Nonlocal reflection by photonic barriers

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The time behaviour of microwaves undergoing partial reflection by photonic barriers was measured in the time and in the frequency domain. It was observed that unlike the duration of partial reflection by dielectric layers, the measured reflection duration of barriers is independent of their length. The experimental results point to a nonlocal behaviour of evanescent modes at least over a distance of some ten wavelengths. Evanescent modes correspond to photonic tunnelling in quantum mechanics.

I. INTRODUCTION

We are used to measuring a reflection time from partial reflection of light, for instance by a sheet of glass, that is determined by sheer thickness. The reflection is observed only after a time span corresponding to twice the layer thickness multiplied by the group velocity of light in glass. Three hundred years ago Newton conjectured that light was composed of corpuscles and argued rather in the case of partial reflection by two or more surfaces: "Light striking the first surface sets off a kind of wave or field that travels along with the light and predisposes it to reflect or not reflect off the second surface." He called this process 'fits of easy reflection or easy transmission' \[1\]. As theory and experiments have shown this is not correct. In the case of dielectric media with a positive real part of the refractive index \(n\) like glass, the reflection is composed of components from both the front and the back surface reflection of the sheet of glass.

Surprisingly, in the case of reflection of particles by an opaque photonic barrier, where the index of refraction is purely imaginary, Newton’s conjecture seems to be close to reality: Partial reflection by opaque photonic barriers suffers a short but constant time delay independent of the barrier’s length. A barrier is called opaque if its transmission is less than \(1/e\). For the photonic barriers
investigated here, the incident particles can be simulated by localized wave packets. We found that for these wave packets the reflection time equals the transmission time observed in photonic tunnelling experiments \cite{2}. This behaviour is opposite to the partial reflection of dielectric sheets and may be explained by a nonlocality of evanescent modes in opaque barriers. Nonlocality and causality were investigated in Ref. \cite{3} and quite recently with respect to superluminal photonic tunnelling by Perel’m\'an \cite{4}.

II. EXPERIMENTAL SETUP

The experimental setup and the investigated photonic barriers are sketched in Fig. 1 and 2, respectively. For the time domain measurements, pulse–like signals with halfwidths of $\Delta t = 8.5$ ns, corresponding to a frequency–bandwidth of $\Delta f = 80$ 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 $P = 1$ mW it can be estimated that each pulse is built by an ensemble of $P \Delta t/h f_c \approx 10^{12}$ single photons. The microwave pulse was transmitted to the photonic barriers via a parabolic antenna; the reflected signal was received by a second antenna. A HP-54825 oscilloscope detected the envelope of the reflected microwave signal. 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 approximately $5^\circ$ a direct coupling between them was excluded.

The barriers consist of two photonic lattices (periodic dielectric quarter wavelength structures) which are separated by an air gap, Fig 3. 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 signal, the thicknesses of the Perspex $b = 5.0$ mm and the air layers $a = 8.5$ mm present a quarter of the microwave carrier’s 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. These reflections interfere constructively and result in a total reflection of nearly the same magnitude as the incident signal. The air space $d = 189.0$ mm
FIG. 1: Experimental setup for reflection time measurement. A pulse–like signal of halfwidth \( \Delta t = 8.5 \) ns (corresponding to a bandwidth \( \Delta f = 80 \) MHz) is modulated on a carrier in the microwave region \( f_c = 9.15 \) 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.

between the two lattices forms a cavity and extends the total length of the barrier. The resonance frequencies of the cavity are given by multiples of \( f_{\text{res}} = c/2d = 794 \) MHz. The frequency spectrum of the microwave signal lies completely in the nonresonant ‘forbidden’ frequency region between the two resonances of the cavity at \( 11 \cdot f_{\text{res}} \) and \( 12 \cdot f_{\text{res}} \).

The calculated transmission and reflection of the barriers consisting of 8, 4, and 2 layers of Perspex are displayed in Fig. 3. There are five pronounced forbidden bands separated by resonance transmission peaks of the cavity in the frequency range displayed. Within a frequency band of approximately \( 9.15 \) GHz\( \pm 100 \) MHz around the carrier frequency \( f_c \) the complete structure behaves like a photonic barrier. Due to destructive interference the transmitted signal is exponentially attenuated by the number of Perspex layers.

### III. PARTIAL REFLECTION BY PHOTONIC BARRIERS

For a normal dielectric medium with a real index of refraction \( n > 1 \), e.g. a sheet of glass, the propagation of the reflected microwave pulse is expected to be reshaped by partial reflections at the sheet’s two surfaces. The maximum intensity of the reflection depends on the thickness of the sheet and varies sinusoidal. This behaviour is due to interference between waves reflected by the front and back surfaces of the single sheet. We are now investigating the behaviour of the photonic barriers sketched in Fig. 2, which have a purely imaginary index of refraction.
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 to enlarge the barriers’ extension without increasing the attenuation. Metallic mirrors at the front or back surface of the structure are used to simulate an ideal reflection.

A signal sent to the metallic mirror, placed at the front surfaces \(x_0\) of the barriers, is reflected and the reflected signal is detected by the oscilloscope after a certain time delay, 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 the end of the barrier at \(x_0 + x_8\) is expected to arrive at a time \(t = 2x_8/c = 1.87\) ns, see Fig. 4.

The partial reflection by the photonic barriers revealed a strange behaviour: if the length of the barrier was shortened from 8 to 4 or 2 layers (Fig. 3), the time delay of the reflection kept 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. This delay time corresponds to the tunnelling time \(\tau \approx 1/f_c\) for a signal in the microwave frequency range \(f_c = 9.15\) GHz [2, 3].

To add further credibility to the time domain measurements, the reflection experiment was
FIG. 3: Transmission $T$ (left) and reflection $R$ (right) for the photonic barriers consisting of 8, 4, and 2 layers of Perspex. The frequency band $9.15\ \text{GHz} \pm 40\ \text{MHz}$ of the microwave pulse lay inside a transmission gap where for the longest barrier only $T^2 = 0.25\%$ of the signal’s intensity is transmitted, while the rest of the pulse is reflected, according to the relationship $R^2 = 1 - T^2$.

verified in the frequency domain using guided microwaves and a network analyzer HP-8510. The photonic lattices were constructed from layers of Perspex inside X-band waveguides in an analogous arrangement to the above presented free space experiment [6]. The geometry of the structure ($a = 12\ \text{mm}$, $b = 6\ \text{mm}$, and $d = 130\ \text{mm}$) resulted in a forbidden band around $f_c = 8.44\ \text{GHz}$ of width $\Delta f \approx 100\ \text{MHz}$. Because the reflections at the Perspex layers inside the waveguide are stronger than in free space, the largest barrier consists of 6 layers of Perspex. To obtain a higher resolution we also used barriers with odd numbers of 3 and 5 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 could be reconstructed by Fourier transforms. In order to simulate the reflection at a photonic barrier, the frequency components within the band gap at $f_c$ was used to construct the pulses. Figure 5 shows the reconstructed pulses after a reflection by barriers of 3, 4, 5, and 6 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.
FIG. 4: Signals reflected by barriers of different lengths: An ideal 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 the back surface $x_0 + x_8$ of the longest barrier is detected after the expected propagation time of approximately $2x_8/c \approx 1.9$ ns. The three other pulses were reflected by the barriers consisting of 8, 4, and 2 layers of Perspex. The time delay of the three reflected pulses keeps mainly constant while the magnitudes of the signals depend on the number of Perspex layers. The short reflection time $t \approx 100$ ps corresponds to the tunnelling time $\tau \approx 1/f_c$ for a transmission through the barrier. A slightly larger delay time for the structure consisting of 2 layers indicates an insufficiently opaque barrier.

IV. CONCLUSIONS

In both experiments the applied signal pulse had a carrier frequency $f_c$ in the center of the photonic barriers’ forbidden band gap and a narrow frequency–bandwidth $\Delta f$ about 1% of $f_c$. Thus all frequency components of the signal were evanescent. In this case there is no finite phase–time or group delay expected nor observed for the wave packet inside a barrier [5, 8]. Such a behaviour seem to explain the experimental data of reflection by opaque barriers: 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
FIG. 5: Signals reflected by photonic barriers inside a waveguide consisting of 6 to 3 layers of Perspex. The solid pulses indicate the position of a reflection by metallic mirrors at the front and behind the largest photonic barrier of 6 layers with a total length of $x_6 = 214$ mm. The dashed pulses are the reflections at the barriers consisting of 6, 5, 4, and 3 layers of Perspex. The reflections of the barriers were detected after a short time delay of approximately $t = 100$ ps, which equals the tunnelling time $\tau$ (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).

field intensity of evanescent modes, i.e. of the probability in the wave mechanical particle analogy.

In measuring the reflection duration of wave packets by photonic barriers we observed that the partial reflection by the back surface has an instantaneous effect on the amplitude, whereas the reflection duration is not changed. Obviously the information on photonic barrier length is available at the barrier’s front surface within the short tunnelling time. This is a strange property which Newton suggested erroneously to explain partial reflection of corpuscles by dielectric layers [1].
REFERENCES

[1] R. P. Feynman, *QED: The strange Theory of Light and Matter*, Princeton University Press, Princeton NJ (1988) p.22.

[2] A. Haibel, G. Nimtz, *Ann. Phys. (Leipzig)*, 10, 707 (2001).

[3] G. C. Hegerfeldt, S. N. M. Ruijsenaars, *Phys. Rev. D* 22, 377 (1980).

[4] M. E. Perel’man, preprint (2001).

[5] S. Esposito, Phys. Ref. E, in print, preprint physics/0102020 (2001).

[6] R.–M. Vetter et al., to be published.

[7] Th. Hartman, *J. Appl. Phys.* 33, 3427 (1962).

[8] G. Nimtz, W. Heitmann, *Prog. Quantum Electronics* 21, 81 (1997).

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