Passive system with tunable group velocity for propagating electrical pulses from sub- to superluminal velocities

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(Received 29 October 2003; revised manuscript received 24 December 2003; published 6 May 2004)

We report an observation of tunable group velocity from sub-luminal to superluminal in a completely passive system. Electric pulses are sent along a spatially periodic conducting medium containing a punctual nonlinearity, and the resulting amplitude-dependent phase shift allows us to control dispersion and the propagation velocity at the stop band frequency.

DOI: 10.1103/PhysRevE.69.056602 PACS number(s): 42.70.Qs, 42.25.Bs, 73.40.Gk

Controlling the propagation velocity of electromagnetic pulses has been the object of much research recently because it offers an extra degree of flexibility for processing signals. A number of schemes have been studied to achieve this goal, including electromagnetically induced transparency [1,2] and stimulated Raman processes [3,4], where dispersion has been shown to be tunable by coupling optical fields between atomic levels. Experiments have recently demonstrated very slow [5] and superluminal [3] propagation of light in such media. In solids, photonic crystals and Bragg gratings also have dispersive properties that can be tuned to some extent and, for example, birefringence in photonic crystals have been used recently to control the propagation speed of optical pulses [6,7]. Other than these few experiments, not much work has been done in exploiting other kinds of nonlinearities to control the propagation of electromagnetic waves. In this paper, we demonstrate a system in which the group velocity of an electric pulse is controllable with its amplitude. By combining the peculiar dispersive properties of a spatially periodic conductor with a simple semiconducting nonlinear component, we show that the enhanced interaction caused by the confinement of the electric field leads to large variations in the speed of the pulse envelope.

The system under study is a conducting wire with a spatially periodic impedance, or the so-called coaxial photonic crystal which has been used recently to study effects such as photonic band gap and defect modes in the microwave spectrum [8], nonlinearities [9], and superluminal and negative pulse propagation [10–12]. Such a periodic structure exhibits bands of frequencies that are not allowed to propagate (or are strongly reflected) where anomalous dispersion and superluminal group velocity are observed. In the stop bands, the interaction between the electromagnetic field and the medium is enhanced because of multiple scattering, and as a result the influence of a nonlinearity on the pulse propagation is magnified. In optical materials, nonlinearities produce phase shifts that are intensity dependent, and a wide assortment of effects result from it. At lower frequencies, in the electronic domain, an equally important number of interesting effects can be created and observed with nonlinear components, the simplest and most widely used of which is the *p*-*n* junction. Semiconductor diodes respond in a very nonlinear fashion, with both the amplitude and frequency of the applied signal. This behavior is demonstrated in Fig. 1, where the current-voltage characteristic curves are plotted for two diodes (1N4007) connected in parallel and for a sinusoidal signal with frequency ranging from 100 Hz to 15 MHz. The diodes are oriented in opposite polarity to create a nonlinear symmetrical response. As expected, an important drop in resistance occurs at higher voltages, but the effect strongly varies with frequency. This frequency dependence suggests a dispersive mechanism of the diode conductivity or, equivalently, a frequency-dependent phase shift, but this quantity is not available from the *I*-*V* curves. One obtains this additional information by directly measuring, across the diodes, the phase shift between the oncoming and outgoing wave with the diode pair connected in series with a fixed resitance. Using a 50 Ω resistance we obtained Fig. 2, where the measured phase shift per unit of frequency is plotted, a quantity that is proportional to an effective index of refraction. The phase shift is explained from the device capacitance (25 pF) and other space charge effects in the depleted region that are dependent on the electric field amplitude. For the purpose of this work, it is not necessary to theoretically model the details the diodes response, but it is important to characterize them enough to explain the results discussed later in this paper. As the figure shows, the diodes behave in such a way that the dispersion is increasingly

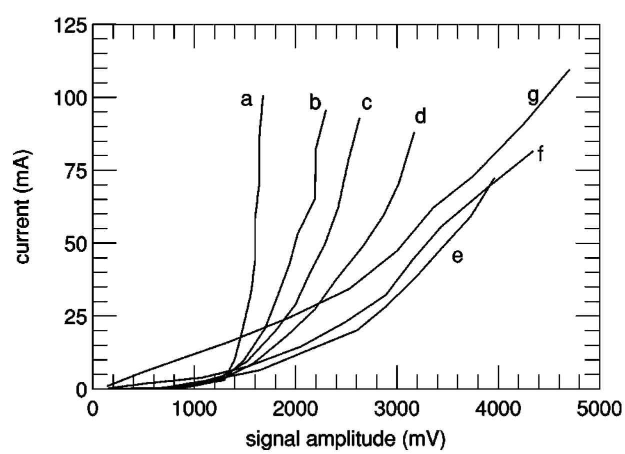

FIG. 1. Current-voltage curves for two diodes 1N4007 connected in parallel and opposite polarity. The applied sinusoidal signal has a frequency of (a) 100 Hz, (b) 500 kHz, (c) 1 MHz, (d) 2 MHz, (e) 5 MHz, (f) 10 MHz, and (g) 15 MHz.

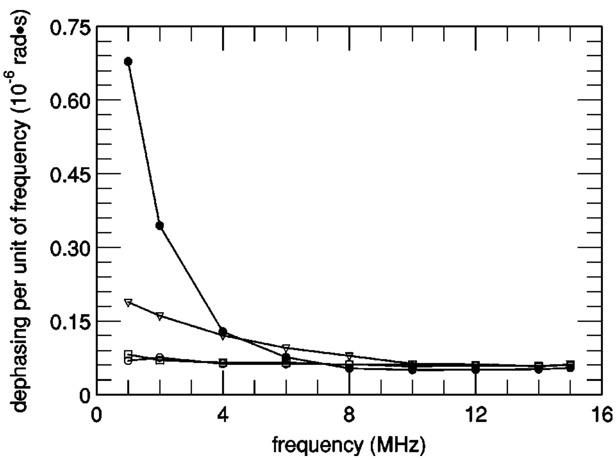

FIG. 2. Phase shift across the diode pair per unit of frequency for a sinusoidal wave with an amplitude of 0.3 V (empty circles), 0.6 V (squares), 1 V (triangles), and 3 V (full circles).

anomalous with higher signal amplitude. The diodes are, in this case, essentially pointlike compared to the signal wavelength, so it is not practical to talk about group velocity dispersion. However, incorporating such point nonlinearity to a periodic medium such as the coaxial photonic crystal should influence the overall dispersion charachteristics because the local phase shift will depend on the wave amplitude at that location, and that varies with frequency. An optically similar (but not equivalent) situation would be a thin layer of material having an intensity-dependent index of refraction (as with the optical Kerr effect) placed between two Bragg mirrors.

Next, we study the impact of the nonlinearity on the transmission characteristics of the coaxial photonic crystal and on the electric pulse propagation. A system made of 12 pairs of 50 Ω and 75 Ω coaxial segments, each measuring 5 m in length, were connected in a row to create a medium with periodic impedance for electric waves. In the 9 to 11 MHz spectral range, a deep stop band appears as predicted by theory, but the transmission pattern is altered when the diode

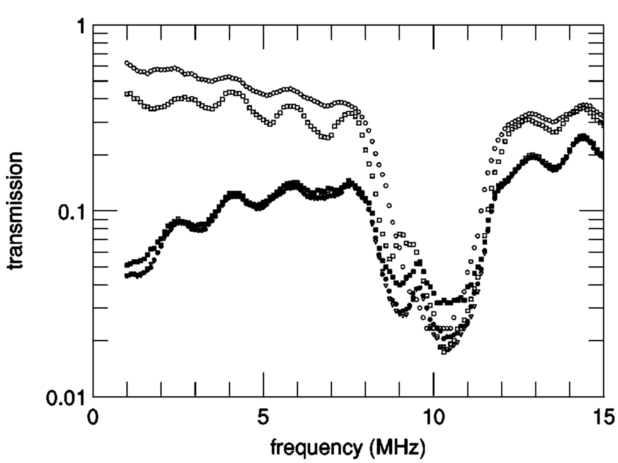

FIG. 3. Transmission spectrum of the coaxial photonic crystal with the diode pair in the middle for a sinusoidal wave with an amplitude of 3 V (empty circles), 1 V (empty squares), 0.3 V (triangles), 0.2 V (full circles), and 0.1 V (full squares).

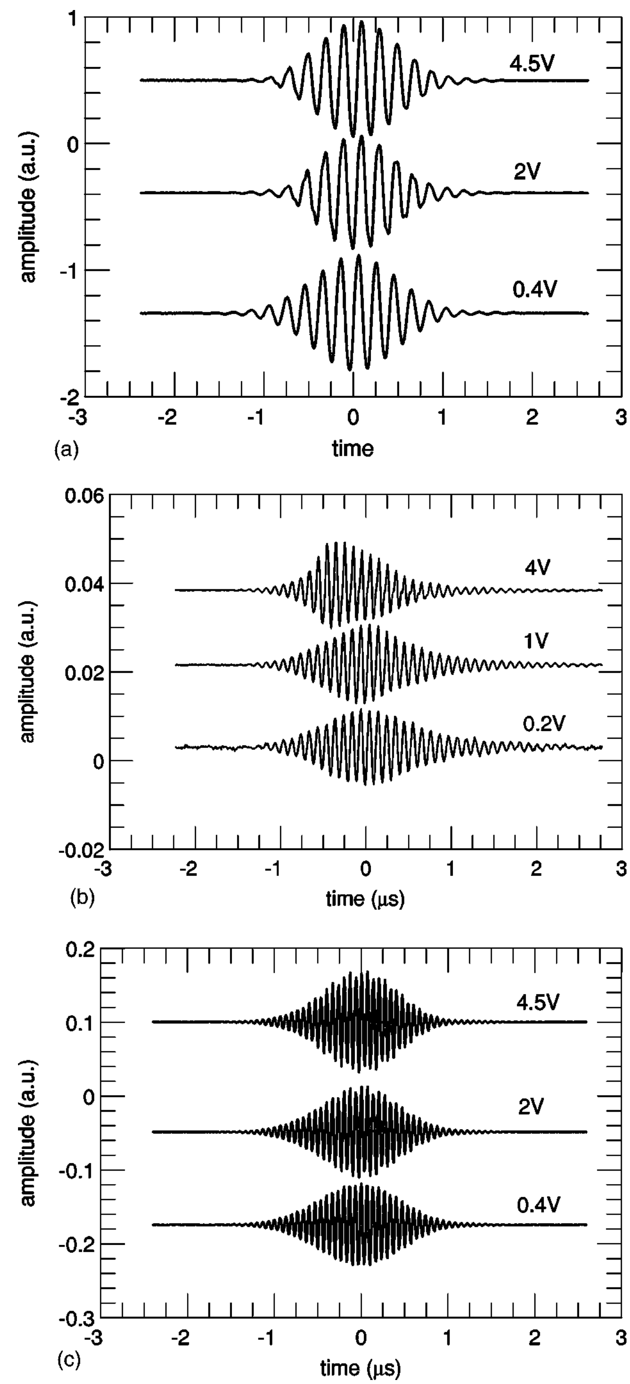

FIG. 4. Output pulses through the coaxial photonic crystal for various envelope amplitudes. Carrier frequencies are (a) 5 MHz, (b) 10 MHz (band gap frequency), and (c) 15 MHz.

pair is inserted in the middle of the structure, between unit cells No. 6 and No. 7. Figure 3 demonstrates the effect by plotting the transmission coefficient (the ratio between the output and input amplitudes) of a sinusoidal wave with various input amplitudes. In agreement with the I-V curves of Fig. 1, a marked drop in transmission is observed for voltages of less than 1 V and this “nonlinear absorption” is expected to reduce the group velocity of weak signals. Absorption has indeed been pointed out as a mechanism for

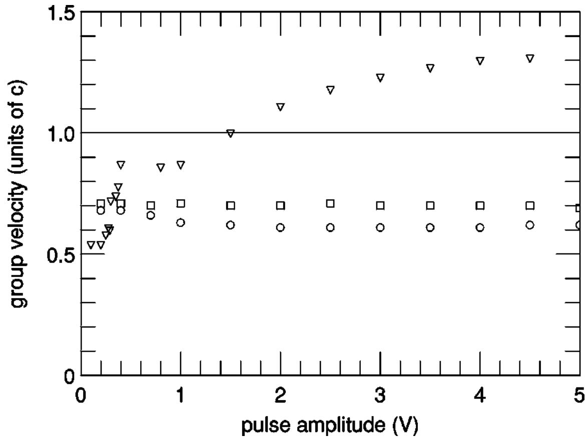

FIG. 5. Group velocity for a pulse with a carrier frequency of 5 MHz (circles), 10 MHz (triangles), and 15 MHz (squares). The duration of the Gaussian envelope is 1.2 μs for all cases (FWHM).

reducing superluminal group velocities in periodic media to subluminal level [13,14].

In the band gap region, near 10 MHz, the group velocity in the coaxial crystal without diodes was measured to approach 3*c* [10], while it is close to the phase velocity of the bulk coaxial line ($\sim 2/3c$) at other frequencies. The group velocity has been characterized in detail elsewhere (see Ref. [11]). To study the system in the nonlinear regime, with the addition of the diode pair, a programmable wave generator was used to launch a wave with a Gaussian envelope and a given carrier frequency, and the time delay between the input and output pulses was measured on a 1 GHz oscilloscope to determine the group velocity. A center-of-mass approach was used to determine the pulse centers in order to limit the effect of noise and distortion [11]. Figures 4(a)–4(c) shows a few typical traces of the outgoing pulse for carrier frequencies of 5, 10, and 15 MHz, as well as for various envelope amplitudes. As the input amplitude is increased, the pulse envelope is shifted to the left (to earlier times) when the carrier frequency is 10 MHz, but this is not the case at 5 and 15 MHz, frequencies that are located outside the band gap. The temporal shift to the left effectively increases the group-velocity, and Fig. 5 shows the measured group velocity as a function of input amplitude for the three carrier frequencies. Little change is observed at 5 and 15 MHz for input amplitudes ranging from 0 to 5V, but in the stop band, the group velocity begins at a subluminal level, at a value close to the phase velocity, and then increases rapidly to become superluminal above 1.5 V. This subluminal to superluminal transition is, to our knowledge, the only such observation in a passive physical system. Interestingly, the change in velocity is highest at the stop band frequency, where the dispersion curves are flat (see Fig. 2) and, where the transmission variation is less sensitive to amplitude (see Fig. 6). The only difference between frequencies inside and outside the band gap are the amount of the resonance between the scattered fields and the periodic medium. At 10 MHz, it is clear that resonance plays an enhancing role for the interaction between the electric field and the nonlinearity, as phase shifts add up constructively in each component of the scattered field. Nonlinearities are thereby amplified, as is the case with optical systems of a similar nature.

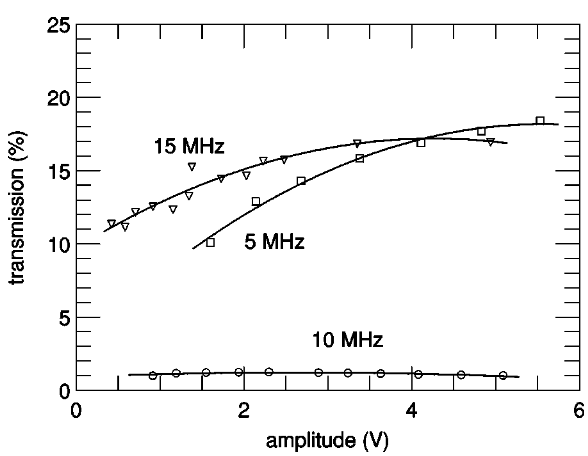

FIG. 6. Ratio between the output and input amplitudes for a sinusoidal signal of varying amplitude. Solid curves are polynomial fits.

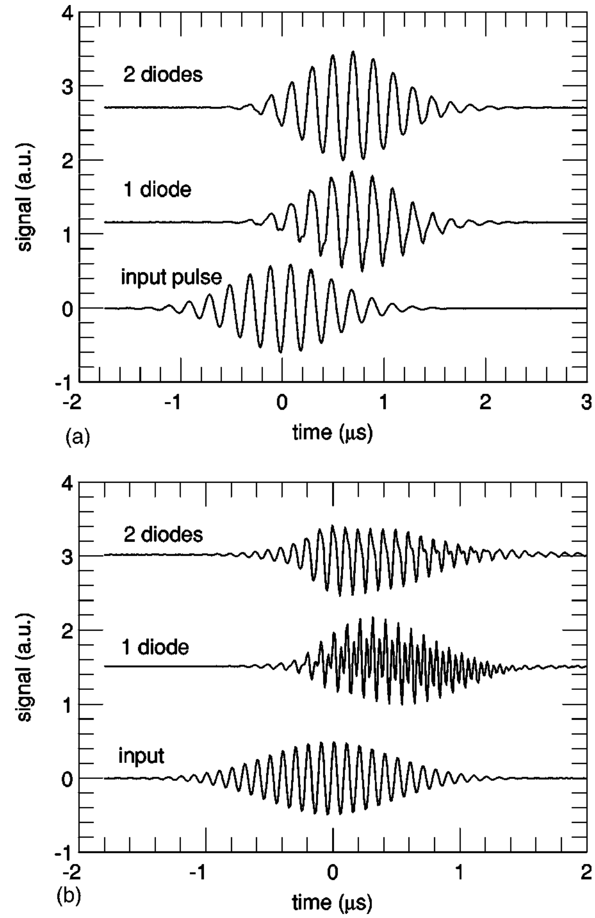

FIG. 7. Input and output pulses with carrier frequency of (a) 5 MHz and (b)10 MHz propagating through the periodic system with one and two diodes (asymmetrical vs symmetrical response).

It could be argued that the group velocity is artificially modified by the action of the diodes cutting the back of the pulse more than its front. If such effect could be envisioned in a complex, multicomponent electronic circuit including amplifiers and filters, there is nothing in the $p-n$ junction that should preferentially transmit the leading edge of the signal over its trailing edge. Instead, the variation in group velocity appears to be entirely accounted for by the dispersive properties of the diodes arising from their nonlinear response in frequency and amplitude.

The effect of having one diode versus two diodes in parallel was also studied. Figures 7(a) and 7(b) show the input and output pulse shapes for one and two diodes at 5 and 10 MHz. The signal apprears smoother with the two diodes layout, while higher harmonics with the single diode configuration are especially noticeable at 10 MHz which are probably due to the asymetrical nature of the single diode response. Note that a similar type of assymetry is responsible for the $\chi^{(2)}$ component of the nonlinear optical susceptibility and processes such as second harmonic generation. The additional spectral content has a profound impact on the group velocity: with two diodes at 10 MHz, group velocities of 0.83, 1.00, and 1.43c were measured for input pulse amplitudes of 0.3, 1.5, and 5 V, respectively. With one diode and at the same frequency, the corresponding velocities were only 0.63, 0.70, and 0.8c. On the other hand, attempts to break the diode symmetry with external means do not seem to affect the propagation, as no measurable change in velocity was observed when a bias was applied across the diode pairs while the pulse was propagated through the system.

In conclusion, we have demonstrated a completely passive and relatively simple system in which electric pulses travel at a velocity that is widely tunable with amplitude. Through the nonlinear response of the diode and the enhanced interaction between the field and the medium, the pulse velocity is tunable from subluminal to superluminal velocities, making it a unique system in that regard. The extra degree of flexibility offered by this variable velocity could find interesting applications in signal processing. This work also suggests an optical equivalent to this system, like a thin saturable absorber embedded in periodic lattice, where the group velocity of light pulses could be controlled.

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