Tunneling of Optical Pulses through Photonic Band Gaps

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Propagation of electromagnetic wave packets through 1D photonic band gap materials has been studied using 12 fs optical pulses. The measured transit time is found to be paradoxically short (implying superluminal tunneling) and independent of the barrier thickness for opaque barriers, in analogy to the behavior of electrons tunneling through potential barriers. Shortening of Fourier-limited incident wave packets is observed upon transmission through these linear systems. Although in apparent conflict with causality and the uncertainty principle, neither of these general principles is violated because of the strong attenuation suffered by the transmitted signals.

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The tunneling of a particle through a potential barrier that is absolutely opaque classically is one of the most striking features of quantum mechanics. Whereas stationary tunneling rates have been calculated and experimentally verified for a number of different systems, thus far only very few experiments provided some (indirect) information of the temporal dynamics of particle tunneling. In solid states systems the major difficulty stems from the fact that the barrier traversal times of electrons are of the order of $10^{-14}-10^{-15}$ s [1], i.e., orders of magnitude shorter than the highest time resolution achievable in electronics.

Clearly and unambiguously interpretable experimental studies of the temporal aspects of tunneling would be important not only for semiconductor device physics but also from a fundamental physical point of view because of a few surprising and as yet unverified theoretical findings from the past. The first theoretical study of the dynamics of electron tunneling dates back to the early years of quantum mechanics [2] and led to the conclusion that "there is no appreciable delay in the transmission of the (wave) packet through the barrier ...." Later, a more quantitative investigation by Hartman [3] yielded a *finite* tunneling time which, however, became independent of the barrier thickness for thick (opaque) barriers. This implies that the effective tunneling velocity can, in principle, increase infinitely with increasing barrier thickness, in apparent contradiction to Einstein's causality.

Steinberg, Kwiat, and Chiao recently reported superluminal tunneling of single photons through a 1D photonic band gap barrier transmitting $T \approx 1\%$ of the incident radiation [4]. We have extended this study to barriers of $T \approx 10^{-4}$ by using classical wave packets. More than 3 decades after Hartman's classic work, this Letter presents what is to our knowledge the first direct time-domain experiments that support Hartman's prediction of the lack of dependence of tunneling time on barrier thickness. Relating the results of such an *optical* experiment to electron tunneling is warranted by the formal analogy between the time-independent Schrödinger equation and the Helmholtz wave equation describing the propagation of monochromatic electromagnetic waves [5].

Beyond the above mentioned difficulties associated with electron tunneling experiments, the suitability of the group delay or phase time (the energy derivative of the transmission phase shift) deduced from the wave packet propagation approach [2,3] as a physically meaningful, precise measure for the barrier traversal time has been questioned [6]. The major problems in measuring the phase time originate from (i) a distortion of the shape of the transmitted wave packet and (ii) a shifted energy spectrum, making the propagation velocity on the two sides of the barrier different [7]. Both these effects can severely impair the accuracy of time-of-flight measurements.

Recently a close analogy between electron tunneling across a rectangular potential barrier and classical electromagnetic (em) pulse propagation through a waveguide with an evanescent region (cutoff frequency higher than that of the em wave) was established [8], followed by a series of reports on superluminal tunneling of microwaves [9]. Nevertheless, because of the close correspondence between the momentum-versus-energy function for the electron in the barrier and the wave-number-versus-frequency function for the em wave in the cutoff region (henceforth dispersion relations) the problems associated with a spectral distortion in the barrier are here in existence to the same extent as in electron tunneling.

By contrast, using 1D photonic band gap materials as the optical barrier provides ideal conditions for tunneling experiments because (i) the group velocities of the incident and transmitted wave packets are equal and known, and (ii) the dispersion and transmission curves are slowly varying over a broad frequency range around the center of the photonic band gap. This is revealed by Fig. 1, showing the group delay and intensity transmittivity for multilayer dielectric mirrors, which exhibit a 1D photonic band gap. The important implication of (i) is that the evaluation of the tunneling time from time-of-flight mea-

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