Nonreciprocal optical manipulation using dynamic modulation

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***Abstract*—Nonreciprocal optical components are crucial for important applications such as optical signal processing and laser feedback protection. While magneto-optic materials have traditionally been used to break reciprocity, they are incompatible with optoelectronic materials and are thus difficult to be integrated into on-chip photonics platforms. On the other hand, non-reciprocity can be introduced by dynamic modulation of materials' refractive indices. Since such modulation is compatible with the optoelectronic platform, this approach has shown great promise for constructing nonreciprocal optical devices. Here, we summarize how such dynamic modulation can be used to enable optical circulation on a photonic crystal slab, as well as to achieve direction-dependent absorption in a micro-ring resonator.**

I. Introduction

Motivated by the demands of integrated silicon photonics, there are significant interests in constructing on-chip optical isolators for important applications such as optical signal processing and laser feedback protection. Optical isolation requires the breaking of Lorentz reciprocity, which has traditionally been achieved through magneto-optic materials. Nevertheless, since most optoelectronic materials do not exhibit magneto-optical properties, it has been challenging to introduce magneto-optical materials in integrated photonics [1, 2].

Another approach for breaking reciprocity is through dynamic modulation of the refractive index of materials [2]. While this method requires external energy input, it is compatible with optoelectronic materials and thus has generated much interest in recent years. Many dynamic modulation methods are based on the concept of photonic transition, where one considers a photonic system that supports two optical modes at frequencies ω_1 and ω_2. In this setup, modulating the system at frequency $\Omega = \omega_1 - \omega_2$ induces a photonic transition between these two optical modes. In such a transition, the upward and downward transition acquire an opposite phase, which can be used to break reciprocity [2].

In this work, we summarize the construction of two nonreciprocal optical devices using dynamic modulation. First, we demonstrate that in a photonic crystal slab, modulation can induce photonic transitions between the slab's guided resonance modes, which can be used for optical circulation. Second, we show that by modulating the refractive index of a micro-ring resonator, we can induce nonreciprocal Rabi splitting between its modes and achieve direction-dependent optical absorption.

II. Optical circulation using a photonic crystal slab

In the first demonstration, we describe the use of dynamic modulation to enable nonreciprocal optical circulation on a photonic crystal slab [3]. Consider a photonic crystal slab that is shown in Fig. 1(a), which consists of a reflecting substrate (gold), a silicon slab (gray) with a periodic grating on top (dark gray). Because of the grating's periodicity, such a structure supports various guided resonance modes. In Fig. 1(b), we plot the band diagram of the photonic crystal slab and highlight three modes: mode $|1\rangle$ at frequency ω_1 with Bloch wave vector $K_1 = 0$, mode $|2\rangle$ at frequency ω_2 with wave vector $K_2 = 0.4\pi/a$, and mode $|3\rangle$ at frequency ω_2 with wave vector $K_3 = -K_2$. These guided resonance modes couple to different input/output ports as labeled in Fig. 1(a). Specifically, mode $|1\rangle$ couples to s_{1+} and s_{1-}, mode $|2\rangle$ couples to s_{3+} and s_{2-}, and mode $|3\rangle$ couples to s_{2+} and s_{3-}. Without modulation, this photonic crystal slab is reciprocal, and the three ports can be described by a symmetric scattering matrix.

To break reciprocity, we modulate the refractive index of the photonic crystal slab at frequency $\Omega = \omega_1 - \omega_2$ with a spatiotemporal phase gradient $K = K_1$. In doing so, as seen in Fig. 2(b), such modulation induces a photonic transition between modes $|1\rangle$ and $|2\rangle$ but not with $|1\rangle$ and $|3\rangle$, which is nonreciprocal. This means that an incident wave from port s_{1+} can scatter into port s_{2-} through photonic transition between $|1\rangle$ and $|2\rangle$, an incident wave from s_{2+} simply reflects from the slab into s_{3-}, and an incident wave from s_{3+} can scatter into s_{1-}. The scattering matrix of this device becomes asymmetric, and it can be used for optical circulation. In Fig. 1(c), we provide full wave simulations of this modulated guided resonance slab [4], and indeed, we observe that wave from s_{1+} is converted into s_{2-}, wave from s_{2+} is reflected into s_{3-}, and wave from s_{3+} is converted back into s_{1-}. Therefore, we have demonstrated that a spatiotemporally modulated photonic crystal slab can be used for nonreciprocal optical circulation [3].

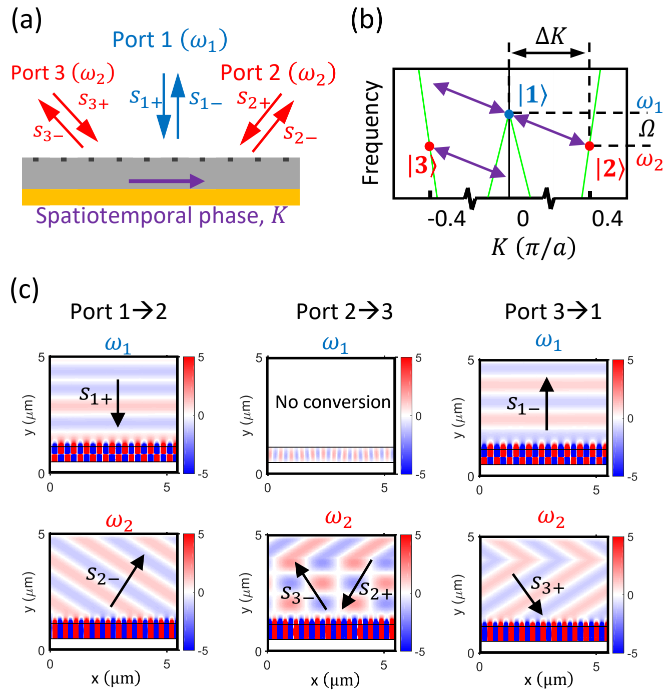

Fig. 1. (a) Schematic of the guided resonance slab as well as its input and output ports. (b) Band structure of the guided resonance modes (green), with the photonic transition modes highlighted. (c) Field patterns from a full wave simulation showing optical circulation.

III. Nonreciprocal optical absorber

In the second demonstration, we show that a dynamically modulated ring resonator can be used as a nonreciprocal optical absorber [5]. We consider a silicon ring resonator structure that is shown in Fig. 2(a). This ring supports an even mode at frequency ω_1 and an odd mode at frequency ω_2. These modes can rotate either in the forward counter-clockwise (CCW) direction or backward clockwise direction (CW), and they are respectively coupled to a forward and backward incident wave from the straight waveguide. Both modes are critically coupled to an external straight waveguide such that an input wave at frequency ω_1 or ω_2 is perfectly absorbed by the ring. Without dynamic modulation, such absorption occurs both for the forward and backward waves.

In order to break reciprocity, we apply a dynamic modulation at frequency $\Omega = \omega_1 - \omega_2$ with a modulation phase that is phase-matched only between the two CCW modes, which induces a strong coupling for the CCW modes but weak coupling between CW modes. With Floquet analysis, we plot the quasi-energy of the modes of this modulated system in Fig. 2(b), which shows that the Floquet eigen-states of the ring resonator experience strong Rabi-splitting in the forward direction but weak Rabi-splitting in the backward direction [5]. To obtain direction-dependent optical absorption, we operate around frequency ω_{in} as labeled in Fig. 2(b). An incident wave sent in the backward direction at ω_{in} coincides to an absorptive Floquet mode, whereas an incident wave sent in the forward direction does not correspond to any absorptive Floquet modes.

To show such direction-dependent absorption, we plot the field profiles of a full wave simulation in Fig. 2(c) [4]. For a backward propagating wave, we see that the input wave is critically coupled with a resonant mode of the ring, resulting in full absorption and no transmission. On the other hand, for a forward propagating wave at the same frequency, it is decoupled from the resonant mode of the ring, which results in high transmission and low absorption. Therefore, dynamic modulation enables the device in Fig. 2(a) to be used as a nonreciprocal optical absorber.

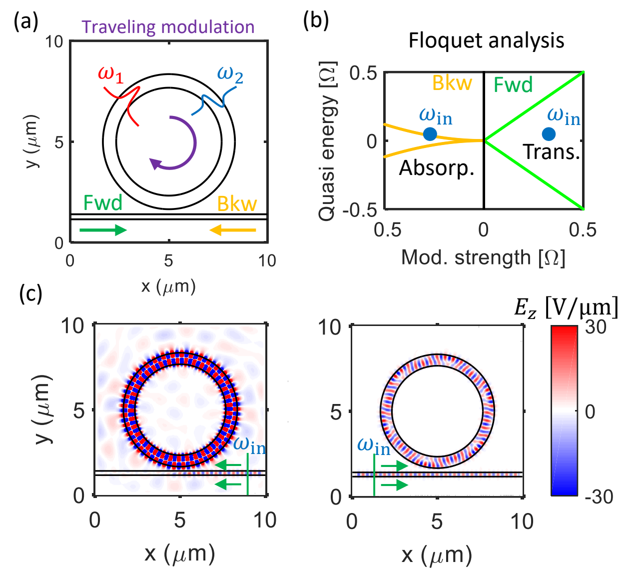

Fig. 2. (a) Schematics of a modulated ring resonator that supports an even mode at frequency ω_1 and odd mode at frequency ω_2. (b) Plot of the Floquet modes of the ring in both forward and backward direction, which shows different degrees of Rabi-splitting. (c) Field patterns showing nonreciprocal optical absorption between forward and backward directions.

IV. Conclusion

In conclusion, we have demonstrated that dynamic modulation enables photonic transitions that can be used for nonreciprocal applications such as optical circulation and direction-dependent absorption. Unlike devices that contain magneto-optic materials, such non-reciprocity is compatible with optoelectronics platforms and show great promise for optical manipulation on an integrated photonics platform.

References

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