Electromagnetic Modeling in Combination with Wave Digital Approach for Efficient Analysis of Microstrip Bandpass Filters with a Dual-Passband Response

Biljana P. Stošić and Nebojša S. Dončov

Abstract – **In this paper, an efficient technique, combining an electromagnetic (EM) modeling with a wave digital approach, is used for analysis of a 2.4/5.2 GHz dual-band microstrip bandpass filter (BPF). The studied BPF with dual passbands is composed of two parallel coupled microstrip lines and stepped-impedance-resonator. Step in width discontinuities and coupled-line sections, present in this filter layout, make analysis of this filter computationally very demanding and run-time consuming if only EM modeling is used. The described technique first uses a full-wave EM approach to generate equivalent circuit parameters of mentioned discontinuities from its S-parameters. The wave digital models of the equivalent circuits are then developed and incorporated into an equivalent wave digital network efficiently representing the complete microstrip structure. Three cases of BPF with different parallel coupled line dimension (varied dual-passband widths), are considered here in order to validate the presented combined wave digital/EM technique.**

Keywords – **Bandpass filter, dual-passbands, wave digital approach, electromagnetic modeling.**

I. Introduction

Nowadays, the trend is to take advantage of the accessible and powerful full-wave electromagnetic (EM) simulators, which can provide numerical calculation of the structure characteristics. The circuit designers use these EM modeling tools to simulate and test their designs before major expenses are committed to circuit construction and experimental verification. The numerical calculation of the structure characteristics must be fast and of high accuracy because the realistic and real-time simulations are essential for proper and timely design.

Filters are important and essential components in modern wireless and mobile communication systems for several decades [1-3]. In a case of microstrip circuit design one can commonly encounter many different types of discontinuities in the filter topology such as steps, open-ends, and gaps [4]. Conventional modeling of discontinuities by full-wave numerical techniques, especially differential ones based on space and time discretization, can be computationally very demanding and time-consuming. It usually requires a very fine numerical mesh to accurately describe EM field distribution around discontinuities and calculate the real characteristics of the complete circuit. Therefore, efficient discontinuity representation in the form of equivalent circuit suitable to be easily integrated into the otherwise coarse numerical mesh is of key importance for accurate and fast circuit simulation by full-wave EM modeling tools.

In recent years a wave digital approach has become a useful tool for efficient modeling and analysis of different physical systems. The entry point, for any study of numerical methods based on wave and scattering ideas, must necessarily be a review of wave digital filters (WDFs) [5-6]. The term "Wave digital filters" was first reported in the early 1970s by A. Fettweis [5]. He proposed a class of digital filters of particular interest. Some numerical simulation techniques, as well as WDF theory are listed in [7-8].

A novel technique combining one-dimensional wave digital approach [8] with an equivalent discontinuity model, obtained from a full-wave EM tool, has been presented in [9-11] to accurately and efficiently describe microstrip structures with different discontinuities but only of one type. In the proposed technique, the presence of discontinuity has been described by appropriate equivalent circuit, derived from scattering matrix calculated by full-wave EM modeling. These equivalent circuits are then represented by their corresponding wave digital models in order to be further incorporated into an equivalent wave digital network (WDN) used to model the complete structure with considered discontinuity. This combined approach has showed a great potential in terms of computing time compared to the full-wave EM modeling of complete circuits and in terms of accuracy compared to existing discontinuity closed-form expressions formulations. Also, WDF concept, consisting of network with the wave digital elements such as unit delay elements and adaptors, is therefore very suitable for easy and efficient integration of equivalent circuits of discontinuities. In addition, as it deals with signal flow graphs, it is much closer to the software implementation of the considered EM problem model compared to some classical full-wave EM modeling techniques.

The efficient modeling and analysis of different types of microstrip filters (low-pass and band-pass) with step discontinuities have been done in [9-10]. An equivalent circuit is generated in the form of lossless transmission line capable to account for different line width ratio cases for which errors, when existing closed-form expressions are used [12], are more then 10%.

The conventional design method of the parallel-coupled bandpass filter (BPF) that uses several quarter-wavelength ($\lambda/4$) coupled-line sections was well documented in [1]. The parallel-coupled BPF consisting of series of half-wavelength line resonators that are positioned so that

Biljana P. Stošić and Nebojša S. Dončov are with University of Niš, Faculty of Electronic Engineering, Department of Telecommunications, Aleksandra Medvedeva 14, P.O. Box 73, 18000 Niš, Serbia, E-mails: biljana.stosic@elfak.ni.ac.rs, nebojsa.doncov@elfak.ni.ac.rs.

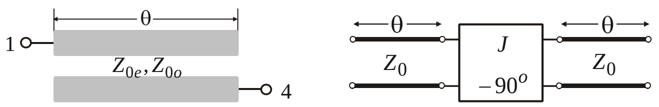
adjacent resonators are parallel to each other along one-half of their lengths has been considered in [13]. Equivalent circuits of these gaps are represented in the form of admittance (J)-inverters and half-wavelength resonators. Admittance inverters ($J, -90^{o}$) are used to transform a filter layout into an equivalent circuit which is modeled and analyzed by use of wave digital approach. The resulting wave digital network is represented as a cascade connection of frequency-independent two-port network model of admittance inverter based on parallel adaptor network and frequency-dependent two-port unit elements.

This paper presents the application of combined EM modeling/wave digital filter technique for an efficient analysis of a dual-band microstrip BPF whose design is presented in [15]. A 2.4/5.2 GHz dual-band microstrip BPF is composed of two parallel coupled microstrip lines (PCML) and one stepped-impedance-resonator (SIR), so in its layout it has two different types of discontinuities: step discontinuity and gap discontinuity. Each discontinuity type is represented by its corresponding wave digital model as described in [9] and [11], respectively. Three cases of BPF with different parallel coupled line dimension (varied dual-passband widths), are considered here in order to validate the presented technique.

II. Modeling Approach for Dual-band BPF

A. PCML Model

In order to model coupled-line sections, an equivalent circuit described in [11], is used. According to this, a single coupled-line section from Fig. 1*a* is approximately modeled by the equivalent circuit consisting of one J-inverter and two $\lambda/4$ resonators shown in Fig. 1*b*. It is done by calculating the *ABCD* matrix of the coupled-line section and showing that it is equal to the *ABCD* matrix of the equivalent circuit for electrical length $\theta = \pi/2$.



(a) (b)

Fig. 1. (a) A single coupled-line section (two coupled $\lambda/4$ open lines), (b) Equivalent circuit of the coupled line section

The admittance inverter constant J is determined by

$$J = \frac{Y_0}{2} \cdot (Z_{0e} - Z_{0o}), \quad (1)$$

where Z_{0e} and Z_{0o} are even- and odd-mode characteristic impedances of a single coupled-line section of electrical length θ, and Y_0 is its characteristic admittance.

Synthesis of wave digital network model of admittance inverter with characteristic impedance $1/J$ that transforms its load admittance by -90° is described in [13]. Obtained model, based on two-port parallel adaptor network, allows for an easy integration into equivalent wave digital network.

Wave digital networks of admittance inverters that transfor their load admittances J by $+90^{\circ}$ assigned as (J,$+90^{o}$) and by -90° assigned as (J,-90^{o}), are described in details and developed in [14] based on scattering parameter formalism and two-port networks of parallel or series adaptors.

B. Dual-band BPF Model

Development of an equivalent wave digital model of a dual-band BPF from [15] is shown in Fig. 2. Fig. 2*a* shows the physical layout of the studied BPF with dual passbands composed of two PCMLs and one SIR. A network representation with several cascaded two-port subnetworks of half a symmetrical structure is shown in Fig. 2*b*. The next step in development of an equivalence is to replace each PCML (Fig. 1*a*), assigned as $C-line$ in Fig. 2*b*, with its equivalent circuit shown in Fig. 1*b*, as well as subnetworks corresponding to SIR with uniform transmission lines. A half of the resultant equivalent circuit is shown in Fig. 2*c*. It contains *J*-inverters and uniform transmission lines. Final step is to form wave digital network given in Fig. 2*d* from resultant circuit given in Fig. 2*c*. To do this, blocks of the *J*-inverters (ADP-Inv) are modeled by their wave digital models based on two-port parallel adaptor network [11]. Each of the blocks corresponding to uniform transmission lines is modeled by several cascaded unit elements (UEs) [8]. The resultant wave digital network is then analyzed using earlier developed one-dimensional wave digital approach [8].

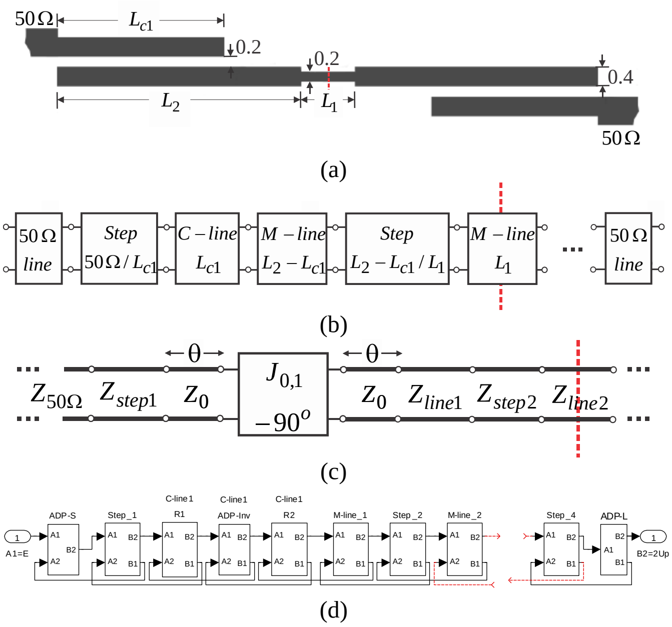


Fig. 2. Development of an equivalent wave digital network model for a dual-band BPF, (a) Physical layout of BPF (top view), (b) Network representation with cascaded subnetworks of half a symmetrical structure, (c) Resultant circuit using equivalent circuits for each subnetwork of half a symmetrical structure, (d) Wave digital network

III. Analysis Remarks

A BPF is designed in [15] on the substrate Rogers 6010, with a relative dielectric constant of 10.8, and thickness of 0.635 mm. The design parameter dimensions are chosen as following: $L_2 = 10.5\,mm$ and $L_1 = 1.4\,mm$. BPF with varied dual-passband widths obtained by varying length of coupled-line sections L_{c1} is analyzed here using the proposed combined technique.

A. PCML Characterization

Two-port PCML from Fig. 3, for three different physical lengths $L_{c1} = 9\,mm$, $L_{c1} = 7.3\,mm$ and $L_{c1} = 5.6\,mm$, is characterized.

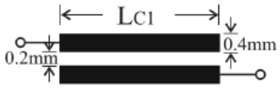


Fig. 3. Two-port PCML

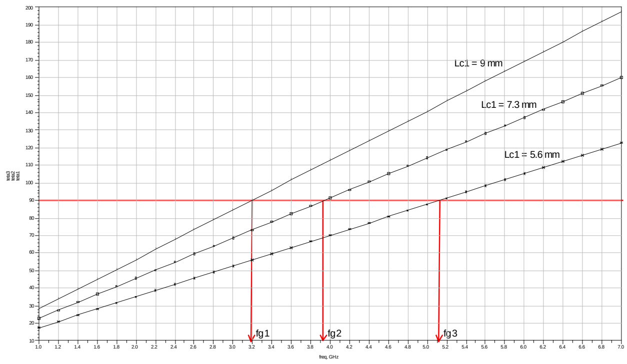


Fig. 4. Electrical line lengths for different L_{c1}

Fig. 4 illustrates the equivalent electrical line lengths versus frequency for different physical line lengths L_{c1}. These graphs are used to find frequencies on which these PCMLs are quarter-wavelength long. For PCML of physical length $L_{c1} = 9\,mm$, the frequency is $f_{g1} = 3.2\,GHz$, for PCML of $L_{c1} = 7.3\,mm$ it is $f_{g2} = 3.925\,GHz$, and for the third case of PCML of $L_{c1} = 5.6\,mm$ it is $f_{g3} = 5.125\,GHz$.

B. Simulink-based Model of Microstrip BPF Structure

In Figs. 5-9, Simulink-based blocks of the microstrip BPF (shown in Fig. 2*a*) are given. Individual blocks shown in Figs. 6-9 are putted together to represent BPF in block diagram form as shown in Fig. 5.

Each of the blocks in Fig. 5 represented by uniform transmission line (Step_1 to 4, M-line_1 to 3, C-line1 to 2) is modeled by several cascaded UEs. Simulink-based model of block represented by eight cascaded UEs is shown in Fig. 9.

Complete WDN is analyzed based on its Simulink model and MATLAB code.

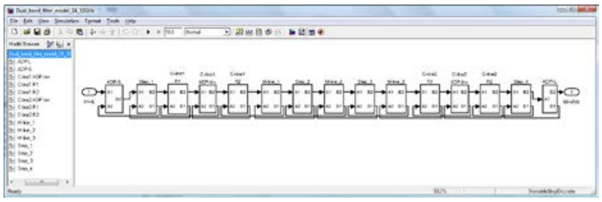


Fig. 5. Simulink-based WDN model of microstrip BPF structure

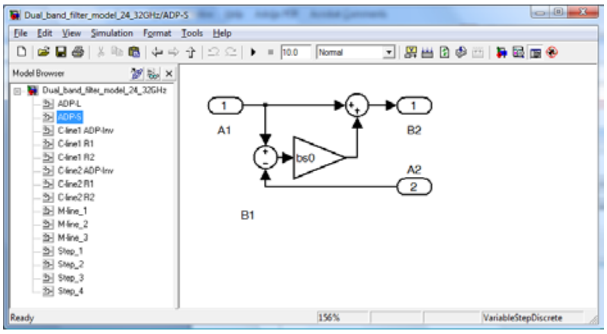


Fig. 6. Simulink-based model of two-port adaptor ADP-S

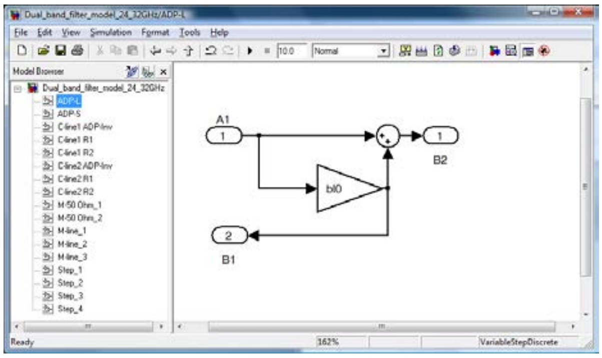


Fig. 7. Simulink-based model of two-port adaptor ADP-L

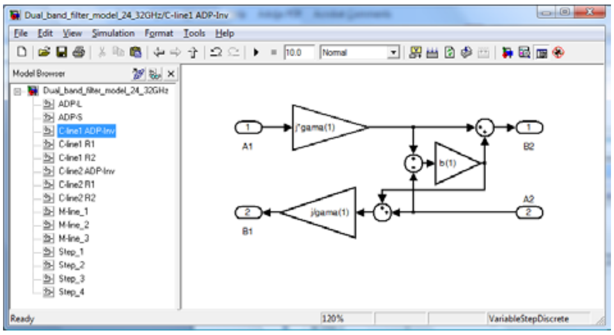


Fig. 8. Simulink-based model of two-port adaptor C-line1 ADP-Inv

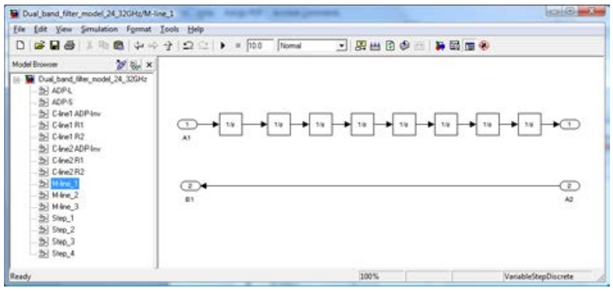


Fig. 9. Simulink-based model of block contains eight cascaded UEs

C. Modeling and Analysis Results

Layout of the structure under investigation shown in Fig. 2*a* contains two types of step discontinuity: symmetrical (composed of lines of lengths L_2 and L_1) and asymmetrical (composed of $50\,\Omega$-lines and lines of lengths L_{c1}). They are analyzed by use of EM tool in the frequency range (1-7) *GHz*, and S-parameters are obtained in Touchstone file format. Then, S-parameter data are taken to generate an equivalent model in the form of lossless transmission line. Equivalent model parameters characteristic impedance and delay are $Z_{cstep} = 128.9557\,\Omega$ and $T_{step} = 0.0020\,ns$ for symmetrical step, as well as $Z_{cstep} = 91.7216\,\Omega$ and $T_{step} = 0.0016\,ns$ for asymmetrical step discontinuity.

Applying the full-wave EM modeling tool, the characteristic impedances of the even- and odd-modes in the PCLM are calculated. They are used to obtained J-inverter network parameter given by (1) of two PCMLs. For each equivalent PCML model, J-inverter constants are: $J_{9mm} = 0.005535$, $J_{7.3mm} = 0.005541$, $J_{5.6mm} = 0.005459$. The other parameters are calculated according to equations given in [12]. For chosen port resistance $R_1 = Z_0$ the parameters for *J*-inverter multipliers shown in [13] are: $\gamma_{9mm} = 3.088$, $\gamma_{7.3mm} = 3.072$, $\gamma_{5.6mm} = 3.101$ and $\beta_{9mm} = -0.85768$, $\beta_{7.3mm} = -0.85741$, $\beta_{5.6mm} = -0.86131$. Analysis results are:

- BPF with PCMLs of length $L_{c1} = 9\,mm$: For the given error of 1%, a multiple factor is $q = 1$ and a total minimal number of sections in WDN is $n_t = \sum_{k=1}^{13} n_k = 280$. The numbers of sections in individual uniform segments $n_k = round[q \cdot T_k / T_{\min}]$ are 28, 1, 49, 49, 8, 1, 8, 1, 8, 49, 49, 1 and 28, respectively. A minimum delay is $T_{\min} = \min\{T_1, T_2, ..., T_{13}, T_{step}\} = T_{step}$. A real delay of the structure is $T_\Sigma = \sum_{k=1}^{11} T_k = 448.2232\,ps$. A total delay for the digital model of the structure is $T_t = n_t \cdot T_{\min} / q = 448.7969\,ps$. A sampling frequency of the digital model is found as $F_s = n_t / T_t = 623.8901\,GHz$. A relative error of delay is $er = [(T_\Sigma - T_t)/T_\Sigma] \cdot 100\,\% = -0.12801\,\%$.

- BPF with PCMLs of length $L_{c1} = 7.3\,mm$: A total minimal number of sections in WDN is 264. The numbers of sections in individual uniform segments are 28, 1, 40, 40, 18, 1, 8, 1, 18, 40, 40, 1 and 28, respectively. A real delay of the structure is $T_\Sigma = 422.2704\,ps$. A total delay for the digital model of the structure is $T_t = 423.1513\,ps$. A sampling frequency of the digital model is $F_s = 623.8901\,GHz$. A relative error of delay is $er = -0.20862\,\%$.

- BPF with PCMLs of length $L_{c1} = 5.6\,mm$: A total minimal number of sections in WDN is 246. The numbers of sections in individual uniform segments are 28, 1, 31, 31, 27, 1, 8, 1, 27, 31, 31, 1 and 28, respectively. A real delay of the structure is $T_\Sigma = 395.9972\,ps$. A total delay for the digital model of the structure is $T_t = 394.3002\,ps$. A sampling frequency of the digital model is $F_s = 623.8901\,GHz$. A relative error of delay is $er = 0.42854\,\%$.

The two-port parallel adaptor coefficients [13] in WDF network from Fig. 5 are $\beta_{Source} = -\beta_{Load} = -0.07085$.

In Fig. 10, the magnitude of transmission coefficients in dB versus frequency for all three studied BPF cases are shown. Zooms of passband regions are shown in Figs. 11 and 12.

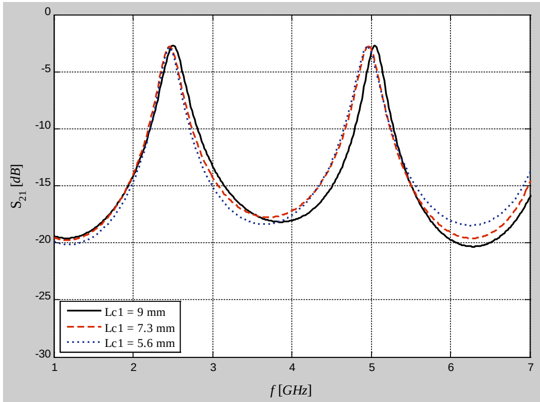


Fig. 10. The magnitudes of the transmission coefficients in dBs for all analyzed cases

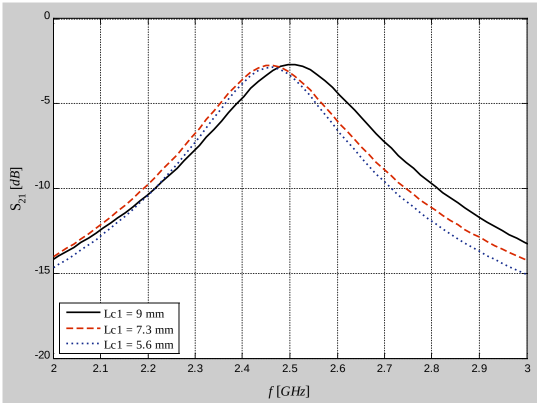


Fig. 11. The magnitudes of the transmission coefficients in dBs for all analyzed cases in the first pasband region

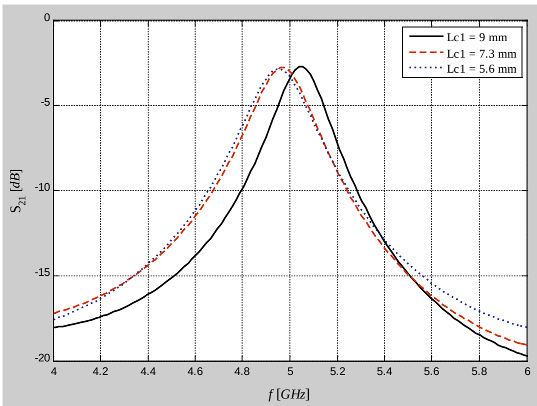


Fig. 12. The magnitudes of the transmission coefficients in dBs for all analyzed cases in the second passband region

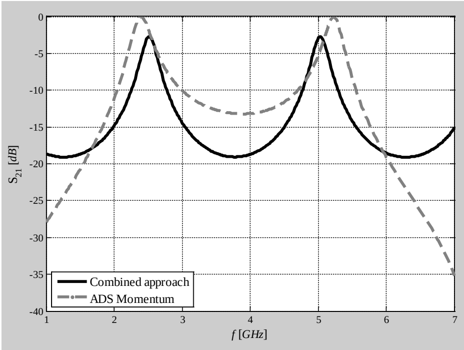


Fig. 13. Comparison of the magnitudes of the transmission coefficients in dBs for BPF with PCMLs of length $L_{c1} = 9\,mm$

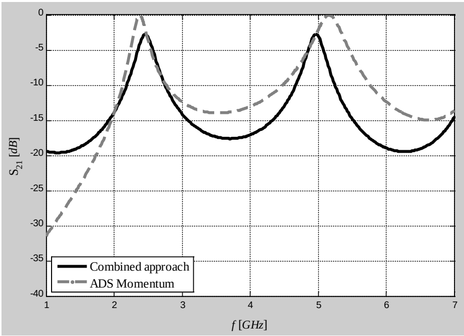


Fig. 14. Comparison of the magnitudes of the transmission coefficients in dBs for BPF with PCMLs of length $L_{c1} = 7.3\,mm$

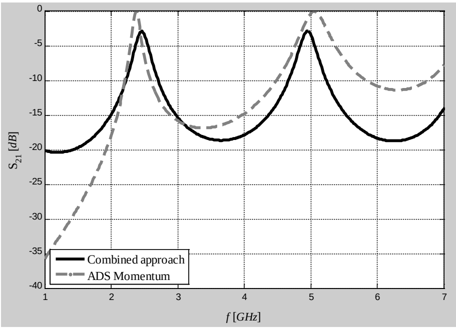


Fig. 15. Comparison of the magnitudes of the transmission coefficients in dBs for BPF with PCMLs of length $L_{c1} = 5.6\,mm$

Results calculated by proposed combined approach for all three studied BPF cases are compared with results obtained by the EM modeling simulator in Figs. 13-15, respectively. The curves are slightly shifted one from another and it is still an open issue and will be the subject of further researches of the authors.

IV. CONCLUSION

A model has been presented for calculating the scattering parameters of a dual-band BPF. Comprehensive comparisons between the results which are obtained by using the created model on one side, and those obtained by analysis in some other EM simulator on the other side, are shown for all analyzed cases and practical ranges of physical dimensions.

This example together with other BPF examples considered in [10-11] confirms that BPFs with freedom in layout implementation can be accurately and fast simulated by proposed technique. The discontinuity model is capable to represent it without any restriction in its dimensions and substrate permittivity.

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