pheromones that might act as an alarm signal to dangerous insects.

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COMMUNICATIONS ARISING

Optics

Mechanism for 'superluminal' tunnelling

In their discussion of a mechanism that I proposed[1] to explain the apparent superluminal (that is, faster than light) tunnelling of light pulses observed in photonic barrier experiments[2–5], Büttiker and Washburn[6] used an old 'reshaping' argument[7] that is at variance with my model[1] and is not supported by the bulk of the experimental tunnelling evidence. The mechanism I proposed agrees with experiment and resolves a long-standing paradox — namely, the lack of dependence of tunnelling time on barrier length for thick barriers (the Hartman effect)[8,9].

The reshaping mechanism that is cited by Büttiker and Washburn[6] requires that the tunnelled pulse be shortened and reshaped, as shown in their Fig. 1. According to this mechanism, the transmitted pulse is 'front-loaded' so that only the leading edge of the incident pulse survives the tunnelling event without being severely attenuated to the point that it cannot be detected[6]. A direct corollary of this description is that if the pulse has two humps, only the leading edge of the first hump is transmitted, resulting in a shortened, reshaped, single-humped pulse (Fig. 1).

In reality, most tunnelling experiments reveal transmitted pulses that are neither reshaped nor shortened[2–5], which is borne out by numerical simulations[1,10]. As distortionless tunnelling is a narrow-band phenomenon, the pulses used in these experiments are of necessity long compared with the barrier width (reshaping only occurs when they are not[3]). Hence, the interaction is a quasi-steady-state process.

If the incident pulse is much longer than the transit time of a light front through the sample, it does not really propagate through the barrier: it simply modulates the energy stored in the barrier from the moment of turn-on. The output adiabatically follows the input with a delay proportional to the stored energy, just as a capacitor introduces delay in an electrical circuit. What is really observed then is a phase shift in an amplitude modulation.

Figure 1 shows a simulation of a tunnelling double-peaked pulse based on my model[1]. There is no reshaping or pulse shortening, only delay and attenuation. The reshaping argument applies only to the very leading edge (the front, or 'turn on'), which can propagate through the barrier before the steady-state reflectivity builds up. There are irreconcilable differences between this mechanism and the reshaping model.

The mechanism that I proposed readily explains the Hartman effect[8,9]. The delay of the peaks becomes independent of the barrier length because the stored energy saturates with length[9]. This delay time (which is proportional to stored energy) is not a propagation delay and should not be linked to a velocity. It tells us the time it takes for energy to be stored and released by the barrier[10]. Because of the analogy between the Helmholtz equation for electromagnetic waves and the Schrödinger equation for quantum particles, this mechanism also applies to quantum-mechanical tunnelling.

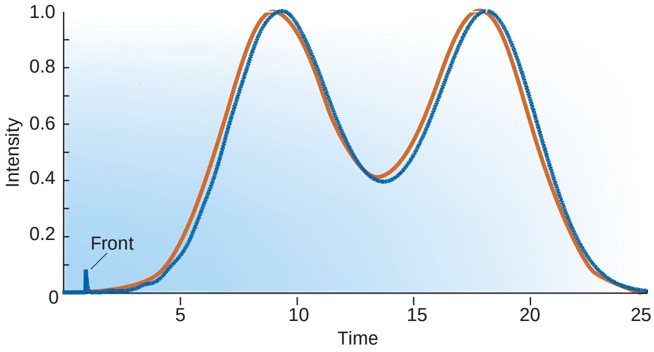

Figure 1 Tunnelling of a double-peaked pulse for a barrier consisting of a periodic dielectric structure of length L and a transmission of 1.4×10^{-3}. The delay of the tunnelled peaks (full line) relative to the input peaks (dashed line) is $0.25L/c$, or one-quarter the transit time L/c through an equivalent distance *in vacuo*. This short delay is not a propagation delay but a cavity decay time. The 'front' propagates at c. It has nothing to do with the actual tunnelling, which occurs far behind the light front. The mechanism cited by Büttiker and Washburn[6] applies only to the front.

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Büttiker and Washburn reply — Winful objects to our appeal[1] to pulse reshaping discussed in refs 2,3. It is these discussions, however, that show that causality is maintained in the tunnelling process and that no fundamental tenet of modern physics is called into question. Although these discussions were put forth for short pulses, they are not, in principle, limited to this case. Indeed, pulse reshaping also occurs for long pulses, even if only at the leading edge of the pulse.

We contend that the positions of the peak maxima are not causal, and hence are not a meaningful quantity for the definition of speed or tunnelling time. This is true for short pulses, but even more so for longer ones: the broader a wave packet becomes, the less significant is the position of its peak. As the central point in this debate is a meaningful tunnelling time, we largely ignored peak maxima in our discussions.

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— a value that is close to the theoretical limit.

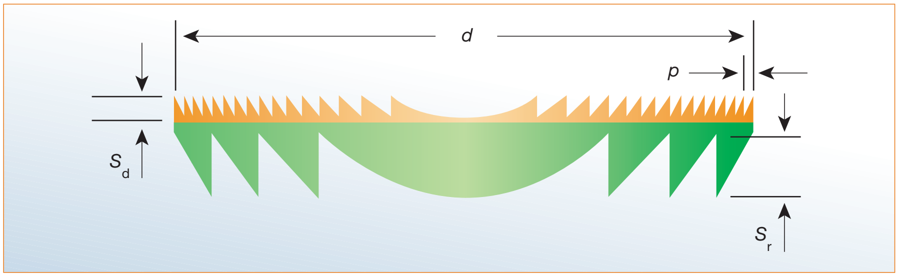

Figure 1 An achromatic refractive/diffractive lens. The diffractive component (orange) could be a phase Fresnel lens (as shown) or a (phase) zone plate. The refractive component (green) is stepped to avoid excessive absorption. Its curvature is exaggerated here for clarity. The same principle can be used both in astronomy[3] and in microscopy/microlithography[1], but with different parameters (Table 1). In the microscope objective case, stepping the refractive component introduces no error; in the astronomical case, some resolution is lost, but multiple passbands increase the throughput. d, Diameter of the lens; S_d and S_r are the depth of the steps in the diffractive and refractive components, respectively, and correspond to phase shifts of an integer number of cycles at the nominal wavelength; p is the finest pitch of the diffractive element.

In astronomy, it is angular resolution that is important. For X-rays, the best available angular resolution (0.5 arc seconds (arcsec) with the Chandra observatory[5]) is about 10^4 times worse than the diffraction limit. There are good reasons for trying to do better: attaining one of astronomy's 'holy grails' — to 'see' a black hole by imaging the space-time around the supermassive objects at the centres of active galaxies — would require resolution below 1 microarcsec, corresponding to the diffraction limit for a 60-cm-diameter system using 500-keV γ-rays, or a 60-m-diameter one using 5-keV X-rays.

In microscopy, the best resolution is obtained using Fresnel zone plates and the closely related phase Fresnel lenses. These are highly chromatic, with a focal length that is inversely proportional to wavelength, so the best resolution is obtained with essentially monochromatic radiation. Wang *et al.*[1] have proposed a scheme for making an achromatic X-ray lens by combining a Fresnel lens with a refractive component (Fig. 1). Such lenses should have the same high resolution but with a larger useful bandwidth.

Fresnel lenses have also been considered for high-energy astronomy[2,3,6], and the achromatic Fresnel lens scheme suggested by Wang *et al.* has also been proposed in that context[3]. Figure 1 shows a general achromatic lens scheme of this type. It has even been shown (L. Speybroeck, unpublished work, and ref. 6) that the second derivative of focal length, as well as the first, can be corrected by separating the two components — a configuration that may also find application in microscopy.

The achromatic configuration proposed for microscopy differs in one detail. Wang *et al.* suggest taking advantage of the high dispersion that occurs close to X-ray absorption edges. Over wider bands and for short wavelengths, λ, the dispersion, D, that they define is close to zero, but correction remains possible because of the λ^{-2} component in the expression for the focal length, f. The radii of curvature of the refractive components are much less favourable, but in astronomy the considerations are different. Spatial resolution, which is of interest in microscopy, depends on $\lambda f/d$, where d is the diameter of the lens, whereas angular resolution depends only on λ/d. Thus, long focal lengths can be used for astronomy, minimizing both the chromatic aberration that requires correction and the curvature of the components needed to correct it. Furthermore, with large d and short λ, micro-arcsec resolution does not necessarily require perfect phase coherence.

Building a micro-arcsec telescope based on a Fresnel lens will not be easy. The focal length could be up to a million kilometres, and two or three separate satellites carrying the lens(es) and the focal plane array will have to be positioned with centimetre accuracy. But micro-arcsec imaging is an important target (NASA recently included a black-hole imager in its SEUS Roadmap[7]) and other approaches to achieving this goal, such as an X-ray interferometer carried on a flotilla of spacecraft[8,9], have requirements that are just as extreme, if not more so.

Although overall system performance, including spacecraft positioning for example, will have to be taken into account, for Fresnel-lens-based telescopes the purely optical performance can be predicted with confidence. The basic physical principle has already been demonstrated in microscopy, where achromatic lenses will presumably also soon come into use. The different requirements of astronomy merely require a change of scale: lenses of many metres in diameter with millimetre-scale zones, instead of sub-millimetre lenses with zones of the order of 50 nm (Table 1). Constructional tolerances will be correspondingly easier to achieve.

An achromatic Fresnel-lens telescope measuring 10^{11} m in length will certainly not be built very soon. Perhaps experience with lenses that are limited by diffraction at the nanometre scale will give us the confidence to proceed to imaging black holes with millions of times the mass of our Sun.

Table 1 Lens parameters for astronomy and microscopy/microlithography

		Astronomy[3]	*Microscopy*[1]
Lens diameter		5 m	1 mm
Focal length at nominal wavelength		+40,000 km	+22.475 mm
Wavelength, λ (photon energy)		0.062 nm (20 keV)	1.335 nm (929 eV)
Theoretical resolution		5×10^{-6} arcsec	35 nm
Diffractive component			
	Pitch at edge	0.5 mm	60 nm
	Focal length	+20,000 km	+22.475 mm
Refractive component			
	Material	Polycarbonate	Copper
	Focal length	−40,000 km	–
	Maximum thickness*	20 mm	<1 μm

Apart from the obviously disparate scales, the differences are driven by the dispersion $Z=(d\delta/d\lambda)(\lambda/\delta)$, where $\delta=1-\mu$ and μ is the refractive index. We adopt this measure of dispersion instead of the parameter $D=df_1/d\lambda$ used in ref. 1 as it includes the dispersion present even at short wavelengths, where the atomic scattering factor f_1 is constant. Well above absorption edges (astronomy), Z is very close to -2, independent of the material. In the band close to the copper L absorption edge (microscopy/microlithography), Z is large and varies in the range -800 to $+250$.

*Based on 50% mean transmission.

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erratum

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The following information was omitted from Fig. 1 of this communication: time is in units of the transit time, *L/c*, through an equivalent distance *in vacuo*; the brown curve is the incident pulse and the blue curve represents the tunnelled pulse; also, the tunnelled pulse has been scaled by a factor of 1/0.0014 to make it visible.