Experimental Observation of Linear and Nonlinear Optical Bloch Oscillations

R. Morandotti,* U. Peschel,† and J. S. Aitchison
Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G128QQ, United Kingdom

H. S. Eisenberg and Y. Silberberg
Department of Physics of Complex Systems, The Weizmann Institute of Science, 76100 Rehovot, Israel
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We experimentally demonstrate the occurrence of optical Bloch oscillations in a waveguide array with linearly growing effective index of the individual guides. We monitored the output profiles for varying propagation lengths and observed a periodic transverse motion of the field and a complete recovery of the initial excitation. The action of the focusing nonlinearity leads to a loss of recovery, symmetry breaking, and power-induced beam spreading.

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Discrete systems such as semiconductor superlattices, molecular chains, waveguide arrays, or coupled pendula share a lot of interesting and somehow intriguing features. One of the most remarkable is the occurrence of Bloch oscillations [1]. For example, if a static electric field is applied perpendicularly to a semiconductor superlattice, charged particles do not react on the electric force as expected. An oscillating current is generated in contrast to the dc flow observed in bulk materials [2]. Because of the fundamental relevance of discreteness in nature we expect to find similar effects in other systems of quite different origin. In fact, Bloch oscillations occur in molecular chains [3] and were experimentally observed for atoms captured by optical potentials [4]. Similar evolution equations in optics and quantum mechanics indicate the relevance of Bloch oscillations in optical systems under appropriate conditions. It was shown that the transmission spectrum of certain layer structures [5] or chirped fiber gratings [6] reproduces the spectral properties of biased semiconductor superlattices, which are characterized by series of equidistant peaks, the so-called Wannier-Stark ladder. In particular, the two cases above are simply the Fourier representation of Bloch oscillations with respect to either the angle of incidence [5] or the wavelength [6]. Recently, it was suggested that waveguide arrays with a varying effective index of the individual guides are an ideal environment to observe optical Bloch oscillations in the space domain [7]. Here we use arrays of AlGaAs waveguides to demonstrate this goal. In addition to the test of the linear properties this material system enables us to investigate the influence of nonlinearity on the field evolution. The nonresonant instantaneous cubic nonlinearity in semiconductors operated below half the band edge is analog to a pointlike scattering of interacting particles in quantum mechanics [8]. Therefore we can study dephasing effects with the tools of nonlinear optics on an accessible, i.e., millimetric, scale. Besides this fundamental interest, the practical importance of waveguide arrays is quite obvious. It was suggested that a linearly growing effective refractive index induced via the electro- or thermo-optical effect might be used to steer signals into a desired output channel. Further, waveguide arrays are basic components of high power semiconductor lasers, where the onset of nonlinearly induced filamentation and self-focusing can cause a basic limitation of the achievable output power. As we will show here the field in an array with linearly increasing effective index spreads due to the action of a focusing nonlinearity, therefore avoiding filamentation to a certain extent.

The sample under investigation consisted of 25 ridge waveguides (for a schematic drawing see top of Fig. 1). It was etched 1.2 μm deep on top of an AlGaAs slab waveguide composed by a 1.5 μm thick guiding layer of $Al_{0.18}Ga_{0.82}As$, sandwiched between two layers of $Al_{0.24}Ga_{0.76}As$. These upper and lower claddings were 1.5 and 4.0 μm thick, respectively. To obtain a linear increase of the effective index the rib width was varied from 2 to 3.4 μm, corresponding to an index difference of $\delta n = 1.275 \times 10^{-4}$ between adjacent guides. To ensure constant coupling also the spacing between the guides was varied from 6.6 to 3.3 μm (see top of Figs. 1 and 2). Finally, the sample was cleaved into pieces of different length varying from 3 to 18 mm to allow for an insight into the field evolution. To measure the optical response of the sample the setup described in [9] was used. Light pulses of 180 fs duration were generated at a wavelength of $\lambda = 1.53$ μm, which is well below half the band gap resulting in the suppression of two photon absorption. We used an elliptically shaped input beam with a width varying from 3 to 20 μm. The image of the output field was recorded with an infrared camera. To compare the results obtained from samples of different length special care was taken to keep the initial conditions constant. To adjust the output images the initial beam was tilted to illuminate the array boundaries. Additionally, the geometrical properties of the array, which guarantee a symmetric intensity distribution for an excitation of the central guide, were used to identify the central guide in the

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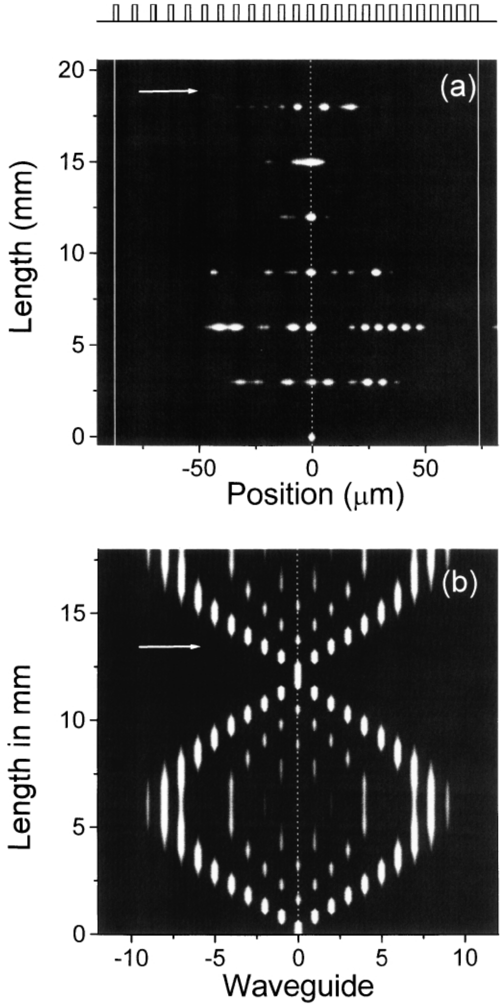

FIG. 1. Low power Bloch oscillations for a single waveguide excitation. Here the power distribution is shown as a function of the propagation length. (Beam width: 3 μm. Solid line: array boundaries. Dashed line: input guide. Arrow: direction of growing index.) (a) Experimental; (b) simulation.

output field distribution. Remaining deviations between different results are mainly due to small fluctuations in the excitation conditions as, i.e., small initial tilts around the normal incidence ($\pm 0.2°$).

Assuming that in every guide only one mode was excited, a coupled mode theory can be applied. In the ideal case [i.e., continuous wave (cw), no absorption] the equations of motion of the optical field in the waveguide array are described as follows:

$$i \frac{da_n}{dz} + \delta \beta n a_n + C(a_{n-1} + a_{n+1}) + \gamma |a_n|^2 a_n = 0 , \tag{1}$$

where a_n accounts for the amplitudes of the individual guides. In our case the wave-number difference between adjacent guides amounts to $\delta \beta = 520 \text{ m}^{-1}$ and the coupling constant was about $C = 1240 \text{ m}^{-1}$. The nonlinear coefficient was determined to be $\gamma = 6.5 \text{ m}^{-1}\,\text{W}^{-1}$.

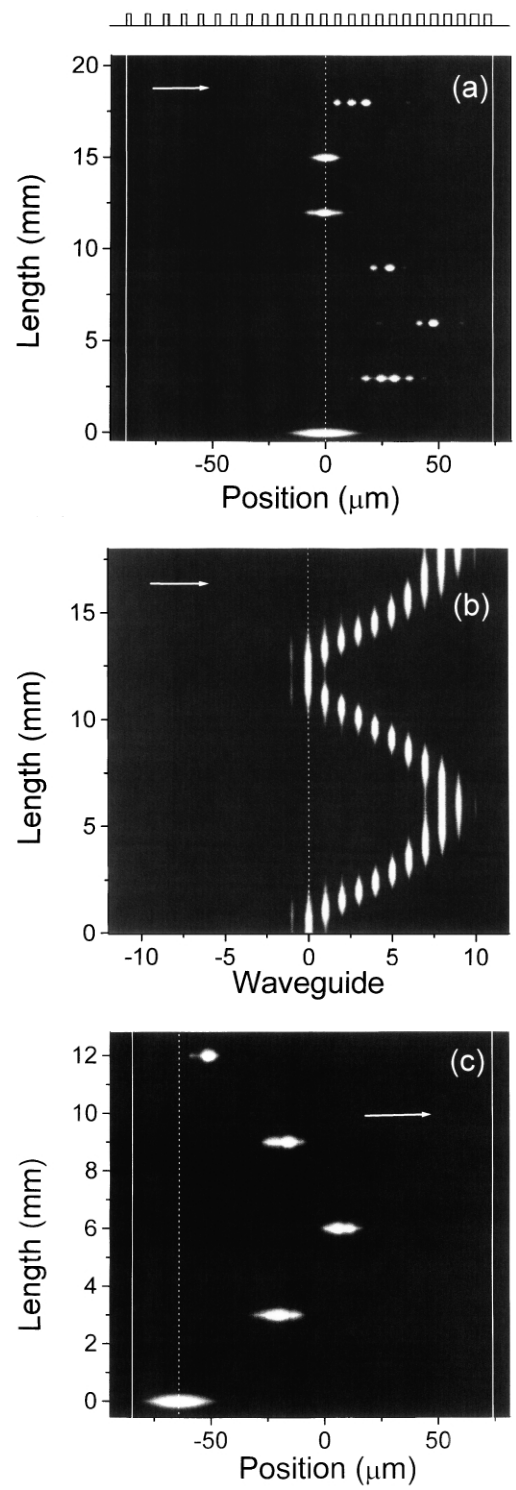

FIG. 2. Low power Bloch oscillations for a broad beam excitation. (Beam width: 20 μm. Solid line: array boundaries. Dashed line: input guide. Arrow: direction of growing index.) (a) Experimental (input: central guide); (b) simulation (input: central guide); (c) experimental (input guide: -8).

Hence the array was designed in a way that the nonlinearity for peak power levels up to 2000 W could compete with both the linear coupling constant and with the index differences. For low power excitation, the experimental situation is well described by Eq. (1). Although they do not influence the physics considerably, the transient behavior and the influence of losses were taken into account for higher power levels in order to obtain a more accurate modeling. In our sample the dispersion is normal and amounts to $1.35 \times 10^{-24}\ \mathrm{s^2\,m^{-1}}$. Therefore, our low power pulses of about 180 fs duration spread in the longest sample (18 mm) by a factor of 2.3 only. Although this spreading increases due to the action of the nonlinearity it is still too weak to have significant impact. The same yields for the absorptive effects which amount to $\alpha_1 = 1\ \mathrm{cm^{-1}}$ in case of linear and $\alpha_3 = 10^{-4}\ \mathrm{m^{-1}\,W^{-2}}$ in case of three photon absorption.

Let us deal with the linear or low power case first. Figure 1(a) shows the experimentally observed field evolution for a narrow input beam (3 μm) launched into the central waveguide only, where Fig. 1(b) displays the respective simulation based on Eq. (1). Similarly to the case of a homogeneous array, the field first spreads into both directions. Obviously, the action of the linear potential does not result in a deflection of the field but in a subsequent refocusing of the beam. Consequently, a periodic breathing or Bloch oscillations are observed. The main reason for this nontrivial behavior is attributed to the discreteness of the system. In contrast to a continuous system the linear eigenmodes of the array with a linear index gradient have a limited extension and equally spaced discrete propagation constants—the so-called Wannier-Stark ladder. Hence after a certain propagation length (in our case 12 mm) every initial distribution is recovered because the phase differences between the modes have reached multiples of 2π. In between, a considerable broadening of the optical field distribution may occur accordingly to the extension of the linear modes of the array. It was suggested [7] that this spreading should be about $8C/\delta\beta$. We observed a maximum width of the field distribution of about 17 waveguides, which agrees fairly well with this prediction. Another striking feature is the apparent symmetry of the power distribution. There is no shifting into the direction of growing indices as one would find in a continuous system. Local asymmetries are mainly due to a varying interference between adjacent guides. A more detailed theoretical analysis [7] reveals that only the power distribution is symmetric, where the phase of every second guide is flipped by π. If only guide 0 is excited the symmetry relation

$$a_n(z) = (-1)^n a^*_{-n}(z) \tag{2}$$

is always fulfilled. The reason for this behavior is that the pointlike initial beam excites the whole spectral domain or, using a quantum mechanical picture, the whole Brillouin zone including in- and antiphase modes. These correspond to the cases in which the phase difference between adjacent guides is zero, center of the Brillouin zone, and π, edge of the Brillouin zone, respectively. Inphase modes are equivalent to particles with positive mass and follow the index gradient as expected while traveling towards increasing indices. In contrast, the antiphase modes have a negative effective mass and move into the opposite direction. During propagation a phase difference between adjacent guides is accumulated; i.e., the effective particles move in the Brillouin zone. Consequently, the fields turn, a refocusing occurs, and the initial distribution in the Brillouin zone is recovered.

In case of a wider beam and for still low power levels [see Figs. 2(a) and 2(c)] the field evolution travels across the array periodically, but almost no spreading occurs, as demonstrated by both the experimental [Fig. 2(a)] and numerical [Fig. 2(b)] results. The reason for such different behavior with respect to the size of the input beam is the phase dynamics of the single waveguide excitation. As mentioned above at the early stage of the evolution a phase flip of π is observed between adjacent guides at the low index side. Now the field originating from many excited guides starts to interfere destructively. Consequently, the light is eliminated at the low index side and the beam stays confined. It only reverts its direction of motion when it reaches the so-called Bragg angle and back reflection on the array occurs. As long as the boundaries of the array are not touched, this behavior is the same for any input condition [compare Figs. 2(a) and 2(c)]. This diffraction-free propagation of broad beams might be useful for future steering applications. In case of a variable linear potential across the array, a signal can be steered without deteriorating.

Using again a quantum mechanical analogy, both position and momentum are equally uncertain for the wider input beam. Hence, only a part of the momentum space is populated. The motion across the Brillouin zone is now accompanied by an equivalent turn of the propagation direction in real space. If the excitation leaves the Brillouin zone on one side, it enters it again on the opposite and a periodic motion follows.

No matter how many waveguides are excited, maintenance of the exact phase relation between the individual guides is vital for the behavior observed above. Therefore, we expect to find considerable changes due to the action of the focusing cubic nonlinearity of the material. The most significant effect of a power increase is the loss of recovery after multiples of the Bloch-oscillation period [see Figs. 3(a) and 3(b)]. According to the actual power levels, the individual guides accumulate quite different amounts of phase shift and do not reach multiples of 2π for the same propagation length. But also the field evolution within one oscillation period changes considerably. In case of the single waveguide excitation the symmetry of the power distribution [see Eq. (2)] disappears. Because of the power-induced index increase, the input guide becomes resonant with the high index region of the array. Therefore the light tends to move towards growing indices as in a continuous system. Also in case of wider

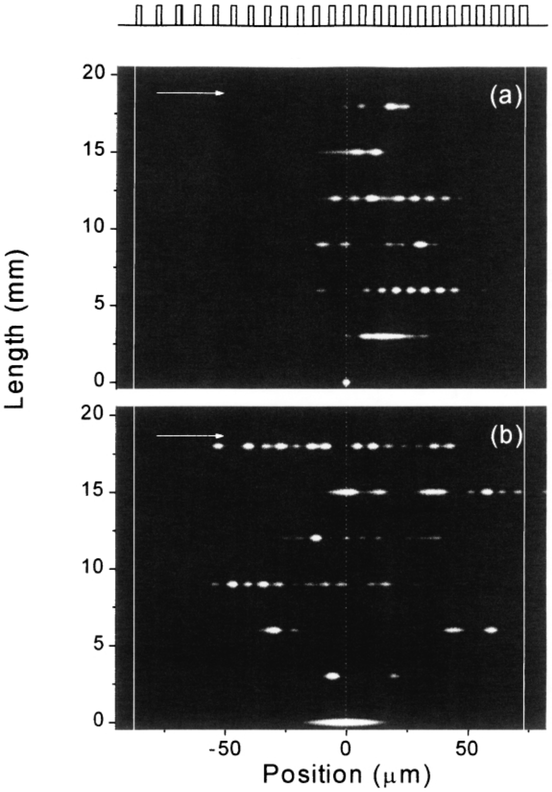

FIG. 3. High power field evolution (around 2000 W peak power). (a) Experimental results for a single waveguide excitation [same parameters as Fig. 1(a)]; (b) experimental results for a wide beam [same parameters as Fig. 2(a)].

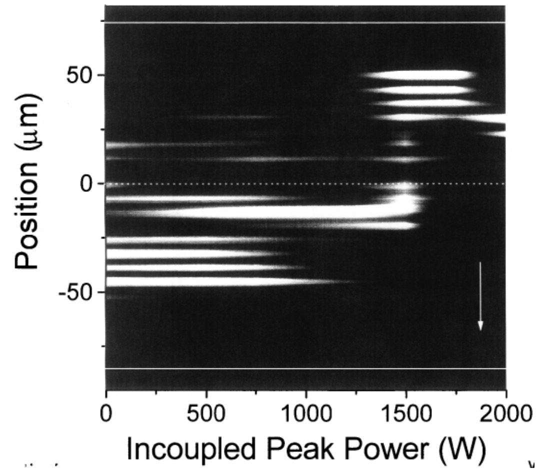

FIG. 4. Power-induced scanning of a wide beam [same parameters as Fig. 3(b)].

input beams the nonlinearity disturbs the phase relations [see Fig. 3(b)], which are vital for the confinement of the beam. Now the field starts to spread although the nonlinearity is focusing. This inversion of the effective action of the nonlinearity might be useful in stabilizing high power laser arrays against a power-induced filamentation due to the index increase induced by gain saturation.

In general the onset of the nonlinearity tends to randomize the field distribution. The strong coherence disappears and the light starts to behave more and more in a conventional way. Similar effects are observed in quantum mechanical systems for higher densities, where point-like scattering suppresses coherent recovery and particles become classical objects. The effect induced by the nonlinearity as observed here can be well reproduced by numerical simulations based on Eq. (1) (not shown here). These strong power-induced changes of the field distribution might be useful for signal steering and switching applications. With the onset of nonlinearity, the beam scans almost completely the array (see Fig. 4).

In conclusion, we have observed optical Bloch oscillations in a waveguide array. In strong analogy to quantum mechanical systems the initial distribution recovered after one oscillation period. We found a single waveguide excitation to spread symmetrically over the whole array before refocusing into the initial guide. In contrast, a broad beam moves across the array without changing its shape considerably. As soon as the linear phase relations are disturbed by the onset of the nonlinearity, the recovery is incomplete and the field distribution starts to disperse. Nonlinearity results in an almost immediate symmetry breaking and in strong steering effects.

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*Electronic address: morandot@elec.gla.ac.uk
†Present address: Friedrich-Schiller-Jena, Max-Wien-Platz 1, 07743 Jena, Germany.

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