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Technology for High Quality Factor Membrane Filters in Organic Multilayer PCBs

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***Abstract*—This article presents technology for a membrane (structured sheet metal) band pass filter with a high quality factor integrated in organic multilayer printed circuit boards (PCB). Creating a cavity in the multilayer board by milling and subsequently copper-plating, the loss of the filter resonators is reduced. The membrane fabricated from sheet steel is silver-plated to obtain a very high conductivity. The connection of the membrane and the PCB is established with a soldering process. A microstrip transition from the substrate to the cavity is included in the filter design. In order to validate the approach an interdigital band pass filter with five resonators at 5 GHz and 12% bandwidth was implemented, showing a minimum measured insertion loss of 0.57 dB.**

Keywords*—*microwave filters, band pass filters, Q factor, membrane filters, interdigital filters

I. Introduction

Membrane structures within cavities are frequently used in microwave circuits because they offer a reduction of attenuation due to lossy substrates. A huge part of the developments belongs to micromachining techniques dealing with silicon [1], [2]. The on-wafer technology employs thin membranes consisting of silicon substrate material, i.e. SiO_2 or GaAs, to mount microwave structures [3].

In a PCB it is challenging to realize low-loss filters. One possibility are filter blocks integrated into PCBs [4] offering very high Q factors. The main disadvantages of these components are integration issues and cost. A trade-off between cost and insertion loss exhibits the substrate integrated waveguide (SIW), trying to combine the advantages of the rectangular waveguide and the PCB [5], [6]. The drawback of this technique is the field distribution being guided completely in the substrate. If no low-loss substrates can be applied, the realizable Q factor reaches at most a moderate level.

In contrast, the technology proposed in this paper provides high Q factors up to 1300 integrated in a PCB by guiding the wave almost entirely in air. The basic idea is presented in Fig. 1 showing schematically the top view and the cross-section of the PCB with the incorporated structured membrane (shielding omitted for clarity). Having generated a metallized cavity in the PCB, a silver-plated membrane is soldered on top representing a quasi air-guided microstrip circuit. The structure depicted in Fig. 1 is an interdigital filter, the common microstrip line is connected via a special transition to an air-guided one. For mechanical support of the steel membrane thin substrate pillars are present in the PCB cavity.

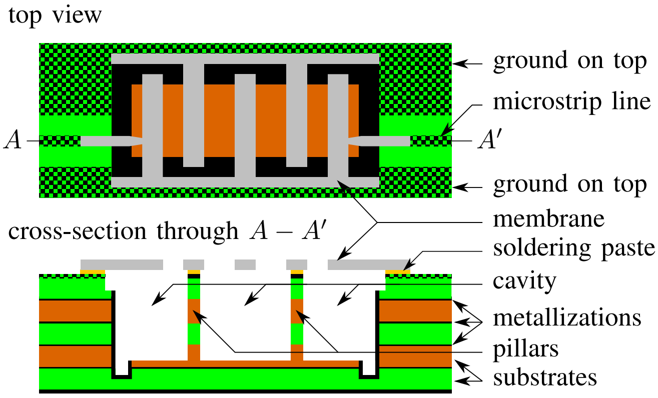


Fig. 1. Illustration of the membrane filter integrated into a multilayer printed circuit board (the required shielding structure is omitted).

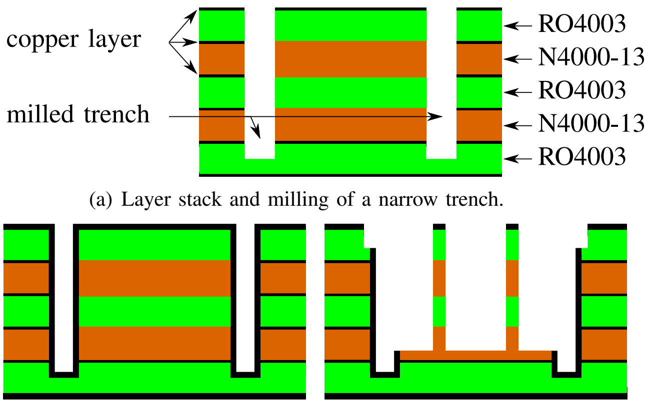
The production process of the membrane and the PCB is described in Section II. Investigations on the Q factor of a microstrip resonator in this technique are undertaken in Section III followed by the filter design and measurements in Section IV.

II. Technology

The fabrication of the proposed filters includes three parts: the membrane, the multilayer PCB, and the assembly of both.

The structured membrane is produced by a laser cutting process to obtain an accuracy of ±50 µm with a sheet thickness of 500 µm. Steel is selected as membrane material because of its high bending stiffness. To increase the conductivity, the sheet steel is coated with a silver layer of about 7.5 µm.

The multilayer PCB requires four processing steps shown in Fig. 2. In this example a six metallization layer structure is used. The total PCB thickness is about 1.7 mm consisting of three layers of *Rogers* $RO4003$ with a thickness of 305 µm and two prepreg layers *Nelco* $N4000$-13 with a thickness of about 330 µm to connect the substrates. At the beginning the layer structure with patterned metallizations is fabricated. Afterwards, a trench is milled in the PCB marking the outline of the cavity (Fig. 2(a)). Subsequently, the side walls of the trench are copper-plated (Fig. 2(b)). At the end of the PCB production another milling step is required to obtain the



(a) Layer stack and milling of a narrow trench.

(b) Copper plating of trench.

(c) Milling of cavity excluding pillars and partial opening for the transitions.

Fig. 2. Fabrication process of the PCB.

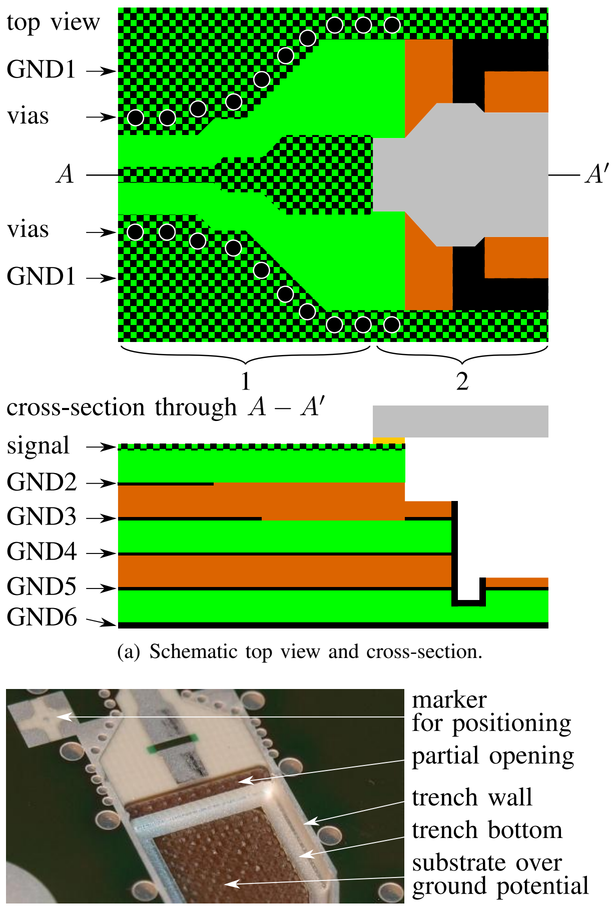
cavity with optional pillars and to partially open the copper-plated sidewalls in the area of the transitions (Fig. 2(c)). For technological reasons, a 100 µm thin substrate layer at the bottom of the cavity is unavoidable. The influence of this layer on the resonator's unloaded Q will be discussed in Section III.

The transition of the substrate-guided microstrip line into the quasi air-guided one is described next. The configuration is shown in Fig. 3(a). On the left side, the transmission line cross-section is a 50 Ω grounded coplanar line with vias connecting the ground layers. Based on the principle of [7], the ground planes GND2 and GND3 are removed under the transmission line in area 1, GND4 being the reference potential of the microstrip line. Thus the strip is widened offering a larger connection area between the printed strip on the PCB and the membrane strip. The basic idea of area 2 in Fig. 3(a) is to counterbalance the enlargement of the air-guided microstrip line by partly eliminating the substrate under the short taper. Additionally, the metallization pattern of GND3 can be designed to reduce reflections at the discontinuity. These adjustments are sufficient to achieve a reflection coefficient of a back-to-back transition lower than −29.5 dB up to 11.5 GHz in the simulation with *CST Microwave Studio* [8]. A manufactured transition without the membrane is depicted in Fig. 3(b). The two brown areas show the upper and the lower prepreg layer resulting from different milling depths. Additionally, the trench and a marker structure are readily identifiable. The latter helps to position the membrane on the PCB.

The simulated and three measured curves from identically build up transitions are illustrated in Fig. 4, where the differences are caused mainly from the individually soldering. The measured reflection coefficient is smaller than −20 dB in the specified band. The insertion loss of the transition increases with frequency and is about 0.33 dB at 5 GHz for the back-to-back composition.

III. Investigation of Quality Factor

After designing the transition, single resonators for an interdigital filter are investigated. The quality factor is the most important figure of merit being estimated in a simulation. With



(a) Schematic top view and cross-section.

(b) Realized transition.

Fig. 3. Transition for a cavity height of 3.5 substrate layers.

the equation

$$Q_u = \pi f_0 \tau_{21} \frac{10^{IL/20\,\mathrm{dB}}}{10^{IL/20\,\mathrm{dB}} - 1} \tag{1}$$

the unloaded Q can be calculated from the group delay τ_{21} at the resonance frequency f_0 with weak coupling to the feed lines [9]. To this end, the insertion loss IL at resonance should not be less than 30 dB. The shielding described in Section IV has been replaced for these simulations with a conducting wall. Figure 5 contains the results for the unloaded Q. The dependency of the Q factor on the cavity height is much stronger than on the resonator width in the examined case. The maximum unloaded Q is reached by increasing the resonator width and the distance to ground. In this case, for a cavity height of 1.5 mm and a resonator width of 6 mm, the resulting Q factor is 1392. All simulations were carried out with the remaining 0.1 mm thick substrate sheet of *Rogers RO*4003 over the bottom ground and a 0.5 mm thick resonator. The unavoidable addition of the 0.1 mm substrate layer reduces the unloaded Q from 1457 by 4.5%.

IV. Filter Design and Measurements

In this chapter, an interdigital Chebyshev membrane filter is outlined at 5 GHz with five resonators and a bandwidth of 12%. The design is based on the determination of the coupling

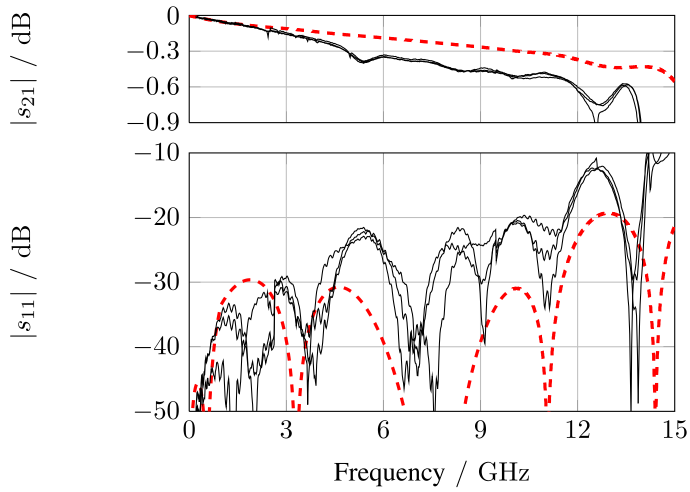


Fig. 4. Simulated (- - -) and measured (——) scattering parameters of the back-to-back transition for a cavity height of 3.5 substrate thicknesses.

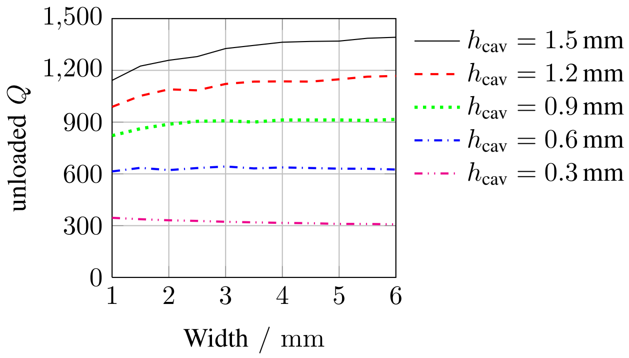


Fig. 5. Q factor over resonator width for different cavity heights

coefficients and the external Q factors to obtain the desired filter behavior [9]. The feed lines are located normal to the outer resonators [10]. A schematic structure of the membrane is shown in Fig. 6. The markers for positioning the membrane over the PCB are located in the frame parts. After the soldering process, the two frames are removed at the predetermined breaking points. A scanning electron microscope picture of a predetermined breaking point is depicted in Fig. 7.

In order to prevent radiation from the membrane filter, a shielding is realized with a cover plate snapping into a bendable copper wall. Due to the shielding a rectangular cavity is generated, in which waveguide modes and cavity resonances can be excited. These modes are suppressed by integrating pins connecting the cover plate and ground metallization in the PCB. In Fig. 8(a) an open structure without the shielding cover is shown. The complete band pass filter is displayed in Fig. 8(b) with soldered pins and cover plate. The measurements were executed with a TRL-calibration deembedding the cables and the SMA-connectors. The simulated and measured scattering parameters are compared in Fig. 9. The frequency shift from 4.989 GHz in the simulation to 4.787 GHz in the measurement corresponds to 4.05%. The reasons for the displacement are mostly fabrication tolerances in the PCB. In comparison to the simulation, the trench is about 90 µm

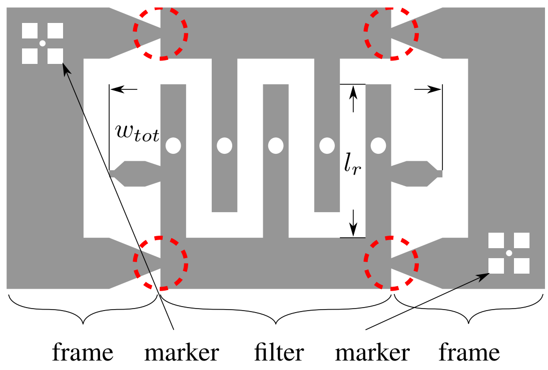


Fig. 6. Schematic view of the membrane with markers and predetermined breaking points (- - -), $l_r = 12.3$ mm, $w_{tot} = 77$ mm.

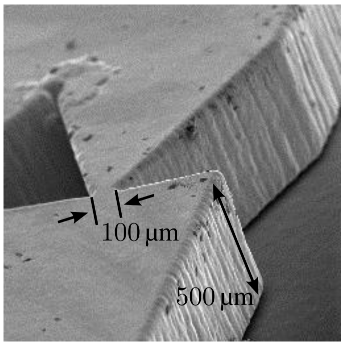


Fig. 7. Scanning electron microscope picture of a predetermined breaking point.

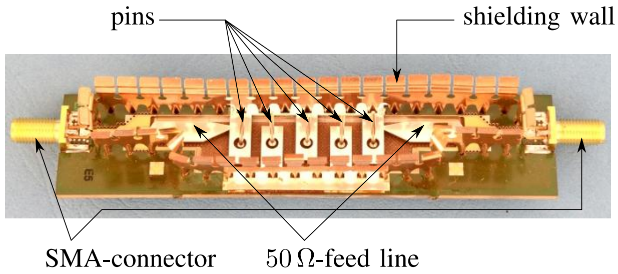
too deep and, simultaneously, the substrate layer over the bottom metallization is 80 µm too thick. Both changes cause an extension of the electrical length of the resonators.

The measured reflection coefficient of −15.5 dB differs from the simulated value of −20 dB due to fabrication tolerances. The minimum measured insertion loss of 0.57 dB at 4.8 GHz fits well to the simulated one of 0.51 dB at 5 GHz. Losses of about 0.29 dB result from the transitions. With the following formula a rough approximation of the unloaded Q is possible [11], in which Δf is the absolute filter bandwidth and g_i are the filter coefficients:

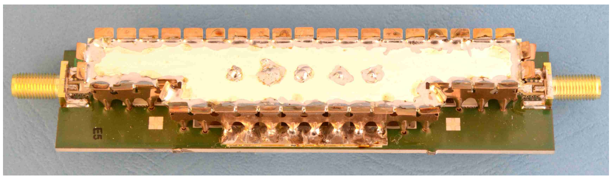
$$Q_u = \frac{4.343 f_0}{\Delta f \, \frac{IL}{\text{dB}}} \sum_{i=1}^{N} g_i. \tag{2}$$

According to this, the insertion loss of 0.28 dB yields an unloaded Q of 775. The degradation of the Q factor is attributed to the substrate pillars under the interdigital resonators. These points of support guarantee stability and a mechanical resonance frequency of the interdigital resonators higher than 5 kHz. For interdigital filters with a center frequency of about 7.5 GHz the bars are sufficiently short, so that the substrate post can be omitted and unloaded Q values over 1300 are realizable.

The stop band characteristics of the band pass filter are demonstrated in Fig. 10. The reduced stop band attenuation in the measurement is induced by external coupling of the SMA-connectors outside of the filter shielding and is independent of the filter performance. If this external coupling is suppressed by absorbing material, the blue dotted curve is



(a) Open structure without the shielding cover.



(b) Completely integrated filter with soldered shielding components.

Fig. 8. Realized membrane interdigital filter at 5 GHz.

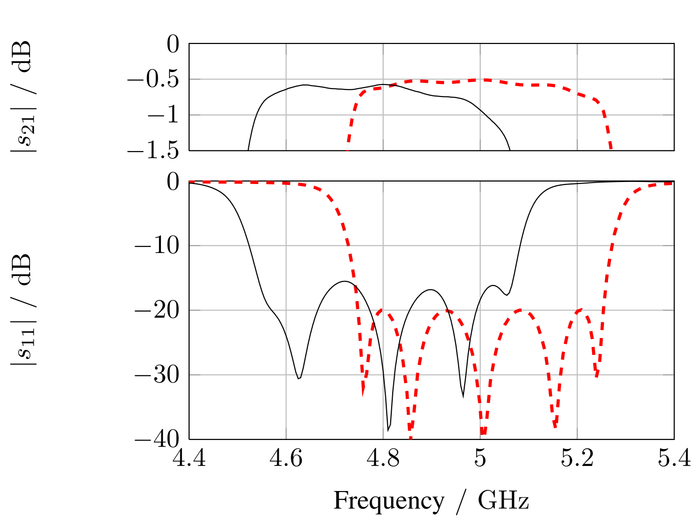


Fig. 9. Simulated (- - -) and measured (——) scattering parameters of the membrane interdigital filter at 5 GHz.

obtained showing an attenuation better than 80 dB from 6 GHz to 11.5 GHz. Above 11.5 GHz rectangular waveguide modes are excited having an orthogonal E-field to the integrated pins in the cavity. The cutoff frequency of these spurious modes can be augmented by further decreasing the shielding height.

V. Conclusion

A novel membrane integration process for high Q factor circuits in PCBs is presented. In this technique, a silver-plated sheet steel is located over a metallized cavity of a PCB. The connection between the substrate-guided and the air-guided microstrip line is realized with an integrated transition. The functional principle has been verified for a transition to a cavity height of 3.5 substrate layers.

The investigations on the unloaded Q of the quasi air-guided microstrip resonators show realizable values up to 1300.

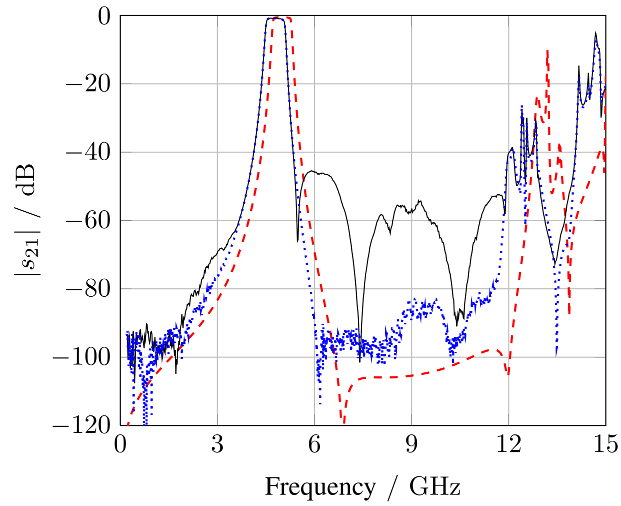


Fig. 10. Transmission factor amplitude $|s_{21}|$ of the membrane interdigital filter at 5 GHz in simulation (- - -), measurement (——), and measured without crosstalk of the SMA-connectors (⋯⋯).

For the verification of this technique, a 5 GHz interdigital filter has been implemented. The measurements demonstrate a displacement of the center frequency of 4% due to systematic fabrication discrepancies in the PCB. The experimental return loss achieved a level better than 15.5 dB and a minimum insertion loss of 0.57 dB. The stop band contains no spurious frequencies up to 11.5 GHz.

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