Optical Bloch Oscillations in Temperature Tuned Waveguide Arrays

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We report the observation of optical Bloch oscillations in waveguide arrays. The required linear variation of the propagation constant across the thermo-optic polymer array was obtained by applying a temperature gradient. Bloch oscillations manifesting themselves as transverse oscillations of the propagating light beam can be attributed to the existence of localized states (Wannier-Stark states) with equidistant eigenvalue spacing (Wannier-Stark ladder). The period and amplitude of the oscillations can be controlled by varying the temperature gradient.

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The question how electrons will behave in a crystal lattice if a dc electric field is applied was raised by Bloch and Zener early in this century [1] and was thereafter controversially debated for a long time [2]. Taking advantage of the recent progress in semiconductor growth technology, the issue was settled by experimentally observing a Wannier-Stark ladder (WSL) [3] and later Bloch oscillations (BO) of electrons [4] in semiconductor superlattices. Inspired by these achievements, similar phenomena were found in other physical systems, as, e.g., for cold atoms in optical lattices [5] and for light beams in periodic structures [6,7]. Moreover, it was pointed out that the basic phenomenon can be described by a unified discrete model [8].

An array of evanescently coupled optical waveguides is a prominent example of a discrete periodic dynamical system. Intrinsic localization (discrete soliton formation) in arrays with different kinds of on-site nonlinearity has been theoretically predicted [9,10] and recently experimentally confirmed in AlGaAs waveguide arrays [11]. Beyond the fundamental interest in optical waveguide arrays (OWAs) as a convenient laboratory for the study of dynamical effects in discrete systems they have a fair potential in all-optical signal processing [12]. In addition to nonlinear localization effects we recently predicted the existence of Wannier-Stark states (WSSs) as well as WSLs and consequently the emergence of optical BOs in OWAs with a linearly varying propagation constant across the array [7]. In contrast to semiconductor superlattices with temporal current oscillations on a femtosecond time scale the direct measurement of BO amplitudes is feasible because BOs in OWAs manifest themselves as a stationary spatially periodic path of a discrete light beam on an accessible spatial scale of some micrometers. In superlattices they could be measured only indirectly via the field shift of the WSL transitions caused by the small dipole field of the oscillating electrons [13]. Furthermore, the control of initial conditions is difficult in condensed matter experiments, e.g., the coherent excitation of free electrons which is necessary to detect BOs. In contrast, the excitation of a discrete light beam in an OWA by a laser source is a simple task, which even allows one to precisely generate complex phase and amplitude distributions.

The aim of this Letter is to experimentally prove that a thermo-optically tuned OWA exhibits supermodes that correspond to WSSs with propagation constants forming a WSL and that these features cause the existence of BOs, the amplitudes and periods of which can be controlled by the temperature gradient. We fabricated a homogeneous OWA of 75 waveguides in an inorganic-organic copolymer on thermally oxidized silicon and glass wafers with copolymer cladding by uv lithography. Each waveguide had a cross section of $3.5 \times 3.5\ \mu\mathrm{m}^2$ and provided low loss single mode waveguiding (<0.5 dB/cm) at $\lambda = 633$ nm. The uniform separation d of adjacent guides was $8.5\ \mu$m to achieve efficient evanescent coupling (see Fig. 1). The 4.5 cm long OWAs were

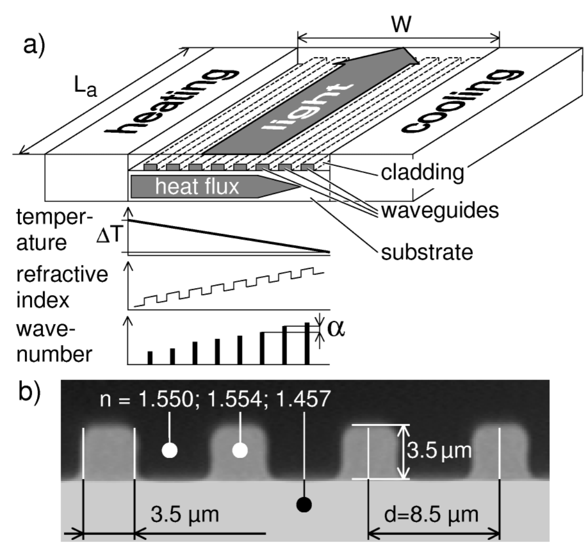

FIG. 1. Thermo-optic polymer OWA sandwiched between two copper blocks at different temperature. (a) Schematics. (b) OWA before applying the polymer cladding.

fabricated on a 4 in. wafer and subsequently cut into samples of width W ranging from 500 to 1000 μm using a dicing saw. The uniform OWA was detuned by taking advantage of the thermo-optic effect in the polymer (thermo-optic coefficient $n_{\mathrm{th}} = -10^{-4}\ \mathrm{K}^{-1}$). By heating and cooling the opposite sides of the array (Fig. 1) a transverse linear temperature gradient was established, leading to a linear variation of the refractive index as well as the propagation constants of the waveguides across the array. Simultaneously a homogenous evanescent coupling constant C was preserved.

The analogy of the field evolution in a thermo-optically detuned OWA to the motion of electrons in a crystal with an external field applied is evident; i.e., the transverse periodic structure of the OWA compares to the periodic potential of the crystal in one dimension and the temporal variation of the lattice position of the electrons corresponds to the longitudinally varying transverse position of a finite width light beam in the OWA. Similar to the tight-binding model for the description of the electron motion we can describe the light propagation by the coupled mode equations for the field envelopes [7]

$$\left(i\frac{d}{dz} + \alpha n\right)a_n(z) + C[a_{n+1}(z) + a_{n-1}(z)] = 0, \quad (1)$$

where the wave number of the mode in the guide with $n = 0$ has been separated. Here α is the wave number spacing between two waveguides, introducing a linear transverse potential, and $a_n(z)$ is the z-dependent field envelope in the nth waveguide. The same way as the linear potential for the electrons, the potential in the OWA can be continuously varied as $\alpha = 2\pi n_{\mathrm{th}}\Delta T d/(\lambda W)$ by changing the temperature difference ΔT between the edges of the OWA. As previously stated, the emergence of BOs is closely related to the existence of an equidistant eigenstate spacing, the WSL. The eigenstates (WSSs) of the OWA appear as localized supermodes [7]

$$u_n^m(z) = \sqrt{2\pi}\, J_{-n+m}(2C/\alpha)\exp(-i\beta_m z) \qquad (2)$$

that exhibit an identical shape (except a shift of the center) with eigenvalues $\beta_m = m\alpha (m \in G)$ corresponding to the temperature detuned propagation constant of the waveguide m at which the supermode m is centered. Thus, any input distribution $a(0)$ excites a certain set of WSSs (2). The beating of these states situated on an equidistant eigenvalue ladder β_m leads to a periodic recurrence of $a(0)$ after $z = jz_o = j2\pi/\alpha (j \in G)$.

Hence, the experimental verification of this periodic recurrence can be considered as a proof of the WSL. There are two distinct cases for $a(0)$, namely, the initial excitation of either a single or of a few waveguides. The first situation, e.g., $a_0(0) = 1$, results in a periodic breathing [14] with no change of the beam center (first momentum)

$$a_n(z) = J_{-n}\left[\frac{4C}{\alpha}\sin\left(\frac{\alpha}{2}z\right)\right]\exp\left[i\frac{n}{2}(\alpha z - \pi)\right]. \quad (3)$$

Equation (3) represents likewise the Green's function of the detuned OWA and is shown in Fig. 2a. If a few guides are excited, as, e.g., for a Gaussian excitation $a_n(0) = \exp[-(n/w)^2]$ of width $w = 4.0$, a periodic motion of the first momentum, which is the very BO, emerges as shown in Fig. 2b. The calculated intensity profiles have been simultaneously obtained by solving the scalar wave equation in the inhomogenous medium and by solving Eq. (1), where the good correspondence of the two methods is due to the weak coupling of the waveguides.

The periodic evolution in both cases can be attributed to the beating of eigenmodes with equidistant wave numbers. But there is also an intuitive optical picture that explains the behavior shown in Fig. 2 in terms of total internal and Bragg reflection. In looking at the phase fronts in Fig. 2b (dashed lines) one observes that the initially flat phase of the Gaussian excitation develops a phase tilt toward a growing wave number upon propagation. At maximum elongation (half the oscillation period, $z = \frac{\pi/2}{C}4.5$) the phase tilt has risen to a phase difference of π between adjacent waveguides. This is the boundary of the Brillouin zone of the local dispersion relation of the OWA (see, e.g., [15]). At this point the corresponding transverse wave vector is such that the beam experiences a Bragg reflection at the periodic array. Therefore the phase front is reversed corresponding to a change to the opposite boundary of the Brillouin zone. In the following the linear index ramp slows down the transverse motion of the beam toward lower indices by flattening the phase front and, eventually, leading to total internal reflection at the opposite turning point after a full oscillation and so on.

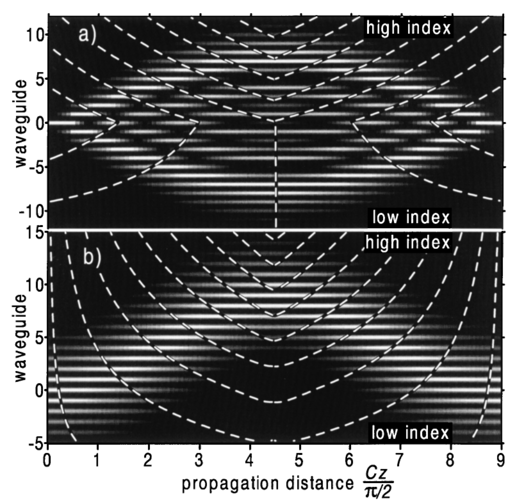

FIG. 2. Simulated field propagation in a linearly detuned OWA (phase fronts: dashed lines). (a) Single waveguide excitation—periodic breathing; (b) BO of a discrete Gaussian beam ($\alpha = 0.\bar{4}C$).

The periodic breathing of a single waveguide excitation can be similarly explained [7].

In our experiment we first checked the OWA homogeneity without any temperature gradient. The coupling constant C was estimated by exciting a single waveguide, where a spreading across $\sim$25 waveguides in the output (see Fig. 3a) gives $C = 125\ \mathrm{m}^{-1}$. The output field coincides with that theoretically calculated; therefore we assume a good homogeneity. By continuously increasing the transverse potential α, i.e., tuning ΔT, we detected the output intensity profile at the array end face ($z = 4.5$ cm). In Fig. 4 it is displayed together with the simulated output. The measured narrowing of the output field up to the recurrence to the single waveguide input at $\alpha = 140\ \mathrm{m}^{-1}$ with a subsequent spreading and another recurrence at $\alpha = 280\ \mathrm{m}^{-1}$ can clearly be attributed to the existence of a WSL. Here a change of the potential α has two consequences. First, it results in a variation of the oscillation period $z_o = 2\pi/\alpha$ which means that for $\alpha = 70\ \mathrm{m}^{-1}$ we detect the output after half an oscillation period $z_o/2$, at $\alpha = 140\ \mathrm{m}^{-1}$ after a full period z_o, etc. Second, the elongation of the oscillation is changed as $\sim 4C/\alpha$, which stems from a modification of the degree of localization of the WSSs and therefore the number of waveguides over which a localized excitation spreads in the course of an oscillation. This decreases the maximum elongation for higher oscillations, e.g., at $\alpha = 210\ \mathrm{m}^{-1}$ ($3z_o/2$), compared to the elongation at $\alpha = 70\ \mathrm{m}^{-1}$ ($z_o/2$). The reasonable recurrence to the single waveguide excitation after a full oscillation (Fig. 3b) proves the perfection of the WSL. The measured periodic breathing is likewise a visualization of the Green's function of the detuned OWA. This direct measurement is very peculiar, in that the excitation of a single particle is impossible in, e.g., superlattice experiments.

In contrast to the periodic breathing, the phenomenon of BO is usually attributed to oscillations of the first momentum of a density distribution, due to the superimposed oscillation of many excited particles. In OWAs this can be achieved by the simultaneous excitation of some waveguides. While increasing ΔT we measured the oscillating transverse motion of the output beam center displayed in Fig. 5a for a Gaussian excitation of width $w = 4$ being compared to the simulations in Fig. 5b. The output shows the same period as in Fig. 4. The decrease of the maximum elongation from $\alpha = 70$ to $210\ \mathrm{m}^{-1}$ is again due to the stronger localization of the WSSs for higher α as $\sim 4C/\alpha$. Furthermore, for increasing α the spreading of the excitation is reduced down to a minimum at $\alpha = 140, 280, \ldots\ \mathrm{m}^{-1}$ where after full BOs the initial Gaussian distribution of the excitation is recovered. The simulations revealed that in the experiment the initial elongation was not exactly zero due to a slight phase tilt of 0.095° in the initial excitation. The theoretically predicted translational invariance of the BO on the transverse position in the waveguide array could also be confirmed in the experimental investigations.

BOs, being a purely linear phenomenon of Wannier-Stark state beating, have also been found in nonlinear environments, as, e.g., in the Ablowitz-Ladik lattice [5]. But, by contrast, our theoretical investigations showed that for self-phase modulation by an on-site Kerr nonlinearity [9] dephasing leads to a disintegration of the WSL. Therefore BOs as well as the recurrence of the initial excitation cease to exist.

In summary, we have shown the first experimental evidence of optical Bloch oscillations in waveguide arrays. The thermo-optical tuning of the linear potential offered the possibility to continuously vary the Wannier-Stark ladder spacing and the oscillation period. The presented results prove that optical waveguide arrays are

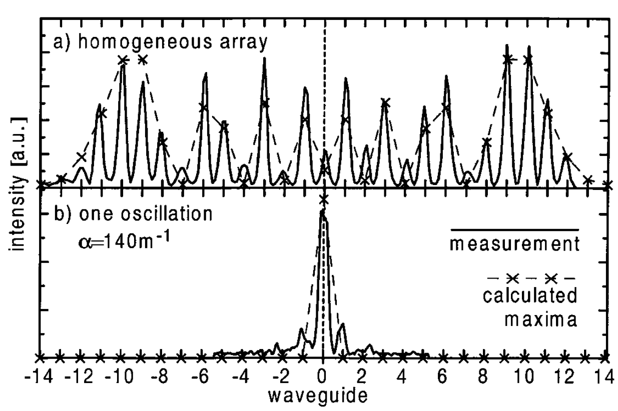

FIG. 3. Output for single waveguide excitation. (a) Uniform OWA ($\Delta T = 0$), (b) with refractive index gradient ($C = 125\ \mathrm{m}^{-1}$).

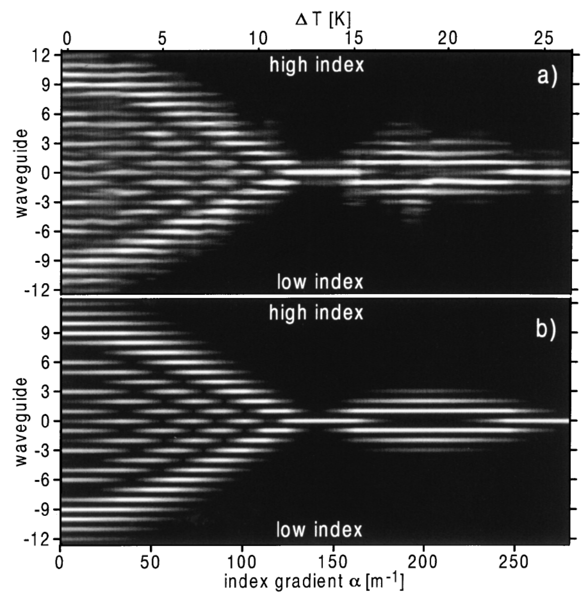

FIG. 4. Output intensity vs α for single waveguide excitation; (a) experiment; (b) simulations ($C = 125\ \mathrm{m}^{-1}$).

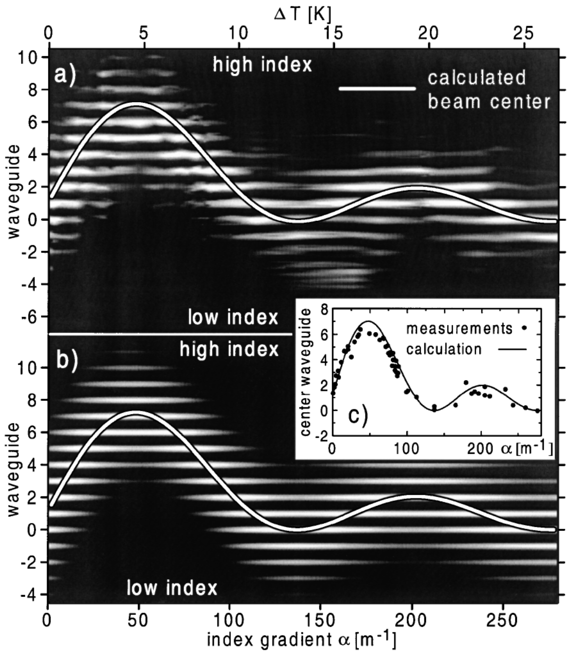

FIG. 5. Output intensity for a Gaussian excitation vs α. (a) Experiment; (b) simulations; (c) beam center (first momentum) of the output intensity ($C = 105\ \mathrm{m}^{-1}$).

an interesting laboratory for quantum transport in lattices. Photons have a much longer coherence length than electrons. Thus in the used low loss waveguide arrays, dephasing does not limit the observability of the presented coherent effects. Further work should continue to investigate other aspects of quantum transport, e.g., Landau-Zener tunneling by interpreting the not yet considered transmission losses, and should take advantage of the special experimental properties of OWAs, e.g., the ease of generating special excitations, the possibility to observe the otherwise fast evolution dynamics as a stationary field distribution along the propagation direction by measuring the scattered light from the top of the array, and the opportunity to coherently change the potential as well as the lattice along the oscillation periods in the OWA in order to observe resonant effects [16].

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