Magnet-Free Routes to Nonreciprocal Photonics

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Abstract *In this talk, we discuss our recent progress in the context of integrated photonic systems that exploit temporal modulations, opto-mechanical phenomena and nonlinearities to enable nonreciprocity without the need for a magnetic bias, and their implications for robust topological propagation of light on chip.*

Introduction

Nonreciprocal responses are usually achieved in optics using magneto-optical phenomena and materials [1]-[2], which are known to break one of the assumptions of the Lorentz reciprocity theorem. However, this approach has several drawbacks, including the scarcity and cost of magneto-optical materials, their relatively large insertion loss that each of this device introduces in the optical path, the weakness of these phenomena as the frequency grows, and their lack of compatibility with silicon technology and hence their challenges in integration.

Time modulation is an interesting alternative to magnetic bias, as it has been recognized by many scientists over the years [3]-[10] in different frequency regimes and for different applications. Metamaterials offer a path to make these phenomena more efficient, compact, and optimize their metrics of performance, to the point of making time modulation an attractive alternative to magnetically biased devices [11]. We have been working on this topic for a few years [12]-[22], proposing various magnet-free routes towards non-reciprocal devices for guided waves and free-space radiation that can outperform magnetic circulators or isolators in terms of several metrics of performance. One opportunity is offered by electro-optical modulation schemes, but they tend to be limited in modulation speeds and amplitudes. Nonlinearities offer the possibility of modulating the underlying materials optically, offering exciting directions for magnet-free integrated photonic devices breaking reciprocity. In addition, nonlinearities combined with geometrical asymmetries can provide a bias-free route to nonreciprocity, by using the signal itself entering the device to break transmission sysmmetry.

Arrays of these elements open also other interesting opportunities in the context of topological metamaterials [22]. More generally, temporal modulations break the limitations of static, passive, linear metamaterials and open tremendous opportunities for new frontiers of wave manipulation. In this talk, we will focus on outlining the significant opportunities and challenges in implementing these systems.

As an example of the complexity of light-matter interactions in these systems, it is sufficient to point out that, in order to break reciprocity, the speed of modulation needs to be typically comparable with the time the wave spends inside the device, but given the challenges in modulating with large speeds, we typically rely on highly resonant elements that slow down the wave. This implies that conventional time-domain techniques to analyze these modulated elements may be largely inefficient, and analytical or frequency-domain techniques may be preferable. During the talk, we will discuss a few approaches we have pursued to efficiently analyze these structures, and the application of these techniques for the design and implementation of various nonreciprocal and topological metamaterials.

Parametric Metamaterials

In addition to non-reciprocity, time modulation opens related opportunities for other unusual wave interactions. An example is the possibility to pump energy in the system by extracting it from the modulation network. The most common way of achieving this parametric gain phenomenon is to modulate at twice the signal frequency, which may be used to amplify the signal traveling in the modulated system, or broaden its bandwidth of operation [23].

Another opportunity is provided by commutated networks, which can convert frequencies with large efficiency, a functionality that can be exploited to establish new regimes of wave propagation and overcome the trade-off between delay and bandwidth in delay elements [24]. These systems, typically implemented in arrays of modulated elements, are difficult to model, analyze and synthesize, and efficient numerical techniques are extremely important to provide a route towards their implementation. During our talk, we will elaborate on our approaches to the analysis, design and implementation of these systems, and discuss their impact on various photonic technologies of interest from radio-frequencies to optics.

Conclusions

Modulated and nonlinear structures are ideally suited to open a magnet-free routes to nonreciprocal photonics, which is ideally suited for optical and quantum computing and lidar systems. In this talk, we will discuss the basic principles behind this technology, our recent implementations, and the potential impact on photonic technologies of this work.

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