Slow and Stopped Light in Metamaterials

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Abstract

The prospect of achieving extreme slow- and stopped-light in metamaterial and plasmonic waveguides has recently attracted intense attention. Here we will elucidate the mechanisms by which complete stopping of light may be achieved based on the 'trapped rainbow' principle. While decoherence mechanisms may destroy the zero-group-velocity condition for real-frequency/complex-wavevector modes, we show that metamaterial and nanoplasmonic waveguides also support complex-frequency/real-wavevector modes that uphold the light-stopping condition.

1. Introduction

Metamaterials (MMs) [1, 2, 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 lead to novel, solid-state slow-light waveguide concepts that could complement 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.

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

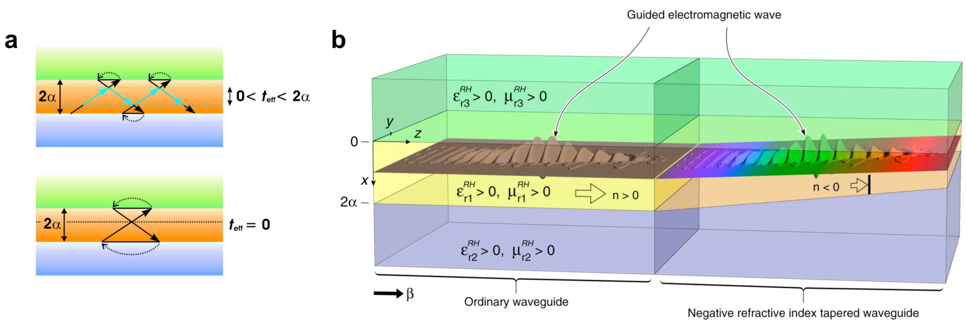

Fig. 1: 'Trapped rainbow' light slowing and stopping in nanoplasmonic metamaterials. (a) The negative refractive index in the core layer (of thickness 2α) of a metamaterial heterostructure causes negative Goos-Hänchen phase shifts in the zigzag propagation of a light ray. (b) When the thickness of the core layer varies slowly in space, each frequency of a light pulse adiabatically stops at a distinct spatial location, resulting in the formation of a trapped rainbow.

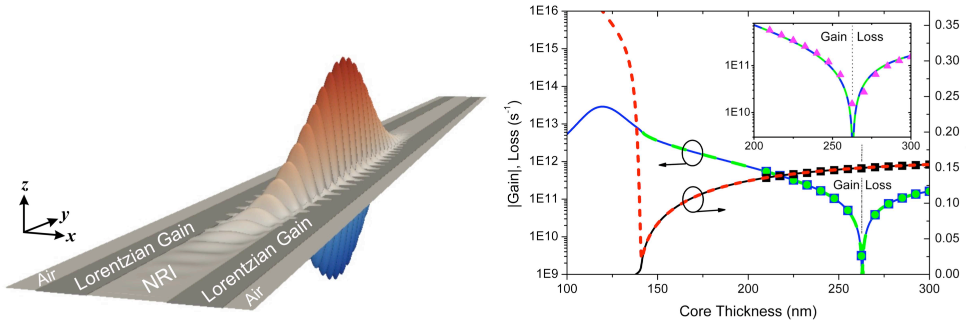

Fig. 2: Left: Schematic illustration of an active, slow-light metamaterial-waveguide heterostructure for mitigating losses in the negative-index (slow- and stopped-light) regime(s). Right: Comparison between FDTD (finite-difference time-domain; symbols) and TMM (transfer-matrix method; lines) calculations of the temporal losses/gain and group velocity of the complex-ω and complex-k solutions with varying core thickness. 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 Poyntings theorem within the FDTD method.

of approximately 10 to 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, 10, 11]. Similar considerations also apply for CROWs (e.g., coupled photonic crystal cavities, microrings, Fabry-Prot cavities), in which the propagation of light closely obeys a tight-binding model [12].

2. Complex-ω stopping of light in metamaterial and nanoplasmonic waveguides

Recent scientific breakthroughs have shown that it is 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). Atomic EIT (where the highest deceleration factors have been observed) in ultracold or hot gases and not solid-state materials, CPO and SBS use strong resonances are threfore 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. 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 [13, 14] and 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 [15] or generation of nanoscale Fano-type resonances [16]. A fundamentally different approach has recently been proposed [6, 17, 18, 19, 20] that relies on the use of waveguide heterostructures featuring negative electromagnetic/optical parameters (permittivity, permeability, refractive index) as illustrated in Fig. 1. This 'trapped rainbow' approach allows for extremely large bandwidths [6, 19] over which the slowing or stopping of the incoming optical signals can be achieved, as well as for ultrashort device lengths [21]. A major decoherence mechanism that could here hinder the attainment of light stopping is the presence of dissipative losses. These may be – but not necessarily [22, 23, 24, 25, 26] are – considerable for plasmonic metamaterials with negative electromagnetic parameters. Fig. 2 (red dashed line) shows that in the presence of losses indeed destroys the zero-v_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. 2, right) that uphold the light-stopping condition. These solutions can be obtained under non-continuous (i.e., pulsed) excitations [26] that do not fix the frequency to a real value, and in setups that maintain the reality of the wavevector. Fig. 2 (right) shows 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 (left) vary with core thickness. 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. 2 (right)).

3. Conclusions

The ability to stop light could enable a host of exciting and technologically important applications. Stopped-light metamaterial or plasmonic heterostructures are expected to be useful for enabling low-threshold, cavity-free nanolasing, 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.

References

[1] P. Markos, C. M. Soukoulis, Wave Propagation: From Electrons to Photonic Crystals and Left-Handed Materials, Princeton University Press, Princeton, 2008.
[2] V.M. Shalaev, A.K. Sarychev, Electrodynamics of Metamaterials, World Scientific Pub., New Jersey, 2007.
[3] N. Engheta, R.W. Ziolkowski (eds), Electromagnetic Metamaterials: Physics and Engineering Explorations, Wiley-IEEE Press, New York, 2006.
[4] P.W. Milonni, Fast Light, Slow Light and Left-Handed Light, IOP Publishing, New Work, 2005.
[5] J.B. Khurgin, R.S. Tucker (eds), Slow Light: Science and Applications, Taylor and Francis, New York, 2009.
[6] K.L. Tsakmakidis, A.D. Boardman, O. Hess, *Nature*, vol. 450, p. 397, 2007.
[7] B. Corcoran, et al. *Nature Photonics*, vol. 3, p. 206, 2009.
[8] F. Xia, et al. *Nature Photonics*, vol. 1, p. 65, 2006.
[9] A. Petrov, et al. *Opt. Express*, vol. 17, p. 8676, 2009.
[10] D. P. Fussell, et al. *Phys. Rev. B*, vol. 78, p. 144901, 2008.
[11] R.J.P. Engelen, D. Mori, T. Baba, L. Kuipers, *Phys. Rev. Lett.*, vol. 101, p. 103901, 2008.
[12] A. Yariv, Y. Xu, R.K. Lee, A. Scherer, *Opt. Lett.* vol. 24 (1999) 711.
[13] N. Papasimakis, V.A. Fedotov, N.I. Zheludev, S.L. Prosvirnin, *Phys. Rev. Lett.* , vol. 101, p. 253903, 2008.
[14] P. Tassin, et al. *Phys. Rev. Lett.* , vol. 102, p. 053901, 2009.
[15] N. Liu, M. Hentschel, Th. Weiss, A. P. Alivisatos, H. Giessen, *Science*, vol. 332, p. 1407, 2011.
[16] B. Lukyanchuk, et al. *Nature Materials*, vol. 9, p. 707, 2010.
[17] K.L. Tsakmakidis, A.D. Boardman, O. Hess, *Nature*, vol. 455, p. E11, 2008.
[18] E.I. Kirby et al., *Phys. Rev. B*, vol. 84, p. 041103(R), 2011.
[19] Q. Gan, Z. Fu, Y.J. Ding, F.J. Bartoli, *Phys. Rev. Lett.*, vol. 100, p. 256803, 2008.
[20] Q. Gan, Y.J. Ding, F. J. Bartoli, *Phys. Rev. Lett.* , vol. 102, p. 056801, 2009.
[21] J.-S. Li, *Opt. Laser Technol.* , vol. 41, p. 627, 2009.
[22] S. Xiao, et al. *Nature*, vol. 466, p. 735, 2010.
[23] S. Wuestner, A. Pusch, K.L. Tsakmakidis, J.M. Hamm, O. Hess, *Phys. Rev. Lett.* , vol. 105, p. 127401, 2010.
[24] A. Fang, Th. Koschny, C.M. Soukoulis, *Phys. Rev. B*, vol. 82, p. 121102(R), 2010.
[25] J.M. Hamm, S. Wuestner, K.L. Tsakmakidis, O. Hess, *Phys. Rev. Lett.*, vol. 107, p. 167405, 2011.
[26] A. Pusch, S. Wuestner, J. M. Hamm, K.L. Tsakmakidis, O. Hess, *ACS Nano*, vol. 6, p. 2420, 2012.