

Pseudo-Elliptic Substrate Integrated Waveguide Filters with Higher-Order Mode Resonances

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Abstract — Two substrate integrated waveguide (SIW) pseudo-elliptic bandpass filters are presented that utilize higher-order mode cavities. In the first filter, two full-wave TE_{102} resonators and two fundamental TE_{101} resonators in a compact structure are properly coupled to generate two transmission zeros in a four-pole SIW filter. The coupling matrix of the structure with a centre frequency of 10 GHz and 200 MHz bandwidth is designed, and good agreement is achieved with simulations of two commercially available field solvers. In the second topology, by using symmetric inductive discontinuities and two rectangular SIW cavities, TE_{102} and TE_{301} modes are excited and generate two transmission zeros, one on each side of the passband. This dual-mode SIW filter with a centre frequency of 10 GHz and bandwidth of 300 MHz has been prototyped, and the measured data are in good agreement with results obtained from the coupling matrix and CST Microwave Studio.

Index Terms — Substrate integrated waveguide (SIW); transmission zero; bandpass filter; pseudo elliptic filter; dual-mode filter; coupling matrix.

I. INTRODUCTION

Technical specifications in wireless communication systems keep increasing the demand for high performance RF/microwave filters with compact size, sharp selectivity, high integration, and easy manufacturability. Although waveguide technology exhibits very low loss and provides high-Q resonators, it is bulky, heavy, and difficult to integrate with planar circuitry. On the other hand, although most passive and active circuits can be integrated in microstrip technology, the loss and quality factor as well as the cost of packaging and/or shielding are not acceptable for the fast-growing wireless communication markets.

Substrate integrated waveguide (SIW) is a promising technology that combines relatively high Q-factor and low insertion loss merits of traditional rectangular waveguides with the simplicity of planar fabrication and low-cost integration of microstrip technology [1-4].

Elliptic and quasi-elliptic bandpass filters with cross coupling are standard solutions to filtering specifications involving sharp selectivity, low in-band insertion loss, and high out of band rejection [5, 6]. However, both the unloaded Q-factor and the dimension of a SIW cavity decrease with increasing frequency. In order to obtain high-performance filters, higher-order mode cavities can be utilized [7-9].

Therefore, two SIW pseudo-elliptic bandpass filters using TE_{m0n} resonances are presented in this paper. First, a four-pole SIW filter with two TE_{102} and two TE_{101} resonators is

used to create transmission zeros on either side of the passband.

Dual-mode resonators are widely used in filter design due to their ability to reduce the number of physical resonators and improve selectivity [10, 11]. Therefore, in the second design, we use dual-mode cavities resonating in TE_{301} and TE_{102} modes. All four resonances are properly coupled to generate a four-pole SIW filter with two transmission zeros close to the passband of the filter. The main advantage of the proposed structures, as compared to [8], is their symmetry with respect to the filter centre, which reduces the number of parameters in the final optimization process.

II. SYNTHESIS AND DESIGN OF FILTERS

The basic design of cross-coupled microwave filters in waveguide technology is well known, e.g. [12]. However, instead of extracting a coupling matrix for a folded prototype and applying matrix rotations [12], we arrive at the coupling matrix by optimization according to [13]. This has the advantage of enforcing the selected filter topology and the signs of the matrix elements. Once the coupling matrix is obtained, the individual coupling apertures are successively adapted using a mode-matching routine, e.g. [14].

A. SIW Filter in Single-Mode Topology

Fig. 1 shows the coupling scheme and dimensions of the single-mode four-pole SIW filter which is composed of two TE_{101} (resonators 1 and 4) and two TE_{102} (resonators 2 and 3) cavities. Traditionally the input and output ports are coupled to only a single resonator. In this design, however, the input and output signals are coupled simultaneously to two resonators but most strongly to the full-wave resonators. It is obvious from Fig. 1a that the coupling scheme creates two main signals paths between source (S) and load (L) which generate two transmission zeros, one on the left and one on the right side of the passband.

The coupling matrix of the 200 MHz bandwidth filter with in-band return loss of 20 dB at 10 GHz is given in (1) and, in all entries except for the diagonal, reflects the fact that the structures is symmetric with respect to the centre point of the filter. The diagonal suggest opposite detuning which is a result of the coupling from resonators 2 to 3 via the longitudinal magnetic field component [15] whereas all other couplings are realized by coupling the transverse magnetic component.

$$M_1 = \begin{bmatrix} 0.000 & 0.566 & 0.852 & 0.000 & 0.000 & 0.000 \\ 0.566 & 1.149 & 0.000 & -0.266 & 0.000 & 0.000 \\ 0.852 & 0.000 & -0.507 & 0.646 & -0.266 & 0.000 \\ 0.000 & -0.266 & 0.646 & 0.507 & 0.000 & 0.852 \\ 0.000 & 0.000 & -0.266 & 0.000 & -1.149 & 0.566 \\ 0.000 & 0.000 & 0.000 & 0.852 & 0.566 & 0.000 \end{bmatrix} \quad (1)$$

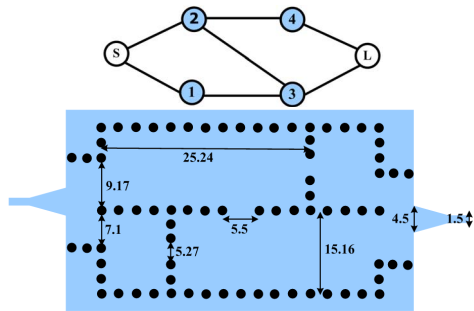


Fig. 1. Coupling scheme and configuration and dimensions in mm of the four-pole quasi-elliptic SIW filter with single-mode cavities. (Actual number of via holes according to inset of Fig. 2).

After determining the initial aperture and cavity dimensions, the filter dimensions are fine-optimizing for 10 GHz midband frequency, 200 MHz bandwidth, and 20 dB return loss. To speed up optimization, the circuit is first optimized in rectangular waveguide technology using the μ WaveWizard. Then all square walls in the middle of the filter with the fixed width of $d_{square}=0.85$ mm are replaced by circular via holes with a periodic distance of $S=1.5$ mm and a radius of

$$r_{circle} = d_{square} / (1 + 1/\sqrt{2}) \quad (1)$$

which leads to a via-hole diameter of 1 mm. For the surrounding walls, the waveguide width and length are transferred to equivalent SIW parameters W_{eff} and L_{eff} , respectively, [16]. Finally, a linear microstrip taper is designed to connect a 50 Ω microstrip line to a SIW that propagates the fundamental TE_{10} mode [17].

The filter circuit is depicted in the inset of Fig. 2. The ideal circuit response of the coupling matrix and the simulation results from HFSS and CST are illustrated. Symmetrical frequency response and high selectivity of the filter are

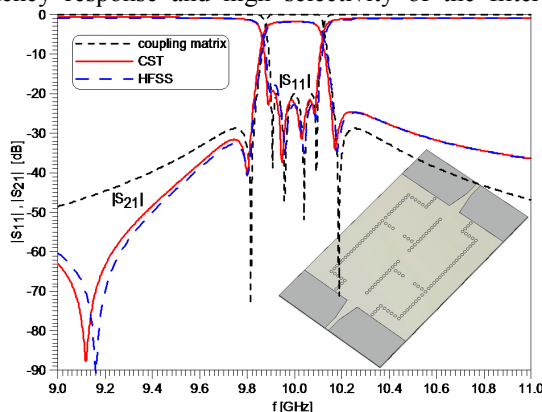


Fig. 2. Schematic and ideal coupling matrix response and simulation results using HFSS and CST of the four-pole SIW filter with single-mode cavities (c.f. Fig. 1).

demonstrated. The small shift between HFSS and CST analyses are attributed to the fact that via holes in CST are modeled by smooth curves of order two, while in HFSS they are approximated by a linear triangular mesh. The simulation results of this single mode topology with HFSS and CST, as shown in Fig. 2, validate the design approach and coupling matrix. Note that since the coupling matrix is based on four single-mode resonators, it cannot reproduce the transmission zero at approx. 9.15 GHz that is created by bypassing the fundamental-mode resonance (TE_{101}) of the TE_{102} resonators.

B. SIW Filter in Dual-Mode Topology

The coupling scheme and dimensions of the dual-mode SIW filter are shown in Fig. 3. It consists of two dual-mode cavities resonating in the TE_{301} modes (resonances 1 and 4) and the TE_{102} modes (resonances 2 and 3, c.f. Fig. 3a). The four-pole filter produces two transmission zeros, one on each side of the passband.

With a bandwidth of 300 MHz at 10 GHz, in-band return loss of 20 dB and transmission zeros at 9.775 GHz and 10.225 GHz, the coupling matrix is given by:

$$M_2 = \begin{bmatrix} 0.000 & 0.864 & 0.533 & 0.000 & 0.000 & 0.000 \\ 0.864 & 0.436 & 0.000 & -0.212 & 0.729 & 0.000 \\ 0.533 & 0.000 & -1.148 & 0.055 & -0.218 & 0.000 \\ 0.000 & -0.212 & 0.055 & 1.148 & 0.000 & 0.530 \\ 0.000 & 0.729 & -0.218 & 0.000 & -0.431 & 0.865 \\ 0.000 & 0.000 & 0.000 & 0.530 & 0.865 & 0.000 \end{bmatrix} \quad (3)$$

Note that the coupling matrix is asymmetric due to the different sizes of the cavities (c.f. Fig. 3b). Since the TE_{102} mode changes the direction of the transverse magnetic field component relative to that of the TE_{301} mode, couplings 1-3 and 2-4 are negative while all other couplings are positive. In order to fit both resonating modes (TE_{301} and TE_{102}) in the dual-mode cavity, the cavity dimensions are chosen such that the two resonance frequencies are equal

$$f_{102} = f_{301} = \frac{c}{2} \sqrt{\left(\frac{1}{L_{eff}}\right)^2 + \left(\frac{2}{W_{eff}}\right)^2} = \frac{c}{2} \sqrt{\left(\frac{3}{L_{eff}}\right)^2 + \left(\frac{1}{W_{eff}}\right)^2} \quad (4)$$

where c is the velocity of propagation in the substrate with relative permittivity of ϵ_r , and W_{eff} and L_{eff} are the equivalent width and length, respectively, of the rectangular SIW resonator [16]. The initial dimension ratio of the dual-mode

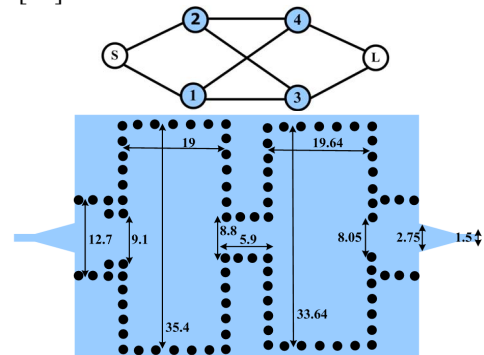


Fig. 3. Coupling scheme and configuration and dimensions in mm of the four-pole quasi-elliptic SIW filter with dual-mode cavities. (Actual number of via holes according to Fig. 4).

SIW cavity can be acquired by $L_{eff}/W_{eff} = \sqrt{8/3}$.

The position of the transmission zeros at either side of the passband can be determined by changing the width of the SIW cavities. The lengths of the resonators are fixed by the operating frequency. We then determine the widths and lengths of coupling apertures to control the bandwidth such that the filter bandwidth increases with aperture size. Finally, the filter is fine-optimized within CST.

III. EXPERIMENTAL RESULTS

The dual-mode filter in Fig. 3b is prototyped on RT/Duroid 5870 substrate with relative permittivity of 2.33, height of 508 μm and a loss tangent of 0.0012. The center frequency is 10 GHz with a bandwidth of 300 MHz. The diameters of all via holes are 1 mm with center to center spacing of 1.5 mm. For the measurements, a TRL calibration is used to deembed the coax-to-microstrip-to-SIW transitions. A photograph of the fabricated SIW filter is depicted in the inset of Fig. 4.

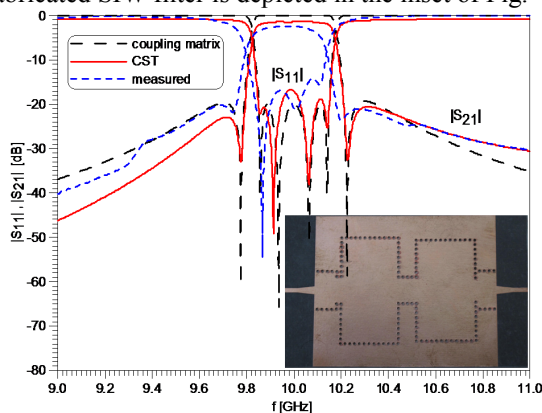


Fig. 4. Photograph of manufactured 4th-order dual-mode SIW filter with measured, simulated (CST) and coupling matrix responses.

Fig. 4 shows a comparison between results from the coupling matrix, CST and measurements. Good agreement between the coupling matrix and CST is observed for the passband and the transmission zeros; note that CST includes losses compared to a lossless calculation via the coupling matrix. Simulations and measurements are in reasonable agreement. The deviations are attributed to the rough fabrication process which left several via holes only partly plated through. The measured insertion loss is about 2 dB, and the return loss is better than 15 dB. Overall, the filter demonstrates a very good performance, sharp selectivity, small size, and reasonable insertion loss.

IV. CONCLUSIONS

Two different pseudo-elliptic 4th-order coupling schemes using higher-order mode resonances in SIW cavities are presented. By coupling the input and output to two resonators, two main signal paths are created that produce two transmission zeros. The first filter uses TE₁₀₁ and TE₁₀₂

resonators and is symmetric with respect to its center. The second one uses dual-mode TE₃₀₁ and TE₁₀₂ cavities and is symmetric with respect to its horizontal axis. Simulations and measured results confirm the validity of the proposed design approach by demonstrating very good agreement. The filters are well suited for low-cost production and sharp selectivity performance in microwave and millimeter-wave planar integrated circuits.

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