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Extreme control of light in metamaterials: Complete and loss-free stopping of light

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A R T I C L E I N F O

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A B S T R A C T

We present an overview of recent advances within the field of slow- and stopped-light in metamaterial and plasmonic waveguides. We start by elucidating the mechanisms by which these configurations can enable complete stopping of light. Decoherence mechanisms may destroy the zero-group-velocity condition for real-frequency/complex-wavevector modes, but we show that metamaterial and nanoplasmonic waveguides also support complex-frequency/real-wavevector modes that uphold the light-stopping condition. A further point of focus is how, by using gain, dissipative losses can be overcome in the slow- and stopped-light regimes. To this end, on the basis of full-wave finite-difference time-domain (FDTD) simulations and analytic transfer-matrix calculations, we show that the incorporation of thin layers made of an active medium, placed adjacently to the core layer of a negative-refractive-index waveguide, can fully remove dissipative losses – in a slow- or stopped-light regime where the effective index of the guided lightwave remains negative.

1. 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 invisibility cloaks.

Recently it has been theoretically demonstrated [6] that these two highly technologically important areas of research, which were until now following parallel tracks, could in fact be combined and potentially lead to novel, solid-state slow-light waveguides that could outperform existing slow-light designs and structures in terms of the degree to which light can be decelerated – conceivably, even down to a complete halt, at ambient conditions and optical bandwidths.

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 approximately 10–100. Theoretically, the deceleration of light herein arises via periodic back-reflections from an assumed *perfect* periodic lattice (used in obtaining the band diagram) and as such, in practice, it is sensitive to structural fluctuations and disorders – particularly, close to the zero-group-velocity point. These random, tiny (nm-scale) fluctuations lead to a disorder-induced 'smearing out' effect in the attained group refractive indices close to the band-edge points [9,10]. Practically, this results in slow-down factors that normally do not exceed a few hundreds [9–11]. Similar considerations also apply for CROWs (e.g., coupled photonic crystal cavities, microrings, Fabry–Pérot cavities), in which the propagation of light closely obeys a tight-binding model [12].

By contrast, it has been theoretically and experimentally established that metamaterials can be insensitive to the presence of even a high degree of fabrication disorder [13,14], 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 preclude the attainment of an effective refractive index. Further, by deploying suitably designed all-semiconductor based [15,16] (i.e., not metallic) metamaterial waveguides that include active/gain layers, we may engineer practical slow-light structures wherein the optical (dissipative) losses of the guided slow-light pulses can be reduced by orders of magnitude – or completely eliminated – compared to their passive counterparts.

In the following, we start our analysis by concisely reviewing the basic premises of slow/stopped light in negative-constitutive-parameters metamaterial and nanoplasmonic 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;

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hence, even inside such ‘imperfect’ (but realistic) structures a guided light pulse may still be dramatically decelerated and stopped. 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. Finally, we conclude by summarizing the basic findings of the present work.

2. ‘Trapped rainbow’ stopping of light in metamaterial and nanoplasmonic waveguides

Recent scientific breakthroughs within the optical engineering community have proved that it is indeed possible to dramatically decelerate or ‘store’ light by exploiting a variety of physical effects, such as electromagnetically induced transparency (EIT), coherent population oscillations (CPO), stimulated Brillouin scattering (SBS), and photonic crystal waveguides (PCWs). However, such approaches bear inherent limitations that may hinder either their practical deployment or their ability to completely stop light. For instance, so far atomic EIT (where the highest deceleration factors have been observed) uses ultracold or hot gases and not solid-state materials, CPO and SBS are very narrowband (typically, several MHz) owing to the narrow transparency window of the former and the narrow Brillouin gain bandwidth of the latter, while PhCs are prone to tiny fabrication imperfections (nm-scale disorder) that can considerably modify (shift) the photonic bandgaps. 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 [9–11]. Appreciable light deceleration, by up to approximately a factor of a hundred, can also be obtained with solid-state (e.g., metamaterial) analogues of EIT [17,18]. A strong point of this approach is that the slowing-down of light can be achieved over an ultra-thin and compact (planar) area, which may further find applications in improved biomolecular sensing [19] or generation of nanoscale Fano-type resonances [20]. However, here too, the reliance on a resonance-based deceleration mechanism unavoidably implies that the increased (compared with ultra-cold gases) damping rates associated with the solid-state structure(s) operating at ambient condition leads to a broadening and lowering of the attained group indices, thereby prohibiting the attainment of true light stopping.

In an effort to overcome the above limitations of positive-index slow-light schemes, a fundamentally new approach has recently been proposed [6,21–29]. This method relies on the use of waveguide heterostructures featuring *negative* electromagnetic/optical parameters (permittivity, permeability, refractive index), wherein the power-flow direction inside the negative-parameters regions is opposite to the one in the positive-index regions, resulting in a pronounced deceleration of the guided electromagnetic energy (see Fig. 1). 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

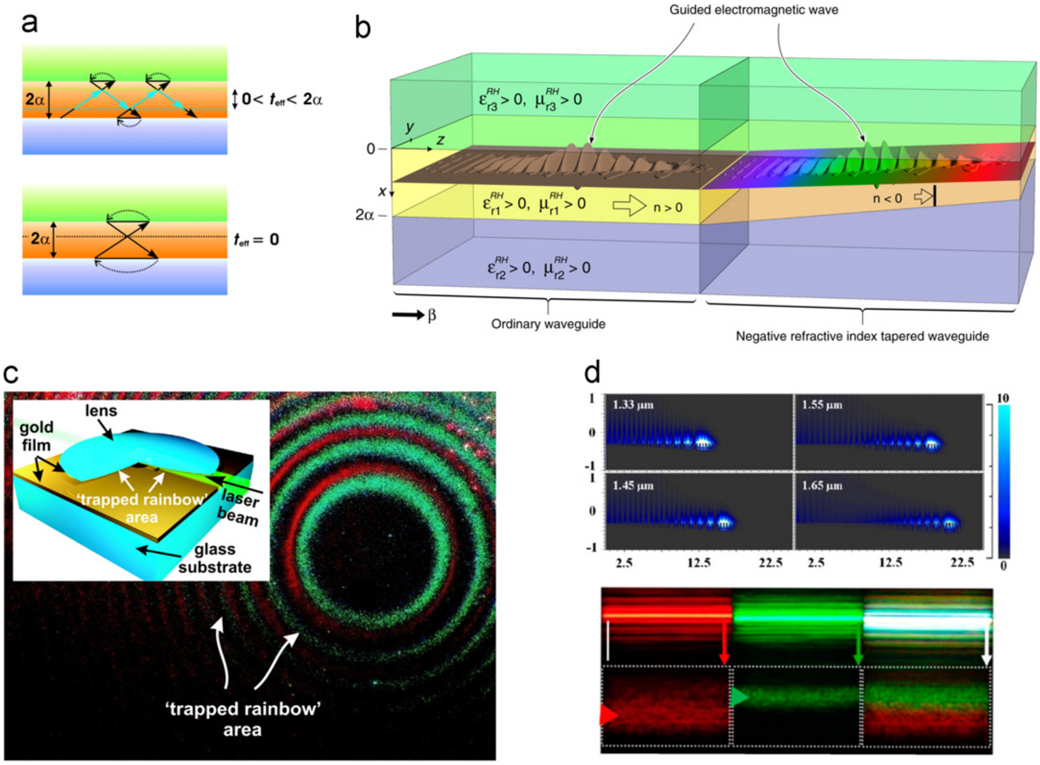

Fig. 1. Light slowing and stopping in nanoplasmonic metamaterials. (a) The negative refractive index in the core layer (of thickness 2α) of a metamaterial heterostructure causes negative Goos-Hänchen phase shifts in the zigzag propagation of a light ray. The thickness of the core layer is thereby compressed to $t_{\mathrm{eff}} < 2\alpha$ (upper part). For an appropriate choice of optogeometric parameters the effective thickness becomes zero (lower part). A light ray beginning from any point in that zero-thickness line (dashed line in the lower part) cannot but stay at that point, thereby giving rise to a zero group velocity. (b) When the thickness of the core layer varies slowly in space, each frequency of a light pulse adiabatically stops at a distinct spatial location, resulting in the demultiplexing of the pulse's spectrum and the formation of a ‘trapped rainbow’. (c) Experimental observation of a quasistatic ‘trapped rainbow’ in a tapered plasmonic waveguide. Different ‘colours’ of light, injected from the side (see inset), stop without back-reflections at prescribed spatial loci, in accordance with theory. (d) Slow light and Fourier spectral decomposition in a tapered plasmonic grating. Computational results for telecommunication wavelengths are shown in the upper part, while the lower one shows the experimental confirmation at visible wavelengths. Figures adapted with permission from Ref. [6], ©2007 NPG; Ref. [29], ©2010 AIP; Ref. [24], ©APS; and Ref. [30], ©2011 NAS (USA). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 be realised by even amorphous and highly disordered metamaterials. This approach allows for extremely large bandwidths [6,27,30] over which the slowing or stopping of the incoming optical signals can be achieved, as well as for ultrashort device lengths [32].

When the thickness of the core layer in metamaterial or plasmonic waveguides is made to vary slowly with distance, experiment [33–36] and theory [6,21–30] reveal that a light frequency injected into the tapered waveguide adiabatically stops and accumulates at a finite-thickness critical point inside the guide. Assuming a parabolic group-velocity υ_g profile with distance (with $\upsilon_g=0$ at the critical point), it is straightforward to show that the time it takes for the lightwave to *exactly* reach the critical point diverges logarithmically [6,30]; hence, light is not back-reflected. If a light *pulse* is in-coupled into the structure, each frequency component of the pulse may stop at a different spatial location inside the tapered guide, leading to the demultiplexing of the pulse's spectrum and the formation of a 'trapped rainbow' [6] (Fig. 1(b)). Because of the anomalous frequency dispersion of the negative refractive index of the core layer, the largest (smallest) wavelength components of the pulse stop at the smallest (largest) thicknesses of the taper. In Ref. [33] the stopping of each light wavelength has been experimentally achieved in the regime where the effective refractive index was becoming zero; hence the effective light wavelength was diverging and one was entering the quasi-static regime (Fig. 1(c)). A major current goal, hence, is to observe the same light-stopping effect in the full electrodynamic regime. A similar light deceleration mechanism can be exploited in any medium that is characterised by a negative electromagnetic parameter, such as e.g. plasmonic nanoguides. Fig. 1(d) illustrates exemplary theoretical and experimental investigations of such tapered metallic (negative-ε) structures capable of slowing-down light over a spectrum of several hundred nanometres in the visible regime.

It is interesting to point out that, in addition to metallic (metallodielectric) metamaterial or plasmonic slow-light structures, we may 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 [15,16] 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 [31] – 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 [32]. Existing molecular beam epitaxy (MBE) facilities are indeed capable of growing such high-quality semiconductor superlattices owing to mature, optimised growth-temperature, composition and doping-profile techniques.

3. Light stopping in the presence of metamaterial losses and fabrication disorder

An important consideration in assessing the potential of nanoplasmonic 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 losses and/or fabrication disorder. A decoherence mechanism that could here hinder the attainment of light stopping is dissipative losses, which may be – but are not necessarily [37–40] – considerable for plasmonic metamaterials with negative electromagnetic parameters. Fig. 3 (red dashed line) shows that the presence of losses indeed destroys the zero-υ_g point for modes characterized by real frequency (ω) and complex wavevector (k). However, for the same lossy configuration, there also exists another class of modes belonging to the complex-frequency (or complex time, t), real-wavevector domain (black solid line in Fig. 3) that uphold the light-stopping condition. These solutions can be obtained under non-continuous (i.e., pulsed) excitations [41] that do not fix the frequency to a real value, and in setups that maintain the reality of the wavevector. The dispersion diagrams (group velocities and modal gain) shown in Fig. 3 have been obtained by solving *exactly* Maxwell's equations for the heterostructure of Fig. 2 based on the transfer-matrix method (lines), as well as by analyzing in the time-domain the longitudinal propagation of cleanly-excited (single) Gaussian pulses using the finite-difference time-domain method (symbols).

In Fig. 3 we examine how the spatial and temporal losses (or gain) experienced by, both, the central frequency of a pulse and the pulse as a whole (guided along the active slow-light metamaterial heterostructure of Fig. 2) vary with core thickness. The complex-ω solutions can be calculated with the finite-difference time-domain

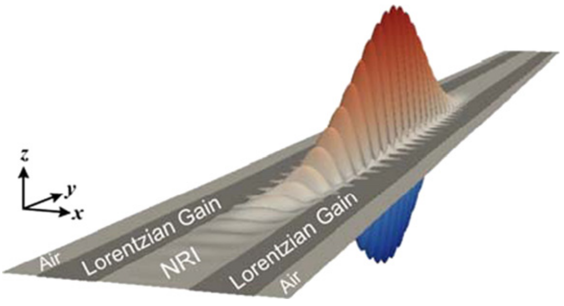

Fig. 2. (Color online) Schematic illustration of an active, slow-light metamaterial-waveguide heterostructure for mitigating losses in the negative-index (slow- and stopped-light) regime(s).

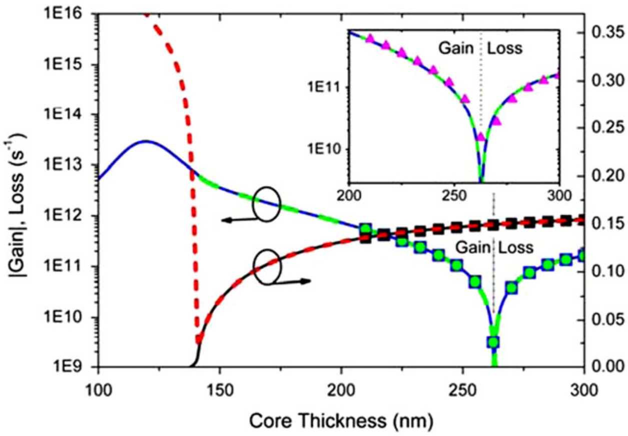

Fig. 3. (Color online) Comparison between FDTD (symbols) and TMM (lines) calculations of the temporal losses/gain and group velocity of the complex-ω and complex-k solutions with varying core thickness (case III). Shown are the group velocity (υ_g) of the complex-ω solutions (solid black), the group velocity of the complex-k solutions (red dashed line), the imaginary part of the complex-ω solutions (solid blue) and the imaginary part of the complex-k solutions multiplied by υ_g (green dashed). The inset shows the rate of energy loss (or gain) for the whole wavepacket (purple symbols) with varying core thickness as calculated by the discrete Poynting's theorem within the FDTD method.

(FDTD) method by recording the spatial variation of the field amplitude along the central axis of the heterostructure at two different time points, and then dividing the spatial Fourier transforms of the two longitudinal spatial profiles. The rate of energy change for the whole wavepacket (total loss or gain) is calculated using the discrete Poynting's theorem integrated over a spatial region sufficiently wide to contain the pulse. Fig. 3 shows that for core thicknesses above 262 nm the central frequency of the pulse experiences loss. For smaller thicknesses, for which the amplitude of the field increases inside the gain region, we find that the gain supplied by the cladding strips overcompensates the loss induced by the core layer. At a core thickness of 262 nm the central frequency experiences neither gain nor loss, while the wavepacket as a whole experiences gain (inset in Fig. 3). In all cases we have verified that $\mathrm{Re}\{n_{\mathrm{eff}}\}<0$ (data not shown here).

Overall, we find excellent agreement and consistency between five distinct sets of results: the spatial losses/gain (multiplied by the group velocity [25]) for the central frequency as calculated by the FDTD (green dots) and the transfer-matrix method (TMM) (green dashed line), the temporal losses/gain for the central frequency as calculated by the FDTD (blue squares) and TMM (blue dashed line), and the temporal losses of the whole wavepacket as calculated by the FDTD method (purple symbols in the inset of Fig. 3). This fact provides further evidence that loss compensation is in principle possible in the slow-light negative-index regime, including the light-stopping point at around 137 nm. Note that for core thicknesses smaller than around 140 nm the group velocity of the complex-k mode characteristically differs from that of the complex-ω mode (red dashed and black solid lines in Fig. 3). As with the case of SPPs in plasmonic films [41], the group velocity of the complex-k state exhibits a "back-bending", never becoming zero, while that associated with the complex-ω state may reduce to zero even in the presence of excessive gain (or losses). Further, unlike the complex-k state, the optical losses experienced by the complex-ω mode increase only moderately and smoothly compared to the normal metamaterial regime. We note that while usually, in positive-index slow-light structures, decoherence mechanism(s) of the order of only a few percents completely destroy the zero-υ_g condition (e.g., disorder in periodic structures), here the same condition is robust to the presence of even high degrees of decoherence (e.g., of the order of 100% when $\mathrm{Im}\{n\}\approx\mathrm{Re}\{n\}$).

Stopped-light metamaterial or plasmonic heterostructures are expected to be useful for enabling low-threshold, cavity-free nanolasers, efficient harvesting of light, enhanced nonlinear effects on the nanoscale and quantum nanoplasmonics (owing to the dramatically enhanced density-of-states in that regime). Thus, the applications herein targeted are viable (standard and emerging) *nanoplasmonic* ones – but, now, in the extreme regime where light completely stops and interacts even more strongly with matter. By contrast, applications such as optical buffers, together with their associated figures-of-merit (such as the 'delay-bandwidth' product), are rather better suited for and more relevant to ultralow-loss atomic-optics or transparent-dielectric based configurations.

4. Conclusions

The ability to stop light could enable a host of exciting and technologically important applications. In this article, we have introduced the basic concepts behind light-stopping in media with *negative* electromagnetic parameters, the intricacies involved in trying to attain this new type of light localization, as well as the ways to overcome them. We have shown that plasmonic metamaterial waveguides can enable complete light stopping under realistic experimental conditions. 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, the scheme invokes solid-state materials and, as such, it is not subject to low-temperature or atomic coherence limitations. The negative-index approach, in particular, inherently allows for high in-coupling efficiencies [6], polarization-independent operation, and broadband function, since the deceleration of light does not rely on refractive-index resonances.

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