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Modulation of the photonic band structure topology of a honeycomb lattice in an atomic vapor

Yiqi Zhang [a,*], Xing Liu [a], Milivoj R. Belić [b,*], Zhenkun Wu [a], Yanpeng Zhang [a,*]

[a] Key Laboratory for Physical Electronics and Devices of the Ministry of Education & Shaanxi Key Lab of Information Photonic Technique, Xi'an Jiaotong University, Xi'an 710049, China

[b] Science Program, Texas A&M University at Qatar, P.O. Box 23874 Doha, Qatar

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In an atomic vapor, a honeycomb lattice can be constructed by utilizing the three-beam interference method. In the method, the interference of the three beams splits the dressed energy level periodically, forming a periodic refractive index modulation with the honeycomb profile. The energy band topology of the honeycomb lattice can be modulated by frequency detunings, thereby affecting the appearance (and disappearance) of Dirac points and cones in the momentum space. This effect can be usefully exploited for the generation and manipulation of topological insulators.

1. Introduction

A honeycomb lattice is not a Bravais lattice [1–3], which makes it fundamentally different from the related hexagonal lattice [4,5]. In recent years, honeycomb lattices in different physical systems [6–13] have attracted an increased attention from research community. An especially interesting development occurred when it was realized that photonic topological insulators can be produced in honeycomb lattices [8]. Floquet topological insulators can confine the propagating light beam at

* Corresponding authors.
E-mail addresses: zhangyiqi@mail.xjtu.edu.cn (Y.Q. Zhang), milivoj.belic@qatar.tamu.edu (Milivoj R. Belić), ypzhang@mail.xjtu.edu.cn (Y.P. Zhang).

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the edges without scattering energy into the bulk, thus becoming robust against scattering from defects. Such useful properties result from the topologically protected edge states, which are mainly determined by the topological structure in the momentum space and are protected by the symmetry. The edge states are quite stable and independent of the surface structure of the material [14–16]. Recently, unconventional edge states [11] and pseudospin [13] of honeycomb lattices have also been demonstrated. The novel findings related to honeycomb lattices, as well as photonic topological insulators, can have potential applications in quantum computing [17], optical modulators [18] and optical diodes [19]. Honeycomb lattices can be conveniently formed by the femtosecond laser writing technique or by the optically induced method. The first method is exclusively used in solid materials [8,11], while the second method can be used in both solid [13] and gaseous [20] materials.

As far as we know, honeycomb lattices are mostly investigated in solid materials [21,8,11,13]. In addition to solid materials, they are also reported in gaseous materials [22,23,12,20]. However, some extra conditions are required for the hexagonal lattice to form in such materials. In atomic vapors, when the three-beam interference pattern serves as the dressing field, the dressed atomic states will exhibit controllable optical properties. In the last decade, periodically dressed atomic vapors – such as rubidium vapor – were intensively investigated, leading to the observation of many interesting effects, including enhanced multi-wave mixing (MWM) signals due to Bragg reflection of photonic band gap (PBG) structures [24]. Also, the Talbot effect of MWM [25] and the nonreciprocity of light [26] have been explored, to name a few interesting effects.

In this paper, we investigate the influence of frequency detunings and the power of coupling fields on the topology of the photonic band structure of honeycomb lattices that are induced in atomic vapors through the three-beam interference method. We would like to point that the investigation carried out in this paper can be extended to explore the generation of topological insulators in atomic vapor ensembles [20] and also applied to on-chip crystals, such as praseodymium doped yttrium orthosilicate (Pr^{3+}:Y_2SiO_5) crystal [27–29], which exhibits similar properties to those of atomic vapors.

The organization of the paper is as follows. In Section 2, we introduce the theoretical model. In Section 3, we present the results, which include the changes in the refractive index (RI) of the material in Section 3.1 and in the corresponding PBG structures in Section 3.2. Section 4 explores an explanation of the results and demonstrates how frequency detunings affect the topology of PBG structures. In Section 5, we conclude the paper.

2. The model

We start from a Λ-type electromagnetically induced transparency (EIT) system [30,24,31–33], as depicted in Fig. 1(a). In the figure, the probe field E_{10} connects the transition $|0\rangle \rightarrow |1\rangle$, and the coupling field E_{12} connects the transition $|1\rangle \rightarrow |2\rangle$. We assume that there are three broad coupling fields at the same frequency. The three coupling fields are launched into the medium in parallel and propagate paraxially along the same direction z, with the angle $2\pi/3$ between any two of them in the transverse (x, y) plane. Therefore, they form the two-dimensional hexagonal interference pattern in the transverse plane. Such an optically-induced hexagonal lattice can be written in the form:

$$G = G_{12}[\exp(ik_{12}\mathbf{b}_1 \cdot \mathbf{r}) + \exp(ik_{12}\mathbf{b}_2 \cdot \mathbf{r}) + \exp(ik_{12}\mathbf{b}_3 \cdot \mathbf{r})] \tag{1}$$

where $\mathbf{b}_1 = (-1/2, -\sqrt{3}/2)$, $\mathbf{b}_2 = (-1/2, \sqrt{3}/2)$, and $\mathbf{b}_3 = (1, 0)$. The wave number k_{12} corresponds to the coupling fields, and G_{12} represents the Rabi frequency of the coupling fields, defined as $G_{12} = \mu_{12}E_{12}/\hbar$, with μ_{12} being the electric dipole moment. Thus, one obtains

$$|G|^2 = |G_{12}|^2 \left[4\cos\left(\frac{3}{2}k_{12}x\right)\cos\left(\frac{\sqrt{3}}{2}k_{12}y\right) + 2\cos\left(\sqrt{3}k_{12}y\right) + 3 \right].$$

Since level $|1\rangle$ is dressed by the coupling fields, it will split into two sublevels $|+\rangle$ and $|-\rangle$ as shown by the two curves in Fig. 1(a), with the eigenfrequencies

$$\ell = -\frac{1}{2}\Delta_{12} \pm \sqrt{\frac{1}{4}\Delta_{12}^2 + |G|^2},$$