Advances in Science and Technology *Online: 2010-10-27*
ISSN: 1662-0356, Vol. 75, pp 256-265
doi:10.4028/www.scientific.net/AST.75.256

Trapped Rainbow Storage of Light in Metamaterials

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Keywords: Slow light, metamaterials, negative refractive index, plasmonics, waveguides, adiabatic variation.

Abstract. We review recent theoretical and experimental breakthroughs in the realm of slow and stopped light in structured photonic media featuring negative electromagnetic parameters (permittivity/permeability and/or refractive index). We explain how and why these structures can enable complete stopping of light even in the presence of disorder *and*, simultaneously, dissipative losses. Using full-wave numerical simulations we show that the incorporation of thin layers made of an active medium adjacently to the core layer of a negative-refractive-index waveguide can completely remove dissipative losses – in a slow-light regime where the effective index of the guided wave is negative.

Introduction

Metamaterials (MMs) [1-3] and 'slow light' (SL) [4,5] have, in the last decade, evolved to two of the largest and most exciting realms of contemporary science, enabling a wealth of useful applications, such as *sub*-diffraction-limited lenses, ultra-compact photonic devices and, even, invisibility cloaks.

Recently it has been theoretically demonstrated [6] that these two highly technologically important areas of research, which were until now following separate/parallel tracks, could in fact be combined, with the potential of leading to novel metamaterial-enabled slow-light structures that can improve on existing slow-light designs and structures (in terms of the degree to which light can be decelerated, as well as of performance, functionality and efficiency); see Fig. 1.

Indeed, some of the most successful slow-light designs at present, based on photonic-crystals (PhCs) [7] or coupled-resonator optical waveguides (CROWs) [8], can so far efficiently slow down light by a factor of only 40 – otherwise, large group-velocity-dispersion *and* attenuation-dispersion occur, i.e. the guided light pulses broaden and the attainable bandwidth is severely restricted. Unfortunately, this limitation directly imposes an *upper limit* on the degree to which one can shrink the area of the corresponding slow-light devices (compactness), as well as reduce the driving electrical power. This is simply because the less a guided slow-light pulse is decelerated inside a waveguide, the less it is spatially compressed; thereby, the less is the reduction that can be achieved to the length (or area) occupied by the slow-light device. In addition to the aforementioned issues, it has by now also been realised that such positive-index slow-light structures are, unfortunately, *extremely* sensitive to the presence of (even *weak*) fabrication disorder [9] – to the point that a disorder of only 5-10 nm (at a wavelength of 1550 nm) leads to group velocities that can never, *even in the presence of dispersion*, be smaller than approximately *c*/300 [4,10].

By contrast, it has been theoretically and experimentally established that metamaterials are almost completely insensitive to the presence of *even a high degree* of fabrication disorder [11,12], since their properties arise from an averaged/effective response of their constituent 'meta-molecules', without necessarily requiring a 'perfect' lattice crystal – a situation which is similar to, e.g., crystalline or amorphous silicon, where the presence or not of a periodic atomic lattice does not, of course, preclude the attainment of an effective refractive index. This ability of metamaterial-based heterostructures to dramatically decelerated or even *completely* stop [6] light under realistic experimental conditions, has recently led to a series of experimental works [13,14] that have provided spectroscopic evidence (but not yet an unambiguous proof) for the observation of 'trapped rainbow' light-stopping in metamaterial waveguides – to our knowledge, the first experimental works to provide a telltale spectroscopic fingerprint of 'true' light-stopping in solid-state structures.

Moreover, as will be explained in the following, it can be shown (based on analytic theory and computational simulations) that negative-refraction (or negative-refractive-index) metamaterial-enabled slow-light structures enable efficient deceleration of light by factors of, *at least*, *tens of thousands without* suffering from the aforementioned group-velocity- and attenuation-dispersion limitations.

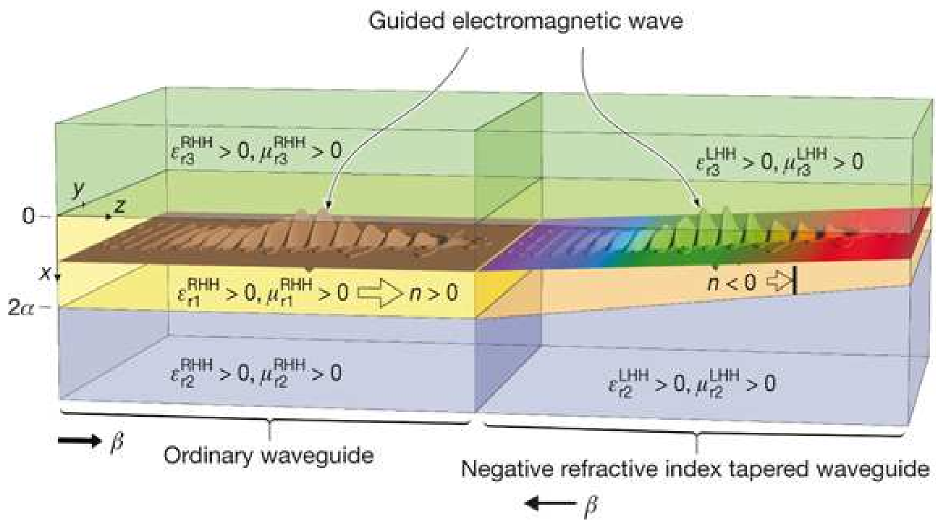


Fig. 1. The 'trapped rainbow' principle [source: K.L. Tsakmakidis, A.D. Boardman and O. Hess: "'Trapped rainbow' storage of light in metamaterials," Nature Vol. 450 (2007), p. 397]. Owing to negative Goos-Haenchen shifts, light is slowed and eventually stopped/stored in an adiabatically tapered negative-refractive-index waveguide – with each frequency 'stopping' at a different point in space.

Thus, these structures are, upon judicious construction and optimization, expected to lead to reductions in the size of and power consumption in photonic devices and systems that are considerably greater compared to what can be achieved with other technologies (based on, e.g., PhCs and/or CROWs). For instance, recent theoretical studies and computational simulations (see also below) suggest that *dispersionless* slow group velocities of light pulses in multilayer negative-refraction MM waveguides can dramatically increase the induced phase shifts in Mach-Zehnder modulators, to the point of reducing the length of the modulator's arms from a typical (present) value of a few mm down to only a few tens of microns (see, also, e.g.: Ref. [15]) – a result far better than what has been achieved with the best present, e.g., PhC based designs. Similarly promising results can also be achieved for a number of other photonic components, such as switches, buffers, filters, dispersion compensators, and so forth.

By deploying suitably designed *all-semiconductor based* [16,17] (i.e., not metallic) metamaterial waveguides that include active/gain layers, we can engineer practical slow-light structures wherein the optical (dissipative) losses of the guided slow-light pulses are reduced by orders of magnitude – or completely eliminated – compared to their metallic counterparts; a further key requirement for any useful slow-light structure. Moreover, in such structures light can be in-/out-coupled much more efficiently compared to, e.g., their PhC counterparts [6], and can be *completely* stopped even when large material losses are present. For these reasons, 'slow-light' designs based on metamaterials may conceivably lead to novel and practical designs for ultra-compact and ultralow-power photonic components, devices and systems.

In what follows, we begin by concisely reviewing the basic premises of (dispersionless) slow/stopped light in negative-constitutive-parameters metamaterial and plasmonic waveguides. We proceed by studying the waveguide dispersion equations in the presence of disorder and/or dissipative losses, and show that the zero-group- and zero-energy-velocity points are preserved; hence, a guided light pulse can still be dramatically decelerated and stopped inside these lossy structures. Next, we show how the incorporation of thin layers made of an active/gain medium placed adjacently to the core of a negative-index metamaterial waveguide can lead to a complete elimination of the dissipative losses experienced by a guided, slow-light pulse.

Main features of 'trapped rainbow' light-stopping in metamaterial and plasmonic waveguides

As was mentioned above, while recent scientific breakthroughs within the optical engineering community have proved that it is indeed possible to dramatically decelerate or 'store' light by resorting to a variety of physical effects [electromagnetically induced transparency (EIT), coherent population oscillations (CPO), stimulated Brillouin scattering (SBS), photonic crystals (PhCs) and surface plasmon polaritons (SPPs) in metallodielectric waveguides (MDWs)], such approaches nonetheless normally bear inherent weaknesses that may hinder their practical applications. For instance, so far EIT uses ultracold or hot gases and not solid-state materials, CPO and SBS are very narrowband (typically, several kHz or MHz) owing to the narrow transparency window of the former and the narrow Brillouin gain bandwidth of the latter, SPPs in MDWs are very sensitive to small variations of the media interfaces and are relatively difficult to excite, while PhCs are prone to tiny fabrication imperfections (nm-scale disorder) [18,19] that can considerably modify (shift) the photonic bandgaps. Furthermore, approaches based on PhCs or CROWs can efficiently slow down light typically by a factor of around 40 – otherwise, large group-velocity-dispersion *and* attenuation-dispersion occur [7,8]. For these reasons, so far it has only been possible to obtain stored (i.e., not – strictly speaking – stopped) light, wherein slowed-down photons were converted to (stored in the form of) metastable atomic or acoustic states (coherences) and subsequently revived/released by the action (turning 'on') of a coupling field. An unambiguous experimental demonstration of 'true' stopping of light, involving the attainment of a divergence in the group index of a light pulse (with its photons continuously preserving their identity, i.e. without being converted to a polariton) has, so far, remained elusive.

In an effort to overcome the above intrinsic limitations of positive-index slow-light schemes, a fundamentally new approach has been recently proposed [6,20,21]. This method relies on the use of negative-refractive-index, NRI, (or negative-refraction) waveguides, wherein the power-flow direction inside the NRI regions is opposite to the one in the positive-index regions, resulting in a pronounced deceleration of the guided electromagnetic energy (see Fig. 2). The scheme uses efficiently excitable waveguide oscillatory modes and is remarkably simple, since the slowing of the guided modes is performed *solely* by adiabatic decrease of the core thickness. The scheme is, also, resilient to fabrication disorder/imperfections because it does not rely on the use of stringent conditions (such as a 'perfect' photonic-crystal lattice or attainment of ultralow temperatures, etc) for decelerating and stopping light, but rather on the deployment of *negative* bulk/effective electromagnetic parameters (such as, e.g., negative refractive index or, simply, negative permittivity) that can readily be realised by even *amorphous* and *highly disordered* metamaterials [11,12]. Furthermore, these metamaterial heterostructures can be designed in such a way that they exhibit *zero* group-velocity-dispersion *and* attenuation-dispersion, even in the 'stopped-light' regime [22] (see also Fig. 3). In doing so, we are able to allow for extremely large bandwidths over

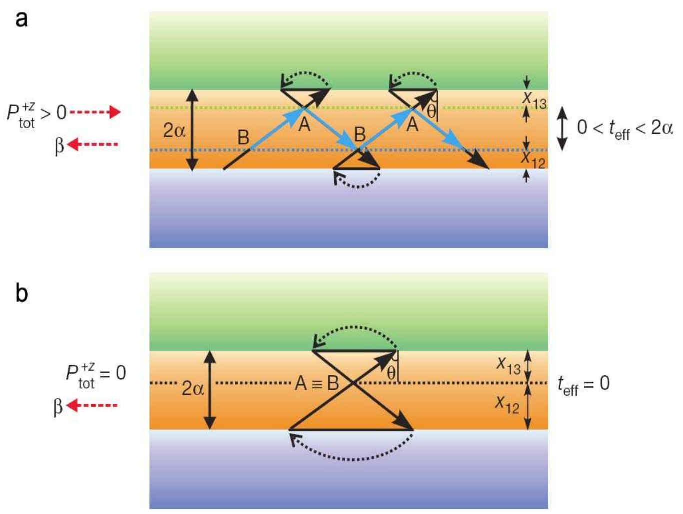


Fig. 2. Slow and stopped light in negative-refractive-index hetero- structures. (a) Slow zigzag ray propagation along a NRI hetero- structure**.** (b) Here, the ray returns exactly to its original point; the ray, thus, becomes permanently trapped (zero group velocity, $v_g = 0$) and an 'optical clepsydra' is formed.

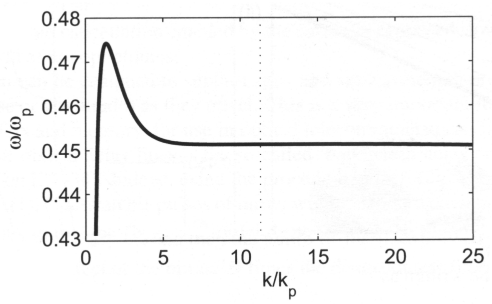


Fig. 3. An example of a dispersion diagram in a suitably designed multilayer metamaterial heterostructure in which, both, zero group velocity and *zero group-velocity dispersion* are simultaneously achieved. Note how from the negative-refraction region ($d\omega/dk < 0$) one enters the region (highlighted by the dotted line) where the group velocity *and* the group-velocity dispersion become simultaneously zero. [source: A. Karalis, *et al.*: "Tailoring and cancelling dispersion of slow or stopped and subwavelength surface-plasmonodielectric-polaritonic light," Proc. SPIE Vol. 7226 (2009), p. 72260l].

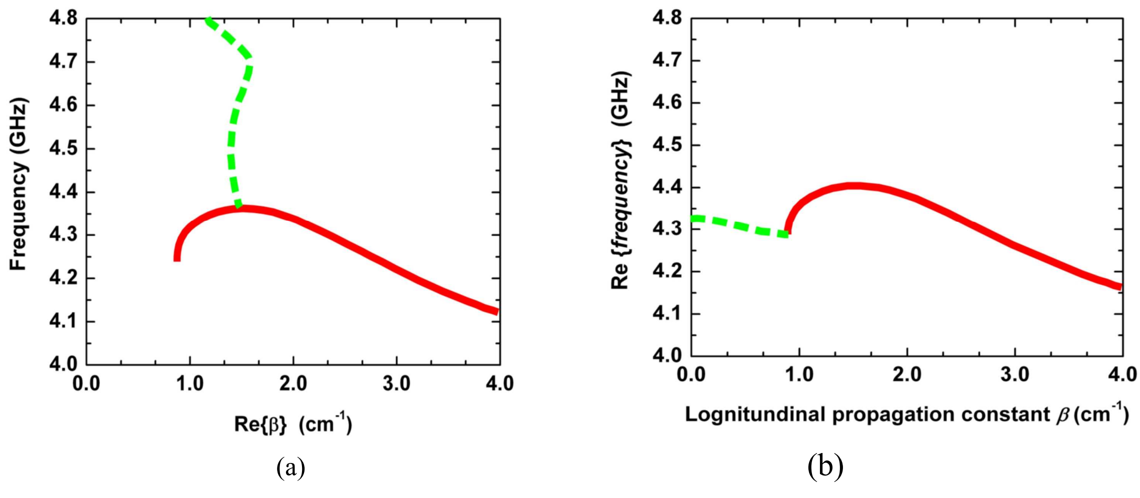
which the slowing [23] or stopping [22] of the incoming optical signals can be achieved, as well as for ultrashort device lengths. This approach also has the important advantage that it can facilitate very efficient butt-coupling, directly to a slow mode alone because: i) It supports *single-mode* operation in the slow-light regime [21]; ii) The characteristic impedance of the NRI waveguide can be appropriately adjusted by varying the core thickness [6]; and iii) The spatial distribution of the slow mode closely matches that of a single-mode dielectric waveguide [6]. These conclusions have been drawn following *exact* manipulations of Maxwell's equations, without invoking paraxial, heuristic or other approximations.

It is interesting to point out that, in addition to metallic (metallodielectric) metamaterial or plasmonic slow-light structures, we can also deploy *all-semiconductor* based, negative-refraction, heterostructures to realise 'trapped rainbow' slowing or stopping of light. Such semiconductor-heterostructure designs have recently been experimentally shown [16,17] to enable negative refraction at infrared wavelengths (8.4 μm to 13.3 μm), and (upon heavy doping) they can indeed be extended to the telecommunication – or even the ultraviolet [24] – regime. Owing to their negative-refraction property, these structures can facilitate slow-light propagation, and would be particularly well-suited for the compensation of optical losses by means of active semiconductor cladding layers, as well as for a variety of slow-light devices, such as, e.g., (ultra-compact) modulators [15].

Light stopping in the presence of metamaterial losses and fabrication disorder

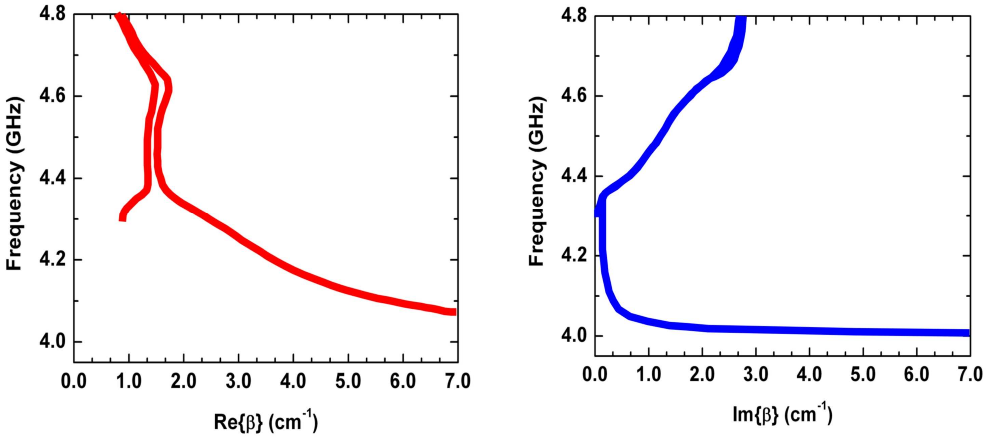
An important consideration in assessing the potential of metamaterial heterostructures for 'stopping' light pulses ($\upsilon_g = 0$) is the degree to which such a feat can be achieved in the presence of realistic (residual) losses and/or fabrication disorder. Already our theoretical studies [6,21,25] have shown (see also Figs. 1 and 2 above) that very large light-decelerations can be achieved in metamaterial waveguides – even when dissipative (Ohmic) losses are present [26]. More recently, we have ascertained [27] that complete 'stopping' of light inside negative-index metamaterial waveguides is, also, possible when dissipative losses remain in the structure. This realisation stems from the fact that light *pulses* (i.e. not sinusoidal, single-frequency waves) are, in the presence of losses, characterised by a *complex frequency* and a *real* wavenumber [26] (see also Fig. 6 below) – in contrast to sinusoidal waves, which are characterised by a *complex* frequency when dissipative losses remain in the structure. This feature becomes even more prominent in the stopped-light regime, where (owing to the fact that light does *not* propagate any more) a consideration of *spatial* losses (*complex* wavenumber) lacks any appreciable physical meaning [22,28], and one should instead consider *temporal* losses (complex *frequency*).

Our analytic studies reveal that a zero group velocity ($\mathrm{Re}\{d\omega/d\beta\} = 0$), i.e. complete adiabatic stopping of light pulses, can indeed be achieved even when residual dissipative losses remain in the metamaterial waveguides (see Fig. 6 below). In fact, it turns out that the overall optical losses of a light *pulse* in the 'stopped'-light regime are orders of magnitude *smaller* compared to the losses that a 'stopped' sinusoidal wave experiences [cf. Fig. 5(b) and Fig. 6(b)]. Thus, bringing a guided light pulse to a complete halt inside metamaterial waveguides results in, amongst others, a substantial *minimisation* of the overall optical losses – since the pulse, being 'stopped', does not experience propagation losses anymore, but only temporal losses [22,26,28] at the location where it is 'stopped'/stored.



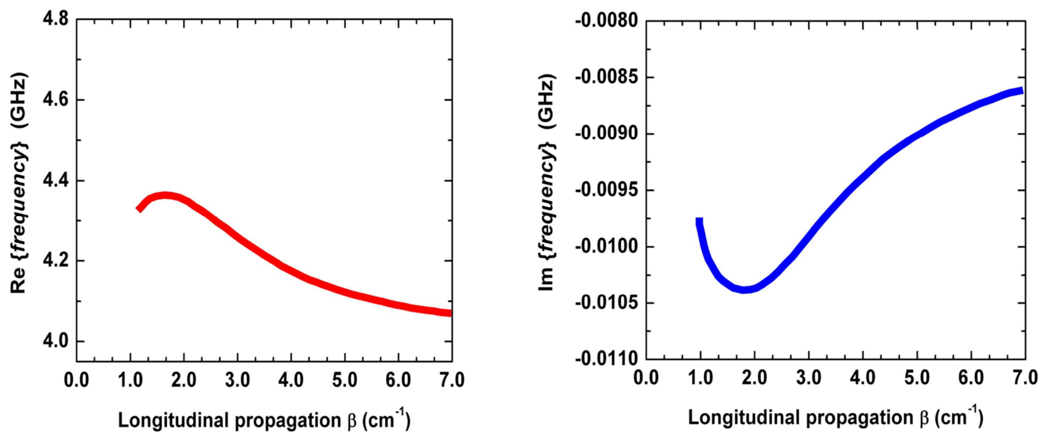
(a) (b)

Fig. 4. (a) Real-frequency/complex-wavenumber dispersion diagram of a *lossless* negative-index waveguide. (b) *Complex*-frequency/*real*-wavenumber dispersion diagram of the same waveguide as in (a).



(a) (b)

Fig. 5. Variation of the frequency versus (a) the real part and (b) the imaginary part of the *complex* wavenumber in the waveguide of Fig. 4(a) when dissipative losses are, now, present.



(a) (b)

Fig. 6. Variation of (a) the real part of the frequency and (b) the *imaginary part of the frequency* versus the *real* wavenumber in the waveguide of Fig. 4(b) when dissipative losses are, now, present.

Furthermore, a series of recent works [11,12,29] have conclusively shown that metamaterials can, when judiciously designed, be completely insensitive to *even high degrees* of fabrication disorder. This is simply because metamaterials owe their effective properties to an *averaged* electromagnetic response of their constituent meta-molecules, without necessarily requiring a ‘perfect’ lattice to achieve negative electromagnetic responses. Semiconductor-based metamaterial heterostructures are, also, expected to exhibit minimal sensitivity to fabrication disorder, since therein we do not make use of plasmonic meta-molecules, but planar semiconductor layers – one or more of which exhibit a negative electric permittivity below its plasma frequency. Current molecular beam epitaxy (MBE) facilities are indeed capable of growing high-quality semiconductor superlattices owing to mature, optimised growth-temperature, composition and doping-profile techniques.

Compensation of optical losses by use of gain

Although, as we saw in the previous section, a light pulse can be stopped inside a lossy metamaterial waveguide, the pulse still experiences considerable (temporal) losses. In this section, we show how, in a suitably designed metamaterial heterostructure, the losses that a slow-light pulse experiences can be completely removed by using gain (stimulated emission). An example of such a structure is schematically illustrated in Fig. 7, where we note that gain media/layers are placed adjacently to the negative-refraction semiconductor-heterostructure core layer. Similar loss-compensation configurations have recently been shown to work remarkably well [30], to the point of even allowing for *lasing* [31] in hybrid plasmonic-dielectric configurations. It turns out that by properly adjusting the 'pump' laser intensity, the (negative) imaginary part of the refractive index of the gain medium can become equal (in magnitude) to the (positive) imaginary part of the effective refractive index of the metamaterial heterostructure, so that losses can be *altogether* eliminated.

Indeed, in Fig. 8 below we are presenting numerical results (confirming the aforementioned conclusions) that were obtained using full-wave, finite-difference time- domain (FDTD) simulations of pulse propagation in the metamaterial

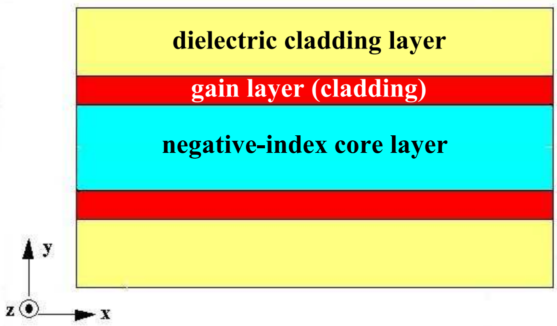


Fig. 7. Schematic illustration of the metamaterial-waveguide configuration for the (complete) compensation of the dissipative losses arising from the negative-index core layer.

waveguide structures of the type shown in Fig. 7. Four simulations were run, and in each simulation an oscillatory mode pulse was injected into the waveguide. The simulations examined the effect on the pulse when: only gain is present (the metamaterial is modelled as being lossless); only losses are present (the gain material is removed); neither losses nor gain are present; and both gain and losses are present. A NRI material was used for the core layer, which had a width of $0.4\lambda_0$ (λ_0 being the free-space wavelength of the pulse's central frequency). The gain layers were positioned immediately adjacent to the core layer, and extended outwards into the cladding for a distance of $0.25\lambda_0$. The rest of the cladding (shown in yellow color in Fig. 7) was assumed to be a non-dispersive material with a refractive index of 1 (air).

For simplicity, both the permittivity and permeability response of the NRI material are simulated using the same Drude model. Thus, the refractive index of the NRI material is given by: $n(\omega) = 1 - \omega_p^2/(\omega^2 + i\omega\Gamma)$, where $\omega_p = \sqrt{5}\omega_0$ is the plasma frequency and Γ is the collision frequency, which is set at: $0.002\omega_0/(2\pi)$. This gives the metamaterial a refractive index of: $n(\omega_0) = -4 + i0.0016$.

In our simulations, the response of the gain material is simulated using a Lorentz material model: $\varepsilon(\omega) = \varepsilon_\infty + \Delta\varepsilon\,\omega_L^2/(\omega_L^2 - i2\delta\omega - \omega^2)$, with: $\varepsilon_\infty = 0.9946$, the Lorentz resonance frequency $\omega_L = 0.6\omega_0$, the damping coefficient $\delta = 20\omega_0/(2\pi)$, and $\Delta\varepsilon = -1$.

The effective refractive index of the waveguide is extracted from the simulation by recording over time the H_z-field amplitude of the pulse at two points along the waveguide's central axis. Using the Fourier transforms of these results, the change in phase and amplitude undergone by each frequency between the two points can be calculated, from where the real and imaginary parts of the effective refractive index can then be obtained. An exemplary plot of the so-extracted imaginary part of the effective index of the guided light pulse is shown in Fig. 8. We note that when gain layers are placed adjacently to the negative-index core layer, the loss experienced by the guided light pulse is (at a given frequency) completely removed (red crosses in Fig. 8). For higher frequencies, this slow-light, negative-phase-velocity pulse is *amplified* while propagating inside the negative-index waveguide. Further evidence for the removal of losses is shown in Fig. 9, from where it can be directly seen that the incorporation of gain layers restores completely the amplitude of the slow-light, negative-phase-velocity pulse.

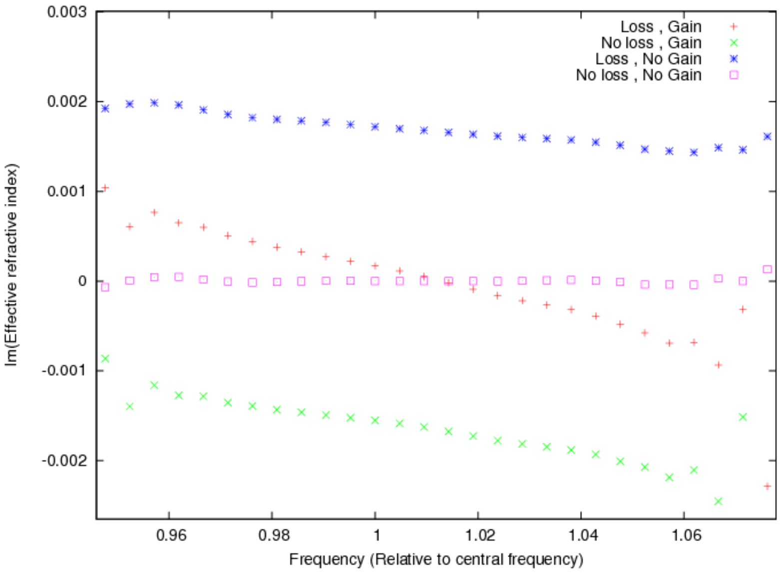


Fig. 8. Variation with frequency of the imaginary part of the effective index of a guided pulse in a negative-refractive-index waveguide for the cases where the NRI core layer is: lossless (pink square symbols); lossy (blue, tilted double-cross symbols in the upper part of the graph); lossy and gain cladding layers are used (red crosses); lossless and gain cladding layers are used (green tilted crosses in the bottom part of the graph).

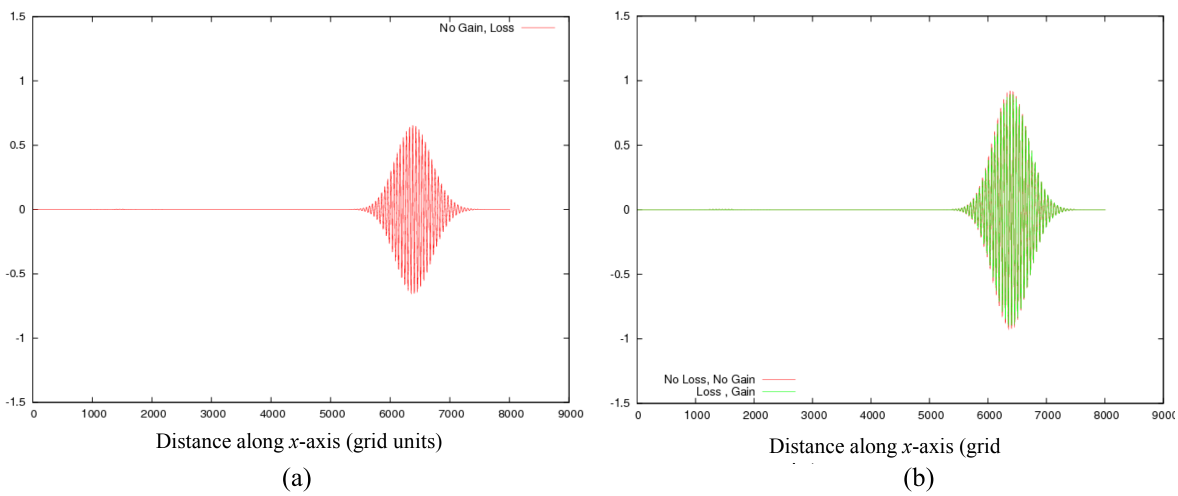


Fig. 9. Pulse propagation along the waveguide of Fig. 7 in the case where: (a) The core-layer is lossy. (b) The core-layer is lossy and gain is used in the adjacent cladding-layers.

Conclusions

In summary, we have shown that metamaterial waveguides with negative electromagnetic parameters (permittivity, permeability, refractive index) can enable complete stopping of light under realistic experimental conditions [6,13,14]. This attribute is underpinned by the resilience of the deceleration mechanism in these structures to fabrication imperfections (e.g., disorder) and dissipative losses. By nature, these schemes invoke solid-state materials and, as such, are not subject to low-temperature or atomic coherence limitations. The NRI-based scheme, in particular, inherently allows for high in-coupling efficiencies, polarization-independent operation, and broadband function, since the deceleration of light does not rely on refractive index resonances. This versatile method for trapping photons opens the way to a multitude of hybrid, optoelectronic devices to be used in 'quantum information' processing, communication networks and signal processors, and conceivably heralds a new realm of combined metamaterials and slow light research.

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