Quasi-Elliptic Triple-Stopband Filter Based On Six Cross-Coupled SIW Resonators

Mahbubeh Esmaeili and Jens Bornemann, *Fellow, IEEE*

***Abstract*—A new K-band triple-stopband filter in substrate integrated waveguide (SIW) technology is introduced. The filter consists of six rectangular cavities resonating in their fundamental TE_{101} mode. Main and cross couplings between resonators are used to design a filter with six transmission zeros, separating three stopbands and four passbands. A corresponding coupling matrix is presented. The initial filter covers an overall bandwidth of 4.50 GHz at center frequency of 19.50 GHz. The three stopbands are located at 17.6, 19.56, and 21.34 GHz with bandwidths of 0.92 GHz, 0.82 GHz, and 0.85 GHz, respectively. The two passbands located between the three stopbands have center frequencies of 18.70 and 20.56 GHz with corresponding bandwidths of 0.97 GHz and 0.88 GHz, respectively. The filter is prototyped and measured. Good agreement between simulated and measured results proves the reliability and robustness of the design method.**

***Index Terms*—Coupling matrix, cross-coupled resonators, substrate integrated waveguide (SIW), triple-stopband filter.**

I. INTRODUCTION

MULTIBAND microwave filters are one of the most interesting passive components in modern wireless communication systems due to their ability to cover several frequency bands by using a single microwave device. For instance, dual-band filters are used in GSM and CDMA mobile phones or WLAN networks. Tri-band filters are employed by tri-band universal mobile telecommunication system (UMTS) devices as well as WiMAX systems [1]. In some applications, it is advantageous to design, e.g., a triple-stopband filter to replace a dual-bandpass filter. Dual- and triple-bandstop filters can also be used to eliminate dual-band or triple-band wireless services where they are not desired.

In comparison with multi-stopband microstrip filters [2]–[4], multiband substrate integrated waveguide (SIW) filters have higher quality factor, lower insertion loss and offer a shielded environment which make them more attractive towards higher frequencies.

A few dual-passband filters are reported in SIW technology. A triple- and two dual-passband SIW filters with Chebyshev and quasi-elliptic responses are designed and prototyped in [5] based on cross-coupled resonators. A triple-bandpass filter is reported in [6] based on in-line cascaded singlets, and the proposed method can be extended to design multi-passband filters by increasing the number of cascaded singlets.

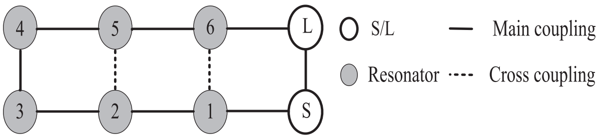

Fig. 1. Configuration of the six cross-coupled resonators creating a triple-band bandstop filter.

Multi-*stopband* filters, as opposed to multi-*passband* filters, have been theoretically investigated based on coupling matrix designs. In [7], the analytic methods to synthesize a coupling matrix representing direct-coupled quasi-elliptic single- and dual-stopband filters are presented. A frequency transformation method to synthesize direct-coupled multi-stopband coupling matrices is presented in [8]. An analytic method is reported in [9] to synthesize multi-passband coupling matrices that can be used to synthesize multi-stopband filters by adopting the method presented in [10].

Despite all multi-stopband coupling matrix investigations, to the best of the authors' knowledge, multi-stopband filters in SIW or waveguide technology have not been reported, neither in direct-coupled nor cross-coupled topology.

Therefore, in this letter and for the first time, we introduce a triple-stopband filter in SIW technology based on cross-coupled resonators. The corresponding coupling matrix of the filter is synthesized and used in the design and optimization process.

II. FILTER DESIGN

The design process starts with synthesizing the scattering parameters of a triple-*passband* filter consisting of six cross-coupled resonators as shown in Fig. 1. Then we replace S_{11} with S_{21} and S_{21} with S_{11} and, therefore, the scattering parameters of a triple-*stopband* filter are obtained in terms of rational functions [10].

Having the responses of a triple-stopband filter in the form of rational functions allows us to synthesize a coupling matrix representing the filter to be designed [10], [11]. The so-obtained coupling matrix is presented in (5), as shown at the bottom of the next page. (Note that all resonators are synchronously tuned). The proposed bandstop filter has six transmission zeros (TZs) located in the stopbands, and six reflection zeros (RZs) located on both sides of the stopbands which result in sharp roll-offs. The center frequency, f_0, and overall bandwidth, BW, of the

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The authors are with the Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC V8W 2Y2, Canada (e-mail: mesmaei@uvic.ca; j.bornemann@ieee.org).

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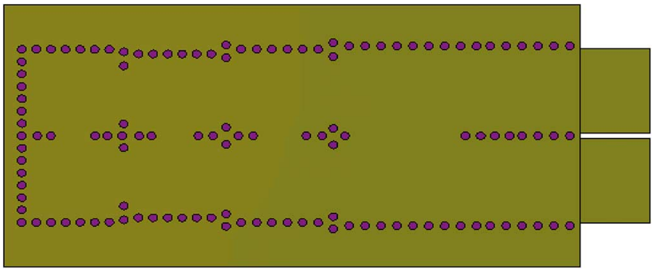

Fig. 2. Six-pole triple-stopband filter in SIW technology with waveguide ports.

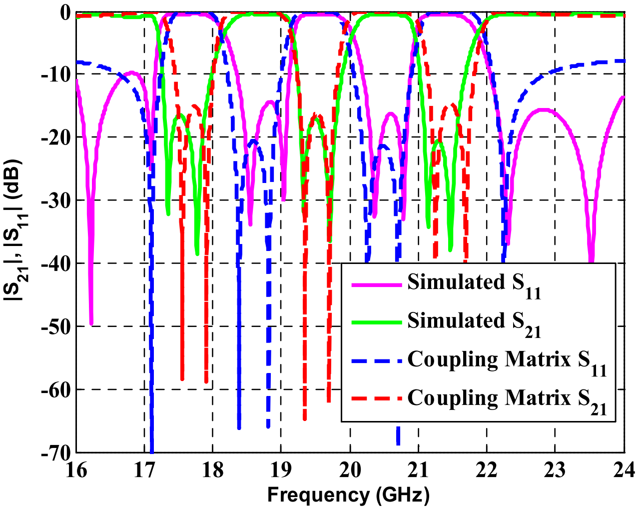

Fig. 3. Scattering parameters of the triple-stopband filter; simulated (CST—solid lines) verses coupling matrix (M—dashed lines).

initial filter are chosen to be 19.5 GHz and 4.5 GHz, respectively.

The symmetry of the filter in Fig. 1 implies a symmetric coupling matrix with $M_{S1} = M_{6L}$, $M_{12} = M_{56}$ and $M_{23} = M_{45}$, as shown in (5). Note that similar to a single-stopband filter, source-load coupling is required. However, since the number of RZs is equal to the number of resonators, the source-load coupling value is different from unity [10].

First, the initial size of the resonators are calculated based on their resonant frequencies

$$f_0 = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\frac{1}{a_{eff}^2} + \frac{1}{l_{eff}^2}} \qquad (1)$$

where a_{eff} and l_{eff} are the waveguide resonator's effective width and length. The eigenmode solver of CST is used to simulate a pair of coupled TE_{101} resonators. The coupling curve shows two split resonant frequencies, f_1 and f_2, that are used to calculate the coupling coefficient, k_{ij}, between two resonators [12]

$$k_{ij} = \frac{f_1^2 - f_2^2}{f_1^2 + f_2^2} \qquad (2)$$

where the normalized coupling coefficients, m_{ij}, are calculated by

$$m_{ij} = k_{ij}\frac{f_0}{BW}. \qquad (3)$$

The size and position of each aperture located between two coupled resonators are swept in the CST eigenmode solver until the desired corresponding coefficient k_{ij} is obtained [12].

Then the filter is designed in H-plane waveguide technology using the commercial software package μWave Wizard. The source waveguide's width, a_e, is determined by the cutoff frequency of the structure, f_c, which is chosen appropriately based on the center frequency and bandwidth of the filter [5]

$$a_e = \frac{c}{2f_c\sqrt{\varepsilon_r}} \qquad (4)$$

where ε_r and c are the substrate's dielectric constant and speed of light in the free space, respectively.

Following this step, the designed filter in waveguide technology is properly translated to SIW technology using the procedure described in [13].

Fig. 2 shows the final SIW filter with waveguide ports. The cut-off frequency of the waveguide port is 15.8 GHz, and RT/Duroid 6002 with dielectric constant of 2.94, loss tangent of 0.0012, and thickness of 0.508 mm is chosen as substrate. The diameters of all via holes are 0.5 mm, and the minimum center-to-center pitch between any two adjacent vias is greater than 0.7 mm and less than 1 mm to prevent manufacturing difficulties as well as power leakage, respectively. The simulated response of the filter is shown in Fig. 3 and compared with that calculated from the coupling matrix, M.

Generally, the coupling matrix elements are frequency dependent. Although a coupling matrix with frequency independent elements is acceptable for narrowband applications, the frequency independent coupling matrix synthesized in this letter presents a triple-stopband filter with almost equi-ripple stopband and passband levels that provides a good starting point

$$M = \begin{bmatrix} 0 & 0.6140 & 0 & 0 & 0 & 0 & 0 & 0.6114 \\ 0.6140 & 0 & 0.6970 & 0 & 0 & 0 & 0.3717 & 0 \\ 0 & 0.6970 & 0 & 0.4866 & 0 & 0.1637 & 0 & 0 \\ 0 & 0 & 0.4866 & 0 & 0.1469 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.1469 & 0 & 0.4866 & 0 & 0 \\ 0 & 0 & 0.1637 & 0 & 0.4866 & 0 & 0.6970 & 0 \\ 0 & 0.3717 & 0 & 0 & 0 & 0.6970 & 0 & 0.6140 \\ 0.6114 & 0 & 0 & 0 & 0 & 0 & 0.6140 & 0 \end{bmatrix} \qquad (5)$$

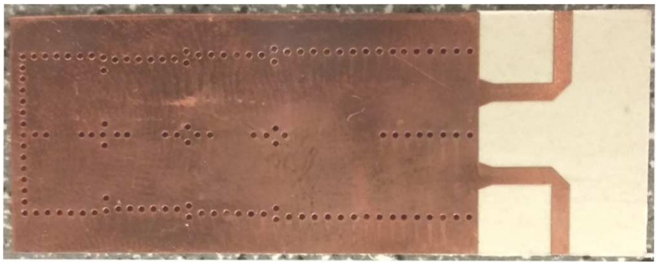

Fig. 4. The triple-stopband filter fabricated in SIW technology with microstrip ports and SIW-to-microstrip transitions.

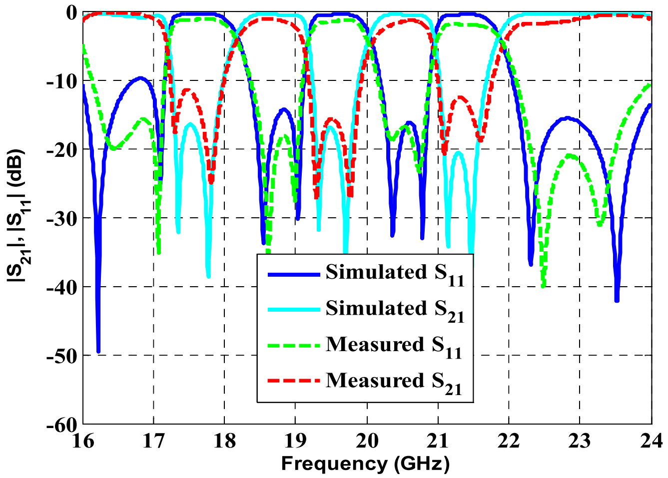

Fig. 5. Comparison between measured and simulated scattering parameters of the triple-stopband SIW filter.

for the filter design. The full-wave frequency simulator of CST takes into account all frequency components to calculate the frequency responses of the filter. This is the reason for some simulated TZs and RZs, as well as levels of some return losses in the passbands and insertion losses in the stopbands, not precisely matching those obtained from the coupling matrix. It should be noted, however, that there is still acceptable agreement between the locations of the TZs and RZs obtained from CST and the coupling matrix for the designed filter, even though the overall fractional bandwidth is 23%. The left-most and the right-most RZs in Fig. 3 are attributed to the distance between the source/load aperture and the rest of the filter as well as its size. Corresponding TZs in a passband design are observed in [14], and it is demonstrated that they can be added to the coupling matrix by introducing detuned resonators.

III. EXPERIMENTAL RESULTS

A top view of the prototyped filter, with bent microstrip ports and SIW-to-microstrip transitions, is depicted in Fig. 4. A Thru-Reflect-Line (TRL) calibration kit is used to deembed the effects of the microstrip lines and their transitions to coaxial ports.

Fig. 5 shows the comparison between simulated and measured results. Good agreement is observed. The locations of the simulated TZs and RZs in the stopbands and passbands are well reproduced in the measurements. The insertion loss in the two passbands is measured better than 1.54 dB, and the return loss in both passbands is better than 17 dB. In addition, the attenuation in the first, second and third stopband are better than 12 dB, 15.5 dB, and 12.5 dB, respectively.

The measured responses show a very small upward frequency shift. We attributed this frequency shift to the via holes which, when fabricated using a drill size of 0.5 mm, turn out to be slightly larger than the nominal value. The larger diameters of the via holes decrease the resonators' effective widths and lengths and cause small increases in the resonant frequencies of the resonators. Moreover, this shift is within the relative permittivity tolerances of 2.94 ± 0.04.

IV. CONCLUSION

A six-pole quasi-elliptic triple-stopband filter is introduced. In addition to main couplings between resonators, source/load and cross couplings create three stopbands separated by two passbands. The designed filter is prototyped in SIW technology which considerably decreases the weight and size of the filter as well as manufacturing cost compared to an all-waveguide implementation.

The synthesized coupling matrix and simulated results are in good agreement with measurements which validates the reliability of the design procedure.

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