LIGHT TRAPPING

Absorbing light using time-reversed lasers

Laser cavities can be reverse engineered to create an efficient light trap

By **Jacopo Bertolotti**

In 2019, researchers from the Massachussetts Institute of Technology made headlines when they created the "blackest" material to date, which had the ability to absorb 99.995% of incident light (*1*). More than aesthetics, there are many technologies that can benefit from maximizing light absorption—for example, in photovoltaics because of the need to absorb and convert as much light as possible into electricity, or on the interior surface of a light sensor because of the need to minimize unwanted stray light. Although there are many ways to create something that can absorb some light, the endeavor gets more and more difficult the closer it gets to 100% absorption. On page 995 of this issue, Slobodkin *et al.* (*2*) report on a design principle that can absorb light on the basis of "coherent perfect absorption" (*3*), which can theoretically absorb 100% of the light incident on the device.

Intuitively, one might assume that a material with a larger absorption coefficient would lead to it being a better light absorber, but this is not always the case. For example, a sharp change in the value of the absorption coefficient will lead to the reflection of a large fraction of the incident light, which sends the light away instead of letting it be absorbed. This is why many metals make for very good mirrors despite having a decent absorption coefficient (*4*). One possible solution to this conundrum of absorption versus reflection is to use a material with a low absorption coefficient. This allows light to enter the medium without being reflected away, and consequently, the light remains in the medium for a long time and is gradually absorbed. This phenomenon can be observed in the darkness at the bottom of the ocean, where most of the sunlight has been absorbed by water, which itself is nearly transparent.

However, the obvious practical problem with this approach is the amount of space it requires, which limits its usefulness for most applications. A well-established approach to obtaining a similar absorption in a smaller volume is to trap the light inside the medium. This is achieved in those "ultrablack" paints by using diffusive materials, in which the light is scattered many times and thus takes a long time to exit the medium (*1*). Although this approach works well to remove unwanted light, many applications aim to absorb light for use as energy (such as a solar panel). It can thus be difficult to integrate, for example, the photovoltaic material with the black paint to improve the overall efficiency of the device.

One way to help a functional absorber, such as a photovoltaic cell, to absorb light is to create an environment that can trap light for the absorber. This is the purpose of the cavity used by Slobodkin *et al.* Electrodynamic phenomena are invariant under time reversal, which means that if a certain electrodynamic effect exists, then there should also exist a time-reversed equivalent (*5*). Because the time-reversed equivalent of light emission is light absorption, any system that emits light can, in principle, also be used to absorb light. In particular, lasers use a cavity to trap the light around a light emitter to control and amplify it. Replacing an emitter with an absorber (even a poor one) will make the system operate in reverse and absorb the light very efficiently (*3*). However, the problem with this design approach is that a laser cavity traps only specific patterns of light (modes), and thus time reversal can be used only to absorb light that happens to be in one of the specific modes. Any other mode, such as beams coming at a different angle or having a different shape, will not be stable in the cavity and will not be absorbed as much. What is needed is a cavity that traps all possible modes.

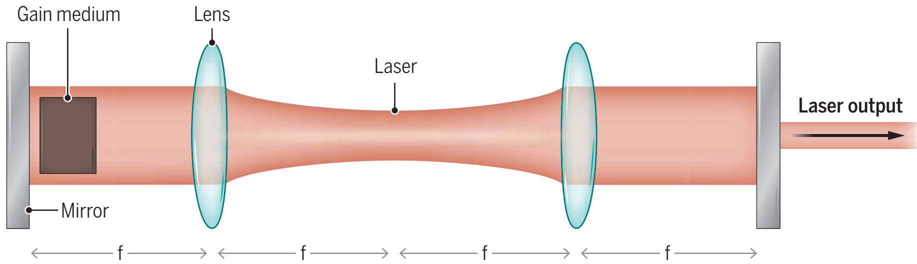
Slobodkin *et al.* designed a system that can trap all modes of light by using so-called "degenerate" optical cavities (*6*). An optical cavity is said to be "degenerate"

As amplification, so absorption

Inside a degenerate optical cavity, light rays are reflected and refracted so that they always follow the same trajectory, which keeps all light modes circulating in the cavity. Although this design was originally devised to amplify light in a laser, it can be adapted for light absorption. f, focal length of lens.

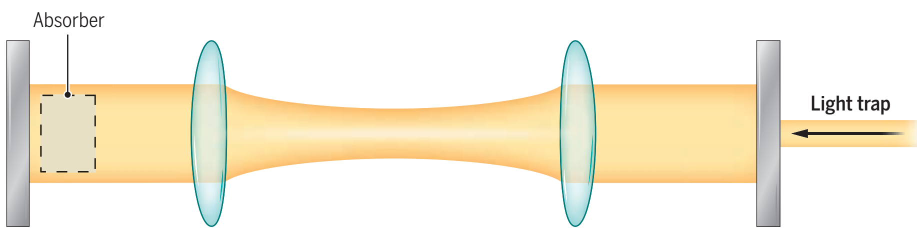
For amplification

Light is kept circulating in the cavity and is amplified at each passage by the gain medium. However, a small fraction of light escapes the cavity as the laser emission.



For absorption

When the gain medium is swapped for an absorber, the trapped light will gradually be absorbed. This makes the degenerate cavity a universal light absorber.



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when any ray of light will eventually retrace its own path in the cavity. The simple design by Slobodkin *et al.* uses two mirrors on the outside and two lenses on the inside (see the figure). The light is trapped between the mirrors, and the addition of lenses helps guide the rays to always hit the same spot on the mirrors after each reflection, making the system degenerate. As a result, any light trapped between the two mirrors and the two lenses is kept circulating inside the cavity and absorbed at each reflection (*7*).

Although the experimental implementation of Slobodkin *et al.* is just a proof-of-principle device, it points to what can be done with this method in the future. Albeit only achieving around 95% absorption in their demonstration, their design strategy—known as "massively degenerated coherent perfect absorption"—can in principle absorb 100% of the incident light.

Their proof-of-concept device is also surprisingly robust to imperfections in its fabrication. This is somewhat unusual for a method that relies on wave interference because it is not uncommon for a misalignment of just a few tens of nanometers to destroy the desired effect.

"…any system that emits light can, in principle, also be used to absorb light."

Although the exact design of the device may not be ready for immediate applications, it provides the distinctive advantage of enhancing the absorption of any other device without modifying it, which could be used to improve the efficiency of photodetectors or photovoltaic units. The use of a cavity also opens the way to very sophisticated manipulations of absorption. By exploiting the techniques developed for lasers, it should be possible to design cavities that only trap certain frequencies. This would allow frequency-dependent absorption or the use of different frequencies of light to accumulate different phase retardations to generate time-dependent absorption. ■

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CORONAVIRUS

Wildlife trade is likely the source of SARS-CoV-2

Multiple transmissions from wildlife at a market in Wuhan probably led to SARS-CoV-2 emergence

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Almost all pandemic viruses have zoonotic origins, including severe acute respiratory syndrome coronavirus (SARS-CoV) and SARS-CoV-2 (*1*). During SARS outbreaks between 2002 and 2003, a live animal source of SARS-like viruses was identified at a market in Guangdong, China, providing unequivocal understanding of its zoonotic origin. Although the most probable reservoir animal for SARS-CoV-2 is *Rhinolophus* bats (*2*, *3*), zoonotic spillovers likely involve an intermediate animal. Various SARS-CoV-2–susceptible intermediate animals were sold at the Huanan Seafood Wholesale Market in Wuhan, such as raccoon dogs, foxes, and mink. But these were unavailable for testing, so direct evidence of an animal source is lacking. Thus, it remains unknown exactly how SARS-CoV-2 emerged and led to the COVID-19 pandemic. On pages 951 and 960 of this issue, Worobey *et al.* (*4*) and Pekar *et al.* (*5*), respectively, provide quantitative evidence that SARS-CoV-2 emergence was likely caused by multiple zoonotic transmissions due to wildlife trading at the Huanan Market.

The search for the origin of SARS-CoV-2 resulted in numerous discoveries of SARS-CoV-2–related viruses in bats and other susceptible animals, with implications for virus evolution. The most closely related bat coronaviruses to SARS-CoV-2, which were sampled in Laos, share an ancestor from ~30 years ago (*3*). At the genomic level, two of these viruses (BANAL-103 and BANAL-52) harbor a nearly identical receptor binding motif (responsible for human cell entry) to SARS-CoV-2 (see the figure). However, 30 years of evolution could have led to substantial mutational changes in the viral genome (*2*). Therefore, continual sampling of SARS-CoV-2–related viruses in bats and other susceptible animals in Southeast Asia and China may still help characterize the evolution and origin of SARS-CoV-2, even if the intermediate animals from the Huanan Market that carry the direct ancestor of the SARS-CoV-2 strains isolated in COVID-19 patients in Wuhan are no longer available.

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Even without the intermediate animal, likely because Huanan Market was cleared from 1 January 2020, it is still possible to learn how SARS-CoV-2 may have emerged. Available epidemiological, genomic, and human demographic data from the location where human infections first emerged, which is not necessarily the place of virus evolutionary origin, can be analyzed to understand the beginning of the pandemic. To test whether Huanan Market is the source of the COVID-19 pandemic, Worobey *et al.* provide epidemiological evidence that the early cases were centered around the market, not other places frequently visited by people in Wuhan. Moreover, subsequent human-to-human transmissions shifted from the market and its neighborhood to more populated areas of Wuhan, particularly those with susceptible elderly people.

Was wildlife trading the origin of the early COVID-19 outbreak at Huanan Market? Worobey *et al.* provide evidence that there was trading of SARS-CoV-2–susceptible wildlife spanning several years immediately before December 2019. This created opportunities for close, sustained contacts between these animals and humans at the market, laying the foundation for potential zoonotic spillover. Moreover, Worobey *et al.* find that the market stalls that sold susceptible wildlife species are spatially correlated with SARS-CoV-2–positive environmental samples. Some of these sampled objects were used to handle wildlife, such as a metal cage and carts (*6*). At the beginning of the pandemic, two viral lineages of SARS-CoV-2 (termed S and L) were revealed from the viral genomes of early cases (*7*) and later termed A and B. These strains only differ by two mutations. However, how these lineages relate to an early zoonotic spillover was unclear owing to the lack of a direct ancestor virus for comparison. Worobey *et al.* established epidemiological links of early cases of the two viral lineages A and B to the market, and these lineages were present in the positive environmental samples from the market (*6*).

How could zoonotic transmission lead to the emergence of two viral lineages at

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