Experimental Observation of Rabi Oscillations in Photonic Lattices

Ksenia Shandarova, Christian E. Rüter, and Detlef Kip*
Institute of Energy Research and Physical Technologies, Clausthal University of Technology, 38678 Clausthal-Zellerfeld, Germany

Konstantinos G. Makris and Demetrios N. Christodoulides
School of Optics-CREOL, University of Central Florida, Orlando, Florida 32816-2700, USA

Or Peleg and Mordechai Segev
Department of Physics, Technion-Israel Institute of Technology, 32000 Haifa, Israel
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We demonstrate spatial Rabi oscillations in optical waveguide arrays. Adiabatic transitions between extended Floquet-Bloch modes associated with different bands are stimulated by periodic modulation of the photonic lattice in the propagation direction. When the stimulating modulation also carries transverse momentum, the transition becomes indirect, equivalent to phonon-assisted Rabi oscillations. In solid state physics such indirect Rabi oscillations necessitate coherent phonons and hence they have never been observed. Our experiments suggest that phonon-assisted Rabi oscillations are observable also with Bose-Einstein condensates, as well as with other wave systems—where coherence can be maintained for at least one period of the Rabi oscillation.

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Since the famous work of Rabi in 1936, it has been well known that in quantum systems a periodic modulation can stimulate a resonant transition from one energy level to another and back [1]. A typical example is a two-level atomic system, where an electromagnetic wave whose frequency is tuned to the energy gap between the two states causes periodic population exchanges accompanied by emission and reabsorption of a photon. Rabi oscillations are known to occur in a universal fashion in many different physical systems, including excitonic transitions in semiconductors [2], spin flips in quantum dots driven by magnetic fields [3], Bose-Einstein condensates (BECs) [4], etc. In all cases observed so far, however, the oscillations involve direct transitions only; that is, either the states possess the same momentum or, in a periodic potential, the momentum difference is an integer quanta of lattice momentum. In principle, the momentum difference between the two states can be supplied by another entity: a phonon, or any other kind of wave carrying momentum, could facilitate indirect Rabi transitions. However, the coherence between the interacting systems must be maintained for a time interval of at least half a period of the Rabi oscillation. Otherwise, adding some randomly fluctuating phase to the modulation makes the interaction products unable to interfere constructively; hence, the efficiency of the transition process decays rapidly with the loss of coherence [5]. As such, in solid crystals (e.g., semiconductors) one cannot efficiently isolate a single phonon; hence, it is impossible to observe such phonon-atom-photon interactions leading to phonon-mediated Rabi oscillations. For this reason, to the best of our knowledge, phonon-assisted Rabi oscillations have never been observed.

The hope for ''indirect Rabi oscillations'' is coming now from a different arena. The concept of Rabi oscillations has recently been extended to optical systems, where light propagation is limited to certain modes or bands. Typical examples where such interactions have been predicted are multimode waveguides [6] and photonic crystals [7–10]. In such systems, periodic modulation of the propagation properties (absorption or refractive index) in the direction of propagation leads to adiabatic coupling between different modes, manifested by periodic revivals of the light intensity patterns associated with these modes. Rabi oscillations are a conceptual phenomenon, which is universal to systems driven periodically in their evolution coordinate. As we discuss below, a similar situation occurs also with matter waves in optical lattices, where Rabi oscillations can be stimulated in a fashion similar to what we study here, in photonic lattices.

Here, we follow a recent prediction [9] and present spatial Rabi oscillations in photonic lattices. We experimentally demonstrate adiabatic transitions between extended Floquet-Bloch (FB) modes associated with different bands, where the transitions are stimulated by periodic modulation of the lattice. The transitions occur only when the corresponding selection rules of momentum and parity conservation are fulfilled. When the lattice modulation is strictly longitudinal (i.e., in the propagation direction, normal to the waveguide array), the transitions are direct (band to band), corresponding to Rabi oscillations in the usual sense [1–4]. On the other hand, when the stimulating modulation also carries transverse momentum, the transition becomes indirect, equivalent to phonon-assisted Rabi oscillations. Our experiments suggest that

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phonon-assisted Rabi oscillations could also be observable in the aforementioned BECs, as well as in other wave systems—wherever coherence can be maintained for at least one period of oscillation.

Our particular experimental system follows the proposition in [9], where light is propagating in a one-dimensional waveguide array, with an additional modulation superimposed. The propagation of the light electric field E along the z direction in a lattice that is transversely modulated along x, with additional periodic refractive-index modulation along x and z, is described by the paraxial wave equation:

$$i\frac{\partial E}{\partial z} + \frac{1}{2k}\frac{\partial^2 E}{\partial x^2} + \frac{k}{n_e}[\Delta n(x) + \delta n(x, z)]E = 0. \quad (1)$$

Here k is the wave number, n_e is the substrate index, $\Delta n(x)$ is the transverse periodic modulation defining the lattice, and $\delta n(x, z)$ describes the additional periodic modulation stimulating the Rabi oscillation. In this sense, $\delta n(x, z)$ is equivalent to the modulation terms in quantum mechanics, for example, the time-varying dipole moment induced by a photon [1]. In our samples, $\Delta n(x)$ is realized by Ti in-diffusion in photorefractive $LiNbO_3$, defining the waveguide array. The additional modulation $\delta n(x, z)$ is realized by two-beam holographic recording of an elementary refractive-index grating. The grating vector K is aligned at an angle φ relative to the z direction, i.e., $\tan(\varphi) = \Delta k_x/\Delta\beta$, with Δk_x and $\Delta\beta$ being the transverse and longitudinal components of K, respectively. In this scheme, the photorefractive properties of our sample are periodically modulated: the concentration of the photorefractive centers (Fe^{2+} and Fe^{3+}) is periodically modulated along x due to the modulated Ti concentration forming the array [11]. When illuminated with a uniform intensity, such modulated trap densities lead to modulated photovoltaic currents [12], which in turn generate a modulated refractive-index change, in this case in the x direction, of the same spatial modulation as the permanent lattice modulation $\Delta n(x)$. Using a separation ansatz, the additional periodic modulation is described by

$$\begin{aligned}\delta n(x, z) &= \delta n(x)\delta n(z)\\ &= \delta n_0 \cos(\Delta k_x x)[1 - \varepsilon\cos^2(\pi x/\Lambda)]\cos(\Delta\beta z),\end{aligned} \quad (2)$$

where δn_0 is the amplitude, ε (with $0 \leq \varepsilon \leq 1$) describes the additional transverse modulation due to the modulated Ti concentration, and Λ is the lattice constant of the waveguide array having an index modulation $\Delta n(x) = \Delta n_0 \cos^2(\pi x/\Lambda)$ (at the surface $y = 0$). Solving the related linear eigenvalue problem leads to solutions of the form $E_l(x, z) = A_l(z)U_l(x)\exp(i\beta_l z)$, where A_l is the amplitude, U_l is the normalized transverse mode profile, and β_l is the propagation constant of mode l. Here the index l covers both band index and transverse Bloch momentum of the modes. By using the related orthogonality relations of these modes, adiabatic transitions among different FB modes l and m can be described by a system of coupled equations

$$\begin{aligned}i\frac{\partial A_l}{\partial z} &= -\frac{1}{2}M_{lm}A_m\exp(-i[\beta_l - \beta_m - \Delta\beta]z)\\ &\quad\times \delta(k_{xl} - k_{xm} - \Delta k_x),\end{aligned} \quad (3)$$

which are similar to equations for probability amplitudes for a quantum system driven by a classical field. In Eq. (3), the delta function accounts for the conservation of transverse momentum, whereas the exponential function describes the longitudinal phase matching condition. Thus only for $\Delta\beta = \beta_l - \beta_m$ full power exchange between modes l and m can be expected. The integral $M_{lm} = \int_{-\Lambda/2}^{\Lambda/2} U_l(x)\delta n(x)U_m(x)dx$ accounts for the transversal overlap of modes l and m with the modulation $\delta n(x)$. The modulation amplitude of the distortion δn_0 scales the magnitude of M_{lm} and is inversely proportional to the spatial coupling length. When $\delta n(x)$ is symmetric, mode coupling is limited to those with equal parity. However, when $\delta n(x)$ is asymmetric, as is the case for a *tilted* grating ($\varphi \neq 0$) superimposed on the periodic medium, modes of different parity are coupled, too.

Figure 1(a) presents the calculated band structure (effective refractive indices n_{eff} of FB modes versus Bloch momentum k_x) for TE polarization, within the Brillouin zone. The parameters are related to our $LiNbO_3$ waveguide array where the ferroelectric c axis is parallel to the transverse direction x. This sample has a grating period of $\Lambda = 8\ \mu$m and a substrate index $n_e = 2.242$ (wavelength $\lambda = 514.5$ nm) and its first three bands arise from guided modes (i.e., each waveguide has three guided modes; hence, the effective index n_{eff} of FB modes from these bands is larger then the substrate index n_e). Possible band-to-band tran-

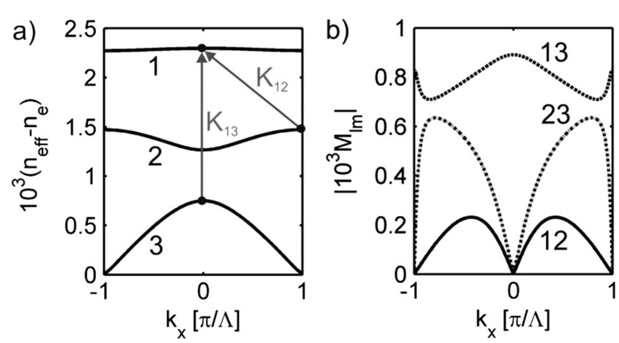

FIG. 1. Band structure and calculated overlap integrals. (a) Band structure of our waveguide lattice where the first three bands arise from guided modes. The arrows indicate both direct transitions (K_{13}, coupling bands 1 and 3 at $k_x = 0$) and indirect transitions (K_{12}, coupling bands 1 and 2 via a tilted grating with $\Delta k_x = \pi/\Lambda$). (b) Spatial overlap integral M_{lm} of possible direct FB mode transitions as a function of Bloch momentum.

sitions among different FB modes include both direct (for example, K_{13}) and indirect (for example, K_{12}) transitions. For the case of direct transitions (nontilted grating, $\Delta k_x = k_{xl} - k_{xm} = 0$), Fig. 1(b) shows the calculated overlap integral M_{lm} as a function of Bloch momentum k_x. Here we have taken the additional modulation amplitude to be $\delta n_0 = 3.5 \times 10^{-4}$, aligned under $\varphi = 0$, and the parameter ε is set to $\varepsilon = 1$. Interband transitions are most effective between the first and third band in the whole Brillouin zone. Lower conversion efficiencies are obtained for other band combinations (1–2 and 2–3), which both reduce to zero in the center and at the edge of the Brillouin zone (because at these positions parity conservation is not fulfilled).

Figure 2 depicts numerical examples of spatial Rabi oscillations, for both direct (coupling bands 1 and 3 at $k_x = 0$) and indirect transitions (coupling band 1, $k_x = 0$, and band 2, $k_x = \pi/\Lambda$). The parameters used for the lattice and the periodic modulations are related to the experimental values obtained in our $LiNbO_3$ sample. In Fig. 2(a) direct transitions among band 1 and 3 (having the same parity) with a spatial coupling length (inverse Rabi frequency) of about 0.85 mm are observed. Remarkably, complete coupling, i.e., full energy transfer to the other mode, is obtained on a length scale that is equal to only $\sim 20\Lambda_z$, where Λ_z is the grating period of the periodic modulation along z, with $\Delta\beta = 2\pi/\Lambda_z = 2\pi(n_{\mathrm{eff},1} - n_{\mathrm{eff},3})/\lambda$. For the example of an indirect transition in Fig. 2(b) coupling bands 1 and 2, the spatial Rabi frequency is slightly smaller (i.e., larger coupling length), which is mainly attributed to the chosen set of parameters (i.e., smaller ratio $\delta n_0/\Delta n_0$) and the smaller overlap of the two interacting modes with the induced modulation.

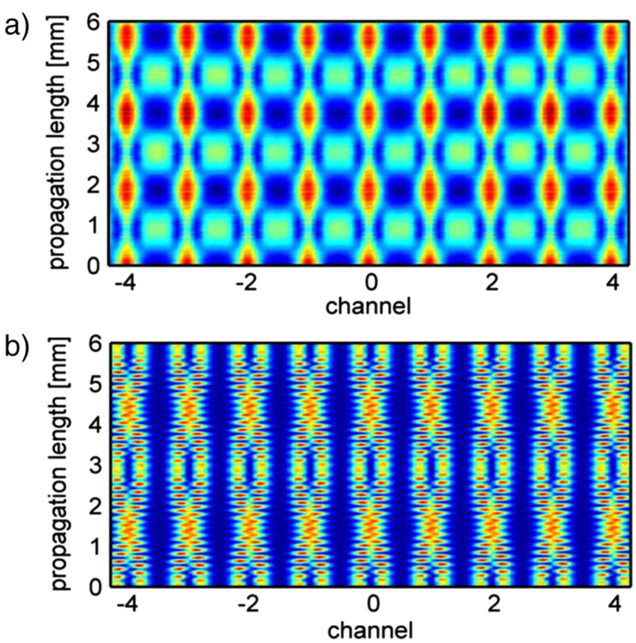

FIG. 2 (color online). Simulations displaying periodic transitions between FB modes. (a) Direct transition between bands 1 and 3 in the center of the Brillouin zone at $k_x = 0$. The simulation parameters are for a lattice with $\Lambda = 8\ \mu$m, a ratio $\delta n_0/\Delta n_0 = 0.3$ between the modulation stimulating the transition and the modulation defining the lattice, $\varepsilon = 1$, and $\Delta k_x = k_{x1} - k_{x3} = 0$. (b) Indirect transition using a tilted modulation, leading to coupling of band 2 that is excited with Bloch momentum $k_x = \pi/\Lambda$ with modes in band 1 at the center of the Brillouin zone $k_x = 0$. Here the parameters are $\delta n_0/\Delta n_0 = 0.1$, $\varepsilon = 1$, and $\Delta k_x = k_{x1} - k_{x2} = \pi/\Lambda$ for the same lattice as in (a).

Experimentally, our waveguide array consists of 250 parallel channels, fabricated in an Fe-doped $LiNbO_3$ substrate using Ti in-diffusion [13]. The effective periodic index modulation of the lattice is described by $\Delta n(x) = 0.0023\cos^2(\pi x/\Lambda)$, with $\Lambda = 8\ \mu$m. Iron, which exists as Fe^{2+} (electron donators) and Fe^{3+} (electron traps) in $LiNbO_3$, increases the impurity level and thus increases the photorefractive effect. The additional modulation stimulating the transition is induced by means of a holographic grating of grating vector K, recorded with green light of an Ar^+ laser ($\lambda = 514.5$ nm) using a two-beam interference setup. The grating vector can be aligned to be either parallel or tilted under an angle φ relative to the z axis. The experimental range of accessible nonlinear index changes δn_0, in relation to the (linear) periodic modulation Δn_0 of the lattice, is typically $\delta n_0/\Delta n_0 \approx 0.1$–$0.3$.

After recording the modulation causing the transition, we excite pure FB modes in the modulated waveguide arrays by means of a prism-coupler setup [14]. We use low light intensities (power well below 100 nW per channel); hence, the coupling between bands is strictly a linear effect, arising from the additional modulation. We monitor the light intensity distribution on the lattice output, which is imaged onto a CCD camera. The propagation lengths within the array can be varied by changing the distance Δz between the in-coupling (prism) position and the sample output face. Here the spatial resolution is limited to ± 0.2 mm, which is mainly due to the final width (along z) of the coupling point at the prism base–waveguide array interface.

For the case of direct Rabi transitions, the experimental results in Fig. 3(a) show the intensity structure at the lattice output, for five different propagation distances Δz, for excitation either at band 1 (left-hand panel) or at band 3 (right-hand panel) with the prism coupler. An almost complete conversion of the power carried by modes is observed at a (full) coupling length of about 1.67 mm. In another experiment, we recorded tilted gratings K_{12} [see Fig. 1(a), where the transverse part $\Delta k_x = \pi/\Lambda$ acts as a "coherent phonon"] and observed periodic coupling between band 2 excited at $k_z = \pi/\Lambda$ and band 1 at $k_z = 0$. The corresponding output intensity patterns after different propagation lengths are shown on the right-hand side of Fig. 3(b). Here the experimentally obtained spatial Rabi frequency is

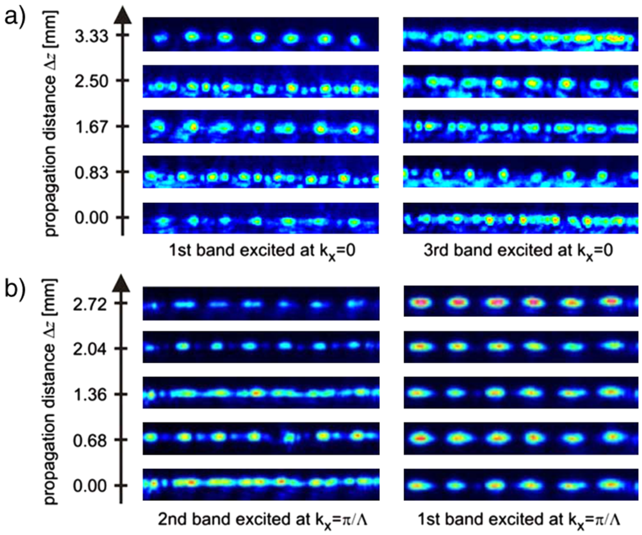

FIG. 3 (color online). Interband transitions induced in periodically distorted photonic lattices. (a) Direct Rabi transition of FB modes between bands 1 and 3. Shown are photographs of the output intensity of the FB modes, after different propagation distances Δz, when a pure mode either in band 1 (left-hand panel) or in band 3 (right-hand panel) is excited with the prism coupler. (b) Indirect Rabi transitions of FB modes between bands 1 and 2.

slightly larger when compared with the situation in Fig. 3(a), which may be attributed to a more effective charge transport along the ferroelectric c axis in this situation when compared to a nontilted grating. In contrast to the symmetric behavior observed for direct transitions, here the "diagonal" transition (i.e., coupling band 1 at $k_z = \pi/\Lambda$ with band 2 at $k_z = 0$) is suppressed due to the phase mismatch $\Delta\beta$ between the respective propagation constants; thus, the intensity of the output facet in Fig. 3(b) (right-hand panel, showing modes of the excited band 1) remains unchanged.

In conclusion, we have reported the first experimental observation of (spatial) Rabi oscillations occurring in an optical photonic lattice, including both direct and indirect transitions. Most intriguing are the indirect Rabi transitions, which necessitate a coherent contribution of transverse momentum, that is, a phonon, which in atomic systems must be phase correlated with both the optical field and the atoms. Naturally, in solid state such experiments with indirect Rabi transitions are possible only at extremely low temperatures, and as such, they have never been observed before. In BECs, however, it is possible to use Bogoliubov oscillations to generate sound waves that would remain phase correlated (coherent) with the BEC [15,16]. Hence, our experiments here show the way to observe indirect Rabi oscillations with cold atoms, where both the lattice and the additional periodic modulation are induced by interfering light waves, and the atoms transfer coherently between bands, with the momentum mismatch supplied by coherent phonons within the BEC. Finally, another very interesting challenge that is yet to be explored is adding nonlinearity to the system, and to observe Rabi oscillations of solitons [9].

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*d.kip@pe.tu-clausthal.de

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