Visual Observation of Zener Tunneling

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(Received 10 August 2005; published 18 January 2006; corrected 23 January 2006)

We experimentally investigate photonic Zener tunneling between the bands of a waveguide array by directly monitoring the propagating light inside this structure. For strong transverse index gradients we observe Zener breakdown as regular outbursts of radiation escaping from the Bloch oscillations. Tunneling to higher order photonic bands and Bloch oscillations in different bands have been detected.

DOI: 10.1103/PhysRevLett.96.023901 PACS numbers: 42.25.Fx, 42.25.Bs, 42.81.Qb, 42.82.Et

Particles in periodic potentials or lattices as electrons in crystalline solids or custom-made semiconductor superlattices and Bose-Einstein condensates in optical lattices, as well as photons in photonic crystals or waveguide arrays, have energies confined to bands in momentum space, which may be separated by gaps [1]. Their dynamics becomes particularly intriguing if a constant force is superimposed on the periodic potential. In 1934 Zener [2] predicted that for this scenario electron wave packets do not delocalize but undergo high frequency periodic oscillations [Bloch oscillations (BOs)] [3]. The unambiguous experimental verification of BOs failed for many decades. Only the invention of superlattices (SLs) made of semiconductors [4] led to the observation of electronic Wannier-Stark ladders (WSLs) [5] and BOs [6]. However, accounting for the fact that these fundamental effects require only a Bloch particle or wave (coherent wave in a lattice) exposed to a linear potential they have been proven in other physical settings such as, e.g., ultracold atoms in accelerated optical lattices [7] or photons in photonic lattices [8–11].

Zener argued that BOs do not persist forever, but are damped by, e.g., interband transitions [Zener tunneling (ZT)]. The breakdown of BOs is expected to happen when the energy difference imposed on a period of the lattice by the linear potential reaches the order of the gap to the next band. In view of applications the control of this breakdown is even more relevant, because in contrast to ideal BOs it induces a dc current of particles. Examples are the electrical breakdown in dielectrics [2] or Zener diodes (see Ref. [12] and references therein), electrical conduction along nanotubes [13] and through SLs [14], pair tunneling through Josephson junctions [15], and spin tunneling in molecular magnets [16]. In some experiments the different time constants of the decay of BOs and spectral broadening of respective resonances were attributed to ZT [14]. However, despite the impressive progress of spectral transmission measurements in biased semiconductor SLs [17], it remained difficult to distinguish ZT from the unavoidable dephasing, which also limits the BO lifetime. In contrast, photons may overcome the dephasing problem, because photon-photon interactions caused by optical nonlinearities can be neglected for common intensity levels. This has been proven by ZT observation in spectral and time-resolved transmission measurements in photonic SLs composed of a Bragg mirror with chains of embedded defects of linearly varying resonance frequency [18]. In this experiment it was attempted to create an identical environment for photons as that which electrons encounter in semiconductor SLs. Both enhanced transmission peaks and damped BOs due to ZT have been observed. But optics can do even better by really providing a laboratory for a direct visual observation of BOs and ZT. This has been verified in recent experiments on photonic BOs [9,10] in waveguide arrays. There the lattice was formed by an array of evanescently coupled waveguides, where the external potential was mimicked by a linear variation of the effective indices of the modes achieved either by a temperature gradient across a thermo-optic material [9] or by changing the waveguide geometry [10]. The major difference to experiments in SLs is that instead of the temporal photon dynamics a spatial pattern of fluorescent light is observed on top of the sample avoiding resolution of fast temporal oscillations or transmission spectra.

Using this technique we report in this Letter the first direct visual observation of Zener tunneling and the associated BO decay by monitoring the evolution of light in a photonic lattice. To this end, light was fed into a thermo-optical waveguide array. For an increasing index gradient a comprehensive picture of the coherent tunneling phenomena to higher order bands, viz. Zener tunneling, associated with the BO decay has been directly observed.

In detail, we have used the setup displayed in Fig. 1(a). Waveguide arrays with a length of 6 cm were fabricated by

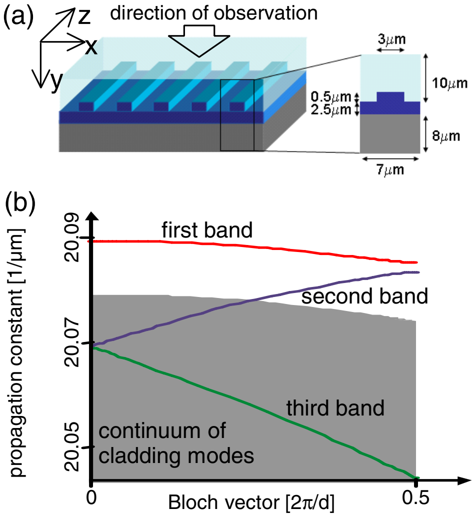

FIG. 1 (color online). (a) Schematic drawing of the polymer waveguide array used in the experiment (b) Corresponding band structure of the waveguide array where the second band already intersects with the spectral continuum of the cladding modes. The gap between the first and second band is minimal at the edge of the Brillouin zone.

UV lithography from an inorganic-organic polymer ($n_{\mathrm{Co}} = 1.5615$ @ $\lambda = 488$ nm) on 4″ Si-wafers covered with SiO$_2$ ($n_{\mathrm{S}} = 1.457$ @ $\lambda = 488$ nm) with a polymer cladding ($n_{\mathrm{Cl}} = 1.5595$ @ $\lambda = 488$ nm). Every array consisted of 150 rib waveguides being 2.5 to 3.0 μm wide, and separated from its neighbors by $d = 5.5$ to 7 μm. For a clear observation of photonic Zener tunneling ridge waveguides of 0.5 and 1 μm height on a 2 mm-thick waveguiding layer have been used.

When applying a temperature drop ΔT between the simultaneously heated and cooled opposite array sides, the thermo-optic effect (thermo-optic coefficient of the polymer $r_{\mathrm{th}} = -2 \times 10^{-4}\ \mathrm{K}^{-1}$) causes the required index gradient. Hence, the wave number grows linearly in the transverse direction with an inclination of $\alpha = 2\pi r_{\mathrm{th}} \Delta T/(W\lambda)$, where $W = 1$ mm is the width of the array and $\lambda = 488$ nm the laser wavelength. Using a cylindrical telescope and a microscope objective, a variable elliptical beam was coupled into the array front facet exciting the desired number of guides. The propagation of light down the sample was recorded by a CCD camera, mounted on top of the array and moved along the propagation direction. To eliminate the deteriorating speckle pattern the intrinsic fluorescence of the polymer was recorded in a wide spectral domain ($\lambda = 500$–650 nm) rather than detecting the scattered light itself.

Before presenting the experimental results we discuss some characteristic features of the setup, first without transverse index gradient. The array is periodic in transverse (x) direction and translationally invariant in propagation (z) direction (see Fig. 1). Thus, eigenmodes are Bloch waves with a Bloch vector k pointing in the x direction. Respective propagation constants k_z in the z direction are arranged in bands with respect to k. Field distributions belonging to the highest order band are centered at the waveguides. Eigenstates of lower bands start to couple to cladding modes, which are barely confined in the y direction. Because the cladding is fairly thick (10 μm) a quasicontinuous set of these modes exists and already the second band of the array dips into this continuum [shaded area in Fig. 1(b)]. Previously localized modes start to leak into the cladding, but can still guide light in the array over a certain distance. The field $a(x, y, z)$ confined to the waveguides can be expressed by a superposition of Bloch waves belonging to distinct bands m and having a Bloch vectors k within the first Brillouin zone $-\pi/d \leq k \leq p/d$ defined by the spacing d between adjacent guides. Thus, a particular light distribution may be represented by an amplitude distribution $g_m(k, z)$ of the corresponding Bloch waves.

A wide beam, extending over several waveguides, excites primarily fundamental waveguide modes. Hence, its Fourier spectrum is localized within the first band ($m = 1$) and its amplitude distribution $g_1(k, z)$ has its maximum around some mean Bloch vector k_0. For an unbiased array the modulus of the spectral distribution $|g_1(k, z)|$ does not change upon propagation. However, if a transverse index gradient α is applied the band structure breaks into a ladder (WSL) with spectrally isolated eigenstates (Wannier-Stark states) being localized in real space [3]. Now light evolution represents a complex interference phenomenon of these states. However, for a shallow gradient the picture of continuous bands can be retained [2], but now the initial spectral distribution $|g_1(k, 0)|$ will be drawn towards the high-index side. According to the "acceleration theorem" [2] the localized excitation moves through the Brillouin zone with constant velocity like

$$|g_1(k, z)|^2 = |g_1(k - \alpha z, z = 0)|^2 \tag{1}$$

while preserving its shape. The corresponding evolution of the excitation in real space is known as BO. It appears as an oscillatory motion of the beam across the array and reproduces the shape of the respective band in momentum space. It leads to a complete recovery of the initial distribution $a(x, y, z)$ after each complete crossing of the Brillouin zone at multiples of the Bloch period

$$z = 2\pi/(\alpha d). \tag{2}$$

For an increasing transverse force higher order bands come into the play. The index gradient can cause the propagation constants of different bands to overlap in adjacent parts of the array, thus inducing phase matching between the bands. As a result, an excitation consisting of first band modes will couple to the second and higher bands. Ultimately, ZT will lead to the decay of lowest order band BOs. Obviously, this tunneling increases with decreasing band gap. Tunneling between the first and the second band therefore happens predominantly at the

Brillouin zone edge [see Fig. 1(b)]. For small transverse gradients and narrow band gaps the tunneling rate upon each Bloch oscillation $|R|^2$ can be approximated by [2]

$$|R|^2 \approx \exp\left(-(\mathrm{Im}k_x)_{\max}\frac{\Delta k_z \pi}{2\alpha}\right), \tag{3}$$

where Δk_z is the band gap width and $(\mathrm{Im}k_x)_{\max}$ the maximum of the imaginary part of k_x in the gap center. To obtain a sufficiently strong coupling within array dimensions we have chosen a geometry with a fairly small band gap of $\Delta k_z = 1.83 \times 10^{-3}\ \mu\mathrm{m}^{-1}$, i.e., $\Delta k_z/k_z \approx 10^{-4}$, by forming the waveguides as shallow grooves (0.5 to 1 μm) in a thick (2 μm) polymer layer. Thus we follow the original intention of Zener [2], who studied electron motion in a weakly modulated linear potential. Because of this shallow potential the band structure, shown in Fig. 1, has been calculated by fully accounting for the periodic potential and not using the tight-binding model which is restricted to nearest-neighbor interactions. A 25 μm wide elliptical input beam illuminated about five waveguides entailing a narrow angular spectrum. The height of the input beam was adjusted to 3 μm in order to excite mainly modes of the lowest order band. Light propagation for a transverse index gradient of $\alpha = 6.2 \times 10^{-5}\ \mu\mathrm{m}^{-2}$ ($\Delta T = 24$ K) was monitored [see Fig. 2(a)] and compared with respective numerical solutions [see Fig. 2(b)]. Both measurement and simulation show that light performs BOs, the shape of which is notable. While the frequently used tight-binding (or coupled-mode) model predicts a sinusoidal trajectory, we observe a kind of connected parabolas with rounded shapes in the low-index area and almost cusps on the high-index side. To understand this phenomenon one has to keep in mind that Bloch waves always travel normal to their band. The cusps appear, just when the field distribution reaches the edge of the Brillouin zone, where the inclination of the band structure changes suddenly. Therefore the direction of propagation of respective Bloch waves is also flipped and a steep edge appears in the trajectory. In contrast, when the field passes the center of the Brillouin zone, where the first band is only slightly curved, it experiences a much smoother turn. Note that the resulting trajectory is solely a consequence of the particular band structure (see Fig. 1), which considerably deviates from that obtained by using tight-binding models.

It can be clearly recognized from Fig. 2 that light escapes from BOs at the high-index turning points corresponding to the Brillouin's zone edge. This is the very manifestation of Zener tunneling from the first to the second band [see Fig. 2(b)]. At these edges the band gap attains its minimum [see Fig. 1(b)] and the tunneling rate its maximum with about 8%.

To clearly identify Zener tunneling as the source of these bursts of radiation we varied the index gradient α by changing the temperature difference ΔT. The acceleration theorem Eq. (1) predicts the BO period to be proportional to the inverse of the gradient [see Eq. (2)]. The particular propagation distances, for which outbursts of radiation were detected followed the same rule—a $1/\Delta T$ dependence [see Figs. 2(c) and 2(d)]. Hence, the observed radiation was strictly correlated with the BOs as expected from Zener tunneling.

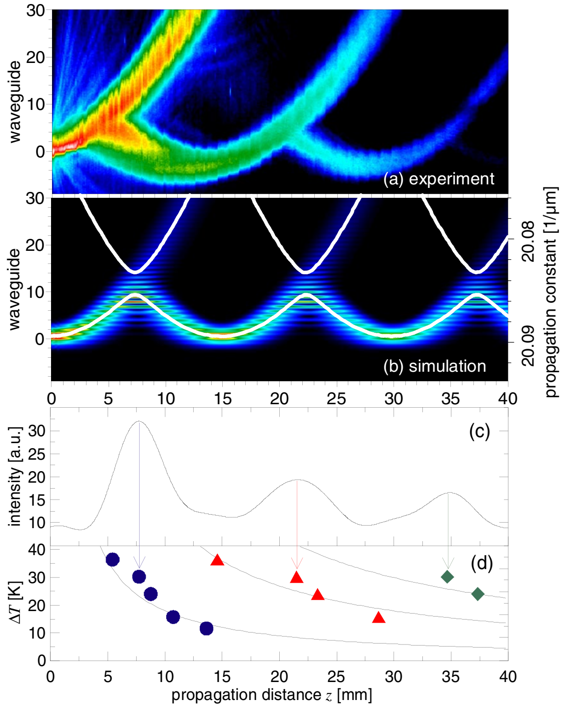

FIG. 2 (color online). Bloch oscillations and Zener tunneling in a waveguide array when several waveguides are excited by a 25 μm wide elliptical beam. (a) Experiment, (b) corresponding simulation (beam propagation method) for a temperature difference of $\Delta T = 24$ K. (c),(d) Positions of outbursts of radiation caused by Zener tunneling in dependence of the applied temperature difference ΔT. In correspondence to the Bloch oscillation period, a $1/\Delta T$ dependence is observed.

In principle, light tunneled to the second band follows the band structure [see Fig. 2(b)] and may again perform BOs. However, the gaps between higher bands are smaller than the first gap and light successively tunnels towards higher bands without having the chance to complete further oscillations.

To complete the picture another experiment has been carried out, which can hardly be performed in semiconductor SLs. Rather than exciting a few waveguides (narrow Fourier spectrum) light was fed into a single waveguide of the array (homogeneous excitation of the entire Brillouin zone). There are also BOs because the existence of the WSL entails the recovery of any initial excitation. While for broad excitations BOs are observed as a transverse motion of the beam center, this center is now at rest but the field distribution breathes (see Fig. 3). Thus, ZT will appear too but with a different pattern. Because the entire Brillouin zone is excited and some part of the spectral

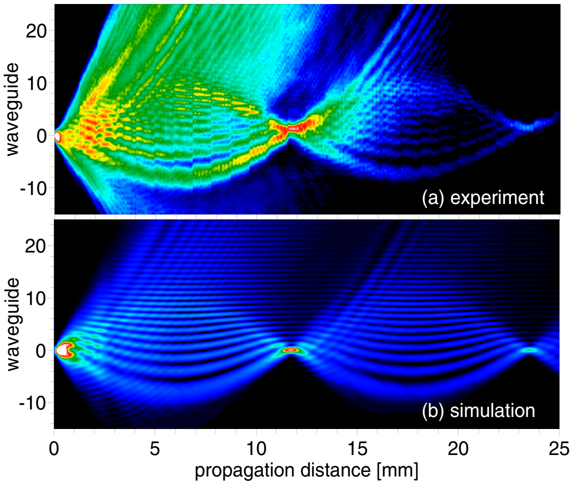

FIG. 3 (color online). Bloch oscillations and Zener tunneling in a waveguide array when the entire Brillouin zone spectrum is excited by shining light in a single waveguide. (a) Experiment, (b) corresponding numerical simulation (temperature difference $\Delta T = 35$ K).

distribution is always located at the band edge, tunneling appears upon the whole BO period. However, at the points, where the initial field distribution recovers and light focuses to the initial waveguide tunneling is particularly pronounced. If light is concentrated in a single waveguide all radiation escaping due to ZT is in phase and must follow the same path. Because of constructive interference a well-defined trace of fluorescence can be observed to cross the sample. In contrast radiation emanating between the points of refocusing is distributed over many guides and no coherent enhancement occurs.

In conclusion, we have reported the first direct visual observation of Zener tunneling. We displayed both the trace of damped Bloch oscillations and Zener tunneling. Zener tunneling was observed as regular outbursts of radiation escaping from the Bloch oscillations into higher order bands. All measurements are in excellent agreement with numerical simulations well beyond the tight-binding model.

This work was supported by grants from the Deutsche Forschungsgemeinschaft, Bonn, and the Federal Ministry of Education and Research (InnoRegio).

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