

Applications of artificial transmission lines with active negative reactances to design of ultra-wideband microwave devices

D. V. Kholodnyak, V. M. Turgaliev, A. S. Rusakov, P. A. Turalchuk, I. B. Vendik

Microwave Microelectronics Laboratory, Department of Microelectronics & Radio Engineering, St. Petersburg Electrotechnical University "LETI"
5, Prof. Popov Str., 197376, St. Petersburg, Russia
Fax: + 7 (812) 3460867; email: Dmitry.Kholodnyak@mwlab.spb.ru

Abstract

Advantages of artificial transmission lines with negative reactances are considered as applied to design of ultra-wideband microwave devices. The use of specific dispersion properties of the right- and left-handed transmission lines consisting of negative reactances to achieve flat 0° , 90° , and 180° phase characteristics over a wide frequency range is demonstrated. Potential applications are outlined and illustrated by some examples. Practical implementation of negative reactances as negative impedance converters based on a pair of transistors is discussed.

1. Introduction

The non-Foster networks containing active negative reactances are very promising for a design of microwave devices with a drastically extended operational frequency band [1], [2]. In practice, a negative capacitance or inductance can be realized as a negative impedance converter (NIC) using a pair of transistors [3]. Artificial transmission lines (ATLs) consisting of negative reactances exhibit completely different dispersion properties with respect to those of the normal right-handed (RH) and left-handed (LH) transmission lines (TLs). The transmission coefficient phase of a negative-reactance ATL (either RH or LH) rises with increasing frequency. A proper combination of RH TL, LH TL, and negative-reactance ATL sections makes it possible to achieve a flat phase characteristic over a wide frequency range. It offers a great opportunity to design ultra-wideband directional couplers, filters, phase shifters etc. The applications and some design examples are discussed in the paper.

2. Artificial transmission lines consisting of positive/negative reactances

Though the unit cells of artificial RH and LH TLs are generally the low-pass and high-pass structures (see insets in Fig. 1-a and Fig. 1-b), there is a clear difference between TL sections and filters. The transmission-line approach is very popular because it allows an easy control of the input matching and the incurred phase by choosing proper values of the TL characteristic impedance Z_0 and the electrical length θ , correspondingly. The equations for *LC*-parameters of the unit cells of artificial RH and LH TLs given through the parameters Z_0 and θ can be found in [4].

The dispersion properties of RH and LH TLs result in a linear (Fig. 1-a) or non-linear (Fig. 1-b) decrease of the phase characteristic for increasing frequency, respectively. Assuming the unit-cell *LC*-parameters can be negative, one can obtain very specific dispersion properties. A rise of the phase characteristics could be achieved for artificial RH and LH TLs employing negative reactances. A RH TL with negative series inductors and shunt capacitors provides a linear rising phase of the traveling wave (Fig. 1-c) whereas a LH TL with negative series capacitors and shunt inductors gives a non-linear rise of the phase (Fig. 1-d).

Note that the phase characteristics shown in Fig. 1 correspond to the perfect infinite periodic ATLs consisting of the unit cells shown in insets. These ATLs are considered to be perfectly matched.

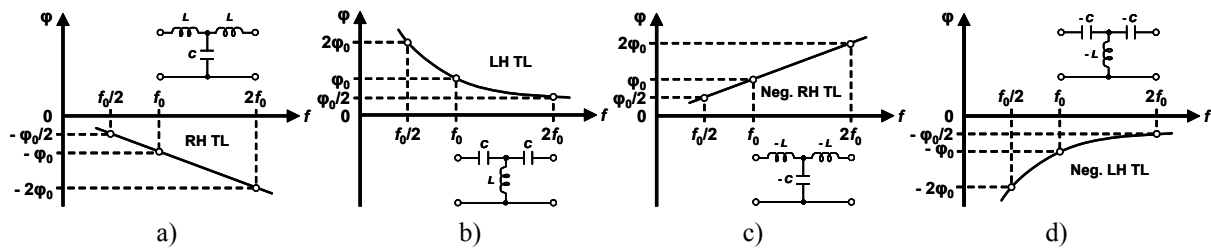


Fig. 1: Phase characteristics of different artificial transmission lines: (a) RH TL; (b) LH TL; (c) negative-reactance RH TL; (d) negative-reactance LH TL. Insets illustrate unit cells of the transmission lines.

Using a combination of artificial RH and LH TLs with both positive and negative reactances, one can engineer ATL sections exhibiting a flat phase characteristic over an extended frequency range [2].

Let us consider a cascade of a RH TL section (Fig. 1-a) and a negative-reactance RH TL section (Fig. 1-c) of the same characteristic impedance Z_0 . If the phases incurred by the TL sections at the central frequency f_0 are the same by absolute value but of opposite signs: $-\varphi_0$ and φ_0 , the overall phase incursion along such a network is $\varphi = -\varphi_0 + \varphi_0 = 0^\circ$. It is clear from Fig. 1-a and Fig. 1-c that the 0° phase characteristic is perfectly flat within the whole operational frequency band. The same result can be obviously obtained by a cascade of LH TL section (Fig. 1-b) and negative-reactance LH TL section (Fig. 1-d). The broadband networks with the perfectly flat 0° phase characteristic can find various practical applications including in-phase power division [5], switchable channel phase shifters etc. Note, that RH TL can be implemented as a natural TL section: stripline, microstrip, coplanar etc.

A phase incurred by a cascade of RH TL section and negative-reactance LH TL section (or vice versa) can amount to -90° ($+90^\circ$) with the only deviation of $\pm 11.25^\circ$ over the two-octave bandwidth. Such a network can be considered as a broadband immittance inverter that is well suited for the design of wideband and multiple-band filters. As an example a triple-bandpass filter for WLAN applications at 2.45 GHz, 3.5 GHz, and 5.5 GHz was designed. Besides, the 90° flat-phase ATLs are beneficial for the design of broadband directional couplers. The branch-line directional coupler with the operational bandwidth extended to one octave (2:1) was reported in [2] as the first example. Using the same concept we have recently designed an ultra-wideband branch-line directional coupler for application in 3.1-10.6 GHz frequency band (3.42:1).

A similar approach can be used to engineer an ATL with a 180° phase characteristic as a combination of RH and LH TL section with positive and negative reactances. However, the phase variation within the operational bandwidth of such 180° ATL will be twice more with respect to the 90° phase ATL. Instead, we suggested a different non-Foster network exhibiting the constant 180° phase incursion and the perfect input matching in an almost unlimited frequency range [6]. The network can be considered as two cascaded identical capacitive Π -circuit immittance inverters [6], which are in turn a particular case of an ATL with $\theta = 90^\circ$. This frequency-independent phase inverting network is very suitable for a design of ultra-wideband 180° phase shifters. Furthermore, it can be favorably used to enhance the operational bandwidth of a rat-race ring by replacing the 270° long TL section with a combination of a 90° TL section and the broadband 180° ATL.

3. Practical implementation using real transistors

The NICs based on a pair of transistors are used for practical implementation of negative reactances [3]. Either bipolar transistors or field-effect transistors (FETs) can be employed. Nonlinear effects, stability, and power efficiency considerations have to be taken into account while designing a network containing active components.

Fig. 2 presents the design and characteristics of the 90° ATL based on a natural RH TL section and an artificial negative-reactance LH TL. The ATL for S-band applications (2-4 GHz) was implemented on $23 \times 30 \times 0.5 \text{ mm}^3$ Arlon 250 printed circuit board (PCB) using NE3210S01 hetero-junction FETs by NEC and surface-mount components of biasing networks. The simulation revealed that, the amplitude

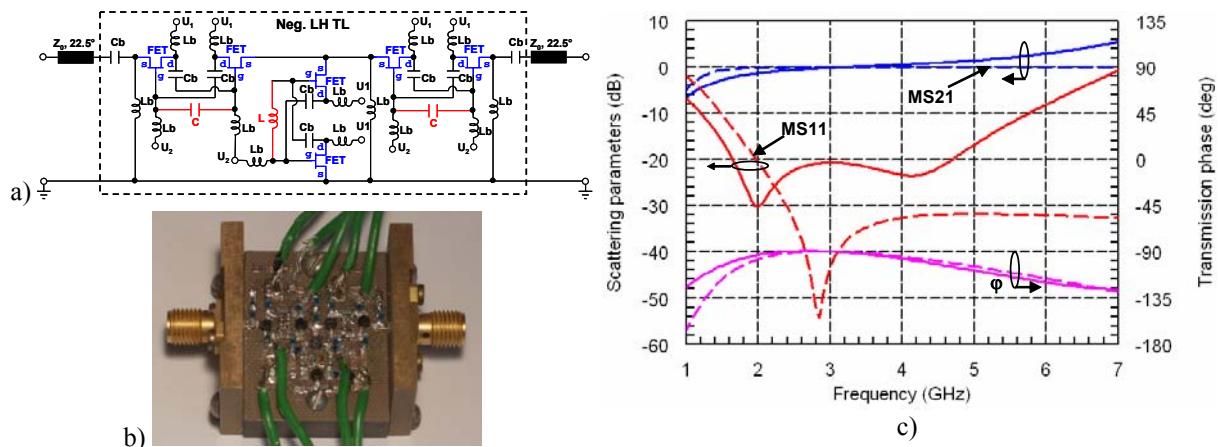


Fig. 2: The 90° negative-reactance ATL: (a) the equivalent diagram with biasing networks; (b) a test structure; (c) characteristics simulated using idealized FETs (dashed lines) and model parameters of NE3210S01 (solid lines).

and phase characteristics of the ATL based on idealized FETs, which were simulated using the Curtis model with no parasitics taking into account, are close to the characteristics of the network with ideal negative reactances in a very broad frequency band. Parasitics of a real transistor, especially the lead inductance of discrete components, narrow the frequency band where the two networks can be considered as equivalents. According to the simulation results, employment of NE3210S01 FETs provides the specified bandwidth of one octave for the 90° ATL under consideration. Within the frequency band 2-4 GHz the return loss is better than 20 dB, the phase error does not exceed 6° (Fig. 2-c). Since the network stability factors are $K > 1$ and $B_1 > 0$, the network is unconditionally stable in the operational bandwidth. A preliminary experimental investigation has proved the ability of the developed 90° ATL to operate as it was predicted by the simulation.

Unpackaged transistors having less parasitics are preferable to be used rather than the packaged ones. A high potential of the networks proposed can be realized to the best advantage by moving from discrete components to a monolithic implementation.

4. Conclusion

It has been demonstrated that different combinations of RH and LH TLs with positive and negative reactances allow providing 0°, 90°, and 180° flat-phase characteristics within a wide frequency range. Advantages of using these non-Foster networks to design broadband microwave devices have been considered. Practical implementation of negative-reactance ATLs with the aid of NICs based on real transistors has been discussed.

References

- [1] S.E. Sussman-Fort and R.M. Rudish, Non-Foster impedance matching of electrically-small antennas, *IEEE Trans. Antennas and Propagation*, Vol. 57, No. 8, pp. 2230-2241, 2009.
- [2] D. Kholodnyak, I. Munina, P. Kapitanova, V. Turgaliev, A. Rusakov, P. Turalchuk, I. Vendik, D. Stöpel, S. Humbla, J. Müller, and M.A. Hein, Broadband directional couplers and power dividers based on metamaterial transmission lines, *Proceedings of Metamaterials'2010*, pp. 591-593, Karlsruhe, Germany, 13-16 September 2010.
- [3] J.G. Linvill, Transistor negative impedance converters, *Proceedings of IRE*, Vol. 41, pp. 725-729, 1953.
- [4] I.B. Vendik, D.V. Kholodnyak, and P.V. Kapitanova, Microwave phase shifters and filters based on a combination of left-handed and right-handed transmission lines, in *Metamaterials Handbook, Vol. II. Applications of Metamaterials*, Edited by F. Capolino, Taylor & Francis – CRC Press, 2009.
- [5] M.A. Antoniadis and G.V. Eleftheriades, A broadband series power divider using zero-degree metamaterial phase-shifting lines, *IEEE Microwave and Wireless Comp. Lett.*, Vol. 15, No. 11, pp. 808-810, 2005.
- [6] D. Kholodnyak, V. Turgaliev, A. Rusakov, K. Zemlyakov, and I. Vendik, A frequency independent phase inverting all-pass network suitable for a design of ultra-wideband 180° phase shifters, *Proceedings of 41st European Microwave Conference*, Manchester, UK, 10-13 October 2011 (accepted).