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# Tunable microwave devices based on left/right-handed transmission line sections in multilayer implementation

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*Metamaterial transmission lines can be realized as a combination of right- and left-handed transmission line (TL) sections exhibiting positive and negative dispersion. This approach gives additional degrees of freedom for improving the performance of microwave devices. Artificial right- and left-handed sections, which are based on lumped-element unit cells consisting of inductance and capacitances (LC-cells), are used. This makes it possible to decrease dimensions of the devices drastically. Furthermore, using variable capacitors in LC-cells allows designing tunable devices. This paper presents the results of design, numerical simulation, and experimental investigation of a tunable rat-race ring and free-of-spurious response dual-band filter manufactured as integrated ceramic multilayer circuits based on low-temperature co-fired ceramics. Commercial semiconductor varactors have been used as tunable components.*

**Keywords:** Metamaterial transmission line, Directional coupler, Stepped impedance resonator, Dual-band filter, Tunability

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## I. INTRODUCTION

Resonators based on transmission line (TL) sections have a set of resonant frequencies, related to the fundamental mode and higher harmonics. For TLs exhibiting a linear dispersion characteristic, the resonant frequencies are integer multiples of the fundamental mode. As a consequence, filters built from TL resonators exhibit additional passbands at higher frequencies. For many practical applications it is necessary to reject the higher-order harmonics. A common way to suppress the higher harmonics is the use of stepped impedance resonators (SIRs) for the filter design [1–6]. As a rule, the SIR is designed as cascaded sections of TLs like microstrip lines or coplanar waveguides. In those TLs the dispersion is positive and the propagation constant is directly proportional to the frequency. Such TLs are named as the right-handed (RH) ones. As an alternative, TLs with negative dispersion can be employed as well. In such TLs the propagation constant is inversely proportional to the frequency. They are known as metamaterial TLs or left-handed (LH) TLs [7, 8]. Using a combination of RH and LH TLs allows designing resonators and filters with highly suppressed spurious responses [9–13]. Moreover, dual-band resonators and filters for two arbitrary resonant frequencies and with suppressed higher harmonic response can be designed using different dispersion characteristics of the RH and LH TLs [12, 13].

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Using the lumped LC-equivalents of the quarter-wavelength RH/LH sections of distributed TLs, one can design directional couplers with drastically reduced dimensions keeping the same performance [14]. Involving tunable capacitances in RH/LH TL sections enables the design of tunable microwave devices.

The goal of this paper is to discuss a novel approach to the design of tunable directional couplers, resonators, and filters using RH/LH TL sections. A combination of artificial RH/LH TL sections implemented as lumped-element T- or Π-networks is used. This paper presents the design of the devices using multilayer low-temperature co-fired ceramics (LTCC) technology. A tunability of the devices is estimated.

## II. RAT-RACE RING DESIGN

### A) Miniature rat-race ring

Rat-race ring is a four-port device consisting of three TL sections with electrical lengths of 90° and one TL section with an electrical length of 270°. A conventional implementation based on distributed TLs leads to rather large size of the device, especially in the lower part of microwave region. A miniaturized version of the rat-race ring can be designed by replacing the distributed TL sections by lumped-element T- or Π-networks. Figure 1(a) shows a rat-race ring in which the electrically long 270° TL section is replaced by an artificial LH TL with an electrical length of −90° implemented as a Π-network, whereas three 90° TL sections are realized as artificial RH TLs also based on Π-networks [15]. The parallel tanks appear at ports 1 and 4 when all the TL sections in the rat-race ring are replaced by lumped-element Π-networks. These tanks are removed from the circuit because they do not influence characteristics at the central frequency.

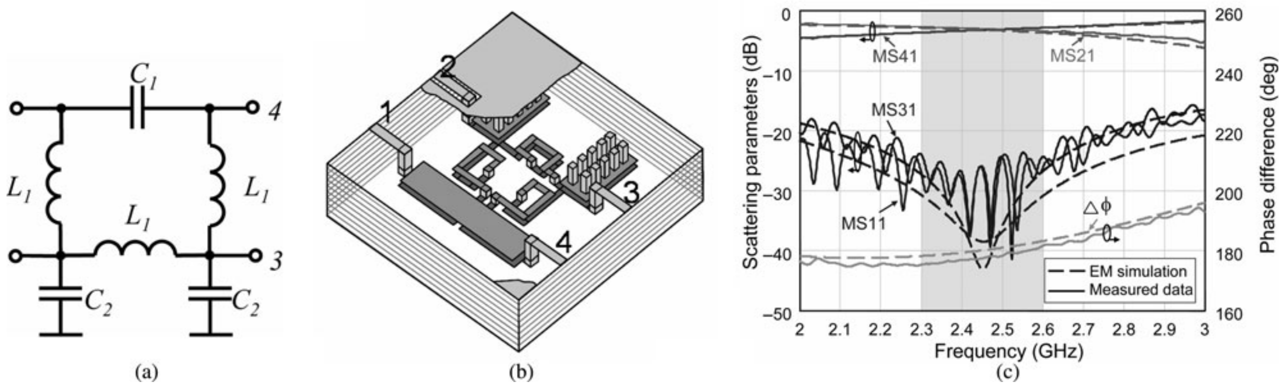


**Fig. 1.** Miniature lumped-element rat-race-ring: (a) equivalent circuit, (b) layout of the multilayer LTCC structure, (c) simulated and measured scattering parameters.

The LTCC technology was used for the multilayer implementation of the rat-race ring shown in Fig. 1(b) [16, 17]. The device uses eight layers of the 95 μm thick DuPont Green Tape$^{TM}$ 951 LTCC ($\varepsilon_r = 7.8$). The silver paste DP6145 was used for metallization. The fired thickness of the metallization layer was 9–11 μm. Parallel-plate capacitors and two-turn stacked inductors were used. The size of the device designed for the central frequency of 2.45 GHz is 7.5 mm × 7.5 mm × 0.76 mm, which that corresponds to $0.17\lambda_g \times 0.17\lambda_g \times 0.02\lambda_g$ ($\lambda_g$ is guided wavelength). The scattering parameters of the rat-race ring measured with the HP 8510C vector network analyzer are presented in Fig. 1(c) in comparison with the results of electromagnetic simulations of the multilayer structure. At the central frequency 2.45 GHz, the measured insertion loss was less than 0.2 dB. In the frequency range 2.2–2.7 GHz, the device provided equal power division with the amplitude unbalance less than ±1 dB. The measured return loss and the isolation were better than 20 dB. The phase difference between the output signals was 180–1/+7° over the frequency range under consideration. The measured data agree well with the results of simulations, indicating a reliable LTCC microwave design.

## B) Tunable rat-race ring

Using tunable capacitors in the artificial RH and LH TL sections gives a possibility to tune the frequency response of the rat-race ring [15, 18]. For the Π-networks representing the quarter-wavelength sections of LH or RH TLs with the characteristic impedance $Z_o$, the following identities are valid at the central angular frequency $\omega_o$:

$$\omega_o L = Z_o, \qquad (1)$$

$$(\omega_o C)^{-1} = Z_o, \qquad (2)$$

where $L$ and $C$ are the inductance and capacitance of the Π-network, respectively.

Keeping $Z_o = const.$ and $L = const.$, one can tune the frequency $\omega_o$ by using a variable capacitor $C_{var}$:

$$\omega_o = \frac{1}{\sqrt{LC_{var}}}. \qquad (3)$$

Until today, most electronically tunable devices use varactor diodes as tuning elements, as they provide fast tuning and a low control voltage of few volts. We consider two different varactor diodes, to optimally exploit the potential tuning range. The fixed capacitors $C_1$ and $C_2$ (Fig. 1(a)) were replaced by the hyperabrupt silicon varactors SMV1231 (VD1) and SMW1233 (VD2) from Skyworks Inc. as shown in Fig. 2(a). The resistors R and blocking capacitors $C_b$ and $C_1$ were used to apply biasing voltage.

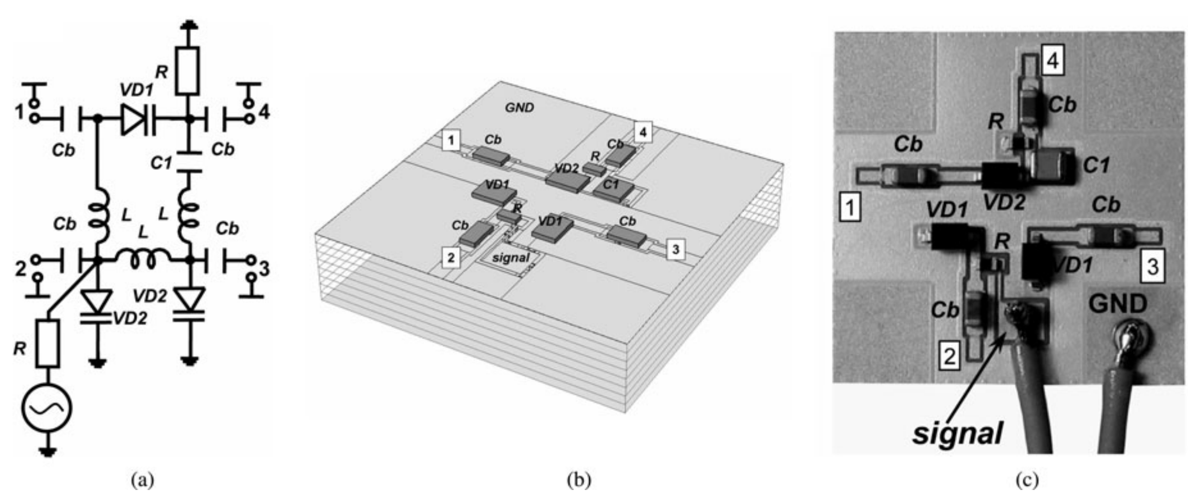


**Fig. 2.** Tunable rat-race-ring employing semiconductor varactors as tunable capacitors: (a) equivalent circuit, (b) layout of multilayer LTCC structure with SMD components on the top, (c) top view of the manufactured LTCC module.

Figure 2(b) shows the LTCC module of the tunable rat-race ring. The inductors $L$ were embedded into eight LTCC layers as in the non-tunable case. The other components are SMD, which were mounted on the top of the ceramic module (Fig. 2(c)). The size of the tunable rat-race ring module is 16 mm × 16 mm × 0.76 mm. The measured device performance for different values of the biasing voltage applied to the varactors is presented in Fig. 3. The reflection coefficient and the isolation remained better than 20 and 14 dB, respectively. The increase of the measured insertion loss up to 1.3 dB can be explained by the additional loss inserted by the varactor diodes. The unbalance of power division between the device output ports across the 200 MHz band was ±1 dB for all biasing voltages applied. The tuning range of 1.4–2.4 GHz was observed experimentally, which corresponds to the estimated tunability of 70%.

## III. DUAL-BAND FILTER DESIGN

### A) Dual-band SIR

In order to obtain more freedom for the design of resonators free of higher-order harmonics, we suggested a SIR based on cascaded LH and RH TL sections (Fig. 4(a)) [11, 12]. To obtain a specific stopband behavior, the electrical lengths $\theta_R$ and $\theta_L$ and the ratio of the characteristic impedances $Z_L/Z_R$ of the LH TL and RH TL sections have to be adjusted. These parameters can be derived from the resonance conditions for the fundamental mode at $\omega_o$ and the first higher frequency $\omega_1$:

$$\tan(\theta_{oL}) = -(Z_R/Z_L)\cot(\theta_{oR}), \quad (4)$$

$$\tan\left(\theta_{oL}\frac{\omega_o}{\omega_1}\right) = (Z_L/Z_R)\tan\left(\theta_{oR}\frac{\omega_1}{\omega_o}\right), \quad (5)$$

where $\theta_{oR}$ and $\theta_{oL}$ are the electrical lengths at $\omega = \omega_o$.

According to equations (4) and (5), the length of the RH TL section decreases with increasing the frequency $\omega_1$. The resonance characteristics are also influenced by the characteristic impedances: the higher the ratio $Z_R/Z_L$, the higher the $\omega_1$.

The equivalent circuit of the SIR is shown in Fig. 4(b). The LH TL section was realized as a lumped-element T-network. The RH TL section was designed as a cascade of a distributed line and an artificial TL implemented as lumped-element Π-network. The inset of Fig. 4(c) presents the microstrip structure of the SIR embedded in nine layers of the 95 μm thick DuPont Green Tape$^{TM}$ 951. The size of the entire LTCC multilayer module is 22 mm × 20 mm × 0.76 mm, while the area occupied by the SIR is 10 mm × 8 mm. The simulated and measured scattering parameters of the dual-band SIR designed for applications at $f_o = 2$ GHz and $f_1 = 3$ GHz are compared in Fig. 4(c). For five tested structures the spread of the measured resonant frequencies $f_o$ and $f_1$ was 10 MHz (0.4%) and 35 MHz (1.43%), respectively. No spurious response was observed in a wide frequency range up to 8 GHz.

### B) Dual-band filter free-of-spurious response

As a further step, a two-pole filter for dual-band application was designed on the basis of the proposed SIRs with capacitive

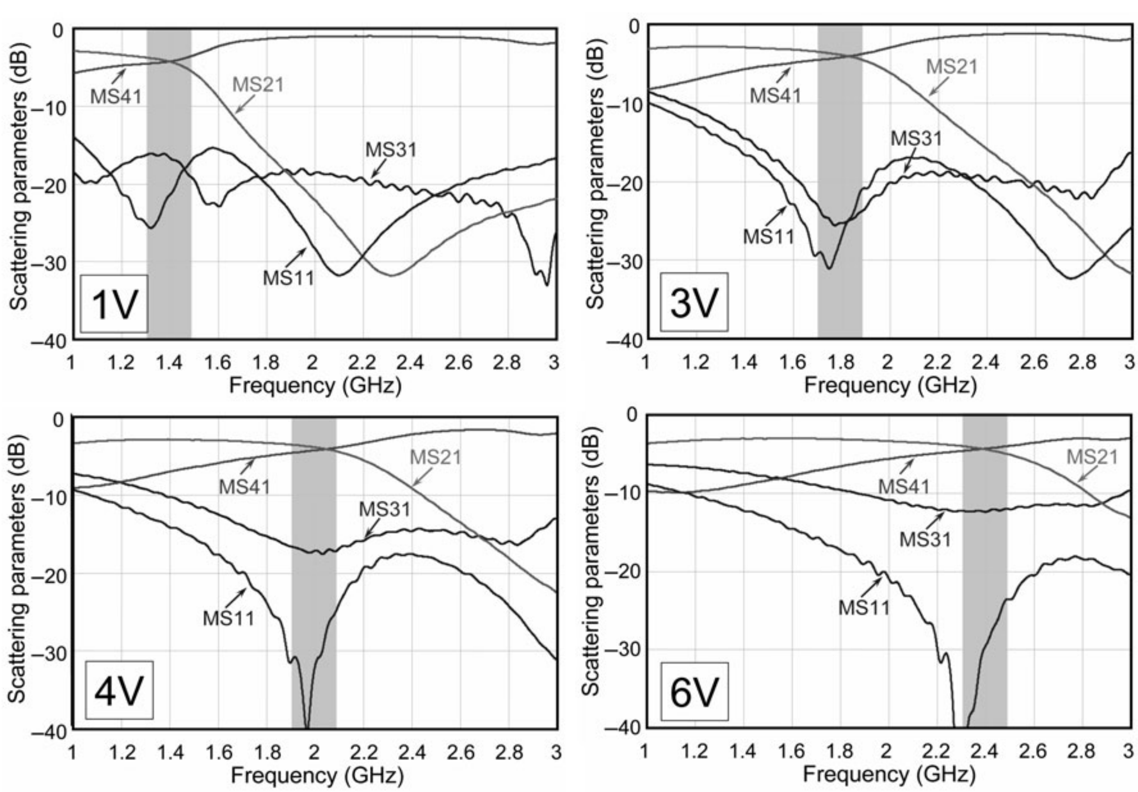


**Fig. 3.** Measured characteristics of the tunable rat-race ring for different biasing voltages applied to the varactors.

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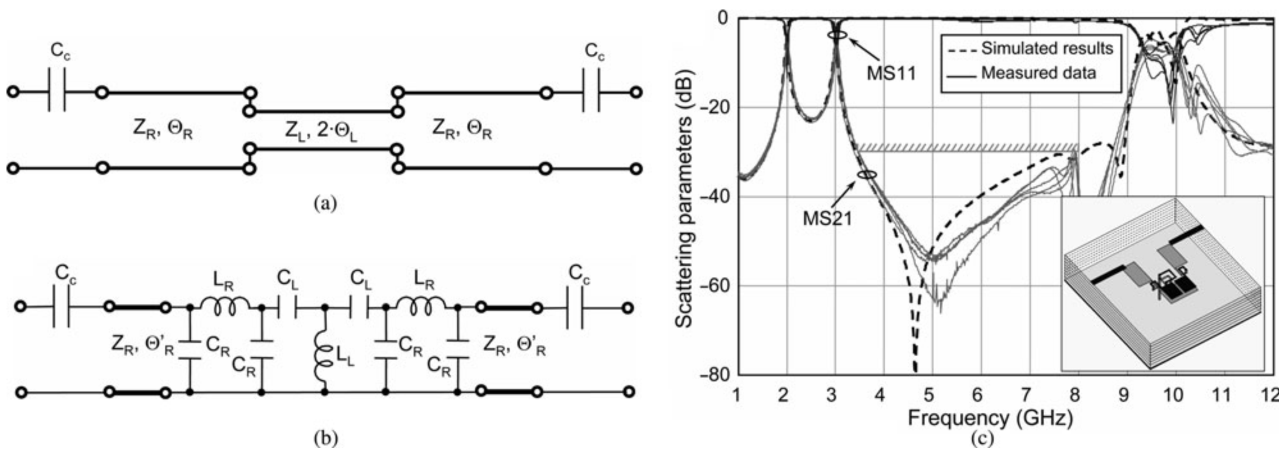


**Fig. 4.** SIR based on cascaded RH and LH TL sections: (a) schematic diagram, (b) equivalent circuit, (c) measured and simulated scattering parameters. The inset shows the layout of the SIR multilayer LTCC module.

couplings. The size of the entire multilayer LTCC filter module is 30 mm × 22 mm × 0.76 mm, with the area occupied by the filter is 20 mm × 8.5 mm.

Figure 5 shows the narrowband and wideband performances obtained by the electromagnetic simulation of the lossy filter structure in comparison with measured data for five samples of LTCC filter. The filter passband is 150 MHz for both the operational frequencies ($f_0 = 2$ GHz and $f_1 = 3$ GHz). The simulated and measured return loss was better than 16 dB, the measured isolation between the passbands was better than 20 dB, which corresponds well with the results of electromagnetic simulations. The measured insertion loss remained below 2.3 dB at $f_0$ and 3.6 dB at $f_1$. Due to the high accuracy achievable in the LTCC process flow (10 μm variation of line width is achievable), the deviations of the central frequencies from the design value were less than 1.2% (30 MHz) for $f_0$ and 2% (50 MHz) for $f_1$ for the five samples measured. The filter designed exhibits no spurious response up to 10 GHz.

## C) Tunable dual-band filter

To design a highly flexible filter, we analyzed a possibility to control the frequency location of the passbands by using variable capacitors as constituents of the artificial RH and LH TL sections of the dual-band filter. The simulation revealed distinct difference between controlling the capacitances of the LH and RH TL sections. By tuning serial capacitances of the LH TL section, only the lower passband could be shifted. In turn, controlling the shunt capacitances of both the RH TL sections results in a shift of both the passbands to higher frequencies [18]. Simultaneous tuning of the capacitances of the LH and RH TL sections allows independent shifting of the both passbands. In the last case, the ratio of the central frequencies of the two passbands or the difference between them can be kept constant.

For the first investigation, the tunable dual-band filter with variable series capacitors of the LH TL sections was designed. LTCC implementation of the tunable filter was based on non-tunable version and is depicted in Fig. 6(a). The hyperabrupt silicon varactors SMV1232 were employed as tunable components. To apply the required tuning voltage, 1 MOhm resistors were used. The size of the tunable filter was kept the same as in the case of non-tunable version. The results of the experimental investigation are presented in Fig. 6(b). The shift of only the lower passband was observed, as it was predicted by the electromagnetic simulation. The measured tunability of the lower passband was estimated as 28%.

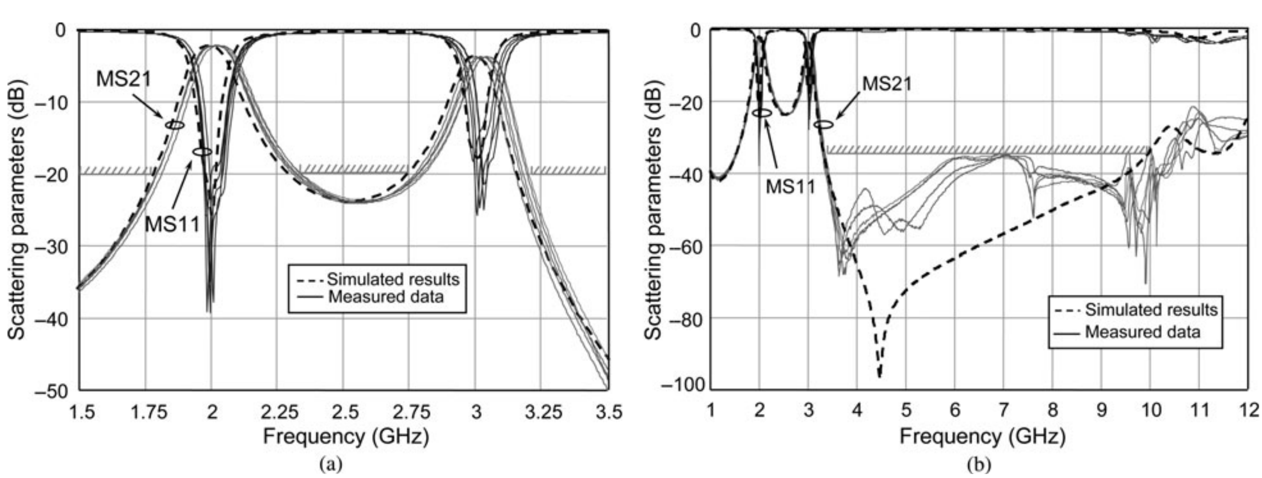


**Fig. 5.** Results of EM simulation and measurements of the dual-band filter free-of-spurious response.

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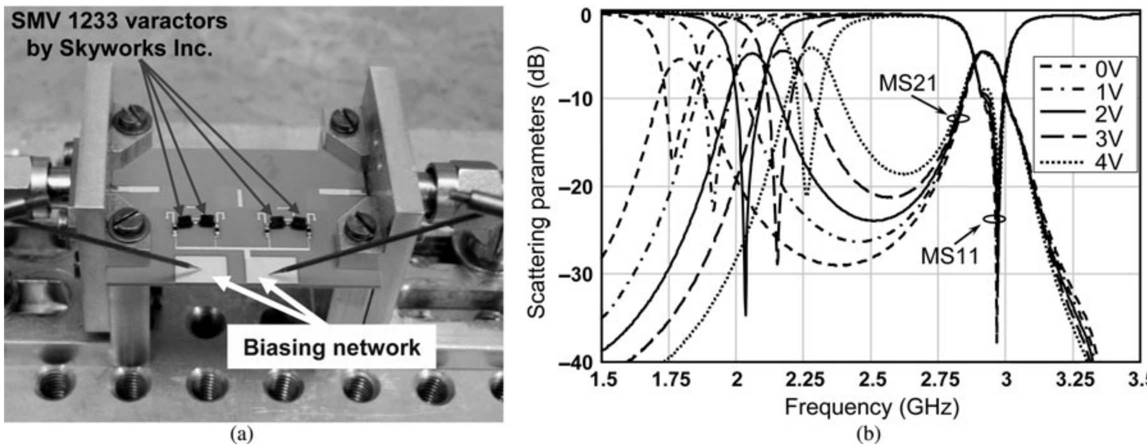


**Fig. 6.** Dual-band filter tuned by the series capacitances of the LH TL section: (a) experiment setup, (b) measured performance of the tunable filter.

## IV. CONCLUSIONS

An approach to the design of tunable directional couplers and filters based on a combination of RH and LH TLs sections have been presented. Artificial implementation of RH and LH TLs as T or $\Pi -$ networks based on lumped elements gives additional potential to improve the device performance. It has been shown that the capacitors of the artificial RH/LH TL sections can be successfully replaced by semiconductor varactor diodes in order to design tunable miniature microwave devices. This was confirmed by the results of numerical simulation and experimental investigation of the tunable rat-race ring and dual-band filter.

For a higher integration of the microwave devices, the ceramic multilayer LTCC technology was successfully applied. Due to the high accuracy achievable in the LTCC process flow, the measured data of the devices agreed well with the results of electromagnetic simulations. The high resolution and excellent reproducibility was demonstrated.

The combination of careful design of combined RH and LH TL structures with a reliable three-dimensional low-cost fabrication technology opens a high potential for commercial applications of such devices.

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