Design of a Low Loss Substrate Mounted Waveguide (SMW) Filter Employing Individual Resonators

Jan Schorer[1], Jens Bornemann[1] and Uwe Rosenberg[2]

[1] Department of Electrical and Computer Engineering, University of Victoria, Victoria, BC, Canada
[2] Mician Global Engineering GbR, Bremen, Germany

Abstract — A surface mounted waveguide (SMW) resonator filter, embedded in substrate integrated waveguide (SIW) technology, is presented. It is designed by using a mode-matching technique (MMT) together with extracted pole filter synthesis. The center frequency is set for K-band operation. The filter consists of three individual resonators and exhibits a high unloaded Q factor compared to other SMW and regular, pure SIW filters. Simulation and measurement data are in good agreement. Additionally, a study on the resonator height is included. The presented filter is easy scalable and adaptable to low cost, high volume production by employing standard printed circuit board (PCB) processing technology.

Index Terms — Substrate integrated waveguide, substrate mounted waveguide filter, mode matching technique, filter design.

I. INTRODUCTION

To accommodate increasing data rates and the recent, ongoing development towards higher frequencies for communications electronics of all sorts, the industry is demanding smaller, highly integrated components, also suited for high volume, cost effective production. One approach to accommodate these needs is the system on a substrate (SOS) approach [1]. Substrate integrated waveguide (SIW) [2] and substrate mounted waveguide (SMW) resonators [3] are two highly scalable and versatile technologies fitting this concept.

Recently published results, combining the two technologies [4], show promising achievements in overcoming typically high dielectric losses in pure SIW resonators [5]. This approach also provides a fully shielded electromagnetic environment, which typically cannot be maintained when combining planar transmission lines and SMW resonators [6].

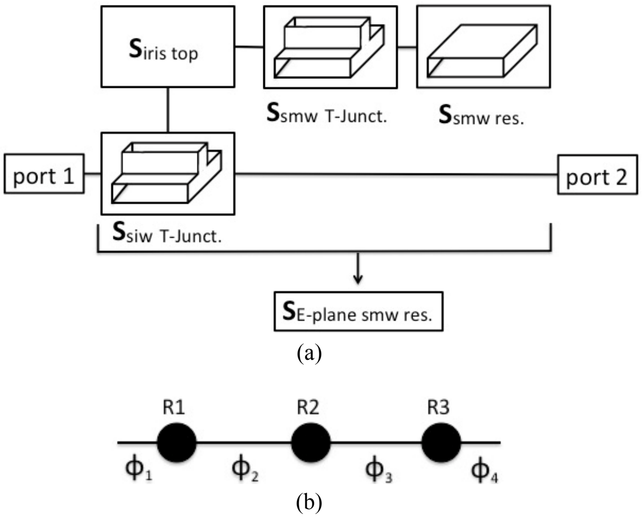
While SMW filters published so far are coupled resonator filters [7], the prototype presented in this paper is a filter comprised of individual SMW resonators, creating arbitrarily placeable transmission and reflection zeros. This particular design accommodates standard PCB processes and is expected to be more robust with respect to manufacturing tolerances. In addition, the effect of thermal expansion during a soldering process is minimized. Standard, well-known filter theory can be employed for the synthesis of the proposed single SMW resonator filters to yield a simple filter structure. Since the dielectric is absent in the resonator, the Q factors increase to values known from conventional waveguide structures [4].

II. THEORY

A. Filter Synthesis

The initial filter synthesis is performed employing impedance inverters whose values are matched to another set of impedance inverters related to the structure of the filter. The second set is obtained by full-wave electromagnetic modeling, using the mode-matching technique (MMT) [8], of the actual filter structure. The MMT is well-known as an efficient method for the calculation of confined wave guiding structures. Furthermore, the extracted pole synthesis method [9] is used.

The setup used to adapt the MMT to the filter topology is given in Fig. 1a. It represents the cascaded single sub-scattering matrices, utilized to obtain the overall scattering matrix ($S_{\text{E-plane SMW res.}}$) for a single surface mounted waveguide resonator, and allows the extraction of an impedance inverter value. The filter topology is presented in Fig. 1b. The resonating nodes (R1-R3) are the single cavities. They all are connected with pieces of SIWs for the required phase adjustments ($\phi_{1\text{-}4}$).



(a)

(b)

Fig. 1. a) MMT block structure of SMW resonator; b) filter topology.

B. Single Resonator

Apart from the design procedure, a single surface mounted waveguide resonator is examined. The focus of this study lies

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in the obtainable Q factors related to the resonator dimensions. Focusing on the TE_{101} resonance, it becomes obvious that in the intended setup, the critical and tunable dimension for the resonator Q is the height b of the resonator

$$\frac{1}{Q} = tan\delta + \left(\frac{(kad)^3 b\eta}{2\pi^2 R_s} \frac{1}{l^2 a^3(2b+d)+(2b+a)d^3}\right)^{-1} \qquad (1)$$

where a, b, d are the resonator dimensions; l, m, n are mode indices; R_s is the surface resistance; k is the wave number; and δ is the loss tangent.

Therefore, a parametric simulation is carried out investigating this correlation at 19 GHz. The results, Q factor and the amount of conductor losses, are presented in Fig. 2 (the dimensions of the model are adjusted for each height to maintain resonance frequency). The data is obtained using CST Microwave-studio's eigenmode solver and is normalized to the Q of the 1 mm resonator height. A Q factor increasing with resonator height is observed. A curve fitted to the data points suggests an upper threshold for the Q factor. However, this cannot be seen in (1). An explanation for this upper limit can be found when comparing the ratio of conductor (second term (1)) and volume (first term (1)) losses. This assumption can be justified focusing on the amount of conductor loss (red data points in Fig. 2), which is increasing for higher Q values.

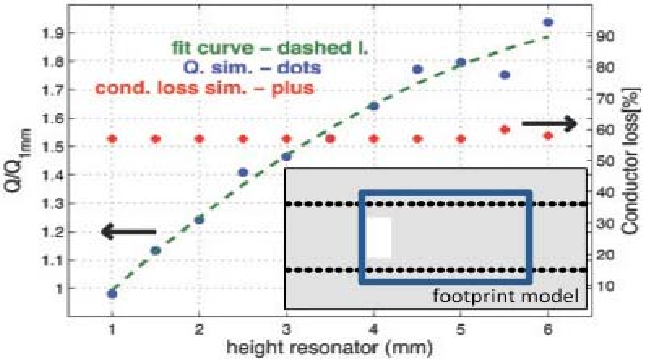


Fig. 2. Normalized Q value, conductor losses versus resonator height, and footprint of used CAD model.

III. PROTOTYPE DESIGN

The designed prototype is presented in Fig. 3. Top, bottom and side views of the structure, together with its dimensions, are displayed. The dimensions are obtained following the routine described above. When extracting the poles, all three are chosen to be located in the lower rejection band of the filter, e.g. [10]. (According to extracted pole theory, they might as well be placed above the passband.) The prototype is manufactured using a standard CNC process to mill the cavities into a copper 101 alloy. For easy manufacturing, a corner radius of 1.5 mm is introduced to the cavities. The substrate is Rogers RT/duroid 6002 with a permittivity of 2.94 and height of 508 µm. During the PCB process, via-holes with a radius of 0.65 mm and a pitch of 1 mm are drilled. After the via-hole metallization process, the copper cladding adds up to a total thickness of 34 µm. The irises are cut out in the bottom and top PCB plane. Alignment of the parts is achieved using pins. Screws are used to hold and press the assembly together. Applying a conductive silver paste between the layers minimizes losses occurring due to the sandwich construction. A tolerance analysis identified the dimensions of the SMW parts to be most critical. However, when comparing the affordable tolerances to achieve a 15 dB return loss as reported in [7], the single distributed SMW filter is more robust requiring only ±20 µm manufacturing accuracy. Nevertheless, this prototype has been manufactured to ±10µm. To access the circuit in a test fixture, microstrip-to-SIW transitions are added to the filter. For the measurements, these transitions are de-embedded applying a thru-line-reflect (TLR) calibration with custom-made calibration standards, moving the measurement reference plane inside the SIW.

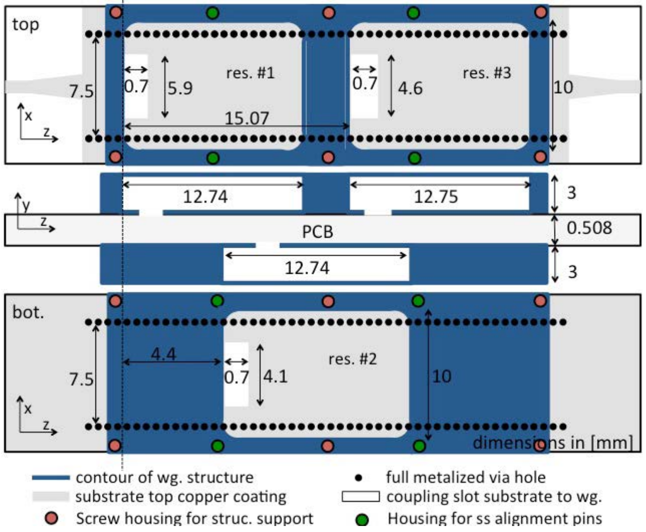
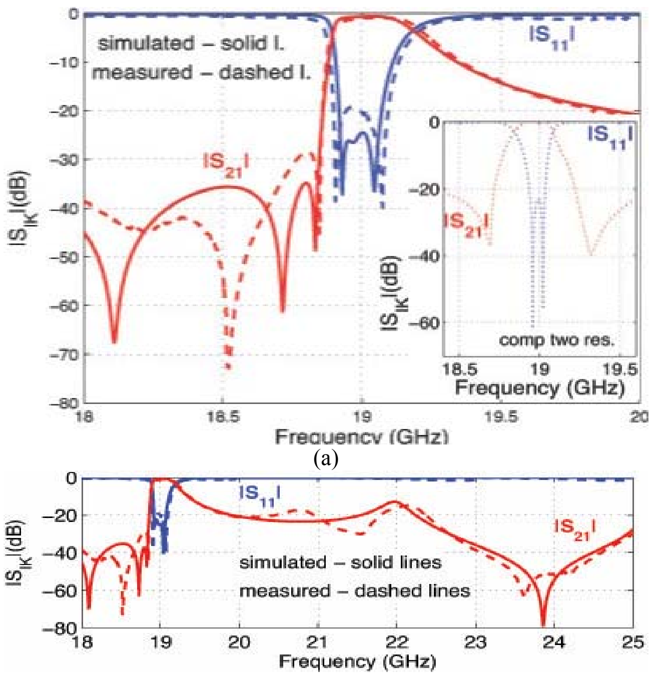


Fig. 3. Dimensions of manufactured SMW filter prototype.

IV. RESULTS

The S parameters of the simulation and measurement data are displayed in Fig. 4. Fig. 4a gives a detailed view (18 to 20 GHz), and Fig. 1b focuses on a wider band (18 to 25 GHz). Comparing the simulation to the measurement, generally good agreement is observed. In the passband, the S_{21} parameter is almost identical between simulation and measurement; only a slight widening can be seen. Also the magnitude is marginally lower for the measured data set. This is expected taking connection losses between the three components and surface oxidation of the copper into account. Comparing the lower rejection-band, one can clearly identify the three transmission zeros for both data sets. However, the agreement is not as good as for the passband. While the transmission pole closest to the pass-band is in good agreement, the two further away are off, resulting in 5 dB less suppression at about 18.8 GHz.

The two passband skirts have the same gradient in measurement and simulation; they present the same selectivity



(a)

(b)

Fig. 4. Comparison between simulation and measurement of prototype; (a) narrowband, (b) wideband.

levels. Due to the asymmetric design, one can observe the advantage of increased selectivity, obtained by locating poles close to the passband. The S_{11} parameter suggests an about 5 dB higher input reflection level in the passband for the measured data. The detuned resonator and other marginal disagreements in the S parameters are caused by a misalignment of the top resonator layer, covering small parts of the coupling irises. This is confirmed by a tolerance analysis, which is not presented here due to the lack of space. The data for the extended band is in good agreement and does not show any major spurious effects. The additional small resonance, which can be seen only in the measurement data at around 20.8 GHz, is well suppressed. Moreover, in a practical application, one of the transmission zeros can be used to suppress this resonance. As an example, the inset in Fig. 4a shows the response of a two resonator design, where the transmission zeros are placed on either side of the passband.

TABLE I Single Resonator, Average Quality Factors (CST)

Res. #	1	2	3	avg.
Q con.	67%	88%	72%	75%
Q vol.	33%	12%	28%	25%
Q total	2395	3581	2969	2981

The obtained Q values and the ratio of conductor to volume losses are presented in Table I. An average ratio of 25/75 for the losses and a Q value of almost 3000 are observed.

V. Conclusion

A high Q (2981), low loss surface mounted waveguide filter employing individual cavities has been synthesized, manufactured and measured. The obtained results are in good agreement. The design exhibits a robust, highly integrable and easy to manufacture solution to overcome dielectric losses in passive SIW circuitry. The improvement comes with a small increase in manufacturing complexity; however, the required technology is completely available within standard PCB manufacturing processes. The results obtained are superior to designs published so far. A parametric study on the single resonator height aids in the synthesis of these filters by scaling the achievable Q factor.

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