Left-Handed Transmission Lines and Filters with Low-Loss and Broadband Characteristics

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1. Introduction

As there is a growing interest in metamaterials and left-handed (LH) materials, it is necessary to develop new approaches to better understand these structures and discover their potential applications. We propose here a transmission line (TL) approach of left-handed materials that presents the advantage of being based on a well-established method and of providing at the same time an insight very different from that of previous approaches. In addition, we introduce practical discrete elements and microstrip realizations of the LH-TL, which exhibit good transmission characteristics, and might therefore be integrated into realistic microwave applications.

2. The transmission line (TL) approach of LH materials

The ideal LH-TL is the electrical dual of the conventional right-handed (RH) line, in which the inductance/capacitance have been swapped (S. Ramo, J.R. Whinery and T. Van Duzer, "Fields and waves in communication electronics", Wiley, 1994) and also series/parallel arrangements have been inverted in the presence of losses. In this line, left-handedness is straightforwardly understood from the propagation constant, which reads in the lossless case: $\beta(\omega) = -1/(\omega\sqrt{LC})$, and yields the antiparallel velocities $v_p = -\omega^2\sqrt{LC} < 0$ and $v_g = +\omega^2\sqrt{LC} > 0$. This line, in which the characteristic impedance is still the same as in the conventional line $Z_c = \sqrt{(L/C)}$, exhibits equivalent parameters $\varepsilon(\omega) = -1/(\omega^2 L)$ and $\mu(\omega) = -1/(\omega^2 C)$, which are shown to satisfy the entropy condition and to be associated with a negative index of refraction $n = -\sqrt{(\varepsilon_r\mu_r)}$. The present expression for $\varepsilon(\omega)$ is similar to that proposed in previous works at low frequencies, but the expression for $\mu(\omega)$ is different from previously reported "plasma-like" expressions, which are of a resonant type and therefore associated with a very narrow bandwidth. An essential characteristic of the LH-TL is that it is theoretically lossless, with infinite bandwidth and moderate to small dispersion (zero dispersion when $\omega\rightarrow\infty$), which are three remarkable features not shared by previously reported LH structures.

3. Principle of realization of an artificial LH-TL

In the transmission line approach, a LH line of length p with arbitrary *times unit length* series capacitance (C') and parallel inductance (L') is realized in a *discrete lumped-elements* form by repeating periodically (period is just a convenience, not an EM condition!) N times a unit cell constituted of a series capacitor (C_u) and a shunt inductor

(L_u). In the presence of losses, prescribed by a *times unit length* admittance (G') and resistance (R'), a conductance (G_u) in parallel with C_u and a resistance (R_u) in series with L_u are naturally added to the unit cell. The values of $C_u/L_u/G_u/R_u$ in each cell are set as the times unit length corresponding parameters of the line *divided* by the length of the unit cell p_u, where $p_u=p/N$ (e.g. $C_u=C'/p=C'N/p$). In this manner, the information on the length of the line is included in the values of the $C_u/L_u/G_u/R_u$ elements. The approximation of the line obtained thereby is excellent in condition that the immittances ($Z'dz/Y'dz$) values of the unit cell be sufficiently small, which ensured by the condition $p<<\lambda$, naturally satisfied in a lumped-elements realization. The resulting ladder-type circuit is fundamentally a *highpass filter*, the cutoff frequency of which is the cutoff of the lumped-elements approximation, given by $1/(4\pi\sqrt{(L_u C_u)})$ when $N\rightarrow\infty$. At frequencies sufficiently higher than cutoff, the circuit is perfectly equivalent to the theoretical LH line, with lossless transmission (if $G'=0$ and $R'=0$ have been chosen) and moderate dispersion over an unlimited bandwidth from cutoff to infinity. The only difference with the ideal line is that the circuit exhibits left-handedness only above its cutoff frequency. A diversity of ladder-type circuits, with more complex transmission characteristics, can be designed in addition to the fundamental LH-TL described above, by introducing modification in the unit cell of the model.

4. Left-handedness identification procedure

In order to identify and characterize the left-handeness of the line, the following must be noted. The phase of the signal always starts to cumulate when the electrical length of the line is zero; the starting point for the phase is therefore the open-circuit point in the Smith Chart. In the LH-TL, the expression for $\beta(\omega)$ shows that λ is proportional to ω, and not to $1/\omega$ as in a RH-TL, in the same manner as in any highpass filter as a consequence of standard frequency transformation from lowpass. Therefore, it is at *infinity* that the electrical length of the line is zero, and the phase of the transmission parameter S_{21} rotates counter-clockwise as frequency *decreases* in the Smith Chart starting from the open-circuit point corresponding to $\omega=\infty$. To compute the ω–β diagram, it suffices then to unwrap the phase of S_{21} from $\omega=\infty$, take the opposite sign and divide by the length of the line, since $\beta=-\varphi\{S_{21}\}/p$. We show that this procedure yields a ω–β diagram in perfect agreement with the theoretical formula for the LH-TL down to cutoff. For other circuits, for instance with dispersive C_u and L_u, the LH range can be determined by inspection of the signs of the phase and group velocities computed form the $\beta(\omega)$ function.

5. Microstrip implementation of a LH-TL/Filter

In principle, the discrete realization of a LH line can be transposed to a *quasi-lumped* form in different technologies by translating the capacitors/inductors into their appropriate equivalent. We investigate here a microstrip LH structure mimicking the discrete elements approximation of LH-TL, using interdigital series capacitors and shorted-stub shunt inductors. Although these C/L components are strongly dispersive, they provide a good approximation of the ideal LH-TL over a broad bandwidth of the order of 100% with moderate losses. The proposed structure might be extended to a 2D diffraction surface, with potentially better performances than previous LH structures.

6. Conclusions

A TL approach has been proposed to describe LH materials and synthesize artificial LH lines/filters. Using this approach, the fundamental properties of LH materials have been derived in a simple manner. The principle of realization of the line using discrete elements has been demonstrated, and shown to exhibit left-handedness, without losses and with zero dispersion over an unlimited bandwidth above cutoff of the resulting highpass filter. The procedure to compute the dispersion diagram and thereby identify the left-handed effect has been described. A microstrip LH structure has been demonstrated, with characteristics approaching those of the discrete versions of the line, and therefore of potential interest for practical microwave applications. These might include for instance predistortion circuits for filters and active devices and enhanced forward couplers.