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Systematic Design of Wideband Bandpass Filters Based on Short-Circuited Stubs and $\lambda/2$ Transmission Lines

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***Abstract*—In this paper, a new technique to design wideband bandpass filters BPFs is proposed. It is based on the classical filter topology formed by shunt short-circuited stubs connected by transmission lines, where the $\lambda/4$ connecting lines are replaced by $\lambda/2$ lines. In this way, the connecting lines have a double functionality: to control the coupling between resonators and to add additional poles, increasing the filter order up to $2N-1$, where N is the number of short-circuited stubs. In addition, their function as inverters is, theoretically, for all spectrum, avoiding the limitation of the $\lambda/4$ lines working as inverters or the coupled-line coupling mechanisms of classical configurations, which are of narrowband nature. Design equations are provided with up to N degrees of freedom, which allows for a proper selection of impedance values for the filter design. As a verification, a 5th-order BPF of fractional bandwidth 50% centered at 2.5 GHz and with a Chebyshev response is implemented, fullfiling the expections and validating, in this way, the proposed approach.**

***Index Terms*—bandpass filter (BPF), microstrip, resonator, short-circuited stub, wideband, transmission zero.**

I. Introduction

BANDPASS filters (BPFs) are an essential component in any microwave system, since they allow the signals of the band of interest to pass through while rejecting others coming from external systems which can interfere degrading the system's performance, but also rejecting those produced by the active parts of the system itself (i.e., harmonics and intermodulation products). In addition, they also reduce the noise of the system, increasing its dynamic range, and therefore, its performance. BPFs can be implemented in different technologies, such as rectangular and circular waveguide, planar technology, coaxial, and the recent substrate integrated waveguide SIW. When size is a constraint and the power signal requirements are not high, microstrip technology is, without a doubt, one of the preferred technologies due to its low cost and easy integration with other components, which allows for the integration of the whole transceiver in the same board. The design of narrowband BPFs has been widely addressed in the literature, and the synthesis process is, regardless the technology, very well established [1]–[3]. For the design of wideband and ultra-wideband BPFs (let us say, those filters with fractional bandwidths FBWs higher than 20%), the narrowband design approaches start failing, mainly due to the narrowband nature of the elements used in the implementation of the topologies: $\lambda/4$ lines acting as inverters, coupling dispersion between resonators in coupled-line configurations, etc. In this regard, one can see that different approaches have been addressed in the last years for the design of wideband BPFs, such as the use of multiple mode resonators MMRs (with a big number of configurations and variations: stepped impedance, stub loaded, ring, etc) [4]–[7], multilayered structures to get broadside —and consequently, strong— couplings [8]–[11] or signal interference techniques [12]–[17]. All these approaches although presenting very interesting features, as transmission zeros TZs generation for the case of signal interference techniques, ultimately depend on the particularities of the topology, and consequently, their filter order and filter characteristics are normally predefined.

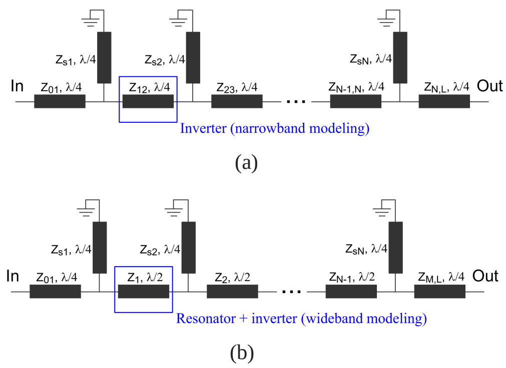

Fig. 1. (a) Conventional BPF topology. (b) Proposed topology for the systematic design of wideband BPFs.

In this paper, a modification of the classical filter configuration formed by shunt short-circuited stubs connected by means of $\lambda/4$ transmission line inverters, is performed (see Fig. 1). This modification consists of the replacement of the $\lambda/4$ transmission lines by $\lambda/2$ lines. Now, in this arrangement, the $\lambda/2$ connecting lines do not only control the coupling between resonators, but they also add a pole per each line, increasing in this way the order for the same number of elements up to $2N-1$, where N is the number of short-circuited stubs. In addition, as will be shown, the coupling between resonators is controlled without any dispersion or bandwidth limitation, which allows for the development of a systematic methodology for the design of wideband BPFs. This approach is different from that of [18] where a similar configuration is used but from a high-pass filter design perspective. For validation purposes, a 5th-order BPF with a Chebyshev response and centered at 2.5 GHz with a fractional bandwidth of 50% is implemented and has successfuly proved the effectiveness of the proposed

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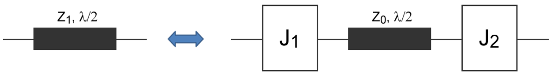

Fig. 2. Equivalent circuit for an arbitrary transmission line.

methodology for the design of wideband BPFs.

II. Proposed Synthesis Method

Fig. 1(a) shows the scheme of a conventional topology to design wideband BPFs [1], [2], based on shunt short-circuited stubs with characteristic impedances Z_{si} connected by transmission lines of impedance $Z_{i,i+1}$, where all elements measure $\lambda/4$ at the design frequency and the number N of shunt stubs define the filter order. The short-circuited stubs work as resonators whereas the connecting transmission lines as inverters. This topology can be appropriate for the design of BPFs with relatively large bandwidths, but, ultimately, its maximum bandwidth is limited by the narrowband nature of the $\lambda/4$ connecting lines working as inverters. Fig. 1(b) shows the proposed configuration in this paper to carry out the wideband BPF synthesis method. It is also formed by shunt short-circuited stubs, but the $\lambda/4$ transmission lines are replaced by $\lambda/2$ connecting lines. These lines have now a double functionality, they work as inverters controlling the coupling between resonators, and they also work as resonators, increasing, in this way, the order of the filter up to $2N-1$. In addition, their function as inverters is wideband (a priori, for all spectrum), which allows for the synthesis of wideband and ultra-wideband BPFs from a systematic filter design method.

A. Modeling the connecting $\lambda/2$ transmission line

Fig. 2 shows the equivalent model for a $\lambda/2$ transmission line of arbitrary impedance Z_1. The equivalent circuit is formed by a $\lambda/2$ transmission line with characteristic impedance Z_0 connected at its two ends to two admittance inverters, with inverter values J_1 and J_2, respectively. If the ABCD parameters are computed for both the line and the equivalent model, one can easily see that both circuits are exactly equivalent if the following condition is met:

$$Z_1 = \frac{1}{Z_0 \cdot J_1 \cdot J_2} \tag{1}$$

and $J_1 \approx J_2$. This equivalence is, a priori and theoretically, for all frequencies, thus, the coupling dispersion phenomenon which usually happens for coupling configurations based on $\lambda/4$ line inverters or on coupled-line mechanisms is fully avoided. It is also worth mentioning that the condition $J_1 \approx J_2$ can be obtained even though the coupling levels between each pair of resonators are not the same (as usually happens), if proper susceptance values are used for each stub.

B. Modeling the input/output line inverters

In the proposed filter topology of Fig. 1(b), all elements have a wideband behaviour (from a synthesis point of view) except for the input/output inverter lines, which are still $\lambda/4$ lines. However, a strategy can be tackled to increase the operational bandwidth of these end lines. The input admittance of the filter at its ends (inverter line + source/load) can be computed and approximated by using a Series Taylor expansion of first-order around ω_0, obtaining

$$Y_{in} = \frac{Y_{01}^2}{Y_L} + j\frac{\pi Y_{01}}{2\omega_0}\left[1 - \left(\frac{Y_{01}}{Y_L}\right)^2\right] \cdot (\omega - \omega_0) \tag{2a}$$

$$Y_{in} = \frac{Y_{01}^2}{Y_L} + jB_{\text{inv,eq}}(\omega) \tag{2b}$$

where Y_L is the source/load admittance and is typically Y_0, and ω is the angular frequency. If we inspect (2a), the $\lambda/4$ end line is equivalent to a pure admittance inverter with $J_{01} = Y_{01}$ connected to a susceptance $B_{\text{inv,eq}}$. The latter can be absorbed by the first/last short-circuited stub of the filter configuration in a similar fashion as in [19], thus, increasing in this way the operation bandwidth of the $\lambda/4$ end lines working as inverters.

C. Synthesis Equations

Next, the synthesis equations for the design of wideband BPFs from a systematic methodology are found. The proposed circuit of Fig. 1(b) can be redrawn by using the equivalent circuits previously discussed to be seen as in Fig. 3(a). This circuit can be mapped into the LPF prototype of Fig. 3(b) of order $M = 2N - 1$, where C_i's are, initially, arbitrary capacitor elements, and the inverters are frequency-invariant whose parameters are [1], [2]

$$J_{01} = \sqrt{\frac{Y_0 C_1}{g_0 g_1}},\ J_{i,i+1} = \sqrt{\frac{C_i C_{i+1}}{g_i g_{i+1}}} \text{ and } J_{\text{ML}} = \sqrt{\frac{Y_0 C_M}{g_M g_{M+1}}} \tag{3}$$

where g_i's are the LPF prototype elements. Now, if we perform a direct mapping between both circuits of Fig. 3 at $\Omega = 0 \rightarrow \omega_0$ and at $\Omega_1 \rightarrow \omega_1$, where Ω is the angular frequency of the LPF prototype, we get the following set of synthesis equations:

- For the short-circuited stub j ($j = 2, 3, \ldots$ to $N-1$), its characteristic admittance is

$$Y_{sj} = -\Omega_1 \cdot C_i \cdot \tan\left(\frac{\pi}{2}\frac{\omega_1}{\omega_0}\right) \tag{4}$$

  where Ω_1 is the cut-off frequency of the LPF prototype, and C_i ($i = 3, 5, \ldots$ to $M-2$).
- For the first and last short-circuited stubs ($j = 1, N$),

$$Y_{sj} = -\left(\Omega_1 \cdot C_i - B_{\text{inv,eq}}(\omega = \omega_1)\right) \cdot \tan\left(\frac{\pi}{2}\frac{\omega_1}{\omega_0}\right) \tag{5}$$

  where C_i ($i = 1, M$) maps to the stubs $j = 1, N$.
- For the connecting lines, Z_k ($k = 1, 2, \ldots$ to $N-1$),

$$Z_k = \frac{1}{Z_0 \cdot J_{2k-1,2k} \cdot J_{2k,2k+1}}. \tag{6}$$

- And finally, whereas C_i ($i = 1,\ 3,\ \ldots$ to M) are free parameters, the C_i ($i = 2,\ 4,\ \ldots$ to $M-1$) are fixed and equal to

$$C_i = \pm\frac{\pi}{\Omega_1 Z_0} \cdot \text{FBW} \tag{7}$$

  which comes from approximating the input admittance of the $\lambda/2$ transmission line by the first two terms of a Series Taylor expansion and mapping them to the corresponding capacitor susceptance of the LPF prototype.

With this set of design equations, the synthesis of a wideband or even ultra-wideband BPF can be performed, where

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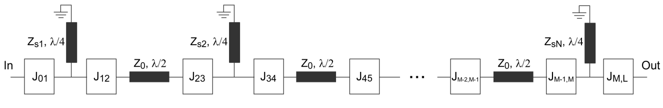
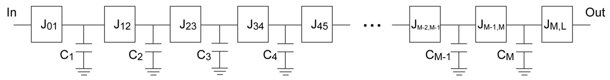


(a)

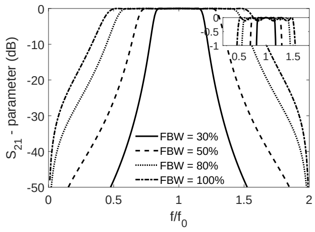


(b)

Fig. 3. (a) Equivalent circuit of the proposed filter configuration. (b) LPF prototype

FBW	$Z_{01}=Z_{5L}$	$Z_{s1}=Z_{s3}$, Z_{s2}	$Z_1=Z_2$
30	53	18, 10	158
50	53	33, 17	100
80	53	59, 35	67
100	53	84, 56	58

(a)



(b)

Fig. 4. Design examples. (a) Transmission line impedance values. (b) S_{21}-parameter.

coupling dispersion is not a limiting factor, and with sufficient degrees of freedom (N for a filter of order $M = 2N - 1$) to obtain feasible impedance values both for the stubs and the $\lambda/2$ connecting lines.

D. Design examples

To demonstrate the potential and validity of the proposed design methodology, four 5th-order BPFs with 0.01 dB-ripple Chebyshev response, and with FBWs ranging from 30% to 100% are designed. The filter topology has, therefore, $M = 5$ and $N = 3$, and is, consequently, formed by three short-circuited stubs, two $\lambda/2$ connecting lines and two $\lambda/4$ inverter lines. By using the equations (3) to (7), and letting $\Omega_1 = \pm 1$ for $\omega_1 = \omega_0 \cdot (1 \pm \mathrm{FBW}/2)$ (where either of the signs leads to the same solution), we still have three free parameters (C_1, C_3 and C_5), which we can be adjusted for convenience (in these examples, $C_1 = C_5 = 0.0135$ for all examples, whereas C_3 is varied between 0.018 and 0.027). In Fig. 4(a) the design values are given for the four filter examples whereas their corresponding filter responses are shown in Fig. 4(b). From this figure, it can be seen that the design method works well even for FBWs as wide as 100% (3-dB bandwidth around 115%), where no bandwidth contraction is observed and just a slight increase of the in-band ripple value is noticed.

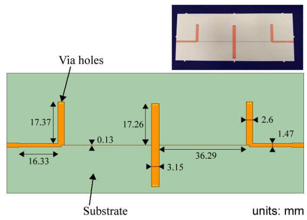
III. Experimental Validation

In order to validate the proposed methodology for the design of wideband BPFs, a 5th-order BPF with a 20 dB-ripple Chebyshev response centered at $f_0 = 2.5$ GHz and with FBW $= 50\%$ is designed and implemented on Rogers substrate RO4003C ($\epsilon_r = 3.55$, substrate thickness $h = 0.813$ mm, metal thickness $t = 18$ μm and loss tangent $\tan\delta = 0.0027$). With the following values $C_1 = C_5 = 0.0135$ and $C_3 = 0.023$ we obtain the design impedances: $Z_{01} = Z_{5L} = 60$ Ω, $Z_{s1} = Z_{s3} = 36$ Ω, $Z_{s2} = 17$ Ω and $Z_1 = Z_2 = 131$ Ω, which can be implemented by using standard PCB prototyping

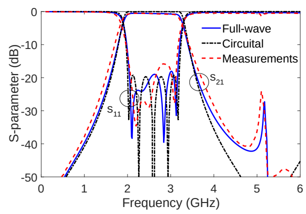
TABLE I
Comparison with other Wideband BPFs

Ref.	Technology	Design Procedure	Adjustable Order	Design Bandwidth Range	TZ
[4]	Single layer	MMR	No	~ 60-120%	Yes
[5]	Single layer	MMR	No	~ 50-80%	Yes
[8]	Multilayer	CL-BC	Yes	~ 70-120%	Yes
[13]	Single layer	SIT	No	~ 20-50%	Yes
[14]	Single layer	SIT-CL	No	~ 70-120%	Yes
[16]	Single layer	SIT-CL	No	~ 50-120%	Yes
This work	Single layer	Stubs - TLines	Yes	~ 30-120%	Yes

MMR: Multiple Mode Resonator; CL: Coupled-Line; BC: Broadside Coupling; SIT: Signal-Interference Techniques



(a)



(b)

Fig. 5. (a) Layout. (b) Circuital, full-wave simulated and measured responses.

techniques. Please note that C_1 is made equal to C_5 in order to obtain a symmetrical topology.

The filter layout is plotted in Fig. 5(a). It should be noticed that in order to implement the 17-Ω short-circuited stubs, two 34-Ω stubs have been arranged in parallel. Please also note that no attempts to miniaturize has been made since the goal is to demonstrate the concept. Fig. 5(b) shows the circuital simulation along with the full-wave simulated and measured responses, where a good agreement can be observed among all of them, validating, in this way, the proposed approach. The full-wave simulated and measured in-band return loss are higher than 18 and 16 dB, respectively, whereas the simulated and measured insertion loss is 0.5 dB at the center frequency. The filter presents deep rejection levels at both sides of the passband. In this regard, the three short-circuited stubs are creating 3 TZs at $2f_0$, whereas the two $\lambda/2$ connecting lines are generating 2 transmission poles at the same frequency, leading to one net TZ. This is reflected in the measured response with a peak around $2f_0$, which is, anyway, lower than 25 dB, and whose corresponding losses are essentially dissipative (no radiation is observed). Table I shows a comparison among different topologies and approaches to design wideband BPFs. The proposed method in this paper stands out for its very wide bandwidth design range and design systematic methodology, as a difference from other approaches where the filter characteristics (order, ripple...) are normally pre-established by the particularities of the topology.

IV. Conclusions

A new systematic technique to design wideband BPFs has been suggested in this paper. The filter configuration is based on shunt short-circuited stubs connected by means of $\lambda/2$ transmission lines. These lines provide a wideband modeling of the coupling between the short-circuited stubs and add a pole per each line, increasing the filter order up to $2N - 1$, where N is the number of stubs. A systematic design methodology has been provided with up to N degrees of freedom. The proposed approach has been verified by means of the implementation of a 5th-order filter with a bandwidth of 50% and centered at 2.5 GHz, which has shown a good agreement with the circuital and full-wave simulated responses.

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