Low-Loss Wideband Bandpass Filters Using Semi-Distributed Unit Cells

Jakub Sorocki, Konrad Janisz, Ilona Piekarz, Slawomir Gruszczynski, Krzysztof Wincza
AGH University of Science and Technology
30-059 Krakow, Poland
jakub.sorocki@agh.edu.pl

***Abstract*— In this paper, a realization of low-loss wideband bandpass filters utilizing a periodic structure approach is presented. The recently developed novel semi-distributed composite right-left handed unit cell is considered and adopted for the design of the proposed filters. It is shown that an appropriate balancing of the structure, i.e. selection of circuit parameters allows for achieving very broad passband. Moreover, a suspended microstrip technique is utilized to reduce total insertion loss of the circuit. The presented approach has been confirmed by realization of an exemplary low-loss wideband bandpass filter. Measured operation band is within 1.0 – 9.4 GHz with total loss ranging between 0.35 to 1.8 dB. The obtained results proved the applicability of the presented approach.**

Keywords—balanced composite right/left handed unit cell; 3D printing; distributed elements; low-loss filter; wideband bandpass filter.

I. Introduction

Recently, left-handed metamaterial structures have gained interest of scientific community and variety of practical applications in microwave circuits have been proposed. Due to the fact, that homogeneous materials of left-handed properties do not exist in nature, an effectively homogeneous metamaterial structures composed of identical, electrically small unit cells are of interest. In [1]-[3] a composite right/left-handed (CRLH) unit cell (UC) operating in microwave frequency range has been proposed. Since such structures feature composite character, a broadband operation can be obtained by appropriate balancing of the left- and right-handed bands. Such feature might be, among others, useful for realization of wideband filters, which are required for many microwave applications. Various unit cell models and their application in the design of filters have been presented in literature, e.g. [1]-[7].

In this paper, a novel low-loss filter optimized for wideband bandpass operation designed using periodic structure approach is presented. Recently developed semi-distributed unit cell featuring composite right/left-handed character has been considered and adopted as a basic building block of the proposed circuit. It has been shown in [8] that such a unit cell can feature periodic, wide passband character with narrow stopbands. Here, we have focused our investigation on realization of one very wide continuous passband. Moreover, a suspended microstrip technique has been employed to reduce total insertion loss of the circuit. Such a feature allows for handling higher power signals extending circuits` potential range of applications. The performance of the presented filter has been theoretically investigated and experimentally verified. The obtained results have proven usefulness of the presented approach.

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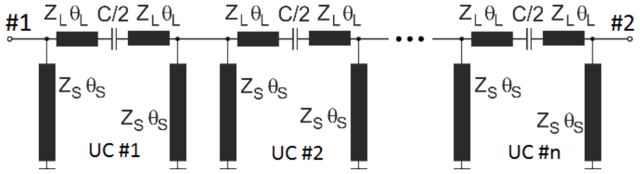


Fig. 1. Schematic diagram of the proposed wideband bandpass filter being a cascade connection of *n* identical semi-distributed-element unit cells (UC).

II. Analysis and Design of Filters` Unit Cell

A schematic diagram of the proposed filter being a cascade connection of *n* identical unit cells is presented in Fig. 1. As seen, each unit cell is semi-distributed one i.e., it is composed of sections of transmission line and lumped capacitor. Such an approach has been proposed for several reasons. First of all, it allows for insertion losses reduction which are mainly related to lumped elements (e.g. SMD components), especially for higher frequencies, in comparison to other circuits where all-lumped-elements or quasi-lumped-elements unit cells are used. Additionally, upper frequency limit of operation is dictated only by the used capacitor while in other cases is related to combination of all components properties. Secondly, the parasitic effects of lumped elements cannot be predicted and controlled in a rigorous manner while transmission line sections operation can be accurately modeled with no frequency limitation. Moreover, well known transmission line analysis can be applied for circuit performance prediction and modelling which is very important when such a unit cell is to be designed for application in a broadband circuits, e.g. wideband filters. Thus, transmission line parameters can be easily translated into physical dimensions with no need for parasitic elements extraction as in the case of other mode to physical structure translations. On the other hand, many of the proposed composite right/left-handed unit cells are modeled using series-C_L/shunt-L_L related to left-handed region of operation and series-L_R/shunt-C_R which relates to right-handed region of operation. In the presented case, transmission line sections realizing unit cells can accurately model impedance of real series inductance and shunt capacitance related to right-handed band, whereas a short-ended transmission line and series lumped capacitor model series capacitance, as well as shunt inductance of left-handed band. Exact analysis of circuit operation and design equations allowing for realization of balanced structure i.e., having continuous transition between left- and right-handed bands with no stopband have been provided in [8].

In this paper, we investigate the applicability of such unit cells for realization of wideband bandpass filters. The design approach has been reconsidered and numerical analysis using MATLAB has been employed for determination of circuit parameters. Lower f_L and upper f_H cut-off frequencies and pass band center frequency $f_0 = 0.5(f_H+f_L)$ as well as ideal impedance match to the system impedance $Z_0 = 50\ \Omega$ at f_0 are the design goals while electrical lengths θ_{0L} and θ_{0S} both defined at f_0, impedances Z_S and Z_L and capacitance C (see Fig. 1) are design parameters. Performance of the unit cell featuring different operational bandwidth $BW = f_H/f_L$ has been investigated as well as design parameters for each case have been calculated assuming center frequency of f_0 = 5.5 GHz and BW range of 4 to 12. Such an approach allows to verify the possibility of physical realization of bandpass filters featuring appropriate BW. Calculated data sets have been summarized in Table I and corresponding S-parameters of a single unit cell modeled using ideal elements are shown in Fig. 2.

TABLE I. BANDWIDTH OF THE UNIT CELL AND CORRESPONDING VALUES OF THE DESIGN PARAMETERS, F_0 = 5.5 GHZ

BW	θ_{0L}(deg)	θ_{0L}(deg)	Z_L (Ω)	Z_S (Ω)	C (pF)
4	13.51	95.46	142.6	62.9	1.11
5	16.38	95.10	104.6	81.7	1.41
6	17.78	94.54	89.3	99.2	1.69
7	18.62	94.04	80.6	117.0	1.99
8	19.11	93.66	75.6	132.9	2.25
9	19.51	93.45	71.4	152.1	2.57
10	19.79	93.15	68.6	169.3	2.87
11	19.99	92.73	66.5	186.0	3.15
12	20.11	92.55	65.1	200.2	3.39

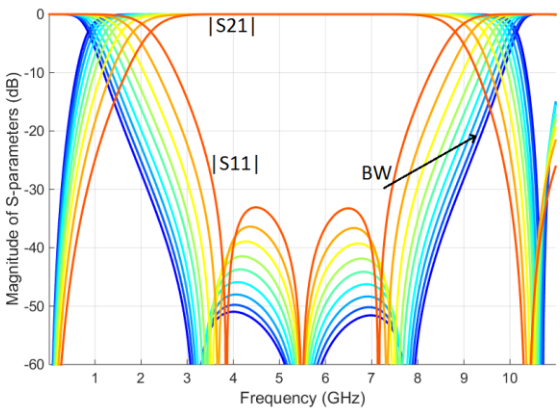
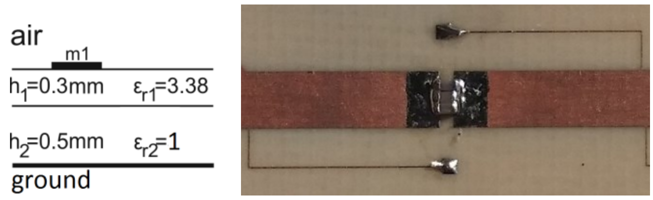


Fig. 2. Calculated frequency response of a single unit cell assuming different passband bandwidths and design parameters as listed in Table I.

In order to experimentally verify the performance of a filter composed of above presented unit cell, an exemplary circuit has been designed. As a building block, unit cell featuring $BW = 10$ where f_L = 1 GHz while f_H = 10 GHz has been used for which design parameters are listed in Table I. Knowing distributed elements' parameters, transmission lines geometry can be calculated and unit cell can be designed. For the circuit design, a suspended microstrip dielectric structure shown in Fig. 3a has been utilized. Such an approach allows for reducing total insertion loss in comparison to microstrip structure since most of the EM field propagates in lossless air. Layout of the physically realized semi-distributed unit cell has been shown in Fig. 3b where each constituting element i.e., series transmission lines in series with lumped SMD capacitor as well as shunt transmission lines can be easily distinguished. Three standard SMD 0402 capacitors, 0.5 pF each, have been used to realize $C/2$ = 1.44 pF and better distribute capacitance across width of the series transmission lines. Different C value in relation to assumed one enforce slight circuit tuning to maintain its performance. Overall size of the unit cell equals 18.36 x 6.65 mm, series transmission line width is w_l = 2.55 mm and shunt transmission line width w_s = 0.1 mm and length l_s = 10 mm not including via pad and via.



(a) (b)

Fig. 3. Cross-section of the utilized suspended microstrip structure where thin microwave laminate (h_1) is elevated (h_2) over the ground plane (a). Photograph of the physically realized semi-distributed unit cell (b).

III. UWB BANDPASS FILTER REALIZATION AND EXPERIMENTAL RESULTS

The presented semi-distributed unit cell has been used to design a low-loss bandpass filter. The filter has been composed of three cascaded unit cells to improve its selectivity i.e., to increase sharpness of attenuation slope as it can be seen in Fig. 4 where ideal elements' S-parameters calculated for such connection are presented. It has to be noted however, that f_H is slightly shifted downwards.

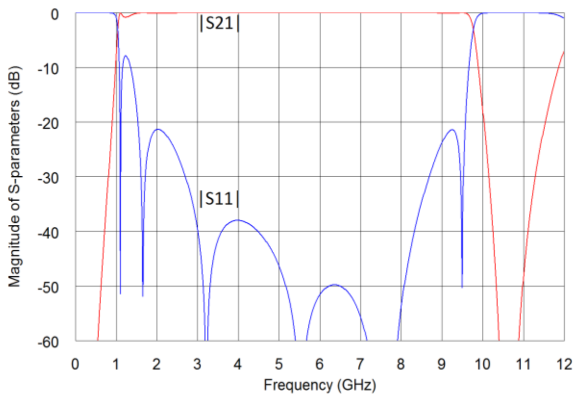


Fig. 4. Calculated frequency response of $n = 3$ cascaded ideal elements unit cells.

The designed filter has been manufactured and measured. Photograph of the realized circuit is presented in Fig. 5, whereas measured frequency response shown in Fig. 6. As seen the circuit features wideband bandpass characteristic with 3-dB cut-off frequencies at f_L = 1.0 and f_H = 9.4 GHz which is very close to predicted bandwidth and therefore is suitable for broadband applications. The discrepancy between theoretical and measured performance is mainly a result of parasitic elements and frequency limitation of the utilized SMD components as well as manufacturing accuracy. Next, measured attenuation slopes at both edges of passband are very sharp. For lower band edge, 30 dB attenuation is obtained within 0.42 GHz from the cut-off while for upper band edge 0.76 GHz from the cut-off. In order to further investigate performance of the realized filter, group delay as well as total loss have been determined and presented in Fig. 7 and Fig. 8, respectively. As it can be seen group delay introduced by the filter is relatively flat with mean value of 0.45 ns. Moreover, total loss within of the proposed filter including dielectric, conductor and radiation losses is between 0.35 to 1.8 dB over the entire passband.

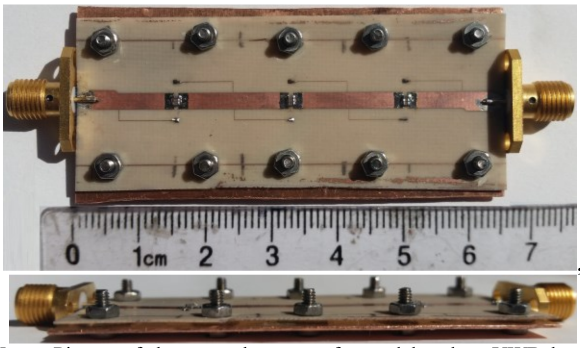


Fig. 5. Picture of the exemplary manufactured low-loss UWB bandpass filter composed of three unit cells. Overall size of the filter equals 55 x 6.65 mm excluding input transmission lines.

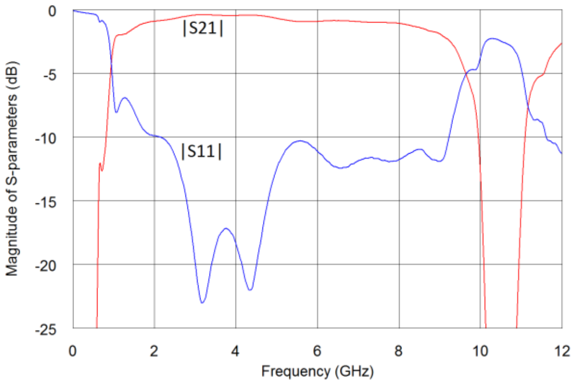


Fig. 6. Measured frequency response of the manufactured UWB filter: red– transmission, blue – reflection coefficient.

IV. Conclusion

Novel realization of low-loss wideband bandpass filter has been presented utilizing the periodic structure approach. The circuit utilizes recently developed semi-distributed unit cell optimized for broadband operation and allowing for simple physical realization. The presented theoretical analysis has been confirmed by realization of an exemplary low-loss bandpass filter in suspended microstrip technique. The obtained measurement results have proven the performance and applicability of the presented approach.

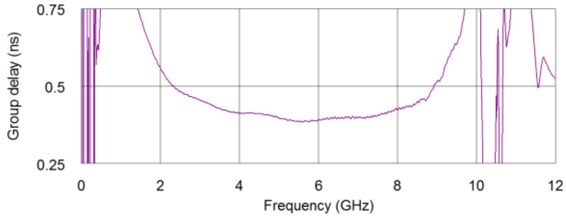


Fig. 7. Measured group delay of the manufactured UWB filter.

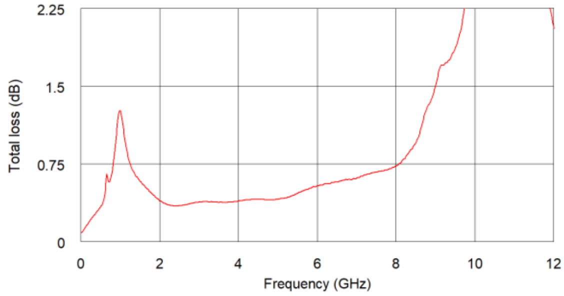


Fig. 8. Measured total loss of the manufactured UWB bandpass filter.

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