Insertion loss measurement of a lowpass microwave filter manufactured on FR4 laminate

Aurel Chirap, Valentin Popa
Department of Computers, Electronics and Automatics
Stefan cel Mare University of Suceava
Suceava, Romania
aurel@eed.usv.ro; valentin@eed.usv.ro

Abstract — In this paper a microstrip low-pass filter modeling and designed for UTMS-2100 band is presented. The full wave EM simulated and measured results are compared and a good agreement has been achieved for this low-pass filter fabricated prototypes. The measured insertion loss is 28.6 times higher for the FR4 laminate as for the reference laminate.

Keywords — microstrip filters; microwave filters; loss measurement; insertion loss, dielectric losses, dielectric substrates; FR-4; RO4003C.

I. INTRODUCTION

Most often, filters are used for selection or suppression of specific frequency bands. Furthermore, they are utilized for adapting impedances between the functional blocks of high-frequency systems. The passive components with lumped parameters (capacitors, inductors) are frequently used in designing filters. Passive filters with lumped parameters elements operate well up to several hundred MHz frequencies, but above this level, the performance of the filter varies significantly. Is it possible to use passive circuit elements with distributed parameters, in which case the performances of the device are dependent on the characteristics of the laminate used, in special of the substrate losses [1],[2],[3].

The present study aims at estimating the losses caused by the substrate electric properties, in particular, loss angle tangent. For this objective achievement we are proposing a working method based on following steps:

1. Modeling a microstrip technology filter allowing the pass of the UTMS-2100 frequency band.
2. Simulation and designing of two prototype filters; the first one, used as a reference and realized on a laminate (producer certified), as RO4003C[4]; the second one, realized on an ordinary laminate, as FR4 [5], used for comparing.
3. Measurements for both prototypes and results evaluation.

II. FILTER MODELING

The circuit elements with distributed parameters can be produced on plane structures using short-circuited line stubs or open-circuited transmission line stubs, that are characterized by Z₀ impedance and electrical length.

Two successive conversions described in [2] are necessary for prototype filter elements transformation into circuit elements with distributed parameters. The first one, Richard’s conversion, allows the replacement of the lumped parameters inductors and capacitors with short-circuited or open-circuited transmission line stubs, with length l=λ/8, where λ is the line wavelength at the cut-off frequency, ω₀.

Fig. 1. Equivalent circuits a Kuroda identity.

Thereby, an inductor can be replaced with an short-circuit transmission line stub, characterized by L impedance, while a capacitor can be replaced with a open-circuit transmission line stub, characterized by 1/C impedance (Fig. 1). However, from a practical point of view, it is difficult to design short-circuit transmission line stubs, but is possible to transform them in open circuit line stubs. This is possible through application of the Kuroda identity (Fig. 1), which allows conversion a short-circuit stub into open-circuit stub by adding a line segment, called unit element, with length l=λ/8 and impedance z=1 at both ends of the line stub. This unit element does not affect the filter functionality and n depends on impedances rate: n²=1+z²/z₁.

The proposed low-pass filter prototype is a 3rd order Chebyschev filter, with a cut-off frequency f₀=2.2 GHz (Fig. 2). The g constants for element values (L and C) determining

978-1-5090-1993-9/16/$31.00 ©2016 IEEE
according with [2] are \( g_0=1, g_1=1.5963, g_2=1.097 \) and \( g_4=1 \). After Richard’s and Kuroda transformations we obtained the result shown in TABLE I.

Finally, the circuit has been scaled in impedance and frequency (\( f_C=2.2 \) GHz) by multiplication of Kuroda values from TABLE I. with the characteristic impedance value (\( Z_C=50 \Omega \)). The length of the line stubs is equal with \( \lambda/8 \) at 2.2 GHz frequency. Thereby, the low pass filter model is obtained and presented in Fig. 3, where each segment has the designed impedance and \( \ell \) electrical length.

### III. GEOMETRICAL DIMENSIONS AND FILTER SIMULATION

The model described in section II will be converted into physical circuit, for each laminate type (RO4003C and FR4) with parameters presented in TABLE II.

### TABLE II. PARAMETERS OF LAMINATES

<table>
<thead>
<tr>
<th>Laminate</th>
<th>RO4003C</th>
<th>FR4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric thickness (mm)</td>
<td>1.52</td>
<td>1.52</td>
</tr>
<tr>
<td>Copper thickness (µm)</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Relative dielectric constant, ( \varepsilon_r )</td>
<td>3.55</td>
<td>4.3</td>
</tr>
<tr>
<td>Loss tangent, ( \tan \delta )</td>
<td>0.0027</td>
<td>0.018</td>
</tr>
</tbody>
</table>

With impedances, the electrical lengths of the line stubs, the laminate parameters and software program ADS (Advanced Design System) is possible to obtain physical dimensions of metallic strips (width and length for each segment), presented in TABLE III.

### TABLE III. PHYSICAL SIZE A THE STUB LINES

<table>
<thead>
<tr>
<th>Laminate</th>
<th>RO4003C</th>
<th>FR4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z_0 ) [( \Omega )]</td>
<td>( w ) (mm)</td>
<td>( \ell ) (mm)</td>
</tr>
<tr>
<td>----------</td>
<td>---------</td>
<td>-----</td>
</tr>
<tr>
<td>45.59</td>
<td>3.887</td>
<td>10.128</td>
</tr>
<tr>
<td>81.32</td>
<td>1.344</td>
<td>10.572</td>
</tr>
<tr>
<td>129.82</td>
<td>0.356</td>
<td>10.938</td>
</tr>
<tr>
<td>50.00</td>
<td>3.357</td>
<td>5.100</td>
</tr>
</tbody>
</table>

#### A. Simulated in circuit mode

Schematics with circuit elements based on dimensions from TABLE III and type T link elements to connect them have been used for our filter simulation. Fig. 4 is the simulation result in ADS Circuits simulator and it shows the dispersion parameters S11 (return loss) and S21 (insertion loss) for reference laminate (RO4003C).

By analyzing the diagram, it can be seen that the return losses reach the minimum at 2.144 GHz, frequency near the central frequency of the UTMS-2100 downlink band (2.140 GHz).
GHz). The frequency bandwidth at -10 dB and VSWR = 2 is 470 MHz, sufficiently wide to include the UTMS-2100 band.

The Fig. 5 shows the reference filter characteristics (RO4003C) compared with an FR4 laminate filter. It can be observed a 36 MHz frequency gap above the reference and reflection losses higher with 10 dB, for FR4 laminate.

Fig. 5. Circuit simulated S11(return loss) and S21(insertion loss), comparative results for both laminates.

B. Full wave EM simulation

IV. FILTER PERFORMANCE MEASUREMENT

The two filters presented in Fig. 7 have been produced on an LPKF Protomat-S62 plotter with a 0.5 μm precision using laminates RO4003C and FR4.

Fig. 7. Fabricated prototype filters. a) RO4003C - Rogers RF laminate. b) FR4- Fibreglass laminate. c) Device used for calibrating VNC

The dispersion parameters S11 and S21 have been measured with the vector analyzer (VNA) N9912A[6]. To exclude the parasitic elements associated with the SMA connectors, the device presented in Fig. 7.c has been introduced into the calibration circuit of the VNA.

The simulated and measured return losses are shown in Fig. 6.a, and the simulated and measured insert losses can be found in Fig. 6b. The full wave EM-simulation shows good agreement with experimental results.

The measured and comparison S-parameters are demonstrated in Fig. 8.

V. RESULT AND DISCUSSION

After the circuit simulation, it can be seen that the model is valid regarding the design requirements and that the identified differences between the FR4 laminate filter and the reference filter are small.

Fig. 6 shows a 240 MHz gap in frequency for EM simulation versus in circuit simulation, but a very similar evolution of S11 for EM simulation and measured parameter with VNA. The same difference in frequency is recorded for S21. From the comparative evaluation of the measurement results it is clear that the insertion losses (S21) at 1.9 GHz are 0.048 dB for the RO4003C laminate and 1.376 dB for FR4. These values are approximately constant all along the band pass frequency. Thereby, it has been established that the FR4 filter has insertion losses 28.6 times bigger than the RO4003C reference filter.
Using Richard’s and Kuroda transformations a 3rd order Chebyshev filter was modeled with distributed circuit elements. This model has been used for prototype manufacturing. EM simulation has proved the necessity of optimization. The measured insertion loss is 28.6 times higher for the FR4 laminate as for the reference laminate RO4003C. As for designing an RF energy harvesting device, the laminate plays an essential role in the overall performance, this paper demonstrated that RO4003C laminate is the best solution.

VI. CONCLUSION
Using Richard’s and Kuroda transformations a 3rd order Chebyshev filter was modeled with distributed circuit elements. This model has been used for prototype manufacturing. EM simulation has proved the necessity of optimization. The measured insertion loss is 28.6 times higher for the FR4 laminate as for the reference laminate RO4003C. As for designing an RF energy harvesting device, the laminate plays an essential role in the overall performance, this paper demonstrated that RO4003C laminate is the best solution.

ACKNOWLEDGMENT
This paper has been supported by the research plan of Ministry of Education and Scientific Research from Romania. The authors also acknowledge the technical support of Dan Alin POTORAC, Keysight Technologies and Rogers Corporation.

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