Zener tunneling of light in an optical superlattice

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ABSTRACT

We report on the observation of resonant Zener tunnelling of light waves in an optical superlattice. The one dimensional (1D) structures are made in free-standing porous silicon and are designed specifically to exhibit two photonic minibands. A controlled optical path gradient has been maintained over the sample thickness which resulted in tilting of photonic minibands and formation of optical Wannier-Stark ladders. At a certain value of optical gradient the two minibands couple within the extension of the structure and a resonant tunnelling channel through the superlattice forms, resulting in a very high transmission peak. Ultrafast time resolved transmission experiments were performed: excitation of the Wannier-Stark states causes the appearance of photonic Bloch oscillations, which are strongly damped when Zener tunneling modes are excited. The observed phenomenon is the optical analogue of resonant Zener tunnelling in an electronic superlattice.

INTRODUCTION

The electrical charge transport phenomena in solids lay in the basics of functionality of semiconductor electrical devices. Among the various transport phenomena the electrical Zener breakdown of solids has been one of the most intriguing topics. Originally formulated by Zener in 1934 [1], the problem suggests that at high electric fields a quantum particle in a crystal can be accelerated to higher energy bands without extra energy by simply tunnelling through the forbidden energy region. This theory predicts a tunnelling event of a particle into a continuum of states of the other energy band and is known in the literature as *non-resonant* Zener tunnelling. On the other hand, *resonant* tunnelling of charge carriers can be realized between Wannier-Stark ladders (WSL) of different energy bands [2]. A WSL is formed in the energy spectrum of particles as a set of equidistant states when electric field is applied to a crystal. These are not stationary states and, therefore, are *localized* in space. The experimental proof of Zener tunnelling phenomena was delayed for several decades, because of the experimental difficulties arising with the very high electric fields needed to tilt enough energy bands of usual crystals.

Resonant Zener tunnelling was observed for the first time in electronic superlattices [3]. The typical bandwidth in a superlattice is in the order of some 100 meV therefore the observation of Zener tunnelling between energy minibands is possible at much lower electric fields. Since the invention of superlattices [4] an intensive research has been carried out for observing WSLs [5] and Zener breakdown [6, 7].

The analogies between transport phenomena of electrons in semiconductors and light propagation in complex photonic structures are established by the researchers [8]. Very recently 1D optical superlattices were realized, where the formation of optical WSLs and time-resolved photonic Bloch oscillations where demonstrated [9]. In these structures the constant optical path gradient, $\Delta\delta$, along the 1D, plays the role of electric field which tilts the photonic bands.

In this paper we report on the observation of *resonant Zener tunnelling* both in static and time-resolved transmission measurements. The experiments have been carried out on specifically designed optical superlattices, in which two photonic minibands are formed.

EXPERIMENT

A 1D optical superlattice is realized by stacking two quaterwave-thick dielectric layers, call A and B, with refractive indices n_A and n_B and physical thickness d_A and d_B, in such a way that identical cavities separated by Bragg reflectors are formed. This is essentially a coupled microcavity structure (CMC) [10] centered at $\lambda_c = 4n_A \times d_A = 4n_B \times d_B$, in which the degeneracy of the cavity modes splits up and a photonic miniband is formed in the stop band region of the spectrum. In order to build a superlattice that exhibits two minibands, one should couple within the same structure two sets of cavities of C and D type, which are centered at different wavelengths λ_1 and λ_2, respectively. The corresponding structure will have the following sequence of layers: BABABAB $(CC)_1$ BABABAB $(DD)_1 \cdots (CC)_m$ BABABAB $(DD)_m$ BABABAB, where m is the number of cavities of each type[*]. In our experiment we have chosen m=6, $\lambda_1 = 0.81\lambda_c$ and $\lambda_2 = 0.88\lambda_c$.

We have grown the optical superlattices by electrochemical etching of (100)-oriented heavily doped p-type silicon substrates. The growth procedure is detailed elsewhere [9, 10]. The refractive indices were determined to be $n_A = n_C = n_D = 1.5$ and $n_B = 2.12$. The physical thickness of the layers were controlled by adjusting the duration of the etch times. Etch stops were used at the end of the growth of each layer to allow etchant recycling. A negative refractive index gradient, resulting in an optical path gradient, was achieved by changing the duration of the etch stops. We produced samples with controlled gradient values in the range from $\Delta\delta = 0$ to 18%. The superlattice structures were made free-standing by applying an electropolishing current pulse at the end of the growth process.

The light intensity distribution inside this structure in the absence of optical path gradient (Fig. 1a) is calculated by transfer-matrix method [11] and shows the formation of two flat minibands MB1 and MB2 (intense lines, stretching through the sample). These are separated by a photonic minigap (dark region), which is centered at $\lambda_0 = 0.8458\lambda_c = 1560$ nm. The calculated transmission spectrum of the structure (Fig. 1b) is compared with the experimental one (Fig. 1c), measured between 900 to 2000 nm with a spectrophotometer. It is known that porous silicon samples suffer from lateral inhomogeneities due to doping variations of the Si wafers, which lead to wider and less intense spectral features measured with broad beams [10]. For this reason some spectra were measured in a high-resolution transmission setup with a very small numerical aperture (NA~0.0075), where a tunable laser source, focused to a 35 μm spot, was used. In this way, narrow peaks with high intensity can be measured.

An introduction of optical path gradient of ~6.7% tilts the photonic band structure and results in the formation of optical WSLs in both minibands (Fig. 2a). The WSLs appear in the form of equally spaced in frequency and spacially localized states (Fig. 2b). The spatial confinement of localized states causes a decrease of absolute transmission from 50% in the flat band case (delocalized states) down to 2%. Fig. 2c shows the measured transmission spectrum of the superlattice with tilted minibands, where the WSLs can be appreciated.

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[*] Note that C and D are also quaterwave-thick, so that (CC) and (DD) form $\lambda_1/2$ and $\lambda_2/2$ cavities respectively.

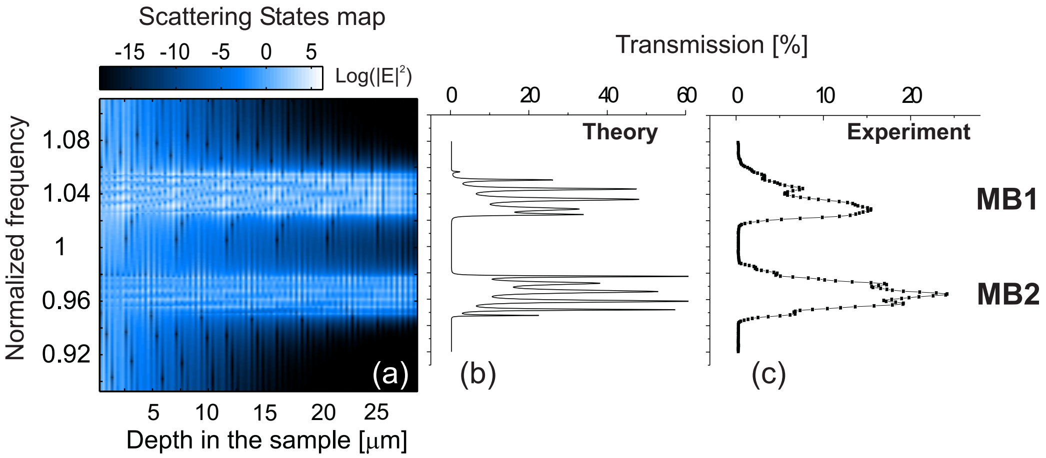

Figure 1. (a) Transfer matrix calculation for the intensity distribution of the light inside the sample. The intensity is plotted as a color scale versus the normalized frequency ω/ω_0, where ω_0 is the minigap central frequency, and depth inside the sample. The flat miniband situation with $\Delta\delta = 0\%$ is considered. Two minibands MB1 and MB2 separated with a minigap region are s seen in the calculated (b) and experimentally measured transmission spectrum (c).

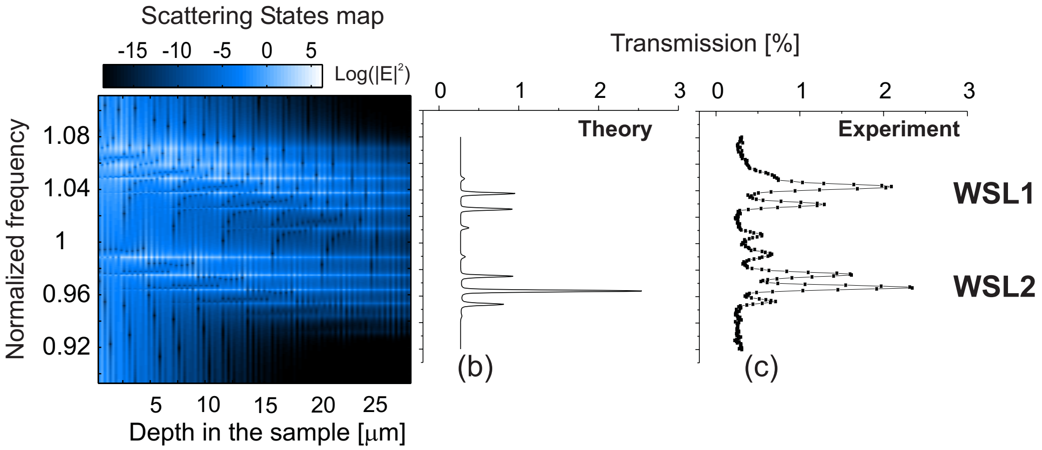

Figure 2. (a) Optical WSLs of localized modes are formed in two minibands at $\Delta\delta = 6.7\%$. Transmission goes down to 2%: theory (b) and experiment (c).

At a critical degree of band tilting ($\Delta\delta$~10.3%) the WSLs in two minibands couple within the extension of the structure. Coupling induced delocalization of two anti-crossing states takes place, which appears as an intense *resonant tunnelling* channel (Fig. 3a). The resonant Zener tunnelling manifests as an enhanced transmission peak peak in both calculated (Fig. 3b) and measured transmission spectra (Fig. 3c).

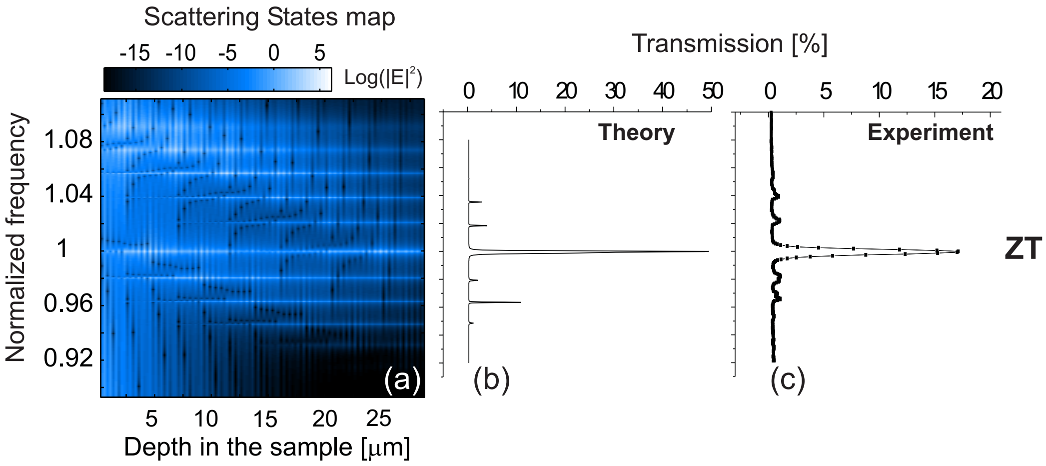

Figure 3. (a) The two WSLs couple at $\Delta\delta = 10.3\%$ and form a resonant tunnelling channel through the sample. Resonant Zener tunnelling is predicted by theory (b) and confirmed experimentally (c) as an enhanced transmission peak in the center of the minigap.

In order to examine Zener tunnelling regime in detail we have grown a superlattice structure with lateral (*in-plain*) variation in $\Delta\delta$ around 10.3%. In this way the system was studied at different values of gradient between 6.5% to 10.7%. High-resolution transmission measurements are performed for this sample. In the vicinity of the threshold gradient the transmission spectrum is very sensitive to small changes of the optical path. In Fig. 4 the calculated transmission values at ω_0 for $\Delta\delta$ in the range $0 \div 25\%$ are compared with the experimental data. The correspondence between the experimental and calculated transmission values is excellent.

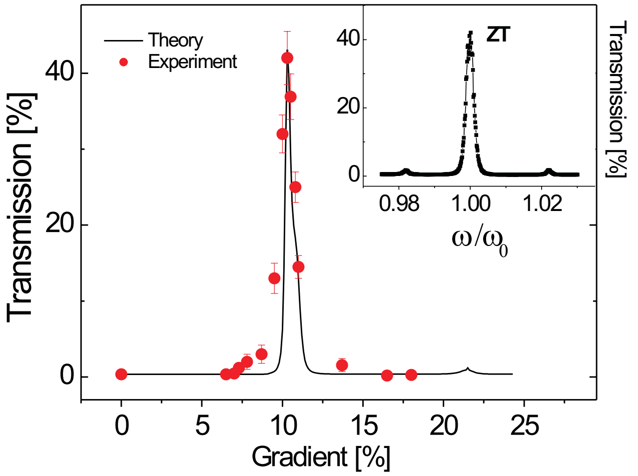

Figure 4. The comparison between the experimental transmission values of the maximum transmission (line) around the central frequency ω_0 as a function of the gradient and the transfer matrix calculations (dots). The inset shows the transmission spectrum of the tilted superlattice around the value of the optical path gradient where the first anti-crossing of the optical Wannier-Stark ladders and hence Zener tunnelling occurs.

The inset in Fig. 4 reports an example of highly resolved transmission spectrum in the Zener tunnelling condition with a 42% transmission peak. The analysis of spectra around the Zener tunnelling regime show that, together with the increase of the transmission value, the resonant transmission peak gets wider.

We have looked at the time response of our optical superlattice performing ultrashort pulse propagation in the Zener tunneling regime. An optical gating technique based on signal upconversion was used, which is detailed in [9]. Infrared tunable pulses between 1400 and 1600nm (230 fs duration, bandwidth about 14 nm, average power 100 mW) were sent to the sample. The transmitted pulses were mixed in a non-linear BBO (beta barium borate) crystal with a reference pulse. The sum frequency signal was selected with a prism and detected with a photodiode.

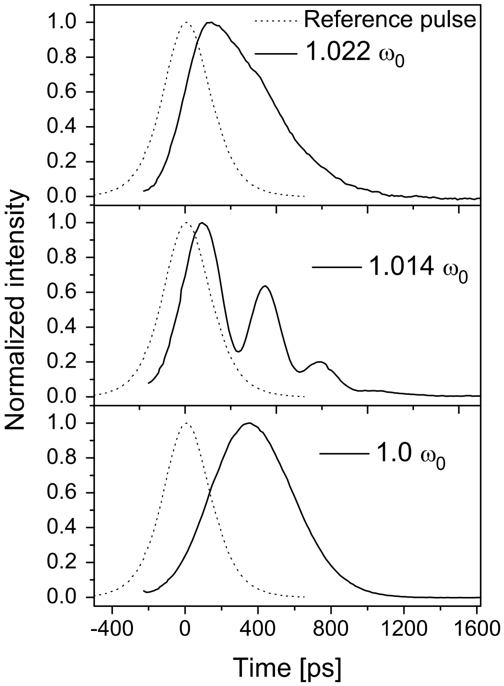

Figure 5. Time-resolved transmitted signals from a double miniband superlattice with optical path gradient in the Zener tunnelling regime. The panels (a), (b), and (c) correspond to different probe wavelengths. (a) A excited single resonance shows a characteristic exponential decay whereas (b) damped Bloch oscillations are observed when exciting two Wannier-Stark resonances. In (c) the Zener tunnelling peak is excited leading to a strongly delayed but nearly symmetric transmitted pulse. The dotted curves refer to the transmission in the absence of a sample.

Figure 5 shows three examples of transmitted pulses centered at different wavelengths. A reference pulse is plotted in dotted line for comparison. When a single Wannier-Stark state is excited (Fig. 5a), the transmitted signal intensity decays exponentially, which is the characteristic behavior of a localized state. The delay of the pulse, defined as the delay of the center of the mass of pulse profile, as expected, is not big, because the light propagates only a short region inside the sample, where the resonance is confined. When the incident pulse excites two resonances, a complex signal oscillating with a period of 200fs, determined by the frequency separation of the excited states, is observed (Fig. 5b). These are the well known photonic Bloch oscillations. In our specific case, these oscillations are damped because of the presence of a loss channel, i.e. the delocalized state showing resonant Zener tunnelling. Finally, Fig. 5c shows the time response of the peak with enhanced transmission at 1560nm. The observed picture is consistent with a double resonance transport behavior. The transmitted pulse has become nearly symmetric and shows a delay of about 500fs. This big delay is now defined by the time needed to build the separate coupled modes of the double resonance. On the other hand, the observed fast decay is understood in terms of good coupling of the resonant tunnelling channel with the outside.

In conclusion we have reported the optical analogue of resonant Zener tunnelling. The observation has been performed via spectral and time-resolved transmission measurements on specifically designed optical superlattices which exhibit two minibands. A controlled optical path gradient along the light propagation direction in the superlattice was used to tilt the photonic band structure. At a critical gradient value, coupling of photonic minibands occurs resulting in delocalization of the optical Wannier-Stark states and consequently Zener tunnelling of the light waves. In this condition enhanced transmission, damped photonic Bloch oscillations, and characteristic propagation dynamics are all observed.

We wish to thank J.H. Korsch for pointing out the problem and Riccardo Sapienza, Paola Costantino, and Stefano Gottardo for help with the time-resolved experiments. This work was financially supported by the INFM FIRB and RANDS projects.

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