Pulse reflection by photonic barriers

G. Nimtz, A. Haibel, and R.-M. Vetter
II. Physikalisches Institut, Universität zu Köln, Zülpicher Strasse 77, D-50937 Köln, Germany
(Received 1 February 2002; published 25 September 2002)

The time behavior of microwaves undergoing partial reflection by photonic barriers was measured in the time and in the frequency domain. It was observed that for opaque barriers the reflection delay is almost independent of the barrier's length. This result corresponds to the Hartman effect in transmission.

DOI: 10.1103/PhysRevE.66.037602 PACS number(s): 42.70.Qs, 41.20.Jb, 03.65.Xp

I. INTRODUCTION

The dynamics of particle reflection has been studied a long time ago, see Ref. [1] for instance. However, there has been not much done on the time of partial reflection by photonic tunneling barriers [2,3]. The traversal time for a particle undergoing a tunneling process can be obtained by comparing the arrival times of the tunneled particle and of particles that passes the same distance without a barrier. From the time difference Δt and the length of the barrier L the transmission time follows by $\tau_{\mathrm{tr}}=L/c-\Delta t$. Due to the small probability of the tunneling process the majority of particles are reflected by the barrier. Because the probability depends on the barrier's length, the reflection should take place somewhere inside the barrier. In the case of symmetric barriers, the short reflection times $\tau_{\mathrm{r}+}$ and $\tau_{\mathrm{r}-}$ at both sides of the barrier are equal to the tunneling time τ_{tr} through the barrier [4]. This is also valid for asymmetric barriers in the evanescent frequency regions, where transmitted pulses become exponentially damped [5].

The partial reflection time studied here is given by the difference of arrival times of wave packets reflected by the photonic barrier of length L and of packets that are reflected by a metallic mirror at the same place. We used microwave pulses to simulate localized quantum mechanical particles [6]. A particle without enough energy to overcome a barrier corresponds to a microwave pulse inside an opaque barrier consisting of evanescent modes only. A barrier is called opaque if its transmission is less than $1/e$. If all relevant frequency components of the pulse are evanescent, the reflected pulse will have in first order approximation the same shape and magnitude as the incident pulse [7]. The propagation of the peak value or center of gravity is described by the stationary phase approximation introduced by Wigner. Based on the principle of causality, Wigner gave a lower limit for the energy derivative of the scattering phase shift [1]. Low and Mende gave evidence that barrier penetration in quantum theory appears as a nonlocal effect. But in their theoretical paper they conclude that such a measurement cannot be made [8]. On the other hand, the experimental results of partial reflection by photonic barriers presented here point to a nonlocal behavior of evanescent modes. Nonlocality and causality were theoretically investigated with respect to superluminal photonic tunneling in Refs. [9–12] and discussed in Ref. [13].

II. EXPERIMENTAL SETUP

The experimental setup and the investigated photonic barriers are sketched in Figs. 1 and 2, respectively. For the time domain measurements, Gaussian-like pulses with halfwidths of $\Delta t \approx 10$ ns, corresponding to a frequency bandwidth of $\Delta f=2/\pi\Delta t\approx 65$ MHz, were modulated on a high-frequency carrier $f_c=9.15$ GHz produced by a microwave generator. Using the power output of the generator $P=25$ MW it can be estimated that each pulse contains an ensemble of $P\Delta t/h f_c=4\times 10^{13}$ single photons. The microwave pulse was transmitted to the photonic barriers via a parabolic antenna, the reflected pulse was received by a second parabolic antenna. An HP-54825 oscilloscope detected the envelope of the reflected microwave pulse. The measurements were performed asymptotically, i.e., a coupling between generator, detector, and devices under test (photonic barriers or metallic mirrors) was avoided by the long optical distances of 3 m and by uniline devices in the microwave circuit. Due to the narrow radiation profile of the parabolic antennas of $\approx 5°$ a direct coupling between them was excluded.

The barriers consist of two photonic lattices separated by an air gap, see Fig. 2. Each lattice consists between one and four equidistant Perspex layers separated by air. The refractive index of Perspex is $n=1.61$ in the measured frequency region. In order to build a photonic barrier for the microwave pulse, the thicknesses of the Perspex $b=5.0$ mm and the air layers $a=8.5$ mm present a quarter of the microwave carriers wavelength in Perspex $\lambda_n=c/nf_c=20.4$ mm and in air $\lambda_0=c/f_c=32.8$ mm, respectively. At each surface of the Perspex layers a part $\rho=(n-1)/(n+1)$ of the incident wave or a factor $|\rho|^2\approx 5$ % of the incoming intensity is reflected.

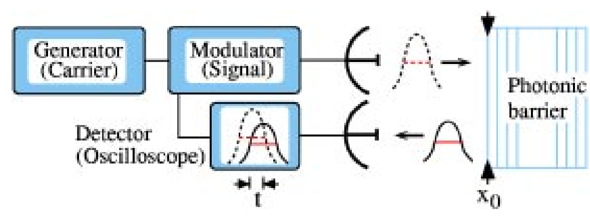

FIG. 1. (Color online only) Experimental setup for reflection time measurement. A Gaussian-like pulse of halfwidth $\Delta t=10$ ns (corresponding to a bandwidth $\Delta f=65$ MHz) is modulated on a microwave carrier $f_c=9.15$ GHz. The microwaves are transmitted and received by two parabolic antennas. The reflection times t for different photonic barriers are compared with the time of a reflection by a metallic mirror at the front surface of the barriers x_0; see Fig. 2.

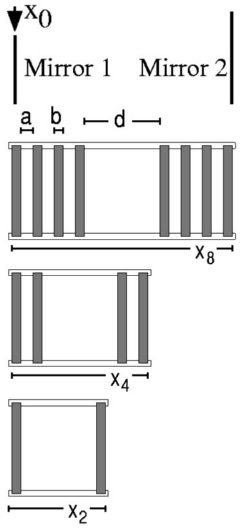

FIG. 2. Three photonic barriers of different total lengths $x_8 = 280$ mm, $x_4 = 226$ mm, and $x_2 = 199$ mm. Each structure consists of an alternating configuration of Perspex layers of width $b = 5.0$ mm separated by air gaps $a = 8.5$ mm. For certain frequencies the transmission of such a structure becomes exponentially damped by destructive interference so that the structure behaves like an opaque barrier; see Fig. 3. The wide air gap $d = 189$ mm allows one to enlarge the barrier's extension without increasing the attenuation and the transmission time. Metallic mirrors at the front or back surface of the structure are used to simulate an ideal reflection.

The reflected waves interfere constructively and result in a total reflection of nearly the same magnitude as the incident pulse. The air space $d = 189.0$ mm between the two lattices forms a cavity and extends the total length of the barrier, as illustrated in Fig. 2. The resonance frequencies of the cavity are given by multiples of $f_{\mathrm{res}} = c/2d = 794$ MHz. All frequency components of the microwave pulse lay in the nonresonant "forbidden" frequency region between the two resonances of the cavity at 11 and $12 f_{\mathrm{res}}$.

The calculated transmission of the barriers consisting of eight, four, and two layers of Perspex is displayed in Fig. 3 (left). There are five pronounced forbidden bands separated by resonance transmission peaks of the cavity in the frequency range displayed. Within a frequency band of ≈ 9.15 GHz± 100 MHz around the carrier frequency f_c the complete structure behaves like a photonic barrier. Due to destructive interference the transmitted part of an incident pulse is exponentially attenuated with increasing number of Perspex layers.

III. PARTIAL REFLECTION BY PHOTONIC BARRIERS

A pulse sent to the metallic mirror, placed at the front surfaces x_0 of the barriers, is reflected and the reflected pulse is detected by the oscilloscope after a certain time delay, see Fig. 1. We will subtract this time delay from all further measurements in order to use the arrival time of that pulse as a time reference $t = 0$. Thus, a pulse reflected by a metallic mirror placed at $x_0 + x_8$ (the end of the barrier) is expected to arrive at a time $t = 2\, x_8 / c = 1.87$ ns, see Fig. 4.

The partial reflection by the photonic barriers revealed a strange behavior: if the length of the barrier was shortened from eight to four or two layers (Fig. 2), the time delay of the reflection was constant whereas the amplitude decreased as a result of the increasing transmission (Fig. 3). The measured time delay of the pulses reflected by the barriers differs approximately $t \approx 100$ ps from the reflection time at the front mirror x_0, see Fig. 4. Incidentally this delay time corresponds to the tunneling time $\tau_{\mathrm{tr}} \approx 1/f_c$ for the microwave pulse in the frequency range $f_c = 9.15$ GHz [14,15].

To add further credibility to the time domain measurements, the reflection experiment was verified in the frequency domain using guided microwaves and a HP-8510 network analyzer. The photonic lattices were constructed from layers of Perspex inside X-band waveguides in an analogous arrangement to the above presented free space experiment. The geometry of the structure ($a = 12$ mm, $b = 6$ mm, and $d = 130$ mm) resulted in a forbidden band around $f_c = 8.44$ GHz of width $\Delta f \approx 100$ MHz. Because the reflections at the Perspex layers inside the waveguide are

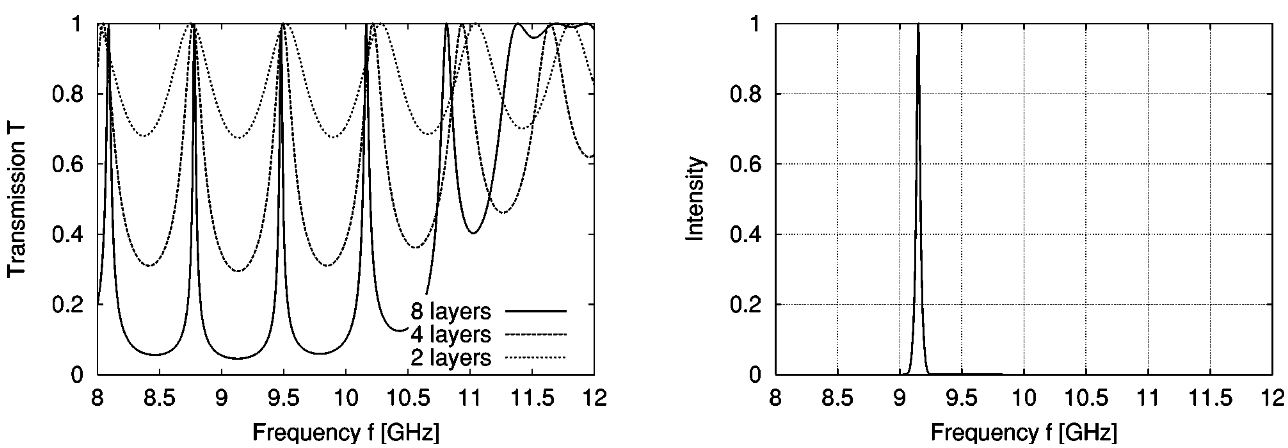

FIG. 3. Transmission T for the photonic barriers consisting of eight, four, and two layers of Perspex (left). The frequency band 9.15 GHz± 30 MHz of the microwave pulse lies inside a transmission gap where for the longest barrier only $T^2 = 0.25\,\%$ of the intensity is transmitted, while the rest of the pulse is reflected, according to the relationship $R^2 = 1 - T^2$. The right hand diagram shows the frequency spectrum of the microwave pulse, being completely inside a transmission gap.

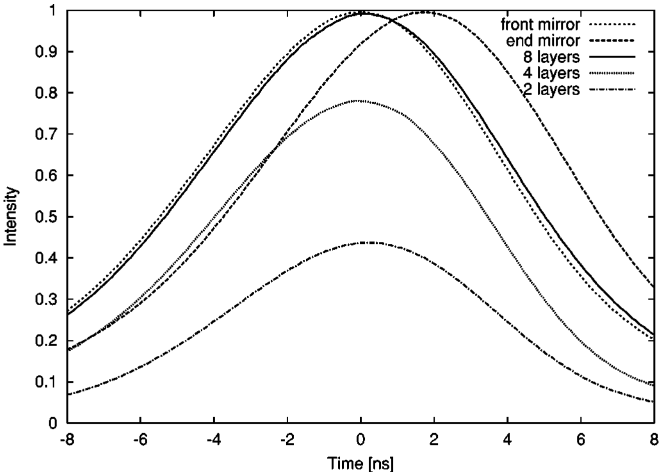

FIG. 4. Partial reflection by barriers of different lengths; reflection by a metallic mirror at the surfaces x_0 of the barriers defines the time $t=0$; see Fig. 2. An ideal reflection by a second mirror at x_0+x_8 (the back surface of the longest barrier) is detected after the expected propagation time of approximately $2x_8/c\approx1.9$ ns. The three other pulses were reflected by the barriers consisting of eight, four, and two layers of Perspex. The time delay of the three reflected pulses keeps mainly constant while the magnitudes depend on the number of Perspex layers. The short reflection time $t\approx100$ ps equals the tunneling time $\tau\approx1/f_c$ for a transmission through the barrier. A slightly larger delay time for the structure consisting of two layers indicates an insufficiently opaque barrier.

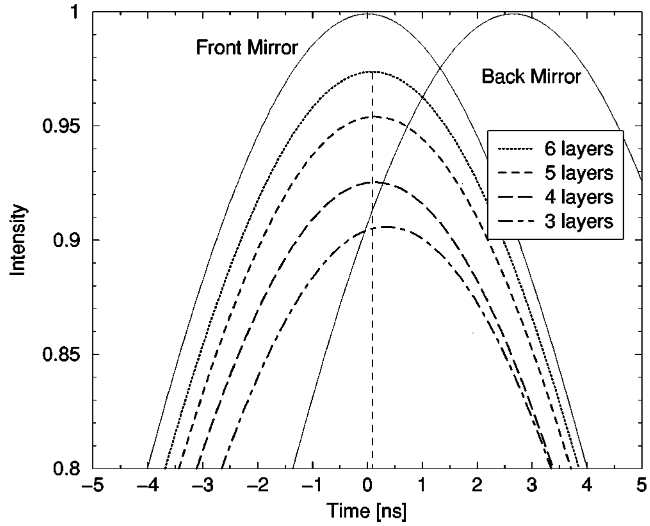

FIG. 5. Reflections by photonic barriers inside a waveguide consisting of six to three layers of Perspex. The solid pulses indicate the reflection by metallic mirrors placed at the front and back surface of the largest photonic barrier of six layers with a total length of $x_6=214$ mm. The dashed pulses are the reflections at the barriers consisting of six, five, four, and three layers of Perspex. The reflections of the barriers were detected after a short time delay of $\approx t=100$ ps, which equals the tunneling time τ (vertical line). The magnitude of the reflected pulses carried the information of the length of the barrier in question ($x_5=196$ mm, $x_4=178$ mm, $x_3=160$ mm).

stronger than in free space, the largest barrier consists of six layers of Perspex. To obtain a higher resolution we also used barriers with odd numbers of three and five layers. As a result, also for these unsymmetrical barriers the transmission and reflection time of a pulse did not depend on the side of incidence.

After measuring the frequency spectra of the barriers for transmission and reflection, the propagation of pulses in the time domain was reconstructed by Fourier transforms. In order to simulate the reflection at a photonic barrier, the frequency components within the band gap at f_c were used to construct the pulses. Figure 5 shows the reconstructed pulses after a reflection by barriers of six, five, four, and three layers. The frequency domain measurements confirm the above presented free space measurements, again the reflection time does not depend on the length of opaque barrier.

IV. CONCLUSIONS

In both the experiments the applied pulse had a carrier frequency f_c in the center of a barrier's forbidden band gap and a narrow frequency bandwidth Δf about 1% of f_c. Thus all relevant frequency components of the pulse were evanescent. In this case there is no finite phase time or group delay expected nor observed for the wave packet inside a barrier [1,3,16]. Such a behavior can explain the experimental data of reflection by opaque barriers. We observed that the partial reflection by the back surface is effecting only the amplitude, whereas the reflection duration is not changed. The information on photonic barrier length is available at the barrier's front surface within the short tunneling time τ_{tr}. In the case of opaque barriers the reflection suffers a short but constant time delay independent of the barrier's length [Hartman effect, Ref. [16]].

In transmission the constant group delay leads to superluminal group velocities for long enough barriers. The group delay time arises at the entrance boundary. The experimental analysis indicates, that the same time delay is in charge of the barrier's reflection time. On the other hand, within this short delay time information about the barrier's total length is available. That means inside a barrier the fields spread out instantaneously, the characteristic behavior of nonlocality. This differs from the reflection by a metallic mirror. Information on the metal barrier length are available only up to the skin depth. In the case of a photonic barrier, the interference causes the reflection while in the case of a metal the reflection is due to free carrier conduction [17].

So evanescent modes appear to be nonlocal at least up to some ten wavelengths, as experiments have shown in this study. The distance of observing nonlocality effects is limited by the exponential decay of the field intensity of evanescent modes, i.e., of the probability in the wave mechanical particle analogy.

ACKNOWLEDGMENTS

We thank P. Mittelstaedt and A. A. Stahlhofen for helpful discussions, B. Clegg for a critical reading of the manuscript, and M. E. Perel'man for giving us the paper on his investigation prior to publication.

[1] E.P. Wigner, Phys. Rev. **98**, 145 (1955).
[2] A.M. Steinberg and R.Y. Chiao, Phys. Rev. A **49**, 3283 (1994).
[3] G. Nimtz and W. Heitmann, Prog. Quantum Electron. **21**, 81 (1997).
[4] S. Longhi, Phys. Rev. E **64**, 037601 (2001).
[5] S. Longhi, M. Marano, P. Laporta, M. Belmonte, and P. Crespi, Phys. Rev. E **65**, 045602 (2002).
[6] S. Longhi, P. Laporta, M. Belmonte, and E. Recami, Phys. Rev. E **65**, 046610 (2002).
[7] A.P.L. Barbero, H.E. Hernandez-Figueroa, and E. Recami, Phys. Rev. E **62**, 8628 (2000).
[8] F.E. Low and P.F. Mende, Ann. Phys. (N.Y.) **210**, 380 (1991).
[9] E. Recami, *Time's Arrows, Quantum Measurement and Superluminal Behavior*, Monografie Scientifiche, Serie Scienze Fisiche (CNR, Firenze, 2001), pp. 17–35.
[10] M. Campi and M.M. Cohen, IEEE Trans. Electron Devices **17**, 157-159 (1970).
[11] M.E. Perel'man (unpublished).
[12] A.A. Grib and W.A. Rodrigues, *Nonlocality in Quantum Physics* (Plenum Press, New York, 1998).
[13] G. Nimtz and A. Haibel, Ann. Phys. (Leipzig) **11**, 163 (2002).
[14] A. Haibel and G. Nimtz, Ann. Phys. (Leipzig) **10**, 707 (2001).
[15] S. Esposito, Phys. Rev. E **64**, 026609 (2001).
[16] Th. Hartman, J. Appl. Phys. **33**, 3427 (1962).
[17] G. D'Aguanno *et al.*, Opt. Lett. **27**, 176 (2002).