

transmission in the adiabatic situation is dominated by electrons where the spin follows the magnetic field,  $\langle T \rangle \approx \langle T_{\downarrow\uparrow} \rangle$ . Hence, the spin-switch effect is masked both in the adiabatic and non-adiabatic situation.

We summarize this *spin-flip effect* as follows [5]: For ballistic microstructures subject to in-plane magnetic fields that are symmetric with respect to the lead axis we have demonstrated how an additional small Aharonov-Bohm flux  $\phi$  can be used to control spin flips of incident polarized electrons, i.e., how to tune the polarization of the transmitted electrons, provided there is only one open channel in the leads. We point out that this effect, which arises from a subtle interference mechanism of the spatial and spin wavefunctions, holds for all degrees of adiabaticity though it is most striking in the intermediate regime, Fig. 2(b,e). In combination with a spin detector such a spin-flip device may be used to control spin polarized currents, similar to the spin field-effect transistor proposed in [1].

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## 1.25 Delay times of localized waves

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Interference of multiply scattered waves is a fundamental mechanism for phenomena in a variety of systems, ranging from electronic microdevices at low temperatures over electromagnetic wave guides and resonators to media which support classical waves, such as the elastic waves in the earth crust which originate from an earthquake or in an explorative underground detonation. Another field of application is in medicine, as in the examination of organs by ultrasound. Wave localization is maybe the most striking phenomenon which arises from multiple scattering. Localization can be understood as the systematic enhancement of the backscattered wave amplitude by constructive interference. In a wave guide geometry, it results in the exponential attenuation of the transmitted intensity

$$I(L) \propto \exp(-2L/\xi) \tag{1}$$

for lengths  $L$  of the wave guide greater than the localization length  $\xi$ , even in the absence of absorption. Localization was first investigated in mesoscopic systems [1]. Recently the undertaking of its realization and observation for microwaves [2, 3] and

optical waves [4, 5, 6] has attracted a lot of interest. One motivation is the prospect of achieving the feedback for a laser not by conventional mirrors but by multiple scattering, especially because wave localization provides a very efficient spatial confinement. However, the wave intensity  $I$  itself is not a good indicator of wave localization, because the same attenuation (1) can also arise from absorption.

Dynamical aspects of wave propagation in the presence of localization can be tested by probing the frequency dependence of the transmitted or reflected wave amplitude. When frequency is changed, the phase  $\phi$  of the scattered wave changes in a systematic fashion: Without any scattering, the phase of the transmitted wave  $\phi = \omega L/c$  allows to extract the travel time

$$\phi' = d\phi/d\omega = L/c \quad (2)$$

of the wave through the wave guide [7]. In a geometric-optics point of view,  $\phi'$  can be interpreted as the travel time even when the wave is scattered many times, which is the case for diffusive wave propagation. However, this “classical” point of view can no longer be adopted if the non-perturbative effect of localization sets in. Recent experiments have succeeded in the direct measurement of the so-called single-mode delay time for specified incident and detected modes, both for microwaves [8] and optical waves [9]. (The attribute ‘single-mode’ means here that only one of the  $N$  propagating modes is excited, and only one mode is selected for detection, but does not imply any restriction of  $N$  itself.) These experimental efforts have promoted the single-mode delay times to quantities of interest in their own right. The measurements have been performed with wave guides shorter than the localization length, and their outcome [the probability distribution function  $P(\phi')$ ] can be successfully described by diffusion theory [10].

Our theoretical investigations of the influence of localization on the delay times is based on the scattering formulation of wave transport and a single-parameter scaling equation, which describes how the statistical properties of the scattering matrix change when the length of the wave guide is increased incrementally. In the localized regime, a stationary limit is obtained for the properties of the reflected wave, while for the transmitted wave only a single dominant transport mode survives. Several indicators of localization can be derived from these observations, such as a strong correlation of the delay times of the different channels in transmission.

We have identified two particularly striking effects. The first phenomenon is a coherent backscattering effect which requires localization [11]: The typical delay times are reduced when the wave is detected in backscattering direction, by a factor  $\approx \sqrt{2}$  [the precise value is  $4096\sqrt{2}/(\pi 1371)$ ], see lower panel of Fig. 1. Without localization there is no dependence of  $P(\phi')$  on the detection direction, see the top panel of Fig. 1. We confirmed these predictions by numerical simulations of wave propagation through a disordered wave guide.

The second phenomenon is seen in the transmitted wave. We predicted a very asymmetric distribution function  $P(\phi')$  [12] (see Fig. 2), while diffusive propagation results in a distribution function which is totally symmetric around the median (same form as the distribution for reflection in the top panel of Fig. 1). This asymmetry indeed has been confirmed in the latest experiment [13] (as well as by our numerics). The functional form of the distribution function fits well with the theoretical predictions,

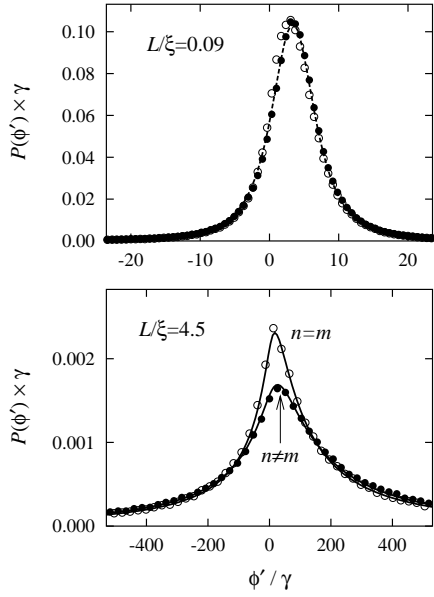


Figure 1: Coherent backscattering effect in the distribution function of delay times. Top: diffusive regime. Bottom: localized regime.

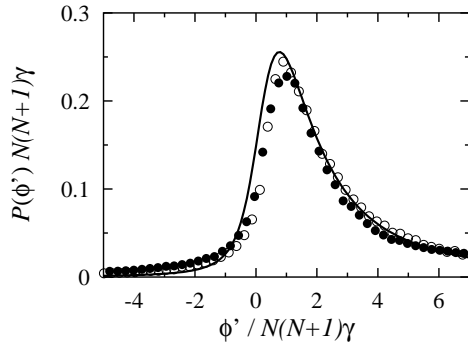


Figure 2: Probability distribution function of the delay time in transmission, from theory and from numerical simulations.

while a theory for the parameters is still missing for the experimental circumstances, in which the wave guide is not much longer than the localization length. Some understanding could be achieved by numerical simulations, which indicate that absorption must be very weak in the experiment (see Fig. 3).

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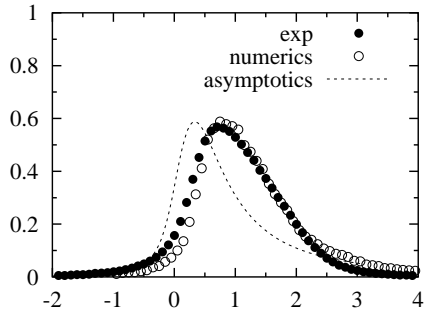


Figure 3: *Probability distribution function of the delay time in transmission, from experiment [13], numerical simulations, and the asymptotical prediction of the theory for a very long wave guide.*

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## 1.26 Hexagonal-shaped microcrystal lasers: Effects of corners and coupling

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A novel class of microlasers based on nanoporous molecular sieve host-guest systems has been fabricated recently [1, 2]. Organic dye guest molecules were inserted into the channel pores of a zeolitic microcrystal host. The aluminophosphate-crystals grow with natural hexagonal-shaped boundaries; see Fig. 1a. In terms of pump energy needed to reach lasing threshold these microlasers are comparable to semiconductor based vertical-cavity surface-emitting lasers (VCSELs). This makes them a promising candidate for future applications as e.g. optical communication devices. In collaboration with experimental physicists of the Technical University of Darmstadt and chemists of the University of Bremen (Volkswagen Foundation Project “Molekularsieblaser-Konglomerate im Infraroten”) we study these microlasers in more detail. In particular, we try to improve their properties by coupling them to each other and/or to passive high-quality microresonators. Our theoretical approach is illustrated in the sequence of Figs. 1a-c. The real microlasers (Fig. 1a) are modelled by two-dimensional passive dielectric resonators using both numerical simulations of the full wave equations (Fig. 1b) and a semiclassical ray model (Fig. 1c). The resonant modes of dielectric cavities can be calculated analytically by means of separation of variables only for special geometries, like the circular cavity. In general, numerical methods are needed. Frequently used is the wave-matching method [3, 4] which is suitable for sufficiently slight deformations of an isolated circular cavity. To treat coupled cavities with sharp corners, we have invented a variant of the boundary element method (BEM) [5].

Figure 1b shows a TM polarized resonant mode of an isolated hexagonal cavity with low refractive index calculated with the BEM. The light is concentrated along the boundary (whispering-gallery mode) and escapes predominantly at the corners. The emission directionality is highly anisotropic, a desired property in optical applications.