New Evanescent-Mode Filter Designs In Circular Waveguide Using a Classical Eigenvalue Mode-Spectrum Analysis

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***Abstract* — New evanescent-mode filter designs in circular waveguide technology are presented. They include circular-waveguide multiple-ridge and T-septum filters and a filter formed by key-shaped inserts in circular waveguide. By utilizing a classical eigenvalue mode-spectrum analysis, the shape and location of the metallic inserts in the circular waveguide's cross section remain arbitrary, thus providing capability for the computation of new cross sections. The implementation of the basic approach is verified by comparison with MMT and CIET codes as well as the μWave Wizard.**

Keywords – waveguide filters; evanescent-mode filters; irregular waveguides; classical eigenvalues; mode-matching techniques; computer-aided design.

I. INTRODUCTION

Among the large variety of nonstandard or irregular waveguide cross sections [1], circular waveguides with metal inserts or ridges have found applications mainly in filters [2] - [4], polarizers [5], antenna feeds [6], [7], and cavities for electron devices [8]. In order to determine the mode spectrum of such nonstandard waveguides, the ridges or metal inserts are either considered of rectangular [9], [10] or conically shaped cross section [3] – [8], [11] – [13], the latter having the advantage of using a single circular-cylindrical coordinate system.

Evanescent-mode filters, sometimes also referred to as below-cutoff filters, are usually implemented by an abrupt transition from a larger to a smaller waveguide. The smaller waveguide is operated below cutoff but contains ridges which act as resonators by lowering the cutoff frequency of the smaller waveguide to approximately that of the larger waveguide, e.g. [3]. Another approach consists in utilizing the waveguide with ridges not just as resonators but also as input and output ports, e.g., [14], thus assuming that a system be realized in a reduced-size, metal-ridged waveguide technology altogether. Such an approach is used in this paper for the development of new circular waveguide evanescent-mode filters.

Previous evanescent-mode filters have employed a given cross section (waveguide filled with metal insert or ridges) for the realization of resonators and/or input/output ports. The shape and location of ridges largely depended on the cross sections whose mode spectra could be analyzed by modal techniques with reasonable effort [3], [14], [15]. However, in order to use arbitrarily located and shaped ridges, especially in circular waveguide housings, a more general approach is required which allows the creation of different irregular circular waveguide cross sections suitable for evanescent-mode filter operation.

Therefore, this paper employs a classical eigenvalue mode-spectrum analysis for the determination of new cross sections with potential for evanescent-mode filter design. A number of new filter configurations is introduced and their suitability for evanescent-mode operation demonstrated

II. THEORY

The classical eigenvalue mode-spectrum analysis employed here follows the basic approach outlined in [16] – [20], but it is translated into the circular-cylindrical coordinated system. Fig. 1 depicts the cross section of a circular waveguide with two conically shaped ridges. The locations of ridges are denoted by coordinates (ρ_i, ϕ_i), and their radial and angular width are given by $\Delta\rho_i$ and $\Delta\phi_i$, respectively. The only restriction is that individual ridges must be connected to the housing or to each other with at least one of them connected to the housing.

Since a full set of accompanying equations is available from a full-length paper [21], we will focus our attention here on the basis functions for computing the mode spectrum and the new filter structures.

In order to determine the mode spectrum of a circular waveguide with N conical ridges (Fig. 1), we expand the longitudinal field components as

$$\begin{Bmatrix} H_z \\ E_z \end{Bmatrix} = \sum_{p=1}^{P} c_n \begin{Bmatrix} h_{zp} \\ e_{zp} \end{Bmatrix} \tag{1}$$

The computation of TE modes is facilitated by using the modes of the circular housing as basis functions

$$h_{zp(m,n)} = J_m\left(k_{chmn}\rho\right) \begin{Bmatrix} \cos(m\phi) \\ \sin(m\phi) \end{Bmatrix} \tag{2}$$

since they satify the bounday conditions for the TE modes immediately. For TM modes, the longitudinal electric field must be forced to vanish over the cross sections of the ridges and therefore, two-dimensional constraint functions are included

$$e_{zp(m,n)} = J_m\left(k_{cemn}\rho\right)\begin{Bmatrix}\sin(m\phi)\\ \cos(n\phi)\end{Bmatrix}\prod_{i=1}^{N} U\left(\frac{\rho-\rho_i}{\Delta\rho_i},\frac{\phi-\phi_i}{\Delta\phi_i}\right) \tag{3}$$

where

$$U\left(\frac{\rho-\rho_i}{\Delta\rho_i},\frac{\phi-\phi_i}{\Delta\phi_i}\right)=\begin{cases}0, & \begin{cases}\rho_i \le \rho \le \rho_i+\Delta\rho_i\\ \phi_i \le \phi \le \phi_i+\Delta\phi_i\end{cases}\\ 1, & \text{everywhere else}\end{cases} \tag{4}$$

Note that the derivatives of (3) contain delta functions which are considered using the sifting theorem.

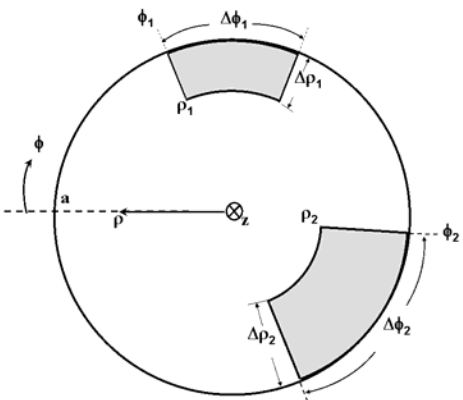

Figure 1. Cross section of a circular waveguide with two arbitralily ridges.

Once the eigenvalues $\underline{k}_c$ and eigenvector matrix $\underline{c}$ are obtained from

$$K\underline{c} = \underline{k}_c^2 M\underline{c} \tag{5}$$

where matrices K and M are given in [21], the coupling integrals from the circular housing to the circular ridged waveguide as well as power normalizations follow straightforwardly [20], [21] so that this approach can immediately be combined with a standard mode-matching technique (MMT) in circular waveguides.

III. Results

A code with up to four ridges has been implemented. The circular waveguide iris filter shown in the inset of Fig. 2 is used to demonstrate that the eigenvalue analysis correctly predicts the mode spectra of regular circular waveguides. The filter performance depicted in Fig. 2 is obtained by employing a single ridge of angular width of 360 degrees for the irises while all other possible ridges are set to zero. Excellent agreement is observed with results obtained from a Coupled-Integral-Equation Technique (CIET) code and the µWave Wizard. For reference and comparison with the evanescent-mode filters presented in this section, note that the radius of the empty circular waveguide is 6.5 mm and that the fundamental TE_{11} mode starts propagating at 13.5 GHz.

The first evanescent-mode filter is presented in Fig. 3. This is the same data used in [21] and is presented here for direct comparison with the MMT. Note that the cross section of the ridged circular waveguide is double-plane symmetric. This is the reason for it to be analyzable by the MMT. Moreover, it eliminates the excitation of asymmetric resonances and, therefore, the next passband occurs beyond 16 GHz. The cutoff frequency of the double-ridged input/output ports is 7.58 GHz.

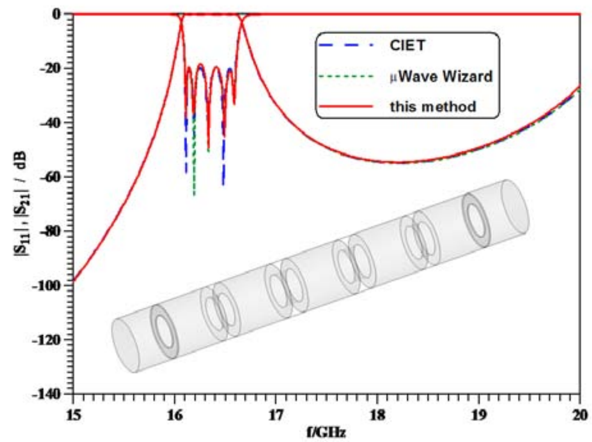

Figure 2. Performance of a five-pole circular waveguide iris filter and comparison with results obtained from a CIET code and the µWave Wizard.

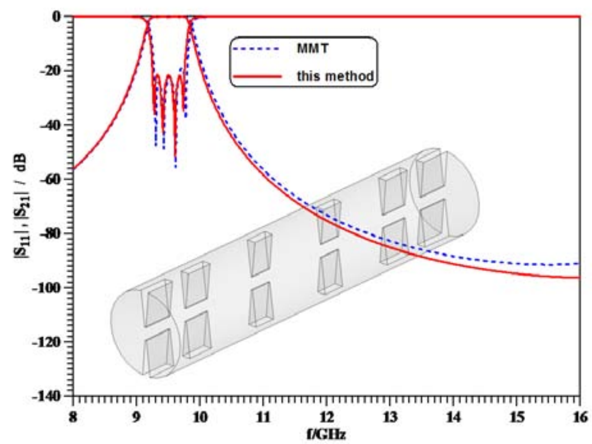

Figure 3. Performance of a four-pole evanescent-mode filter in double-ridged circular waveguide technology and comparison with results obtained from an all-MMT code.

A filter with the same specifications as that in Fig. 3, but with three ridges instead of two, is shown in Fig. 4. The performance is very similar to that in Fig. 3 as far as the passband is concerned. The behavior towards higher frequencies is different, though. This is due to the fact that the cross section is reduced to single-plane symmetry which is responsible for the second passband peak appearing at around 15 GHz in Fig. 4. In comparison with the double-ridge filter, the cutoff frequency of the triple-ridged ports is 7.86 GHz.

The concept is continued with the quadruple-ridge filter in Fig. 5. Note that two-plane symmetry in the cross section is restored and, therefore, the passband peak around 15 GHz, which is caused by asymmetric modes in Fig. 4, disappears in the performance of the quadruple-ridge filter in Fig. 5. The cutoff frequency of the input/out put ports is 7.76 GHz.

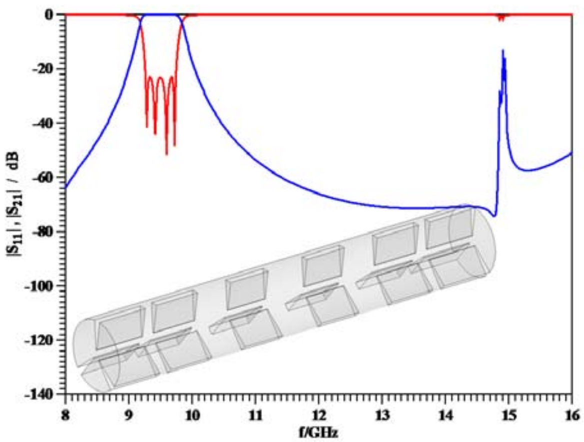

Figure 4. Performance of a four-resonator evanescent-mode filter in circular triple-ridge waveguide technology.

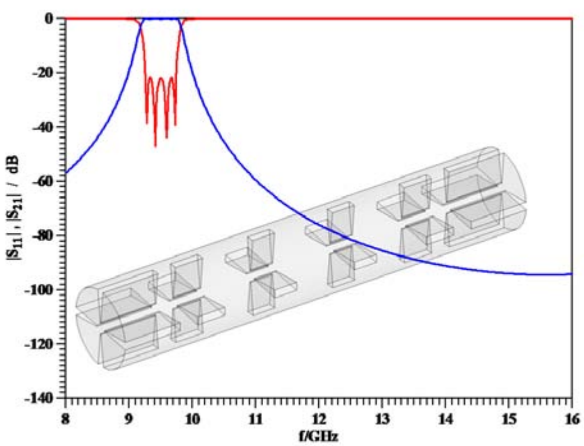

Figure 5. Performance of a four-resonator evanescent-mode filter in circular quadruple-ridge waveguide technology.

In order to reduce the center frequency of these filter, the distance between ridges, currently at 2 mm or 0.15 times the dimension of the housing, must be further reduced. However, this is not advisable from a practical point of view since the field concentration around the tips of the ridges would increase tremendously, thus resulting in increased losses.

A possible alternative is found by reshaping the ridges. Fig. 6 shows a circular T-septum below-cutoff filter designed for a midband frequency of 8.76 GHz. The cutoff frequency of the input/output ports is 7.52 GHz. Although the cross section is only single-plane symmetric, which is associated with the inevitable excitation of asymmetric modes, the midband frequency of the filter is reduced compared to that of the triple-ridge filter in Fig. 4 and, thus, the second passband peak is pushed upwards in frequency to appear at 15.8 GHz in Fig. 6. Similar behavior is observed in [14] for rectangular-waveguide evanescent-mode filters.

A further reduction in cutoff frequency is only possible by increasing the angle of the bar of the circular T-septum. This leads to the development of the key-shaped ridged structure as shown in the Fig. 7. Its cutoff frequency is 6.83 GHz, and the filter is designed for 440 MHz bandwidth at 8.5 GHz and 25 dB return loss. The housing dimensions are maintained at a radius of 6.5 mm. Since the midband frequency is further reduced compared to that of Fig. 6, the second passband peak is moved further upward in frequency and appears now beyond 16 GHz. Moreover, the frequency of minimum transmission is moved from 11.5 GHz in Fig. 6 to 15 GHz in Fig. 7. It is interesting to note that the mode spectrum obtained for the key-shaped cross section includes the well-known solutions for the smaller circular waveguide. Thus the formulation in circular coordinates provides also solutions for standard circular waveguides which appear as part of the arbitrary placement of the ridges in circular waveguide.

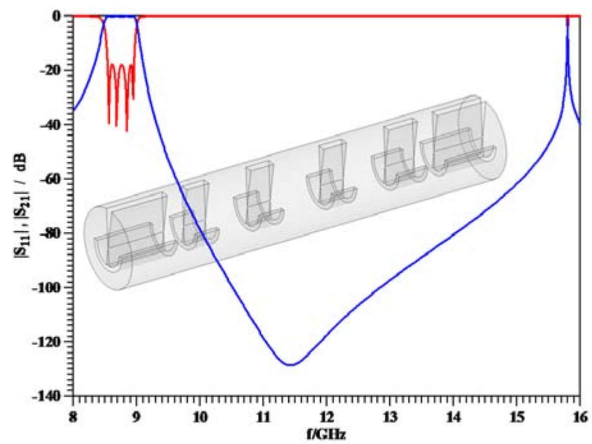

Figure 6. Performance of a four-resonator evanescent-mode filter in circular T-septum waveguide technology.

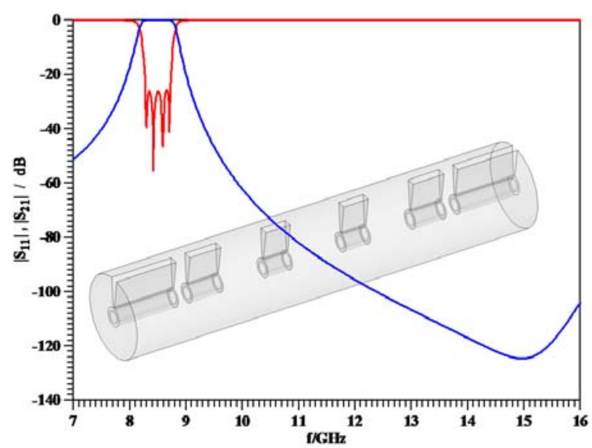

Figure 7. Performance of a four-resonator evanescent-mode filter in circular key-shaped ridge waveguide technology.

Finally, an evanescent-mode filter, which maintains two-plane symmetry and avoids a too close placement of the tips of the ridges, is the double T-septum filter shown in Fig. 8. The midband frequency is at 7.125 GHz and the cutoff frequency of the input/output ports is 5.99 GHz. The performance shows excellent stopband behavior with a second passband beyond 18 GHz. The angular width of the T-septum bars is 90 degrees, and the minimum distance between the ridges is 1.41 mm. Hence, compared to the double-ridge filter of Fig. 3, the distance between the ridges is not only increased, but the maximum field concentration for the same power transfer is divided between two locations of proximity of the ridges. Whereas this is an improvement over the filter in Fig. 3, it is expected, based on measurements conducted in [14], that the passband insertion losses will amount to 2 - 3 dB.

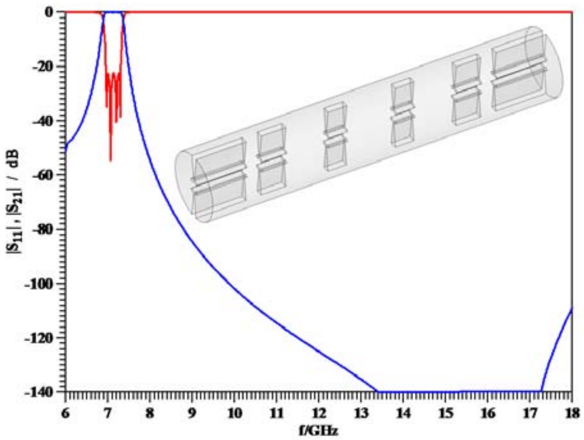

Figure 8. Performance of a four-resonator evanescent-mode filter in circular double-T-septum waveguide technology.

In comparing the cross sections of this section with those that have been treated with an all-MMT approach, we find that the solutions of structures such as displayed in Fig. 4 to Fig. 8 have never been attempted with an entirely MMT-based approach. Hence the eigenvalue mode-spectrum technique presented here provides opportunities for the design of new circuits and components.

IV. Conclusions

New evanescent-mode filter designs in circular waveguide technology are presented. These are multiple-ridge and T-septum filters as well as a filter formed by key-shaped inserts in circular waveguide. The calculation of such cross sections is made possible by employing a classical eigenvalue mode-spectrum analysis which allows varying numbers of metallic inserts in the circular waveguide's cross section be considered at arbitrary locations. This provides an opportunity for new circular waveguide component designs.

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