Low-Loss Pseudo-Highpass Filters Using Distributed-Element Unit Cells

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***Abstract*—In this letter, a novel wideband pseudo-highpass filter is presented. Wideband band-pass unit cells and periodic structure approach is utilized for realization of the filter. Low-losses and circuit properties` control are obtained by the realization of the unit cell using distributed elements only, i.e. transmission line stubs and a coupled-line section as well as the utilization of suspended stripline technique for circuit realization. Theoretical analysis of the unit cell as well as experimental results have been provided. An exemplary manufactured compact low-loss, four-unit-cell filter features 1 - 9 GHz wide fundamental passband with very sharp lower roll-off and minimal insertion losses of 0.24 dB. The obtained results have confirmed the performance of the proposed approach.**

Keywords*—broadand; distributed element unit cell; periodic structure; pseudo-highpass filter.

I. INTRODUCTION

Filters are one of the basic building blocks of any communication system. Analysis and design of such components are subjects of intensive studies of scientific and industrial communities resulting in many different approaches and realizations being proposed. Among others, a periodic structure approach utilizing cascaded, electrically small unit cells (UC) have been explored allowing to reduce filter design to the design of a single UC. In [1] – [10] different UCs have been proposed, including the ones featuring composite right/left-handed properties within microwave range. Very broadband passband response can be obtained in such structures by e.g. appropriate balancing of the left- and right-handed bands. From application perspective, such a feature can be used for realization of wideband filters required in e.g., UWB systems. UCs shown in [1] – [6] have been realized, mostly based on interdigital capacitors and shunt stubs, and analyzed using simplified, lumped elements based models which, however do not provide straightforward translation from model to physical realization. On the other hand, in [7] – [9] a different analysis approach is proposed e.g., in [7] the UCs based on series and shunt multiconductor transmission lines (TL) are presented, whereas in [8] – [10] the Authors have proposed UCs based on series or shunt, coupled or uncoupled TL sections and/or lumped capacitors. The UCs are modeled and design formulas are derived from the TL theory allowing for better understanding of circuits` behavior and direct relation between the model and physical structure.

In this paper, a novel broadband band-pass unit cell is proposed allowing to construct pseudo-highpass filters due to its very wide fundamental passband character with sharp lower roll-off and high fundamental stopband attenuation. The introduced UC is constructed of series coupled and shunt uncoupled TLs and modeled using solely transmission line models allowing for accurate prediction of circuit behavior within wide frequency range. Additionally, there is no need for wire bonds as in [7] or relatively lossy lumped elements as in [8] – [10]. The proposed UC has been theoretically analyzed and appropriate relation between design variables and design goals have been provided. An exemplary filter has been designed, manufactured and measured to experimentally verify the circuit performance. A suspended stripline technique has been used to further reduce insertion losses which make the filter more suitable for handling high power signals.

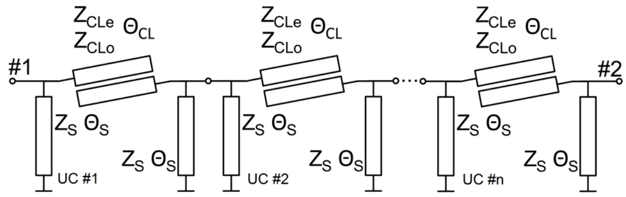


Fig. 1. Schematic diagram of the proposed pseudo-highpass filter realized as a cascade connection of *n* identical UCs composed of a coupled-line section and TL shorted stubs.

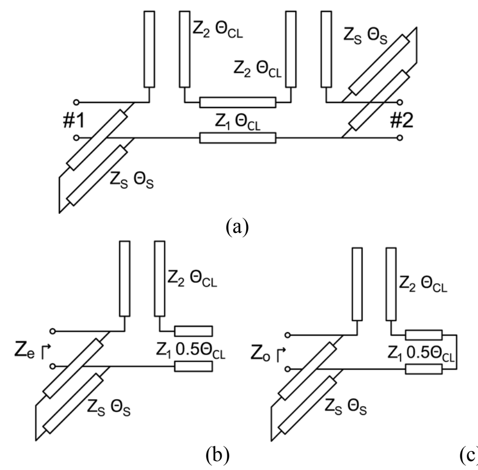


Fig. 2. Two-wire TL model of the proposed UC allowing for its analysis (a). Decomposition into even-mode (b) and odd-mode (c) sub-circuits.

II. Analysis and Design of the Unit Cell

The proposed pseudo-highpass filter is composed of cascaded n identical unit cells as presented in Fig. 1. To investigate the properties and performance of such a filter, a single UC shown in Fig. 2a needs to be analyzed. The UC can be represented as a network composed of open- and short-ended two-wire TL sections as shown in Fig. 2b and 2c respectively. As it can be seen, the circuit features one symmetry axis and therefore can be analyzed using even-/odd-mode excitation method similarly as in [8], [9]. Having calculated input impedances Z_e and Z_o, one can determine UC characteristic impedance Z_B and propagation constant γp [11]:

$$Z_B = \sqrt{-Im(Ze)Im(Zo)} \tag{1}$$

$$\gamma p = arccosh\left(\frac{Z_e+Z_o}{Z_e-Z_o}\right) \tag{2}$$

Moreover, S-parameters of the unit cell are:

$$S_{11} = S_{22} = 0.5\left\{\frac{Z_e-Z_0}{Z_e+Z_0}+\frac{Z_o-Z_0}{Z_o+Z_0}\right\} \tag{3a}$$

$$S_{21} = S_{12} = 0.5\left\{\frac{Z_e-Z_0}{Z_e+Z_0}-\frac{Z_o-Z_0}{Z_o+Z_0}\right\} \tag{3b}$$

where Z_0 is the system impedance. Using formulas (1) - (3), one can find relationship allowing to calculate values of design variables Z_S, θ_{0S}, Z_{CLe}, Z_{CLo}, θ_{0CL} for desired filter parameters, i.e. cut-off frequencies, hence bandwidth $BW = f_H/f_L$ of the fundamental passband and impedance match to Z_B. Since the determination of analytical design equation is hardly possible due to inherent trigonometric functions, a numerical approach has been applied. MATLAB software has been employed to solve nonlinear system of equations allowing to find circuit parameters. It has to be underlined that depending on the application, one can find design variables providing optimized performance of fundamental passband only or higher order passbands as well by appropriate selection of numerical solver`s goals.

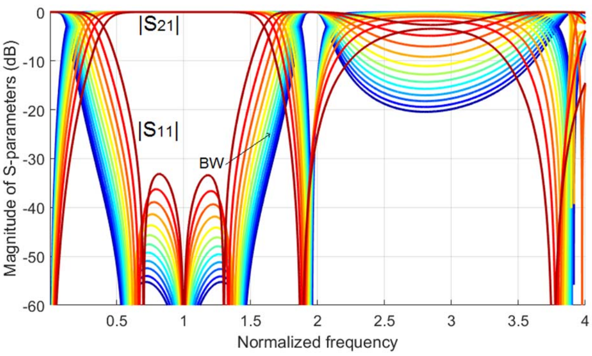


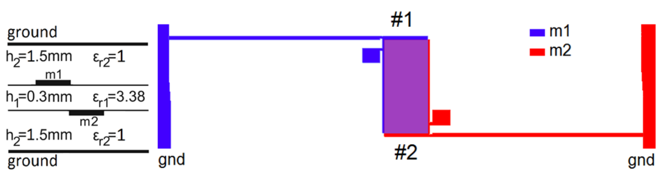
Fig. 3. Calculated S-parameters of a single UC shown in Fig. 2a for a given set of circuit variables listed in Table I resulting in different fundamental passband bandwidths.

To assess the performance of the proposed UC, sets of circuit parameters have been found for BW of fundamental passband ranging from 15 to 5, assuming Z_B = 50 Ω and zeroes of S_{11} @ {f_0, 0.5(f_L + f_0), 0.5(f_0 + f_H)} since three zeroes in reflection coefficient can be realized by a single UC. Such an approach allows also to verify whether unit cell with appropriate transfer function can be physically realized in a selected technique. Calculated data sets have been summarized in Table I while corresponding S-parameters are shown in Fig. 3. As it can be seen, the proposed UC can be physically realized for a wide range of fundamental, pseud-highpass bandwidths. Moreover, width of the stopband between fundamental and second order passband depends on the selected BW and when this parameter is of importance, it is a tradeoff between UC physical realizability and the design goals. Similar behavior was observed in [9] and [10] where in order to realize very broad fundamental passband, relatively narrow fundamental left- and right-handed passbands and second order left-handed passband are merged together. As a result passbands` periodicity is distorted leading to narrow second-order stopband and closely spaced second-order pass band.

TABLE I
Fundamental Passband Bandwidth of the Proposed Unit Cell and Corresponding Design Variables Values, Z_B = 50 Ω

BW	Z_{CLe} (Ω)	Z_{CLo} (Ω)	θ_{0L}(deg)	Z_S (Ω)	θ_{0S} (deg)
14.9	119.8	4.63	40.4	250.3	92.0
12.9	123.7	5.26	39.9	216.9	92.3
11.0	129.3	6.07	39.1	184.1	92.7
9.0	138.3	7.15	38.0	151.1	93.3
7.0	155.3	8.68	36.1	117.3	94.0
5.0	202.1	10.76	31.7	81.7	95.1

In order to experimentally verify performance of the proposed filter realized as a cascade connection of the presented UCs, an exemplary UC has been designed. The circuit has been realized in a dielectric structure presented in Fig. 4a. The suspended stripline technique has been utilized to further reduce total losses of the filter. As a building block, UC featuring BW = 9 with center frequency f_0 = 5 GHz has been used (values of design variables as listed in Table I). Knowing the distributed elements' parameters, TL geometry has been determined, what allows for realization of the unit cell. Layout of the designed UC has been shown in Fig. 4b, where each constituting element i.e., the series coupled-line section and the shunt short-ended TL can be easily distinguished.



(a)

(b)

Fig. 4. Cross-section of the utilized suspended stripline structure where thin Arlon 25N microwave laminate (h_1) is suspended in-between ground planes (h_2) (a). Layout of the designed distributed elements UC (b). Total area of the UC equals 5.45 x 26.65 mm.

It has to be noted, that in the physical realization, connection between TL sections as well as open ends of coupled-line sections introduce parasitic effects. Moreover, due to the utilized dielectric structure, the inductive and capacitive coupling coefficients of the coupled-line section are unequal what negatively influences its performance. The above presented deteriorative effects have been compensated using appropriately placed small capacitors (see Fig. 4b near connection between shunt and series TL) and by slight circuit tuning.

III. Pseudo-Highpass Filter Design and Experimental Results

In the next step, n number of the designed UCs is cascaded to realize the filter complying to the assumed frequency response constraints. Exemplary frequency responses of the filter composed of n = 1 and n = 4 ideal element unit cells have been presented in Fig. 5. As seen, the attenuation roll-off at passbands edges is almost four times steeper for the latter case, however at the expense of four times longer circuit. It is also seen, that the upper cut-off frequency is slightly shifted downwards for $n > 1$.

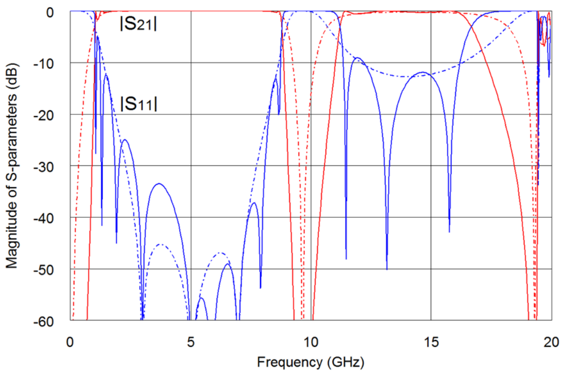
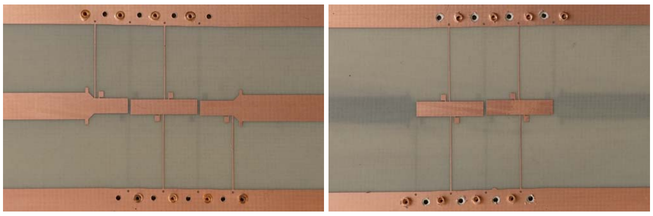


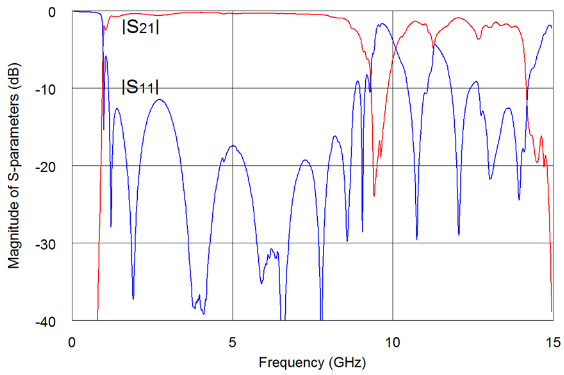
Fig. 5. Calculated frequency response of the filter being a connection of n = 1 (dashed lines) and n = 4 (solid lines) ideal UCs.

The designed filter composed of n = 4 UCs has been manufactured and measured. Thin middle laminate is hosted in a simple two-part metal housing providing structural support and appropriate thickness of air layers h_2. A photograph of the realized circuit is presented in Fig. 6, whereas the measured frequency response is shown in Fig. 7. Circuit has been measured using Agilent 5224A Vector Networ Analyser and additional de-embedded of input 50 Ω transmission lines has been done prior measurements. As it can be seen, the manufactured filter provides useful pseudo-highpass characteristic within very broad frequency range. It is worth underlining that sharp lower band slope and high attenuation within fundamental stopband have been obtained. Moreover, the second passband and narrow stopband between first and second passbands are clearly visible. The fundamental passband is within the assumed BW with impedance match better than 10 dB. The measured minimal group delay introduced by the filter equals 0.25 ns and does not exceed 0.5 ns within 2 – 8.37 GHz band. Moreover, S_{21} insertion loss is below 0.6 dB within 1.5 – 8 GHz band while the total measured insertion loss does not exceed 1 dB within 1.5 – 7.5 GHz band. The observed performance deterioration within higher frequencies range may be caused by additional parasitic effects and manufacturing tolerances; however, it appears in the second passband and above, and does not influence significantly the fundamental passband which is of primary interest. Performance of the proposed filter has been compared with other designs and summarized in Table II. As it can be seen, the proposed filter provides much wider useful fundamental passband as in [2], [5], [7] as well as sharper lower roll-off. Moreover, insertion loss is reduced more than two times compared to [9].

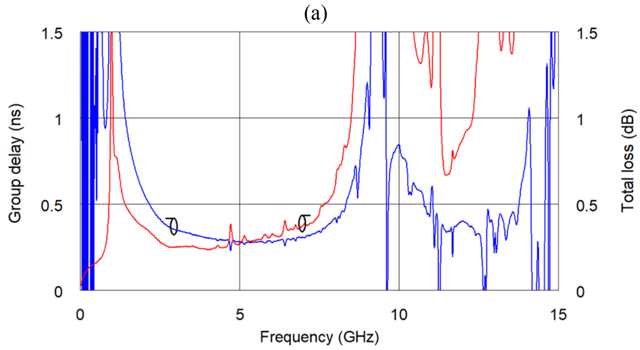


(a) (b)

Fig. 6. Photographs of the manufactured low-loss pseudo-highpass filter being a cascade of four unit cells realized in suspended stripline. Metal m_1 layer on which input and output transmission lines are realized (a) and metal m_2 (b).



(a)



(b)

Fig. 7. Measured magnitude of S-parameters of the manufactured exemplary filter (a) and calculated responding group delay and total loss (b).

TABLE II
Performance Comparison of Different Filters Realizations

	n	techn	char	BW (GHz)	roll-off (dB/GHz)	RL (dB)	IL (dB)
[2]	2	µs	BP	2.5 – 5.2	*~34 / 40	> 12	NA
[5]	7	µs+DGS	BP	2.9 – 15.7	*~15 / 10	> 12	~ 1
[7]	1	µs	BP	2 - 5	80 / 52	> 13	> 0.6

[9]	3	μs	PHP	0.4 – 4.5	311	> 6	> 0.4
#	4	susp sl	PHP	1 – 9.2	213	> 10	> 0.2

this paper; **techn**ique: μs – microstrip, sl – strip line; **char**acteristics: BP – bandpass, PHP – pseudo highpass; roll-off slope: defined between 3 and 23 dB rejection frequency points, given for lower / upper cut-off of fundamental band; IL & RL: insertion and return losses; *not specified directly.

IV. Conclusion

A novel distributed-element UC composed of series coupled-line section and shunt end-shorted TLs has been proposed. It has been shown, that such a cell together with periodic structure approach is suitable for realization of broadband pseudo-highpass filters. Moreover, selectivity of the filter can be controlled by the number of cascaded UCs. To assess the performance of the proposed UC, sets of circuit parameters have been found for BW ranging from 15 to 5. The performance and applicability of the presented approach have been confirmed by measurements of an exemplary low-loss pseudo-highpass filter composed of n = 4 UCs realized in suspended stripline technique.

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