One-way electromagnetic waveguide

Zongfu Yu[1], Georgios Veronis[1], Zheng Wang[2] and Shanhui Fan[1]
[1]Stanford University, Stanford, California, 94305
[2]Massachusetts Institute of Technology, Cambridge, Massachusetts, 02139

Abstract

One-way electromagnetic waveguide modes are theoretically demonstrated. A one-way waveguide provides a fundamental way to eliminate the effects of disorders. It also modifies the fundamentals of waveguide-cavity interaction.

Back reflection caused by disorders scattering is worrisome for nanophotonic devices, particularly for slow slight applications. In systems with broken time-reversal symmetry, the effect of disorders can be suppressed with the use of a *one-way* waveguide. Such a waveguide supports a single forward propagating mode in a given frequency range, while having neither radiation nor backward propagation modes in the same range. Here we present a novel design of such a one-way waveguide formed between a semi-infinite photonic crystal (PC) structure and a semi-infinite metal region with infinitesimal loss.

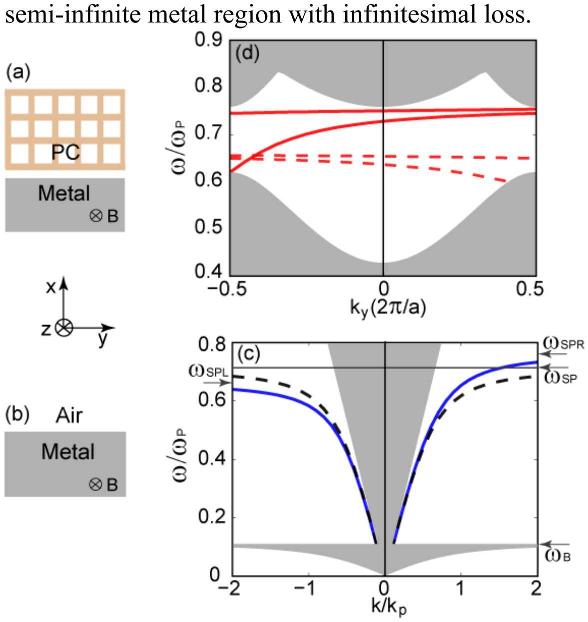

Fig. 1 Structure (a) and dispersion relation (d) of one-way waveguide. Structure (b) and dispersion relation (c) of magnetized metal-air interface. Grey regions represent radiation modes.

The metal is assumed to be a free-electron plasmonic metal under a static magnetic field along the direction perpendicular to the plane of propagation (Fig. 1a).

The design of a one-way waveguide in such structure relies upon the one-way properties of surface plasmon modes at the metal-air interface [1]. In the presence of static magnetic field B in the z direction (Fig. 1b), the cutoff frequencies ω_{SPL} and ω_{SPR} of the left and right propagating surface modes respectively are no longer degenerate, and instead split around $\omega_{SP} \equiv \frac{\omega_P}{\sqrt{2}}$, where ω_p is the bulk plasmon frequency. Within the frequency range $\omega_{SPL} < \omega < \omega_{SPR}$, surface plasmon can only propagate in one direction (Fig. 1c blue lines). An exact one-way waveguide, thus, can be created by placing the metal in close proximity to a photonic crystal such that the frequency range $\omega_{SPL} < \omega < \omega_{SPR}$ falls within the photonic band gap. The gap serves the purpose of eliminating all radiation modes in this frequency range. By choosing the truncation to ensure that the crystal does not support any surface mode at the air-crystal interface, and by placing the photonic crystal close to the metal surface, one can ensure that the overall structure forms a single mode one-way waveguide with its photonic band-structure shown in Fig. 1d. In the frequency range $[0.66\omega_P,\ 0.76\omega_P]$ there are propagating modes along the $+y$ direction but no modes in the opposite direction.

The transport properties of above one-way waveguide are investigated with the finite-difference frequency-domain (FDFD) method. To simulate the effect of disorders scattering suppression, we place metallic particles in the middle of the waveguide (Fig. 2 inset). In the absence of external magnetic field ($\omega_B = 0$), the waveguide is reciprocal and the metallic particle causes significant back-reflection. In contrast, in the presence of an external magnetic field ($\omega_B = 0.1\omega_p$), in the frequency range $[0.66\omega_P,\ 0.76\omega_P]$, no back-reflection is observed. The absence of back-reflection is independent of the specific properties of the scatterers. For example, we see no observable differences in this frequency range as we vary the number of particles placed in the waveguide.

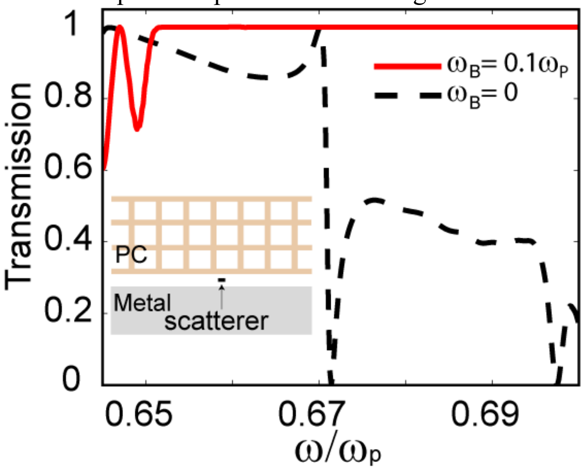

Fig.2 Transmission spectra of one-way waveguide in presence of a scatterer.

The use of a one-way waveguide also fundamentally alters the properties of waveguide-cavity interaction, which is at the heart of many integrated photonic devices. As an example, we consider the properties of side-coupled tunneling between two waveguides through a singly degenerate localized state (Fig. 3a). In these systems, an incident wave (port 1) in the waveguide excites the resonance, which then decays into both waveguides, resulting in a frequency-selective coupling between the waveguides. In the case of reciprocal waveguides, the resonator decays into both the forward and backward directions of each waveguide (Fig. 3b). Consequently at resonance there is always significant reflection. Also the transfers occur to both directions of the output waveguides (ports 3 and 4). In contrast, in the case of one-way waveguides, the resonator decays only into a single direction into each of the waveguides. Consequently, not only is the reflection fundamentally suppressed, but also at resonance complete transfer occurs to only a single direction of the output waveguides. Hence the structure should allow complete channel add/drop tunneling using surface plasmon waves with a single-mode resonator. Since in a reciprocal system, the resonator needs to support at least two modes to allow for complete channel add/drop transfer [2], the use of one-way waveguides fundamentally alters the waveguide-cavity interaction. Fig 3b shows the complete photon tunneling from port 1 to port 3 with two one-way waveguides. Notice that when the magnetic field directions between the two metal regions are the same, the two waveguides have opposite propagation directions due to their orientations.

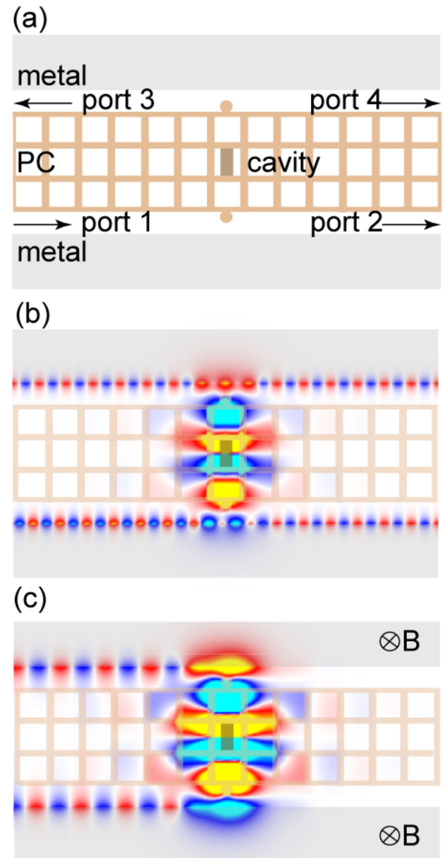

Fig.3 Channel drop tunneling of photons through a singly degenerate localized resonant state. (a) Simulated structure. (b) (c) Field profiles at resonant frequency .

Finally, the bandwidth of one-way propagation is proportional to the amplitude of the external magnetic field. Assuming a static field of 1 Tesla, the one-way frequency range is 28 GHz. Such a bandwidth is sizable in the optical wavelength range.

Reference:

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