FUNDAMENTAL OPTICAL PHYSICS

Uncovering superabsorption

Absorption is often dismissed as a dull phenomenon over which we have little control. Researchers have now used a combination of absorption and interference effects to not only control but also drastically enhance the absorption process.

Ad Lagendijk

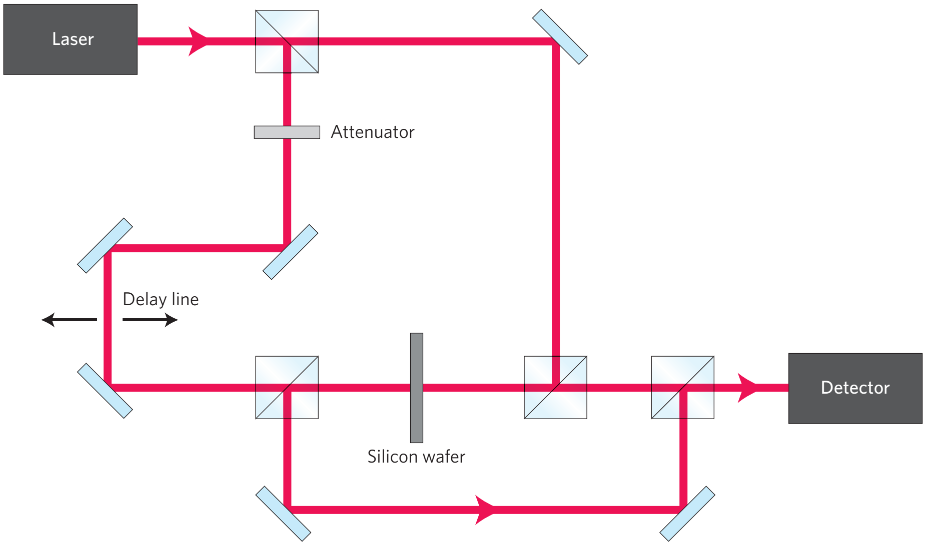

Figure 1 | The set-up of Wan *et al.* A continuous-wave tunable laser beam is sent into a Mach–Zehnder interferometer that contains an absorbing etalon (a polished silicon wafer) in one of its legs. The four beamsplitters cause the beam to circulate in both directions inside the interferometer, thereby exciting the etalon from both sides. The adjustable delay line allows the relative phase between the two counter-propagating beams to be varied.

Absorption comes in many guises, some of which are helpful, some of which are a hindrance. For example, in the field of nanophotonics, absorption plays a crucial but typically unwanted role that prevents a number of envisaged applications. For solar cells, however, optimizing absorption is the design goal.

Wenjie Wan and colleagues from Yale University in the USA have now demonstrated that combining absorption and interference effects allows absorption to be not only controlled but also dramatically enhanced by up to two orders of magnitude. Although demonstrated in a relatively simple optical system, their work highlights a general phenomenon that may force us to reconsider our view of absorption as a dull and unmanageable process.

It is well known that optical systems with gain can lase. One way to understand lasing is by considering power balance; the power inside the laser cavity tends to increase because of optical gain, but also tends to decrease as radiation is lost through the cavity boundaries. The point at which gain compensates exactly for loss is known as the lasing threshold. One can imagine that the time-reversed counterpart of a lasing cavity has an absorption threshold instead of a lasing threshold. The gain in such a cavity would be radiative (the light entering the cavity), and the loss would be due to absorption. At the absorption threshold, absorption would exactly compensate for radiative gain, with all the incident light being absorbed.

This fascinating absorption threshold has not yet been reached, but Wan *et al.* have certainly demonstrated significant progress towards it. Their experiment exploits the fact that absorption is essentially caused by the interference of scattered waves. In fact, all deviation from free-wave motion can be described as a scattering process, and this includes absorption. In this respect, absorbers are simply scatterers whose scattered waves are 180° out of phase with the incoming wave, leading to destructive interference. The researchers boost this destructive interference by externally supplying a wave that participates in the interference process.

Wan *et al.* used a polished silicon wafer for their cavity, because silicon has an intermediate absorption coefficient at the wavelength used in the experiment. If the absorption coefficient of the material is too weak, insufficient absorption takes place to have any effect at all. However, if the absorption coefficient is too high, the required multiple reflections and interference would not take place. The team recently theorized[2] that reaching the absorption resonance of such a cavity would require the imaginary part of the material's index of refraction (n_2) to be of the order of 10^{-3}. The filled cavity functions as a Fabry–Pérot etalon with reflecting walls, providing a quality factor of $Q \approx 840$. The wavelength of the continuous-wave light source used in the experiment could be varied over the interband transition of silicon, allowing the (complex) index of refraction of the cavity to be precisely tuned to the correct level ($n_2 = 0.0008$).

The cavity was placed in one arm of a Mach–Zehnder interferometer (Fig. 1). A set of beamsplitters was then used to circulate the excitation light in both directions inside the interferometer, thus allowing the silicon wafer to be illuminated from both sides at normal incidence. A delay line provided a relative phase difference between the two coherent beams arriving at the wafer. Illuminating the wafer with only one of the two circulating beams gave the conventional picture of light trapped inside a cavity. However, illuminating the wafer from both sides introduced a significant phase-dependent increase in absorption, which the researchers refer to as coherent absorption (Fig. 2). A phase difference of π provided the maximum absorption enhancement of two orders of magnitude.

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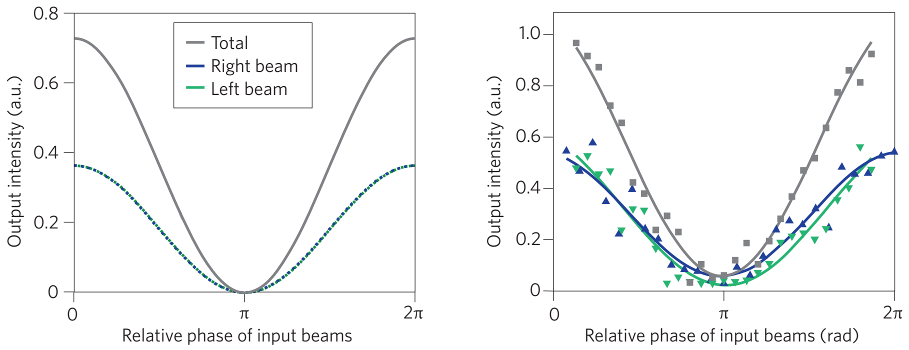

Figure 2 | Phase modulation of beam absorption. Theoretical (left) and experimental (right) normalized output intensity as a function of relative phase between the two (right- and left-incident) input beams. The wavelength was in this case chosen to be as close as possible to a perfect absorption resonance. The intensity minimum at a relative phase of π corresponds to an absorption enhancement of two orders of magnitude.

The laser wavelength was chosen to be as close as possible to the coherent absorption resonance condition (about 998 nm). The theoretical enhancement factor of 10^4 was not obtained because of (foreseen) laser coherence and resolution limitations. Perfect absorption could be obtained if two experimental parameters are varied instead of just one, as in the present experiment.

The observations can be thought of in a number of different ways. For instance, one could say that combining coherent beams in this way leads to a much longer path length (or residence time) inside the cavity due to interference. Alternatively, one could say that the beams leaving the cavity are reduced in intensity because of destructive interference.

Wan *et al.* have demonstrated superabsorption for a simple two-mode cavity, but this phenomenon might also be possible in higher-dimensional systems. One difficulty in attaining perfect absorption in such systems would be producing the many interfering excitation modes required by more complex phase patterns. Despite this, there are many reasons to be optimistic. First, the time-reversed counterpart of perfect absorption — lasing — can already be achieved in more complex systems. Second, the recent invention of wavefront-shaping allows for incredible flexibility in controlling excitation wave patterns, and its efficacy for enhancing absorption has already been demonstrated[3].

Sources are universally considered to be an important ingredient of wave equations, and investigations into their fundamental power balance continue to reveal surprising features[4]. Research into their time-reversed counterparts — sinks — has been delayed for far too long. The seeming lack of interest in light absorption is unjustified, not only because applications such as photovoltaics and medical therapies depend on optimizing the absorption process, but also because it is a fundamental phenomenon. All treatments of absorption are essentially based on an incoherent, mean-field approach, in which a local time-dependent absorption process is approximated by a homogeneous amplitude that decays exponentially in time and space. Unfortunately, however, this simplistic treatment neglects all types of coherence effects and absorption-induced correlations.

Wan *et al.* have demonstrated the controllable nature of absorption, a result that promises to uncover many new surprising properties of sinks. From this work we learn that optical properties such as absorption can be controlled not only by structuring the material system, but also by structuring the incident light. Whether absorption is desired or not, the work of Wan *et al.* is one step towards gaining control. ❐

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References

1. Wan, W. *et al. Science* **331**, 889–892 (2011).
2. Chong, Y. D., Ge, L., Cao, H. & Stone, A. D. *Phys. Rev. Lett.* **105**, 053901 (2010).
3. Vellekoop, I. M., van Putten, E. G., Lagendijk, A. & Mosk, A. P. *Opt. Express* **16**, 67–80 (2008).
4. El-Dardiry, R. G. S., Faez, S. & Lagendijk, A. *Phys. Rev. A* **83**, 031801(R) (2011).

TERAHERTZ QUANTUM CASCADE LASERS

Going ultrafast

A new asynchronous coherent optical sampling method allows for the direct visualization of actively mode-locked quantum cascade laser pulses at terahertz wavelengths.

Roberto Paiella

Over the past decade, quantum cascade lasers (QCLs) have firmly established themselves as the leading semiconductor laser sources for the mid-infrared and terahertz spectral regions. The light-emission mechanism of QCLs involves intersubband transitions between quantized energy states derived from the same energy band (the conduction band), which is radically different from the electron–hole recombination mechanism of traditional interband diode lasers. As a result, QCLs feature a wealth of unique physical properties and operational characteristics that have been widely investigated over the past several years and continue to be the subject of extensive research.

A particularly interesting example is provided by their dynamic properties[1]. In general, laser dynamics is controlled by three separate time constants, namely the laser-cavity roundtrip time, the photon lifetime and the relaxation lifetime of

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