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Higher-order soliton-effect pulse compression in a nonlinear left-handed transmission line

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ABSTRACT

This work introduces a method of pulse compression based on a higher-order soliton effect in a left-handed nonlinear (LH-NL) transmission line with *series* nonlinear capacitances. A circuit simulation of the LH-NL transmission line which is based on a finite-difference method shows that if a higher-order soliton is replaced by a fundamental soliton launched into the line, the self-phase modulation (SPM) will dominate the group velocity dispersion (GVD). As a result, the pulse compression is realized in a specific length dependent on the soliton order.

1. Introduction

Negative refractive index, anomalous frequency dispersion, reversal of Snell's law, of the Doppler effect, and of the Cherenkov radiation are the electromagnetic effects appearing in left-handed (LH) metamaterials. They are not found in nature but are theoretically described by Veselago [1]. Researchers have implemented microwave transmission lines showing the LH metamaterials properties [2–4].

The LH transmission line is intrinsically a dispersive medium. Obviously adding nonlinearity to this transmission line can lead to novel microwave applications such as generation of soliton pulses, pulse shaping and compression [5,6]. It has been shown in [6,7] that the voltage distribution of a balanced composite right-left handed (CRLH) transmission line periodically loaded with *parallel* varactors satisfies a nonlinear Schrödinger (NLS) equation. Hence, bright and dark solitons can propagate along such transmission lines. In a previous work of the present authors [8], it was demonstrated by a reductive perturbation method that the spatial derivative of the voltage distribution of the LH-NL transmission line periodically loaded with a *series* nonlinear capacitance satisfies the NLS equation. Therefore, some methods of pulse shaping and compression such as the higher-order soliton-effect [9–15], self-modulation instability, higher-order nonlinear effect, and higher-order dispersion [9,10] can be used in the LH-NL transmission line [5,6], similar to the methods of nonlinear optics. In [16], the self-modulation instability causes generation of the trains of envelope soliton in the LH-NL transmission line. The reader is referred to [17–19] and their references for some of recent pulse compression techniques.

In this paper, we apply the higher-order soliton effect to pulse compression in a LH-NL transmission line periodically loaded with a *series* nonlinear capacitance and linear parallel inductances. In Section 2, the proposed structure is introduced. The higher-order soliton effect is discussed in Section 3. Simulation results for the verification of the analytical prediction are given in Section 4.

2. Structure of a LH-NL transmission line with series varactors

Fig. 1(a) and (b) shows three- and two- dimensional geometries of two adjacent cells of the proposed LH-NL transmission line in coplanar waveguide (CPW) technology. As shown, the direction of propagation is along the z axis. The stubs in these proposed structures play the role of shunt inductances. To suppress unwanted radiations for the transmission line, two successive stubs are alternatively connected to the two grounds planes of the CPW. Obviously, in certain frequency bands, series varactors and shunt inductors (L_L) turn this transmission line into a LH one. The voltage-dependent capacitance implemented from two zero-bias varactors connected back-to-back is responsible for the nonlinearity of this structure.

A circuit model of this structure is given in Fig. 1(c). Here, v_n and $u_n = v_n - v_{n+1}$ are the voltage of the nth node and the voltage across the nth varactor, respectively. In this model, node voltages and series branch currents are equivalent to the electric (E) and the magnetic (H) field of the actual structure, respectively.

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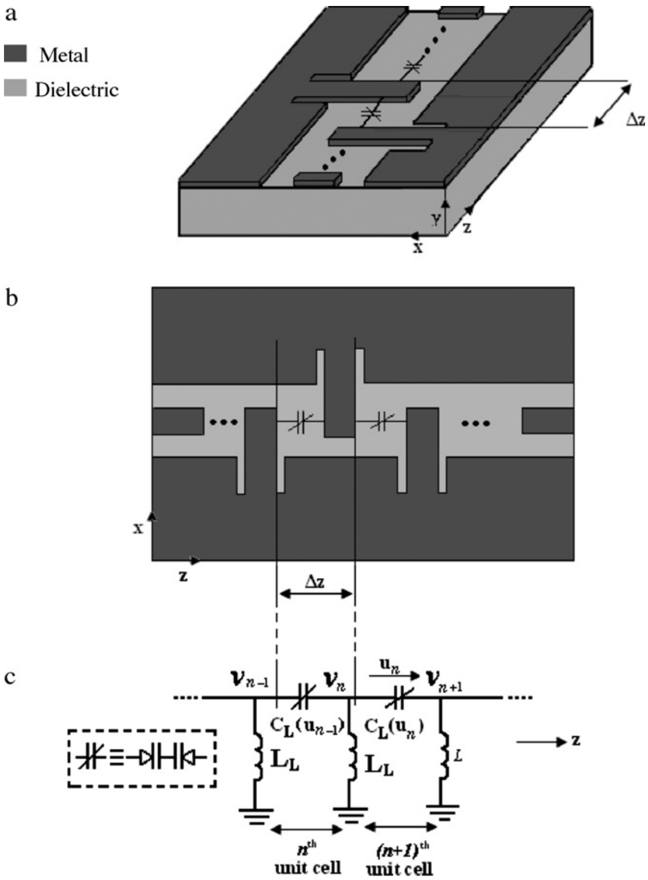

Fig. 1. (a) Configuration of a LH-NL transmission line view, (b) top view, (c) circuit model for the nth cell.

Due to simultaneously existence of the frequency dispersion characteristic and the SPM phenomenon, the LH-NL transmission line can be support soliton wave [5–8]. By making the assumption that the unit cell size (Δz) is very small compared to the wavelength of the propagated signal, it has been shown that the voltage across the varactor (U) satisfies the NLS equation [8]:

$$j\frac{\partial U}{\partial \tau} + P\frac{\partial^2 U}{\partial \xi^2} + Q|U|^2 U = 0, \tag{1}$$

in which

$$\xi = \varepsilon(Z - V_g T), \quad \tau = \varepsilon^2 T. \tag{2}$$

Note that ε is a parameter of small value, V_g denotes the group velocity of the envelope, and the variables T and Z are given by:

$$T = \frac{t}{\sqrt{L_L C_0}}, \quad Z = \frac{z}{\Delta z}, \tag{3}$$

in which L_L and C_0 are the shunt inductance and zero-bias capacitance of the LH-NL transmission line, respectively.

The dispersion coefficient of the NLS equation (P) is always positive but the sign of the nonlinearity coefficient (Q) is determined by the characteristics of the varactor. Depending on the sign of the product PQ, the proposed LH-NL transmission line can generate either bright or dark solitons.

Moreover, we expect that the higher-order soliton effect can be used to render the pulse compression.

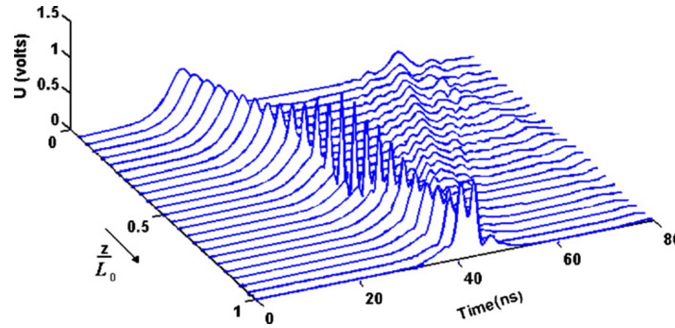

Fig. 2. Envelope waveform at different positions z/L_0 obtained by simulation for a hyperbolic secant excitation.

3. Higher-order soliton-effect pulse compression

In [8], it is demonstrated that the voltage across the varactor (U) of the LH-NL transmission line with the positive nonlinearity coefficient has a bright soliton solution given by:

$$U = A_0 \ \sec h\left(\frac{t}{T_0}\right)\cos(2\pi f t), \tag{4}$$

where

$$T_0 = \sqrt{\frac{8P}{QA_0^2}\frac{L_L C_0}{V_g^2}}, \tag{5}$$

in which P, Q are the coefficients of Eq. (1), and A_0 denotes the soliton amplitude. Now, we define the soliton order as follows:

$$N_s^2 = \frac{QA_0^2 T_0^2}{8P}\frac{V_g^2}{L_L C_0}, \tag{6}$$

If the soliton order is unity ($N_s = 1$), the soliton wave propagates unchanged along the proposed transmission line [8]. In other words, the interplay between the anomalous GVD and the SPM effects leads to soliton generation. But if N_s is less than unity or high dispersive regime, the GVD effect is dominant to the SPM effect and causes pulse broadening. In the case of $N_s > 1$ or high nonlinearity regime, the SPM effect is dominant that leads to periodic pulse shape changing [9,10] so that the pulse is compressed along certain length of the proposed transmission line.

4. Simulation and results

In order to verify the higher-order soliton effect, we have simulated the circuit model of the LH-NL transmission line of Fig. 1(c) with a linear shunt inductance 2.5 nH using well-known methods of circuit analysis. To this end, the circuit is connected to a source with 50 Ω resistance and a load with 50 Ω resistance. The number of cells between the source and the load are assumed to be 260. Now, the circuit is analyzed using a time domain technique based on finite-difference method. For obtaining the positive sign of Q, the varactor characteristic is selected to be $C(u) = 1^{pF}(1 + 3\beta u^2)$ with $\beta = 0.1$.

Now, an input signal with hyperbolic secant form is applied to the circuit model of the LH-NL transmission line, given by:

$$V_{in} = V_0 \ \sec h\left(\frac{t-\tau}{T_0}\right)\cos(2\pi f t), \tag{7}$$

where $V_0 = 1.1$ V, $\tau = 20$ ns, $T_0 = 2.5$ ns and $f = 2.7$ GHz. The simulation shows that the maximum amplitude of the voltage across the first capacitor (A_0) is 0.73 V. Therefore, the calculated soliton order is given by $N_s = 3.55$. The envelope waveform of the propagated pulse along the transmission line is illustrated in Fig. 2, where L_0 is the length of the LH-NL transmission line. Also, the pulse is seen compressed in a certain length of the line. The normalized voltages