

Time resolved optical Bloch oscillations in porous silicon superlattice structures

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We report on the observation of time resolved Bloch oscillations of light waves in optical superlattice structures. The structures are series of coupled microcavities, which are grown in porous silicon with high control of optical parameters. A controlled linear gradient of refractive index along the growth direction was maintained to tilt the photonic band gap of the superlattice. This is in perfect analogy to the tilted electronic miniband structure of a semiconductor in an electric field. In this way an optical Wannier-Stark ladder of equidistant optical modes was formed. Their frequency separation defines the period of the photon Bloch oscillations. The experimental results are in excellent agreement with transfer matrix calculations. The observed phenomenon is the optical counterpart of the well known electronic Bloch oscillations.

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1 Introduction

In 1928 Bloch and Zener predicted that an electron which moves in a semiconductor crystal in the presence of an external static electric field, may suffer a reflection from the energy band edge: its velocity will reach zero at the band edge and change the sign [1]. Therefore an oscillatory motion in the space and time was expected to result. As a consequence, an oscillating electric current should be produced in the crystal by DC voltage. This phenomenon is known in the literature as electronic Bloch oscillations (eBO).

The observation of a Wannier-Stark ladder (WSL), which is the frequency domain counterpart of the time resolved eBO, gave one of the first confirmations of the existence of eBO [2]. A WSL of equidistant energy levels in the electronic band structure is formed when the crystal is exposed to external stationary electric field. However, it took the scientists more than 60 years to observe eBO for the first time in semiconductor superlattices [3]. This long delay in the experimental observation was explained by the fact that electrons lose their coherence in a time much shorter than the expected period of the eBO. Ordinary crystals had to be replaced and specifically designed structures were needed to decrease the expected oscillation period. Semiconductor superlattices are periodic structures where the periodic potential gives rise to the formation of energy minibands. The larger the potential period is, the smaller the Brillouin zone, and therefore the shorter the electronic oscillations in time are. Superlattice presents a big translational period as compared to that of a usual crystal, and thus eBO are much faster, in particular faster than dephasing processes.

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The observed fascinating analogies between electron transport and the transport of optical waves, like the optical counterpart of weak localization [4], Anderson localization [5], short and long range correlations [6], universal conductance fluctuations [7], naturally raise the question if it is possible to mimic the effect of electric field and observe Bloch oscillations for photons in specifically designed photonic crystals. The existence of optical counterpart of WSL has been discussed theoretically [8] and various photonic systems have been proposed and studied experimentally to observe Bloch oscillations of light [9]. However, the observation of Bloch oscillations of optical waves resolved in time remained an issue until recently. Optical superlattices, which are the photonic analogue of semiconductor superlattice structures, were proposed as potentially ideal systems to observe them [10]. The role of the electric field here is played by the optical path gradient along the multilayer growth direction.

In this work we report on the experimental observation of time resolved optical Bloch oscillations (oBO) [11]. This observation was performed in ultrashort pulse time-resolved transmission experiments on optical superlattices, made of porous silicon (PS).

2 Experimental results

2.1 Optical superlattice design

A one dimensional optical superlattice structure can be realized by stacking two PS dielectric layers A and B with different refractive indices in a way to form identical cavities separated by Bragg reflectors. Therefore, they are essentially coupled microcavity structures (CMC) [12]. In these structures the optical coupling between the microcavities is tuned by changing the reflectivity of the Bragg reflectors and causes the formation of extended photonic states, in analogy to the electronic coupling of separate quantum wells in a semiconductor superlattice. Figure 1a shows the electric field intensity distribution inside a CMC system calculated using the standard transfer matrix calculations.

To obtain optical Bloch oscillations (oBO) one has to introduce a gradient in the optical thickness of the layers. This gradient will result in a spatial tilting of the miniband (Fig. 1b) and formation of an optical Wannier-Stark ladder (oWSL). The latter is expected to be observed as a series of narrow equidistant transmission peaks with the frequency separation of the peaks that defines the period T_B of the oBO. The linear change of the optical thickness introduces, to first order, a linear tilt of the miniband [13].

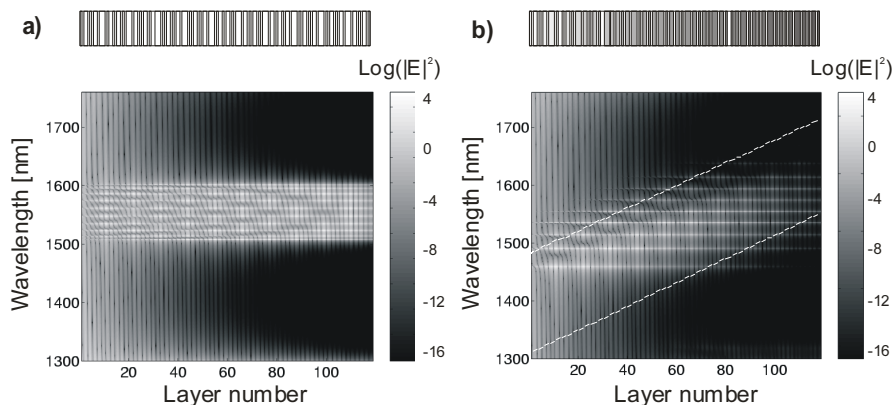


Fig. 1 Scattering state calculation of the distribution of the energy spectrum inside the multilayer. The parameters used in the calculations correspond to samples used in the actual spectrum. Panel a) flat band situation, $\Delta\delta = 0\%$. Panel b) tilted band situation, $\Delta\delta = 14\%$. The dashed lines indicate the theoretical tilting of the miniband. Above each panel the coupled microcavity structure is schematically shown; the grey scale refers to the refractive index variation along the depth in the sample (the darker the larger n).

2.2 Sample preparation

We have grown the optical superlattices by controlled electrochemical etching of heavily doped p-type (100)-oriented Silicon. The structures had the following section $BABABABAB (AA)_1 BABABABAB (AA)_2 \dots (AA)_{10} BABABABAB$, where $m=10$ cavities $(AA)_m$ are coupled through the $BABABABAB$ Bragg reflectors. The refractive indices of layers A and B were defined to be $n_A=1.4$ and $n_B=2.1$. The physical thickness of each layer was chosen such that the optical thickness $\delta \equiv n \times d$, with n the refractive index and d the physical layer thickness, was equal to $\lambda_0/4$ (λ_0 is the central wavelength).

The structures were made free-standing by applying an anodic electropolishing current pulse at the end of the growth, which detached the structures from the substrate [12]. The availability of free standing samples is essential to maintain almost excellent control over the growth parameters and further simplified time resolved transmission measurements with no contribution from the silicon substrate. Particular care was taken to control the anodization conditions which might drift as the total sample thickness increases. The exchange of the electrolyte was improved via etch stops applied after each layer growth and the use of a magnetic stirrer. Moreover, the natural refractive index drift was compensated by changing the etching times of the layers. The process is known to provide excellent control over the layer properties allowing the growth of single microcavities with quality factors of more than 3300 (see, e.g. [12]).

The one dimensional translational symmetry of the system was broken by introducing a gradient in the optical thickness of the layers. This was achieved by changing the duration of the etch stop current, which controlled the refractive index and hence the variation $\Delta\delta$ in the optical thickness of each layer. We produced samples with gradient values in the range from $\Delta\delta = 2$ to 14 %, values that were extracted from the best fit parameters to the transmission spectra.

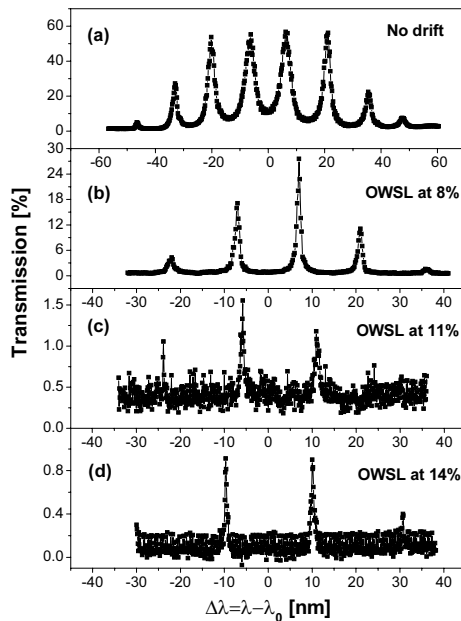


Fig. 2 Transmission spectra of the CMC structures with different gradients of the optical thickness of the layers ($\lambda_0=1.55 \mu\text{m}$ is the central wavelength). Spectrum (a) corresponds to non drifted sample (spatially flat miniband), while (b), (c), (d) show the occurrence of the optical Wannier-Stark ladder with equidistant resonances: the energy separation of the states increases with the increase of the miniband tilt.

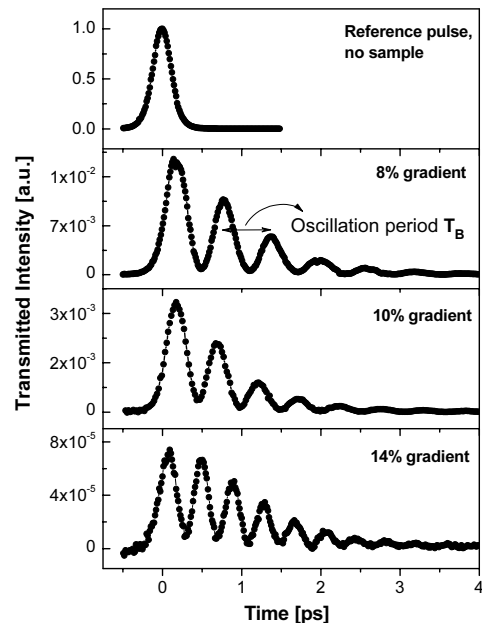


Fig. 3 Temporal response of the system for various values of the optical path gradient $\Delta\delta$. The period of the oscillations and the total transmission decrease while increasing $\Delta\delta$. The top panel shows the undisturbed probe pulse without sample.

In Fig. 2 the transmission spectra of CMC structures with different gradients of the optical thickness are shown. The top panel represents the miniband structure of a non-drifted sample (Fig. 2a). An increase in the drift over a certain value (see the next subsection) results in the occurrence of oWSL: the bigger is the drift value, the larger is the energy separation of the Wannier-Stark states. The resonances become thinner and less intense for the large drift values (Figs. 2b,c,d). This fact is the clear signature of the more and more tilted miniband, which also means higher tunnelling barrier for photons to escape and be transmitted.

2.3 Time-resolved transmission measurements

Time-resolved transmission experiments were carried out using an optical gating technique. This involves mixing a reference beam together with the transmitted signal in a 0.3 mm thick non-linear crystal (β -BBO, β -Barium Borate) to produce a sum frequency signal. The probe beam is obtained from an optical parametric oscillator (OPAL) pumped by a Ti:sapphire laser at center wavelength 810 nm (pulse duration 130 fs, average power 2.0 W, repetition rate 82 MHz) yielding short pulses tunable from 1300 to 1600 nm wavelength (average power 100 mW). The reference pulse at 810 nm wavelength is obtained from the residual Ti:sapphire beam (450 mW average power). The sum frequency signal is detected by a photodiode and a standard lock-in technique is used to suppress noise. A delay line in the reference beam allows to tune the time delay between signal and reference and thus to scan the signal pulse in time.

In the top panel of Fig. 3 we plot the system response without sample from which we determine that the temporal resolution of our system is smaller than 250 fs. The apparatus is designed such that the transmission spectrum of the sample can be monitored during the time-resolved measurement by sampling the transmitted light.

From the time-resolved data we have observed that oscillations occur in transmission, with a period T_B that decreases as $\Delta\delta$ increases (Fig. 3). Both our calculations and experiment show that the optical WSL in our structures is formed above a threshold of gradient ($\sim 7\%$). Optical thickness gradient values below 7% are not sufficient to fully tilt the miniband within the sample thickness. One can see that the transmitted intensity decreases as the gradient increases, which is due to the increased tunnelling barrier for an oscillating photon, as a result of an increased tilt of the photonic miniband (Fig. 1b). In Fig. 4 the measured periods of the Bloch oscillations are compared to the ones calculated through transfer matrix. The experimental data are in excellent agreement with the theoretical prediction. Below the critical gradient value of 7% the occurring oscillations are due to the reflection of light from the sample boundaries, therefore changing the gradient in this range does not influence the oscillation period. At larger values of gradient the oBO period decreases linearly with the increase in the miniband tilt, as expected for Bloch oscillations.

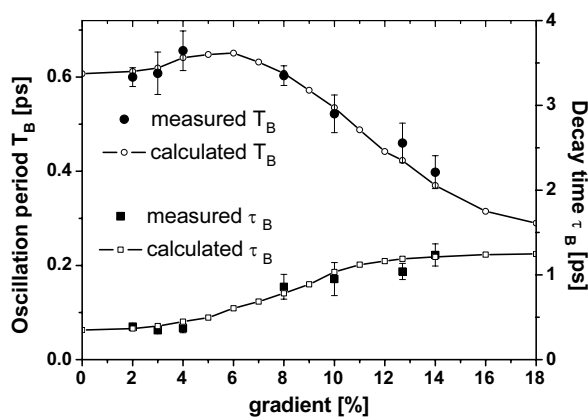


Fig. 4 Experimentally observed oscillation period T_B and decay time τ_B as a function of the gradient $\Delta\delta$. The error bars are the standard deviations obtained from various measurements on several positions on the sample and represent therefore the effect of lateral sample inhomogeneities. The solid lines are the predicted from transfer matrix calculations behaviors of T_B and τ_B .

The oBO decay with a characteristic time τ_b which saturates at large gradients. This is a sign of the increased confinement of the optical modes in the WSL: as the energy band tilt gets steeper and steeper, tunnelling out of the sample becomes more and more difficult, and the transmission losses decrease accordingly. These intrinsic losses are not the only one present in the structure, as light in PS suffers also from external losses. At large gradient values τ_b saturates to 1.26 ps, which is caused by scattering and residual absorption losses in the PS sample. One can consider that $\tau_b^{-1} = \tau_{\text{oBO}}^{-1} + \tau_{\text{ext}}^{-1}$, where τ_{oBO} is the intrinsic decay time of the Bloch oscillation and τ_{ext} is due to absorption and scattering losses. The solid line in Fig. 4 is obtained by taking $\tau_{\text{ext}}=1.3$ ps which corresponds to an extinction coefficient (total losses, absorption + scattering) of $\alpha_{\text{ext}} = 100 \text{ cm}^{-1}$, in agreement with previously determined loss values [12].

3 Conclusions

We have observed the optical counterpart of electronic Bloch oscillations in optical superlattices. A linear variation in the optical constants of the system along the propagation direction allows to form an optical Wannier-Stark ladder and to observe Bloch oscillations of photons resolved in time. Both the oscillation period and the damping time versus the strength of the oWSL are consistent with predictions from transfer matrix calculations. The structures were realized through highly controlled electrochemical etching of silicon. This work demonstrates that PS is a suitable candidate for studying different wave phenomena in one dimensional photonic structures of various design.

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References

- [1] F. Bloch, *Z. Phys.* **52**, 555 (1928); C. Zener, *Proc. R. Soc. A* **145**, 532 (1934).
- [2] A.G. Chynoweth, G.H. Wannier, R.A. Logan, and D.E. Thomas, *Phys. Rev. Lett.* **5**, 57 (1960).
- [3] J. Feldmann, K. Leo, J. Shah, D.A.B. Miller, J.E. Cunningham, S. Schmitt-Rink, T. Meier, G. von Plessen, A. Schulze, and P. Thomas, *Phys. Rev. B* **46**, 7252 (1992); K. Leo, P. Haring Bolivar, F. Brüggemann, R. Schwedler, and K. Köhler, *Solid State Commun.* **84**, 943 (1992); T. Dekorsy, P. Leisching, K. Kohler, and H. Kurz *Phys. Rev. B* **50**, 8106 (1994).
- [4] Y. Kuga and A. Ishimaru, *J. Opt. Soc. Am. A* **8**, 831 (1984); M.P. van Albada and A. Lagendijk, *Phys. Rev. Lett.* **55**, 2692 (1985); P.E. Wolf and G. Maret, *Phys. Rev. Lett.* **55**, 2696 (1985).
- [5] R. Dalichaouch, J.P. Armstrong, S. Schultz, P.M. Platzman, and S.L. McCall, *Nature* **354**, 53 (1991); D.S. Wiersma, P. Bartolini, A. Lagendijk, and R. Righini, *Nature* **390**, 671 (1997).
- [6] N. Garcia and A.Z. Genack, *Phys. Rev. Lett.* **63**, 1678 (1989); M.P. van Albada, J.F. de Boer, and A. Lagendijk, *Phys. Rev. Lett.* **64**, 2787 (1990).
- [7] F. Scheffold and G. Maret, *Phys. Rev. Lett.* **81**, 5800 (1998).
- [8] G. Monsivais, M. del Castillo-Mussot, and F. Claro, *Phys. Rev. Lett.* **64**, 1433 (1990).
- [9] G. Lenz, I. Talanina, and C. Martijn de Sterke, *Phys. Rev. Lett.* **83**, 963 (1999); A. Kavokin, G. Malpuech, A. Di Carlo, P. Lugli, and F. Rossi, *Phys. Rev. B* **61**, 4413 (2000); P. Wilkinson, *Phys. Rev. E* **65**, 56616 (2002); T. Pertsch, P. Dannberg, W. Elflein, A. Brauer, and F. Lederer, *Phys. Rev. Lett.* **83**, 4752 (1999); R. Morandotti, U. Peschel, and J. S. Aitchison, *Phys. Rev. Lett.* **83**, 4756 (1999).
- [10] G. Malpuech, A. Kavokin, G. Panzarini, and A. Di Carlo, *Phys. Rev. B* **63**, 035108 (2001).
- [11] R. Sapienza, P. Costantino, D.S. Wiersma, M. Ghulinyan, C.J. Oton, and L. Pavesi, *Phys. Rev. Lett.* **91**, 263902 (2003).
- [12] M. Ghulinyan, C. J. Oton, G. Bonetti, Z. Gaburro, and L. Pavesi, *J. Appl. Phys.* **93**, 9724 (2003).
- [13] Let us consider the flat bandedge energy, $E_0 \sim 1/\lambda_0$ and the tilted bandedge one, $E \sim 1/\lambda$, where $\lambda = \lambda_0(1 + \Delta\delta)$, with $\Delta\delta$ the optical path gradient. Then for the ratio $\Delta E/E$ (where $\Delta E = E - E_0$) one can write $\Delta E/E = 1/(1 + \Delta\delta) - 1$, which describes a linear tilt.