INLINE WAVEGUIDE FILTERS WITH ARBITRARILY LOCATED ATTENUATION POLES

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Abstract: **A novel waveguide bandpass filter design is presented which allows an inline resonator configuration to produce as many attenuation poles as resonances. The components are based on iris-coupled TM_{110}-mode cavities utilizing propagating but non-resonating TE_{10} or TE_{01} modes to create cross coupling between cavities, input and/or output waveguides. The general design procedure is outlined and demonstrated at two four-pole filter examples. The performances of the final designs are verified by excellent agreement between the results of two independently developed modal analysis tools.**

Key words: **waveguide bandpass filters, elliptic-function filters, filter synthesis**

1. Introduction

Inline waveguide filters have been used for many years in a large variety of applications. Their theory and design in directly coupled resonator arrangements is well known and understood, e.g. [1], [2]. Recently, more stringent filter specifications called for inline resonator designs with attenuation poles (transmission zeros) in the vicinity of the passband. Two principal methods are known to achieve such a design. First, individual coupling elements (impedance inverters) can be made frequency selective. In the passband, their values match those specified by filter synthesis whereas, at certain frequencies away from the passband, the inverter values vanish, thus creating transmission zeros, e.g., [3], [4]. Although this technique can generate a multitude of attenuation poles, their locations are difficult to control, especially if the number of attenuation poles is close or equal to the number of electrical resonators. Secondly, we can apply cross-coupling between adjacent physical resonators. This process is utilized in dual/multi-mode resonator arrangements following design procedures of, e.g., [5] or [6]. Input/output bypass coupling simplifies the design of and performance control in dual/multi-mode resonator filters. However, such designs cannot accommodate input/output multiresonator cross coupling in inline waveguide filter configurations, thus limiting the number of attenuation poles to well below the number of electrical resonances.

Therefore, this paper introduces inline waveguide filters which allow the maximum number of attenuation poles to equal that of electrical resonances. The necessary cross coupling between the input and the output of the filter is achieved by propagating, yet non-resonating modes. Note that in all examples cited above, higher-order mode propagation and related coupling is usually an unwanted effect. Here, we are now making use of the properties of several propagating modes, some of which (TM_{110} modes) are used to create the resonances while others (TE_{10}, TE_{01} modes) are responsible for introducing bypass coupling [7], [8]. Fig. 1 shows an example of such a filter structure. Note that in this specific configuration, there are no irises required at the input and output of the filter.Although the TM_{110}-mode resonators are coupled by inductive or capacitive irises, the interfaces of input and output ports couple directly to the respective adjacent cavities through their transverse magnetic field components.

2. Theory

The theoretical synthesis and design procedure follows essentially the approach proposed in [9]. We start with a topology matrix and verify that the required number of transmission zeros can be achieved with the proposed topology. This is a simple algorithm outlined in [10]. For instance, a four-pole quasi-elliptic function filter with one attenuation pole each below and above the passband can have the following topology matrix:

$$T = \begin{bmatrix} 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix} \qquad (1)$$

Note that the size of the matrix is 6x6 since it includes input and output waveguides. Entries with a value of zero indicate no coupling while unity entries denote possible direct and/or cross couplings. In this example, two bypass couplings (input to resonator 2 and output to resonator 3) create the two transmission zeros. Diagonal elements allow the resonators to be slightly detuned

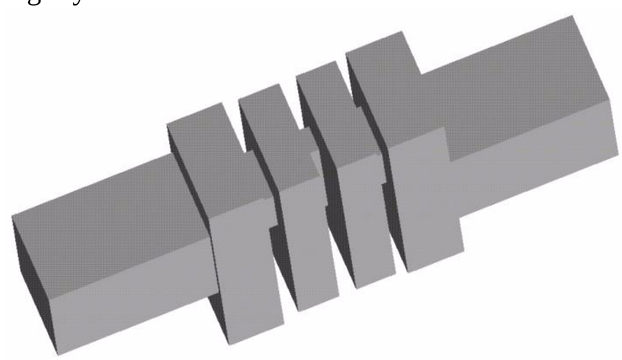

Fig. 1 Inline waveguide filter with arbitrarily located attenuation poles.

The next step involves an optimization algorithm which varies the entries (non-zero elements) of the coupling (topology) matrix until the response of the coupling matrix produces the desired filter characteristics. Note that the optimization, which is extremely fast as it is based on analytically evaluated gradients, includes constraints on the coupling elements such as the sign and/or the order of magnitude. This is especially important in inline filter configurations since the coupling of propagating (non-resonating) modes used for bypass couplings decrease by approximately one order of magnitude per bypassed cavity.

Once a coupling matrix satisfying specifications is obtained, an initial filter configuration is produced by observing the following coupling mechanism of the filter structure. Coupling of the TM_{110} modes in adjacent cavities (c.f. Fig. 1) is performed by their field components through irises in the proximate broad wall having an offset from the center. Input and output waveguides are directly offset-connected to the respective cavity walls to provide coupling of the magnetic field components of the perpendicular polarized TE_{10} waveguide mode and the TM_{110} cavity mode. Since the TE_{10} (TE_{01}) mode is accessible - but not resonating - in the cavities, it can be exploited to transfer portions of the signal energy in parallel to the TM_{110} resonance mode of the cavity. Hence the modes of the irises (or input/output) waveguides simultaneously couple the TM_{110} resonance mode and the non-resonating TE_{10} (TE_{01}) modes. The main inter-cavity couplings as well as those between the input/output waveguides and the respective TM_{110} resonances are controlled by the iris/port center offsets and geometries. The bypass couplings also depend on these parameters and, additionally, on the dimensions of the bypassed cavities, particularly their lengths. Independent control of the main and bypass couplings is chiefly obtained by the port/iris offset locations at one cavity. If we consider for example no offset, the TM_{110} mode is not excited, and energy would be transferred solely into the non-resonating TE_{10} cavity mode (with reflections at the cavity entry and opposite walls). In addition, the relative signs of main and bypass couplings can be controlled by the transformation properties of the TM_{110} resonance [7]. If the offsets at the input and output of an iris have the same direction, then main and bypass couplings have the same sign. An opposite offset direction will change the sign in the main coupling path while the sign of the TE_{10} (TE_{01}) mode bypass coupling remains unchanged [7].

Once an initial design for the cavities, irises and offsets is obtained, the entire filter structure is fine-optimized using the coupled-integral-equations technique (CIET) [11] and a minimax-based optimization strategy [12].

3. Results

Our first example is a four-pole inline filter with three attenuation poles below the passband. The 480-MHz bandwidth is centered at 27.265 GHz; the return loss is set to 23.5 dB; and attenuation poles are set at 25.3 GHz, 26.36 GHz and 26.71 GHz. For this design, the following coupling matrix is obtained.

$$M = \begin{bmatrix} 0.0000 & 1.1092 & -0.1686 & 0.0650 & -0.0105 & 0.0000 \\ 1.1092 & 0.2307 & 0.9367 & -0.2443 & 0.0442 & 0.0000 \\ -0.1686 & 0.9367 & 0.0986 & 0.7561 & -0.2311 & 0.0000 \\ 0.0650 & -0.2443 & 0.7561 & 0.1668 & 0.9992 & 0.0000 \\ -0.0105 & 0.0442 & -0.2311 & 0.9992 & -0.0934 & 1.1239 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.1239 & 0.0000 \end{bmatrix} \qquad (2)$$

Note the decrease in coupling values from the input to the first, second, third and fourth resonator (first row). There is no bypass coupling from the input to the output (upper right zero) and, therefore, a maximum of three attenuation poles can be achieved. Fig. 2 shows the filter response obtained from the synthesis of the coupling matrix (long-dashed lines). The solid lines present the response of the actual design (c.f. inset of Fig. 2) after minimax optimization and analysis with the coupled-integral-equation technique (CIET). This performance is verified by an analysis using the mode-matching technique (MMT, dashed lines). Very good agreement is observed between the responses from the coupling matrix and the final component. Note that in order to demonstrate another useful feature of this inline filter design process, we introduced a 90-degree rotated output waveguide.

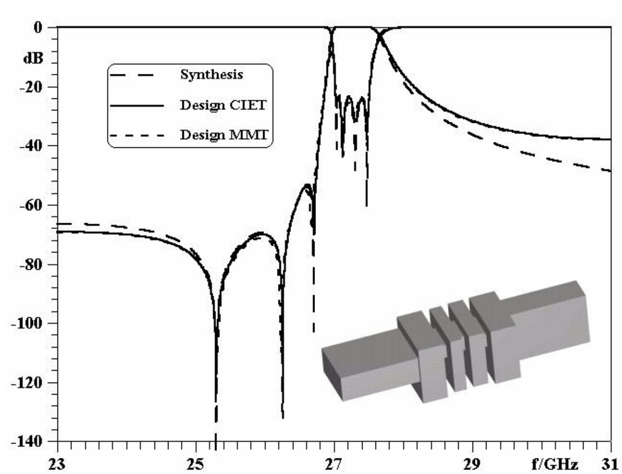

Fig. 2 Four-pole inline TM_{110}-mode filter with three attenuation poles below the passband.

The second example shows a similar four-pole design but with three attenuation poles above the passband. A fourth attenuation pole has been used in the synthesis and was placed at the cutoff frequency of the input/output waveguide. Therefore, input-to-output bypass coupling is required and, consequently, all possible entries of the coupling matrix are present.

$$M = \begin{bmatrix} 0.0000 & -1.2081 & -0.1020 & -0.0227 & 0.0012 & -0.0002 \\ -1.2081 & -0.1140 & 1.0944 & 0.1718 & 0.0034 & 0.0006 \\ -0.1020 & 1.0944 & -0.0198 & 0.8384 & 0.1717 & -0.0227 \\ -0.0227 & 0.1718 & 0.8384 & -0.0202 & 1.0942 & -0.1023 \\ 0.0012 & 0.0034 & 0.1717 & 1.0942 & -0.1146 & -1.2081 \\ -0.0002 & 0.0006 & -0.0227 & -0.1023 & -1.2081 & 0.0000 \end{bmatrix} \quad (3)$$

The related responses and the final design are shown in Fig. 3. The locations of the three attenuation poles used in the final optimization as well as the remainder of the filter characteristic follow the synthesized response (long-dashed lines). The final design (CIET, solid lines) is again verified through results obtained with the MMT (dashed lines).

4. Conclusions

Inline TM_{110}-mode filters present an attractive alternative to state-of-the-art waveguide filter design. The possibility of locating attenuation poles at arbitrary frequencies offers flexible solutions for a large variety of inline filter requirements. The design procedure is demonstrated at two Ka-band examples. Good agreement between synthesized and realized performances is achieved over a wide frequency range. The final designs are verified using two independently developed numerical techniques.

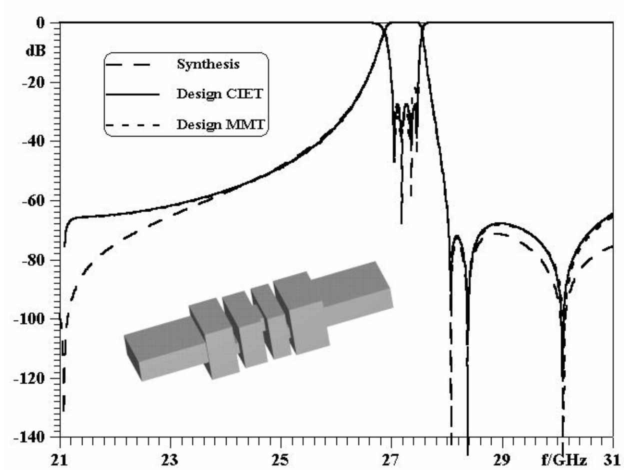

Fig. 3 Four-pole inline TM_{110}-mode filter with three attenuation poles above the passband.

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