Photoelectrons measuring the phase of light

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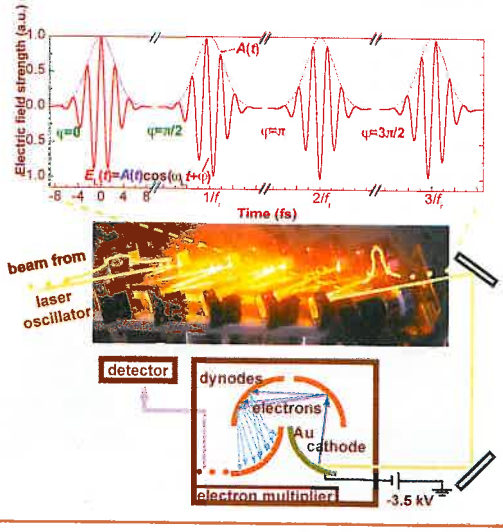
Ultrashort, visible laser pulses have gained immense importance in the past decade. The new technology based mainly on Ti:sapphire lasers has achieved several breakthroughs in respect of increasing the magnification of by far the best temporal magnifying glass mankind has ever had. With this tool even those extremely fast processes can be resolved in time that would normally appear as smeared out just like the images taken with a camera with insufficient shutter speed. These advanced light sources have not only revolutionised femtochemistry by affording an insight into ultrafast chemical processes, earning Ahmed H. Zewail the Nobel Prize for Chemistry in 1999, but have also allowed a huge further step to be made by the production of isolated attosecond (1 as = 10^{-18} s) pulses in 2001 [1]. Interaction of femtosecond pulses with gases results in X-ray generation which, under certain circumstances, can give rise to a single X-ray burst as short as 250 as – an order of magnitude shorter than could have been dreamed of five years ago. Apart from the unprecedented temporal resolution that they provide, these laser-driven X-ray sources afford promise of compact, coherent X-ray diagnostic tools that are so much desired by the medical industry.

Several further intriguing questions are raised, such as, what happens when the length of such a visible pulse (the current state-of-the-art is around 3.5 fs) becomes comparable to the oscillation cycle (2.7 fs at the typical wavelength of 800 nm of Ti:sapphire lasers). Does the momentary amplitude of the oscillations (the envelope of the pulse – see upper part of Figure 1) remain a crucial parameter in determining the interaction of these pulses with matter or has one rather to take the evolution of the actual electromagnetic waveform into account? Intuition, simulations and, most recently, experiments have all indicated that the latter is the case, for example, when one assesses the photoelectron yield from a metal surface induced by controlled, few-cycle optical waveforms, as we have recently shown [2]. If this is true, the standard approach to light-matter interactions aiming only at control over the evolution of the temporal amplitude envelope of such laser pulses has become out-of-date.

Even though there is a wide spectrum of technologies that allow almost arbitrary shaping of the envelope of laser pulses, the control of the actual waveform within the envelope remained a challenge until 2000. It then became possible to gain access to this last final parameter of light in such a way that the end result was a train of ultrashort laser pulses in which the relative phase between the carrier wave and the envelope of the pulse (the carrier-envelope phase, CEP) shifts from one pulse to the next by a known, controlled and stabilised amount (as depicted in the upper part of Figure 1) [3]. Even though this did not imply that the actual carrier-envelope phase value of an individual pulse could be measured, it was a true revolution in another sense. Namely, when one looks at such a phase-stabilised pulse train in the frequency domain one finds that it is composed of a comb of equidistant frequencies with a fixed and stable offset from zero frequency, i.e. a truly unprecedented reference in the visible and near-infrared optical domains [4]. This optical frequency ruler can then be used for metrological applications in a domain that was only accessible before with a dozen synchronised oscillators typically filling an industrial-scale facility. The improvement was immense and this branch of research has been intensively pursued since then. The measuring accuracy has improved by several orders of magnitude thanks solely to this technology. In this way such exciting aspects as, for example, the measurement of the much-debated time drift of fundamental constants have been put within reach. Apart from this most important spin-off of carrier-envelope phase stabilisation, it has opened a new era in the investigation of light-matter interactions.

In 2003 several optically induced phenomena were shown to depend on the carrier-envelope phase. One of them is of particular interest, since it allows unambiguous measurement of the phase of low-energy laser pulses. It is based on the well-known photoelectric effect, the research history of which spans from the late nineteenth century until the present and in which eminent physicists have played a prominent role.

In 1886-1888 Hertz and Hallwachs observed the emission of electrons from a metal surface when light of sufficiently high frequency impinges on it. This process is known as the photoelectric effect. The so-called "light electricity" was explained by Einstein in 1905, for which he received the Nobel prize in 1921. The photon



▶ **Fig. 1:** A train of chirped laser pulses with a central wavelength of 750 nm, produced by a special Ti:sapphire oscillator with a repetition rate f_r=24 MHz, is compressed by 12 reflections off specially coated (chirped) mirrors (middle part of figure) after which the pulses attain a duration of 4 fs. The pulse train has also been carrier-envelope phase stabilised (in a setup not shown in the figure). This results in a waveform evolution similar to that depicted in the upper part of the figure; i.e. every n^{th} laser pulse has the same electromagnetic waveform (in the figure, n=4 for the sake of simplicity; in the experiment n=24 was realised). The pulse train interacts with a gold surface that emits electrons in a multi-photon process. These are then amplified in a multiplier tube, the output signal of which clearly shows a frequency component at f_r/n, this being a clear indication that the emission process is directly sensitive to the actual optical waveform, not just to the amplitude envelope. By means of simulation results the measurement can be calibrated so that we can tell at an arbitrary time the shape of the waveforms interacting with the surface.

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approach of Einstein allowed the early experiments to be explained: the photoelectric effect takes place when the photon energy exceeds the threshold for freeing the electrons from the metal. If it occurs, the number of electrons emitted depends on the light power (i.e. the number of photons) and its polarisation. In addition to these parameters, we have found that the photoelectric effect (photoelectron emission from a gold surface) also depends on the phase of the light (or, more precisely, the carrier-envelope phase) in the case of few-optical-cycle laser pulses.

The mathematical expression for the electric field of a short light pulse ($E_L(t)$ in Figure 1) includes its temporal amplitude evolution ($A(t)$), central carrier frequency (ω_L) and the carrier-envelope phase (φ). It has not been possible to measure the last parameter, the phase, until now, but the photoelectric effect has allowed us to access this quantity, with the indispensable help of colleagues from the National Institute of Advanced Industrial Science, Japan, and Max-Planck-Institut für Quantenoptik, Germany [2]. By utilising the fact that the carrier-envelope phase evolves in the pulse train periodically with a fixed frequency, we have presented experimental proof of the phase sensitivity of photoelectron emission from a metal cathode by demonstrating that the output signal of the multiplier has the same periodic variation (see Figure 1). The known theoretical prediction of the maximum of the photocurrent as a function of the carrier-envelope phase [5] served as an absolute calibration for carrier-envelope phase determination in the experiment. This finding, provided by a compact, solid-state detector, opens the door for the experimental characterisation of the complete waveform of light pulses and the optimisation of a huge variety of nonlinear experiments in optics on femtosecond and attosecond time scales.

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Physics in daily life: Drag 'n' Roll

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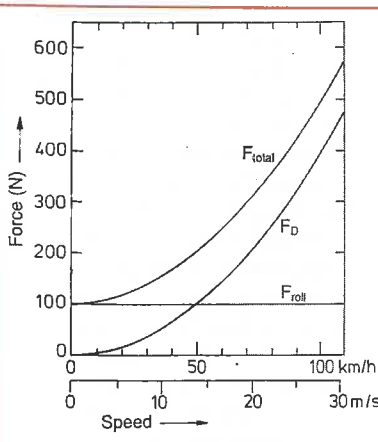
Whether we ride our bike or drive our car: there is resistance to be overcome, even on a flat road; that much we know. But when it comes to the details, it's not that trivial. Both components of the resistance—rolling resistance and drag—deserve a closer look. Let us first remember the main cause of the rolling resistance. It's not friction in the ball bearings, provided they are well greased and in good shape. It's the tires, getting deformed by the road. In a way, that may be surprising: the deformation seems elastic, it's not permanent. But there is a catch here: the forces for compression are not compensated for by those for expansion of the rubber (there is some hysteresis, if you wish). The net work done shows up as heat.

The corresponding rolling resistance is, to a reasonable approximation, independent of speed (which will become obvious below). It is proportional to the weight of the car, and is therefore written: $F_{roll} = C_r$ mg, with C_r the appropriate coefficient. Now we can make an educated guess as to the value of C_r. Could it be 0,1? No way: this would mean that it would take a slope of 10% to get our car moving. We know from experience that a 1% slope would be a better guess.

Right! For most tires inflated to the recommended pressure, $C_r = 0{,}01$ is a standard value. By the way: for bicycle tires, with pressures about twice as high, C_r can get as low as 0,005.

The conclusion is that, for a 1000 kg car, the rolling resistance is about 100N.

What about the drag? In view of the Reynolds numbers involved ($Re \approx 10^6$) forget about Stokes. Instead, we should expect the drag F_D to be proportional to $^1/_2\,\rho v^2$, as already suggested by Bernoulli's law. On a vehicle with frontal area A, one can write $F_D = C_D A \cdot {}^1/_2\,\rho v^2$. Now, C_D is a complicated function of speed, but for the relevant v-range we may take C_D constant. For most cars, the value is between 0,3 and 0,4.



▲ Fig. 1

The total resistance is now shown in the figure, for a mid-size model car (m=1000 kg, $C_r = 0.01$, $C_D = 0{,}4$ and A=2 m²). It is funny to realize that the vertical scale immediately tells us the energy consumption. Since 1 N is also 1 J/m, we find at 100 km/h approximately 500 kJ/km for this car. Assuming an engine efficiency of 20%, this corresponds to about 7 liters of gasoline per 100 km. At still higher speeds, the figure suggests a dramatic increase in the fuel consumption. Fortunately, it's not that bad, since the engine efficiency goes up, compensating part of the increase.

What about the engine power? Since $P = F \cdot v$, we find at 100 km/h about 15 kW is needed. That's a moderate value. But note that, at high speed where drag is dominant, the power increases almost as v^3! Should we want to drive at 200 km/h, the engine would have to deliver the 8-fold power, or 120 kW. That's no longer moderate, I would say, and I'm sure the police would agree....