Subfemtosecond determination of transmission delay times for a dielectric mirror (photonic band gap) as a function of the angle of incidence

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Using a two-photon interference technique, we measure the delay for single-photon wave packets to be transmitted through a multilayer dielectric mirror, which functions as a "photonic band-gap" medium. By varying the angle of incidence, we are able to confirm the behavior predicted by the group delay (stationary-phase approximation), including a variation of the delay time from superluminal to subluminal as the band edge is tuned toward the wavelength of our photons. The agreement with theory is better than 0.5 fs (less than one-quarter of an optical period) except at large angles of incidence. The source of the remaining discrepancy is not yet fully understood.

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In recent years, there has been a great deal of interest in two related topics: tunneling times [1–4] and photonic band gaps [5–7]. A standard quarter-wave-stack dielectric mirror is in fact the simplest example of a one-dimensional photonic band gap, and consequently may be thought of as a tunnel barrier for photons within its "stop band." The periodic modulation of the refractive index is analogous to a periodic Kronig-Penney potential in solid-state physics, and leads to an imaginary value for the quasimomentum in certain frequency ranges—that is, to an exponentially decaying field envelope within the medium, and high reflectivity due to constructive interference (Bragg reflection). We have exploited this analogy to perform a measurement of the single-photon tunneling delay time [8–11], using as our barrier an 11-layer mirror of alternating high ($n=2.22$) and low ($n=1.41$) index quarter-wave layers, with minimum transmission of about 1% at the center of the band gap. We confirmed the striking prediction that drives the tunneling time controversy: in certain limits, a transmitted wave-packet peak may appear on the far side of the barrier *faster* than if the peak had traversed the barrier at the vacuum speed of light c. Meanwhile, several microwave experiments have investigated other instances of superluminal propagation, including electromagnetic analogies to tunneling [12–17].

While in itself, this anomalous peak propagation does not constitute a violation of Einstein causality [18–27], it certainly leads one to ask whether there may exist another, longer time scale in tunneling, with more physical significance than the group (i.e., peak) delay. After all, in a certain sense, the bulk of the transmitted wave originates in the leading edge of the incident wave packet, *not* near the incident peak [28,23,29]. Many theories have been propounded to describe the duration of the tunneling interaction, and the leading contenders involve studying oscillating barriers [1,30] or Larmor precession of a tunneling electron in a barrier with a confined magnetic field [31–33]. It should be stressed that these theories are not intended to describe the propagation of wave packets, but rather the dynamical time scale of the tunneling process; several experiments have supported their predictions [34].

Nevertheless, there is a popular misconception that these times (and in particular the Büttiker-Landauer time in its "semiclassical" or WKB limit—$md/\hbar\kappa$, where κ represents the evanescent decay constant inside the barrier, i.e., the magnitude of the imaginary wave vector) predict the arrival time of wave packets. In [8], we were able to exclude the semiclassical time, but not Büttiker's version of the Larmor time, as describing peak propagation. Furthermore, some workers have expressed concern about the paucity of data supporting the superluminality of the group delay, in spite of our finding of a seven-standard-deviation effect. Microwave experiments have also traditionally been met with skepticism (see, for example, [35].) In light of these objections, we have extended the earlier experiment to study the delay time as a function of angle of incidence. As the angle is changed, the frequency and the width of the band gap change as well, so this is essentially a way to study the energy dependence of the tunneling time.

Our apparatus is shown in Fig. 1. As the technique and the sample have both been described at length elsewhere [36,37,8,38,39], we will content ourselves with an abbreviated sketch of the method. A crystal with an optical $\chi^{(2)}$ nonlinearity is pumped by a cw ultraviolet laser, and in the process of spontaneous parametric down-conversion emits simultaneous pairs of horizontally polarized infrared photons. The two photons in each pair leave the crystal on opposite sides of the ultraviolet pump, conserving momentum. They are correlated in time to within their reciprocal bandwidth of about 15 fs. They are also correlated in energy, their frequencies summing to that of the (narrow-band) 351-nm pump. When the two photons arrive simultaneously at a beam splitter, there is no way to distinguish the two Feynman paths

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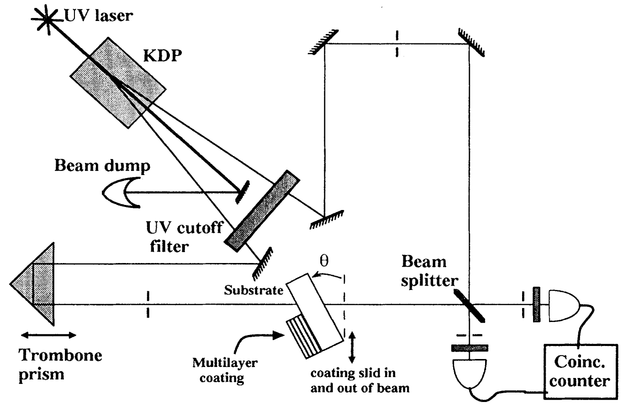

FIG. 1. Experimental setup for determining single-photon propagation times through a multilayer dielectric mirror. By translating the sample, we can observe the interference dip for photons tunneling through the 1.1-μm barrier or for photons traversing an equal thickness of air. We can thus compare arrival times for tunneling and freely propagating wave packets.

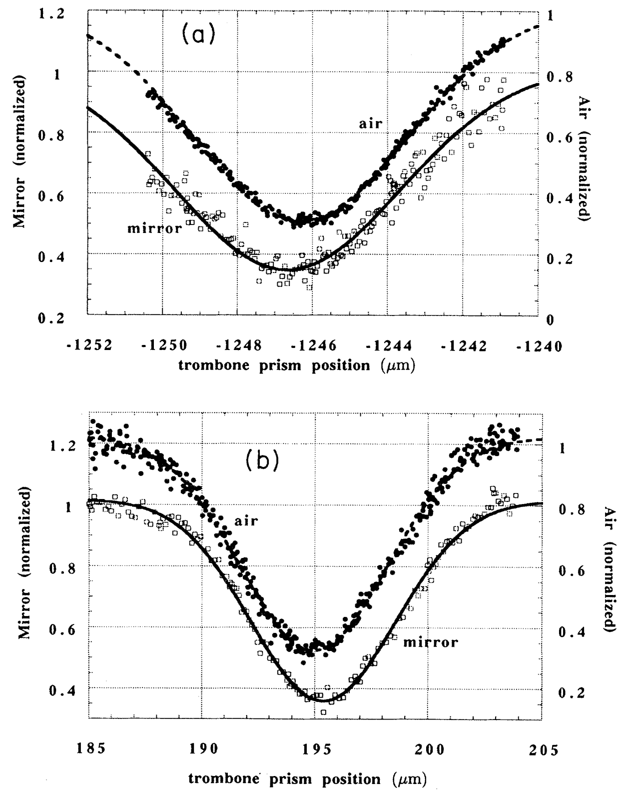

FIG. 2. Coincidence rate versus trombone prism position (see Fig. 1) for p-polarized photons traveling through the reflective coating as well as for those traveling through an equal thickness of air, for (a) normal incidence and (b) 55° incidence.

leading to coincidences between detectors placed at the beam splitter's two output ports: both photons being transmitted, and both photons being reflected. This leads to an interference effect in which the coincidence rate is suppressed (the two photons tending to head off to the same detector). By contrast, if the photons arrive at the beam splitter at different times (on the scale of their 15-fs correlation time), coincidence counts occur half the time. Thus by placing a dielectric mirror in one arm of the interferometer and adjusting the external path length to minimize the coincidence rate, we can measure the delay experienced by the photon wave packets that are transmitted through this barrier. We find that near the transmission minimum, the photons travel through the mirror faster than they travel through an equivalent length of air, whereas when the mirror is angled to bring the band edge closer to the photons' wavelength, they travel slower than through air, as one would expect. Figure 2 shows sample data for these two situations, where the sign change can be clearly seen.

In [8], our results were consistent with the group delay predictions, and also with Büttiker's proposed Larmor time [33], but not with the "semiclassical" time. The measured times exceeded the predictions by approximately 0.5 fs, but this result was at the borderline of statistical significance, and not discussed. Since then, further data taken at various angles of incidence have continued to show a discrepancy, ranging from an excess of 0.5 fs near normal incidence to a deficit of over 1 fs at large angles of incidence. At the same time, the data offer close agreement with the group delay, and appear to rule out identification of the Larmor theory with a peak propagation time. Our attempts to eliminate systematic effects and characterize those that remain were described in [8]. Since then, unable to find any other sources of error to explain the discrepancy, we are convinced that it is a property of the sample under study, and not of the interferometer used for the measurements. We therefore obtained a second dielectric mirror of design parameters identical to the first, to see whether the errors could be attributed to deviations from the ideal quarter-wave-stack structure. As can be seen from Fig. 3, both mirrors show quite similar behavior. Both are 11-layer quarter-wave stacks as described above. Mirror 1 shows a minimum transmission at 692 nm, while mirror 2's

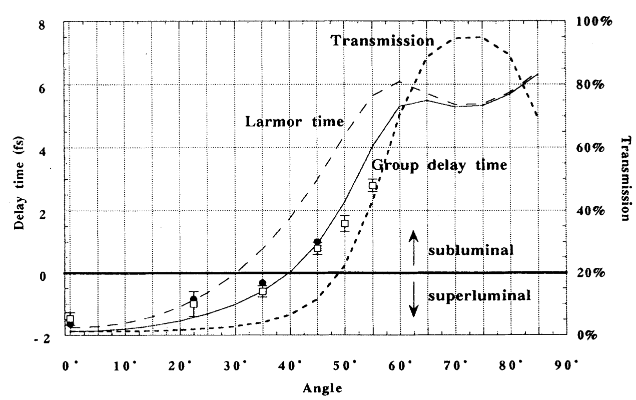

FIG. 3. Left axis: measured delay for mirrors 1 (squares) and mirror 2 (circles) as a function of angle of incidence, to be compared with the theoretical group delay and the Larmor interaction time proposed by Büttiker. Right axis: transmission versus angle of incidence. All curves are for p polarization.

minimum is at 688 nm; this difference is insignificant on the scale of the band gap, which extends from 600 to 800 nm. We conclude that some real effect is at work, modifying the stationary-phase prediction. In principle, frequency-dependent transmission could lead to such an effect, as does second-order group-velocity dispersion; both effects are much too small to explain the present discrepancy. As discussed in [40], attempts to numerically model dielectric mirrors with small, random fluctuations in layer thicknesses were able to produce deviations on the right order, but in general they did not lead to deviations of the form we observed experimentally. It is conceivable that loss or scattering in the dielectrics could also help explain the effect, and we are beginning to investigate this possibility [41]; see also [42,43].

Theoretical curves are plotted along with the data in Figs. 3 and 4. The group delay is calculated by the method of stationary phase. The transmission phase of the 11-layer structure is calculated numerically, and differentiated first with respect to angle of incidence to give the transverse shift and then with respect to incident frequency to give the time delay, according to the formulas $\Delta y = -\partial\phi_T/\partial k_y = -\partial\phi_T/\partial(k\sin\theta) = -(k\cos\theta)\partial\phi_T/\partial\theta$ and $\tau_g = \partial\phi_T/\partial\omega + (\Delta y/c)\sin\theta$, where ϕ_T is the transmission phase [44]. Büttiker's Larmor time [33] is equal to the magnitude of the complex time [45,46] $\tau_c = i\partial(\ln t)/\partial\Omega_L$, where t is the complex transmission amplitude, and Ω_L the Larmor frequency. For our optical structure, an effective Larmor frequency Ω_L corresponds to a uniform (over the barrier region) scaling of the local index of refraction by a factor of $1+\Omega_L/\omega$. Since in the limit of interest, the "in-plane portion" of the Larmor time (i.e., the real part of the complex time) differs little from the group delay, we take them to be equal in order to include the effects of the transverse shift in the Larmor theory. The "out-of-plane portion" (or imaginary part) is calculated numerically, and added in quadrature to the group delay in order to generate the Larmor time. Since our measurements compare the transit time through the barrier with that through air, we subtract the time parallel wave fronts propagating at c would take to reach a point on the far side of the barrier (with a transverse shift of Δy) from both the group delay and the Larmor time, so as to facilitate comparison with the experimental data.

At the moment, more work (both experimental and theoretical) is needed to understand the discrepancy. We are therefore planning to repeat this experiment with s-polarized light (by introducing half-wave plates before and after the sample being studied), which has very different transmission characteristics as a function of angle (also leading to a larger difference between the group delay and the Larmor theories). As shown in Fig. 4, our preliminary data are again consistent with the group delay and not with the Larmor time, but due to the lower transmission for this polarization, we need to improve our signal-to-noise ratio before reaching any definitive conclusions.

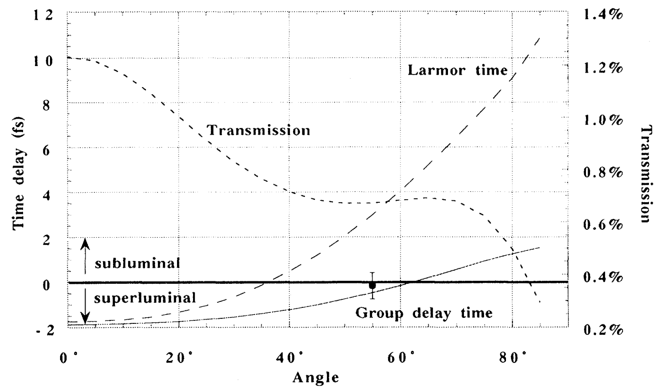

FIG. 4. Same as Fig. 3, but for s polarization. Due to the much lower transmission, only one preliminary data point is shown, but the different characteristics of the theoretical curves for both transmission and delay suggest that upon improvement of our signal-to-noise ratio, further work in this direction may help elucidate the discrepancy between experiment and theory.

The superluminality of the barrier traversal near midgap is now well supported by the data, and the group delay (stationary-phase) theory can be seen to be relatively accurate for a variety of angles of incidence, but there is a residual discrepancy on the order of 0.5 fs, which is not yet fully understood.

Note added. Since the submission of this manuscript, a paper has appeared [47] extending our previous experimental results to barriers of varying thicknesses (and transmission as low as 0.01%) near normal incidence, using classical femtosecond pulses. It reports general agreement with the group delay theory, aside from a discrepancy on the order of 1.5 fs. Two papers have also appeared discussing the effects of dissipation on tunneling times [48,49].

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