Analogo ottico di effetti quantistici in elettronica

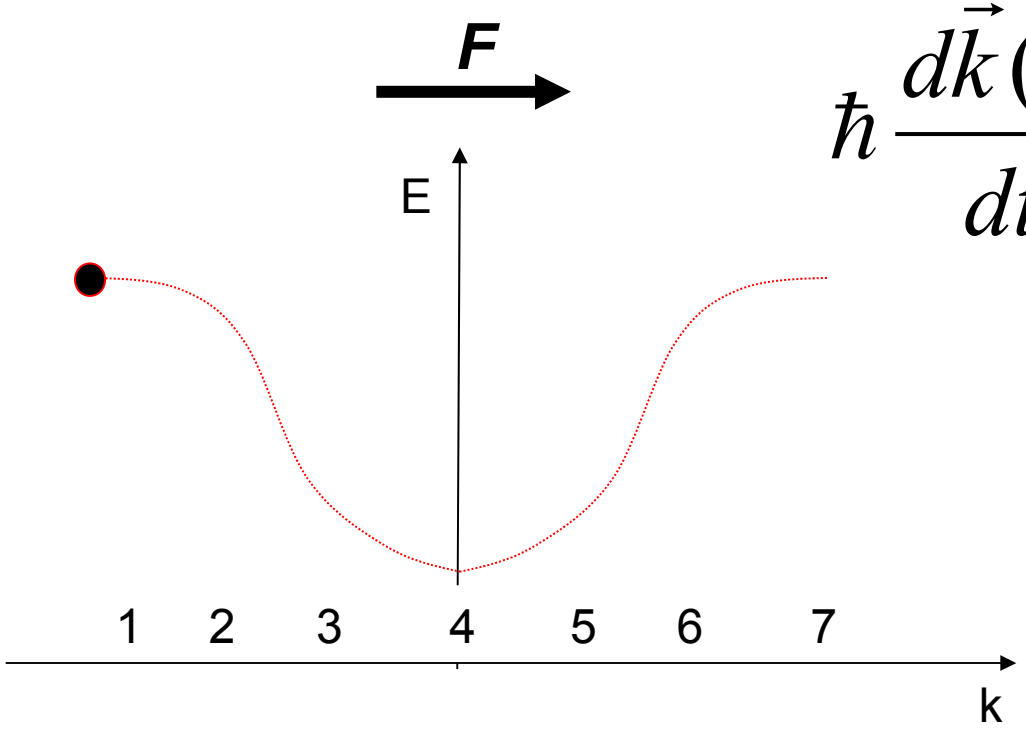
Photonics ⟷ Electronics

- OPTICAL BLOCH OSCILLATION
- OPTICAL ZENER TUNNEL

Oscillazioni di Bloch elettroniche

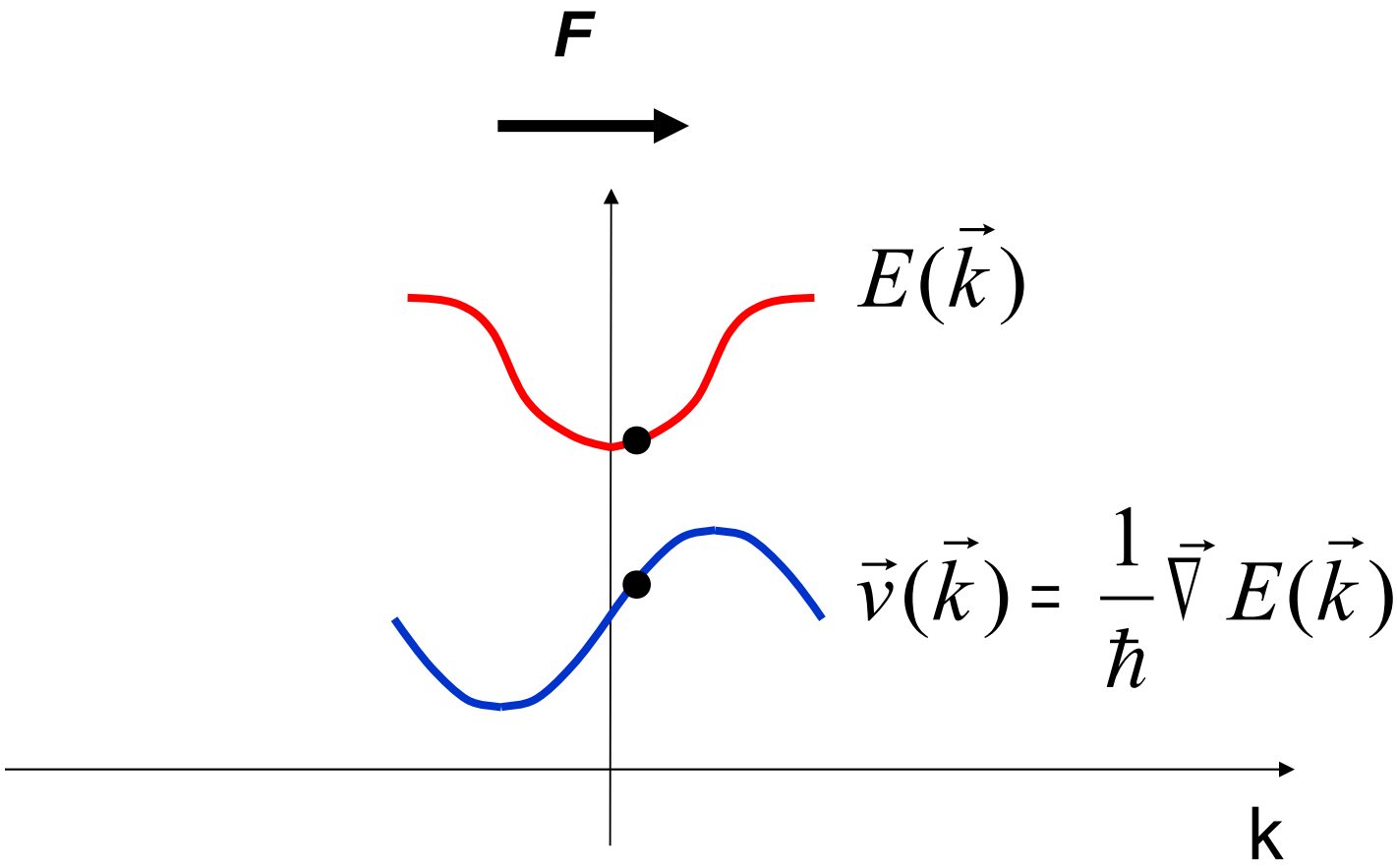
Moto in presenza di una forza esterna

Oscillazioni di Bloch: lo stato cambia in modo periodico



$$\hbar \frac{d\vec{k}(t)}{dt} = \vec{F}$$

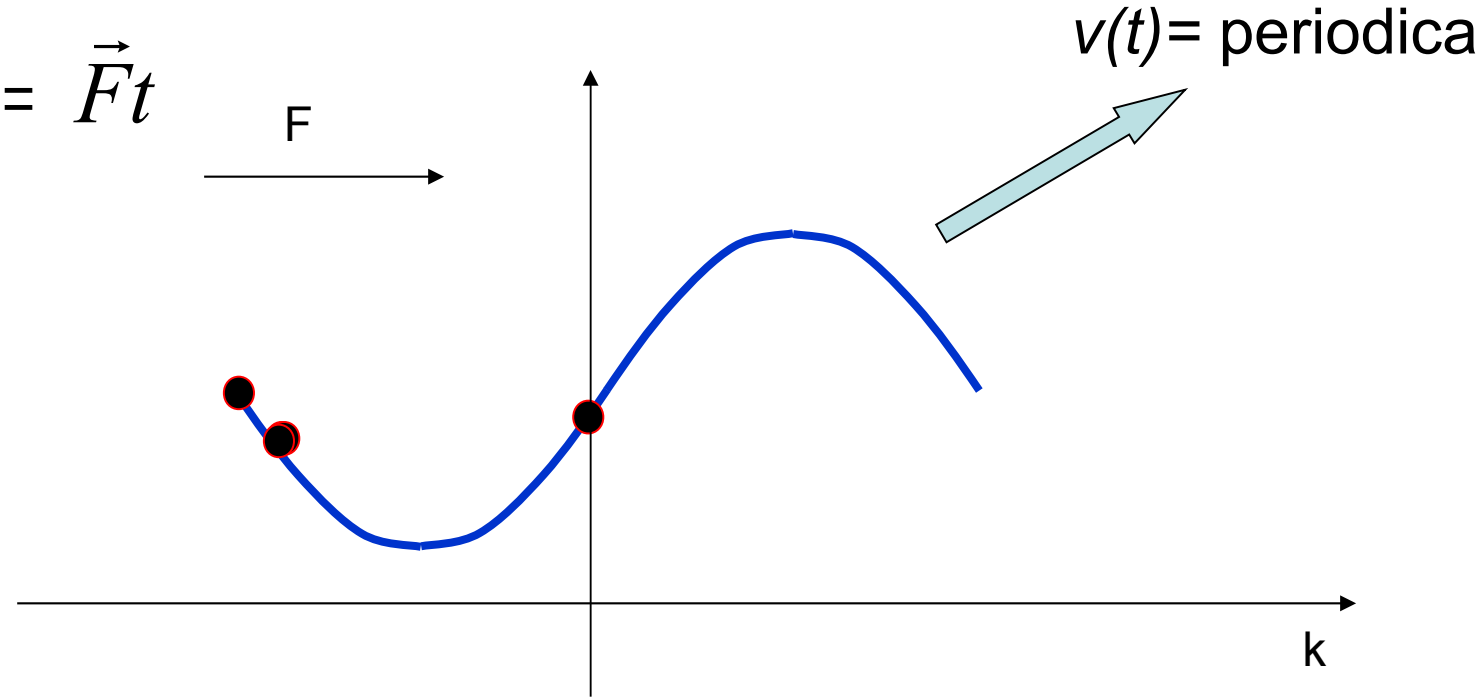
Cosa succede al moto reale dell'elettrone



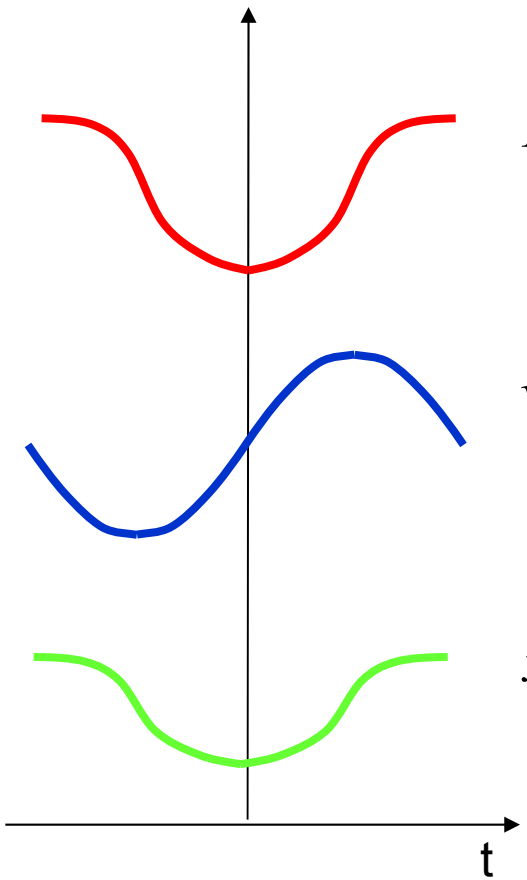
Moto dell'elettrone

$$\vec{v}(\vec{k}) = \frac{1}{\hbar}\vec{\nabla} E(\vec{k})$$

$$\vec{k}(t) = \vec{F}t$$



Moto elettrone



$$k(t) = \frac{F}{\hbar} t$$

$$E(t) = E_0 - \frac{W}{2} \cos\left(\frac{Fa}{\hbar} t \right)$$

$$v(t) = \frac{Wa}{2\hbar} \sin\left(\frac{Fa}{\hbar} t \right)$$

$$x(t) = x(0) + \frac{W}{2F} \left(1 - \cos\left(\frac{Fa}{\hbar} t \right) \right)$$

$$\boxed{\Delta x = \frac{W}{F}}$$

Valori numerici

$FT_B = \hbar 2\pi/a$ $\quad$ $T_B = \hbar 2\pi/(aF)$ $\quad$ $F = eE$

$E = 1000V/1mm = 10^6 V/m$

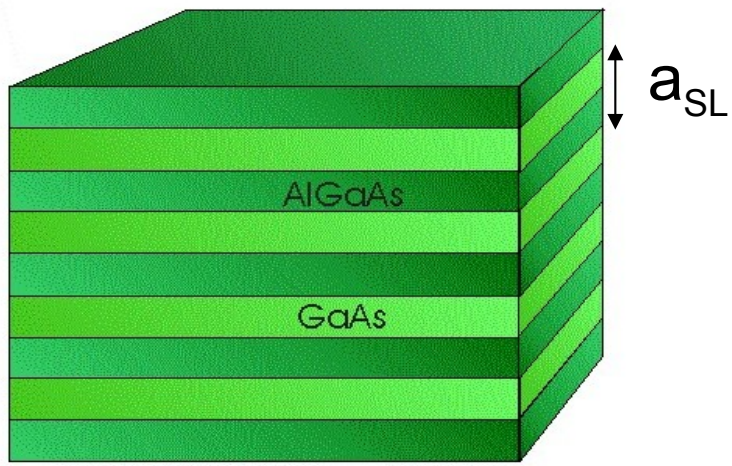
$T_B = (6.6\ 10^{-34} / (1.6\ 10^{-19}\ 10^6 0.5\ 10^{-9}))\ sec = 8\ 10^{-12}\ sec$

$\tau_C = 10^{-13}\ sec$

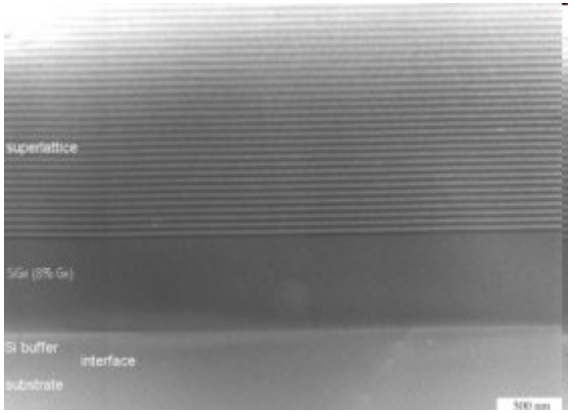
$E > 8 10^7 V/m$

$a > 40\ nm$

Sperimentalmente è stato visto in super reticoli
spontaneous current oscillations



A Superlattice Structure



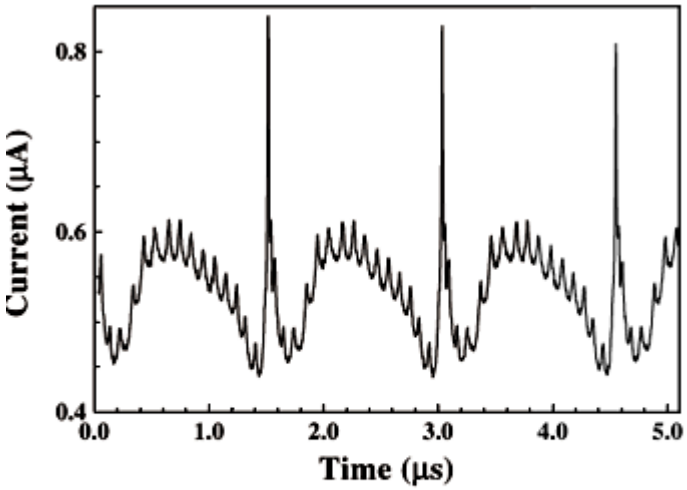
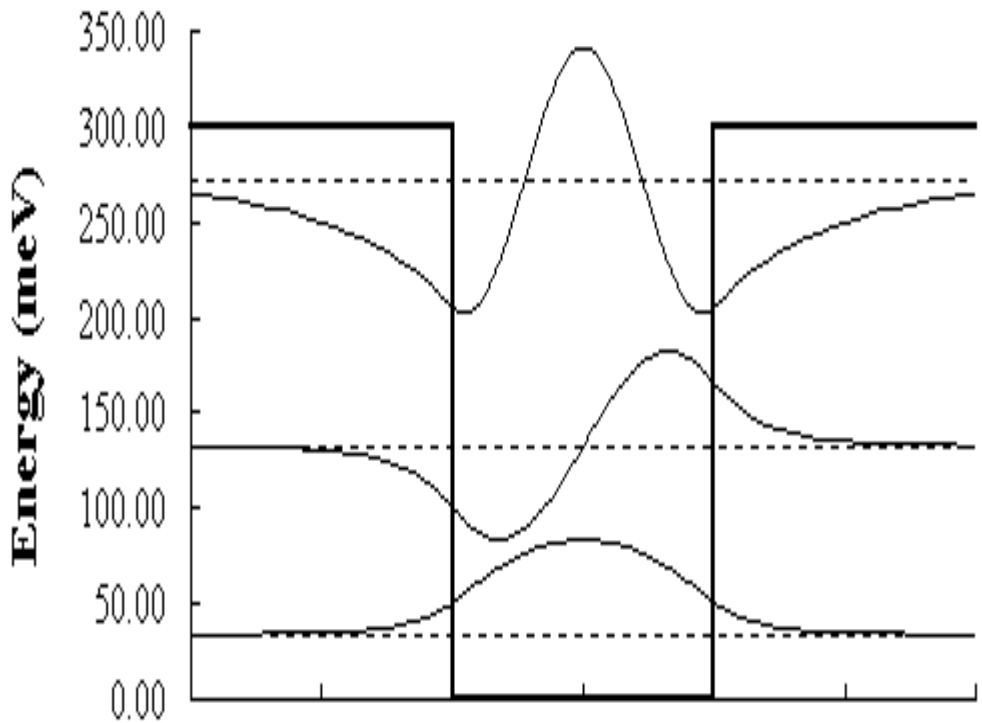
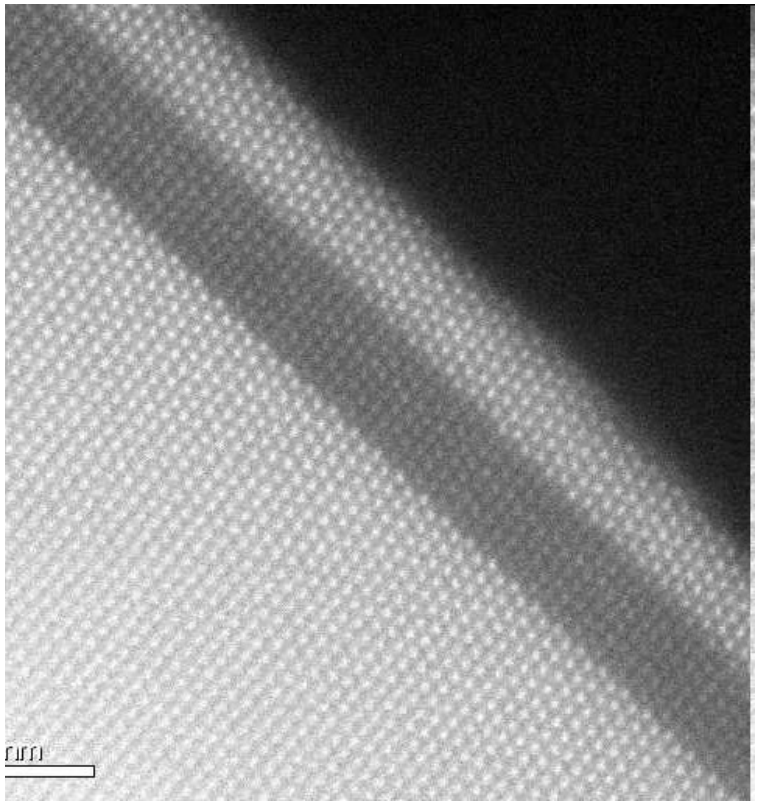


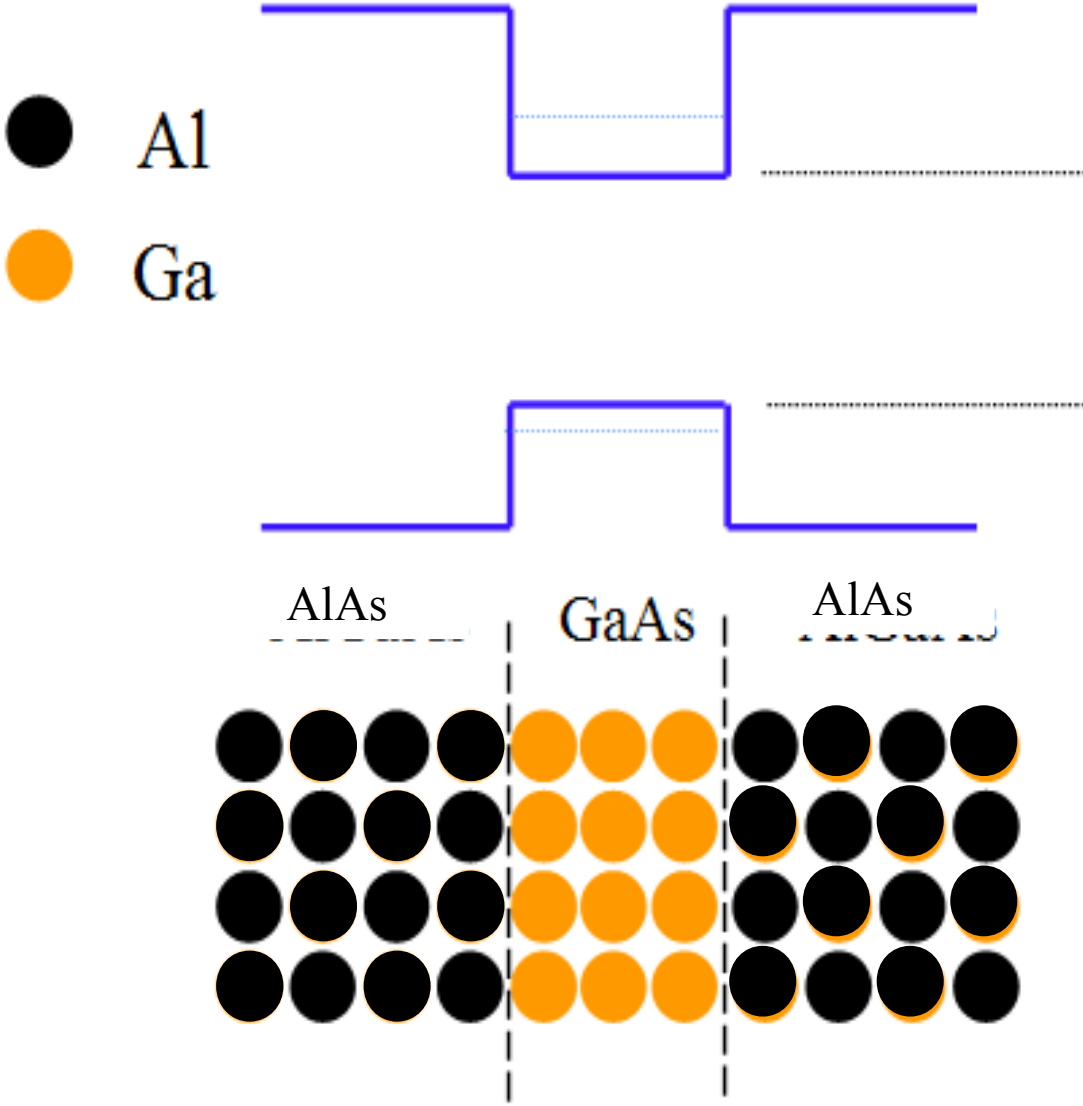
Figure 2. Spontaneous current oscillations in a doped SL with 40 periods, 9.0 nm GaAs wells, and 4.0 nm AlAs barriers for an applied voltage of 2.77 V and a temperature of 6 K. There are 16 spikes in a single period of the 0.65 MHz oscillations.

Quantum well

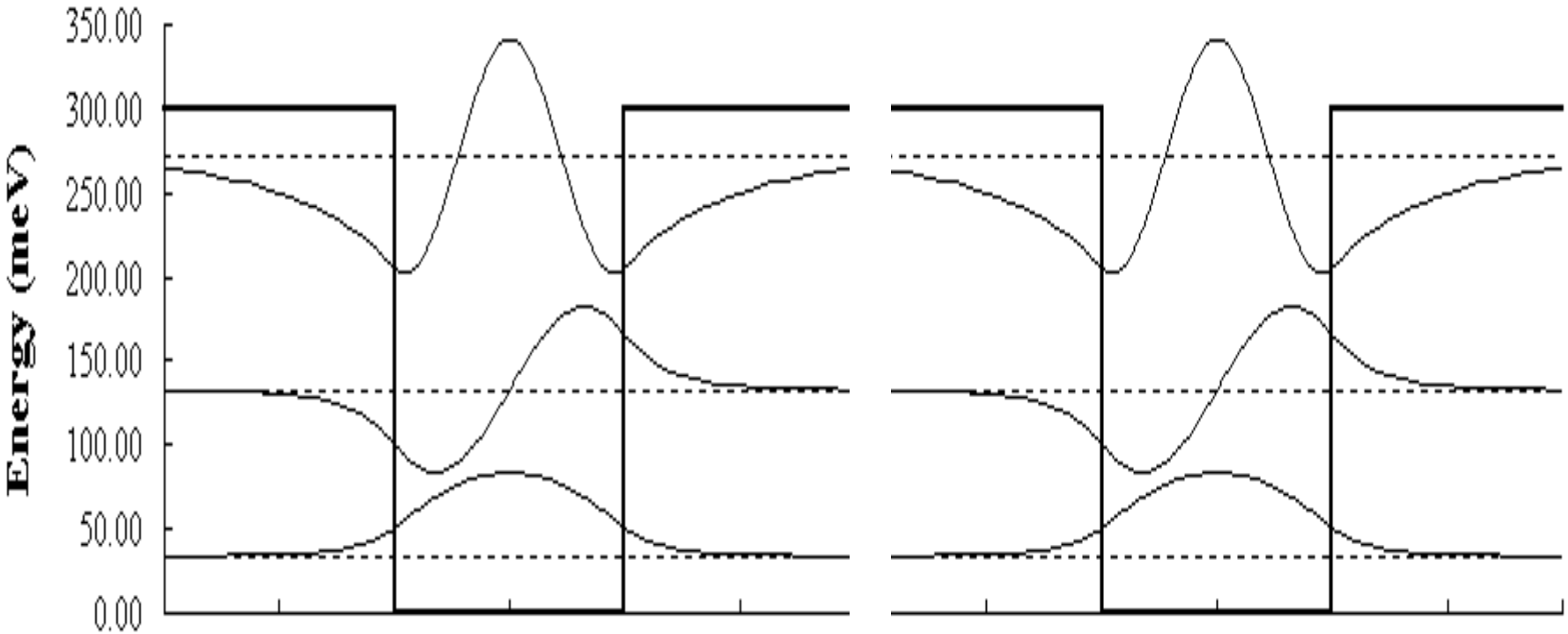


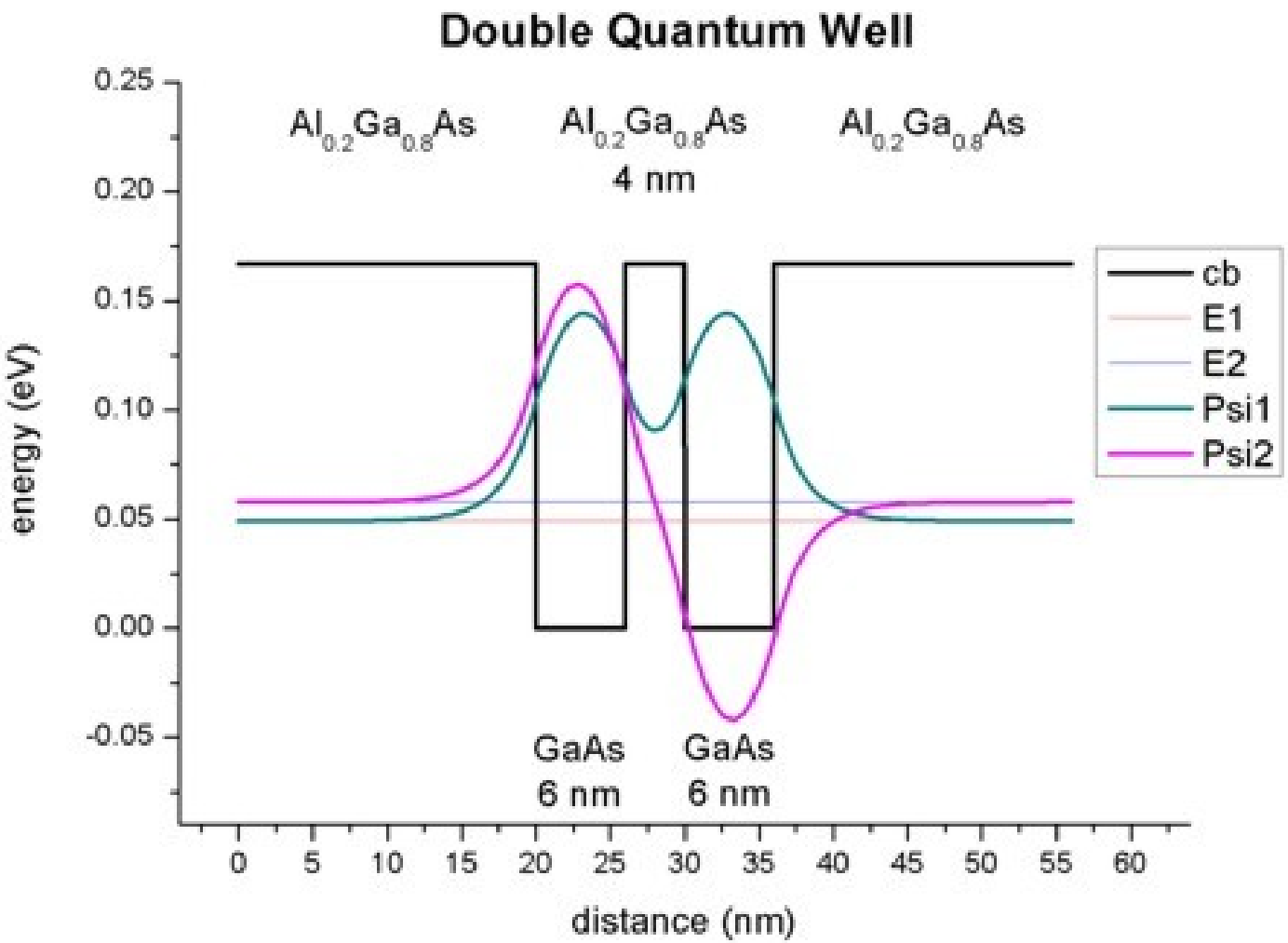
Quantum Well



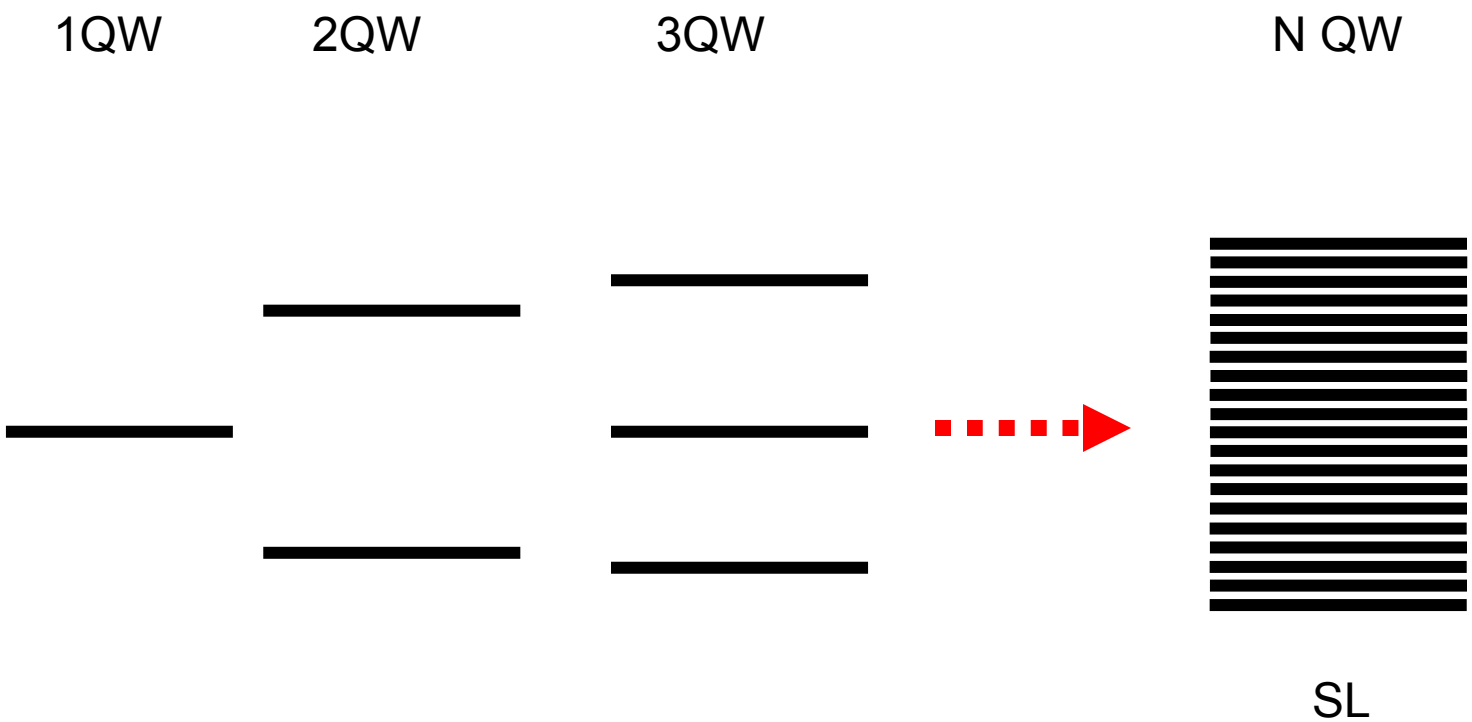


2 Quantum wells

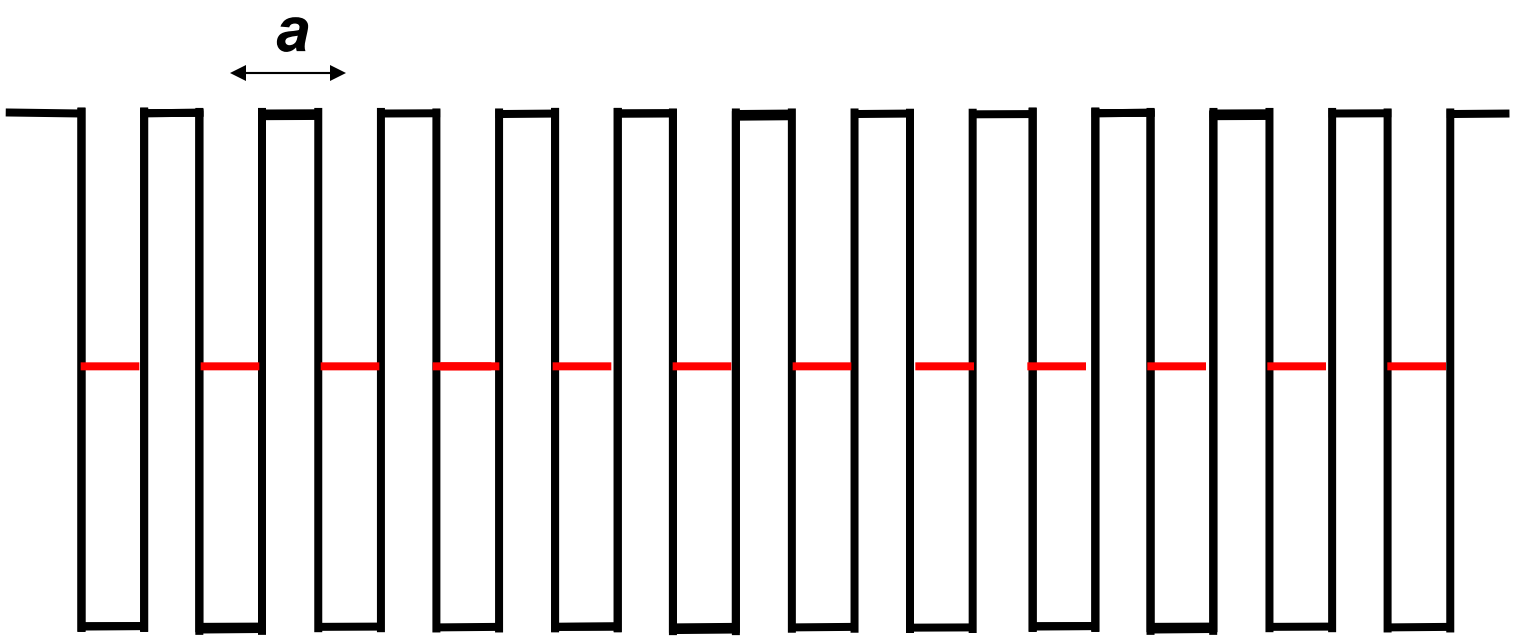



Double Quantum Well
Al0.2Ga0.8As
Al0.2Ga0.8As
4 nm
Al0.2Ga0.8As
GaAs
6 nm
GaAs
6 nm
cb
E1
E2
Psi1
Psi2
energy (eV)
distance (nm)
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
0
5
10
15
20
25
30
35
40
45
50
55
60

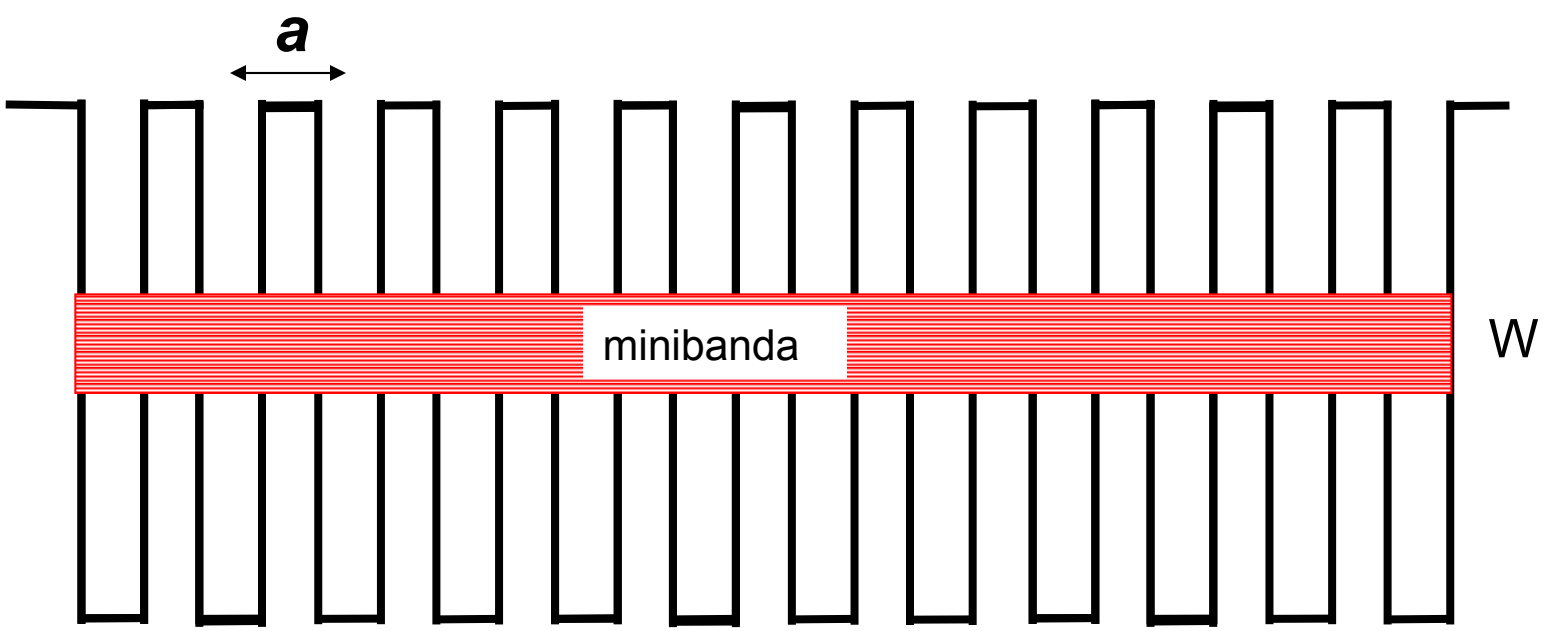
N Quantum wells



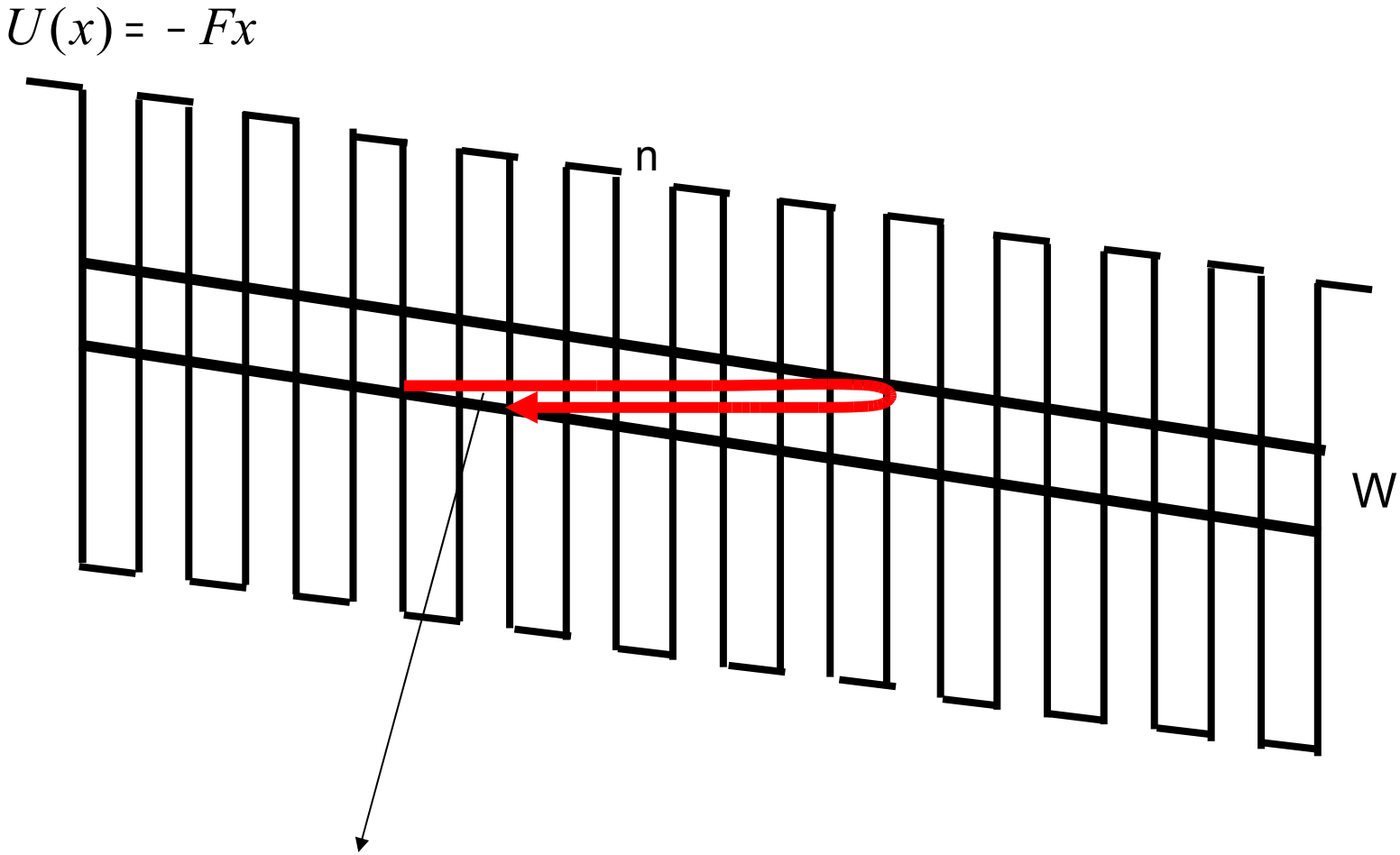
Superreticolo



Superreticolo



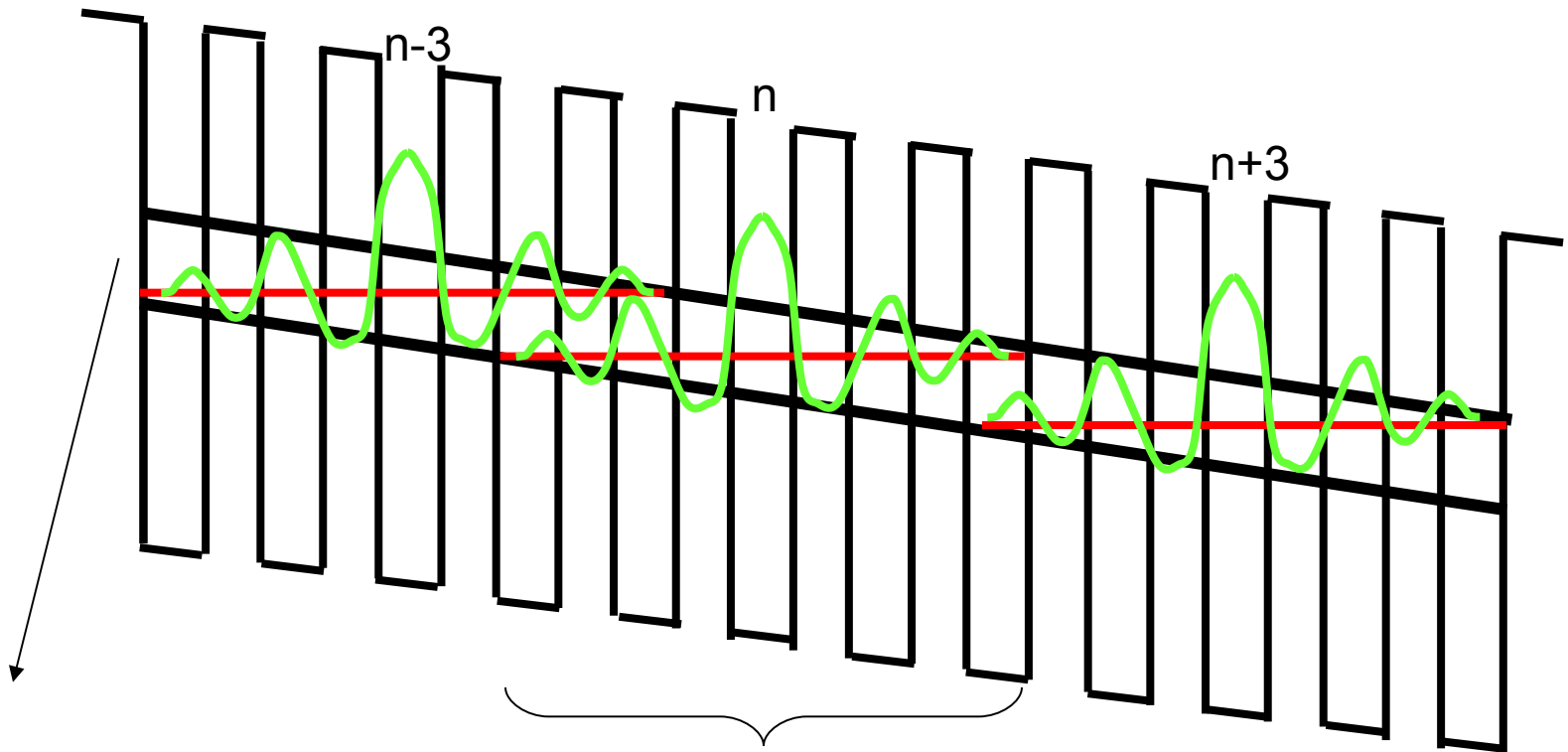
Superreticolo in campo elettrico



Onda elettronica non si propaga su tutto il reticolo
ma viene riflessa dal bordo della minibanda

Superreticolo in campo elettrico

$$U(x) = -Fx$$



Wannier-Stark Ladders

$$\Delta x = \frac{W}{F}$$

$$\Delta E = Fa \quad \Rightarrow \quad \hbar\omega_B = \Delta E \quad \Rightarrow \quad T_B = 2\pi / \omega_B = 2\pi\hbar / Fa$$

BLOCH OSCILLATION

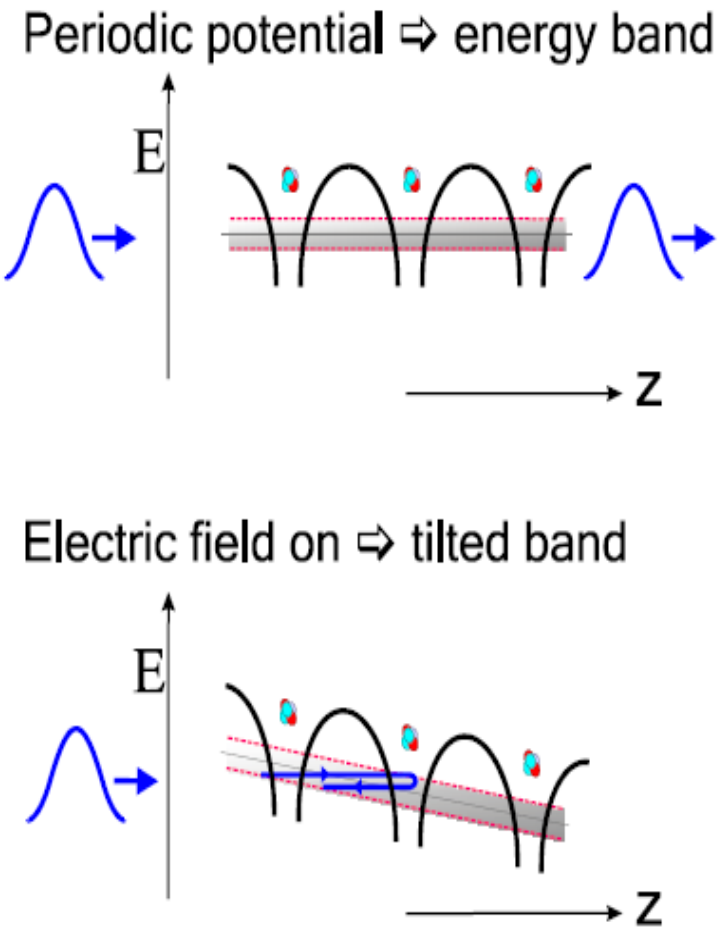
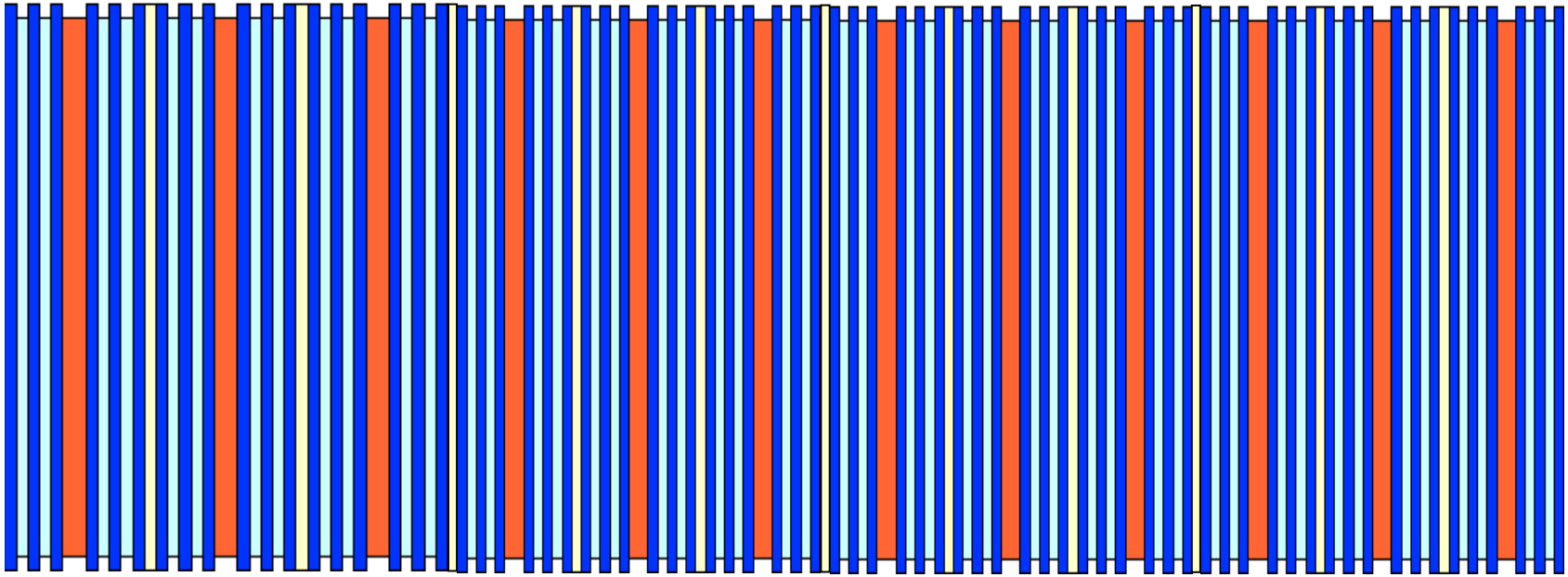


Figure 6.16: Sketch of the electron motion in absence and presence of an external DC electric field.

Minibanda ottica: MC accoppiate



Porous Si

1 MC

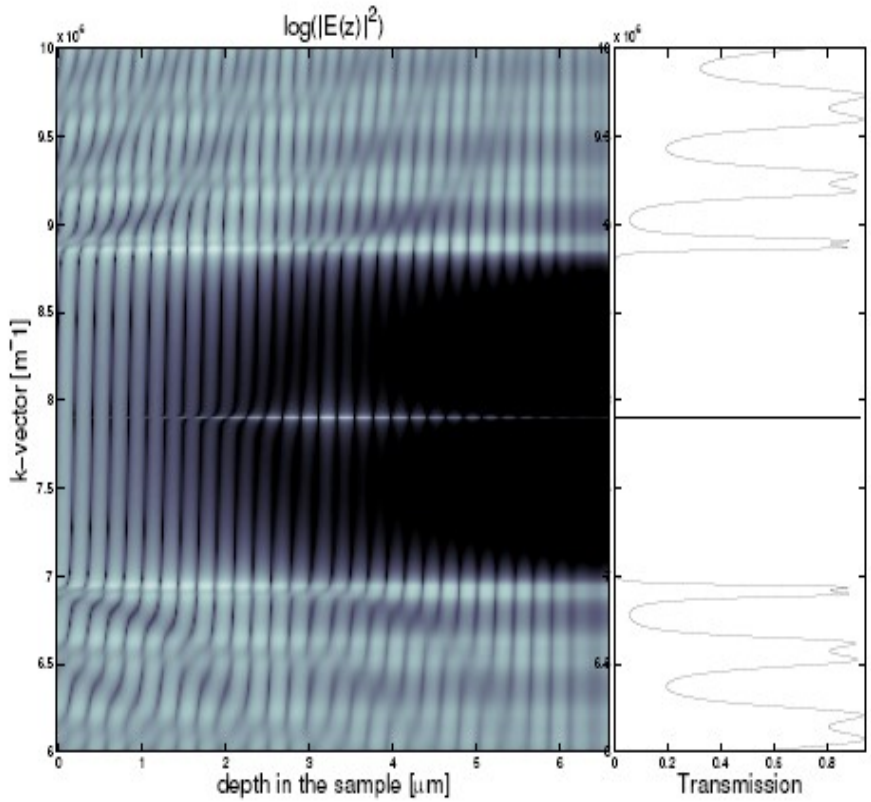


Figure 6.10: (left panel) Scattering state map of a single microcavity made of an extra A layer, surrounded by two Bragg mirrors made of 30 periods AB. Darker areas have a lower intensity. In the middle of the bandgap, the single microcavity is visible. (right panel) The transmissivity of the structure. The two refractive indices are $A = 1.58$ and $B = 2.21$ and the central wavelength is $\lambda = 800$ nm.

2 MC

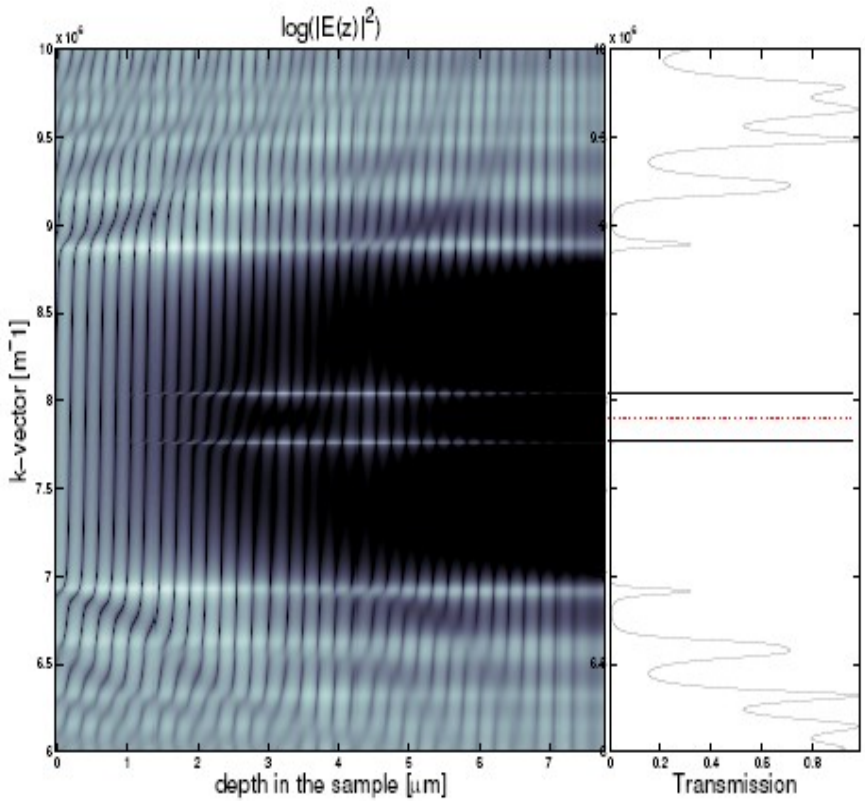


Figure 6.12: (left panel) Scattering state map of a two coupled microcavity whose structure is $dbr\ dbr\ dbr\ A\ dbr\ A\ dbr\ dbr\ dbr$. Darker areas have a lower intensity. In the middle of the bandgap the two splitted resonance frequencies are visible. (right panel) The transmissivity of the structure. The two refractive indexes are $A = 1.58$ and $B = 2.21$ and the central wavelength is $\lambda = 800$ nm.

N MC

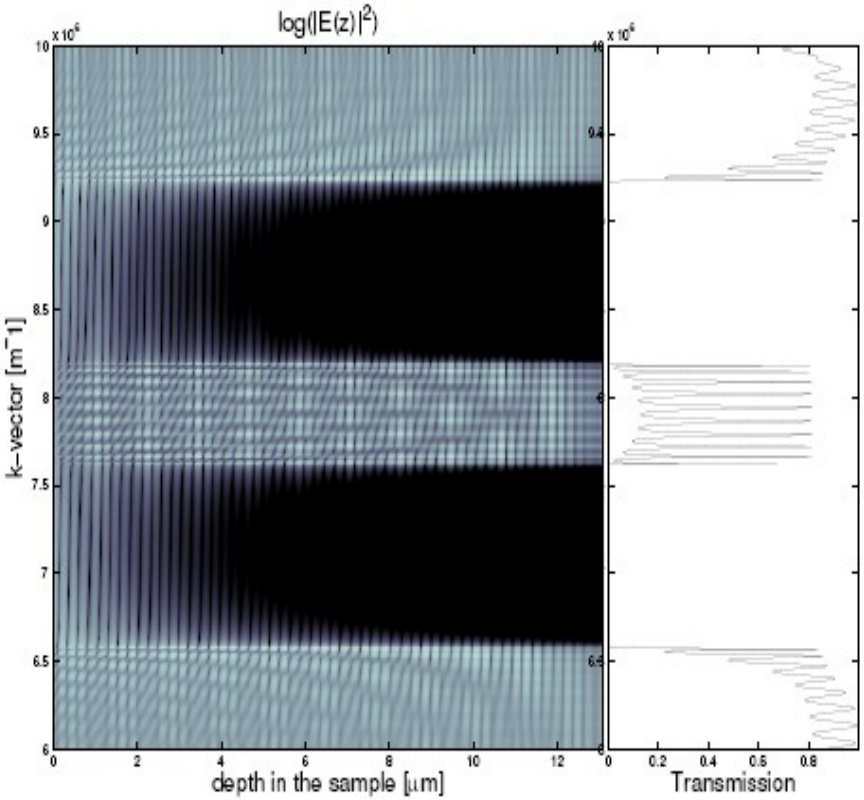
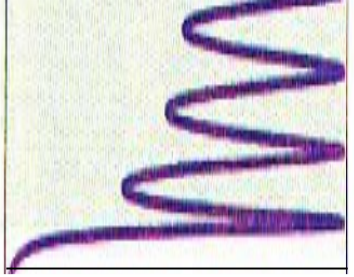
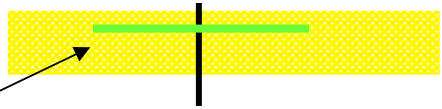


Figure 6.14: Optical superlattice made of 10 coupled microcavities (A) separated by a Bragg mirror with 5 periods AB. A miniband opens. Darker areas have a lower intensity. The two refractive indexes are $A = 1.58$ and $B = 2.21$ and the central wavelength is $\lambda = 800$ nm.

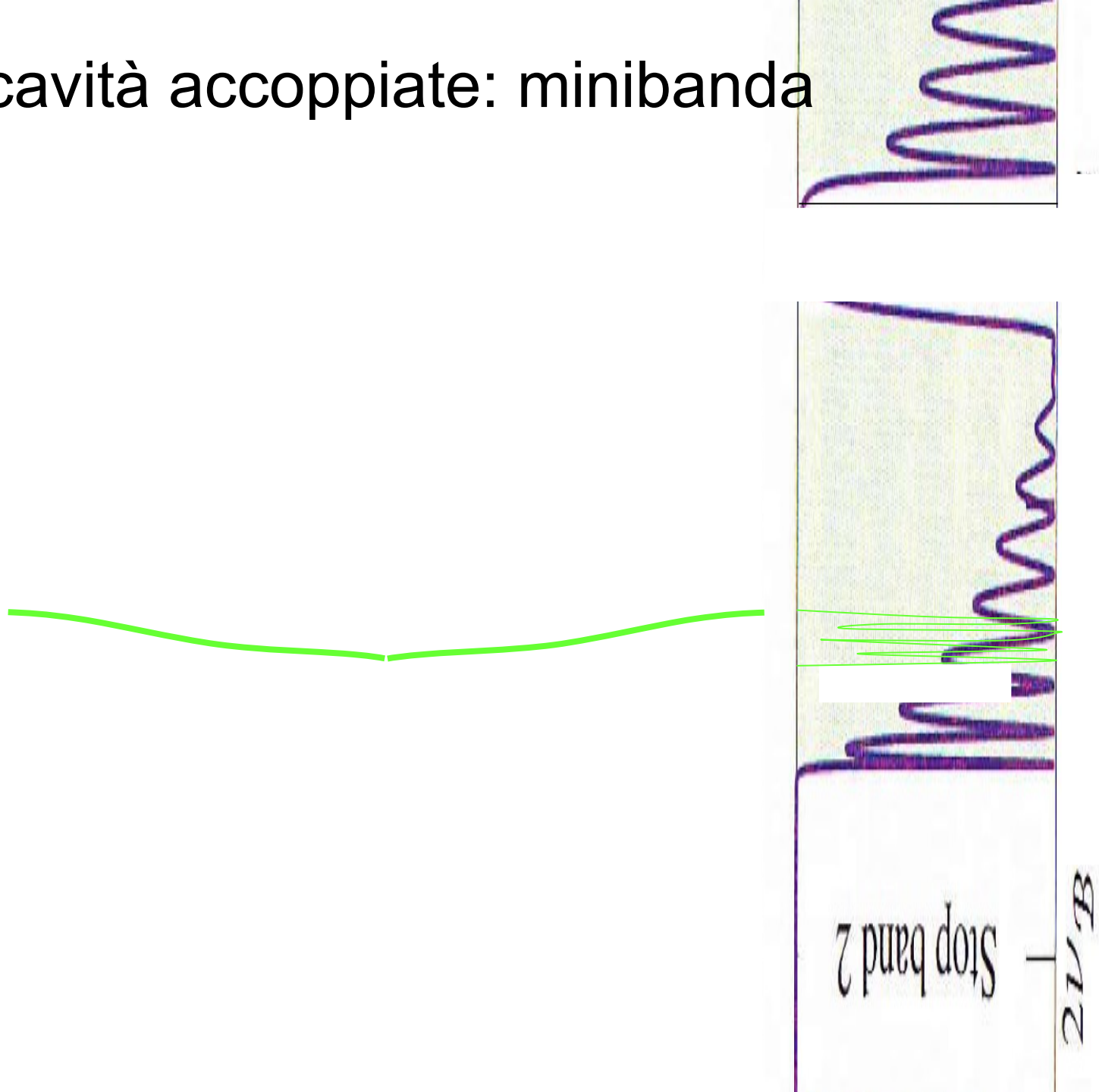
Microcavità $\ell = \dfrac{\lambda}{2}$ con λ nel gap



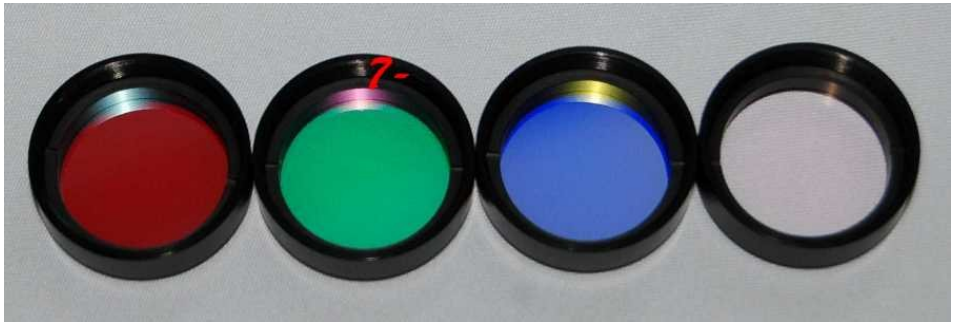


Stato di difetto

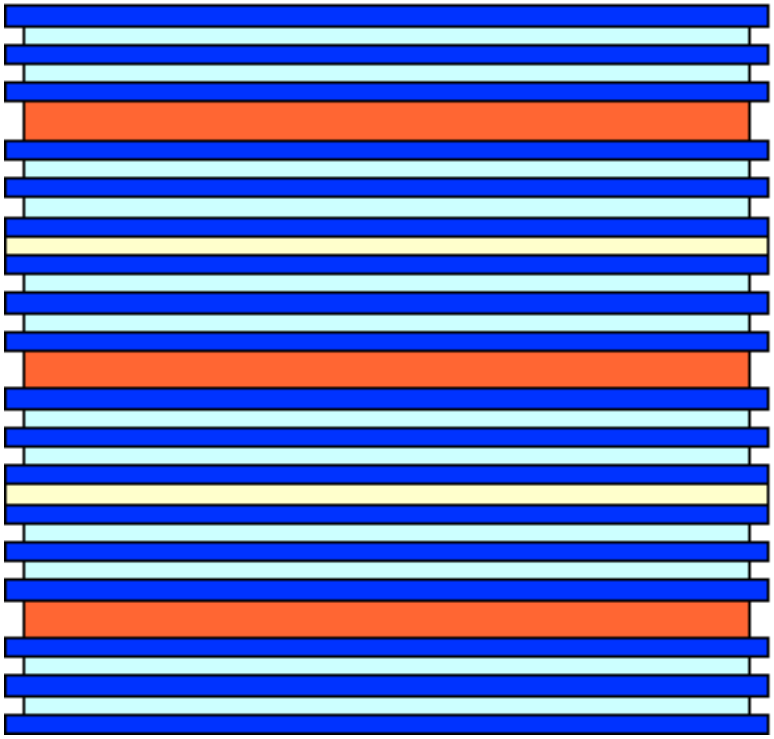
Microcavità accoppiate: minibanda

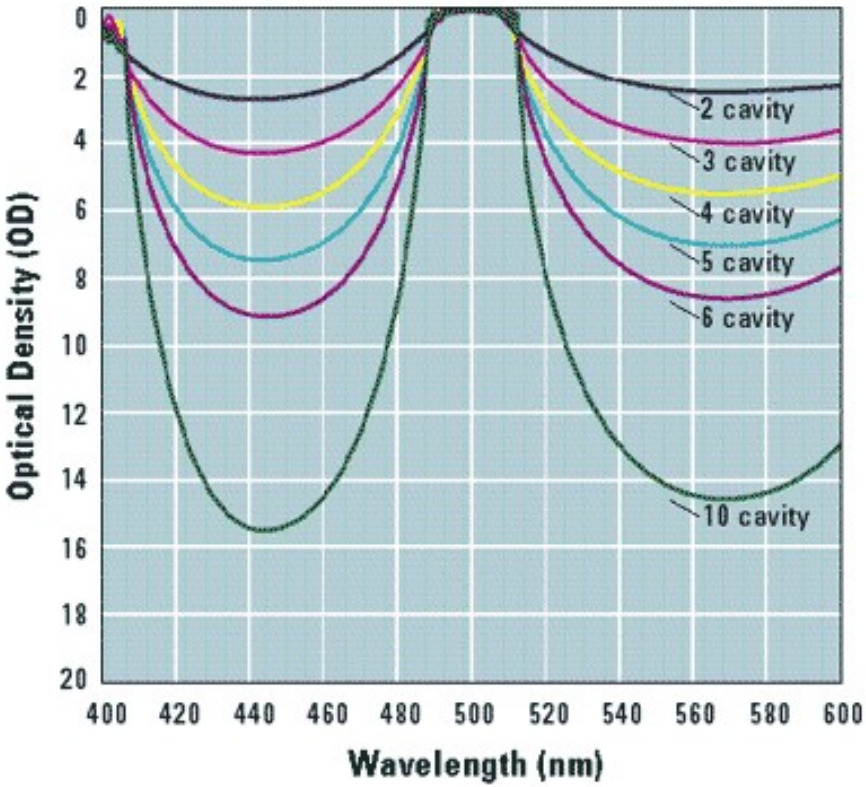


Filtri interferenziali



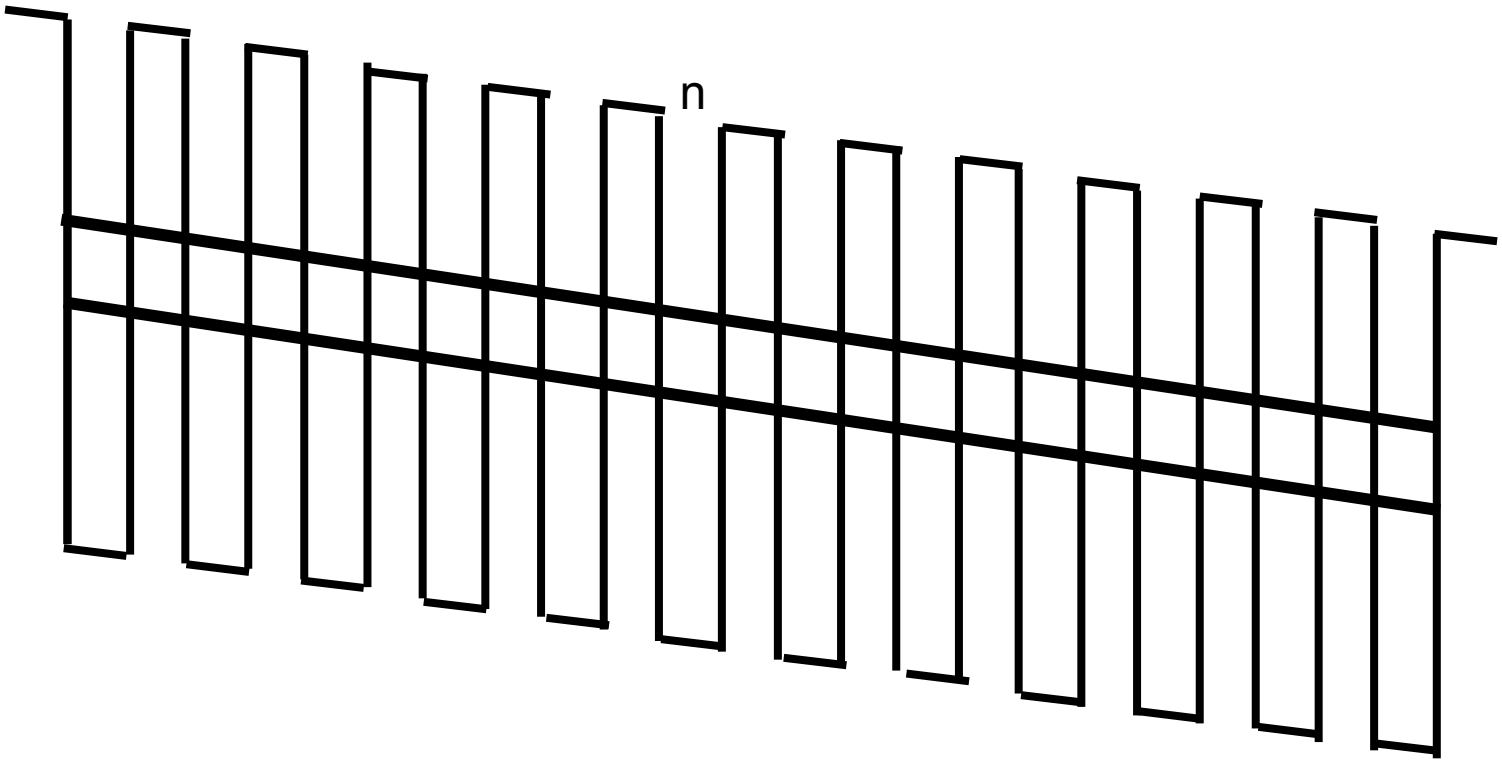
Three Cavity Bandpass Filter





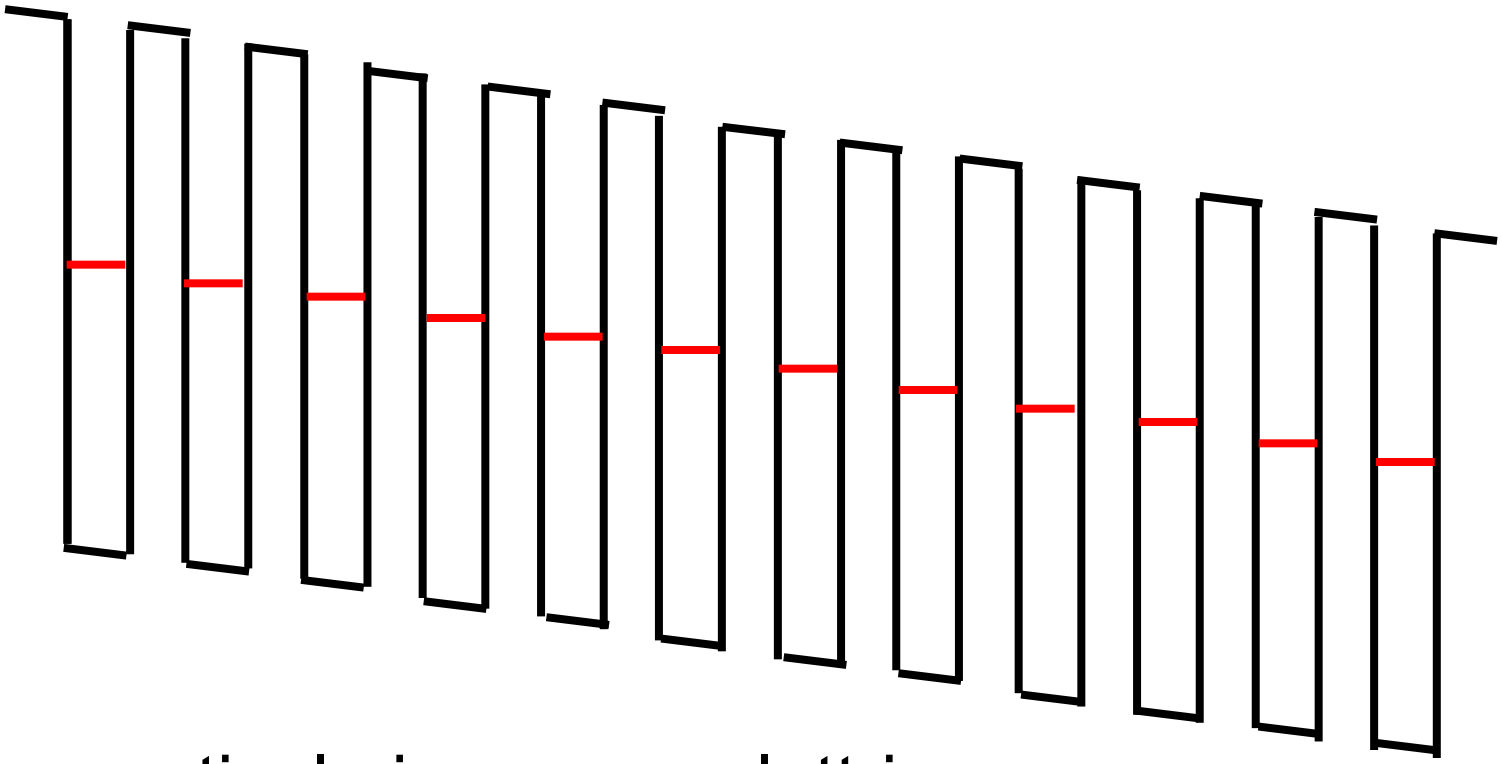
Come mettere un “campo elettrico” per i fotoni?

$$U(x) = -Fx$$



Come mettere un “campo elettrico” per i fotoni?

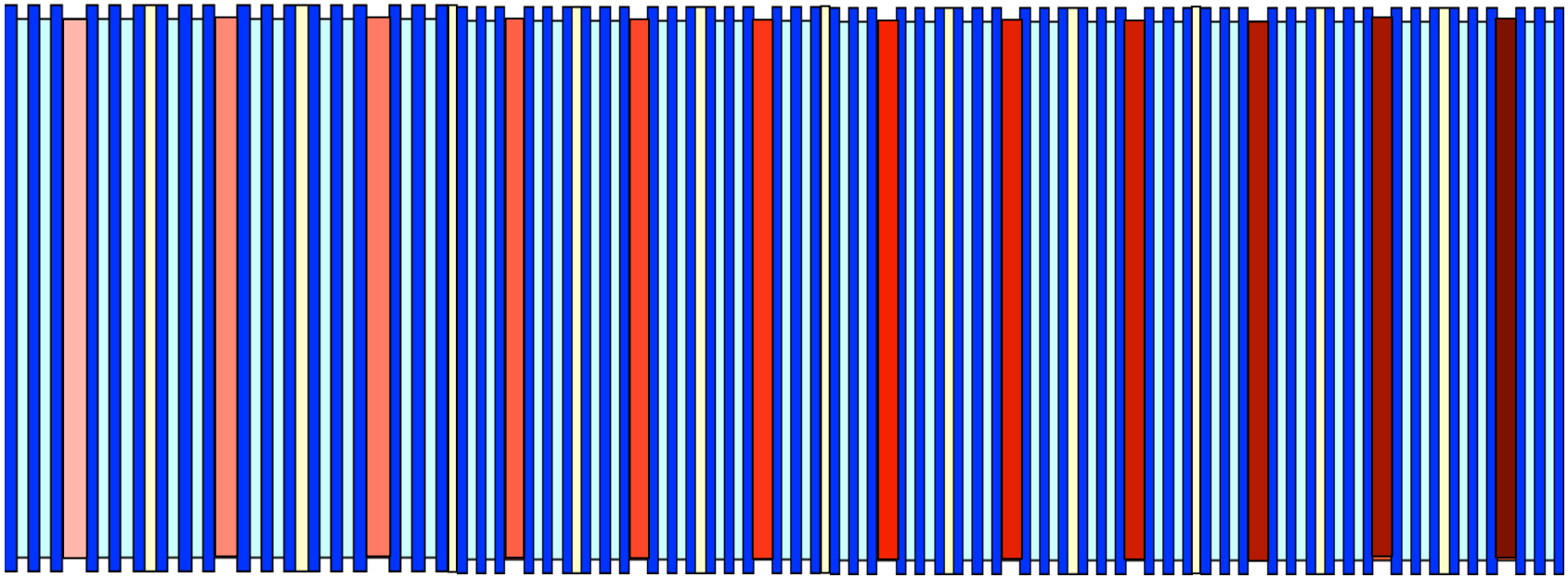
$U(x) = -Fx$



Superreticolo in campo elettrico

$$E_n = -Fx_n$$

Optical Bloch Oscillation:
“campo elettrico”= gradiente ottico (spessore, n)



$$E_n = -gx_n$$

Optical Analogue of Electronic Bloch Oscillations

Riccardo Sapienza,* Paola Costantino, and Diederik Wiersma
European Laboratory for Nonlinear Spectroscopy and INFM,† 50019 Sesto Fiorentino (Florence), Italy

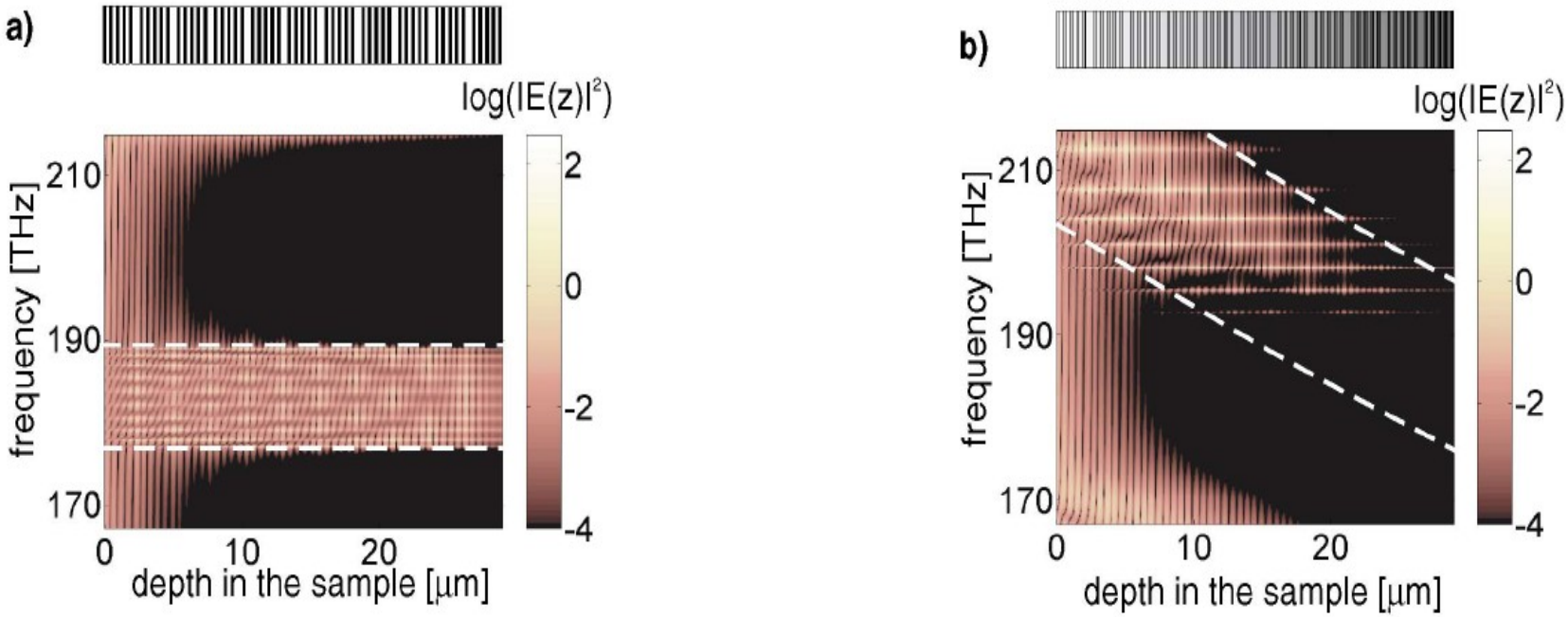


FIG. 1 (color online). Scattering state calculation of the distribution of the energy spectrum inside an optical superlattice composed of ten coupled microcavities. The parameters used in the calculations correspond to samples used in the actual experiment. (a) Flat band situation, $\Delta\delta = 0$. (b) Tilted band situation, $\Delta\delta = 14\%$. The dashed lines indicate the theoretical tilting of the miniband as obtained from Eq. (1). Above each panel the coupled microcavity structure is schematically shown; the gray scale refers to the refractive index variation along the depth in the sample (darker ≡ larger n).

Spettro di trasmissione:

Si vedono gli optical Wannier-Stark ladders

$$E_n = -gx_n$$

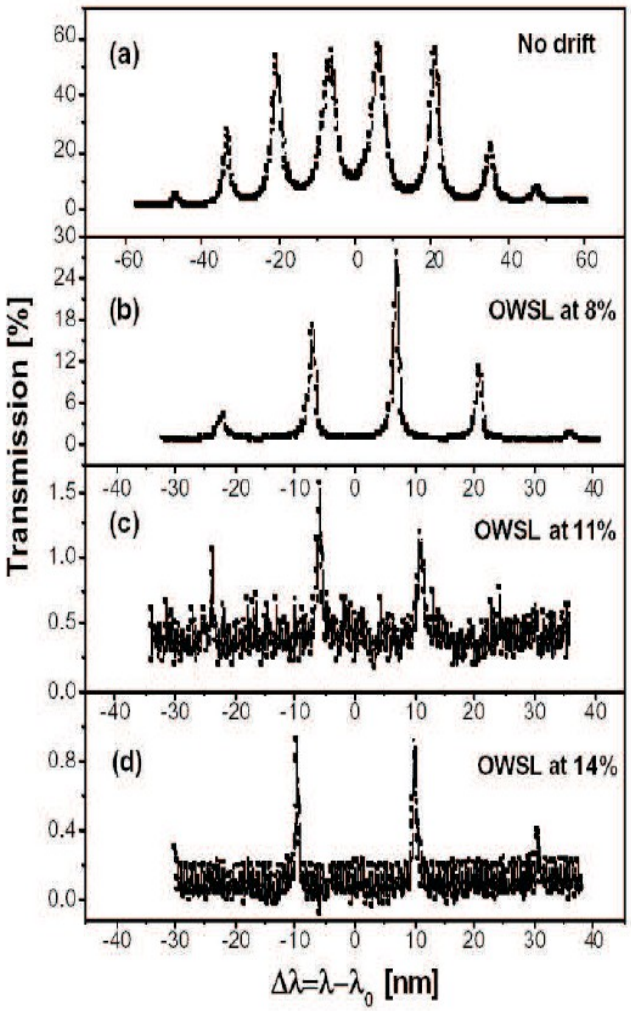


Figure 6.22: High resolution transmission spectra of different coupled microcavities structures with different gradients of the optical thickness of the layers (0 = 1.55 m is the central wavelength). The top spectrum corresponds to the non drifted sample, with thickness compensation. The others (b), (c) and (d) show 8%, 11% and 14% drifts. As drift increases, the optical Wannier-Stark ladder (OWSL) forms, and is observable as equidistant narrow transmission peaks

Trasmissione di un impulso: Bloch oscillation

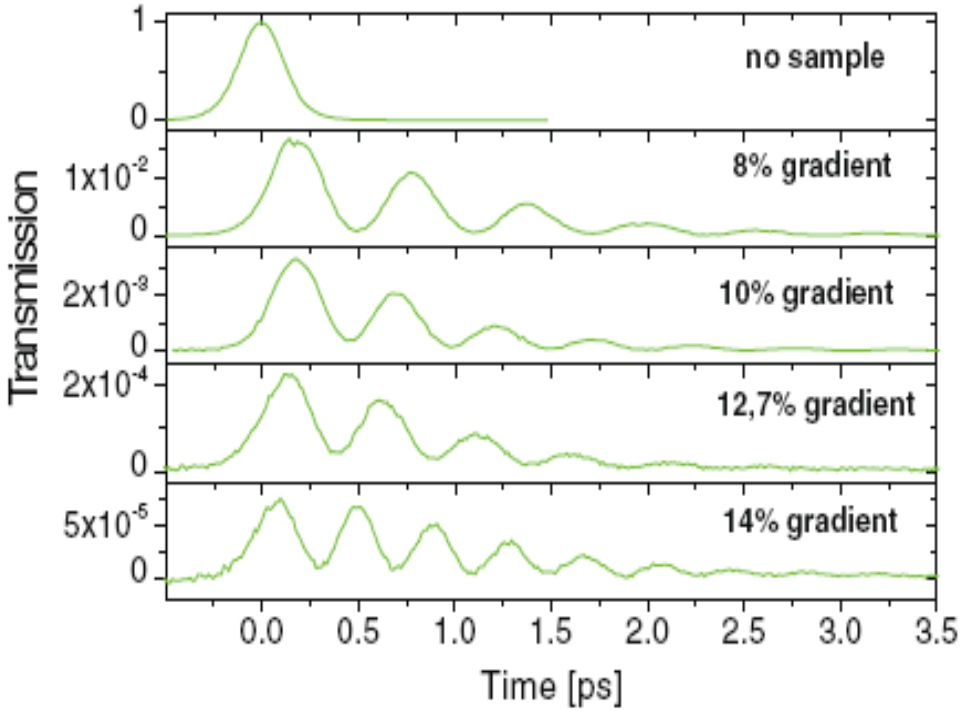


FIG. 3 (color online). Temporal response of the system for various values of the gradient $\Delta\delta$. The observed oscillations are the optical counterpart of time-resolved Bloch oscillations. The period of the oscillations decreases while increasing $\Delta\delta$, and the transmission decreases. The top panel reports the undisturbed probe pulse without sample.

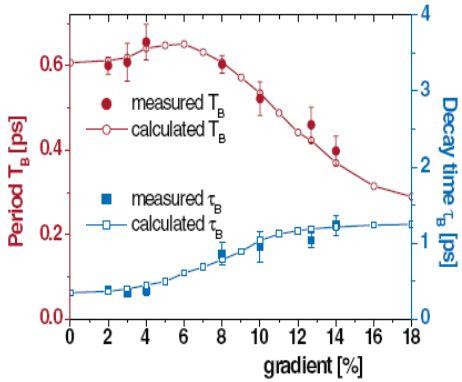
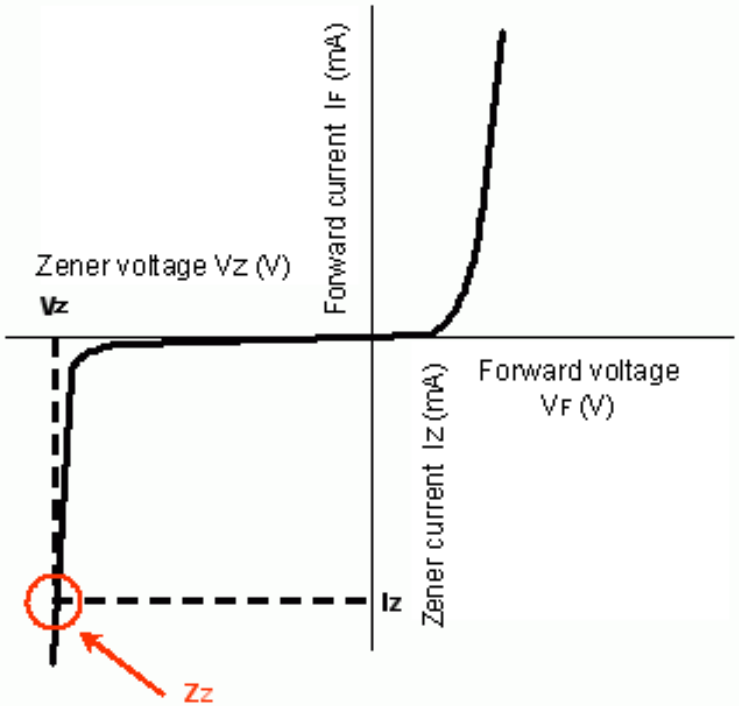


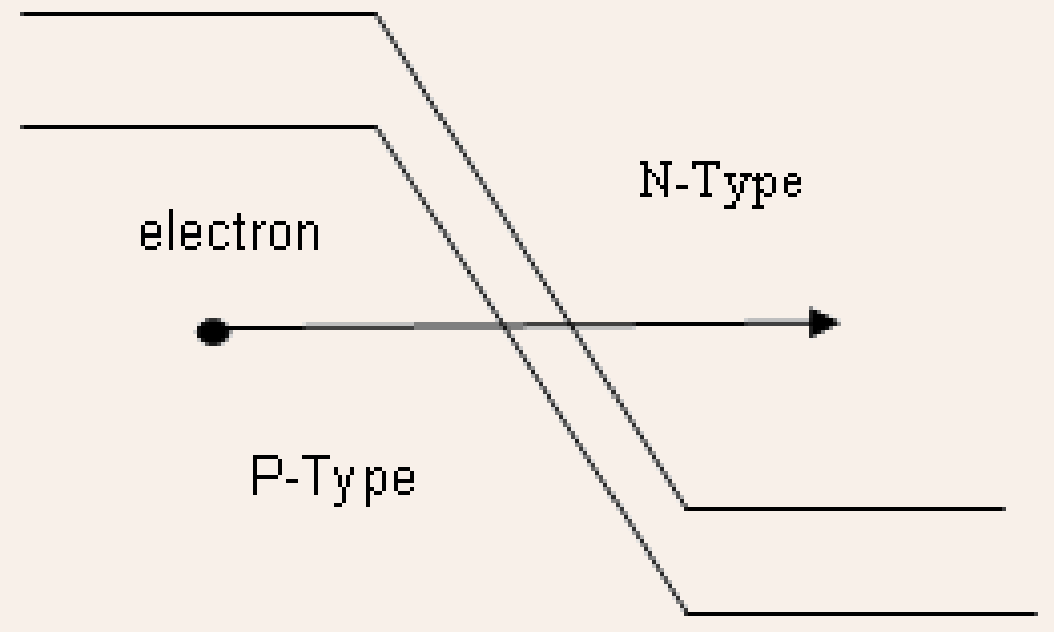
FIG. 4 (color online). Experimentally observed oscillation period T_B and decay time τ_B as a function of the gradient $\Delta\delta$. The error bars are the standard deviations obtained from various measurements on several positions on the sample and represent therefore the effect of lateral sample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

Zener tunnel elettronico



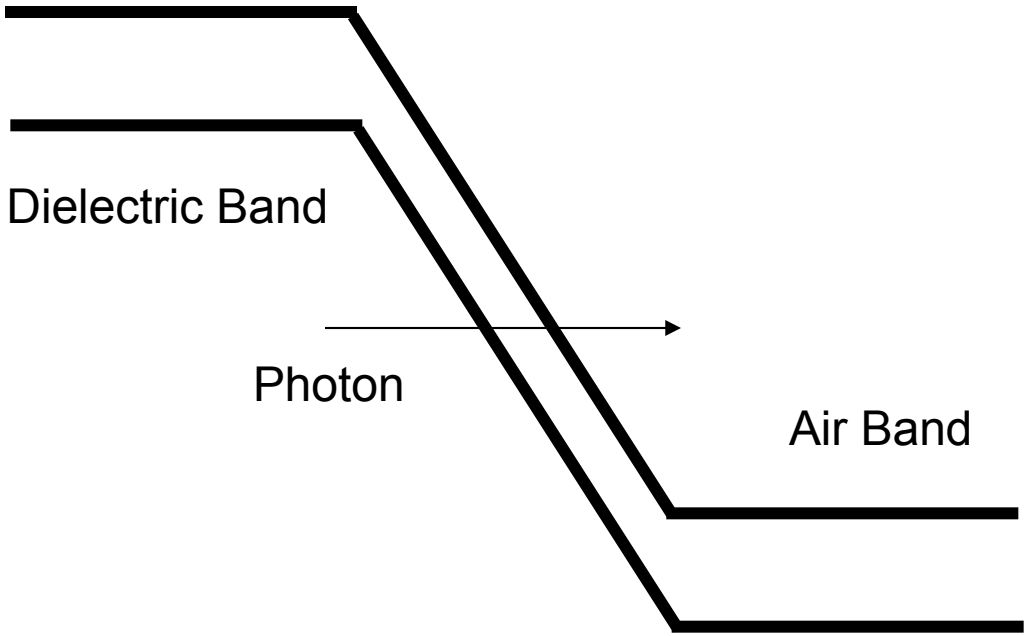
Voltage and current characteristics

Tunneling di elettroni da banda di valenza a banda di conduzione sotto forte campo elettrico

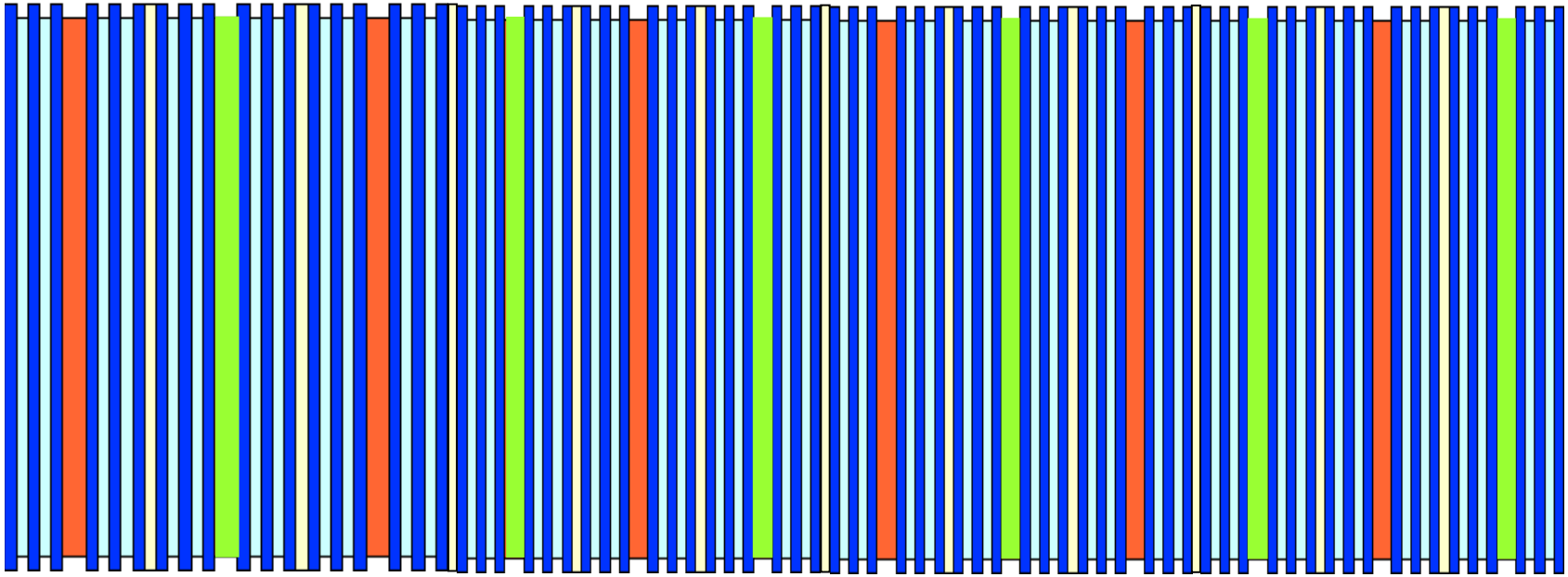


Zener tunnel ottico

Tunneling di fotoni da una banda fotonica ad un’altra sotto forte gradiente ottico



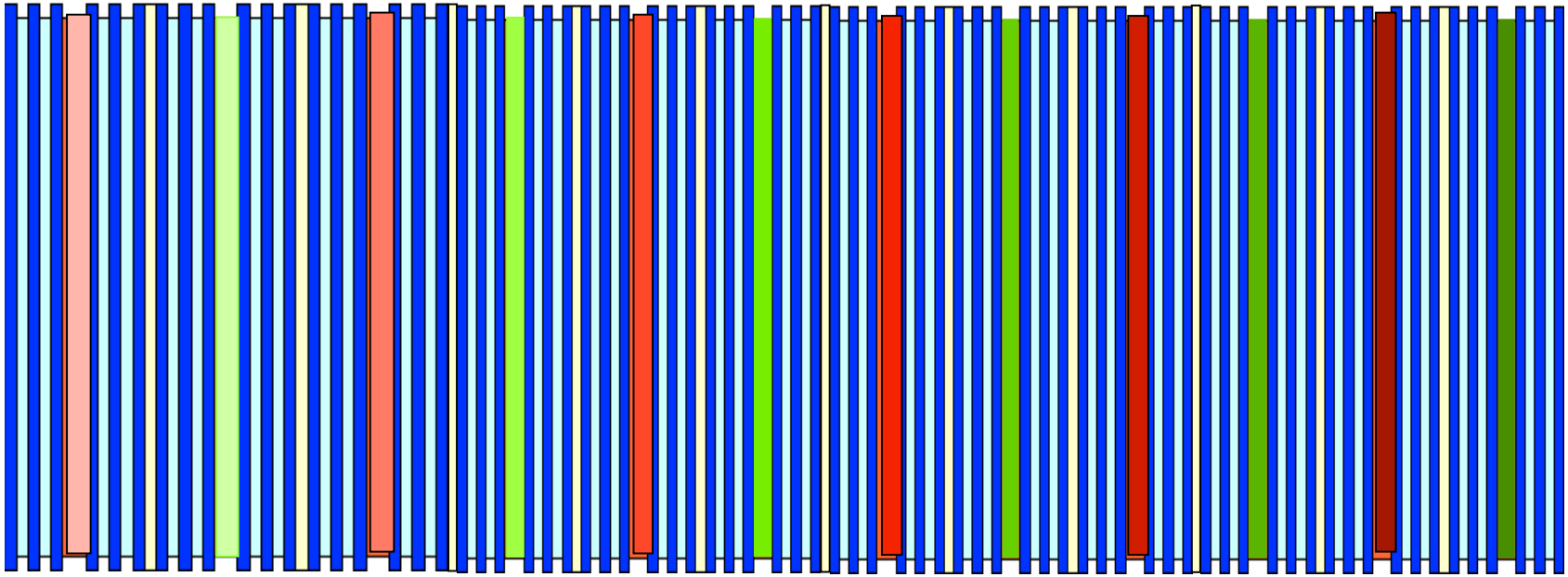
2 Minibande ottiche:
2 sistemi intercalati di MC accoppiate



Zener tunnel ottico

Tunneling di fotoni da una minbanda di cavità accoppiate ad un’altra

Gradiente ottico
2 sistemi intercalati di MC accoppiate



Gradiente ottico
2 sistemi intercalati di MC accoppiate

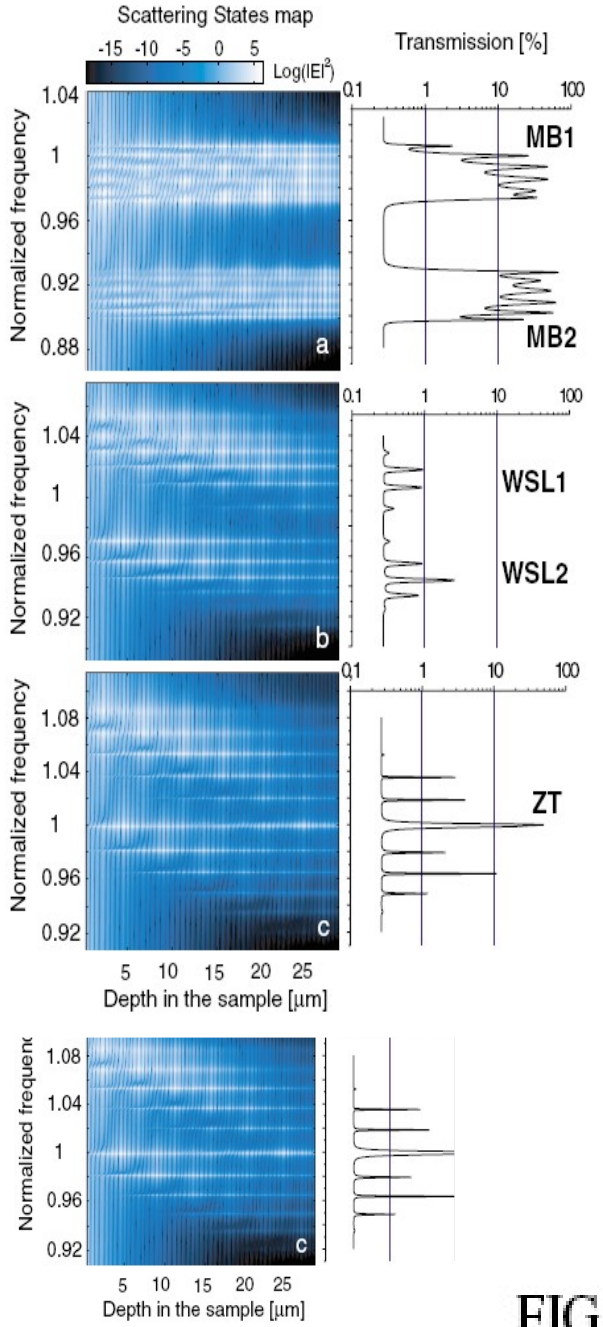


FIG. 1 (color online). Transfer matrix calculatior
tensity distribution of the light inside the sample. Th

HYSICAL REVIEW LETTERS week ending 1 APRIL 2005

ling of Light Waves in an Optical Superlattice

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ceived 23 July 2004; published 30 March 2005)

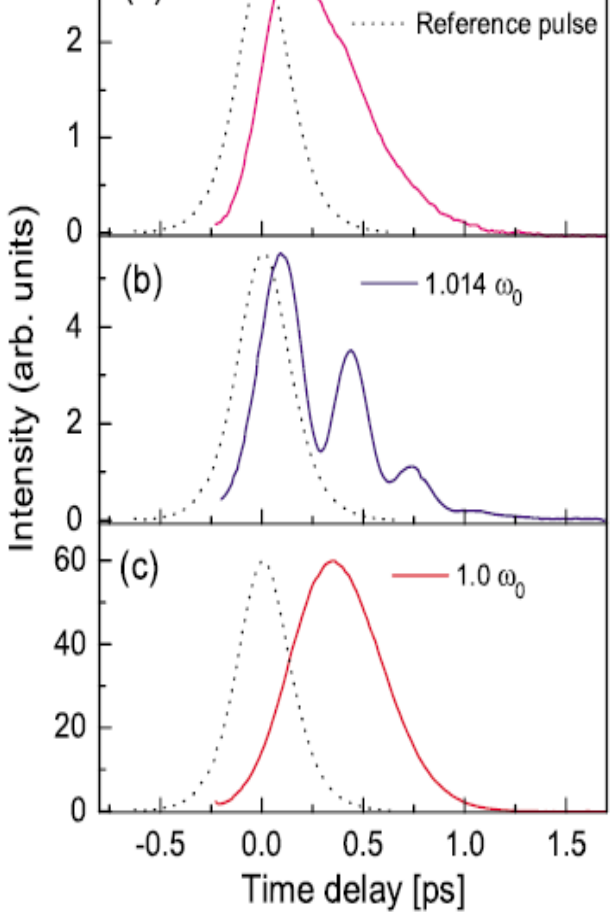
SL1

SL2

FIG. 1 (color online). Transfer matrix calculation for the
tensity distribution of the light inside the sample. The intensit

Spettro di trasmissione:

Si vede un picco stretto di trasmi-
sione all'interno della minibanda



Single mode

OBO

Zener mode