mode, with the TM_{110} angular magnetic field (H_θ) zeros occurring at $0.483 \cdot D/2$. Since the $TE_{112} H_\theta$ fields are finite at these locations, intercavity mode coupling discrimination can be achieved as shown in Fig. 9.

Tuning of the filter was accomplished as for the six-pole filter. The in-band and out-of-band responses shown in Fig. 10(a) and (b), respectively, agree quite closely with the theory, and an experimental Q of 9000 translates into a Q efficiency of 52 percent. It is interesting that extra zeros of transmission occur in the stopband as the result of a small amount of magnetic perpendicular coupling from the H_r field of modes 1 and 8 through the M_{45} slot. Fig. 11 is a photograph of the filter.

$$[M]=\begin{array}{c} \\ 1\\2\\3\\4\\5\\6\\7\\8\end{array}\begin{array}{cccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8\\ \end{array}$$

	1	2	3	4	5	6	7	8
1	0	0.830	0	−0.456	0	0	0	0
2	0.830	0	0.874	0	0	0	0	0
3	0	0.874	0	0.410	0	0	0	0
4	−0.456	0	0.410	0	0.541	0	0	0
5	0	0	0	0.541	0	0.487	0	−0.276
6	0	0	0	0	0.487	0	0.782	0
7	0	0	0	0	0	0.782	0	0.906
8	0	0	0	0	−0.276	0	0.906	0

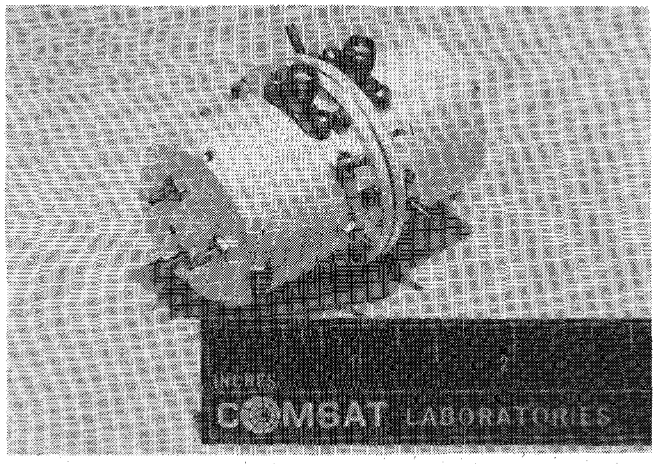

Fig. 11. Quadruple-mode eight-pole filter.

V. Conclusions

This paper has introduced the use of the cylindrical TM_{1m0} modes for the realization of multiple-coupled-cavity filters. Degenerate solutions with the TE_{l1n} modes lead to triple solution sets for $l>1$ and quadruple solution sets for $l=1$. A number of these solutions are particularly suited to multiple-coupled-cavity filters since they achieve wide frequency windows (> 5 percent) and have Q's and volumes appropriate for most channelizing applications.

By using the synthesized coupled-cavity canonical matrix form, the triple and quadruple degeneracies lead naturally to two-cavity six- and eight-pole optimum response filters, thus reducing the number of cavities to 66 and 50 percent, respectively, relative to the dual-mode implementation. Although these designs follow in a similar manner to those described in the literature, extreme care must be exercised in maintaining independent tuning of each mode and, in particular, in achieving independent mode coupling across the iris connecting the two cavities. These concepts are illustrated by the realization of two filters using a 12-GHz, six-pole, elliptic function, 72-MHz bandpass filter, and a 12-GHz, eight-pole, quasi-elliptic function, 50-MHz bandpass filter. Experimental results are in good agreement with theory.

Acknowledgment

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Rene R. Bonetti (M'85–SM'87) received the B.S. degree in electrical engineering from Escola de Engenharia Mauá, IMT, São Paulo, Brazil, in 1971, the M.Sc. degree from the Institute for Space Research (INPE) in 1974, and the Ph.D. degree in microwave circuits from the Technological Institute of Aeronautics (ITA), S. José dos Campos, Brazil in 1978.

From 1972 to 1978 he worked at INPE's Microwave Laboratory in the design and development of active and passive MIC circuits for small earth-station terminals. From 1979 to 1981 he was with Intelsat, Washington, DC, working in the Microwave Circuits Department of COMSAT Laboratories. In 1981 he joined COMSAT Labs as a Staff Scientist of the Microwave Technology Department, where he has been engaged in the study and design of state-of-the-art filters, multiplexers, and subsystems for satellite communications.

Dr. Bonetti was a joint recipient of the 1984 COMSAT Research Award for his work on higher order mode filters.

Albert E. Williams (M'66–SM'78–F'87) was born on March 27, 1940 in Albany, Western Australia. He received the B.E., degree (1st class honors) from the University of Western Australia in 1962 and the Ph.D. degree from University College, London University, in 1966.

From 1966 to 1968 he was a lecturer in the Department of Electrical Engineering at the University of Western Australia and in 1969 he joined COMSAT Laboratories as a member of the technical staff. He is presently manager of the Microwave Networks Department of the Microwave Technology Division.

Dr. Williams has been a major contributor to the development of the dual-mode microwave filter that was first used on Intelsat IV-A satellites and is now standard for all channel filters on communication satellites. In 1966 he was a joint recipient of the IEEE (Lond.) Sylvanus P. Thompson Premium Award and in 1984 a joint recipient of the COMSAT Research Award. He has published over 30 papers and holds five patents.