Dynamic Diffraction and Interband Transitions in Two-Dimensional Photonic Lattices

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(Received 1 December 2010; revised manuscript received 18 January 2011; published 23 February 2011)

We reveal a direct link between two fundamental wave phenomena in periodic media, Pendellösung oscillations and resonant coupling between spectral bands. We experimentally measure the power transfer between laser beams associated with the high-symmetry points in periodic and biased hexagonal photonic lattices. As a result, we demonstrate that Pendellösung oscillations dominate the dynamics of resonant interband transitions on a short propagation scale.

DOI: 10.1103/PhysRevLett.106.083902 PACS numbers: 42.25.Bs, 42.82.Et

Coherent transport of waves in periodic media manifests itself in resonant phenomena such as Bragg scattering of x rays, electrons, and neutrons [1] in crystals, matter waves [2], and visible light [3] in optical lattices. Resonant coupling between two [1,2,4,5] or several [6] forward and Bragg-reflected waves leads to dynamic diffraction and Pendellösung effect [1,2,4,5] with the wave energy oscillating between high-symmetry momentum states. In contrast, the resonant coupling between spectral bands can be induced by an external force, and it leads to Landau-Zener interband tunneling (LZT) [7,8]. These two fundamental phenomena have never been linked before, even though they are observed in essentially similar settings, as coupling between localized momentum states [8].

Periodic photonic structures, such as coupled waveguides [3,9,10] and optical lattices [10,11], allow direct visualization of many fundamental linear and nonlinear phenomena inherent to wave packets and quantum particles of different nature [12], such as electrons in crystals and matter waves in optical lattices [13]. Examples include Bloch oscillations [14], LZT [7,8], as well as nonlinear [10,11,15], disorder-driven [16], and dynamic [17] localization. While the later use narrow [11,15] or partially incoherent [18] beams with wide spatial spectra, broad beams with localized spatial spectra are usually required to selectively access specific Bragg resonances. For instance, one-dimensional (1D) Pendellösung oscillations between forward and Bragg-reflected waves have been demonstrated with quasiplane waves in holographic volume gratings [4] and in microwave photonic crystals [5]. Nevertheless, resonant effects, such as Bloch oscillations [14] and LZT [7,8] can be observed with relatively narrow (and thus experimentally accessible) beams covering only several lattice sites.

In this Letter, we reveal a deep relation between two fundamental wave phenomena, Pendellösung oscillations and interband transitions, in experimental studies of resonant coupling between high-symmetry momentum states of two-dimensional (2D) photonic lattices. In pure periodic lattices these critical points form few-level oscillatory systems, with periodic Pendellösung transfer of population between levels due to interference of two or many Bloch waves; this process is similar to Rabi oscillations and energy beating in coupled waveguides. In the regime of LZT in lattices of a finite length, the observed energy transport between high-symmetry points can be explained by Pendellösung and Bloch oscillations, without significant tunneling between spectral bands.

We begin with the resonant model of interband coupling in hexagonal photonic lattices governed by the Landau-Zener-Majorana (LZM) system [6,19]. As an example, we consider a two-level LZM model of two resonantly coupled plane waves (high-symmetry momentum states) with complex amplitudes $c_{1,2}$:

$$dc_{1,2}/dz = -ib_{1,2}c_{1,2} + i\Omega c_{2,1}. \quad (1)$$

Here, $z$ is the propagation length in the crystal, the coefficients $b_{1,2}$ are proportional to the linear gradient of the refractive index, and the coupling coefficient $\Omega$ is defined by the resonant Fourier component of the lattice potential [20]. Equation (1) describes the asymptotic transfer of populations $|c_{2,1}|^2$ between levels due to interband tunneling, induced by the refractive index gradient. However, at short propagation distances $z = 0$, close to the Bragg resonance, the gradient terms $b_{1,2}c_{1,2}$ are small and can be neglected, thus effectively reducing Eq. (1) to

$$dc_{1,2}/dz = i\Omega c_{2,1}. \quad (2)$$

This generic oscillatory system can be also obtained from the LZM model (1) with zero index gradient, $b_{1,2} = 0$, and thus it describes Pendellösung oscillations along the propagation length [5] of a perfectly periodic crystal. The oscillation frequency $\Omega$ is determined by the
is Bragg reflected and the output contains a second peak beam. We estimate the relative powers localized in Fourier space with its width replicating input intensity profiles, Figs. 1(e)–1(g). The input at the intensity profile between the critical points Y ‘ point. The Bragg-reflected beam remains well localized in real as well as in Fourier space (far field). The lattice Brillouin zone (BZ) and the band-gap spectrum are depicted in Fig. 1(d). The resonant theory [6] predicts that Pendello¨sung oscillations between the two high-symmetry points due to the interference and beating of two Bloch waves. Therefore, the oscillation frequency can also be estimated as $\Omega = \Delta \beta / 2$. Indeed, the latter values of $\Delta \beta L / 2$ [calculated, dashed line in Fig. 1(d)] are close to the experimental data and to the results of full numerical simulations. The Bloch-wave spectrum of the input Gaussian has dominating contributions from the first and second bands (not shown) for the entire range of lattice depths, which further supports the validity of the resonant two-level approximation.

The two-level system (2) offers interesting opportunities to explore phase-only manipulation of Pendello¨sung oscillations in photonics. Figure 2 presents experimental results on two-beam excitation of the two-level system, with the relative phase $\delta$ between input beams at Y-symmetry points, providing full control over output population ratio. This input realizes the following initial conditions for the LZM system (2):

$c_1(0) = 1/\sqrt{2}$ and $c_2(0) = \exp(\delta)/\sqrt{2}$; the solution reads $|c_{1,2}(z)|^2 = (1 \pm \sin \delta \sin 2 \Omega z / 2)$. For a given lattice depth $\Omega$ and crystal length $z = L$, the output
is fully defined by the input phase $\delta$. The Bloch-band population in Fig. 2(d) strongly depends on the phase difference $\delta$ and shows coupling between the two lowest Bloch bands. The experimental measurements in Fig. 2(e) show a remarkable agreement with simple harmonic solutions to Eq. (2), namely, the two cases correspond to different frequencies $\Omega$, and thus different amplitudes of power ratios at $\delta = \pi/2$, as defined by the LZM solution: $\max(|c_1(L)|/|c_2(L)|) = (1 + \sin 2\Omega L)/\cos 2\Omega L$.

More importantly, 2D lattices provide access to multilevel systems, in addition to the 1D Bragg reflection described above. In the configuration in Fig. 3(a), the field amplitudes at $M$ points in momentum space are described by three-level LZM model [20]. By varying the relative phase $\delta$ between two input beams at $M$ and $M'$ points, we are able to distribute and switch the output power between two or three beams, in excellent agreement with resonant theory. Despite the anisotropy of the stretched hexagonal lattice, the experimental outputs in Figs. 3(c)–3(f) clearly show the strong localization at high-symmetry points. Indeed, the measured relative power of the output peaks is in excellent agreement with numerical simulations in Fig. 3(h), and it recovers the corresponding solutions to the Rabi system derived in [20].

In contrast to the Rabi oscillations between waveguide modes [23] or spectral bands [24] in longitudinally modulated waveguides, so far we observed oscillations of populations between high-symmetry points in momentum space, while the Bloch-band populations in Figs. 2(d) and 3(g) are given by the initial excitation. To induce tunneling between different Bloch bands, one needs to break the periodicity of the lattice by additional longitudinal modulation [23,24] or a linear refractive index gradient [7,8]. The latter case corresponds to LZ tunneling and has been previously studied in square lattices [8]. However, no relation between Pendellösung oscillations and the tunneling process has been revealed. The reduction from Eq. (1) to Eq. (2) suggests that, for small propagation distances, the Pendellösung oscillations will dominate the dynamics, while the tunneling process determines the asymptotic power transport.
In order to study experimentally the tunneling dynamics of optical beams in lattices with index gradient, the crystal is illuminated from the top with a transversely modulated incoherent white light which induces a refractive index gradient along the transverse $x$ direction. Since it is not possible to directly observe the evolution of the signal beam inside the crystal, we vary the incident angle and image the output real space and the Fourier space onto a CCD camera [8]. For a fixed crystal length and angles below the Bragg resonance, such an excitation at different transverse wave vector components is equivalent to different starting points in the BZ and thus allows one to infer details of the tunneling dynamics at different stages of the beam evolution. Our results for symmetric LZ tunneling in Fig. 4 confirm theoretical predictions and demonstrate the interplay of both effects at the initial stage of evolution. Since the medium length $L$ is relatively short, it is not possible to reach the asymptotic transfer of population between bands, yet we observe significant transfer of power between resonantly coupled wave packets in Fourier space, shown in Fig. 4(c). The localization of these waves in momentum space corresponds to high-symmetry points in the frame moving in the BZ due to gradient-induced Bloch oscillations, cf. Figs. 4(a) and 4(b). The actual interband coupling is demonstrated in numerical simulations in Fig. 4(f), where the first and third Bloch bands undergo periodic exchange of energy with small and gradual tunneling of power to the second band. Therefore, such regime can be characterized as quasi-Pendell"ossung oscillations.

In conclusion, we have studied Pendell"ossung oscillations and interband Landau-Zener transitions in experiments on resonant coupling between high-symmetry points of 2D photonic lattices. The comparison of both effects shows that, in biased lattices of a finite length, the Landau-Zener tunneling is dominated by Pendell"ossung oscillations allowing for spatial spectral shaping of the waves. Our findings provide an important insight into resonant wave transport in periodic media, and they can be applied to electromagnetic and matter waves.

This work was supported by the Australian Research Council and the German Academic Exchange Service.

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