Reflection revisited

Light is often thought to reflect from a flat surface at the same angle at which it is incident. *Nature Photonics* spoke to Han Woerdman about the observation of angular deviations of reflected beams.

Could you tell me about the early history of reflection of light?
The Greek philosophers are thought to be the first known to have invented the concept of a light ray. The law of reflection itself, which is a follow-up of the concept of the ray, dates back to Euclid around 300 BC and his book *Catoptrics*. This work was then translated by Arab philosophers in the early middle ages and that is the way it came to the west. Newton should also be mentioned here, as in Newton's *Opticks* the law of reflection is one of his axioms.

And what happened in more modern times?
In 1943, the two German scientists Goos and Hänchen performed an experiment showing that in total internal reflection a light beam acquires a lateral shift; this can be seen as a positional deviation of the law of reflection. Because of the Second World War, this work was not published until 1947. That was the starting point of much theoretical work, leading to diffractive corrections to ray optics. The Goos–Hänchen was one of them; several others were predicted, including the angular deviation of the law of reflection. The first experimental demonstration thereof, although with a couple of limitations, was done in the microwave domain in 2006 by Nimtz and collaborators.

What was your motivation for the research?
Our work on the angular shift came out of our work on surface-plasmon-assisted transmission of entangled photons through a gold hole array, which appeared in *Nature* in 2002. We wanted to develop a deep understanding of surface plasmon behaviour, so we went back to the case of a uniform surface to study the effect of a non-local response on the optical reflection from gold. This turned out to be far too small an effect to see, but it gave us the motivation to study the exact nature of optical reflection. The general motivation for investigating the effect at shorter wavelengths than microwave is application-associated.

Left to right: Martin van Exter; Han Woerdman; Michele Merano.

Why does the angular deviation in the reflection occur?
The essence is that a 'ray' is an artificial construct that does not exist in real life. Its closest physical implementation is a beam of light. Such a beam can be viewed as a set of plane waves travelling at different angles. If the beam strikes a surface that has a reflectivity that is less than perfect (R < 100%) then you generally have angular dependence of the reflectivity. That is, each of the plane waves experiences a different strength of reflection, which serves to reshape the reflected beam and alter its direction of propagation into the far field. In our setup a beam is reflected by an air–glass interface and its transverse position is measured with a calibrated split detector.

What were the main challenges in performing the experiment?
The optical source was the main issue. We started out with a semiconductor laser as a light source, but this gave poor results. We then used superluminescent light-emitting diodes which gave a big improvement for two reasons. First is that they have low temporal coherence (the bandwidth is 20 nm), which means that the unavoidable reflections in the optical train do not produce optical speckle. The second reason is that the diode has no cavity and has no transverse modes, so the beam pointing stability is better than that of a semiconductor laser.

Another important point is that in some of the experiments we modulate the polarization. It turns out that it is difficult to modulate the polarization without also slightly modulating the position and angle of the beam. We thought that a single-mode fibre as a spatial filter would solve this problem, but it did not guarantee the spatial stability we required. As a result, we turned to a liquid-crystal-based polarization modulator which works well but depolarizes, say, 1% of the light.

What are the implications of your findings?
Although the angular deviation is usually small (typically 10^{-2} to 10^{-5} rad), if you have a detector or a relevant optical component that is many Rayleigh lengths from the beam focus, the effect can become important. Applications in which this effect may come into play include angular metrology in general and cantilever-based surface microscopy. Other applications that come to mind are interferometry, including situations that may arise in the Laser Interferometer Space Antenna (LISA) or the Laser Interferometer Gravitational-wave Observatory (LIGO).

INTERVIEW BY DAVID PILE

Han Woerdman and his team have a Letter on angular deviations of a light beam upon reflection on page 337 of this issue.