Circular Waveguide TM_{11}-Mode Resonators and Their Application to Polarization-Preserving Bandpass and Quasi-Highpass Filters

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Abstract **— Circular waveguide filters with improved performance are presented. They are based on TM_{11}-mode resonators which permit the filter to be smaller than standard TE_{11}-mode filters, preserve all polarizations due to rotational symmetry, and are flexible with respect to the design of bandpass or highpass filters. In order to demonstrate their advantages, they are compared to a standard TE_{11}-mode design. Design guidelines are presented, and performances of resulting bandpass and quasi-highpass filters are shown. The coupled-integral equation technique (CIET) is used as the main computational tool. All provisional and final designs are verified by comparison with the commercially available software package μWave Wizard.**

Keywords – waveguide filters; circular waveguide modes; polarization; bandpass filters; highpass filters; computer-aided design.

I. INTRODUCTION

Polarization-preserving waveguide filters require components with either two-plane identical ridges, such as quadruple-ridged waveguides [1], [2], or rotational symmetry in the cross section [3]. Both features benefit from extended bandwidth, e.g. [4], through the excitation of only those modes that satisfy structural symmetry along with that of the incoming electromagnetic field, e.g. [5], [6].

Modern microwave filters are required to possess properties such as wide bandwidth, improved out-of-band performance and preservation of all polarizations. While the mechanism to generate attenuation poles at finite frequencies in the filter response is well understood in standard dual-mode filters, e.g. [7], [8], the polarization-preserving specification is not always straightforward in communication equipment, e.g. [9].

Therefore, this paper focuses on the design of rotationally symmetric, thus polarization-preserving, circular waveguide filters. The basic concept is based on using TM_{11}-mode rather than TE_{11}-mode resonators. It is demonstrated that first, such a filter is much shorter than one realized with TE_{11}-mode cavities, secondly, provides transmission zeros below the passband and, thirdly, allows for applications as quasi-highpass filters. The advantage of such a design, which is presented in Section III, becomes apparent when compared to the standard TE_{11}-mode filters in Section II.

II. TE_{11}-MODE FILTERS

The standard circular waveguide iris filter is straightforwardly designed using cascaded half-wave cavities separated by irises which act as impedance inverters [10]. For all examples shown in this paper, we use WC 80 (20.244 mm in diameter) waveguides as input/output ports. Its fundamental TE_{11}-mode cutoff frequency is 8.68 GHz. Due to rotational symmetry, the next excited higher order mode is TM_{11} with a cutoff frequency of 18.1 GHz.

The inset of Fig. 1 shows a standard circular waveguide iris filter which is designed for a center frequency of 11.5 GHz and a bandwidth of 500 MHz. Return loss specifications of 22 dB and stopband requirements dictated the use of seven TE_{11}-mode cavities. This filter is used as the first prototype satisfying the demand for the preservation of polarization. Its length from first to last iris is 131.5 mm with 1 mm thick irises. As can be observed from the performance in Fig. 1, the main passband is well represented but a second wider passband appears already at 15.5 GHz, thus limiting the applicable bandwidth of such a design.

In order to improve the stopband performance, the use of frequency-dependent radial inverters was suggested [3]. Such inverters are capable of producing a transmission zero (also referred to as attenuation pole) on the right or left side of the passband. As shown in Fig. 2, however, the introduction of the transmission zero (at 12.2 GHz) does not offer a solution for the second passband since the electrical lengths of the resonators remain the same. Moreover, employing radial inverters leads to axially asymmetric filter designs as seen in the inset of Fig. 2.

III. TM_{11}-MODE FILTERS

It is obvious that in order to avoid the second passband of the designs in Fig. 1 and Fig. 2, shorter resonators must be employed. This is possible only by using the lowest-order TM-modes as resonators since their resonance does not depend on the cavity length. Fig. 3 shows the field configurations of the TE_{11} mode of a feeding circular waveguide or iris (left) and the TM_{11} mode of a larger resonator [11]. When the resonator is center-fed by the circular iris, the horizontal magnetic field of the iris excites the magnetic field of the TM_{11} resonator mode. Of course, the fundamental TE_{11} mode in the larger resonator is also excited, but the resonator length is chosen short enough so that the TE_{11} mode is not resonating at the frequency of interest.

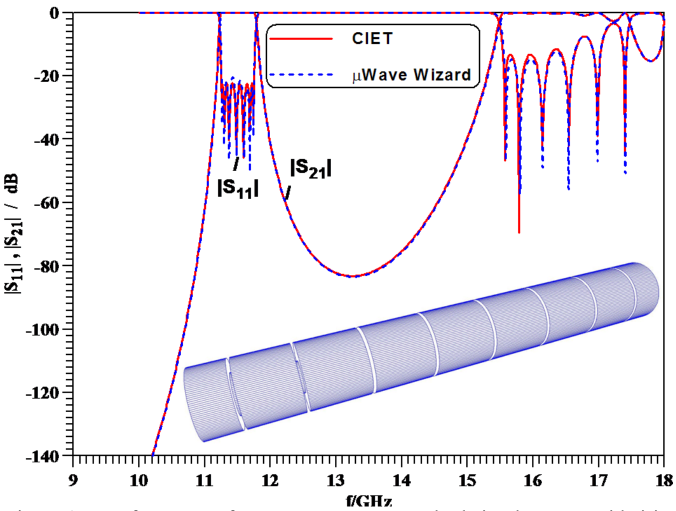

Figure 1. Performance of a seven-resonator standard circular waveguide iris filter designed for 500 MHz bandwidth at 11.5 GHz.

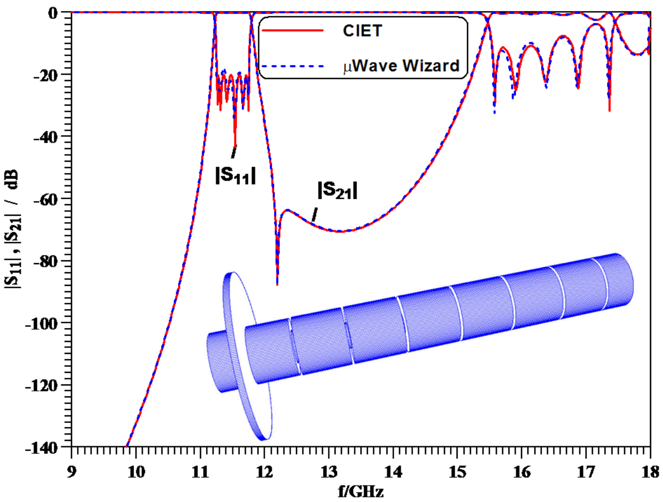

Figure 2. Performance of the filter of Fig. 1 with an added frequency-dependent radial inverter section.

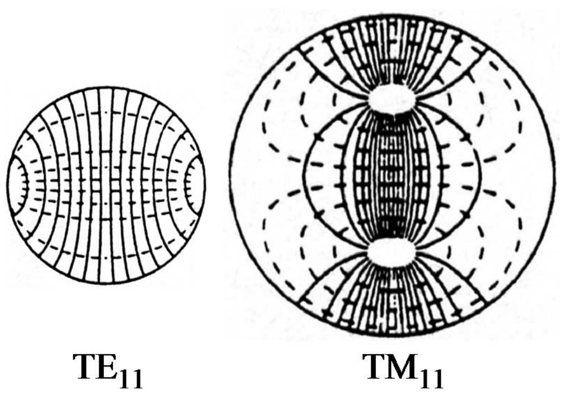

Figure 3. Field plots of circular iris TE_{11} mode (left) and circular cavity TM_{11} mode (right) [11].

Consequently, since the magnetic field lines of the TE_{11} mode extend through the adjacent irises and will close in axial direction while those of the TM_{11} mode remain constant over the length of the resonator, a negative bypass coupling is introduced which creates a transmission zero below the resonance frequency. This is demonstrated in Fig. 4 (and verified by the µWaveWizard), where the resonance appears at 9.625 GHz with a transmission zero at 9.18 GHz. The inset in Fig. 4 thus presents a socalled singlet whose behavior is analog to that of comparable retangular waveguide technology as presented and discussed in [12].

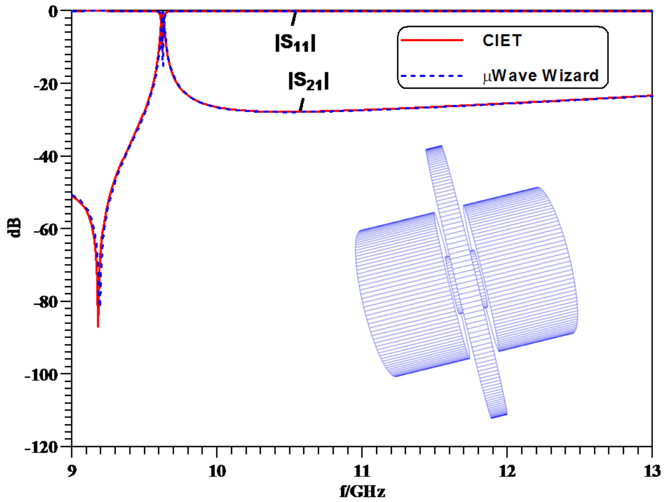

Figure 4. Singlet in circular waveguide technology (inset) and its performance producing one transmission zero and one reflection zero.

From a filter designer's point of view, the possibility of moving the transmission zero to the opposite side of the resonance is an important issue. Unfortunately, as is obvious from the field plots in Fig. 4, this can only be achieved by moving the exciting iris away from the center position of the resonator. Three disadvantages appear immediately: first, the filter will lose its polarization-preserving property; secondly, a different set of modes will be excited due to the asymmetric connection and, thirdly, the new mode set will severely limit the applicable bandwidth of the design. Under such conditions, the next mode to resonate is the TM_{01} mode and, although not shown here for lack of space, it is indeed possible to move the transmission zero to the right side of the resonance when the the TM_{01} resonance is utilized as main resonator.

In order to design a rotationally symmetric bandpass filter, the cross sections of all TM_{11}-mode resonators are first dimensioned according to the resonances of a Chebyshev prototype. The cutoff frequencies of the modes under consideration are

$$f_{cTE_{11}} = 1.8412 \frac{c}{2\pi r}, \qquad f_{cTM_{11}} = 3.8317 \frac{c}{2\pi r} \tag{1}$$

where c is the speed of light and r is the radius of the respective waveguide. The coupling between a smaller waveguide's TE_{11} mode and a larger waveguide's TM_{11} mode can be controlled by [6]

$$P_{TE_{11}\rightarrow TM_{11}} \propto \left|J_1\left(\chi_{11}\, r_1/r_2\right)\right|^2 \Big/ \sqrt{\left|1-\left[\chi_{11}/\left(k_0 r_2\right)\right]^2\right|} \quad (2)$$

where χ_{11} denotes the first zero of Bessel function J_1, k_0 is the free-space wavenumber, and r_1 and r_2 are the radii of the smaller and larger waveguides, respectively.

For resonance frequencies obtained from a Chebyshev filter synthesis, the diameters of the TM_{11}-mode resonators are determined according to (1) under consideration that loading by both irises will move these resonances slightly downward. Iris diameters can be approximately selected from (2) for given coupling coefficients. The entire filter structure is then fine-optimized using the coupled-integral-equation technique (CIET) within a MiniMax optimization algorithm [13]. The optimization is normally set to produce an axially symmetric filter design.

IV. Results

Fig. 5 shows such bandpass filter using seven TM_{11}-mode resonators. Several differences are noted when comparing the filter response of Fig. 5 with that of Fig. 1. We obtain seven transmission zeros below the passband. The transition from stopband to passband between 11 GHz and 11.25 GHz is significantly improved due to the appearance of transmission zeros. This comes at the expense of a reduced stopband performance immediately above the passband. However, this apparent disadvantage is offset by the elimination of the second passband in Fig. 1 (15.5 GHz to 18 GHz), where the filter in Fig. 5 maintains an attenuation of 35 dB. Note that the constant attenuation level towards higher frequencies is in accordance with filter theory since all possible transmission zeros appear below the passband. Finally, the TM_{11}-mode filter in Fig. 5 is considerably more compact as its length between first and last iris is only 31.4 mm – a reduction by more than 75 percent compared to the filter in Fig. 1.

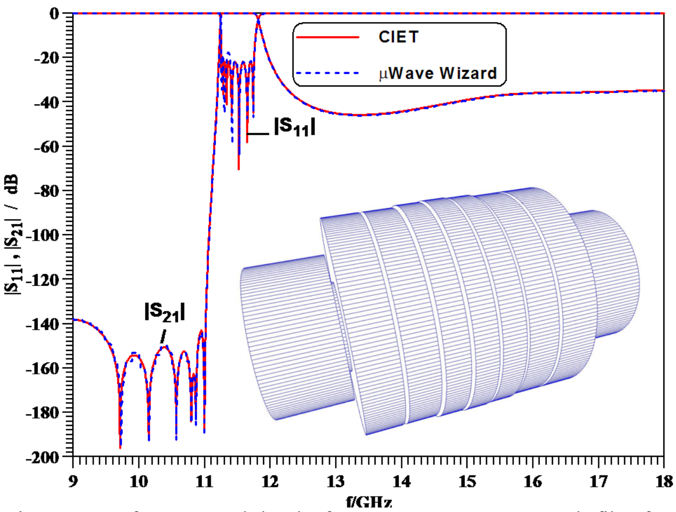

Figure 5. Performance and sketch of a seven-resonator TM_{11}-mode filter for comparison with Fig. 1.

Another advantage of utilizing TM_{11}-mode resonators becomes apparent when further investigating the capabilities of the singlet shown in Fig. 4. By increasing the length of the resonator as well as the diameters and lengths of the connected irises, two more resonances, which appear above that of the TM_{11}-mode can be exploited. This is shown in Fig. 6, where the $|S_{11}|$ minimum at 11.41 GHz is due to the TM_{110} resonance. The TE_{11}-mode resonance in the iris causes the dip at 13.5 GHz, and that at 16.5 GHz is due to the TE_{111} resonance in the large cavity. Consequently, such a combination of axially connected circular waveguide sections is destined for quasi-highpass applications.

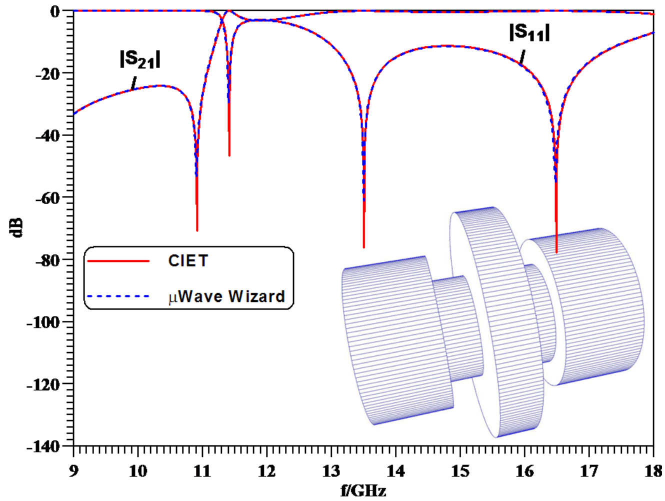

Figure 6. Performance of an extended TM_{110}-mode singlet incorporating resonances of irises and that of the TE_{111} mode.

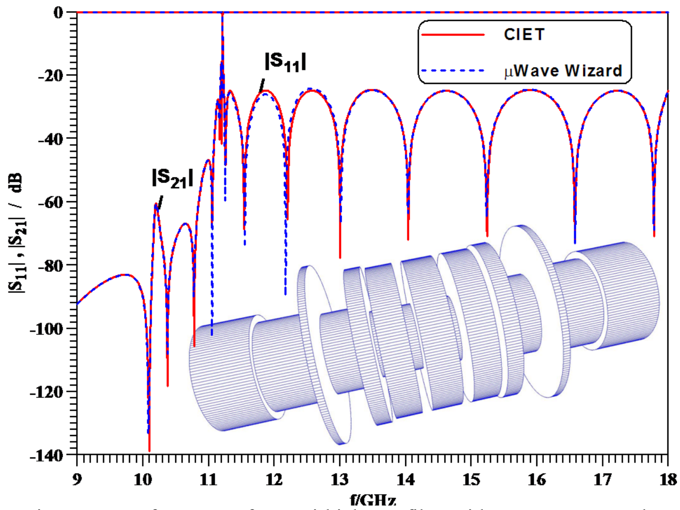

Figure 7. Performance of a quasi-highpass filter with seven TM_{110}-mode resonators and additional resonances according to Fig. 6.

Based on this investigation, a quasi-highpass configuration formed by seven TM_{11}-mode resonantors is assembled and optimized for a roll-off frequency of 12.24 GHz and return loss of 24 dB. The filter is shown in Fig. 7 (inset) together with its performance. The length between input and output iris is 63 mm and thus about twice as long as the bandpass filter depicted in Fig. 5. Note that cross-sectional rotational symmetry and thus polarization preservation has not been compromized.

A comparable quasi-highpass filter in rectangular waveguide technology has been presented in [14]. The excellent agreement between measurements and CIET results in [14] as well as the validation of the filter response in Fig. 7 by the µWaveWizard validate the design procedure for polarization-preserving circular waveguide TM_{11}-mode filters.

V. CONCLUSIONS

TM_{11}-mode filters in circular waveguide technology are presented. A single resonator forms a singlet which creates a reflection zero and a transmission zero below the passband. It is demonstrated that such filters possess a number of significant advantages to standard circular waveguide iris filters. TM_{11}-mode filters are smaller and do not suffer from a second passband within the frequency range of application. They allow for design flexibility with respect to passband or quasi-highpass operation. Moreover, all stuctures exhibit cross-sectional rotational symmetry and thus preserve the polarization of any input signal. Excellent agreement with the commercially available software package µWave Wizard validates the numerical design procedure presented in the paper.

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