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Trapping, Dragging and Boosting Light with Dynamical Metamaterials

Emanuele Galiffi[1], Paloma A. Huidobro[2], Andrea Alu[3], J. B. Pendry[1]

(1) Blackett Laboratory, Imperial College London, South Kensington Campus, London, UK
(2) Instituto Superior Tecnico-University of Lisbon, Lisbon, Portugal
(3) Photonics Initiative, ASRC, City University of New York, New York, USA

Abstract

Time-modulation constitutes a new degree of freedom for metamaterials, promising to open completely new avenues for wave-control. In this contribution we demonstrate a few instances where this capability would enable completely new wave-functionalities. Firstly, we show how simple periodic time-modulation of the conductivity of a flat surface can enable surface-wave excitations with extremely high coupling efficiency in the absence of any near-field coupler. Secondly, we show that modulating multiple parameters of a material results in an artificial form of optical drag, and finally, we demonstrate a new amplification mechanism uniquely enabled by spatiotemporal media, which, remarkably, does not rely on the well-known parametric amplification, but rather on the compression of lines of force.

Introduction

The advent of ultrathin, dynamically tunable materials has sparked unprecedented interest in the possibility of extending the metamaterial concept to the temporal domain. In electromagnetics, near-zero-index materials such as indium-tin-oxide offer unprecedentedly large nonlinearities in the visible and near-infrared, whereas in the mid-infrared and below layered materials such as graphene enable efficient, ultrafast modulation of their carrier density via electro-optical, as well as all-optical techniques. Fuelled by the interest in applications such as nonreciprocal wave propagation, as well as new opportunities for amplification and harmonic generation, the concept of time-varying media promises to revolutionise all wave realms, thus further broadening its range of potential applications and impact. In this contribution, we will present a number of avenues opened by the use of temporal inhomogeneities to trap, drag and boost electromagnetic waves.

Temporal Wood Anomalies

We will first discuss a new method for coupling free-space radiation to surface waves, such as surface plasmons, based solely on temporal modulation. The evanescent character of surface waves implies that their excitation from free space demands the breaking of momentum conservation, and hence the engineering of spatial surface-inhomogeneities such as gratings, or the deployment of near-field probes. These schemes are often impractical, not generally reconfigurable, and prone, in high-mobility layered materials such as graphene, to the introduction of additional losses from fabrication defects. We propose a completely new pathway towards the efficient excitation of surface waves, based on the breaking of temporal symmetry. By proposing and modelling a realistic graphene experiment, we demonstrate that surface waves can be excited with unit efficiency from free space without the need for any surface inhomogeneities, by modulating in time the carrier density of a material (or its surroundings), thus trapping electromagnetic waves in the near-field via time-modulation. This is demonstrated in Fig. 1. [1]

Fresnel Drag in Space-Time Media

Secondly, we demonstrate how the conventional concept of motion may be generalised by considering spatiotemporal modulation of material parameters. We show how a novel form of optical drag can be obtained by engineering a travelling-wave modulation of both dielectric and magnetic parameters of a material. Remarkably, this synthetic Fresnel drag, which has long been known for the case of moving media, is not subject to the conventional limitations imposed by special relativity, as the modulation can be induced by an external pump to sweep the material at superluminal, as well as subluminal speeds. This effect may be realised with current technology by using nonlinear RF components such as varactors [2]. We additionally present effective-medium descriptions of space-time media, which can yield even exact solutions for impedance-matched modulations [3].

Luminal Amplification

In the limit where the phase velocity of the travelling-wave modulation approaches the speed of the waves in the pristine medium, light undergoes a localisation transition: waves are trapped within each period of this synthetically moving grating. These systems, termed

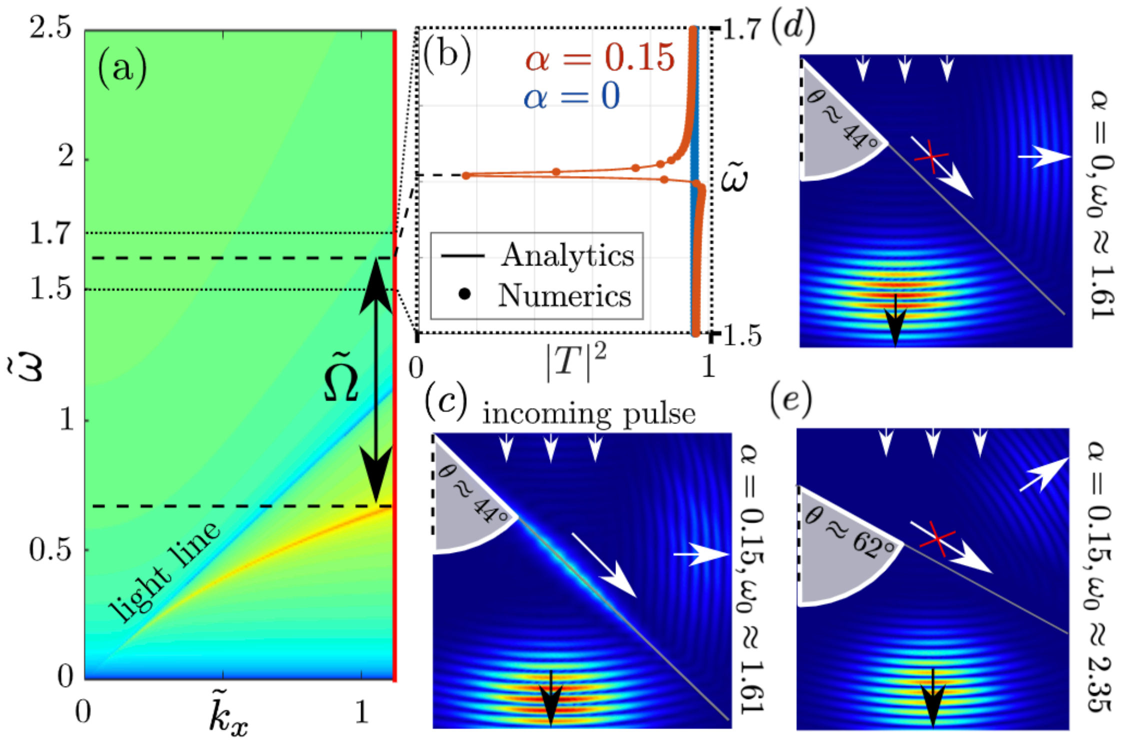

Figure 1: (a) Temporal Wood anomaly concept demonstrated for a conductive sheet with Drude dispersion. Illuminating the time-modulated sheet with oblique incident plane waves leads to a strong coupling efficiency to a surface mode on a flat surface with no near-field couplers, signified by the dip in transmittance (b). (c-e) Finite-element time-domain simulations of a pulse incident on the time-modulated sheet: in (c) the carrier frequency

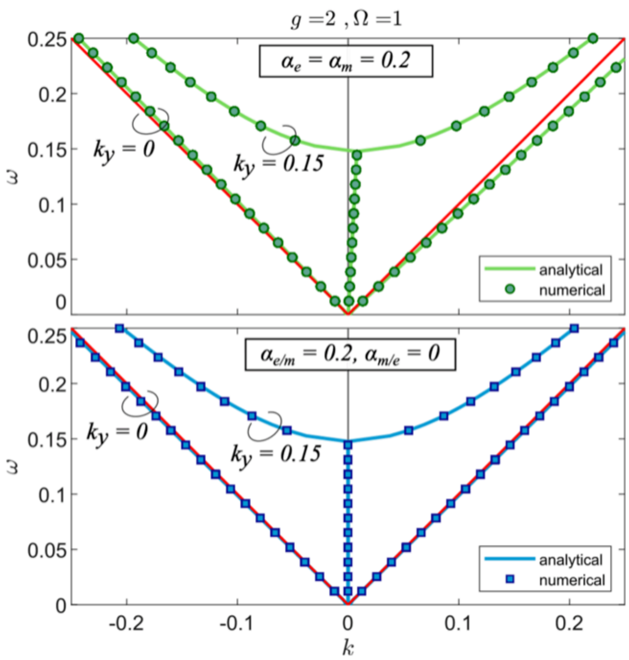

Figure 2: Optical Fresnel Drag in a synthetically moving medium, whose dielectric and magnetic parameters are travelling-wave modulated. Both parameters are modulated in the top panel, producing a clear non reciprocity in the long-wavelength regime, whereas only one parameter is modulated in the bottom panel, resulting in reciprocal bands.

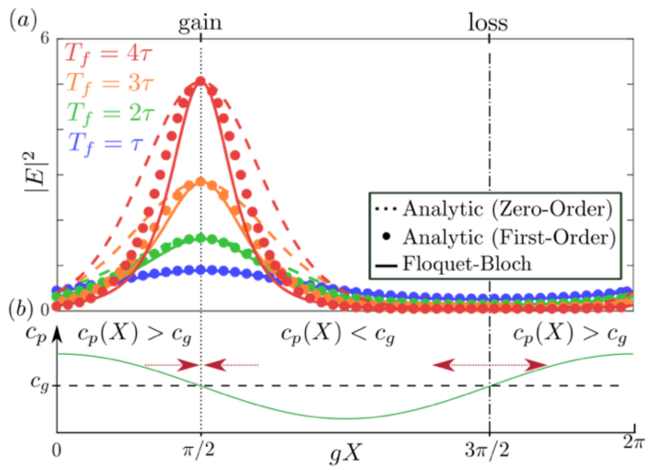

Figure 3: Luminal amplification enabled by a space-time modulation synthetically moving at the speed of light. The amplitude of the nonreciprocal amplification, as well as the compression of the pulse train, increase exponentially.

luminal media, can grab electromagnetic field lines and compress them, while simultaneously amplifying them. As it does not rely on coupling between forward and backward waves such as e.g. parametric amplification, this effect constitutes a truly novel amplification mechanism, which can transform input waves of any frequency, including static fields, into trains of short, intense pulses, generating harmonics with exponential efficiency. We will thus conclude by presenting a comprehensive theory of light compression, amplification and localisation in luminal media, and discuss potential surface-wave implementations, as well as the effect of dispersion [4,5].

References

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