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Electromagnetic Nonreciprocity, Amplification and Mixing in Dispersion-Engineered Space-time-varying Systems

Nima Chamanara*(1) and Christophe Caloz(1)
(1) Department of Electrical Engineering, Polytechnique Montréal, Montréal, QC, H3T 1J4, Canada

Abstract

Dispersion engineering is leveraged for the realization of electromagnetic nonreciprocity, amplification and perfect mixing, in space-time varying systems. It is shown that asymmetric electromagnetic dispersion curves based on space-time modulation represent a technologically viable path for the generation of electromagnetic isolation and perfect mixing. It is also demonstrated that space-time mediated intraband photonic transitions in a properly engineered dispersive system lead to electromagnetic amplification and mixing. The proposed structures may find applications in low-noise mixer-amplifiers and magnet-less isolators.

1 Introduction

Space-time varying media, play a central role in many electromagnetic phenomena and devices. The interest in electromagnetic properties of such media dates back to traveling wave tubes [1] and parametric amplifiers [2]. More recently, it has been discovered that space-time varying media can generate interband/intraband photonic transitions [3,4]. In this case, a waveguide state is transformed into another state, that may correspond either to the same mode or a different mode, as it propagates through a properly designed space-time varying section of the waveguide. Such oblique transitions have been used to produce magnet-less nonreciprocity [3,4].

Although there has been many efforts to produce similar magnet-less nonreciprocal systems based on oblique photonic transitions in recent years [3–5], there has been little or no studies on the effects of dispersion in such systems. In this paper we perform an accurate and systematic study of dispersion engineering in space-time varying structures. It is demonstrated that a combination of space-time variation and dispersion engineering would lead to a wealth of novel phenomena and applications [6].

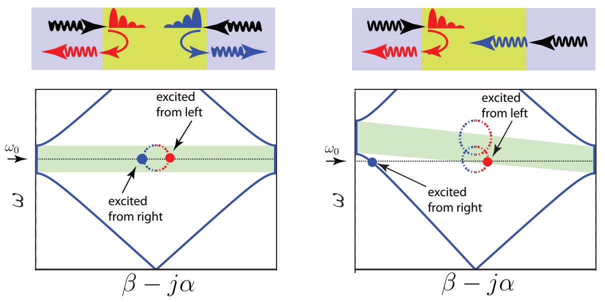
The organization of the paper is as follows. In Sec. 2, space-time engineering is used to design dispersive structures that exhibit asymmetric electromagnetic bandgaps for opposite directions of propagation. This asymmetry is then leveraged for the generation of electromagnetic isolation and perfect mixing, i.e. mixing without undesired intermodulation effects. In Sec. 3, dispersion engineering is used to efficiently control the power flow in intraband photonic transitions mediated by space-time variation. It is shown that, with proper dispersion engineering, intraband photonic transitions lead to electromagnetic amplification and mixing. The corresponding structures may find applications in space-time low-noise mixers/amplifiers and magnet-less isolators.

2 Electromagnetic Nonreciprocity and Perfect Mixing based on Space-time Engineered Asymmetric Dispersion Curves

Consider a conventional reciprocal structure, such as for instance a Bragg grating or a waveguide filter, that supports photonic bandgaps, as illustrated in Fig. 1(a). As the structure is composed of reciprocal materials, the bandgaps are perfectly horizontal in the dispersion diagram, i.e. symmetric with respect to positive and negative wavenumbers.

In the bandgaps, the electromagnetic modes supported by the structure take on an imaginary wavenumber and hence become evanescent. Thus, when a wave incident on the structure is modulated at a frequency falling within a gap, it excites an evanescent gap mode. This mode, marked by a red dot in Fig. 1(a), decays exponentially inside the structure. Therefore, assuming a proper choice of parameters, almost no power is transferred across the structure and, as a result of energy conservation, almost all of the incident power is reflected. Since the dispersion curves are symmetric with respect to the wavenumber axis, when the structure is excited from the opposite end, the symmetric evanescent mode, marked by the blue dot in Fig. 1(a), is similarly excited, and most of the power is reflected.

Next consider a structure with an oblique, and hence asymmetric, bandgap, as shown in Fig. 1(b). When such a structure is excited from the left at the frequency corresponding to the horizontal line in Fig. 1(b), the evanescent mode, marked by the red dot, is excited. If the structure is long enough, almost no power reaches the opposite end of it and the wave is fully reflected. In contrast, when the structure is excited from the right, the mode marked by the blue dot in Fig. 1(b), i.e. a propagating mode, is excited. Therefore, the incident electromagnetic power is transferred to the other side of the structure, and, assuming proper matching, is fully transmitted across it.



(a) (b)

Figure 1. Principle of nonreciprocal Bragg reflection based on asymmetric photonic bandgaps. The solid and dashed curves represent the real (β) and imaginary (α) parts of the wavenumber, respectively. The harmonic time dependence $e^{j\omega t}$ is assumed throughout the paper. The horizontal line corresponds to the excitation frequency ω_0. (a) A reciprocal structure with symmetric bandgaps. (b) A nonreciprocal structure with tilted bangaps.

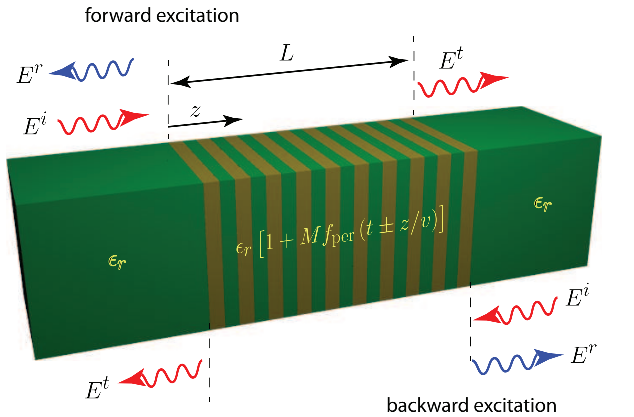


Figure 2. Scattering from a space-time modulated slab. A finite part of a material with permittivity ε_r is spatio-temporally modulated with a space-time varying permittivity. The structure responds differently when excited from the left side or the right side, and is therefore nonreciprocal. Top arrows represent forward excitation, where the structure is excited from the left. Bottom arrows represent backward excitation, i.e. the structure being excited from the right.

The asymmetric bandgaps presented in Fig. 1(b) are produced in space-time periodic media with permittivity $\varepsilon(\mathbf{r},t) = \varepsilon_0\varepsilon_r\left[1 + M f_{\text{per}}\left(t \pm z/v\right)\right]$, where f_{per} is a periodic function and M is the modulation depth [7]. We analyze the space-time modulated slab presented in Fig. 2 using the mode matching technique and identify all the excited modes inside the slab and all the generated harmonics outside the slab for forward and backward excitation as in Fig. 2 [6]. It is shown that when the structure is excited in the gap, it exhibits electromagnetic isolation. The isolation level is controlled by the length and modulation depth [6], and the unidirectional bandwidth is controlled by the width of the bandgap. The required modulation frequency is relatively low and may be produced by acoustic waves. The electromagnetic wave incident at the isolated port is fully reflected and frequency shifted, without generating undesirable intermodulation effects. Therefore, the structure exhibits efficient mixing as well. The space-time varying structure is realized by a varactor loaded microstrip line, with a space-time varying bias voltage [6]. Its operation is verified experimentally at microwave frequencies.

3 Electromagnetic Amplification and Mixing based on Dispersion Engineered Intraband Photonic Transitions

Consider an electromagnetic wave or a waveguide mode that exhibits weak dispersion over a given frequency band, as shown in Fig. 3(a). By applying a periodic spatio-temporal modulation,

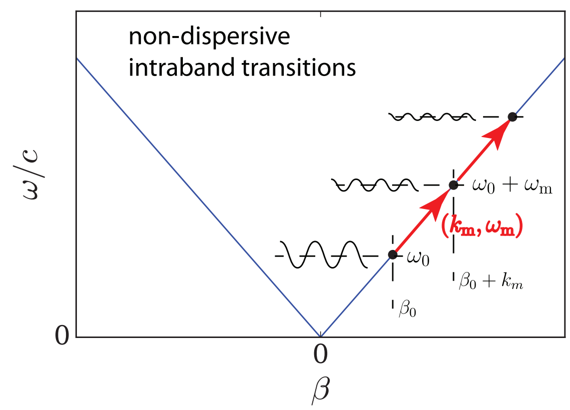
$$\varepsilon_r(z,t) = \varepsilon_r[1 + M\cos(\omega_{\text{m}}t - k_{\text{m}}z)], \quad (1)$$

to a section of the waveguide, a forward mode, initially excited at frequency ω_0, gradually acquires energy that promotes it to the frequency $\omega_1 = \omega_0 + \omega_{\text{m}}$ within the same band. Such intraband transitions in space-time varying media have been used for producing electromagnetic nonreciprocity and mixing [4]. However, as $(\beta_1 + k_{\text{m}}, \omega_1 + \omega_{\text{m}})$ corresponds to another state of the waveguide it acts as a new excitation state at a further position along the structure, leading to the aforementioned cascading effect with undesired harmonics. This process is schematically shown in Fig. 3(a). Since energy is continuously pumped into the system, the total energy increases exponentially. However, part of this energy is lost in the undesirable space harmonics.

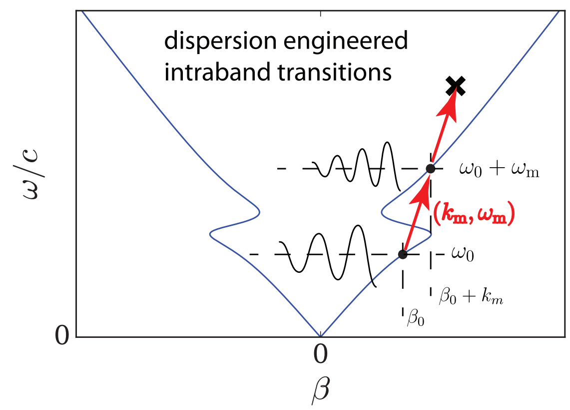
Consider now the waveguide mode in Fig. 3(b). The waveguide is again excited at the frequency ω_0, and a spatio-temporal modulation with momentum and frequency $(k_{\text{m}}, \omega_{\text{m}})$ is applied to it. This modulation may be provided, for example, in terms of spatio-temporal variation of the dielectric density,

$$n(z,t) = n[1 + M\cos(\omega_{\text{m}}t - k_{\text{m}}z)], \quad (2)$$

mediated by an acoustic wave. The dispersion curve is reshaped, such that consecutive transitions are inhibited. Such dispersion can be achieved using dispersion engineering techniques based on electromagnetic phasers [8]. We used the plane wave expansion method to find the Bloch wavenumber and the corresponding eigenmodes propagating in the periodic structure. The system supports complex modes in the form of growing waves that carry real power. A slab of such a periodic dispersive medium is then excited at the frequency ω_0 and analyzed using the full-wave mode-matching technique.



(a)



(b)

Figure 3. Dispersion engineered intraband photonic transitions. Space-time variation is used to generate intraband transitions between two states of a waveguide mode. $(k_{\rm m}, \omega_m)$ represent the spatio-temporal frequencies of the space-time varying media. (a) In a non-dispersive structure, successive transitions lead to a cascading effect, with an infinite number of undesirable harmonics. (b) In a dispersion engineered structure, the transitions are produced in a controlled fashion, suppressing the undesirable harmonics.

It will be theoretically demonstrated, that the state at the incident frequency ω_0 and that at the frequency $\omega_0 + \omega_{\rm m}$ exponentially grow along the structure, while all the states at frequencies $\omega_0 + n\omega_{\rm m}$, with $n \neq 1$ are excited only very weakly, as a result of the dispersion engineering of the waveguide mode [9]. The structure therefore operates as an efficient mixer-amplifier. The effective refractive indices seen by the different growing waves are generally different and can be adjusted by proper dispersion engineering. Therefore, depending on the application, one of the two states may be matched to the output, while the undesirable one is highly reflected at the boundary of the slab. Due to the oblique nature of its transitions, the structure is nonreciprocal. It may find applications in low-noise space-time amplifiers, mixers and a diversity of other magnetless nonreciprocal systems.

4 Conclusions

An accurate and systematic study of dispersion engineering in space-time systems will be presented at the conference. It is demonstrated that a combination of space-time variation and dispersion engineering would lead to a wealth of novel phenomena and applications. It is shown that asymmetric electromagnetic dispersion curves based on space-time varying systems, represent an effective method for the generation of electromagnetic isolation and perfect mixing. Moreover, it is demonstrated that space-time mediated intraband photonic transitions in a properly engineered dispersive system, leads to electromagnetic amplification and mixing. Such devices may find applications in low-noise mixer-amplifiers and magnet-less isolators.

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