Slow Light in Nanophotonic Materials

From 'Trapped Rainbows' to Quantum Memories

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Abstract—**We analyze and compare the salient features of slow-light propagation in a variety of nanophotonic structures, including metamaterial, plasmonic and photonic crystal waveguides. We discuss the possibility of stopping light in nanoplasmonic metamaterials, and coherently storing quantum information in semiconductor quantum dot ensembles.**

Keywords—slow light; metamaterals; plasmonics; photonic crystals; quantum dots; waveguides

I. INTRODUCTION

Metamaterials (MMs) [1], [2] and 'slow light' (SL) [3], [4] 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, 'invisibility' cloaks, and ultra-compact photonic devices.

Recently, it has been theoretically demonstrated [5] that these two highly technologically important areas of research, which were until now following separate tracks, could in fact be combined, with the potential of leading to novel metamaterial-enabled slow-light structures that can improve (in terms of the degree to which light can be decelerated, as well as in terms of performance, functionality and efficiency) on existing slow-light designs and structures.

In what follows, we begin by concisely reviewing the basic premises of slow/stopped light in metamaterial and plasmonic waveguides featuring negative electromagnetic constitutive parameters (permittivity/permeability/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. Section III provides a brief overview of various, so called, 'trapped rainbow' light-slowing/stopping schemes that have recently been reported, along with their merits and limitations. Further, on the basis of full-wave numerical simulations, it will be reported (during the course of the presentation) 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 section IV we explain that it is, in principle, possible to realize controlled storage and release of photonic space-time quantum coherences in quantum dot nanomedia subjected to coherent tunable light signals. Finally, section V summarizes the paper, presenting the main conclusions of the present review.

II. SLOW AND STOPPED LIGHT IN METAMATERIALS

Some of the most successful slow-light designs at present, based on photonic crystals (PhCs) [6] or coupled-resonator optical waveguides (CROWs) [7], can so far efficiently slow down light by a factor of 40 – otherwise, large group-velocity dispersion *and* attenuation-dispersion occur, i.e. the guided light pulses broaden and the attainable bandwidth is severely restricted. Furthermore, it has by now been realised that such *positive*-index slow-light structures are, unfortunately, extremely sensitive to the presence of (even weak) fabrication disorder [8] – 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 $c/300$ (refs. [3], [9]).

In an effort to overcome the above intrinsic limitations of *positive*-index slow-light schemes, a fundamentally new approach has been recently proposed [5]. 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 Figure 1). The scheme is 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 [10], [11] – 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 a bulk/effective (positive) refractive index.

Moreover, 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 [12]. In doing so, we are able to allow for extremely large bandwidths over which the slowing or stopping of the incoming optical signals can be achieved, as well as for ultrashort device lengths. This ability of metamaterial-based heterostructures to dramatically decelerated or even *completely stop* [5] light under realistic experimental conditions, has recently led to a series of experimental works [13], [14] that have provided spectroscopic evidence 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.

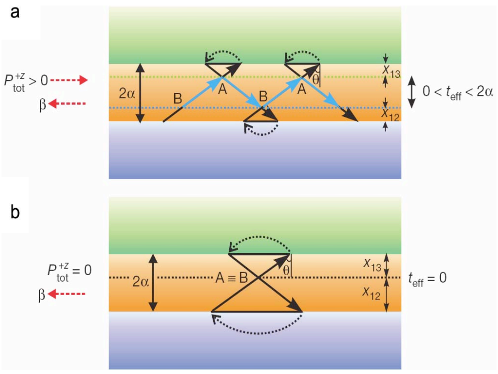

Fig.1. Slow and stopped light in negative-refractive-index hetero-structures. (a) Slow zigzag ray propagation along a NRI heterostructure. (b) Here, the ray returns exactly to its original point; the ray, thus, becomes permanently trapped (zero group velocity, $v_g = 0$) and an 'optical clepsydra' is formed.

III. Further Schemes For Slowing And Stopping Light

As was explained above, the 'trapped rainbow' method for stopping light relies critically on the presence of negative Goos-Hänchen phase shifts (see Fig. 1), as well as on the occurrence of mode-degeneracy points in the modal dispersion diagrams [5], [15], both of which require media with negative optical parameters, e.g., negative permittivity – but *not* necessarily negative refractive index. For instance, a plasmonic waveguide having a core of a material with negative (real part of) permittivity in the optical regime supports surface plasmon polaritons (SPPs) whose cycle-averaged power flow inside the negative-ε core is negative (owing to the negativity of ε). This can result in zero total cycle-averaged power flow, P_{tot} [15], at a particular (mode-degeneracy) point along the waveguide and, accordingly, in zero group (or energy) velocity at that point. As a result, in addition to the initially proposed negative-index based method towards broadband 'trapped rainbow'-stopping of light [5], scientists have now theorized a number of alternative metamaterial structures and geometries that can achieve similar feat. Some of these are, now, summarized below.

A first approach relies on the use of extremely anisotropic metamaterial wire waveguides made up of alternating metallic and dielectric discs [16]. In these structures the effective permittivity of the metamaterial wire is negative in the transverse direction but positive in the longitudinal direction, leading to zero-group-velocity (mode-degeneracy) points for the supported oscillatory modes, similar to those appearing in a negative-index waveguide. The light-stopping is achieved by an adiabatic *increase* of the wire radius to the zero-v_g point. A further interesting scheme uses, so called, 'spoof' SPPs in engineered metallic gratings in the THz regime (where the metallic losses are very small) to bring them to a complete halt at different points along the grating, depending on the frequency of the guided SPP wave [17], [18]. The authors of that work have, thus, showed that different 'colours' of light can adiabatically be stopped at different waveguide thicknesses, forming (THz) 'trapped rainbows'. In a different approach, He *et al*. [19] demonstrated that using a waveguide with a photonic crystal in its *negative*-refraction regime can, also, lead to temporarily halting individual light frequencies at distinct points along the waveguide. An advantage of this scheme is that, being all-dielectric, is almost insensitive to material dissipative losses. 'Trapped rainbow' stopping of light inside a hollow, air waveguide with anisotropic metamaterial cladding has been demonstrated numerically by Jiang *et al*. [20], while slow light propagation with very low group velocity dispersion in a negative-index waveguide with plasmonic claddings was reported by Dong *et al*. [21]. An NRI thin-cladding waveguide structure for temporarily stopping light has been proposed by Kim [22], while a detailed feasibility study for light-stopping in plasmonic waveguides has recently been reported by Park *et al*. [23]. More recently, Bai *et al*. [24] have demonstrated by using numerical simulations how optical information can controllably be stored in and released from a NRI waveguide. It should be herein noted that an advantage of the NRI (double-negative) slow-light structures as compared to their single-negative (e.g., plasmonic) counterparts is that they can facilitate slow light propagation for *both* polarizations (TM and TE) – an attribute that is important for certain slow-light applications, such as in modulators and switches [25].

Finally, it is worth pointing out that negative Goos-Hänchen shifts can exist not only for electromagnetic waves, but also for acoustic waves [26], as well as for matter (e.g., electron or atom) waves [27], [28]. This opens up the remarkable possibility of 'trapped rainbow'-stopping of *matter* waves by means of *light* (e.g., laser 'slabs'), i.e. the reverse of 'trapped rainbow'-stopping of light in meta-material waveguides.

IV. Quantum Dot Nanomaterials For Quantum Memories

Light is a promising candidate for carrying information in classical, but also *quantum* communication systems. In the realization of quantum information technologies, a key requirement is the ability to transmit a photonic qubit *and* to maintain and store quantum coherences. Various experiments have, therefore, focused on an exploration of the coupling of light and matter with the aim to preserve and store quantum coherence. In principle, the realization of such a 'quantum memory' system requires precise knowledge of the coherence properties of the particular material employed, as well as the system itself. So far, concepts and realizations of quantum memory elements have typically been based on atom and ion ensembles, and various investigations have concentrated on atomic vapours or ensembles of atoms, where the transfer of a quantum state between matter and light has, indeed, been achieved [29].

Recently, we have theoretically demonstrated controlled storage and transfer of photonic space-time quantum coherences realized by a quantum dot nano-medium that was subjected to a coherent tunable light signal [30]. This system has a large potential for the realization of a solid-state based controllable quantum memory: Quantum dots can be positioned in a controlled way, addressed electrically and/or optically, embedded into active devices or integrated into larger structures, e.g. arrays or micro cavities to improve the efficiency. Further, they are attractive for quantum experiments, e.g. as single photon sources [31]. Our analysis of spatial coherence patterns that directly profit from the full information represented in the distributions of field-field and field-dipole correlations, demonstrated a strong dependence of *storage* and transfer of quantum coherence on, both, optical and *electrical* excitation conditions. Furthermore, the quantum correlations revealed the influence of intradot hot-carrier relaxation and shed light on the importance of disorder in the dynamic response and coupling of light and matter.

V. CONCLUSION

In summary, we have shown that plasmonic metamaterial waveguides featuring negative electromagnetic parameters can enable complete stopping of light under realistic experimental conditions [5], [13], [14], [17], [18], [23], [24]. 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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