Tunable topology of photonic systems based on transparent conducting oxides

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Abstract: Precise control over topology of a photonic system is highly important for a number of applications, such as topologically protected memory/logic devices and quantum communication applications. Within this work, we show that by integrating new transparent conducting oxides (TCOs) material platforms with a photonic waveguide system it is possible to realize ultrafast optical control over topologically nontrivial photonic states.

OCIS codes: (230.1150) All-optical devices; (230.7370) Waveguides, (260.7120) Ultrafast phenomena

1. Introduction

Symmetry is one the most fundamental concepts underlying a plethora of physics phenomena and lies at the heart of a new paradigm in the topological description of electronic and photonic phases. A novel genus of electronic topological insulators is a time-reversal symmetry protected topological phase of condensed matter. Due to strong spin-orbit coupling this phase exhibits gapless edge/surface states in topological insulator's bulk bandgap. The fascinating concept of protected topological phase has been translated to photonics, boosting up the interest to a new class of topologically ordered optical systems—photonic topological insulators[1,2]. Particularly, photonic topological insulators are realized using metamaterials exhibiting a magneto-optical response from engineered meta-atoms, or all-dielectric metamaterials that exploit electric and magnetic resonances of nanoparticles with high refractive index [3]. Another approach utilizes a system of coupled resonators with controlled coupling that forms topologically non-trivial frequency gaps with robust edge states [4].

On the other hand, recent investigations of optically-tunable TCOs, such as indium-tin-oxide (ITO) and aluminum-doped zinc oxide (AZO), along with the progress in materials engineering, make TCOs promising building blocks for on-chip photonics and planar optics applications. TCOs are optically transparent while having high electrical conductivity, thus holding a promise for enabling a new generation of switchable photonic devices. Optical control can be used for dynamic tuning of TCO's optical properties, which enable both (a) ultrafast carrier recombination (picosecond-scale) and (b) significant relative change of the material optical response. Previously it was experimentally demonstrated that AZO films exhibit fast recovery in less than 1 ps with a relative variation of the transient reflectivity and transmissivity as large as 40% and 30%, respectively [5,6].

Realization of photonic topological insulators on the basis of new material platform of TCOs opens up a way to ultrafast optical/electrical control of gauge magnetic field, which leads to all optical control over topology of the photonics system. Tunable photonic topological insulators are extremely important for realization of a number of applications, such as realization of topologically protected memory/logic devices and quantum communication applications.

2. Ultrafast tunable photonic topological insulator

There are numerous ways of synthesizing gauge magnetic fields in a photonic system. Here, we utilize the approach proposed in [4] and use a 2D array of coupled ring resonators (Fig. 1d). These "site" resonators are coupled by evanescent fields to the ring waveguides, which provide transfer to their nearest neighbors, while "link" waveguides are detuned from resonance wavelength, thus making all the energy confined in the site rings. External gauge magnetic fields are synthesized by shifting one of the link waveguides located horizontally between the site rings in the vertical direction by length ξ. With this shift, photons going anticlockwise (clockwise) around the plaquette acquire a $\alpha(-\alpha)$ phase shift, $\alpha = 2\pi\phi = 4\pi n_{\mathrm{mod}}\xi / \lambda$. The Hamiltonian of such system can be written as

$$H_0 = \sum_{x,y} \hat{a}^{\dagger}_{x,y}\hat{a}_{x,y} - J\left(\sum_{x,y} \hat{a}^{\dagger}_{x+1,y}\hat{a}_{x,y}e^{-iy\alpha} + \hat{a}^{\dagger}_{x,y}\hat{a}_{x+1,y}e^{iy\alpha} + \hat{a}^{\dagger}_{x,y+1}\hat{a}_{x,y} + \hat{a}^{\dagger}_{x,y}\hat{a}_{x,y+1}\right) \quad (1)$$

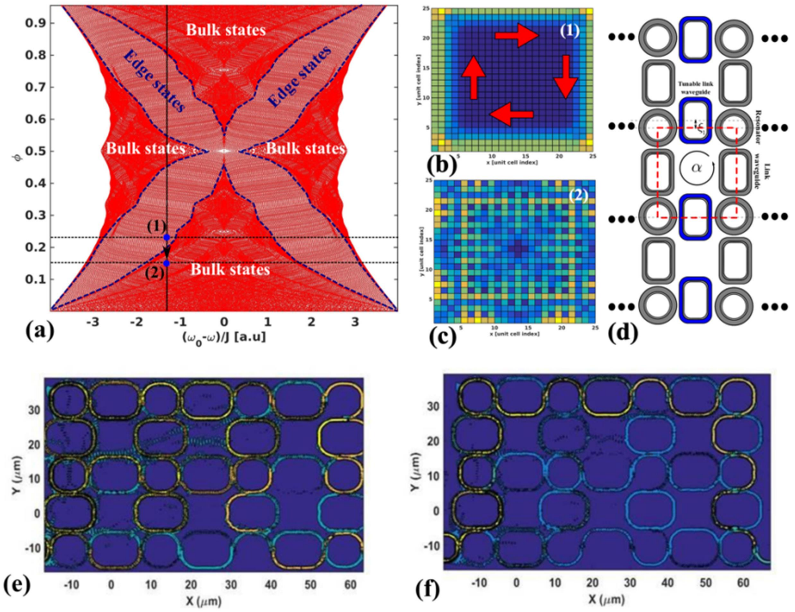

Fig1. Hofstadter butterfly spectrum (a) of the coupled microring resonators with gauge magnetic field. Boundary between bulk and edge states indicated by dashed line; (b) field distribution for edge states (1) inside the array of coupled ring resonators; (c) field distribution for topologically trivial bulk states (2); (d) schematics of the coupled silicon waveguide system with tunable link waveguides, unit cell depicted by dashed red rectangle; (e) intensity distribution inside waveguide array calculated based on finite difference time domain method for topologically protected edge state (refractive index of AZO film $n_{edge} = 0.7 + i0.1$) ; (f) intensity distribution for bulk state (refractive index of AZO film $n_{bulk} = 0.9 + i0.05$)

where $\hat{a}^{\dagger}_{x,y}$, $\hat{a}_{x,y}$ are creation (annihilation) operator at site (x, y) and J is the effective tunneling rate between resonators. Finite size system of coupled resonators with gauge field supports topologically protected edge state (depicted by (1) on Fig.1a), as well as bulk states (depicted by (2) on Fig.1a). Within this work, we propose to use TCOs to achieve ultrafast tunability of the gauge magnetic field by modulating the modal refractive index of the link waveguides, i.e. to tune Aharonov-Bohm phase α , hence to transfer between states (1) and (2). This tunability can be achieved by placing 100-nm-thick AZO film on top of the link waveguide and modulating it with 325-nm pump by exciting interband transitions(Fig. 1d).

To verify our prediction made based on tight-binding model we preformed both (a) transfer matrix method based analysis, as well as (b) finite-difference time domain analysis of the waveguide array with tunable link resonators. Here we considered the system of coupled silicon single mode waveguides (510-nm-wide and 220-nm-height) on silicon-oxide operating at telecom wavelengths. We have shown that by tuning 100-nm AZO film it is possible to switch between topologically trivial bulk state (refractive index of AZO $n_{bulk} = 0.9 + i0.05$, shown in Fig.1e) to topologically protected edge state (refractive index of AZO $n_{edge} = 0.7 + i0.1$, shown in Fig.1f).

3. Conclusion

Within this work we have shown that by integrating new TCO material platform with photonic waveguide system it is possible to realize ultrafast optical control over topologically nontrivial states. Realization of such platform opens up fundamentally new ways of ultrafast all optical control over photonic states. Tunable photonic topological insulators is extremely important for realization of a number of applications such as realization of topologically protected memory/logic devices and quantum communication applications

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4. References

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