3^{rd} URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Quantum Nonreciprocity with Nonlinearity and Weyl semimetals

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Abstract

Here we present our results on isolators suitable for quantum systems. We first discuss the isolation effect obtained by an appropriate combination of quantum nonlinearities and symmetry breaking. Using an example of a two-qubit system, we show that the dark state and its properties are crucial to establishing large nonreciprocity in this class of systems. Then we discuss a novel approach to tunable isolation based on twisted bilayered Weyl semimetals. The approach enables highly efficient tuning of both direction and value of isolation with the relative rotation of Weyl semimetals.

1. Introduction

The emerging field of quantum computing has been rapidly growing and has shown interesting opportunities to overcome the limitations of classical computers for many currently unfeasible problems[1]. A key technology that will be required for quantum computation devices is the unidirectional signal propagation and routing, whereby electromagnetic radiation propagates asymmetrically between two points. This effect, commonly achieved with isolators and circulators, is particularly important to protect JJ-qubits from reflections and noise originating in the readout amplification chain. For example, quantum-limited amplifiers based on parametric processes have been recently developed and used as preamplifiers before high electron mobility transistors. However, they also amplify the reflected signal, producing strongly reflected pump tones. Isolators are required to prevent these signals, along with pump tones that supply energy to the amplifier, from reaching the qubit. Moreover, isolating sensitive quantum devices from room-temperature measurement setups is crucial because these systems have a much larger noise temperature than those required for quantum computing. In addition to quantum computing applications, nonreciprocity is beneficial for quantum communications, on-chip quantum technologies, quantum internet, and sensing[2].

However, most modern non-reciprocal components are realized based on the magneto-optical effect in ferrite materials[3]. These devices are expensive, barely tunable, bulky, and incompatible with planar technologies, including transmission-line quantum circuits. Although isolators based on other approaches, e.g., using two-dimensional magnetic materials and topological isolators/semimetals, time-modulation, and nonlinearity, have been recently extensively investigated, they are still limited in many aspects. Time-modulated isolators require external energy input. And most existing magneto-optical isolators are lacking in terms of tunability.

This work presents our recent results on isolators suitable for quantum systems. We first discuss the isolation effect obtained by an appropriate combination of quantum nonlinearities and symmetry breaking, Fig. 1. Using an example of a two-qubit system, we show that the dark state and its properties are crucial to establishing large nonreciprocity in this class of systems. We discuss how two-qubit devices have been implemented as systems with an asymmetric dependence on the direction of the input field, allowing them to act like unidirectional devices in quantum electronics. Then we discuss a novel approach to tunable isolation based on twisted bilayered Weyl semimetals, Fig. 2. The approach enables highly efficient tuning of both direction and value of isolation with the relative rotation of Weyl semimetals.

2. Nonlinear Quantum Nonreciprocity

We begin our analysis by considering a model which consists of a pair of two-level atoms, with transition frequencies ω_1 and, ω_2 and coupled to a common single-mode waveguide, Fig. 1(a). The atoms are located at coordinates x_1 and x_2 along the waveguide, and we define $L \equiv |x1 - x2|$. The waveguide acts as a feeding channel to excite the atoms and as a reservoir into which atomic excitation can decay. This geometry corresponds to, for example, the system reported in ref.[4].

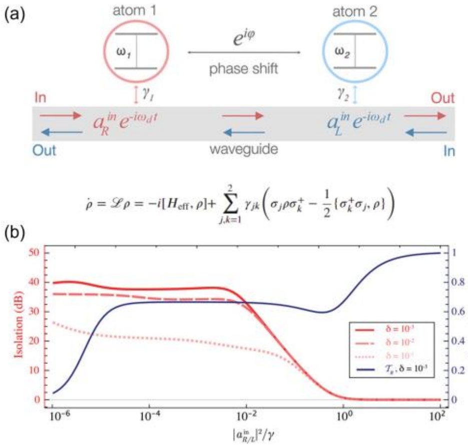

Figure 1. (a) Schematics of a basic system enabling quantum nonreciprocity, consisting of two atoms coupled

to a waveguide. Below: master equation for the reduced density matrix ρ (under a Markov and rotating wave approximation). (b) Isolation in dB (red lines) and transmittance (blue line).

Notably, while the atoms do not interact directly, the common waveguide creates an effective coherent and dissipative coupling between them. Due to this coupling, the eigenmodes of the system are in a general superposition of the atomic states and, for certain values of *L*, the eigenmodes can display strong superradiant or subradiant characters.

Suppose we are not interested in the dynamics of the waveguide modes. In that case, it is possible to “trace out” the waveguide degrees of freedom and obtain an effective finite-dimensional master equation describing only the evolution of the atoms[5]. We also assume that the waveguide field incident from two directions is monochromatic, and it is in a coherent state and driving frequency ω_d. Under a Markov and rotating wave approximation, we obtain the master equation for the reduced density matrix, Fig. 1(a, bottom).

A relevant metric to quantify the nonreciprocity level in this system is its diode isolation, defined as[6] $I = 10\log_{10}(T_R / T_L)$, where T_R, T_L are the system transmissions for excitation from the left and the right side, respectively. The results are presented in Fig. 1(b).
Due to the significant difference in T_R and T_L within the interval of incident powers, the isolation reaches high values, ≈40 dB. If the incident power exceeds γ (waveguide-qubit coupling), the system starts transmitting the signal propagating in both directions, and the isolation tends to zero. Remarkably, high isolation values occur at relatively low incident powers, which contrasts with what is observed in the classical counterparts of these devices[7].

3. Twisted Weyl Semimetal Nonreciprocity

Weyl semimetals (WSs) is a new three-dimensional gapless topological phase of matter attracting a great deal of attention[8], [9]. WSs exhibit many unique and protected optical properties due to the non-trivial topology of Weyl nodes, arousing considerable interest in fundamental science and technology. For electronic Weyl semimetals, the phenomena include the anomalous Hall effect, chiral magnetic effect, and strong magneto-optical Faraday and Kerr effects[10], [11]. In photonics, electronic Weyl semimetals have been recently used to generate non-reciprocal surface plasmons and thermal emitters[12]–[14].

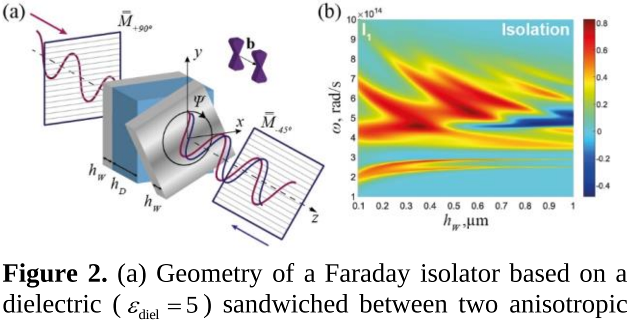

Figure 2. (a) Geometry of a Faraday isolator based on a dielectric ($\varepsilon_{\text{diel}} = 5$) sandwiched between two anisotropic WS slabs. The silver grids depict linear polarizers. The wavy curves denote the electric fields of linearly polarized waves propagating along the $+z$ and $-z$ directions. The $+z$ direction is along the separation of Weyl nodes in momentum space **b**. (b) Isolation spectrum $I_1 = T_{+z} - T_{-z}$ as a function of frequency and thickness of the WS at a rotation angle $\Psi = 90^\circ$.

Here we propose a novel approach to tunable ultrathin optical isolators based on twisted bilayers of anisotropic WSs, **Fig. 2**. The proposed design demonstrates controlled and reversible isolation by tuning the twist angle between the anisotropic layers.

Fig. 2(a) illustrates the first design exploiting the Faraday geometry. The isolator is a three-layer structure consisting of two layers of WSs separated by a dielectric layer ($\varepsilon_{\text{diel}} = 5$). Following reported studies on the optical properties of WSs, we use the standard form of Maxwell equations $\mathbf{D} = \hat{\varepsilon}_{WS}\mathbf{E}$ with the relative permittivity tensor[13], [15] $\hat{\varepsilon}_{WS} = \begin{pmatrix} \varepsilon_d & i\varepsilon_a & 0 \\ -i\varepsilon_a & \varepsilon_d' & 0 \\ 0 & 0 & \varepsilon_d \end{pmatrix}$ and unity magnetic permeability. The off-diagonal components $\varepsilon_a = be^2 / 2\pi^2\hbar\omega$ are caused by the Weyl nodes splitting in the momentum space by the vector $\mathbf{b}$. They are responsible for the strength of magneto-optical activity and breaking the Lorentz reciprocity.

Consequently, WSs enable significant magneto-optical effects for light propagating along this vector ($\mathbf{k} \parallel \mathbf{b}$), where $\mathbf{k}$ denotes the light wave vector. The thickness of the dielectric $h_{\text{diel}} = 0.94$ μm enables the Fabry-Perot mode at the plasma frequency of the WS $\Omega_p = 4.2 \times 10^{14}$ rad/s. The thickness of the WSs $h_W = 0.34$ μm ensures the maximum isolation $I_1 = T_{+z} - T_{-z}$ for the smallest size, **Fig. 1(b)**. The total length of the structure is $L = 1.62$ μm, excluding the thickness of the polarizers. The maximum isolation for selected optimized parameters reaches 60 dB at the frequency $\omega = 5.4 \times 10^{14}$ rad/s.

4. Conclusion

In this work, we have first studied the non-reciprocal response that arises in typical atom-like quantum systems. We have discussed existing approaches to quantum nonreciprocity and considered in more detail how the nonlinearity-based approach can be rigorously analyzed. We have shown that a slowly-decaying state or a dark state can lead to the enhanced non-reciprocal behavior of the system. We have also proposed a novel approach to tunable optical isolation based on twisted bilayered Weyl semimetals. We have revealed that the approach enables highly efficient tuning of both direction and value of isolation with the relative rotation of bilayered Weyl semimetals. The structure of the Faraday isolator with two polarizers consists of two anisotropic Weyl semimetals layers separated by a dielectric. It demonstrates isolation exceeding 50 dB and an insertion loss as small as 0.33 dB.

5. Acknowledgements

This work has been partially supported by the Simons Foundation and the Air Force Office of Scientific Research MURI program.

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