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Miniature microwave devices based on a combination of natural right-handed and metamaterial left-handed transmission lines

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Abstract. The general approach to a design of miniature microwave devices based on a combination of transmission line sections with positive and negative dispersion is considered. Such lines, which are also known as right- and left-handed transmission lines, exhibit different dispersion characteristics. Using combination of these lines gives additional degrees of freedom for improvement of microwave device performance. At the same time, there is a possibility to decrease dimensions of the devices drastically. The following passive devices are under consideration: broadband digital phase shifters, directional couplers, dual-band resonators and filters exhibiting no spurious response. The potential benefit of this approach to the design of microwave devices is discussed.

PACS. 81.05.Zx New materials: theory, design, and fabrication

1 Introduction

Metamaterials demonstrating double-negative or single-negative dielectric and magnetic properties are successfully used for improvement of characteristics and miniaturization of microwave devices and systems. There are many examples of miniaturized antennas, absorbers, microwave ultra-diffractive imaging systems, etc. (see for example [1–4]).

The fundamental electromagnetic properties of metamaterials and the physical realization of these materials are based on different approaches. The transmission line (TL) approach provides a correct description of the physical phenomena of metamaterials and gives an efficient tool for a design of microwave devices [5–7]. In the case of backward wave, the TL is defined as the left-handed transmission line (LH TL) and can be considered as one-dimensional metamaterial. In the case of forward wave as for a conventional TL it is defined as right-handed transmission line (RH TL). Since a real LH TL does not exist in the nature, a more general model of composite right/left handed (CRLH) structure, which includes parasitic RH effects [7], is widely used for practical applications. The use of the term "metamaterial transmission lines" as applied to guiding structures does not mean that we deal with periodic homogeneous media with negative effective permittivity and permeability. We use the fact that these transmission lines exhibit backward wave propagation, i.e. left-handed behaviour. The term "metamaterial transmission lines" has been used by many authors since 2005 [7–11].

The known metamaterial TL can be designed using the unit cell as in [12] or split-ring resonator based unit cell [13]. Additionally, a consideration of pure LH TL seems to be very useful, especially for microwave applications, when parasitic RH effects can be kept negligibly small or compensated by additional components. In this paper we discuss a possibility to design microwave devices based on a combination of RH and LH TLs. The difference in dispersion characteristics of the LH and RH TLs gives additional degrees of freedom for a design of microwave devices with unique characteristics based on a combination of these lines. Using lumped-element T- or Π-cells of artificial LH TL in a combination with natural or artificial RH TL sections makes it possible to design miniature devices with improved performance and enlarged functionality. A set of microwave devices based on quasi-lumped components are considered: (i) broadband digital phase shifters; (iii) directional couplers; (ii) dual-band and/or free of spurious response resonators and filters. Some results of using a combination of RH and LH TLs for the design of microwave devices was presented in our previous paper [14]. The further improvement of the device performance and reduction of their dimensions using multilayer ceramic technology are under consideration.

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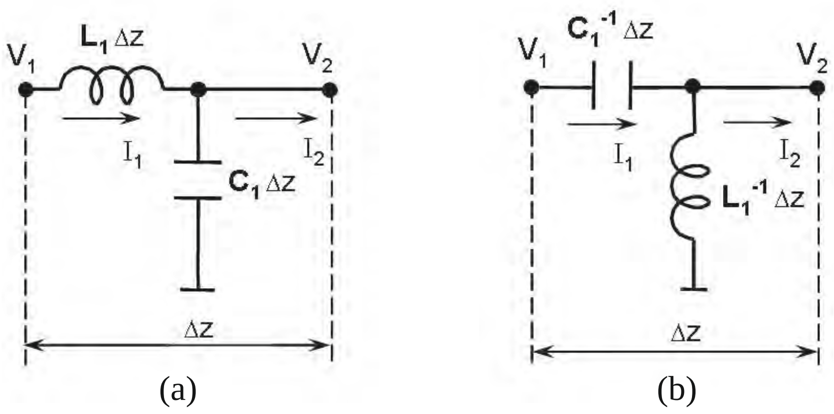


Fig. 1. Equivalent diagrams of the RH TL (a) and LH TL (b) unit cells.

2 Microwave devices based on a combination of LH and RH TLs

The homogeneous TL can be presented as a cascaded connection of the unit cells (Fig. 1). The RH TL can be designed as a natural planar TL (microstrip, coplanar waveguide etc.), though the LH TL can be realized as the artificial structure only.

The RH and LH lines based on the unit cells in Figure 1 are described by different dispersion characteristics. One has for the RH TL

$$k_R = \omega\sqrt{L_1 C_1} > 0 \quad (1)$$

and for the LH TL

$$k_L = -\frac{1}{\omega}\sqrt{\left(\frac{1}{L}\right)_1\left(\frac{1}{C}\right)_1} < 0. \quad (2)$$

Here L_1 and C_1 are defined as the inductance and capacitance per unit length, $\left(\frac{1}{C}\right)_1$ and $\left(\frac{1}{L}\right)_1$ are defined as the inverse capacitance and inductance per unit length. In (1) and (2) $k_{R,L}$ is the wave vector and ω is the angular frequency. A section of a TL of length l can be described by the electrical length defined as $\theta_R(\omega) = \theta_{0R}\frac{\omega}{\omega_0}$ for the RH TL and $\theta_L(\omega) = \theta_{0L}\frac{\omega_0}{\omega}$ for the LH TL, where $\theta_{0R} = k_R l > 0$ and $\theta_{0L} = k_L l < 0$ are defined at the frequency ω_0.

The different dispersion characteristics of the RH and LH TLs can be used for improvement of the microwave device performance. A set of microwave devices was designed, manufactured and tested: (i) ultra wide-band digital phase shifter; (ii) miniature 3-dB hybrid junction; (iii) miniature dual-band resonator and filter free of out-of-band spurious response. All the devices are based on the combination of the artificial LH TL sections and the natural/artificial RH TL sections. The devices were manufactured using the multilayer ceramic technology.

Digital phase shifter is designed as the switchable channel phase shifter based on switching between the RH and LH TLs [15]. Switching between the RH TL and LH TL sections with the electrical lengths, which are the same by absolute value at the central frequency and differ in sign, results in rather parallel runs of the phase characteristics providing almost constant phase shift over a broad frequency band. The channels are switched by two SPDT switches on p-i-n diodes.

The phase shift is determined by the LC-parameters of symmetrical T- or Π-circuits used in the channels of the phase shifter [15,16]. Using equivalence of the $ABCD$ matrix of a TL section with the matrices of T- and Π-circuits, the phase characteristics of the RH and LH TL can be found as

$$\varphi_{RH}(\omega) = -\arccos(A)_{T,\Pi} = -\arccos\left(1-\omega^2 L_R C_R\right), \quad (3)$$

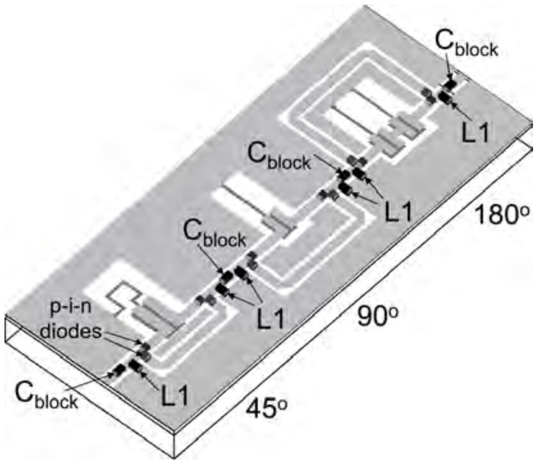
$$\varphi_{LH}(\omega) = \arccos(A)_{T,\Pi} = \arccos\left[1 - 1/\left(\omega^2 L_L C_L\right)\right]. \quad (4)$$

The phase shift is defined as

$$\Delta\varphi(\omega) = \Delta\varphi_{RH}(\omega) - \Delta\varphi_{LH}(\omega). \quad (5)$$

A 3-bit one-octave phase shifter was designed as a cascaded connection of three one-bit phase shifters providing $\Delta\varphi = 45°$, 90°, and 180° correspondingly (Fig. 2a).

The sandwich multilayer technology [17] was used for a realization of the phase shifter. The 1 mm thick alumina substrate and two conductive layers separated by a thin dielectric layer were used to form the artificial LH TL on the top side of the substrate. The RH TL was designed as the natural coplanar waveguide (CPW) section. The surface-mounted p-i-n diodes are situated on the top side of the substrate as well as blocking capacitors and grounded inductors, which provide short-circuiting with respect to the *dc* field. The biasing networks based on surface-mounted LC-components are situated on the bottom side of the substrate and connected to the top layers by via holes. The characteristics for the all eight states of the 3-bit phase shifter, which were obtained by EM simulation of the multilayer structure taking into account the p-i-n diodes and biasing networks, are presented in Figure 2b. In the frequency range 2–4 GHz the phase shift error does not exceed ±8° in the worst case. In the same bandwidth the return loss is about 15 dB and the insertion



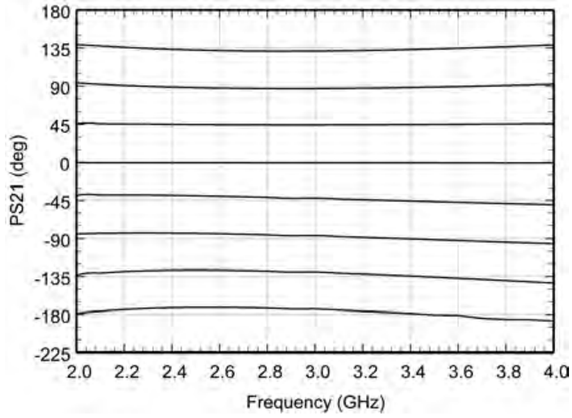


Fig. 2. Design of the 3-bit phase shifter (a) and the EM simulated phase characteristics (b).

loss is less than 1 dB. The area occupied by the device is 45×18 mm^2.

Microwave directional couplers (DC) were designed as quasi-lumped structures containing a combination of RH and LH TL sections. In order to decrease the dimension of the devices designed in [14], we used the multilayer Low Temperature Cofired Ceramic technology (LTCC), which is suitable for a realization of microwave devices based on L-C elements [19–21]. A quadrature branch-line DC with the $\lambda/4$ TL sections is shown in Figure 3a. An equivalent circuit is presented in Figure 3b and 3c. The horizontal branches of the DC are replaced by the RH TL sections, whereas the vertical ones are designed as the LH TL sections (impedance inverter). Both the RH and LH TL sections are designed as symmetrical Π-networks providing $\pm 90°$ phase response at ω_0. The L-C parameters of the network can be found by the formula:

$$\omega_0 L = (\omega_0 C)^{-1} = Z_0, \qquad (6)$$

where Z_0 is the characteristic impedance of the corresponding $\lambda/4$ TL section. Though many different combinations of RH and LH TLs can be used, the equivalent diagram in Figure 3c seems to be optimal one, because of containing only two inductances and having reduced grounded capacitors. The performance of the device is nearly the same as it was obtained for the initial distributed version.

As an example, the RH/LH TL 3-dB hybrid junction is shown in Figure 4a. The DC was accomplished in nine layers of DuPont Green Tape$^{\mathrm{TM}}$ 951 LTCC with the dielectric constant $\varepsilon_r = 7.8$ and the loss factor tan$\delta = 0.002$ (at 2 GHz). The 10 μm thick conductive layers are characterized by $R_{dc} = 0.002$ Ohm/square. Two ground planes covering the multilayer structure are connected to each other by via holes situated along the external perimeter of the structure (not shown in Fig. 4a). The quasi-lumped parallel plate capacitors and two-turn stacked inductors are situated in two conductive layers. Grounded capacitors were realized as parallel-plate capacitors between the inner conductive patterns and the ground planes. Series capacitors were produced by overlapping of the grounded capacitor electrodes. Quasi-lumped inductors have the width of 100 μm. The measured performance of the device is depicted in Figure 4b. The area of the 3-dB DC is 5.8×3.0 mm^2 and is almost twice less, than in the case of using sandwich technology for the 3-dB DC in [14]. The both the return loss and isolation are better than 20 dB. The measured insertion loss is 0.2–0.35 dB, the amplitude unbalance is better than ± 0.8 dB.

Stepped-impedance resonator (SIR) is an attractive component for a design of filters with suppressed spurious response. The SIR based on cascaded RH and LH TL sections [14,18] has additional degrees of freedom making possible to design miniature resonators with suppressed harmonic spurious responses or the dual-band resonators with arbitrary resonant frequencies. Here we present the dual-band resonator based on a cascaded TL sections: a natural RH TL section, L-C-equivalent of the RH TL section, and L-C-equivalent of the LH TL section. This structure has many possibilities of variation of the resonant characteristics: the electrical lengths and characteristic impedances of all three constituents of the resonator. That makes possible to design the dual-band (multi-band) resonator with arbitrary located resonant frequencies. The higher mode resonances can be shifted to higher frequencies and provide a wide out-of-band rejection. An example of the RH/LH TL resonator with symmetrical structure formed by two sections of natural RH TL, two Π-sections of the artificial RH TL, and one T-section of LH TL is shown in Figure 5. Using the resonance conditions for the fundamental mode with the equivalent electrical length $\theta_{equ,1}(\omega_{01}) = \pi$ and the first higher mode with $\theta_{equ,2}(\omega_{02}) = 2\pi$, one can find the lumped component characteristics for chosen resonant frequencies. Since there are redundant parameters of the TL structure, there is a possibility to manage different versions of the set of parameters.

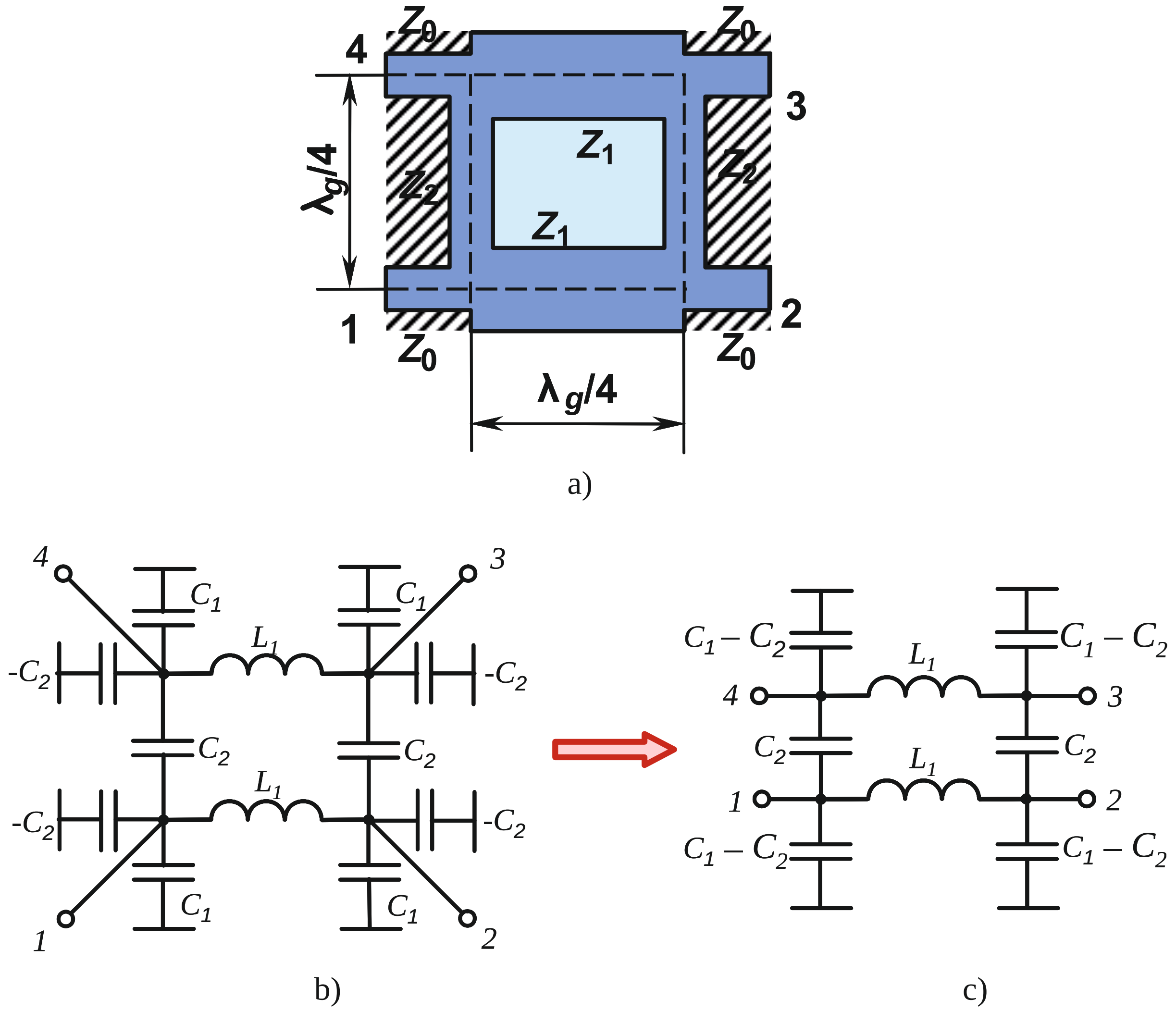


Fig. 3. (Color online) The branch-line 3-dB directional coupler: original microstrip line design (a), equivalent presentation by the Π-circuits (b), and final equivalent diagram of the device.

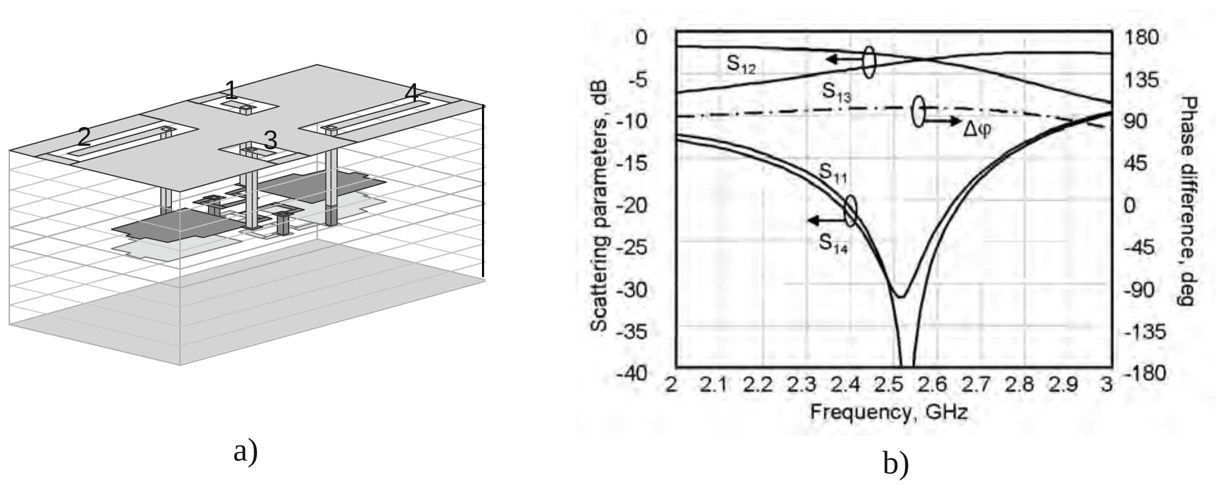


Fig. 4. The multilayer LTCC structure (a) and measured characteristics (b) of the miniaturized 3-dB directional coupler on RH/LH TL sections.

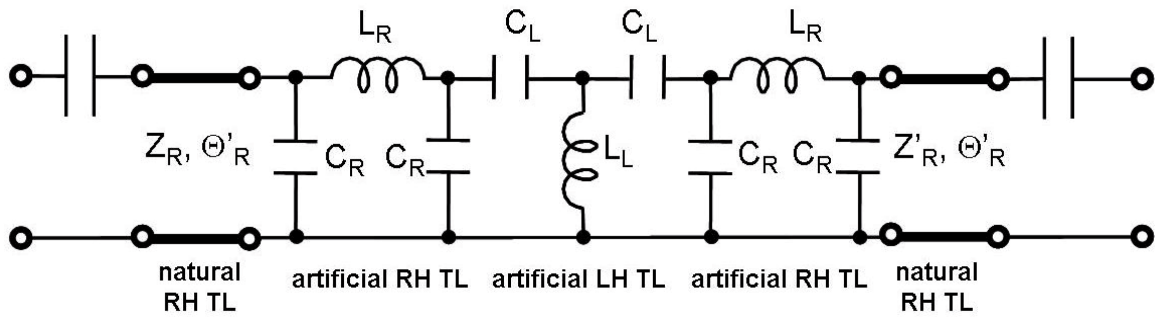
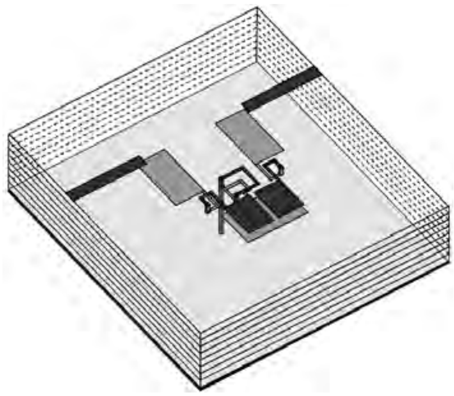
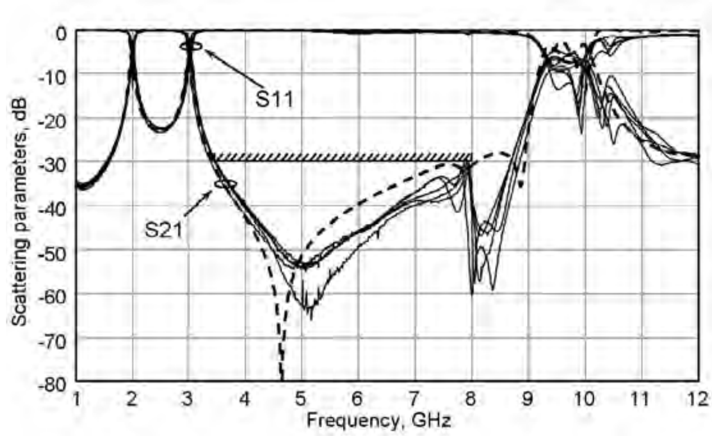


Fig. 5. The equivalent diagram of the RH/LH TL stepped-impedance resonator.



a)



b)

Fig. 6. The structure of the dual-band resonator in the LTCC package (a) and the measured response of five samples of the resonators as compared with the simulated one (dashed lines) (b).

The miniature dual-band resonator was designed and manufactured as the multilayer structure. The resonator exhibits resonances at 2 and 3 GHz. The multilayer LTCC structure of the resonator is shown in Figure 6a [14], and the resonator performance is demonstrated in Figure 6b. The spurious response is observed at frequencies higher than 9 GHz. The area occupied by the resonator is 10×9 mm^2 (the wavelength in the dielectric layer of the structure is 50 mm for $f = 2$ GHz).

The dual-band filter based on the dual-band SIR should provide two pass bands corresponding to the resonant frequencies of the first and second modes of the SIR. The 2-pole filter was designed as a cascaded connection of the LH/RH TL SIRs and its structure is presented in Figure 7a [18,20]. The area occupied by the filter is 20×8.5 mm^2. The performance obtained by the EM simulation of the lossy filter structure is presented in Figure 7b. The filter bandwidth is expected to be 150 MHz for the operational frequencies $f_0 = 2$ GHz and $f_1 = 3$ GHz. The simulated return loss is better than 20 dB and 16 dB for the frequencies f_0 and f_1 correspondingly. The isolation between the operational pass bands is better than 20 dB. In a wide frequency range, the spurious response is not observed up to 10 GHz.

3 Conclusion

The approach to the design of wide-band digital phase shifters, directional couplers and multi-band resonators based on a combination of RH and LH TL sections has been discussed. Application of lumped element equivalents of the distributed TL sections makes it possible to design miniature microwave devices.

Using different dispersion characteristics of the RH and LH TL sections one can design a very broad-band (one octave) and well matched multi-bit phase shifter providing a flat phase shift in all states.

The miniaturized 3-dB hybrid was designed using artificial RH/LH TL sections on lumped elements. The device was designed using multilayer ceramic technology. The designed LTCC device exhibits a high performance and occupies 4–6 times smaller area as compared with respect to the conventional DCs on distributed TL sections. The DC was realized as fully-integrated multilayer structures on LTCC boards and contained no SMD components.

The approach to a design of a dual-band (multi-band) and spurious-free stepped-impedance resonator on a combination of RH and LH TL sections was discussed. The suggested complicated structure of the SIR on RH/LH

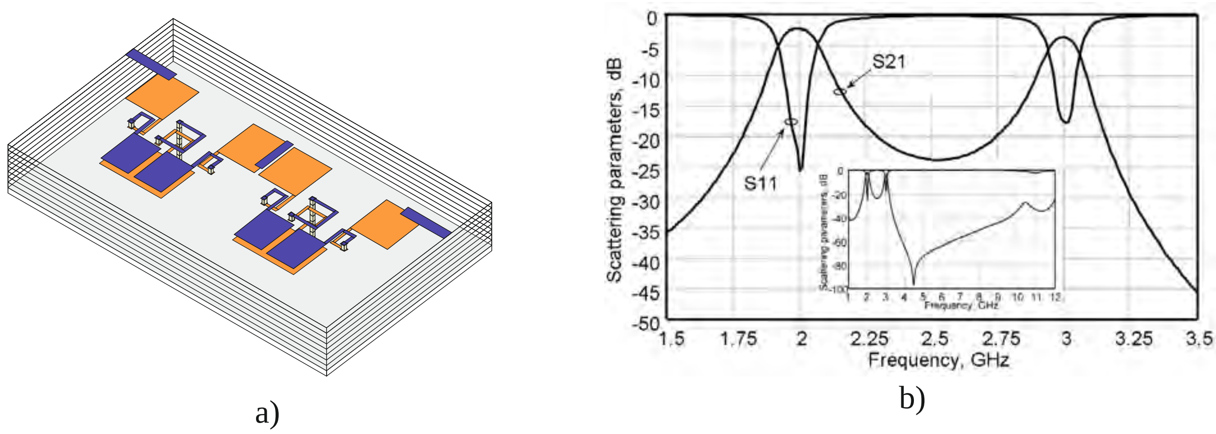


Fig. 7. (Color online) LTCC structure (a) and simulated performance (b) of the dual-band two-pole filter on the dual-band SIRs shown in Figure 6a.

TL sections makes it possible to design the resonator with arbitrary resonant frequencies providing transmittance at desired frequencies and realize a wide stop-band free of spurious responses. Using LTCC technology one can drastically reduce the filter dimensions as compared with distributed stepped-impedance structures. The measured microwave performance of the multilayer LTCC dual-band resonator exhibited high resolution and excellent reproducibility.

The combination of a careful design of combined right- and left-handed transmission line structures with a reliable three-dimensional low-cost fabrication technology opens a wide potential for commercial applications.

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