Mixed-Resonance Compact In-line Pseudo-Elliptic Filters

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Abstract- **The paper presents a new class of compact in-line pseudo-elliptic filters which are based on combining waveguide cavities and resonant irises. Two different configurations, which allow precise control of the direct couplings between the different resonator types, are introduced. Two different 3-pole filters have been designed to demonstrate the feasibility of the principle. The first filter combines a resonant iris and two TE_{101} mode cavities while the second one utilizes two TM_{110} mode cavities and one resonant iris. The latter has been realized and its response measured. Excellent agreement between computed and measured responses is achieved.**

Index Terms—**Bandpass filters, waveguide filters, elliptic function filters, filter synthesis, resonant iris.**

I. Introduction

Elliptic and pseudo-elliptic function filters provide a convenient solution to the constant drive towards size reduction of filtering structures in modern communication systems. In general, a pseudo-elliptic filter with judiciously placed transmission zeros is more compact than an all-pole filter using the same resonator type and meeting the same specifications since the former requires fewer resonators. To further reduce the size and weight of elliptic filters, dual-mode and multi-mode cavities are used [1]. Another approach is to reduce the size of each resonator. Along these lines, and contrary to their common use in evanescent-mode filters, e.g. [2], compact resonant irises, e.g. [3], have been used in designing microwave resonators in filter applications [4]. However, such filters provide only all-pole characteristics, since they consist of successive arrangements of resonant irises and quarter-wavelength waveguide sections.

This paper introduces a new approach for compact filter design, namely the combination of resonant irises with other resonances, such as TE_{101} and TM_{110} rectangular waveguide cavity modes. The reason behind this choice of modes is the flexibility, wide range of coupling arrangements that can be achieved as well as the separate adjustment of coupling between the irises and the cavity modes. To further reduce the size of these filters and increase their cutoff rates, transmission zeros are implemented by using bypass couplings which can be brought about through additional but non-resonating modes in the cavities and resonant irises. The approach is validated by direct comparison of simulated and measured results of a 3[rd] order filter with one transmission zero in the upper stop-band.

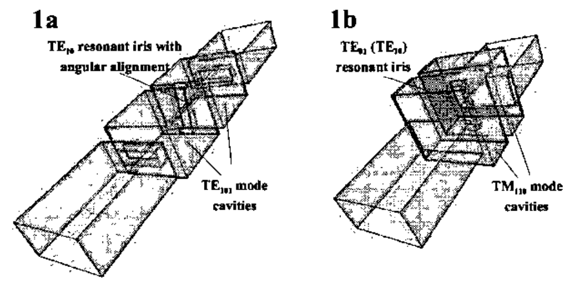

Fig. 1: Filter configurations utilizing cavity and iris resonances. Resonant irises in combination with TE_{101} mode cavities (1a) and with TM_{110} mode cavities (1b)

II. Design Approach

Although the filters designed according to the approach presented here use different types of resonators simultaneously, the model used for their synthesis and design is the standard set of coupled resonators. There is, however, a difference between the roles of the various physical elements of the structure.

The model using coupled resonators to implement a bandpass response requires resonating elements and means of coupling and controlling energy flow amongst them. The resonating elements within these filters are of two types, namely, waveguide cavity resonances and resonant irises. Since the dimensions of a resonant iris are fixed by its resonant frequency, it can no longer be used to control the coupling factor between itself as a resonator and an adjacent cavity, simply because there are no parameters left to adjust. A direct insertion of resonant irises between standard TE_{101} cavities would yield couplings of adjacent (cavity and iris) resonators that are too strong to be useful in filter design. Consequently, the use of resonant irises needs an alternative method of controlling the coupling coefficient between the different kinds of resonators. A suitable approach for the above structure (i.e. TE_{101} and resonant irises) could be to change the angular alignment of the iris with respect to the cavity (see Fig. 1a). Obviously, there will be no coupling if the polarizations of the cavity and the resonant iris are orthogonal (90°). In that case

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the 'iris resonator' is not coupled to the cavity resonance, thus resulting in a weak coupling of the adjacent TE_{101} cavity resonators mainly due to the small dimension (height) of the iris. Thus, the coupling coefficient between cavity and iris resonators can be controlled from zero to a large maximum value by decreasing the angular alignment from 90° (orthogonal) to zero (parallel). To verify this principle, a 3-pole filter has been designed at 28.8GHz (bandwidth 800MHz, 21dB return loss) using two TE_{101} mode cavities with an interconnecting iris according to Fig 1a. Over a wide frequency band, up to 32GHz, the analyzed response, Fig. 2, agrees well with the desired Chebyshev characteristic. Transmission zeros and spurious peaks above 32GHz are attributed to higher-order modes excited in the cavities.

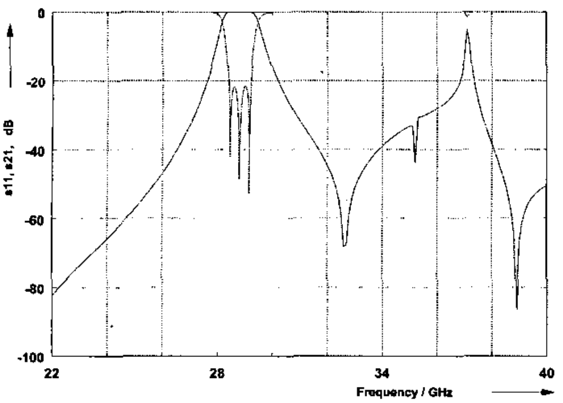

Fig. 2: Analyzed response of 3-pole filter configuration according Fig.1a (rotation of iris 9.83 degrees clockwise from vertical position).

A symmetrical filter design might be suitable for the above 3-pole structure since the angular alignment of the iris is the same for both adjacent cavities. For higher order filter designs, however, different angular alignments to both cavities connected to an iris have to be considered in order to accomplish the different coupling values. Such structures become rather complicated, especially with respect to manufacturing aspects.

Contrary to the above solution, a combination of TM_{110}-mode cavities and resonant irises is an attractive concept for this new kind of filters (cf. Fig 1b). They allow easy realization with rectangular shapes without any special angular alignment in the structure and, additionally, provide a suitable implementation of bypass couplings. The investigation of the fields of the TM_{110} mode shows that a centered iris between two cavities nearly provides sole coupling of the electrical fields. A slot iris at this position with a reasonable length exhibits a negligible coupling of the adjacent cavity modes. Thus there is the possibility to control the coupling of the cavities by merely changing the offset location (orthogonal to the slot width) from zero in the center to a strong maximum value at the respective side walls. In addition, both TE_{10} and TE_{01} resonant irises could be used in these filters. The use of two identically polarized resonant irises at the same TM_{110} cavity yields a strong bypass coupling of the cavity resonance by the non-resonating TE_{10} of the cavity. This effect appears to dramatically restrict the filter design possibilities. However, this problem is easily solved by using orthogonally polarized resonant irises (TE_{10}/TE_{01}) at the same TM_{110} cavity. The introduction of bypass couplings for responses with transmission zeros at finite frequencies can be performed by utilizing non-resonating modes in either, the TM_{110} cavities and the resonant irises. They may be accessible as TE_{10} modes in the cavities or as evanescent higher-order modes of the irises. Note that the coupled magnetic fields of the TM_{110} mode change their direction at the center of the cavity. Consequently, the direction of iris offset locations from the cavity center can be utilized for the transformation of sign conventions in cross coupled sections [5].

The initial design of the filters starts by extracting an appropriate coupling matrix which satisfies the specifications of the filter as well as the topology of the intended implementation. Using the information in the coupling matrix, the dimensions of the resonators, including those of the iris, are determined such that the resonators resonate at or in the vicinity of their respective resonant frequency. The resonance frequency of the TM_{110} mode in a cavity of width a and height b is determined by the well known formula

$$f_r = \frac{v_c}{2}\sqrt{\frac{1}{a^2}+\frac{1}{b^2}} \qquad (1)$$

with cavity dimensions width a, height b and speed of light v_c. An expression for the iris resonant frequency is given in [6]. The fact that the smaller dimension b_{iris} of a slot iris is significantly smaller than the waveguide wavelength of adjacent cavities yields the simple approximation of the iris resonance condition

$$f_r \quad \frac{v_c}{2\,a_{iris}} \qquad (2)$$

Note, that the iris resonant frequency is usually determined by its broad dimension a_{iris} and corresponds to its cut-off frequency.

Once the initial dimensions are known, a careful examination of the field distribution of the different resonators is carried out to determine the possible arrangement to achieve the desired coupling coefficients including their relative signs.

To finalize the design, the dimensions of the filter are optimized using a fast and reliable numerical technique such as the Mode-Matching Technique (MMT) [6] or the Coupled Integral Equations Technique (CIET) [7]. Manufacturing radii can be included in a final fine optimization by employing corresponding software tools, e.g. [8].

III. RESULTS

The procedure described above was applied to the design of a 3-resonator filter with one transmission zero in the upper stopband. The in-band return loss of the filter is 23 dB, with a bandwidth of 450 MHz centered at 27.5GHz. The transmission zero is positioned at 30 GHz.

The starting dimensions of the TM_{110} resonators are straightforwardly determined from the desired resonant frequency (27.5GHz) and the requirement that the TE_{101} mode be non-resonating. In addition, the initial width a_{iris} of the resonant iris is given according to (2). The height b_{iris} and length l_{iris} of the iris can be used for the realization of cross couplings between the adjacent TM_{110} cavity modes; i.e., a small signal portion is transmitted in parallel to the TE_{10} iris resonance by higher-order modes (mainly TE_{01} and TM_{11}) in the iris section.

For the present design, the interface waveguides are directly coupled to the TM_{110} mode cavities. The coupling is solely controlled by the center offsets. Rather strong couplings f the interface waveguide modes with a resonant iris of the same polarization would occur via the non-resonating TE_{10} cavity modes. The suppression of these couplings is achieved by implementing the resonant iris with orthogonal alignment with a lateral offset from the cavity centers.

Reasonable radii were to be considered in the corners of the cavity to cope with easy manufacturing in two halves with state-of-the-art milling techniques. To comply with these specification, the filter structure has been optimized with the commercial CAD μWave Wizard□ [8]. The performance of the obtained design is shown in Fig. 3.

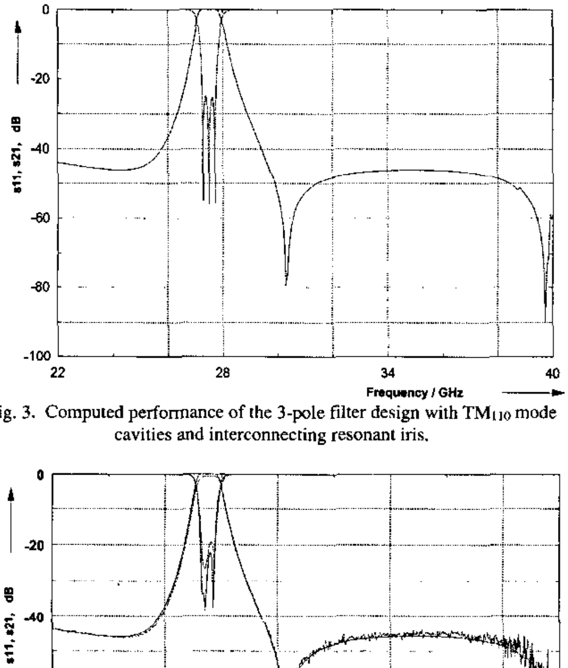

Fig. 3. Computed performance of the 3-pole filter design with TM_{110} mode cavities and interconnecting resonant iris.

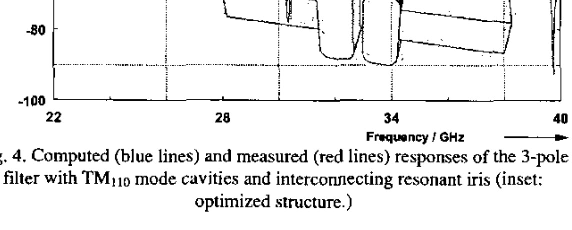

Fig. 4. Computed (blue lines) and measured (red lines) responses of the 3-pole filter with TM_{110} mode cavities and interconnecting resonant iris (inset: optimized structure.)

To finally verify the design approach, the component has been fabricated. Due to manufacturing tolerances of about 0.03mm, a slight degradation in return loss performance was observed. Fig. 4 shows the measured response together with the computed one using the actual fabricated dimensions. Excellent agreement between the two curves in Fig. 4 as well as with the original design prediction (Fig. 3) is observed over a wide frequency range. Note that this compact filter design provides a very good out of band performance as the results demonstrate. The measured insertion loss of the aluminum-block filter without silver plating is 0.6 dB. A photograph of the hardware is depicted in Fig. 5.

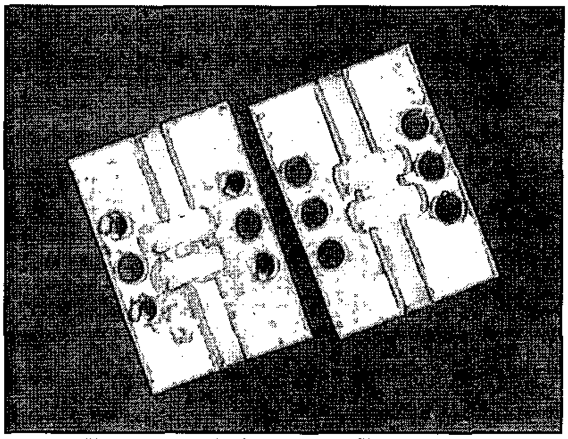

Fig. 5: Photograph of the prototype filter halves.

IV. Conclusions

The combination of direct-coupled resonant irises and cavity modes – both as filter resonant circuits – is shown to provide compact in-line filters. Prerequisite for this basic filter design is the control of the couplings between the waveguide cavities and the resonant irises that are too strong for a filter realization in common standard designs. The remedy to that problem was found by locating the resonant iris near a field zero of the cavity mode and controlling the magnitude of coupling by changing the offset position with respect to the zero. This concept was applied to two different 3-pole filter designs. First, two TE_{101}-mode cavities were interconnected with a resonant iris where the coupling was controlled by an angular offset of a perpendicularly orientated iris. Secondly, TM_{110} resonances were used instead of TE_{101} modes. This allows coupling control by an off-center location of the iris. The latter design, which also considered easy implementation of bypass couplings, was fabricated. Excellent agreement between computed and measured results demonstrates the feasibility of the compact new filter type. Obviously, this design concept is suitable for higher order filters. However, it may be also adapted in sophisticated filter designs using combinations of resonant irises with other cavity types such as circular or coaxial.

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