Bloch oscillations and Zener tunneling of photon pairs

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Optical analogs of electronic quantum effects have been pushed to the few-photon level in waveguide lattices.

Predicted more than 80 years ago, Bloch oscillations occur when electrons in a crystalline potential are driven by an external DC electric field. Rather surprisingly, quantum theory predicts that a DC field produces oscillatory electron motions, which result in an alternating current. This is usually interpreted in terms of Bragg waves scattering off the potential, causing the electrons to oscillate rather than translate through the lattice. In strong DC fields, Bloch oscillations are damped because of particle tunneling into higher-order lattice bands (Zener tunneling). Unfortunately, Bloch oscillations have never been observed in natural crystals because of electron-phonon interactions, which occur on a shorter timescale than the Bloch-oscillation cycle and thus destroy coherent electronic motions. However, they have been seen in solid-state materials after development of high-quality semiconductor superlattices, leading to terahertz radiation from coherently oscillating electrons. More recently, Bloch oscillations of matter waves have also been observed for cold atoms and Bose-Einstein condensates trapped in optical lattices.

Optical and acoustic analogs of Bloch oscillations have also been predicted and observed in recent years. They are generally viewed as classical analogs of electronic or matter-wave Bloch oscillations. In particular, observations of optical Bloch oscillations have been facilitated by the fabrication of photonic lattices, where the spatial structure of the material’s index of refraction creates energy bands and bandgaps analogous to those for electrons in solids. Spatial propagation of light in photonic lattices with a superimposed transverse refractive-index gradient or in circularly-curved waveguide arrays can exhibit properties similar to those of electrons moving through a lattice in an electric field. Optical experiments aimed at demonstrating electromagnetic analogs of electronic Bloch oscillations have been carried out using ‘classical’ light, i.e., the fields contain so many photons that they are clearly wavelike. However, when nonclassical light is used, quantum-interference effects that manifest the particle-like nature of photons should be observable in addition to classical Bragg scattering, such as Hong-Ou-Mandel two-photon quantum interference, which is at the core of quantum circuits. It is generally observed when a photon pair is probed by a 50% beam splitter.

Our recent theoretical work introduced a fully quantized photon field. We showed that nonclassical light consisting of only particle-like quanta can also produce optical Bloch oscillations and Zener tunneling in waveguide lattices. In particular, we showed that Zener tunneling may mix photons among different bands of the lattice and thus acts like a beam splitter in quantum optics.

Quantum interference and photon entanglement can thus occur as light undergoes Bloch oscillations. The simplest case is the appearance of two-photon Hong-Ou-Mandel quantum interference for pairs of correlated photons undergoing Bloch-Zener oscillations in binary arrays (see Figure 1). Consider a binary...
array, made of an alternating sequence of narrow and wide waveguides, and assume that the array is excited by two photons in the Fock state (which describes the number of excitation quanta), $|11\rangle$, such as photons generated by parametric down-conversion (where a nonlinear crystal splits incoming photons into lower-energy photon pairs). The two photons propagate along two inclined directions at suitable incident angles, $\theta_1$ and $\theta_2$—see Figure 1(a)—such that one photon excites the array’s first miniband, while the other excites the second miniband: see Figure 1(b). Classically, the two beams undergo a sequence of Bloch oscillations with periodic crossings after each semicycle, where Zener tunneling occurs, as shown in Figure 1(c). This coherent superposition of Bloch oscillations and Zener tunneling is referred to as Bloch-Zener oscillations. In the quantum regime, Bloch oscillations of the two photons are correlated, and we found that, after each Zener tunneling event, the photons periodically bunch in the same beam, like in a sequence of 50% beam splitters.\(^5\) Photon bunching can be revealed by computing the joint photon probability, $P(1, 1)$, to find one photon in each of the two lattice minibands: see Figure 1(d).

Quantum signatures of nonclassical light undergoing Bloch oscillations can be observed even in absence of Zener tunneling. Consider a singly-periodic waveguide array with a tunable transverse refractive-index gradient excited by two beams tilted at the lattice’s Bragg angle from opposite directions, as shown in Figure 2(a). The first two bands are excited, and photons undergo Bloch oscillations along distinct paths until they recombine after a full Bloch-oscillation cycle: see Figure 2(b). Because of the different paths, the two beams interfere with some phase delay, $\Delta \phi = \phi_2 - \phi_1$, which can be varied by slightly tuning the refractive-index gradient imposed. The lattice thus behaves like a Mach-Zehnder interferometer with controllable phase delay—see Figure 2(c). Quantum interferometry mediated by multi-band Bloch oscillations is expected when the lattice is excited by nonclassical light. We demonstrated a noteworthy example of quantum interference by doubling the interference fringes in photon-counting rates at detectors D1 and D2 for a correlated photon pair undergoing two-band Bloch oscillations.\(^6\) It is a manifestation of the Broglie wavelength of the two-photon entangled state produced after the first beam splitter of the interferometer and probed by the second.

On the basis of the results presented here, we will proceed with further theoretical and experimental studies of classical and quantum-interference phenomena of light propagating in complex periodic, quasi-periodic, or disordered photonic lattices. Investigation of such effects may offer the possibility to engineer photon entanglement and transport nonclassical light through complex photonic structures. This will also provide a novel view of optical-quantum analogs, offering the chance to observe quantum versions of classical wave phenomena.

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References