Periodically Loaded Transmission Line With Effective Negative Refractive Index and Negative Group Velocity

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***Abstract*—We present the design and implementation of a periodically loaded transmission line, which simultaneously exhibits negative refractive index (NRI) and negative group delay (and, hence, negative group velocity). This is achieved by loading the transmission line in series with capacitors and *RLC* resonators and in shunt with inductors. We discuss the dispersion characteristics of such a medium and identify the frequency bands of NRI and negative group delay. The structures are theoretically studied using S-parameters simulations on truncated loaded transmission lines of different lengths, and the predicted results are compared to the measured scattering parameters of such lines printed on circuit boards using coplanar waveguide technology.**

***Index Terms*—Anomalous dispersion, coplanar waveguide, negative group delay, negative group velocity, negative refractive index (NRI).**

I. Introduction

The theoretical possibility for a medium having simultaneous negative permittivity and permeability was first considered by Veselgo in the late 1960s [1]. In these media, the sign reversal for both permittivity and permeability results in a negative index of refraction given by $\sqrt{\varepsilon}\sqrt{\mu}$.[1] Veselago predicted that media with a negative refractive index (NRI), here also referred to as metamaterials, would exhibit many unusual properties such as inverted Snell's law, Doppler shift, and Cherenkov radiation, in addition to unusual focusing properties [1], [2]. However, until recently, these concepts were not verified experimentally since materials with a NRI do not occur naturally. In recent studies, artificial periodic structures having both negative permittivity and permeability, and hence a NRI, have been constructed originally by a group in San Diego and later by a Toronto group [3]–[11]. Two different approaches have been used for synthesizing these periodic structures. In the San Diego approach, negative index materials have been constructed by using one and two dimensional periodic structures made up of split-ring resonators (SRRs) and metallic rods or strip wires (SWs) [3]–[6]. These bulky structures exhibit a NRI around the SRR resonant frequency and hence are inherently narrow-band and lossy. In the Toronto approach, artificial NRI materials have been synthesized by loading a cellular network of transmission lines with series capacitors and shunt inductors [7]–[11]. These structures are completely planar and do not explicitly rely on electric and magnetic resonances to achieve a NRI band; hence are low loss and broadband [11]. Moreover, these are readily scalable from RF and microwave to millimeter-wave frequencies bands (by choosing either chip or printed inductors and capacitors), and are easily fabricated using planar processing and monolithic integration, making them suitable for RF integrated circuit applications.

In this paper, the work by the Toronto group is extended to design a medium for which in addition to negative phase and positive group velocities (backward-waves), the medium also exhibits negative phase and negative group velocities.[2] To achieve this, a resonant circuit is embedded within each loaded transmission line (LTL) unit cell, in effect producing a region of anomalous dispersion for which the group delay is negative. Thus the proposed structure exhibits two important features: a NRI as well as a negative group delay (a negative group velocity.)

It should be pointed out that starting with the original work by Veselago in the late 1960s until the present time, there seems to be a confusion regarding the existence and the meaning of negative group velocity and hence of negative group delay [1], [3]–[5]. While a general discussion of negative group delays and negative group velocities, in slabs having a NRI or in structures consisting of SRRs and SWs is provided elsewhere [12]–[14], an important theoretical conclusion is the fact that under appropriately designed circumstances these metamaterials can exhibit negative group velocities or group delays, the meaning of which is discussed later.

This paper is organized as follows. In Section II, we briefly discuss the meaning of negative group velocity and group delay. Section III describes the dispersion characteristics and the frequency domain simulations of our proposed LTL. In Section IV we present our frequency domain experimental results for a coplanar waveguide realization of the LTL. Section V contains our final remarks and conclusions.

II. Negative Group Velocity and Negative Group Delay

It is a well-known fact that in some circumstances the phase velocity can exceed the speed of light in vacuum (c), hence

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[1]In other words, in this case, one has to choose the negative sign in front of the square root $\pm\sqrt{\varepsilon\mu}$.

[2]The terms positive and negative are used in reference to the incidence wave, i.e., the positive group velocity points away from the source, whereas the negative group velocity points toward the source.

becoming superluminal. However, in these cases, the group velocity, defined as the gradient of the dispersion relation $[\nabla_{\vec{\beta}}\omega\left(\vec{\beta}\right)]$ remains subluminal, thus preserving the requirements of causality and special relativity (Einstein's causality).[3]

Starting with Garret and McCumber's pioneering work [15] a large body of experimental and theoretical work has shown that under appropriately designed circumstances the group or even the energy velocity (defined as the ratio of Poynting vector to stored electromagnetic energy) can become superluminal or negative [[16]–[18] and references therein]. Despite the unsettling connotation associated with terms such as superluminality or negative group velocity, there is a simple physical meaning associated with negative group delay or group velocity. It simply means that in a passive medium supporting such abnormal velocities, the peak of the transmitted pulse (though reduced in magnitude) emerges prior to the peak of the incident pulse entering the medium [15], [16], [19]–[21]. Notwithstanding this abnormal behavior, there is no violation of relativistic causality since it has been shown that there are no causal connections between the incident and transmitted peaks [22], [23]. The essence of this unusual behavior can be described in terms of pulse reshaping in which the medium produces a close copy of the incident pulse (though reduced in magnitude) from the *early parts* of the input signal. As discussed in [16], [18], [21], [24], under no circumstances, the *earliest* part of the transmitted pulse known as the "front," precedes the "front" associated with the input pulse. In short, from the first principle point of view, the front velocity,[4] which is the velocity by which genuine information propagates, remains luminal at all times.

When discussing the problem of wave propagation in the frequency domain, it is more convenient to consider the concept of group delay. This is the delay experienced by the peak of a well-behaved wave packet as it travels in the medium. To discuss the subject of positive and negative group delays, consider the propagation of a narrowband, modulated Gaussian pulse $g(t)$ $(\mathrm{bandwidth} \ll \mathrm{carrier\ frequency}\,\omega_c)$ through a medium characterized by the transfer function $T(\omega) = |T(\omega)|\,e^{j\phi}$. Using the Fourier transform, the output (f_o) and input (g) are related according to [25], [26]

$$f_o(t) = Ag(t-\tau_g)\cos(\omega_c t - \omega_c \tau_p) \tag{1}$$

where τ_p and τ_g are the phase and group delays given by

$$\tau_p = \frac{\phi(\omega)}{\omega}\Big|_{\omega=\omega_c} \tag{2}$$

$$\tau_g = -\left.\frac{\partial\phi(\omega)}{\partial\omega}\right|_{\omega=\omega_c} \tag{3}$$

and A is a constant. When the quantity τ_g is positive, the peak of the output pulse suffers a positive delay with respect to the input. On the other hand, if τ_g is negative, the peak of the output pulse emerges prior to the peak of the input pulse entering the medium and the medium is said to exhibit a negative group delay.

[3]Recall that phase velocity is the velocity by which points of constant phase (e.g., nodes) of a monochromatic wave travel, whereas group velocity is the velocity of the peak (envelope) of a smoothly varying wave packet (pulse) with relatively narrow bandwidth.

[4]Mathematically fronts are points of nonanalyticity.

The relation between the group velocity and the group delay is given by

$$\upsilon_g = \frac{L}{\tau_g} = \frac{L}{\frac{-\partial\phi}{\partial\omega}} \tag{4}$$

where L is the physical thickness of the medium. From (4) it is clear that the sign of group velocity and group delay are the same. Moreover, in the case of a matched medium, i.e., when interface effects are negligible, the phase of the transfer function (ϕ) and the propagation constant (β) are related according to $\phi = -\beta L$. Now, assuming the photon dispersion relation $[\beta = \omega n(\omega)/c]$, the group velocity can be written in its familiar form as

$$\upsilon_g = \frac{L}{\frac{-\partial\phi}{\partial\omega}} = \frac{1}{\frac{\partial\beta}{\partial\omega}} = \frac{c}{n(\omega) + \omega\frac{dn(\omega)}{d\omega}}. \tag{5}$$

III. Frequency Domain Analysis of Periodically Loaded Transmission Lines

The study of periodic filters with the help of dispersion diagrams is a subject well-examined in electromagnetism [27], [28]. A transmission line, periodically loaded with lumped elements, is a periodic structure that can be considered as an effective medium provided that the dimensions of the unit cell are small as compared to the excitation wavelength. Consider a transmission line loaded with a series impedance Z_s and a shunt admittance Y_{sh}. Using the *ABCD* matrix technique [28], the complex propagation constant $(\gamma)$of the periodic structure is given by

$$\cosh\gamma d = \cos[(\alpha + j\beta)d] = \cos kd + j\frac{(Z_s + Y_{sh}Z_o^2)}{2Z_o}\sin kd + \frac{Z_sY_{sh}}{2}\cos kd. \tag{6}$$

Here, α and β are the attenuation and phase constants of the periodically loaded medium, whereas, k, Z_o, and d are the propagation constant, the characteristic impedance, and the length per unit cell of the unloaded line, respectively.

We can select the loading elements Z_s and Y_{sh} in such a way that the resulting LTL exhibits a region of anomalous dispersion and negative group delay in addition to having an effective NRI. For this purpose, we load the transmission line in series with a capacitor C_s and a $R_rL_rC_r$ resonator, and in shunt with an inductor L_{sh}. The unit cell of the proposed periodically LTL is shown in Fig. 1. The series impedance (Z_s) and shunt admittance (Y_{sh}) of (6) are then given by

$$Z_s = \frac{1}{j\omega C_s} - \frac{j\omega\frac{1}{C_r}}{\omega^2 - j\omega\frac{1}{R_rC_r} - \frac{1}{L_rC_r}} \tag{7}$$

$$Y_{sh} = \frac{1}{j\omega L_{sh}}. \tag{8}$$

Note that the resonant frequency of the parallel *RLC* resonator $f_o = 1/2\pi\sqrt{L_rC_r}$ is also approximately the center frequency of the region of anomalous dispersion.

Fig. 2 (solid curve) shows the dispersion diagram of the proposed periodic structure. The component values used to produce the curves are indicated in Fig. 1. The characteristic impedance

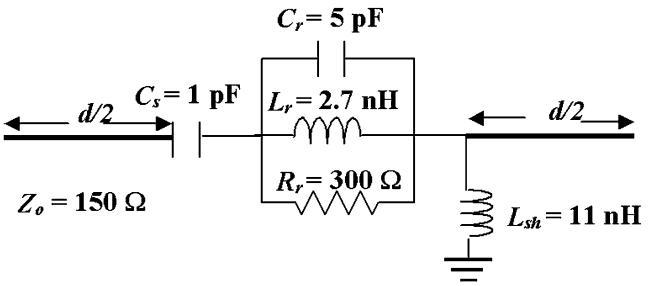


Fig. 1. Unit cell of the proposed loaded transmission line which exhibits NRI as well as negative group delay. Typical component values are also shown.

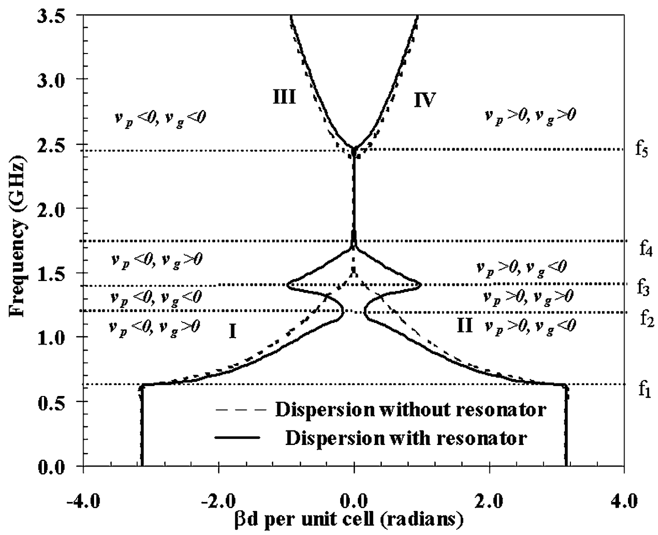


Fig. 2. Dispersion diagram (solid curve) of the proposed transmission line medium exhibiting simultaneous NRI and negative group velocity in the first passband. Dotted curve shows the dispersion of the periodic medium without the *RLC* resonators.

of the unloaded line used in the simulation is 150 Ω and the length of the unit cell (d) is 2 cm. The first passband extends from frequency f_1 to f_4 which also spans the region of anomalous dispersion ($f_2 < f < f_3$). The second stop-band ($f_4 < f < f_5$) and second pass-band ($f > f_5$), along with the appropriate signs for the phase and group velocities in each branch are also shown.

Fig. 2 indicates that within the first pass-band ($f_1 < f < f_4$) there are two branches that can describe the wave propagation in our periodically LTL. These branches are marked with symbols I and II. A question can then be asked: which of the two branches correctly describes the wave propagation through the structure? To answer this we may consider the following. First, the dashed curve in Fig. 2 shows the dispersion relation for a transmission line *without* the *RLC* resonant circuit. In [7], [8] such a transmission line was shown to exhibit an equivalent negative index of refraction, i.e., a negative value for βd, which designates branch-I as the appropriate choice. We may now consider the presence of the *RLC* resonator as a perturbation of the previously studied case, and as such we once again must choose branch-I as our dispersion curve. Second, the difference in the insertion phase for two transmission lines with different length can be used to deduce the proper branch. This point is discussed in the next section, and again it is seen that branch-I correctly describes the wave propagation in the LTL discussed here. Finally, we should note that within the second pass-band ($f > f_5$), the dispersive behavior depicted by the branch-IV properly describes the wave propagation for our LTL.

At this point, a few remarks regarding the relative signs of the phase and group velocity are in order. As Fig. 2 shows, within the first passband for branch-I and for frequencies $f_1 < f < f_2$ the phase and group velocities are antiparallel (have opposite signs). This traditionally describes backward-wave propagation [29] and is the regime under which the theoretical and experimental work in [3], [6]–[8] were carried out. The frequency range $f_2 < f < f_3$ of branch-I corresponds to the region of anomalous dispersion for which the phase and group velocities are parallel and both are negative. This frequency interval designates a band for which the term negative group velocity can be correctly used in connection with NRI metamaterials. The frequency range $f_3 < f < f_4$ is once again the region of backward-wave propagation, whereas for $f > f_5$ in branch-IV, the periodically LTL behaves as a normal medium with parallel and positive phase and group velocities.

So far we have only considered an infinitely long periodically LTL. In the following, the S-parameters[5] will be used to describe the response of a finite length periodically LTL, a unit cell of which was shown in Fig. 1. The number of unit cells (stages) is monotonically increased from one to four, and in order to closely emulate the experimental results the transmission line is terminated with a 50 Ω impedance.

Fig. 3(a) and (b) show the S_{21} (transmission function) magnitude and phase for the periodically LTL as the number of unit cells is increased. The frequency bands corresponding to the first and second passbands and stopbands along with the region of anomalous dispersion are also displayed. As expected, within the region of anomalous dispersion ($f_2 < f < f_3$), the transmission magnitude reaches a minimum value [Fig. 3(a)], and it is within this frequency band that the negative group delay is to be observed [30]. Fig. 3(b) shows the unwrapped transmission phase for the same range of frequencies. From the figure it is clear that within the region of anomalous dispersion ($f_2 < f < f_3$) the derivative of the phase function (ϕ) reverses its sign, hence implying the existence of a negative group delay and group velocity.

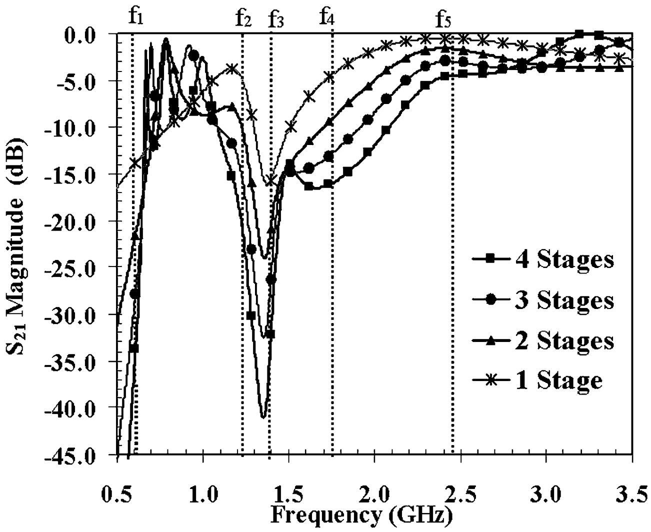
The fact that our periodically LTL, within the frequency bands $f_1 < f < f_4$, exhibits an equivalent negative index of refraction can also be verified from Fig. 3(b). Assuming an unbounded medium, i.e., neglecting the mismatches,[6] the difference between the insertion phases of two LTLs of lengths d_1 and d_2 is given by

$$\Delta\phi = \phi_2 - \phi_1 = -\frac{\omega n(\omega)}{c}\,(d_2 - d_1)\,. \tag{9}$$

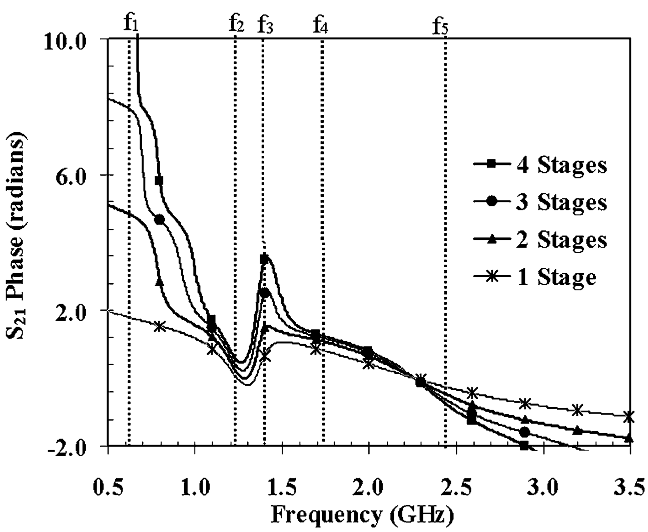
Note that for $d_2 > d_1$ and normal media ($n > 0$), the difference in the insertion phase calculated from (9) is negative ($\Delta\phi < 0$), whereas from Fig. 3(b), in the frequency band $f_1 <$

[5]The S-parameters were calculated using *Agilent-ADS*, S-parameter simulation tool.

[6]Including effects of the boundaries (mismatches) only complicates the calculations but will not change the final conclusions.



(a)



(b)

Fig. 3. (a) Calculated S_{21} magnitude for the periodically loaded transmission line of Fig. 1 with different number of stages. (b) Calculated unwrapped S_{21} phase for the periodically loaded transmission line of Fig. 1 with different number of stages.

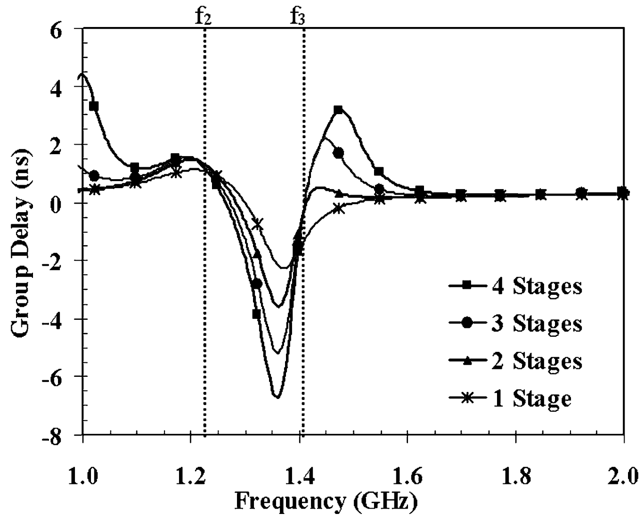


Fig. 4. Calculated group delay for the periodically loaded transmission line of Fig. 1 with one, two, three, and four stages. Figure only shows the region of anomalous dispersion and its vicinity.

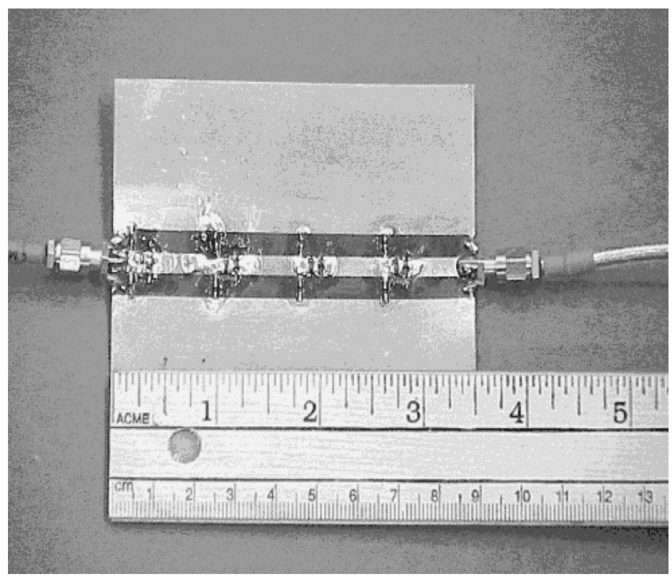


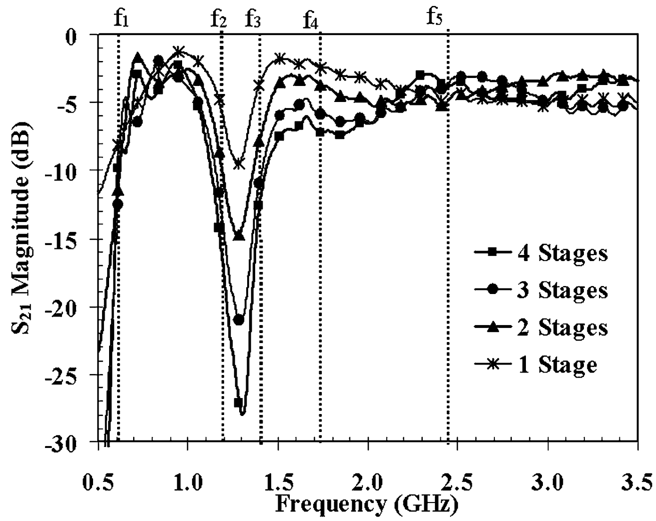
Fig. 5. Photograph of the 4-stage periodically loaded transmission line connected to a vector network.

$f < f_4$, $\Delta\phi$ is positive indicating an equivalent NRI. Interestingly, as Fig. 3(b) implies, for the second passband ($f > f_5$) $\Delta\phi$ is negative implying a normal transmission line operation. Finally, Fig. 3(a) and (b) signify the fact that as the number of stages increases, the finite length LTL more closely approximates the dispersion characteristics of infinitely long LTL depicted in Fig. 2.

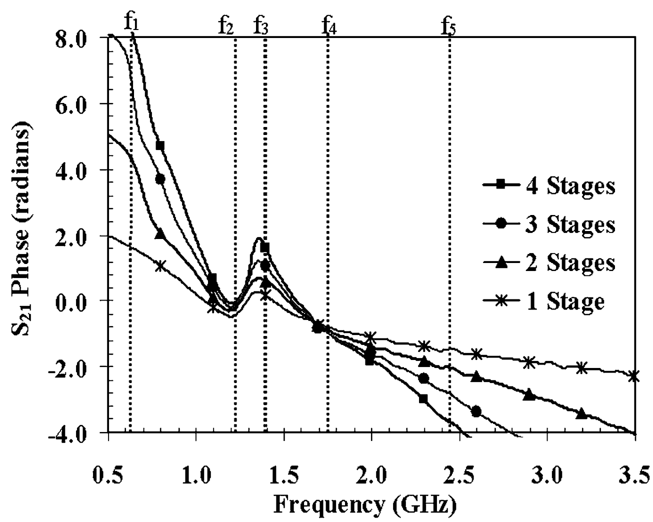
Fig. 4 shows the calculated group delay [(3)] for our periodically LTL with one, two, three, and four unit cells. In accordance with the results for an infinitely long periodically LTL depicted in Fig. 2, it is seen that for a finite length LTL, the group delay is negative within the frequency band $f_2 < f < f_3$, and is positive away from the anomalous dispersion region. It must be noted that as the length of the finite LTL is increased the amount of negative delay (in absolute value) is also increased. In other words, longer transmission lines produce more time advances (negative delays) as compared to shorter lines, however, at the cost of reducing the transmitted signal amplitude. In the next section a frequency domain setup is used to verify our theoretical predictions.

IV. Experimental Results

To verify our theoretical predictions a coplanar waveguide (CPW), printed on Rogers 5880 substrate with dielectric constant of 2.2 and thickness of 15 mil, was designed. The CPW line was periodically loaded with surface-mounted chips of size 1.5 mm by 0.5 mm, such that one unit cell was approximately 2 cm long. To perform the experiment, LTLs with one, two, three, and four unit cells were fabricated. Fig. 5 shows a periodically LTL with four stages connected to a vector network analyzer



(a)



(b)

Fig. 6. (a) Measured S_{21} magnitude of the periodically loaded transmission lines with one, two, three, and four unit cells. (b) Measured unwrapped S_{21} phase of the periodically loaded transmission lines with one, two, three, and four unit cells.

(HP-8722C). A full two-port calibration was performed and the transmission function (S_{21}) was measured.

The magnitude and phase of S_{21} are displayed in Fig. 6(a) and (b), respectively. The stop-, pass-, and the anomalous dispersion bands are also shown. Fig. 6(a) clearly indicates that, in accordance with the theoretical predictions of the previous section, as the number of unit cells is increased, the magnitude of the insertion loss also increases. Furthermore, as discussed earlier, in the frequency band $f_1 < f < f_4$ of Fig. 6(b), the phase difference between two LTL of different length ($d_2 > d_1$) is positive, implying that the periodically LTL exhibits an effective NRI. On the other hand, for $f > f_4$, $\Delta\phi$ is negative, indicating a normal transmission line behavior. Finally, in Fig. 6(b) the region of anomalous dispersion ($f_2 < f < f_3$) can be identified by the reversal of the curve's slopes.

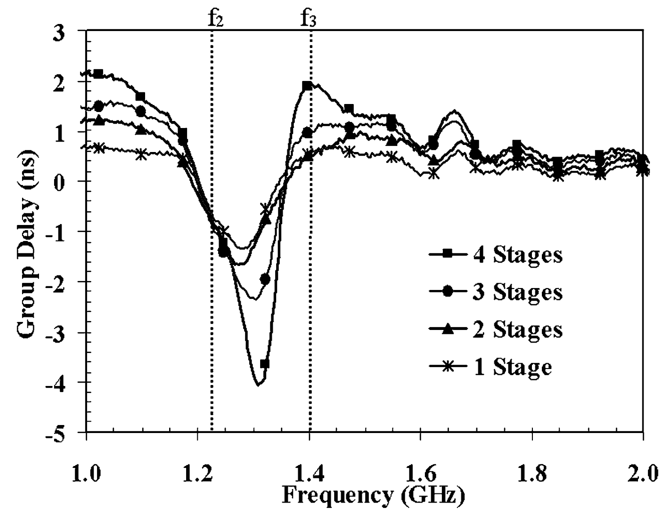


Fig. 7. Measured group delay for the periodically loaded transmission line with one, two, three, and four unit cells. Larger negative delays are measured for longer transmission lines.

While the overall agreement between the theoretical predictions of Fig. 3(a) and (b) and the experimental results of Fig. 6(a) and (b) is relatively good, in general, in comparing these curves a shift of 50 to 80 MHz can be detected. For example, the experimental value for the center frequency of the region of anomalous dispersion is 1.29 GHz, whereas the theoretically predicated value is approximately 1.37 GHz. Moreover, around the resonances, more losses are predicted by the simulations as compared to the experimental results.

These discrepancies can be taken into account by considering a few factors. First, in all our simulations we have used the nominal values associated with the surface-mount lumped elements provided in their data sheets. Our experience has shown that in many cases, in part due to the embedded parasitics, the actual measured values can be different. Second, in our simulations the resistance and conductance associated with the inductor L_r and the capacitor C_r were ignored. The effect of this series resistance for the inductor and conductance for the capacitor is to reduce the overall impedance of the parallel *RLC* resonant circuit, hence reducing the theoretically predicted insertion losses. Third, for the LTLs with more than one stage, the resonant frequency for each stage is slightly different from the others due to variations in the component values. This nonhomogeneity was not taken into account in our theoretical model and in practice it broadens the anomalous dispersion region, thus reducing the overall measured insertion losses in addition to decreasing the slope of the phase within this region.

The group delay for each truncated LTL is shown in Fig. 7. The frequency band of interest is the anomalous dispersion region in which the group delay is more negative for longer transmission lines. The measured maximum group delay for the four cell LTL is approximately -4 ns compared to -7 ns obtained from the simulations. This difference is attributed to the decrease in slope of the transmission phase as discussed above.

V. Conclusion

We present the design and implementation of a periodically LTL that simultaneously exhibits a NRI and a negative group velocity. The proposed transmission line structure is loaded in series with capacitors and resonant *RLC* circuits and in shunt with inductors. The series-C and shunt-L configuration produces backward propagating waves leading to a NRI [11] while the negative group delay is obtained around the resonance of the *RLC* resonator.

It is seen that within the region of NRI, for some frequency bands, the phase and group velocities are anti-parallel. For these frequencies, the term backward-wave is used to emphasize the positive group and negative phase velocities. It is also observed that within the NRI region, one can detect a region of anomalous dispersion for which the phase and group velocities are parallel and both negative. The causal meaning of the negative group velocity, or equally negative group delay, as the shift of the output peak to an earlier time as compared to the input peak is discussed. Finally, a comparison between theoretically predicted and experimentally measured results is provided and a few factors underlying the differences are discussed. The proposed transmission line could be utilized for delay and dispersion management applications on high-speed interconnects and antenna feed networks.

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