SIMPLE DESIGN METHOD FOR MICROWAVE BAND-PASS FILTERS

Grigore-Adrian IORDĂCHESCU, Daniel Alexandru VIŞAN
University of Piteşti, Romania
adi_iord@yahoo.com

Keywords: microwaves, band-pass filters, free design software, microstrip circuits, PCB

Abstract: *In this paper, a simple method for designing and simulating low-frequency band-pass filters of around 1GHz is presented. In this aim, an original combination of three free software applications is proposed. It will be shown that the three applications could successfully replace expensive software packages for the design of microwave band-pass filters. This method can thus be used in universities or at home hobbyists who work with microstrip technology at low microwave frequencies.*

1. INTRODUCTION

An ideal band-pass filter is a device which permits the passage of certain frequency bandwidths, while rejecting all the others. Band-pass filters are extensively used in telecommunications, on both emitter and receiver sides. On the emitter side, sometimes a signal can occupy too wide a bandwidth. Because of telecommunication standards, every channel is constrained to only a limited bandwidth. Thus a band-pass filter can be used, which can limit the emitter signal to only the bandwidth allocated by the standard in use.

On the receiver side, a band-pass filter can be useful for limiting the noise and foreign interferences passing through [1].

A band-pass filter is characterized by its central frequency f_0 and bandwidth Δf; alternatively one can introduce another physical quantity called Q-factor, using a definition [2] analogue to the one for resonators:

$$Q = \frac{f_0}{\Delta f} \quad (1)$$

Considering the large scale usefulness of such filters, it can be well-advised to introduce the subject of designing these filters in university curricula dealing with RF and microwave engineering.

There are many software applications out on the market dealing with the design of such filters. The most expensive ones, such as CST Microwave Studio [3] or AWR Design Environment [4] can be considered too expensive for low-budget universities or at-home hobbyists.

Happily, there are many free small scale applications which can be used together to substitute for some of the design capabilities of the proprietary software. Two of the ones which are worth mentioning are *Vlad's Filter Designer* [5] and *Nuhertz Filter Free* [6]. Sadly, these two later applications don't show the final geometry of the circuit in terms of PCB geometry. They are limited in showing only the lumped element structure of any desired filter. But lumped element filters can be used in practice only for radio frequencies, not for microwave domain. What is needed is a translator-application to make the conversion between lumped element and distributed geometry. To pass from lumped element to distributed geometry (as needed to construct microwave filters) the authors found the possibility of using a novel combination of two free software applications, Smith Chart [7] and TX-Line [8].

Next section of this paper will thus deal with presenting all the software needed to completely design a microwave band-pass filter.

Section 3 will then present the filter design process using the three programs previously explained.

Finally, filter design will be succeeded by a section dedicated to the filter implementation on a PCB board. The conclusions section will close the paper.

2. SOFTWARE APPLICATIONS

The three free software applications that can be used successfully in the design of any microwave filter, including band-pass filters, are presented in this section. The three of them must be used complementarily.

2.1. Filter Free

This application has two operating modes: quick and advanced. For building complex filters, the advanced mode will be used. In this mode, the user can freely choose the filter type (Gaussian, Bessel, Butterworth, Legendre, etc.), the filter class (low pass, band pass, high pass, band stop) and the implementation technology (lumped, distributed, active elements, etc.).

For this paper, a Gaussian filter was chosen. The Gaussian is a filter whose response at a Dirac pulse approximates a Gaussian function. If a step pulse is applied to its entry, the output signal will be monotonic (with no overshoot).

Because this paper is concerned with only band-pass filters, the filter class was chosen “band pass”. The technology was chosen to be distributed, as there are no lumped elements with so small values to be used for microwave filters.

Sadly, because *Filter Free* is a free version of a more complex program, it has some limitations regarding the distributed technology. It does not show the final microstrip circuit for the case of pass-band filters. Nor does it show it for the case of high-pass or band-stop filters. The only case in which it displays the final microstrip circuit is for the low pass filters (Fig. 1 and Fig. 2).

In Fig.1 a circuit made with general transmission lines is obtained for the case of a low-pass filter by the use of *Filter Free*. The same filter is then synthesized in microstrip technology using the same application (Fig. 2).

For the case of pass-band filters this freeware application synthesizes only the general transmission line circuit (analogue to Fig. 1) but does not display the circuit for the particular case of microstrip technology (analogue to Fig. 2).

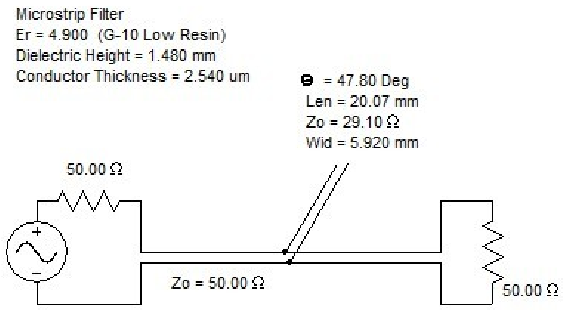

Fig. 1 Transmission line circuit for the case of a Low Pass filter, designed by Filter Free

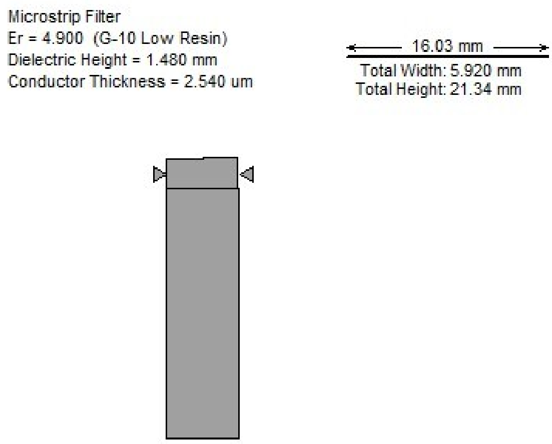

Fig. 2 Microstrip circuit for the case of a Low Pass filter, designed by Filter Free

There is, however, a way around this limitation by using another free application from Texas Instruments called Tx-Line.

2.2. Tx-Line

Tx-Line is a free software application which permits the user to compute the parameters of any transmission line, no matter the technology. It offers every possible technology used for microwaves circuits: microstrip, stripline, CPW, slotline and coupled lines.

For the present paper, the microstrip technology will be used, as this is the cheapest and most convenient for hobbyists and low-budget projects. The rationale behind this is that it can be implemented on printed circuit boards (PCBs).

After choosing the microstrip technology in the upper tabs section, the user has a wide range of geometry and material parameters which can be modified. In our present endeavor, what interests us the most is tuning the width of microstrip lines to obtain a given line impedance.

2.3. Smith Chart

Iowa Hills Smith Chart is a free application allowing the user to build transmission line circuits and to project the circuit on a Smith Chart.

Even if *Filter Free* automatically makes a translation from lumped elements to distributed technology, it does not always make the best choices. Sometimes the circuit lines automatically projected by *Filter Free* have too high or too low impedances. In those cases, Smith Chart can be used to make alternative translations from lumped elements to distributed technology.

Nevertheless, the transmission line circuits presented next in this paper will be those obtained by FilterFree alone. That is why another use of *Smith Chart* application will be shown in the next section. *Smith Chart* can be used to simulate, even though not as precisely as OrCAD package, the behavior of the designed circuits.

3. FILTER DESIGN

This section will deal with the entire process of filter design and simulation using the three applications described in the previous section.

An essential parameter to both FilterFree and Tx-Line programs is the relative dielectric permittivity ε_r of the isolator between the two conductors of a transmission line. Given that the transmission line will be in microstrip technology, the dielectric of the board used must be known.

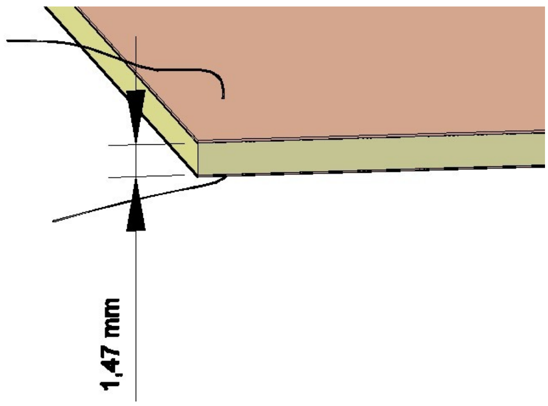

Fig. 3 Setup for measurement of dielectric permittivity

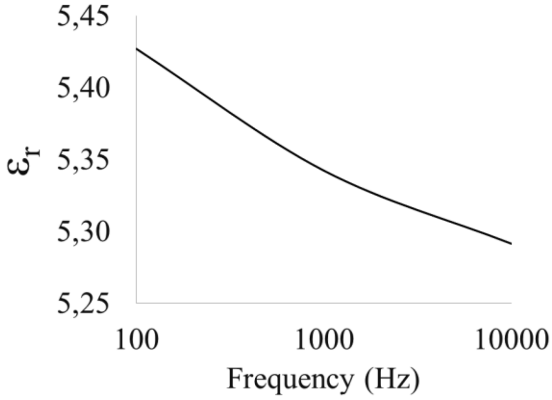

Fig. 4 Measurement of dielectric permittivity as a function of frequency

For the measurement of the dielectric constant of the double coppered board the setup of Fig. 3 has been devised. Firstly, the thickness *H = 1,47mm* of the board has been measured with an electronic caliper. Secondly, the surface $S = 148 \times 200\ mm^2$ of the copper plates was measured with a ruler. Then two wires have been soldered on both copper plates and the capacity *C* of this setup has been measured with a RLC bridge (type Escort ELC-133A) for different frequencies. The dielectric constant ε_r is then calculated for each frequency using the formula for parallel plate capacitors:

$$C = \frac{\varepsilon_0 \varepsilon_r S}{H} \quad (2)$$

The variation of the relative dielectric permittivity in function of frequency is shown in Fig. 4, in which the horizontal scale is logarithmic. The slope of the plot in Fig. 4 is -0.08 / decade. By extrapolation, it was inferred that the value for the dielectric permittivity at 1GHz is around ε_r = 4.9. This value was then used in the following process of design.

Using the value of the dielectric constant ε_r obtained earlier, the *FilterFree* software was used for the synthesis of a Gaussian bandpass filter (Fig. 5) of center frequency $f_0 = 1GHz$ and a bandwidth of $\Delta f = 200MHz$. From equation (1), it can be said that this filter has a low Q-factor of only 5. As can be seen from Fig. 5, only the general transmission lines circuit is shown by *FilterFree*.

To make the translation between a general transmission line circuit and a particular technology such as microstrip, the Tx-Line program can be used.

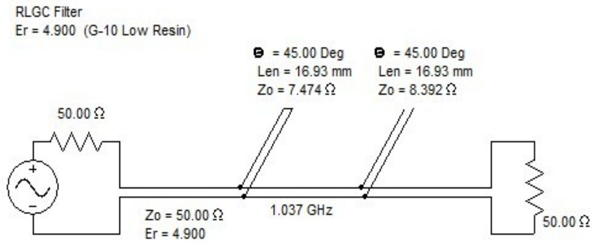

Fig. 5 The transmission line circuit synthesized by FilterFree

What is particularly needed is the width of each one of the three traces of which is composed the circuit of Fig. 5. The transmission line forming between the central trace and the ground plane has 50Ω impedance, while the two stubs which start from the central trace have impedances of approximately 7.4Ω and 8.4Ω respectively. The former ends in a short circuit, while the later ends in an open circuit.

To find the width *W* of each trace, all the other parameters - the dielectric constant, the conducting material and the thickness of the board - are kept constant while varying the width. When the right impedance is reached, the width W is written. For example to synthesize the first stub of Fig. 5 of length *16.93mm* and impedance of approximately *7.4Ω*, a trace of width $W_1 = 30.5mm$ is needed, as shown in Fig. 6.

Correspondingly, a second stub whose characteristic impedance is 8.4Ω should have a width of $W_2 = 26.5mm$.

Analogously, the central trace, of 50Ω impedance, should have a width of only $W_0 = 2.6mm$.

Simulating the circuit of Fig. 5 using the third software from the proposed bundle of preceding section, the results can be seen in Fig. 7. It can be first observed that the parameters of the transmission lines in Fig. 7 are close, but not identical to the ones of Fig. 5.

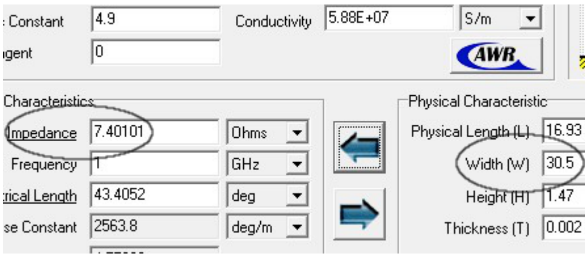

Fig. 6 Screen capture while using Tx-Line for finding the width of each trace

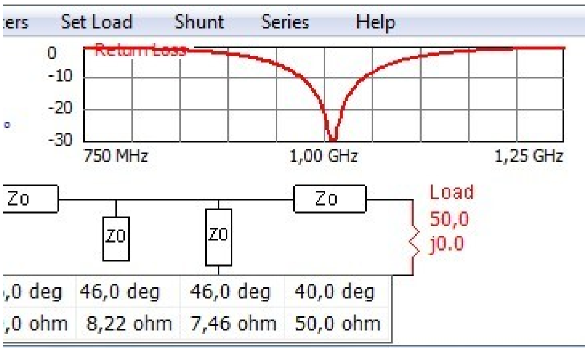

Fig. 7 Simulation of the circuit structure of Fig. 5 using Smith Chart software; upper part shows the reflection coefficient as a function of frequency, while the lower part is a fragment of the circuit itself.

This is because the Smith Chart software did not permit us to fine tune the values of the parameters. This later software has a step size feature for varying the parameters which can be bothersome in situations where precision is needed. For example instead of a phase difference of Θ = 45° in both stubs of Fig. 5, a phase difference of Θ = 46° is used for the stubs of Fig. 6. Nevertheless, it can be seen that even with approximated values for all parameters, one can still observe the drop in the reflection coefficient at around 1GHz. What this means is that at frequencies other than 1GHz, the waves will be reflected by the filter, while at 1GHz the waves will pass forward to the 50Ω load.

4. FILTER IMPLEMENTATION

Translating all the information gathered in the previous section in microstrip technology, the upper side of the final circuit will look like in Fig. 8.

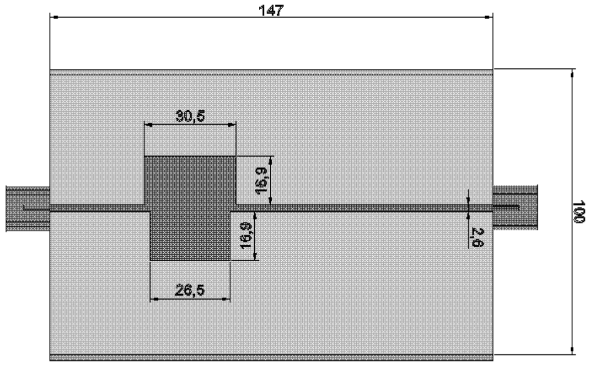

Fig. 8 The circuit of Fig. 5 projected in microstrip form before printing it on board

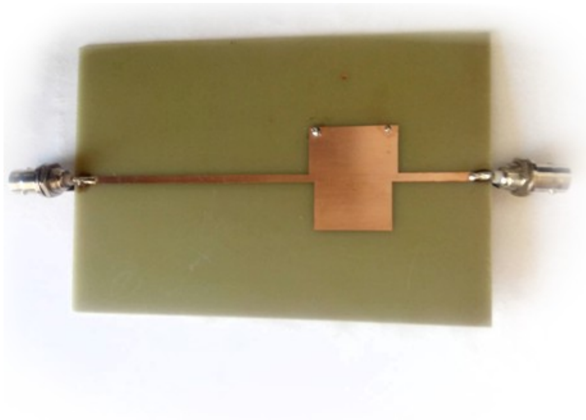

Fig. 9 Photo of the PCB containing the filter

To the left and right of Fig. 8 the central wire of the BNCs can be seen coupled to the main 50Ω trace. The BNC's ground is connected to the other (unseen) side of the board which must be left not etched.

What is not seen in Fig. 8 is that the upper stub (the one of 30.5mm width) is connected to the ground, while the lower one (of 26.5mm width) is left open. The reactances of the two stubs cancel each other out.

Because the main 50Ω trace is adapted to the load at all times and because the capacitive reactance of the lower stub cancels the inductive reactance of the upper one, it will not matter where on the main line the stubs are placed. That is why there is no indication of the position for the two stubs.

After printing the schematics, etching the board and short-circuiting the upper stub, the final printed circuit board will look like in Fig. 9.

5. CONCLUSIONS

This paper presented a collection of free programs which would enable the microwave engineer to freely design microwave band-pass filters. The method was exemplified for the case of a low Q-factor filter implemented on a printed circuit board (PCB). First step was the measurement of the dielectric constant of the material used as an isolator in the PCB. Introducing the measured value as a parameter in the *FilterFree* program, a schematic of the circuit is obtained. This schematic is then particularized for the case of microstrip technology using *Tx-Line* software and simulated using the *Smith Chart* application.

The filters designed in this section could serve a microwave laboratory in a university setup.

Testing of these filters and applying this method for the case of high Q-factor filters will make the object of a future paper by the authors.

6. ACKNOWLEDGMENT

The authors would kindly wish to thank Eng. George Iulian Marin for translating on board the circuit of Fig. 9.

7. REFERENCES

[1] Wikipedia, the free encyclopedia, "Band-pass filter", accessed 10.06.2017: http://en.wikipedia.org/wiki/Babd-pass_filter

[2] Tooley, M. H., "*Electronic circuits: fundamentals and applications*", Newnes pp. 77-78, ISBN 978-0-7506-6923-8.

[3] National Instruments, "National Instruments Design Environment", accessed 10.06.2017: http://www.awrcorp.com/solutions-applications/applications/filter-design

[4] Computer Simulation Technology, "CST introduces new filter synthesis tool", accessed 10.06.2017: https://www.cst.com/company/news/press-releases/cst-introduces-new-filter-synthesis-tool

[5] Microwaves101, "Vlad's Lumped Element Filter Designer", accessed 11.06.2017: https://www.microwaves101.com/encyclopedias/vlad-s-lumped-element-filter-designer

[6] Nuhertz, "FilterFree", accessed 12.06.2017: http://www.nuhertz.com/support/downloads

[7] Iowa Hills Software, "Smith Chart and Bilateral Matching", accessed 12.06.2017: http://iowahills.com/9SmithChartPage.html

[8] National Instruments, "TX-LINE: Transmission Line Calculator", accessed 10.06.2017: http://www.awrcorp.com/products/additional-products/tx-line-transmission-line-calculator