Integrated Linear and Nonlinear Metaphotonics

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Abstract

Integrated metamaterial-driven waveguide devices are of growing importance for potential applications in the health, environment and energy sectors and in the possible design of new computing techniques. The latter will be introduced through the new history editor involving space-time transformations optics. This paper will address both linear and nonlinear waveguide complexities, under the general heading of integrated metaphotonics heading. The results will demonstrate how strong linear modal control emerges from metamaterial choices and how even weak nonlinearity creates new forms of beam and pulse formation. For all the cases analysed, both waveguide complexity and the role of magnetooptics will be introduced.

1. Introduction

Building up a range of integrated metamaterial-driven[1] waveguide devices is not only attractive from a fundamental point of view, but because it initiates the possibility of creating extremely novel down-stream applications. In this presentation a range both linear and nonlinear waveguide complexities will be addressed under the general integrated metaphotonics heading. These will include linear modal control, introduced by certain types of metamaterials[2] and weakly and strongly nonlinear beam and pulse formation. All the cases analysed will be subject to geometrical waveguide complexity and external magnetooptical influence. Loss-controlled metamaterials[3,4,51] have now reached an advanced stage[2], so that building up such a range of integrated waveguide devices is going to be possible with an accessible menu of materials. It is evident, from a fundamental point of view, that it is also going to be possible to imagine a number of important applications that will impact upon the environment, health, energy and computing sectors. The population of the linear guiding domain has traditionally anticipated ways in which modal and interactions can be put in place by using sophisticated waveguides, couplers, and sometimes with external control. The limitations imposed by using traditional single positive materials will be discussed and the routes to massive flexibility offered by metamaterials will be exposed. Moving beyond the linear domain, the development of nonlinear devices is a major goal of this presentation. This is because, when deploying metamaterials, there is such a dramatic and strong effect upon critical operational boundary conditions[6]. It is with all of these outcomes in mind that this presentation is developed, under a general heading called integrated metaphotonics.

2. The linear domain

In the first instance, the *linear domain* will be modelled, dealing with the propagation of planar waveguide modes, in a double negative material. Still within the linear domain, the modelling will be extended to incorporate metamaterials characterised by other important combinations of positive, or negative, relative dielectric permittivity and relative permeability, together with degrees of geometrical complexity. An example of the latter to be discussed uses advanced modelling techniques to access guide tapering of the kind reported in the widely cited trapped rainbows paper[7].Not only will the general properties of linear guides be exposed, but a major step will be taken to introduce externally-driven control through magnetooptic influences. Figure 1 shows for a typical tapered guide filled with a metamaterial that the modal shapes differ quite remarkably at different positions in the taper measured by an effective thickness D. The Figure also shows how an applied magnetic field $\mathbf{H_0}$ can bring the group velocity to zero, hence stopping the light. This is an application of the magnetooptic Kerr effect, but the presentation will also for the first time embrace the much more complex Faraday rotations[8,9], bringing in the special characteristics that polarisation interactions are compelled to assume within metamaterials. This kind of non-reciprocal behaviour will be contrasted with intrinsic chiral behaviour. In order to set up

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another benchmark, the interesting differences that occur when isotropy is replaced by anisotropy will also be a major feature of the discussions. The degree of control obtained by manipulating planar waveguide interfaces is another fascinating outcome that will be a feature of special metamaterials, leading to spectacular linear modal control. Waveguide couplers will be introduced[10], accompanied by a thorough exposition of meta-driven contra- and co-directional coupling[11] and also some discussion of grating structures acting as Bragg reflectors. It is shown that certain systems lead to the possibility of not only slowing light down, but to all-optical computing and to new ideas about switches and X-junctions. All of these outcomes depend intrinsically upon the deployment of modern metamaterials, and it will become apparent that there are certain novel features that emerge from them and these will be made clear in the presentation. Tapered waveguides lead to the beautiful result pioneered in the literature as the *trapped rainbow*[7] but it is very important to understand how these trapped rainbows can be influenced by an externally applied magnetic field. The latter exposition falls neatly into the linear domain that constitutes the early part of this presentation. Fig 1 shows important outcomes of an approach to a tapered waveguide that decreases in thickness from left to right, where, at any point down the guide, D is the local thickness. The figure shows that the stopping capability is controlled by an external magnetic field, $\mathbf{H_0}$, and the modal field cross-sections vary considerably in shape for each normalised localised thickness encountered as progression down a tapered guide proceeds. Nonlinear influences will be addressed below. Transformation optics will be invoked on every occasion that geometrical complexity is encountered and will be developed not only to include magnetooptics but the new work on spacetime effects. Indeed, the presentation will include a fascinating use of the spacetime cloak, or the *history editor*[12], in terms of hidden computing within a traditional data coupler.

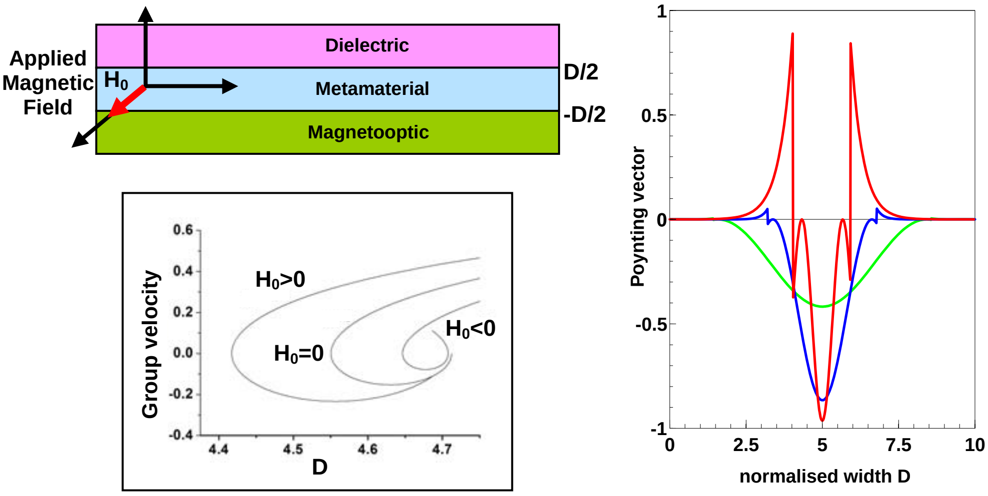

Figure 1. Upper left: The waveguide configuration. Lower left : A plot of wavepacket group velocity versus waveguide core thickness. Right : Modal shapes.

3. The role of nonlinearity

Moving on from the linear cases, the first steps into the nonlinear domain will invoke weak nonlinearity and will bring out some new features of soliton propagation. In fact, some interesting work has recently been presented[13,14]on the management of solitons with specialised metamaterial dispositions, and this will be outlined very carefully in order to focus upon precisely what influence metamaterials really have upon beam and pulse formation and propagation. This work will be presented as precursor to an exact nonlinear theory of guided waves. This exact theory of nonlinear waves in metamaterials also leads to the stopping of light but now it is dramatically controlled by the nonlinearity, as opposed to the earlier linear trapped rainbow development. It is possible to use this power-control in waveguides that do not require the tapering suggested by the earlier work. Indeed, it will be shown that nonlinear trapped rainbows in magnetooptic environments offer an amazing degree of control. In pursuit of this objective, it will be shown that the deployment of magnetooptics will lead to formats that could be the basis of many realistic applications. Nonlinear bulk metamaterial will also be examined using vortices as suitable probes. Many new conclusions will be delivered on this topic, which will emphasize, once again, how a whole range of different metamaterials can be deployed to reveal the fascinating world of nonlinear waves.

Nonlinear vortices are of considerable interest and their behaviour in a variable diffraction environment measured by the parameter $\mathscr{D}$, where $\mathscr{D} = 1$ is the normal diffraction. Metamaterials can be used to control the diffraction environment and, as shown in Fig 2, can lead to parameter values the order of $\mathscr{D} = 0.3$, which results in very intense and highly localised vortices.

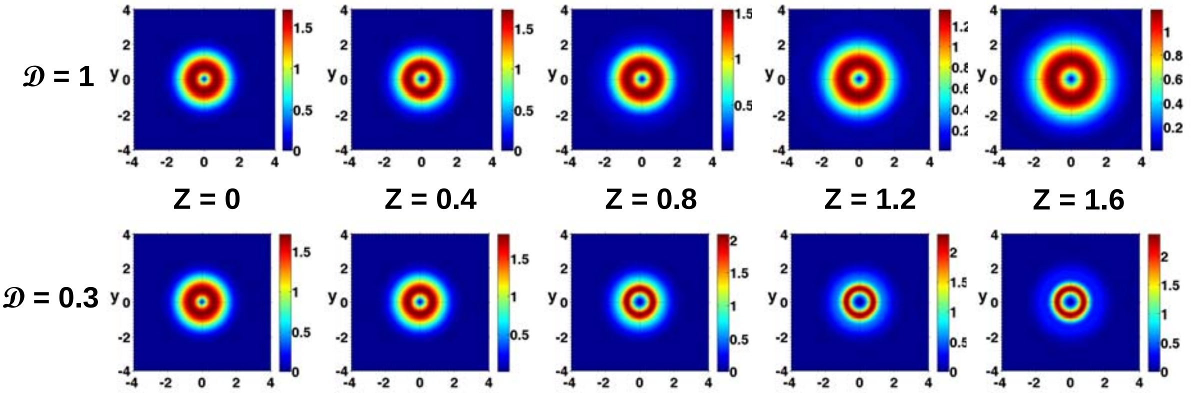

Figure 2. A comparison between standard and 30% diffraction-managed nonlinear vortex propagation.

4. Brief conclusions

A comprehensive discussion of integrated metaphotonics is presented that maps both the linear and nonlinear domains, with the added influence of advanced magnetooptic control. The stopping of light, modal control, rainbow effects and the history editor, which is a recently reported seminal advance in spacetime transformation optics is reported. Many outcomes of full-scale simulations will be reported that will depend upon transformations that can embrace both nonlinear and magnetooptic environments.

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