Time-Domain Measurement of Negative Group Delay in Negative-Refractive-Index Transmission-Line Metamaterials

Omar F. Siddiqui, Suzanne J. Erickson, George V. Eleftheriades, *Senior Member, IEEE*, and Mohammad Mojahedi, *Member, IEEE*

***Abstract*—We have simulated and constructed a one-dimensional metamaterial composed of a periodically loaded transmission line that exhibits both negative and positive group velocities in a band of effective negative index of refraction. The negative group velocity or, equivalently, the negative group delay, is demonstrated theoretically and experimentally in the time domain using modulated Gaussian pulses. Due to this negative delay, we can show an output pulse peak emerging from the loaded transmission line prior to the input peak entering the line, i.e., the output pulse precedes the input pulse. The fact that this surprising behavior does not violate the requirements of relativistic causality is illustrated with time-domain simulations, which show that discontinuities in the pulse waveforms are traveling at exactly the speed of light in vacuum. The pulse-reshaping mechanism underlying this behavior is also illustrated using time-domain simulations.**

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

I. Introduction

In RECENT years, there has been a great deal of interest in artificial materials that have an effective negative refractive index (NRI). These media, also referred to as "left-handed" metamaterials, have properties not found in naturally occurring materials.

It is generally agreed that the phase velocity of an electromagnetic wave in these media is negative according to

$$v_p = \frac{c}{n} \tag{1}$$

where c is the speed of light in vacuum and n ($n < 0$) is the index of refraction. However, there has been some confusion regarding the sign of the group velocity, which is given by[1]

$$v_g = \frac{c}{n(\omega) + \omega\left(\dfrac{dn}{d\omega}\right)}. \tag{2}$$

It was initially stated that left handedness was equivalent to having a negative group velocity (NGV) [1], and that an NGV is a necessary characteristic of left-handed metamaterials [2]. Additional conflicting assertions regarding the existence of an NGV in left-handed media can be found in [3] and [4]. Nevertheless, more careful examination has shown that both the thin-wire split-ring resonator structure of [3] and the *L–C* loaded transmission-line grid of [5] and [6] support *negative phase, but positive group velocities* in the frequency bands originally considered [7], [8].

The confusion discussed above should not lead us to believe that NGVs do not exist at all, in either negative or positive index media. In the pioneering theoretical work of Garrett and McCumber [9], as well as in more recent theoretical and experimental studies [10]–[13], it has been shown that superluminal group velocities (i.e., faster than the speed of light in vacuum c) and NGVs exist, and can be measured.

Superluminal group velocities and NGVs, collectively described as abnormal group velocities, have been experimentally observed in regions of anomalous dispersion in positive index media, and in structures such as photonic crystals, side-by-side prisms, undersized waveguides, resonant circuits, etc. [10], [14]–[18]. Despite an early and somewhat persistent misinterpretation of these experimental results, abnormal velocities do not contradict the requirements of relativistic causality [13], [19]. In fact, it has been shown that negative and superluminal group velocities are the natural consequence of the Kramers–Kronig relations, which, in and of themselves, define linear and causal system behavior [12]. From a theoretical point-of-view, information never travels faster than c in the experiments cited above since group velocity and information velocity are not identical under all circumstances.

Group delay, a concept closely related to group velocity, provides a convenient way to describe the velocity of propagation of electromagnetic wave packets. For a well-behaved wave packet, the group delay is the time delay the pulse envelope experiences as it travels through a medium of length L. This delay is related to the group velocity according to

$$\tau_g = \frac{L}{v_g}. \tag{3}$$

Group delay is also related to the frequency derivative of the transmission phase $\angle T(\omega)$ as follows:

$$\tau_g = -\frac{\partial \angle T(\omega)}{\partial \omega}. \tag{4}$$

Definition (4) is more versatile since it applies both to media with a large spatial extent ($L \gg \lambda$) and to lumped-element

Manuscript received September 25, 2003; revised December 18, 2003. This work was supported by the Natural Sciences and Engineering Research Council of Canada under Grant RGPIN 249531-02 and Grant 203037-02, and by Photonics Research Ontario under Project 03-26.

The authors are with the Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada M5S 3G4 (e-mail: mojahedi@waves.utoronto.ca).

Digital Object Identifier 10.1109/TMTT.2004.827018

[1]Equation (2) assumes matched media, i.e., interface effects are neglected. However, these generally small effects are included in our analysis unless otherwise indicated.

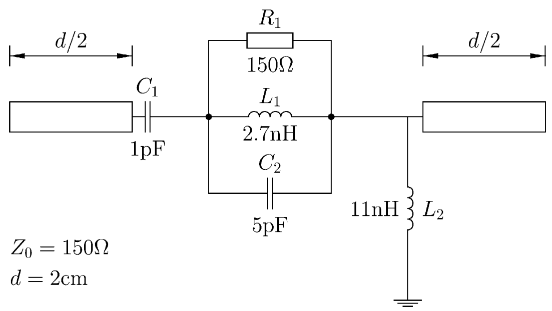


Fig. 1. Unit cell of the PLTL that exhibits the NRI and NGD. Typical component values are shown: Z_0 is the characteristic impedance of the transmission line.

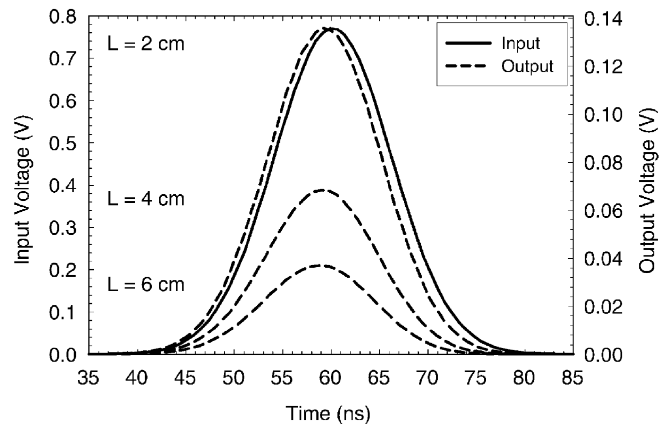


Fig. 2. Time-domain simulations showing the NGD for the 2-, 4-, and 6-cm transmission lines with delays of -0.89 ns, -1.17 ns, and -1.53 ns, respectively.

configurations where the device size is much smaller than the operating wavelength ($L \ll \lambda$).

Under normal circumstances, the group delay is positive, implying that the peak and, hence, the envelope, of the output pulse is delayed with respect to the input peak. On the other hand, when there is a negative group delay (NGD), the peak of the output pulse is advanced, i.e., it precedes the input peak. Causality is not violated by this counterintuitive behavior since there is no causal connection between the input and output peaks [20].

In light of the confusion surrounding NGVs in metamaterials [1]–[4], we may ask whether it is possible to design a left-handed medium that exhibits *negative phase velocities and NGVs* in the same frequency band. In this paper, we describe the time-domain behavior of such a medium, a one-dimensional (1-D) loaded transmission line that supports both positive group velocities and NGVs within the NRI band. The frequency-domain characteristics of this device, including the dispersion relationship and S_{21}-parameters, have been previously discussed in detail in [21]. Section II presents new time-domain simulations, and Section III presents the corresponding time-domain measurements. Final thoughts and remarks can be found in Section IV.

II. Time-Domain Simulations

Fig. 1 shows the loading elements for a 1-D transmission line supporting an NGV in the NRI band. The negative effective index is due to the series capacitor and shunt inductor [5], [6], and the NGV is due to the anomalous dispersion band produced by the *RLC* resonator. With an appropriate choice of component values, the NGD and, thus, the NGV, can occur within the NRI band.

A. NGD

In order to simulate the time-domain behavior, three loaded coplanar waveguide (CPW) transmission lines with unit cells depicted in Fig. 1 were considered. The total lengths of the lines were 2, 4, and 6 cm with 1–3 unit cells, respectively. The transmission lines were excited with Gaussian pulses of temporal length 30 ns, modulated at the resonance frequency of the series *RLC* loading element, 1.3 GHz. The components used in the simulation were assumed to be ideal. Substrate and conductor losses due to the waveguide were taken into account; the numerical values used for the loss tangent, dielectric constant, and conductor thickness were obtained from the Rogers 5880 specifications with a conductor thickness of 17 μm.

These simulations were performed using Agilent Technologies' Advanced Design System (ADS). ADS calculates the signal exiting any distributed structure by convolving the input time-domain signal with the calculated impulse response of the structure. For any element with an exact lumped equivalent model—e.g., a resistor, capacitor, or inductor—ADS calculates the output signal entirely in the time domain without using an impulse response [22].

Fig. 2 shows the calculated voltage waveforms at the input and output of the loaded lines. The peaks of all three output pulses *precede* the input peaks by an amount proportional to the length of the line. In other words, since the longer lines have more unit cells, they generate a greater NGD. This negative delay is mostly due to the series *RLC* resonator and, thus, resonant absorption losses are also introduced, as indicated by the drop in magnitude of the output voltage waveforms. For example, in the case of the 2-cm transmission line, a negative delay of -0.89 ns is predicted, while the output voltage peak is approximately 15% of the input. Note that some of the predicted losses are due to mismatched impedances between the loaded transmission-line section (150 Ω) and the source (50 Ω).

B. Luminal Front Velocity

Fig. 2 shows that the pulse peak and, hence, the pulse envelope, suffers a negative delay. Thus, the pulse propagates with an NGV. Contrary to the traditional point-of-view, negative and superluminal group velocities are, therefore, physical and measurable, and do not contradict the requirements of relativistic causality.

Every causal signal has a starting point in time before which the signal was nonexistent. This starting point is marked by a discontinuity in the pulse envelope or in higher order derivatives of the envelope, at which point the pulse is no longer analytic. These points of nonanalyticity are the conveyers of genuine information; they can be shown to propagate at exactly c [13], [19], [23], and thereby fulfill the conditions of causality.

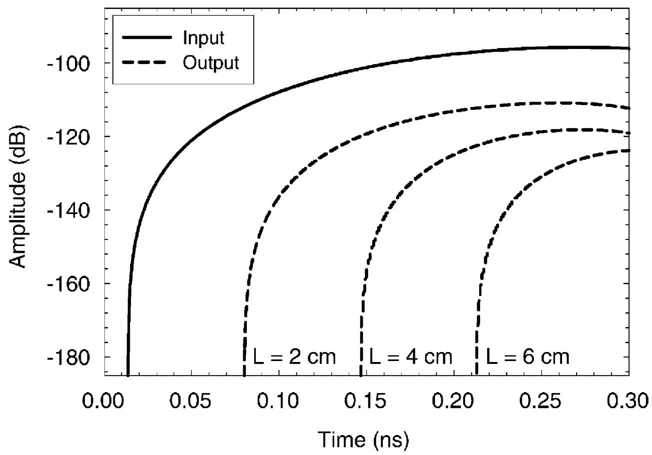


Fig. 3. Modulated pulse fronts from time-domain simulations, plotted on a logarithmic (decibel) scale. The input pulse front always precedes the output front by a time equal to L/c, where L is the length of the line.

The propagation of these discontinuities can be examined using time-domain simulations. The discontinuities in the pulse waveform were established by introducing a "turning-on" point, commonly referred to as the pulse "front." The propagation of the front through the NRI–NGV loaded transmission lines of different lengths can be seen by examining the first 0.3 ns of propagation, shown on a logarithmic scale in Fig. 3. The output pulse fronts for the three circuits all suffer the expected *positive luminal delay* with respect to the input fronts, given by L/c, where L is the length of the transmission line. Thus, the simulations show that causality is preserved since the discontinuities in the pulse travel at exactly the speed of light in vacuum.

While the simulations indicate the causal propagation of information in the points of nonanalyticity, the amplitudes associated with these fronts are particularly small, making their experimental detection a challenging task. This difficulty is the reason that the "signal" we detect practically is not the pulse front, but the maximum or half-maximum of the pulse envelope, which, in turn, can be made to propagate superluminally or with negative velocities.

C. Physical Mechanism Underlying NGD

The mechanism behind the pulse advancement can be explained in terms of pulse reshaping [24]. Using MATLAB, we can study the time evolution of a pulse by considering the spatiotemporal voltage distributions of its individual Fourier components. The system under study, shown schematically in Fig. 4, consists of two sections of a regular transmission line occupying the regions $z<0$ and $z>a$, surrounding a periodically loaded transmission-line (PLTL) section of length a. The PLTL is assumed to be a transmission line of length 2 cm, having a dispersive behavior determined by the dispersion relation [21, eq. (6)], and operated within the anomalous dispersion band, i.e., the PLTL exhibits both NRI and NGV properties.

Consider a modulated Gaussian pulse with center frequency in the anomalous dispersion band, excited on the $z<0$ transmission-line segment. By Fourier analysis, this waveform can be decomposed into many single-frequency sinusoidal components. The peak of the pulse is formed at the position where

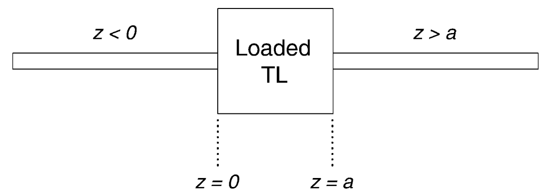


Fig. 4. Schematic diagram of the transmission-line setup used for the simulations that explain the mechanism behind the NGD. The loaded transmission line section exhibits NRI and NGV properties.

these individual frequency components interfere constructively, and the nulls of the pulse are formed where these components interfere destructively.

The space- and time-dependent voltage distribution $\mathcal{V}_n(z,t)$ for the nth spectral component of the Gaussian pulse is given by

$$\mathcal{V}_n(z,t) = \begin{cases} G_n\cos(\omega_n t - k_n z), & z<0 \\ G_n e^{-\alpha_n z}\cos(\omega_n t - \beta_n z), & 0<z<a \\ G_n e^{-\alpha_n a}\cos\left(\omega_n t - k_n[z-a] - \beta_n a\right), & z>a. \end{cases} \quad (5)$$

Here, ω_n and G_n are the frequency and amplitude of the nth harmonic, and k_n is the propagation constant on the regular transmission line in the regions $z<0$ and $z>a$. In the PLTL section $0<z<a$, the propagation and attenuation constants of the nth harmonic are β_n and α_n, respectively, calculated from the dispersion relation [21, eq. (6)]. Note that, according to (5), the peak of the pulse strikes the interface $z=0$ at $t=0$.

Fig. 5(a) displays three spectral components of a Gaussian pulse with frequencies in the anomalous dispersion band at the instant $t=-13$ ns calculated from (5). In addition to the underlying harmonics, Fig. 5(a) also displays the pulse envelope so that the peak location can be clearly identified. It is clear from this figure that the frequency components add up in phase and a peak is formed in the $z<0$ section of the transmission line.

As time progresses, the pulse propagates along the transmission line and the early part of the pulse encounters the PLTL section. By virtue of the phase compensation caused by the anomalous dispersion, the NGD transmission line rearranges the relative phases of the individual frequency components. Since the phase response of the NGD line is approximately linear and the magnitude response is approximately flat over the bandwidth of the Gaussian pulse, the frequency components add up to produce a close copy of the original pulse in the region of $z>a$. This output pulse appears at $t=-0.5$ ns before the input peak reaches the first interface, as shown in Fig. 5(b). Note that the output pulse amplitude is reduced in magnitude relative to the input pulse, though the envelope retains its basic shape. Thus, Fig. 5(b) shows that the peak of the output pulse appears at the output terminal 0.5 ns before the input peak reaches the input terminal.

Note that the effects of reflections from the interfaces in these simulations have been ignored. These reflections produce standing waves in the $0<z<a$ section and, thus, cause a further reduction in the transmitted pulse amplitude; however, they do not affect the location of the pulse peaks.

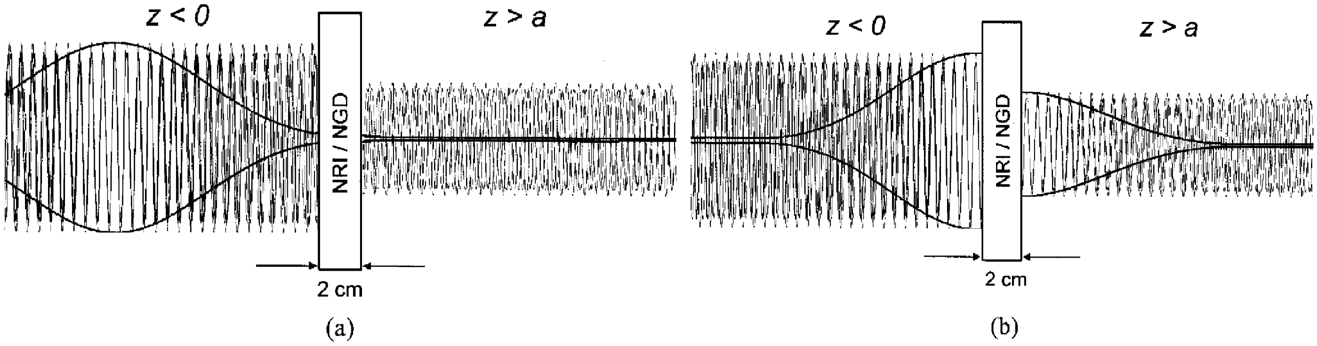


Fig. 5. Simulations illustrating the pulse-reshaping mechanism underlying the NGD. (a) Three frequency components of the Gaussian pulse and the resulting pulse envelope 13 ns before the input peak reaches the loaded transmission line interface. (b) Same three frequency components 0.5 ns before the input peak reaches the interface; at this point, a peak has already formed at the output.

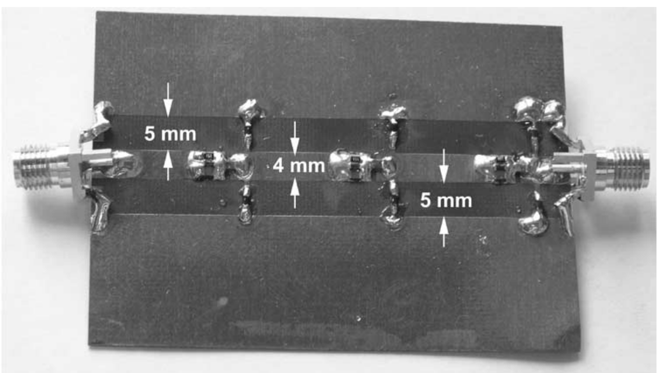


Fig. 6. Three-stage device. All components are commercially available and were surface-mounted manually. The board is Rogers 5880 with a substrate thickness of 0.381 mm, a relative permittivity of 2.2, a loss tangent of 0.0009, and volume and surface resistivities of 2×10^7 M$\Omega \cdot$ cm and 3×10^8 MΩ, respectively. The copper cladding thickness is 17 μm. The center conductor of the waveguide has a width of 4 mm and the slots have a width of 5 mm.

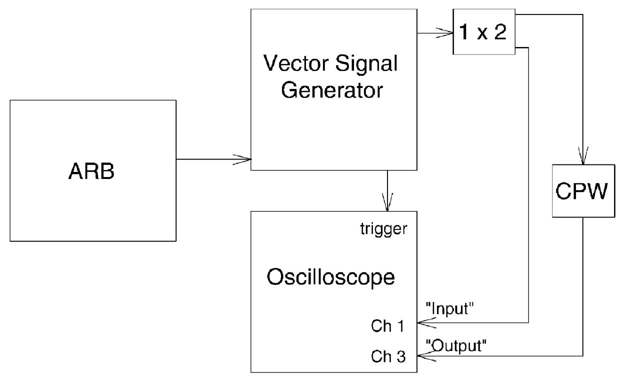


Fig. 7. Schematic diagram of the experimental setup for measuring the NGD in the time domain.

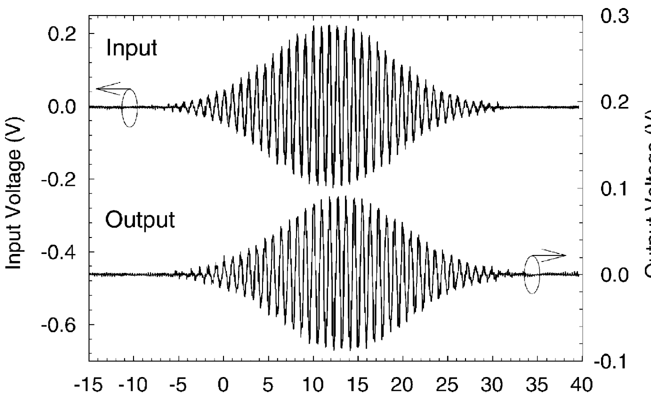
III. Time-Domain Experimental Results

To verify our theoretical predictions and simulation results, a CPW was printed on a 15-mil (0.381 mm) Rogers 5880 substrate with a dielectric constant of 2.2 and a loss tangent of 0.0009. The CPW line was periodically loaded manually with 1.5 mm $\times$ 0.5 mm commercially available surface-mount chips, such that one unit cell was approximately 2-cm long, and transmission lines loaded with 1–3 unit cells were built. The self-resonances of the inductors and capacitors are above the operating frequencies considered. A photograph of the device is shown in Fig. 6.

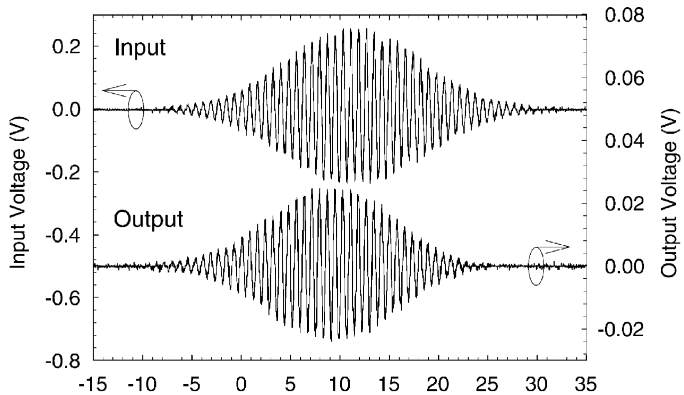
The group-delay measurement setup is shown schematically in Fig. 7. A baseband Gaussian pulse of temporal width 40 ns was created with a Tektronix AWG2041 arbitrary waveform generator (ARB), and modulated with a Rohde & Schwartz SMV03 vector signal generator at frequencies between 1.1–1.5 GHz. The modulated signal was then divided by a 1×2 splitter. Any discrepancy in length between the two cables joining the splitter to the oscilloscope will introduce an inherent delay between the two paths, thereby affecting the accuracy of the final group-delay measurements. Therefore, both outputs of the splitter were initially connected to channels 1 and 3 of the Agilent 54846 Infiniium oscilloscope (bandwidth 2.25 GHz) for a calibration measurement. The delay was measured on the Infiniium scope and electronically equalized to 0 ± 0.1 ns using the oscilloscope internal functions. After this calibration step, the CPW was inserted into the channel 3 cable, as indicated in Fig. 7. In this way, both the input and output signal of the PLTL were simultaneously recorded on the oscilloscope.

Fig. 8(a) shows the behavior of the three-stage loaded transmission line operated at 1.11 GHz in the band of positive group delay, i.e., *away from the anomalous dispersion band*. For this case, a positive group delay of approximately +1.5 ns, due to propagation along the 6-cm line, was observed. Under normal conditions, therefore, the *peak of the output pulse appears at a later time than the peak of the input pulse*. In contrast, Fig. 8(b) shows the input and output pulses when the PLTL is operated *within the anomalous dispersion band* at the resonance frequency of 1.27 GHz, where an NGD of -3.1 ns was measured. Note that, in Fig. 8(b), the output peak precedes the input peak; this unusual outcome is the meaning of the NGD.

Fig. 9 shows the measured input pulse (solid curve) and output pulses (dashed curves) at the point of the maximum NGD, approximately 1.27 GHz, for the one– to three-stage circuits. For clarity, only the pulse envelopes are shown. These curves are the experimental validation of Fig. 2. The envelopes were obtained from the raw data by fitting a three-parameter Gaussian curve to the extracted envelopes. The peak arrival times were acquired from the Gaussian fit parameters to within ± 0.2 ns. At the *RLC* resonance frequency, the one-



(a)



(b)

Fig. 8. Time-domain experimental results for the three-stage negative delay circuit at two frequencies. (a) Positive delay at a center frequency of 1.11 GHz, 160 MHz below resonance. (b) −3.1-ns group delay at the resonance frequency, 1.27 GHz.

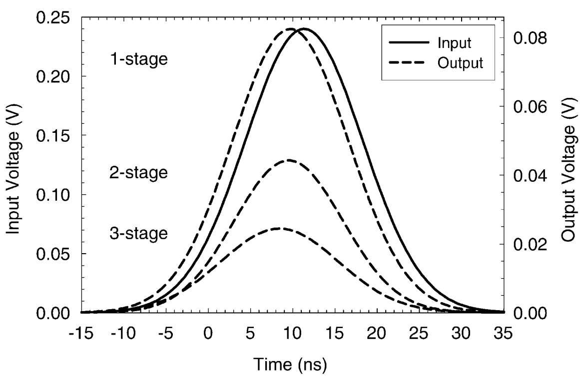


Fig. 9. Experimental results showing extracted pulse envelopes for the one- to three-stage transmission lines with delays of −1.6, −1.9, and −3.1 ns, respectively.

to three-stage circuits exhibit group delays of −1.6, −1.9, and −3.1 ns, respectively. Note that, as expected, the greatest negative delay and greatest attenuation are found for the longest transmission line, and the least negative delay and least attenuation for the shortest line.

Comparing Figs. 2 and 9, there is some discrepancy between the values of the simulated and experimentally determined negative delays. The trend that longer lines have greater negative delay and greater insertion loss is common to both simulation and experiment; however, there is generally less attenuation and more pulse advancement in the experiments. These discrepancies are due to the differences between the components used in simulation and those in the actual devices. First, nominal values for the components were used in the simulations. In practice, however, the components have tolerances of ±5%. By including these tolerances in our simulations, we found that the discrepancies between the measured and calculated group delay can be reduced by half. The group delay is particularly sensitive to changes in the resistor or capacitor in the *RLC* resonator, and variation in these component values will affect the slope of the transmission phase, thus altering the amount of the NGD. Secondly, and more importantly, the simulations use ideal component models and, thus, the self-resonant behavior of the capacitors and inductors was not included. In practice, the self-resonances can change the overall impedance of the *RLC* resonator, affecting the operating frequency, decreasing the attenuation through the device, and increasing the NGD. These two effects may be included in the simulations if measured S-parameters are used for each component, a tedious, but effective method of improving the agreement between experiment and simulation.

IV. Conclusion

We have presented a 1-D PLTL that not only demonstrates a negative index of refraction in a band of frequencies, but also exhibits NGDs or positive group delays and, thus, NGVs or positive group velocities, within this same band. These interesting properties have been previously shown in theory and experiment in the frequency domain [21]. We have now demonstrated them directly in the time domain. Using a Gaussian waveform modulated at approximately 1.3 GHz, the peak of the output pulse has been shown to exit the loaded transmission line before the input peak enters, with an experimentally observed negative delay of −3.1 ns. The time-domain simulations were also used to show that relativistic causality is not violated by this counterintuitive behavior since the pulse fronts always experience a positive and exactly luminal delay. Furthermore, an underlying mechanism for the NGD, based on the idea of pulse reshaping, was proposed and illustrated using the time-domain simulations. This NRI and NGD line may find applications in the dispersion management of high-speed digital interconnects.

Acknowledgment

The authors would like to thank R. Y. Chiao, University of California at Berkeley, and K. J. Malloy, Center for High Technology Materials, University of New Mexico, Albuquerque, for useful discussions.

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Omar F. Siddiqui was born in Karachi, Pakistan, in 1971. He received the B.Sc. degree from the University of Engineering and Technology, Lahore, Pakistan, in 1994, the M.Sc. degree from the University of Texas at Arlington, in 1999, both in electrical engineering, and is currently working toward the Ph.D. degree in electrical and computer engineering at the University of Toronto, Toronto, ON, Canada.

In 1997, he was a Teaching Assistant with the Department of Electrical Engineering, University of Texas at Arlington. From 1998 to 2000, he was a Radio Frequency Engineer with the Code Division Multiple Access (CDMA) RF Engineering Group, Nortel Networks, Richardson, TX. From 2000 to 2001, he was a Hardware Characterization Engineer with Nortel Networks, Ottawa, ON, Canada. His research interests include RF propagation modeling, microwave circuit design, antenna design, and metamaterials.

Suzanne J. Erickson received the B.A.Sc. degree in engineering physics from the University of Toronto, Toronto, ON, Canada, in 2000, and is currently working toward the M.A.Sc. degree in electrical and computer engineering at the University of Toronto.

From 2000 to 2002, she was a Product Engineer with the dense wavelength division multiplexing (DWDM), Fiber Bragg Grating, and New Product Introduction Manufacturing Groups at JDS Uniphase, Ottawa, ON, Canada.

Ms. Erickson was the recipient of the 2000 Centennial Thesis Award for Engineering Science for the best undergraduate thesis in each engineering discipline.

George V. Eleftheriades (S'86–M'88–SM'02) received the Diploma (with distinction) in electrical engineering from the National Technical University of Athens, Athens, Greece in 1988, and the M.S.E.E. and Ph.D. degrees in electrical engineering from The University of Michigan at Ann Arbor, in 1989 and 1993, respectively.

From 1994 to 1997, he was with the Swiss Federal Institute of Technology, Lausanne, Switzerland, where he was engaged in the design of millimeter and sub-millimeter-wave receivers and in the creation of fast computer-aided design (CAD) tools for planar packaged microwave circuits. He is currently an Associate Professor with the Edward S. Rogers Sr. Department of Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada. He has authored or coauthored over 80 papers in refereed journals and conference proceedings. His current research interests include NRI metamaterials, integrated-circuit (IC) antennas and components for broad-band wireless communications, novel beam-steering techniques, low-loss silicon micromachined components, millimeter-wave radiometric receivers, and electromagnetic design for high-speed digital circuits.

Dr. Eleftheriades was a corecipient of the 1990 Best Paper Award presented at the 6th International Symposium on Antennas (JINA) and the Ontario Premier's 2001 Research Excellence Award. His graduate students were the recipients of Student Paper Awards presented at the 2000 Antenna Technology and Applied Electromagnetics Symposium, the 2002 IEEE Microwave Theory and Techniques Society (IEEE MTT-S) International Microwave Symposium (IMS), and the 2002 IEEE International Symposium on Antennas and Propagation.

Mohammad Mojahedi (S'97–M'98) received the Ph.D. degree from the University of New Mexico (UNM), Albuquerque, NM, in 1999.

He was then a Research Assistant Professor with the Center for High Technology Materials (CHTM), University of New Mexico. In August 2001, he joined the faculty of the Edward S. Rogers Sr. Electrical and Computer Engineering, University of Toronto, Toronto, ON, Canada. His research interests are matter–wave interactions, abnormal velocities, metamaterials, photonic crystals, dispersion engineering, quantum-dot and quantum-well lasers, fundamental electromagnetic theory, periodic structures, and macroscale and nanoscale microwave and photonic systems.

Dr. Mojahedi was the recipient of the Popejoy Award for the outstanding doctoral dissertation in physics and engineering at UNM from 1997 to 2000.