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Replicability of a Millimeter-Wave Microstrip Bandpass Filter using Parallel Coupled Lines

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***Abstract*—Replicability of filters is critical especially at millimeter-wave (mm-wave) frequencies, as a manufacturing error of a few tens of microns can significantly shift the frequency response in this range and lumped elements are not available at these frequencies. In this paper, seven replicas of a mm-wave coupled-line 3rd order bandpass filter (BPF) are fabricated and measured under the same test conditions. The filters are designed on a single lot 10 mil-thick Rogers RO4350B substrate. The smallest spacing is 109 µm and the smallest line width is 330 µm. Over seven replicas, the passband is from 34.8±0.2 to 38.1±0.1 GHz; the insertion loss is 3.44±0.32 dB; the typical return loss is 10.18±2.43 dB. The measurement results are in accordance with the EM simulation results. They show that the reflection parameters are relatively sensitive to manufacturing tolerances and connector realization, while the transmission parameters are robust to fabrication variations. This demonstrates a satisfactory manufacturing replicability of microstrip BPF in the Ka-band (26.5-40 GHz), in the scope of radar system design.**

Keywords—parallel coupled line filters, microstrip bandpass filters, millimeter-wave, replicability.

I. Introduction

The spectrum allocation of the 33.4–36 GHz band by German Federal Network Agency for wind turbine structural health monitoring systems has engaged the investigation of imaging radars at mm-wave frequencies. This work proposes a simple, low-cost and replicable 3rd order microstrip BPF that could be integrated in the transmitter of an imaging radar such as proposed in [1]. The filter is typically used to decrease the level of spurious signals such as local oscillator leakages, image frequency or unwanted harmonics.

Microstrip BPFs have the advantage of being compact, lightweight and are compatible with SMD components, but the design becomes challenging at mm-wave frequencies. Low insertion loss (IL) necessitates thin and low-loss substrates such as those based on LTCC technologies [2] or Rogers RT 5880 [3] [4]. Mm-wave coupled line filter dimensions decrease to sub-millimeter dimensions, which makes it difficult to implement via holes [2]. Furthermore, the spacing between the lines reduces greatly with respect to increasing fractional bandwidth. In [3], the authors propose a wideband BPF design solution with minimum 100 µm spacing which is realizable. However, the architecture including the matching network is relatively complex, especially that mm-wave BPF design is sensitive to length variations (Fig. 1).

As an alternative, the design proposed in this paper focuses on a simple parallel coupled-line BPF layout based on Rogers RO4350B substrate. The dielectric constant is 3.48 and the loss tangent is 0.0037, both measured at 10 GHz. The thickness of the substrate is 0.254 mm with 35 µm-thick copper conductor layers. To investigate the manufacturing robustness of the filter, seven replicas have been fabricated externally and characterized. All replicas are built on the same substrate lot. The manufacturer guarantees a design tolerance of 80% of the filter dimension, the conductor spacing tolerance is 30%. This paper aims to show that the proposed and conventional parallel coupled-line filter is realizable and replicable at mm-wave frequencies. This study is essential to ensure that the filter works as expected when integrated in a whole communication or detection system.

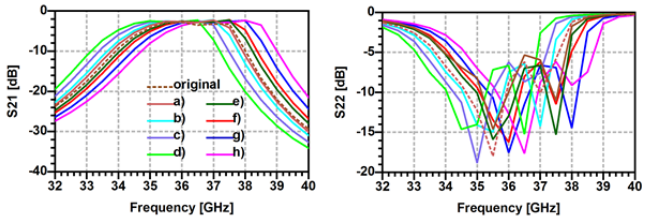

Fig. 1: Frequency response shift due to length modification for S21 and S22. The length of each coupled line has been increased by a) 5 µm, b) 10 µm, c) 20 µm, d) 30 µm, and decreased by e) 5 µm, f) 10 µm, g) 20 µm, h) 30 µm from the original. A shift of 50 µm is a typical error when manufacturing.

Section II briefly recaps the bandpass filter design procedure, while simulation results are described in Section III, and compared to the measurement results in Section IV to demonstrate the good realization and replicability of the design.

II. Filter Design

Let us consider a BPF of order N, of geometric center frequency $f_0 = \sqrt{f_1 f_2}$ and passband frequencies f_1 and f_2. The dimensions of the coupled-line BPF are determined using the classic two-step design equations derived in [5].

First the products of the $J_i Z_0$ the admittance of the ith inverter ($i = 1..N+1$) are calculated for the 1st coupling $J_1 Z_0 = \sqrt{\Delta\pi/2 g_1}$, for the nth coupling $J_n Z_0 = \Delta\pi/2\sqrt{g_{n-1} g_n}$ and for the last coupling $J_{n+1} Z_0 = \sqrt{\Delta\pi/2\, g_n g_{n+1}}$. These products are function of the fractional bandwidth $\Delta = (f_2 - f_1)/f_0$ and the filter prototypes g_i. Then are derived the even mode Z_{0e}^i and the odd mode Z_{0o}^i characteristic impedances for each coupled line i : $Z_{0e}^i = Z_0(1 + J_i Z_0 + (J_i Z_0)^2)$ and $Z_{0o}^i = Z_0(1 - J_i Z_0 + (J_i Z_0)^2)$ respectively.

The physical dimensions of the coupled lines can be approximated and optimized using CAD software.

III. Filter Simulations

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The methodology presented in Section II is applied to design a 3rd order Chebyshev BPF using parallel open-circuited coupled lines with 0.5 dB passband ripples. Given a fixed order, this filter has the advantage of having the sharpest cutoff among the classic filters [5].

The characteristic impedance is 50 Ohm. The center frequency should be 36.3 GHz; the fractional bandwidth is 10%. The filter is overdesigned to 40 GHz to compensate the frequency shift due the fringing fields at the open-circuited stubs.

The layout including the filter, 50 Ohm transmission lines and the landing pads of 2.9 mm SMA connectors is pre-designed and simulated using Keysight ADS. A 3D EM simulation comprising the above mentioned filter layout as well as 3D-drawing of the connectors is performed with ANSYS Electronics. In this simulation, the length of the 50 Ohm line and the tapered transition between the filter and the transmission line, as well as between the transmission line

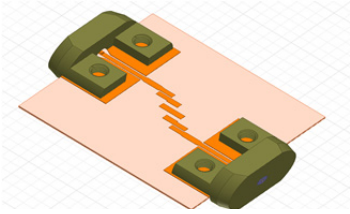

Fig. 2: Coupled-line bsand-pass filter. The outer coupled lines have a width of 417 µm, a spacing of 109 µm and a length of 1173 µm. The inner coupled lines have a width of 509 µm, a spacing of 359 µm and a length of 1136 µm. The filter is connected to the pads of the Hirose HK-LR-SR2 connectors .

and the coplanar waveguide (CPW) structure of the connector footprint are optimized.

Figure 2 exhibits the complete design of the filter. The smallest spacing is 109 µm, and the smallest line width is 330 µm, which are reasonable for manufacturing. The SMA

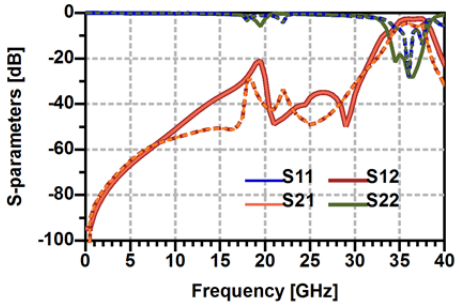

Fig. 3: Proposed filter simulations using Ansys Electronics (solid lines) and Keysight ADS (dotted lines)

connectors are Hirose HK-LR-SR2. Because they are defined from DC to 40 GHz, the analysis is operated within this frequency range.

Figure 3 displays the performance of the filter simulated on ADS and Ansys Electronics. For the whole filter, the IL = 2.5 dB with a 9.9% fractional bandwidth 34.5 - 38.1 GHz, and a return loss > 8 dB. The simulation results are satisfactory for transmitting applications such as in [1] where the reflections are more critical than the insertion loss as the filter is integrated between two amplifiers operating in nonlinear regime.

Note that the ripples present in the stopband are due to the connector landing pads, as highlighted in Figure 4. This frequency corresponds to the main notch. The plot result

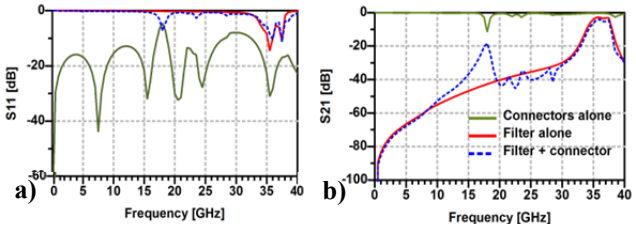

Fig. 4: ADS simulation of S11 (left) and S21 (right) comparison between a thru-line (connector landing pads and tapered 50 Ohm transmission line), the filter alone and the full layout comprising the filter with the connectors pads

indicates that there is radiation at the transition CPW to microstrip.

IV. Filter Measurements

Seven replicas of the microstrip filter are fabricated on the same substrate lot (see Fig. 5). For filters 1, 2, 3 and 6, the connectors landing pads are chosen to be placed at the very edge of the board. Thereby the tight design distance from the edge of PCB to the connectors via holes, recommended by the manufacturer is respected and the connectors are sure to be fixed correctly. However, dicing the PCB can generate copper burrs. In order to investigate the potential consequences of dicing process, the board is cut 200 microns away from the connector landing pads edge for filters 4, 5 and 7 (Fig. 6).

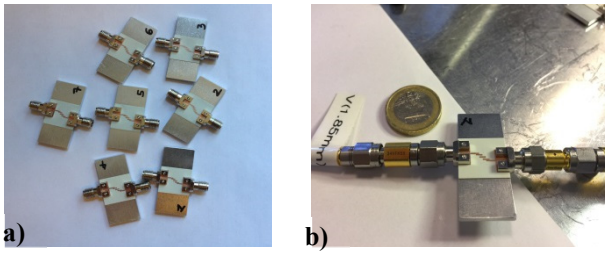

Fig. 5: a) Filter replicas b) Filter measurement setup

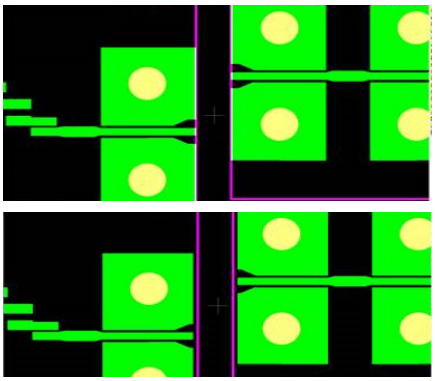

Fig. 6: In purple the PCB outline, in green the copper: a) outline at the border of the connectors landing pads, b) outline 200 microns away from the connectors landing pads

The seven filter replicas have been measured with vector network analyzer Anritsu ME7808B under the same calibration of the instrument, using calibration kit model 3652. We compare the seven replicas to each other and to the simulation results (Fig. 7). There is no substantial distortion of the frequency response as seen in Figure 1. To investigate further the feasibility and replicability of the filter, for each filter replica the center frequency, the fractional bandwidth, the insertion loss and the return loss are determined, respectively. Then, for each of these parameters the average

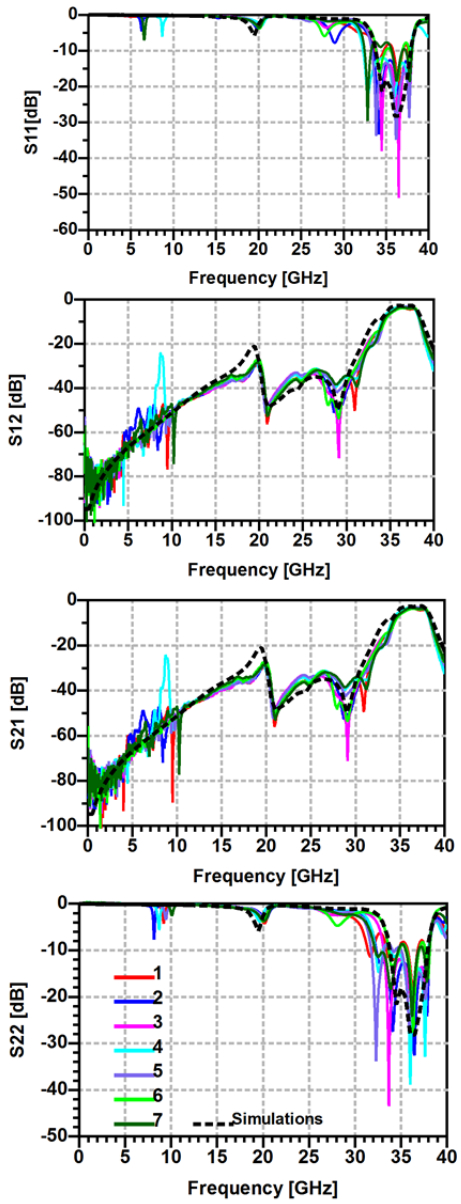

Fig. 7: Simulation and measurements results.

(AVG) and the standard deviation (SD) are calculated and summarized in Figure 8.

In Figure 8, filters 4 and 5 (with 200 µm extra spacing at the PCB edge) are deviating with respect to center frequency, passband and insertion loss, unlike filters 1, 2 ,3. This could be due to a defect on the connectors contact to the PCB. However, it is difficult to conclude on this phenomenon, as filters 6 and 7 do not follow the trend of their fellow filters.

In Figure 7, in the stopband, a notch appears for filter 4. This is due to a poor electrical contact of the connector, and disappeared during measurements when the connector is pressed towards the signal line. It may be due to a manufacturing error, as neither filter 5 nor 7 presents the same notches.

These general results are satisfactory and confirm the fine replicability for mm-wave coupled-line bandpass filters.

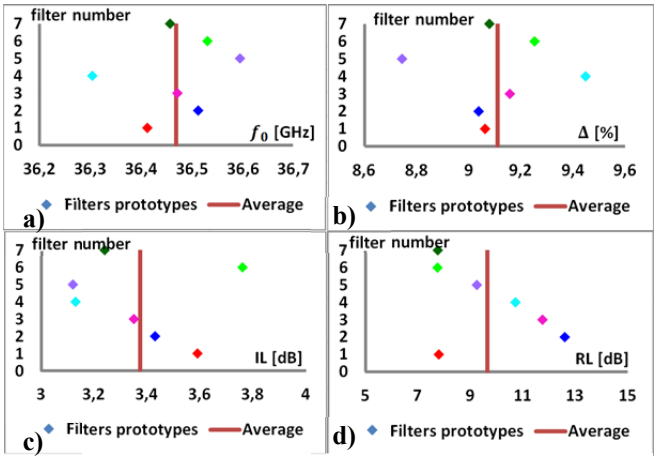

Fig. 8: Measurements results: Statistical comparison of the seven filters a) the AVG center frequency is 36.51 GHz with SD = 0.09 GHz; b) the AVG fractional bandwidth is 9.1% with SD = 0.2%; c) the AVG insertion loss is 3.37 dB with SD = 0.24 dB; d) the AVG return loss is 9.66 dB with SD = 2.04 dB. For transmission parameters, filters 2, 3 and 7 are robust. There is no pattern with respect to reflection parameters. This demonstrates that the RL is sensitive to manufacturing. There is no conclusive impact regarding copper burrs.

V. Conclusion

This paper discussed the realization and replicability of a mm-wave microstrip bandpass filter using parallel coupled lines. The filter was designed and entirely EM simulated. Seven replicas of the filter were fabricated on the same substrate lot and measured. The performance of each filter follows the same trend, and is very similar to the simulation results. It was shown that the reflection parameters are more sensitive to manufacturing tolerance than the transmission coefficients. The results of the replicability investigation of mm-wave coupled-line bandpass filter on microstrip are satisfying. This guarantees the good operation of the filter when integrated in system applications such as imaging radar system design.

Acknowledgment

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