Filter Design Using In-Line Triple-Mode Cavities and Novel Iris Couplings

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Abstract —The introduction of an in-line triple-mode cavity and two new iris coupling methods provide a significant extension in filter designs. It is shown that these principles allow optimal filter realizations with a minimum of triple- and dual-mode cavities. A conspicuous example is the possible elliptic function in-line filter design up to seventh order. Verification of these principles has been obtained through several realized new filter types. Experimental results are provided for elliptic function filters of fifth, sixth (both in in-line configuration) and seventh order using a minimum number of TE_{113}/TM_{012} degeneracies.

I. Introduction

COMMUNICATIONS satellites have grown in transmission capacity from generation to generation. Hence, the requirements on channelizing filters, being generally used in multiplexer structures, have been increased steadily, both in number and in performance. By this, a host of new design ideas has been created since the late 1960's.

An essential breakthrough in a low-mass filter design was achieved by the development of the dual-mode technique, using TE_{11n} modes [1], [2]. The introduction of this technique has led to a mass and size reduction of about 50 percent compared to previously used single-mode filters. Additionally, dual-mode filters provide the possibility to realize nonadjacent couplings, so that an elliptic function response with a minimum number of cavities can be obtained by special arrangements of dual-mode cavities [3], [4].

But in most applications, dual-mode filters have been used in the so called in-line technique; i.e., the cavities are cascaded top by top and the input and output couplings are located at the top of the first and last cavities, respectively. Although elliptic function responses are not realizable for filter orders higher than 5, the in-line technique provides major advances in terms of mechanical design in contrast to the sidewall input and/or output coupling. Hence, dual-mode in-line filters are well suited and are in general use for manifold multiplexer designs [5].

A further step toward mass savings was the development of triple-mode cavities [6]. This applies also to the quadruple-cavity filters, which were investigated by Bonetti and Williams [7]. However, until now, triple- and quadruple-mode cavity designs have been based on top-wall tuning; i.e., tuning and coupling screws of the TM modes and the TE–TM mode couplings (inside a cavity) have been located at one top side of the cavity. Thus it has been impossible to cascade more than two triple- or quadruple-mode cavities in the above way.

As is well known, couplings of degenerate modes within adjacent cavities are obtained by the tangential magnetic field components and/or the perpendicular electric field components (only TM modes) in the aperture region of an iris. An iris, being used between dual-, triple-, and/or quadruple-mode cavities, respectively, must provide independent control of the required couplings by maintaining avoidance or suppression of all other parasitic couplings between the degenerate modes of both cavities.

Until now, only couplings of equal modes have been performed; i.e., only equally polarized TE modes or TM modes, respectively, have been coupled by the irises used (see for example [7, fig. 4]). Parasitic couplings have been avoided by locating the apertures at field zeros (within the iris region), or the aperture shape (generally a slot) has been directed perpendicular to the magnetic fields of the other degenerate modes.

This paper presents new principles for triple-mode filter designs by introducing a sidewall-tuned triple-mode cavity and two novel iris geometries. The sidewall-tuned triple-mode cavity allows the extension of the advantageous in-line technique to the triple-mode filter design. Hence, for higher order filters more than two triple-mode cavities can be cascaded, leading to additional mass reductions. The in-line technique also allows the same easy implementation of triple-mode filters in multiplexer networks.

The iris geometries provide new coupling possibilities between triple-mode and dual-mode cavities as well as

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between triple-mode cavities. Thus, new coupling structures can be obtained to realize optimal filter responses and mechanical designs.

These principles have been verified by the realization of several new filter types. The experimental results of a five-pole dual-/triple-mode in-line filter, a six-pole triple-mode in-line filter, and a seven-pole dual-/triple-mode filter, all providing elliptic function responses, are presented.

II. In-Line Triple-Mode Cavity Design

Resonance circuits at microwave frequencies can be realized by optimal conducting cavities of various shapes. There are an infinite number of independent modes which may be excited within the cavity. Appropriate dimensioning of the cavity allows utilization of several independent resonance modes at the same frequency (called degenerate modes or degeneracies); i.e., each resonance mode forms a filter resonance circuit.

This principle has been adapted to the design of cylindrical cavities. The relations between the cavity dimensions and the resonance modes are determined by

$$\left(\frac{1}{\lambda_r}\right)^2_{\mathrm{TE}} = \left(\frac{\chi'_{mn}}{\pi D}\right)^2 + \left(\frac{q}{2L}\right)^2 \tag{1}$$

for TE degeneracies and

$$\left(\frac{1}{\lambda_r}\right)^2_{\mathrm{TM}} = \left(\frac{\chi_{mn}}{\pi D}\right)^2 + \left(\frac{q}{2L}\right)^2 \tag{2}$$

for TM degeneracies where

- D diameter of cavity,
- L length of cavity,
- λ_r resonance wavelength,
- χ'_{mn} nth zero of Bessel function $J'_m(\chi)$,
- χ_{mn} nth zero of Bessel function $J_m(\chi)$,
- q integer of $\lambda_r/2$ along L,

which results from the field equations considering the boundary conditions.

As is well known, the degeneracies of the TE_{11n} mode are orthogonal and differ only by their angular variations, $\sin\phi$ and $\cos\phi$; i.e., they allow an optimal choice of the cavity dimensions D and L (to get a high unloaded Q factor and to control spurious modes). This dual mode can be combined with additional TE or TM modes to form triple or quadruple degenerate modes. However, this will fix the cavity dimensions for a given resonance frequency as the design formula for TE/TM degeneracies shows:

$$\frac{D}{L} = \frac{2}{\pi}\sqrt{\frac{\chi'^2_{mn\,\mathrm{TE}} - \chi^2_{mn\,\mathrm{TM}}}{q^2_{\mathrm{TM}} - q^2_{\mathrm{TE}}}}\,. \tag{3}$$

The choice of a usable degenerate mode set must consider independent tuning of each mode. Furthermore, couplings between each two modes must be realizable without affecting other cavity degeneracies.

The premise of sidewall tuning is an E-field variation of the corresponding mode in the z direction. This condition is trivial for all TE modes. In the case of TM_{nml} modes it is given for all modes with $l \geq 1$.

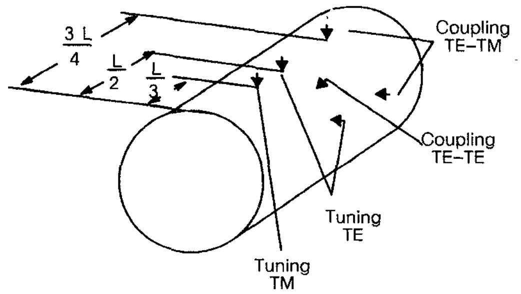

Fig. 1. Tuning and coupling screws of an in-line $\mathrm{TE}_{113}/\mathrm{TM}_{012}$ triple-mode cavity.

The consideration of these constraints for an in-line triple-mode cavity design leads to the well-suited mode combination $\mathrm{TE}_{11n}/\mathrm{TM}_{01(n-1)}$ with $n \geq 2$.

To allow independent tuning, the tuning screws are located at areas with nearly maximum E-field strength of the corresponding mode and E-field zeros of the remaining degeneracies. Thus, the tuning screws of the degenerate TE_{11n} modes are perpendicular to each other and determined by the $\mathrm{TM}_{01(n-1)}$ mode E-field zeros in the z direction (on the sidewall), while the TM mode tuning screws are determined by the E-field zeros of the TE degeneracies. Since intercavity modes can be coupled by equal E-field components, the TE–TM mode couplings are performed by screws which are located between the E-field zeros (in the z direction) of both modes, perpendicular to the third TE degeneracy. The intermode coupling of the degenerate TE modes is obtained by placing a coupling screw at 45° to their E-field direction and, of course, in the E-field zero of the TM mode.

As an example, the configuration of the tuning and coupling screws of a degenerate $\mathrm{TE}_{113}/\mathrm{TM}_{012}$ in-line triple-mode cavity is shown in Fig. 1.

III. Intercavity Couplings

The selectivity provided by a third-order filter is for most applications not sufficient.[1] Hence, several physical cavities are combined to form higher order filters. Usually, they are cascaded top by top separated by irises. Appropriate apertures within the irises provide the transfer of electromagnetic energy between the cavities to obtain the intercavity mode couplings.

If there are several degeneracies within the adjacent cavities, the iris design must be capable of controlling several intercavity couplings independently to obtain the required filter response. This includes, of course, avoidance and suppression of parasite couplings which would impair the filter performance.

In addition to the known iris coupling methods concerning triple-mode filter designs [6], two new iris coupling principles are established, which are well suited for adjacent dual-/triple-mode (TE_{11n}–$\mathrm{TE}_{11n}/\mathrm{TM}_{01(n-1)}$) and

[1]The out-of-band isolation is limited if input and output ports lie in the same physical cavity.

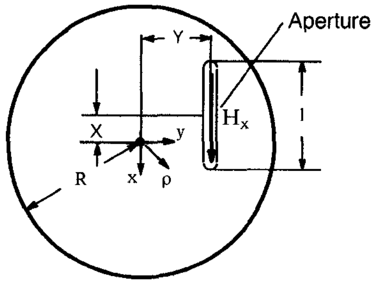

Fig. 2. Iris geometry for TE_{11n}–TM_{01m} mode coupling.

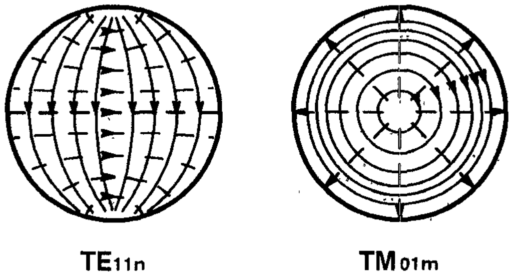

Fig. 3. Field pattern (cross sectional view) (——— H field at iris plane, ---- E field).

triple-mode ($TE_{11n}/TM_{01(n-1)}$) cavities, respectively. Both principles are based upon the slot apertures being parallel to the center of the iris (Fig. 2). Thus, the conditions given by the fields within the iris plane with respect to this slot aperture have been studied.

An iris coupling of two modes can only be obtained if there are equal field components of both modes within the aperture region. This is trivial for equal modes having the same polarization. As is well known, TE modes are only coupled by their magnetic fields being parallel to the aperture, while TM mode coupling is obtained by the parallel magnetic field and additionally the perpendicular electric field in the aperture region.

Fig. 3 shows the field patterns of the TE_{11n} and TM_{01m} modes. The relevant E_z- and H_x-field components of both modes have been investigated for slot aperture regions being parallel to the iris diameter (Fig. 2).

The fields within the iris plane are determined by

$$H_{x\mathrm{TE}} \sim \frac{R}{\chi_{11}\rho} J_1(\chi_{11}\rho/R)\cdot\sin^2\phi + J_1'(\chi_{11}\rho/R)\cdot\cos^2\phi \quad (4)$$

for the TE_{11n} modes and

$$E_{z\mathrm{TM}} \sim J_0(\chi_{01}\rho/R) \quad (5)$$

$$H_{x\mathrm{TM}} \sim J_0'(\chi_{01}\rho/R)\cdot\cos\phi \quad (6)$$

for the TM_{01m} modes where

R radius of cavity,
ρ distance from iris center ($\sqrt{X^2+Y^2}$),
χ_{11} 1.814,
χ_{01} 2.405,
$\sin\phi = X/\sqrt{X^2+Y^2}$,
$\cos\phi = Y/\sqrt{X^2+Y^2}$.

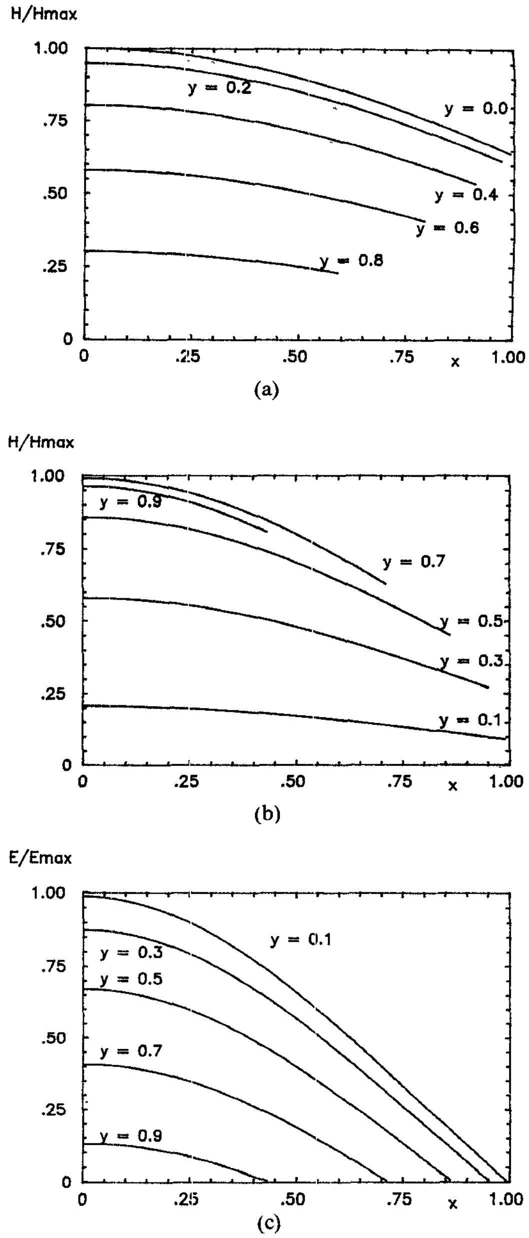

Fig. 4. Computed fields within the iris cross section. (a) H_x field of the TE_{11n} modes. (b) H_x field of the TM_{01m} modes. (c) E_z field of the TM_{01m} modes.

The maximum H_x field of the TE_{11n} mode is located at $\rho = 0$, while the maximum H_x field of the TM_{01m} mode is at $X = 0$, $Y/R = 0.76$, and the maximum E_z field is also at $\rho = 0$.

E_z of the TM mode and H_x of both modes have been computed for lines ($x = X/R$) being parallel to the horizontal diameter ($y = Y/R = \text{const.}$) (Fig. 4). The maximum H_x-field variation along a line x within the iris region with $y = \text{const.}$ is about 35 percent for both modes. However, the H_x variations of both modes are less than 5 percent for typical aperture lengths (about $l/R = 0.5$, i.e., $x = 0.25$), i.e., nearly constant.

Since E_z of the TM mode becomes zero at the radius the field varies from a maximum (at the iris center) to zero for a diameter across the iris plane. This variation is of course smaller for all other parallel lines, due to the smaller field strength at $y \neq 0$.

A. Dual-/Triple-Mode Coupling Aperture

The advanced design of filters using dual- and triple-mode cavities will require couplings of TE and TM degeneracies that are located in physically adjacent cavities.

Since TE modes do not have an electrical field component perpendicular to the iris, a coupling of a TM mode and a TE mode in adjacent cavities can only be achieved by equal magnetic field components in the aperture region.

A coupling of these modes can be performed by one slot aperture (Fig. 2), which is parallel to the horizontal diameter with a distance from it ($y \neq 0$). For that reason, only the magnetic H_x field in the slot direction is relevant for the coupling of these modes.

It should be noted that the H_x field of the TM_{01m} mode changes its direction (180°) at $Y = 0$. Hence, it has a positive and a negative maximum across the diameter of the cavity ($-R \leqslant Y \leqslant R$), but the absolute values are identical.

The coupling factor depends on the H_x field within the aperture region. Therefore, the coupling coefficient between these two modes can be varied by the distance Y and the aperture length l. Since H_x of the TE_{11n} modes has only one direction within the iris region, while H_x of the TM_{01m} modes changes its direction over the cavity diameter by 180°, positive and negative couplings ($-M_{\max} \leqslant Y \leqslant M_{\max}$) can be obtained by appropriate dimensioning of the aperture (Y and l).

Equally polarized TE_{11n} modes located in adjacent cavities (as given for dual-/triple-mode cavity designs) are also coupled by a single slot aperture (which is parallel to the H field). Hence, a coupling between the TM mode of the triple-mode cavity and one TE mode of the dual-mode cavity, as introduced above, can be performed on the premise of a second coupling between this TE mode of the dual-mode cavity and the equally polarized TE mode of the triple-mode cavity.

However, it should be noted that such filter design can only be performed since the iris geometry (Fig. 2) provides the TE–TE mode and the TE–TM mode coupling by maintaining good decoupling between the degenerate TE mode of the dual-mode cavity and the degenerate TE mode as well as the TM mode of the triple-mode cavity.

This means that the two different couplings are provided by a single slot aperture. The different factors for the TM–TE as well as the TE–TE couplings are discriminated by the two parameters Y (parallel distance of the slot aperture from the cavity center) and l (slot length).

B. Triple-Mode Coupling Aperture

Due to the E and H fields of both mode types ($TE_{11n}/TM_{01(n-1)}$) in the iris region, at least two couplings must be performed simultaneously. Thus, the goal of such iris design can only be the optimal discrimination and independence of these couplings. (These couplings do not lead to essential restrictions of triple-mode filter applications, since they can be employed advantageously to generate, for example, elliptic function filter responses.)

A single slot aperture placed at the iris center (Fig. 2; $y = 0$) will provide a coupling between the TE modes having a parallel magnetic field and the TM modes which have a perpendicular electric field in this area. The magnetic TM mode coupling is negligibly small, since the H field is almost perpendicular to the slot direction. (The principle of perpendicular H-field components with respect to a coupling slot is generally used in the dual-mode technique to suppress the undesired intercavity couplings of the orthogonal TE degeneracies.)

Independent control of these couplings can be obtained by varying the relation of slot width to slot length, resulting in different variations of the magnetic and electric polarizabilities of the aperture [8] which determine the coupling factors. However, this solution is restricted to a small variation range, on one side by the smallest slot being accurately manufactured and on the other side by the parasitic coupling of the degenerate orthogonal TE modes of the cavities which would impair the filter realization. An independent control of all three feasible couplings (between the equal polarized modes) is impossible by such a single slot aperture design.

Hence, only relatively small TM couplings can be realized by such apertures without noticeable impairment. Thus the additional control of both couplings, by varying aperture location (Fig. 2; $x = 0$) along the slot axes, need not to be investigated.

An iris design presented in [6] allows the independent discrimination of the three intercavity couplings, but the achievable TM mode coupling is restricted to small values by the same restrictions given above.

Therefore, an iris design has been created which allows the realization of all required TE–TE and TM–TM couplings independently. A single slot iris as presented above for the dual-/triple-mode filter design is not suitable, since not only the desired couplings will be provided but also additional parasitic couplings (relatively strong) between the TE modes of one cavity and the TM modes of the other will occur. These parasitic couplings would make filter design and realization impossible.

Since these undesired couplings cannot be avoided in this configuration, a compensation principle has been established for iris couplings. It is based on the introduction of the same anticoupling; i.e., a coupling which has the same absolute value as the parasitic one but an opposite sign. This anticoupling compensates the parasitic TE–TM coupling (the magnetic TM fields at the apertures is antiparallel to the magnetic TE fields) by providing an additional coupling component for the TM–TM coupling (the magnetic TM fields are parallel at both apertures).

For the present iris design an anticoupling can easily be introduced by a second slot aperture with the same dimensions as the first one, both apertures symmetrically placed with respect to the iris center (Fig. 5). It should be noted that symmetry is not required if different apertures will be used, since the anticoupling can be provided by dimension-

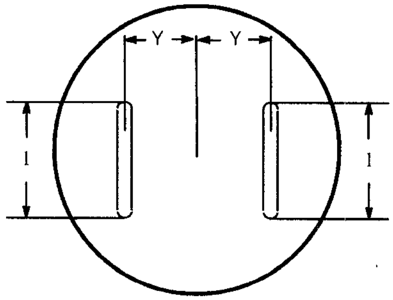

Fig. 5. Iris geometry for TE–TE/TM–TM mode coupling.

ing a different shape and location of the respective aperture. However, in this case the design effort will be essentially increased.

The TM intercavity coupling can be separated into their electrical and magnetic components by the relationship between coupling coefficients and the physical dimensions of the apertures introduced by Kudsia and Matthaei [8], [9]:

$$M_{\mathrm{TM}} = \frac{f_0}{\Delta f} \cdot \frac{\omega^2 \epsilon_0}{J_1^2(\chi_{01}) \pi k_0^4 L R^2} \cdot \left\{ \frac{k_0^4 P}{\omega^2 \epsilon_0} J_0^2(\chi_{01}\rho/R) + \frac{\mu_0 \chi_{01}^2 M}{R^2} J_1^2(\chi_{01}\rho/R) \right\} \quad (7)$$

with

$\omega = 2\pi f_0$

$k_0 = \omega\sqrt{\mu_0 \epsilon_0}$

f_0 center frequency of the filter

Δf filter bandwidth

P electric polarizability

M magnetic polarizability.

From this equation the electrical and magnetic coupling components can be calculated. The comparison of these components shows that the electrical coupling varies from a maximum value at the iris center to zero at the circumference, while the magnetic coupling is zero at the center and has a maximum value at 0.76 ρ.

The electrical and magnetic polarizabilities (P and M) of the slot apertures are determined by their relation w/l (slot width/slot length) [8]. For typical values of $w/l \leqslant 0.2$ the polarizabilities differ by a factor of more than 10.

Consideration of this fact in the above equation shows that the maximum magnetic coupling component will be more than three times the maximum electrical one, but the two are at different locations. Nearly the same electrical and magnetic coupling component occurs between 0.2 to 0.3 ρ, depending of the exact polarizabilities; i.e., the electrical component dominates in the direction to the iris center while the magnetic component dominates in the radial direction.

This two slot aperture design is able to control one TE–TE mode and one TM–TM mode coupling simultaneously. To obtain a third independent coupling of the orthogonal TE degeneracies, further appropriate apertures may be implemented in this iris. These apertures must also be designed taking into account the suppression and avoidance of parasitic couplings.

Note that the iris design must consider all required intercavity couplings, since the TM mode will be coupled by each aperture due to the E_z field. The relations between coupling coefficients and physical aperture dimensions are given in [8].

IV. New Coupling Structures

Each filter design is based on the required transfer function, which is defined as a ratio of two finite polynomials $P(s)$ and $E(s)$:

$$T(s) = P(s)/\alpha E(s), \qquad s = j\omega. \quad (8)$$

The constant α normalizes the amplitude to unity at its highest point.

There are some synthesis methods to solve $T(s)$ for resonator-coupled bandpass filters [10], [11]. The resulting coupling matrix determines series ($M_{i,i+1}$) and shunt ($M_{x,y}$) couplings which may be realized to obtain the required response. The coupling matrix can be converted (without any impact on the transfer function) to obtain a proper coupling structure; i.e., shunt couplings which cannot be realized will be eliminated by the addition of realizable shunt couplings [4].

Both synthesis and conversion must consider the realizable couplings between adjacent cavities. For example, perpendicular degeneracies within adjacent physical cavities cannot be coupled. However, the arrangement of the resonance circuits within the physical cavities allows some freedom in the filter design.

The introduction of the above established in-line triple-mode cavity and the new iris coupling methods in higher order cavity filter designs provide an infinite number of new feasible coupling structures to obtain optimal filter realizations. This relates to the responses (i.e., the desired filter function as well as the spurious responses) by considering the mechanical design constraints according to a desired application. Generally, low-mass in-line structures are preferred, since they allow easy integration into waveguide systems and easy manufacturing.

Fig. 6 shows some advantageous coupling structures for filters up to tenth order providing elliptic function responses and/or in-line realizations. Further examples have been published in [12].

V. Experimental Results

The new design principles outlined above have been applied to several filter realizations. Fig. 7 shows a photograph of the three different types which are discussed below.

A. Five-Pole In-Line Triple-/Dual-Mode Filter

The design of in-line filters using triple-mode cavities is characterized by the need for TE degenerate resonance circuits at the input and output couplings, respectively. Hence, there are a certain number of possible filter realiza-

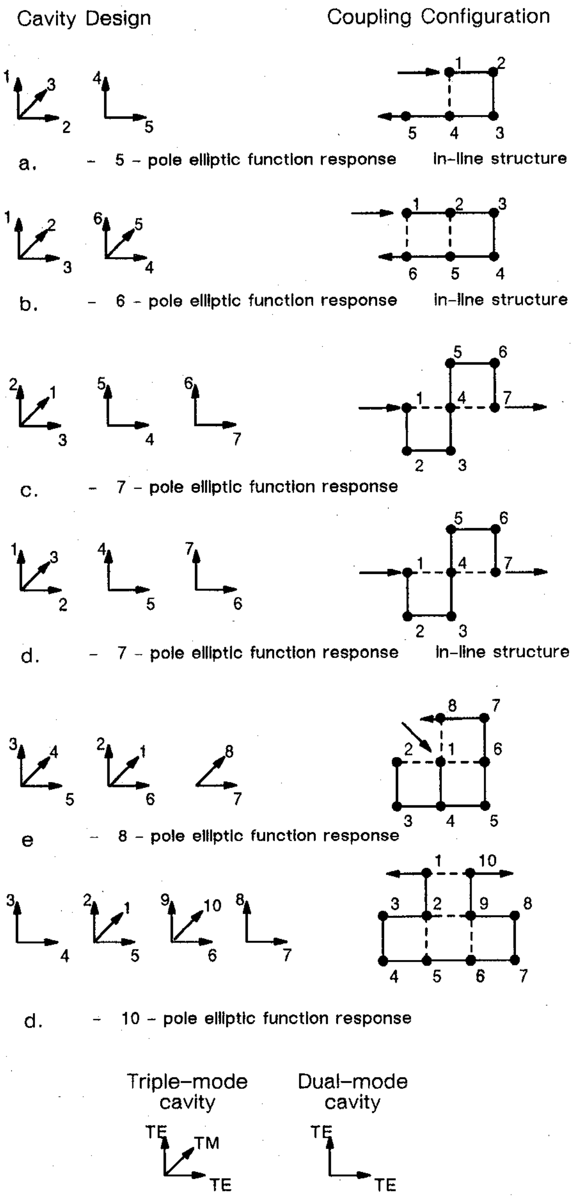

Fig. 6. Some new filter configurations using triple- and dual-mode cavities.

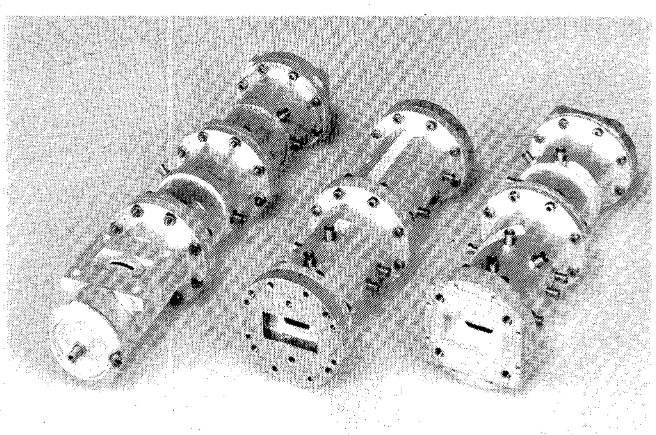

Fig. 7. Photograph of three realized filters (five-pole in-line, six-pole in-line, and seven-pole filter).

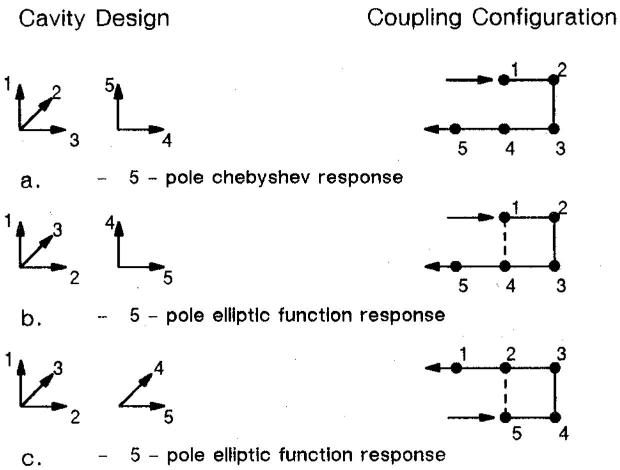

Fig. 8. Coupling structures of five-pole in-line filters.

tions. Fig. 8 depicts three coupling structures, providing symmetrical filter functions, obtained by the desired in-line structure.[2]

Only Chebyshev responses can be obtained by the first solution, while the other two can only be used for realizing elliptic function filters, due to their coupling provision from 1 to 4 and 2 to 5, respectively. Hence, the design of a particular filter response can be satisfied by choosing an appropriate coupling structure.

There are some limitations on the filter design with respect to such coupling structures as given in Fig. 8(b) and (c), i.e., if the TE–TM and TM–TM iris couplings, respectively, are used as a series coupling while the shunt coupling is obtained by the TE–TE iris coupling. A general definition of the limitations gives the maximum value of the ratio of the realizable iris couplings $M_{\mathrm{TM-TE}}/M_{\mathrm{TE-TE}}$ and $M_{\mathrm{TM-TM}}/M_{\mathrm{TE-TE}}$, respectively, for a given filter bandwidth. Since these limitations are more essential for narrow-band filters, they have been investigated for five-pole filters with 0.2 percent equiripple bandwidth.

The maximum value of the ratios is given by

$$M_{\mathrm{TM-TE}}/M_{\mathrm{TE-TE}} \simeq 2$$

in case of adjacent TE–TM triple- and TE dual-mode cavities (single offset slot as e.g., required for configuration Fig. 8(b)), and

$$M_{\mathrm{TM-TM}}/M_{\mathrm{TE-TE}} \simeq 10$$

in the case of adjacent TE–TM triple- and TE–TM dual-mode cavities (two offset slots as e.g. required for configuration Fig. 8(c)).

In spite of these limitations (concerning such special configurations) a practical filter design is possible as the investigations of the five-pole filters have shown (e.g., in the case of configuration Fig. 8(b) (maximum coupling ratio = 2) a notch level of up to 20 dB can be obtained, and configuration Fig. 8(c) (ratio = 10) allows notch levels up to 50 dB).

[2]Unsymmetrical filter functions as presented in [11] have not been considered.

$$
[M] = \begin{array}{c c}
 & \begin{array}{ccccc} 1 & 2 & 3 & 4 & 5 \end{array} \\
\begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{array} &
\left[\begin{array}{ccccc}
0 & 0.952 & 0 & 0 & 0 \\
0.952 & 0 & 0.458 & 0 & -0.595 \\
0 & 0.458 & 0 & 0.954 & 0 \\
0 & 0 & 0.954 & 0 & 0.744 \\
0 & -0.595 & 0 & 0.744 & 0
\end{array}\right]
\end{array}
$$

Normalized coupling matrix

Fig. 9. Realized five-pole elliptic function filter.

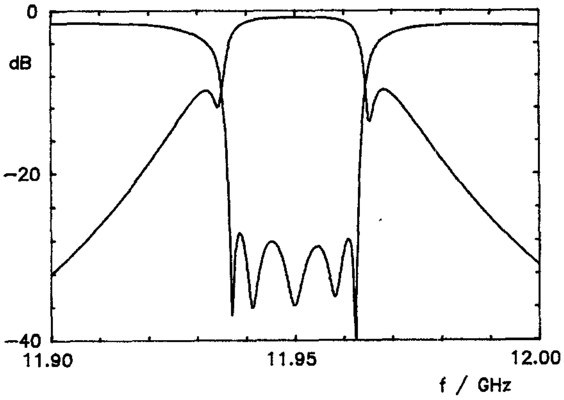

Fig. 10. Measured return loss and selectivity of the five-pole elliptic function in-line filter.

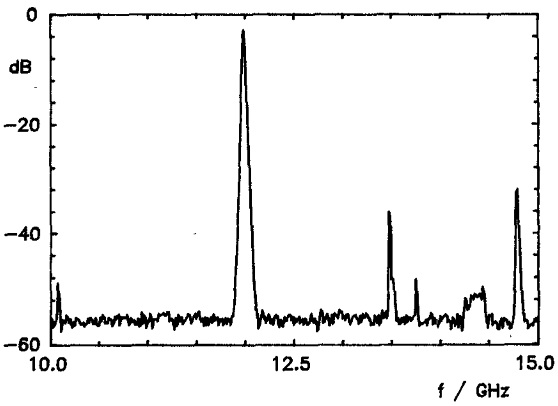

Fig. 11. Measured far-out-of-band rejection.

Since elliptic function responses provide the design of flexible selectivity characteristics, the measured results of a five-pole elliptic function filter are presented. The coupling matrix of this filter is given in Fig. 9; further design parameters are a center frequency of 11.95 GHz, 25 MHz equiripple bandwidth, and a $VSWR = 1:1.10$. The filter design is based on the coupling structure given in Fig. 8(b), i.e., using the in-line triple-mode cavity and the offset slot iris design between dual- and triple-mode cavities.

The measured return loss and the near-band selectivity (Fig. 10) coincide accurately with the theoretical response. Within the band from 10 to 15 GHz a good far-out-of-band rejection is obtained (Fig. 11), although several spurious cavity modes may be excited. The unloaded Q, derived from an insertion loss of 0.64 dB at center frequency, is better than 12 500, which is comparable to a TE_{113} realization using two dual-mode cavities and one single-mode cavity.

$$
[M] = \begin{array}{c c}
 & \begin{array}{cccccc} 1 & 2 & 3 & 4 & 5 & 6 \end{array} \\
\begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{array} &
\left[\begin{array}{cccccc}
0 & 0.933 & 0 & 0 & 0 & 0.051 \\
0.933 & 0 & 0.581 & 0 & -0.280 & 0 \\
0 & 0.581 & 0 & 0.803 & 0 & 0 \\
0 & 0 & 0.803 & 0 & 0.581 & 0 \\
0 & -0.280 & 0 & 0.581 & 0 & 0.933 \\
0.051 & 0 & 0 & 0 & 0.933 & 0
\end{array}\right]
\end{array}
$$

Normalized coupling matrix

Fig. 12. Realized six-pole elliptic function filter.

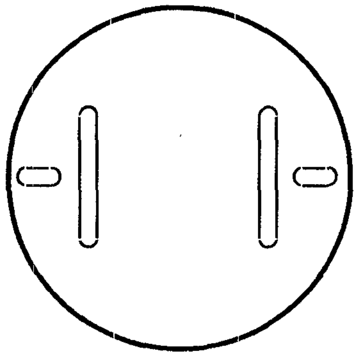

Fig. 13. Iris geometry for TE_{11n}–TM_{01m} mode coupling.

B. Six-Pole In-Line Triple-Mode Filter

As an example of cascaded in-line TE_{113}/TM_{012} triple-mode cavities, a six-pole elliptic function filter has been designed at a 11.95 GHz center frequency with an equiripple bandwidth of 25 MHz ($VSWR\ 1:1.10$).

Elliptic function response is obtained by a canonical coupling structure; the synthesized coupling matrix of the filter is given in Fig. 12.

Discrimination of the required three intercavity couplings is achieved by a convenient iris geometry, depicted in Fig. 13. The series (M_{34}) and shunt (M_{25}) couplings are realized by two parallel offset slots using the compensation method introduced above, while the additional shunt coupling (M_{16}) is obtained by two additional slot apertures that are perpendicular to the magnetic iris fields of the remaining degeneracies.

Note that the shunt coupling M_{16} is usually one order of magnitude smaller than the other ones, yielding to small aperture dimensions. The realization of this coupling by two slots located as close as possible to the circumference will lead to a negligible increase of the coupling M_{25}, since the E_z field of the TM mode is very small in this iris region. This simplifies the iris design, because the two slot pairs can be designed independently, one providing the couplings M_{34} and M_{25} and the other M_{16}.

The experimental results are in close agreement with theory. All six resonances have conveniently been excited and controlled, as the measured return loss and selectivity (Fig. 14) show. Conspicuous also is the good spurious performance of the filter within the band from 10 to 15 GHz (Fig. 15). The same unloaded Q as for the five-pole filter has been achieved (12 500), which is also comparable to a three cavity TE_{113}–dual-mode solution.

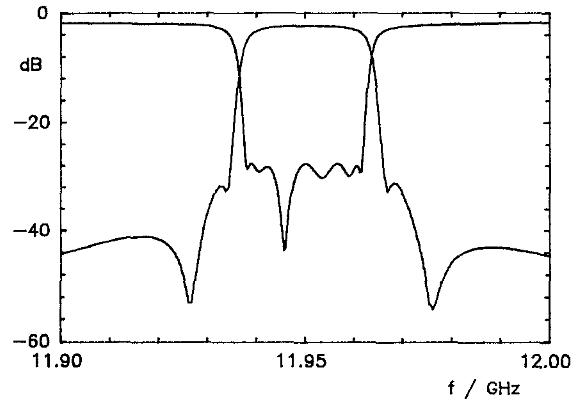

Fig. 14. Measured return loss and selectivity of the six-pole elliptic function in-line filter.

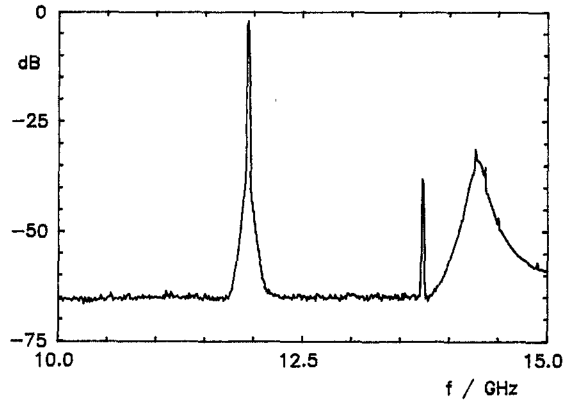

Fig. 15. Measured far-out-of-band rejection.

$$
[\mathrm{M}] = \begin{array}{c} \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \end{array}
\begin{array}{c}
\begin{array}{ccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{array} \\
\begin{bmatrix}
0 & 0.889 & 0 & -0.218 & 0 & 0 & 0 \\
0.889 & 0 & 0.749 & 0 & 0 & 0 & 0 \\
0 & 0.749 & 0 & 0.516 & 0 & 0 & 0 \\
-0.218 & 0 & 0.516 & 0 & 0.387 & 0 & -0.507 \\
0 & 0 & 0 & 0.387 & 0 & 0.902 & 0 \\
0 & 0 & 0 & 0 & 0.902 & 0 & 0.761 \\
0 & 0 & 0 & -0.507 & 0 & 0.761 & 0
\end{bmatrix}
\end{array}
$$

Normalized coupling matrix

Fig. 16. Realized seven-pole elliptic function filter.

C. Seven-Pole Elliptic-Function Filter

A seven-pole elliptic function filter has been designed using the novel coupling structure given in Fig. 6. This configuration allows the location of the input and output ports of the filter, respectively, at the end cavities, which provides an advantageous design in terms of isolation between input and output of the filter.

The synthesized coupling matrix is shown in Fig. 16. Additional design parameters are a center frequency of 11.95 GHz, a 30 MHz equiripple bandwidth, and a $VSWR = 1:1.10$.

The coupling M_{14} is of the TE–TM type introduced above; i.e., M_{34} and M_{14} have been performed simultaneously by a single offset slot aperture between the triple- and dual-mode cavities. The remaining intercavity couplings between the dual-mode cavities are realized in the conventional way, i.e., slot apertures being parallel to the magnetic field in the iris plane of the modes in question and perpendicular to the other degeneracies.

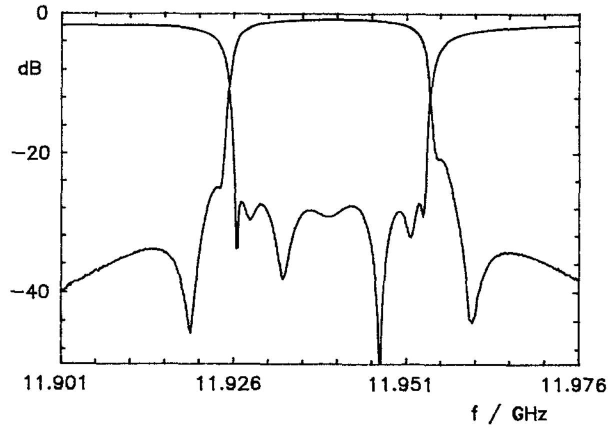

Fig. 17. Measured return loss and selectivity of the seven-pole elliptic function filter.

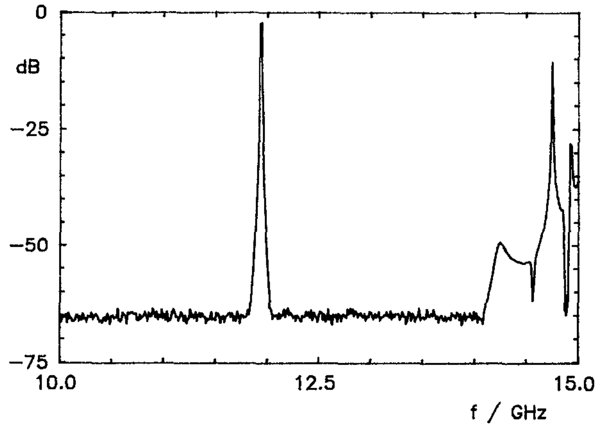

Fig. 18. Measured far-out-of-band rejection.

The tuned responses (return loss and selectivity, Fig. 17) show accurate coincidence with the theoretical ones. The far-out-of-band rejection measurement (Fig. 18) in the band from 10 to 15 GHz shows a wide spurious free band (attenuation more than 60 dB), although several spurious cavity modes may be excited. The obtained unloaded Q has the same value as the previously presented filters (12 500).

VI. Conclusions

New principles in cavity filter design using triple-mode degeneracies have been established by the introduction of an in-line triple-mode cavity design and two novel intercavity coupling methods for use between adjacent triple-mode cavities as well as between triple- and dual-mode cavities, respectively.

It has been shown that these principles provide several advantages in comparison with the well-known filter design, with respect to optimal filter functions and proper filter realizations such as in-line structures.

The application of these new possibilities has been demonstrated by several realized filters whose performance is in close agreement with theory. Remarkable are the similar unloaded Q values for conventional TE_{113} dual-mode applications and the wide spurious free bands.

Due to convenient in-line filter realization using triple or triple/dual degeneracies, such filters can be employed in a variety of multiplexer designs in the same way as conventional filter types. However, it should be noted that in-line elliptic function filters of this new technique can be realized up to seventh order in contrast to in-line dual-mode applications, which can only provide fourth-order elliptic function filters. Another advantage is of course the essential mass savings of the new filter types of up to 33 percent, caused by the reduced number of physical cavities.

The application of these principles in the design of asymmetric filter responses may lead to further advantages. They may also be extended in filter designs using other mode combinations.

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References

[1] A. E. Williams, "A four cavity elliptic waveguide filter," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 1109–1114, Dec. 1970.

[2] A. E. Atia and A. E. Williams, "New types of waveguide bandpass filters for satellite transponders," *COMSAT Tech. Rev.*, vol. 1, no. 1, pp. 21–43, Fall 1971.

[3] R. J. Cameron, "A novel realization for microwave bandpass filters," *ESA J.*, vol. 3, pp. 281–287, 1979.

[4] R. J. Cameron and J. D. Rhodes, "Asymmetric realizations for dual-mode bandpass filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 51–58, Jan. 1981.

[5] C. M. Kudsia, K. R. Ainsworth, and M. V. O'Donovan, "Microwave filters and multiplexing networks for communications satellites in the 1980s," in *Proc. AIAA Conf.*, 1980, pp. 290–300.

[6] W.-C. Tang and S. K. Chaudhuri, "A true elliptic-function filter using triple-mode degenerate cavities," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 1449–1454, Nov. 1984.

[7] R. R. Bonetti and A. E. Williams, "Application of dual TM modes to triple- and quadruple-mode filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-35, pp. 1143–1149, Dec. 1987.

[8] G. Matthaei, I. Young, and E. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures.* New York: McGraw-Hill, 1964, ch. 5.

[9] C. M. Kudsia, "A generalized approach to the design and optimization of symmetrical microwave filters for communication systems," Ph.D. dissertation, Concordia Univ., Montreal, Canada, Nov. 1978.

[10] A. E. Williams and A. E. Atia, "Dual mode canonical waveguide filters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 1021–1026, Dec. 1977.

[11] R. J. Cameron, "General prototype network synthesis methods for microwave filters," *ESA J.*, vol. 6, pp. 193–206, 1982.

[12] U. Rosenberg and D. Wolk, "New possibilities of cavity-filter design by a novel TE–TM-mode iris-coupling," in *1989 IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1155–1158.

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