BROADBAND DIGITAL PHASE SHIFTERS USING METAMATERIAL TRANSMISSION LINES WITH NEGATIVE DISPERSION

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Abstract: *Design of broadband digital phase shifters based on switchable right/left-handed transmission lines is considered. Different practical implementations of the phase shifters designed as microstrip and coplanar multilayer structures containing an artificial quasi-lumped-element left-handed transmission line and an artificial or natural right-handed transmission line are presented.*

Introduction

A conventional transmission line, in which the phase and group velocities are codirectional, has a positive dispersion and is referred to the right-handed transmission line (RH TL). An artificial version of the RH TL can be formed as a ladder network consisting of inductors connected in series and shunt capacitors. According to the principle of duality the transmission line with interchanged inductors and capacitors can be considered as a so-called left-handed transmission line (LH TL) characterizing by a negative dispersion with the opposite directions of the phase and group velocities [1]. The dispersion characteristics of the RH TL and the metamaterial LH TL are rather parallel within a wide frequency range providing almost constant phase difference. This gives a possibility to design broadband digital phase shifters based on switching between the RH TL and LH TL sections [2].

In this paper a design method for such a phase shifter is reported. Two possible realizations using an artificial implementation of both the LH TL and RH TL or a combination of artificial LH TL and natural RH TL sections are discussed. Practical designs of 45°, 90°, and 180° phase shifters realized as microstrip and coplanar multilayer structures are presented.

Design of broadband phase shifters based on switchable right/left-handed transmission lines

The operational principle of a digital phase shifter using switched RH TL and LH TL sections is illustrated by Fig. 1. In one state the signal is going through the RH TL section with a negative phase incursion φ_1 whereas in another state the LH TL section with a positive phase incursion φ_2 is being switched on. Phase shift $\Delta\varphi = \varphi_1 - \varphi_2$ is obtained by switching the signal path with the aid of two SPDT switches. 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 due to different dispersion law, results in providing almost constant phase shift over a fairly large bandwidth. It was theoretically estimated that in the case of the ideal RH TL and LH TL switched by the perfect SPDT switches the phase shift error is ±3% in one octave bandwidth and about ±12.5% over two octaves for any value of the phase shift [3]. Moreover, if the characteristic impedance of the both transmission lines is equal to the port impedance, the perfect matching is provided in any frequency range for the both states.

In fact, a real LH TL does not exist in the nature. Hence, an artificial lumped-element implementation of the LH TL consisting of serial capacitors and shunt inductors has to be used while the RH TL section can be realized as either a lumped-element structure or the natural transmission line. A symmetrical lumped-element T- or Π-network can be considered as an equivalent circuit of a transmission line section with either positive or negative dispersion as shown in Fig. 2. The following equations for LC-parameters can be derived by comparing ABCD-matrices of the transmission line section and the T- or Π-network in the case of the RH TL:

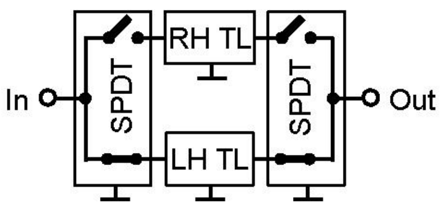

Fig. 1. Digital phase shifter based on switchable RHTL and LHTL sections.

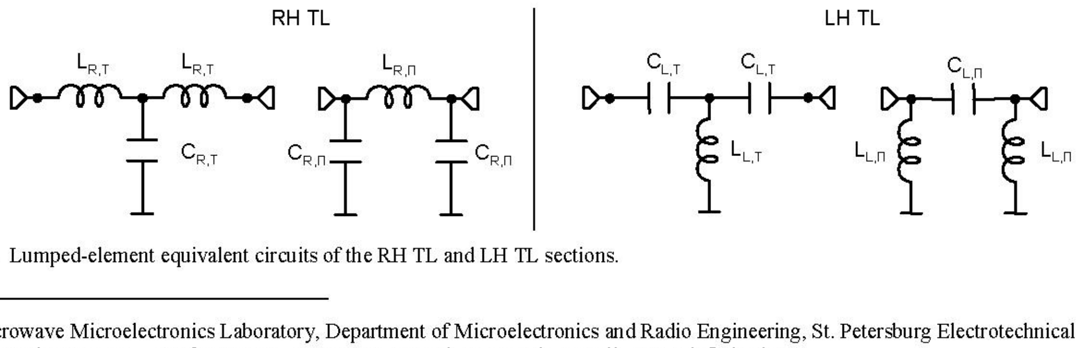

Fig. 2. Lumped-element equivalent circuits of the RH TL and LH TL sections.

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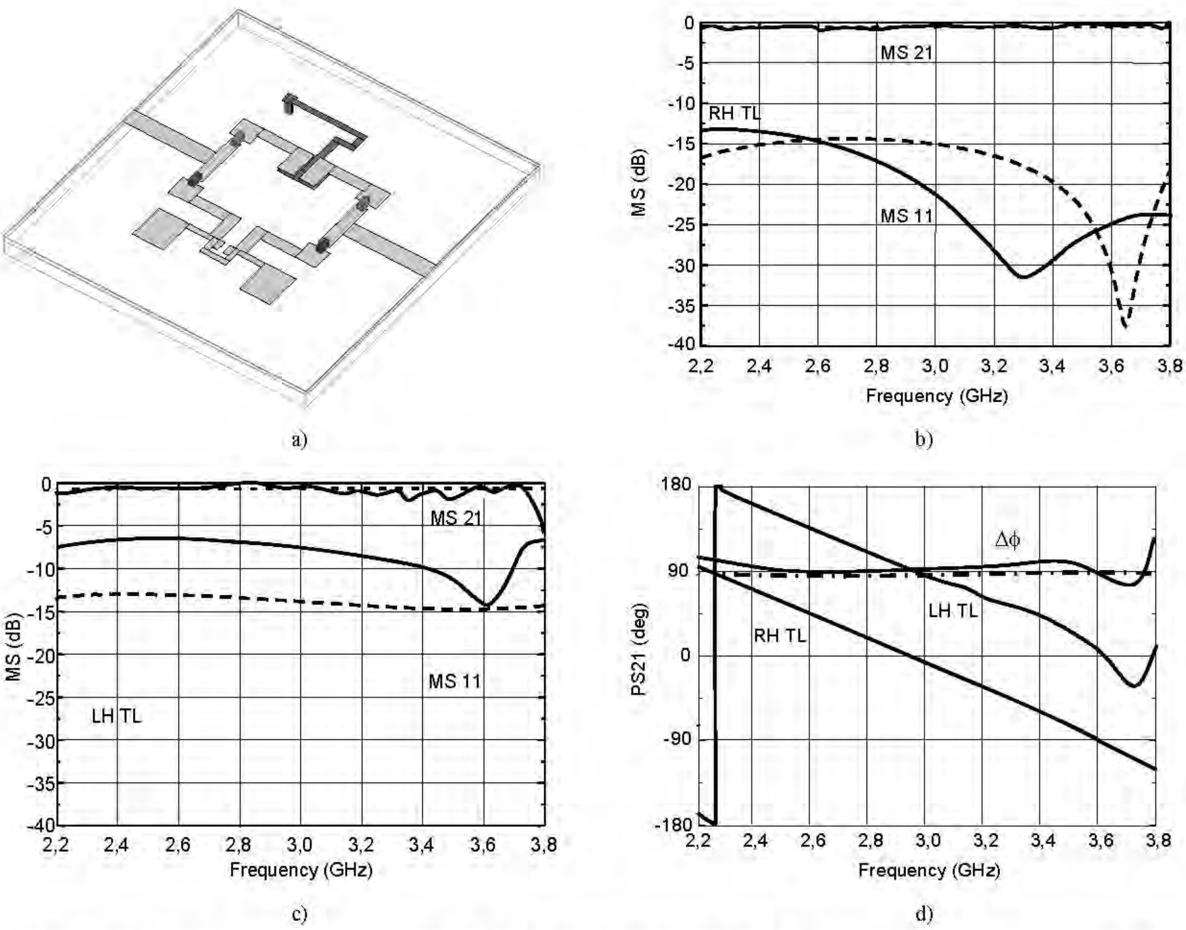

a) b) c) d)

Fig. 3. Microstrip realization and characteristics of the 90° digital phase shifter using artificial quasi-lumped-element implementation of both the LH TL and RH TL (solid lines – measured, dashed lines – simulated).

$$L_{R,T} = \frac{Z_0 \operatorname{tg}(\Theta_0/2)}{\omega_0}, \quad C_{R,T} = \frac{\sin\Theta_0}{\omega_0 Z_0}, \quad L_{R,\Pi} = \frac{Z_0 \sin\Theta_0}{\omega_0}, \quad C_{R,\Pi} = \frac{\operatorname{tg}(\Theta_0/2)}{\omega_0 Z_0},$$

and for the LH TL:

$$L_{L,T} = \frac{Z_0}{\omega_0 \sin\Theta_0}, \quad C_{L,T} = \frac{1}{\omega_0 Z_0 \operatorname{tg}(\Theta_0/2)}, \quad L_{L,\Pi} = \frac{Z_0}{\omega_0 \operatorname{tg}(\Theta_0/2)}, \quad C_{L,\Pi} = \frac{1}{\omega_0 Z_0 \sin\Theta_0},$$

where Z_0 is the characteristic impedance of a transmission line, Θ_0 is the electrical length at the central frequency $\omega_0 = \sqrt{\omega_1 \omega_2}$. The electrical length is considered to be positive for the RH TL and negative for the LH TL.

The presented method was applied to design 45°, 90°, and 180° phase shifters realized as microstrip and coplanar structures. The sandwich multilayer technology [4] was used, in order to form the serial capacitors of the artificial LH TL. Two 15 μm thick conductive layers separated from each other by the dielectric layer with the thickness of 60 μm and the dielectric permittivity $\varepsilon_r = 10.2$ were screen-printed on 1 mm thick alumina substrate. Quasi-lumped grounded inductors were situated on the bottom conductive layer and connected to the ground plane by via holes. The RH TL section was realized on the top conductive layer. In all the phase shifters designed switching the signal path is carried out by surface mounted *p-i-n* diodes. In the open state the equivalent circuit of the p-i-n diode consists of 0.5 Ohm resistor. In the close state the *p-i-n* diode is represented by a series connection of 0.12 pF capacitor and 0.5 Ohm resistor.

A microstrip design of the 90° phase shifter, in which both the LH TL and RH TL are artificial sections realized as quasi-lumped-element T- and Π-networks, correspondingly, is shown in Fig. 3(a). The size of the fabricated phase shifter is $12 \times 10.5 \times 1.1$ mm^3. According to the results of EM simulation taking into account the equivalent circuit of the *p-i-n* diode in two states, the phase shift of 90±2° is provided within the frequency band 2.2–3.8 GHz. The return loss is better than 13 dB over the whole bandwidth in both states. The insertion loss is no more than 1 dB. Simulated amplitude and phase characteristics of the phase shifter are shown by dashed lines in Fig. 3(b)-(d).

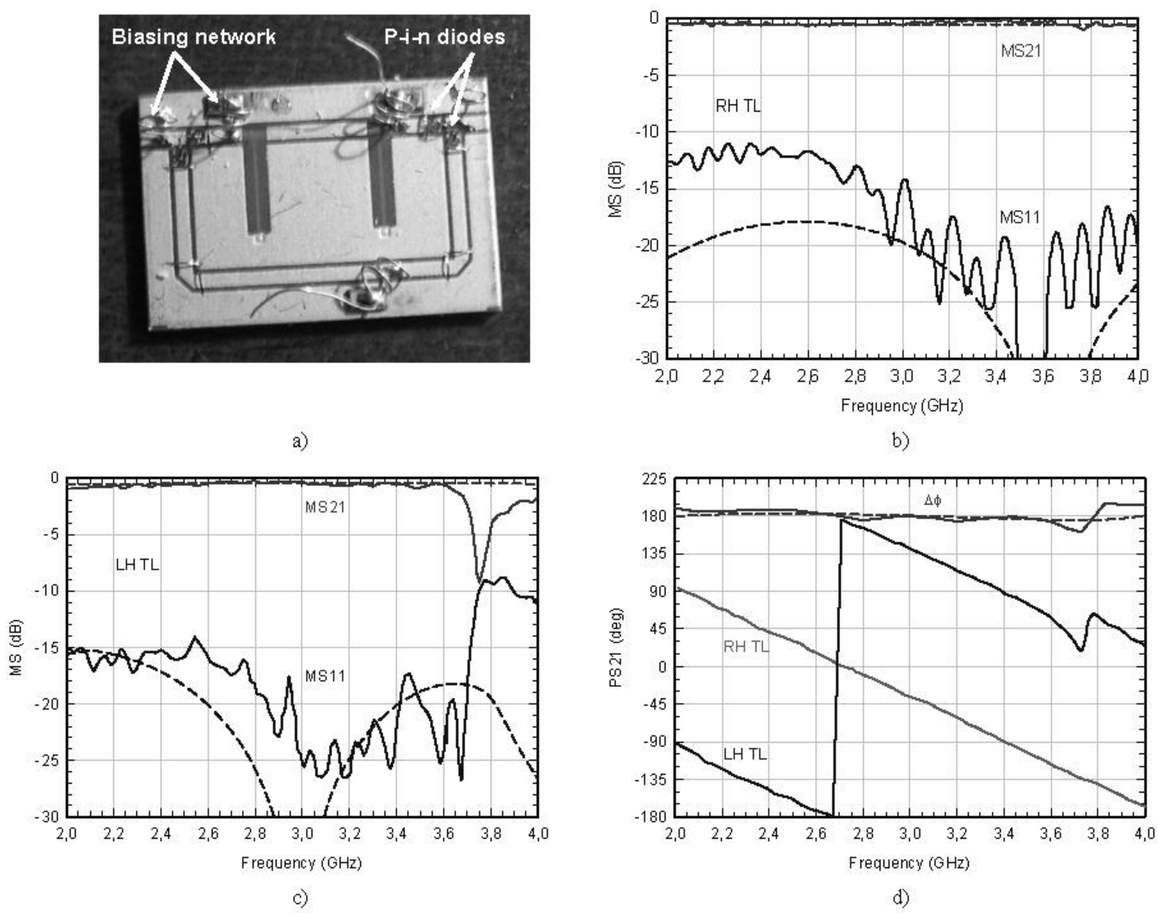

Fig. 4. Coplanar design and characteristics of the 180° digital phase shifter using the artificial quasi-lumped-element LH TL and the natural distributed RH TL (solid lines – measured, dashed lines – simulated).

The experimental investigations were performed using HP 8720B vector network analyzer. Measured characteristics of the 90° phase shifter correspond well to the simulated ones for the RH TL channel and are slightly degraded for the LH TL channel. In the case of LH TL the experimentally observed return loss is no less than 6 dB. The maximum insertion loss is about 2 dB. The measured phase shift is 90±6° in the frequency range 2.6–3.0 GHz. The degradation of the experimental characteristics is caused by manufacturing inaccuracies in a combination with a strong influence of parasitic grounded capacitances in the microstrip LH TL structure.

A coplanar configuration is more suitable for LH TL implementation since the influence of parasitic grounded capacitances can be kept negligibly small. Furthermore, realization of the RH TL as the natural transmission line seems very promising for practical applications. These points are confirmed by the results obtained.

Fig. 4(a) shows the photograph of a coplanar design of the 180° phase shifter with the artificial quasi-lumped-element LH TL section and the natural distributed RH TL section. To extend the operational bandwidth with respect to the input matching, the artificial LH TL was designed as a cascaded connection of two identical quasi-lumped-element T-networks with +45° phase incursion each. The dimensions of the fabricated 180° phase shifter are $21\times14\times1.1$ mm^3. Amplitude and phase characteristics of the phase shifter obtained by EM simulation are presented by dashed lines in Fig. 4(b)-(d). The device provides the 180° phase shift with a variation of ±5° in more than one octave bandwidth (1.8–4.1 GHz, i.e. 85%). In both states the return loss is better than 15 dB and the insertion loss does not exceed 0.55 dB in the same frequency range. The insertion loss level corresponds to the figure of merit of the phase shifter [5] estimated as 330 deg/dB.

The measured characteristics of the 180° phase shifter are plotted Fig. 4(b)-(c) in a comparison with the simulated ones. A good agreement between measured and simulated data is observed excepting a parasitic resonance in the LH TL characteristics at 3.75 GHz, which could be caused by an influence of the surface mounted *p-i-n* diodes and biasing networks. Within the frequency range 2.0–3.6 GHz the experimentally observed phase shift was 180±7°. Measured value of the return loss was not worse than 11 dB for the RH TL being switched on and not less than 14 dB in the case of the LH TL. The insertion loss was not higher than 0.7 dB for the RH TL and no more than 0.9 dB for the LH TL.

A coplanar realization of the 45° phase shifter is depicted in Fig. 5. It is similar to the design of the 180° phase shifter apart from the shorter length of RH TL and the single quasi-lumped-element T-network

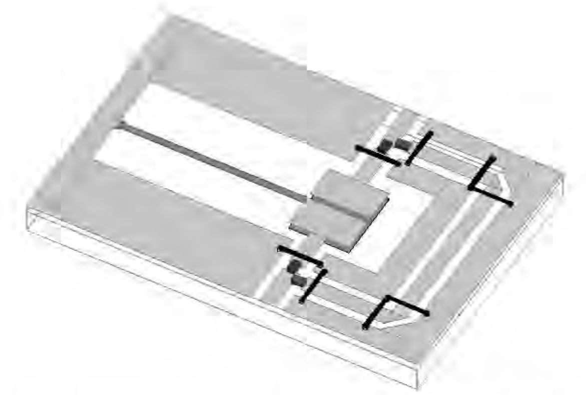

Fig. 5. Coplanar realization of the 45° digital phase shifter using the artificial quasi-lumped-element LH TL and the natural RH TL.

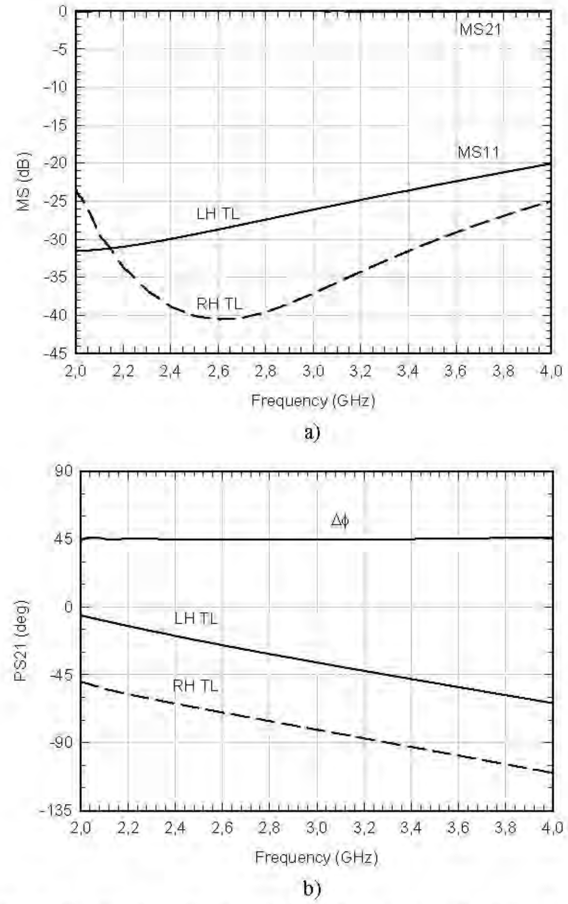

Fig. 6 Simulated amplitude and phase characteristics for the both states of the 45° phase shifter.

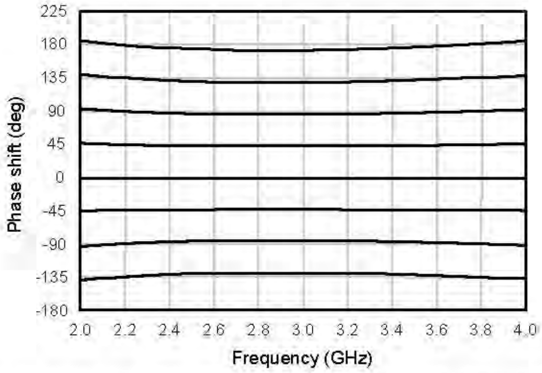

Fig. 7. Calculated phase shift versus frequency for all states of the 3-bit digital phase shifter based on switchable RH TL and LH TL.

implemented as the LH TL. The phase shifter size is $16.5 \times 11 \times 1.1$ mm^3. Simulated amplitude and phase characteristics for both states are presented in Fig. 6. The operating bandwidth is equal to one octave (2-4 GHz). In this frequency range the 45° phase shifter exhibits the phase shift error less than ±1.5°, the insertion loss about 0.15 dB, and the return loss better than 20 dB.

A multi-bit digital phase shifter based on switchable RH TL and LH TL can be designed by cascading several one-bit phase shifters (Fig. 1) with different values of the phase shift. For a digital N-bit phase shifter, the phase shift of the m-th bit is determined as $\Delta\varphi_m = 2\pi / 2^m$, where m = 1, 2, …, N. The equivalent electrical length at the central frequency should be chosen for both the RH TL and LH TL sections as $\Theta_0 = \Delta\varphi_m / 2$. Fig. 7 shows calculated frequency dependence of the phase shift for all eight states of a 3-bit phase shifter based on switchable RH TL and LH TL sections. The predicted phase shift error in the bandwidth of one octave (2-4 GHz) is ±2° for small values of the phase shift and ±8° for the highest value of the phase shift. The return loss in the same bandwidth is estimated as 19 dB in the worst case.

Conclusion

The method to design broadband digital phase shifters using specific dispersion properties of metamaterial transmission lines was reported. Practical realizations of the phase shifters based on switched RH TL and LH TL sections were presented. The results obtained proof the feasibility of the design approach and demonstrate a possibility to design a high-performance multi-bit phase shifter with the operational bandwidth of one octave.

References

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