

Gobbling up light with an antilaser

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An unappreciated symmetry of electrodynamics enables experimenters to fabricate coherent perfect absorbers, devices that act like lasers run backward.

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A basic principle of physics states that elementary physical processes can be reversed in time. For example, a movie of two billiard balls colliding and moving off at different speeds in different directions will look consistent with Newton's laws whether you run it forward or backward. At least it will if the friction between the billiard balls and the surface they are rolling on is negligible. The friction arises from interactions involving microscale processes that cannot be reversed under typical experimental conditions. Friction thus breaks time-reversal symmetry. And if the friction is significant, the movie of billiard ball collisions will look decidedly odd when run backward: The balls that normally slow down while rolling freely on the table will instead pick up speed.

Maxwell's equations for the propagation of electromagnetic waves in vacuum exhibit the same time-reversal symmetry as frictionless mechanics. But when matter is present, interactions between radiation and the medium play the same role as friction. Absorption by the medium affects the radiation propagation, so the passage of radiation through matter violates time-reversal symmetry. The equations governing electrodynamics in the presence of matter, however, exhibit a more general form of symmetry that relates two different types of electromagnetic processes—absorption and amplification.

Trapping with constructive interference

For more than a century, we have known how to make electromagnetic amplifiers, devices that essentially reverse the effects of loss in Maxwell's equations. The first generation of amplifiers was developed at the turn of the 20th century and worked on RF waves. Eventually scientists learned how to amplify microwave and optical radiation and, in the middle of the 20th century, introduced masers and the lasers that are now part of everyday life. The ability of amplifiers to oppose electromagnetic losses leads to a generalization of the usual time-reversal symmetry: Given an electromagnetic process in which a propagating wave is amplified to a certain degree, there exists a time-reversed process with the same degree of absorption. Recently that principle has been applied to demonstrate the time-reversed process of laser emission, an effect called coherent perfect absorption.

The device that behaves like a time-reversed laser is called a coherent perfect absorber (CPA)—informally, an

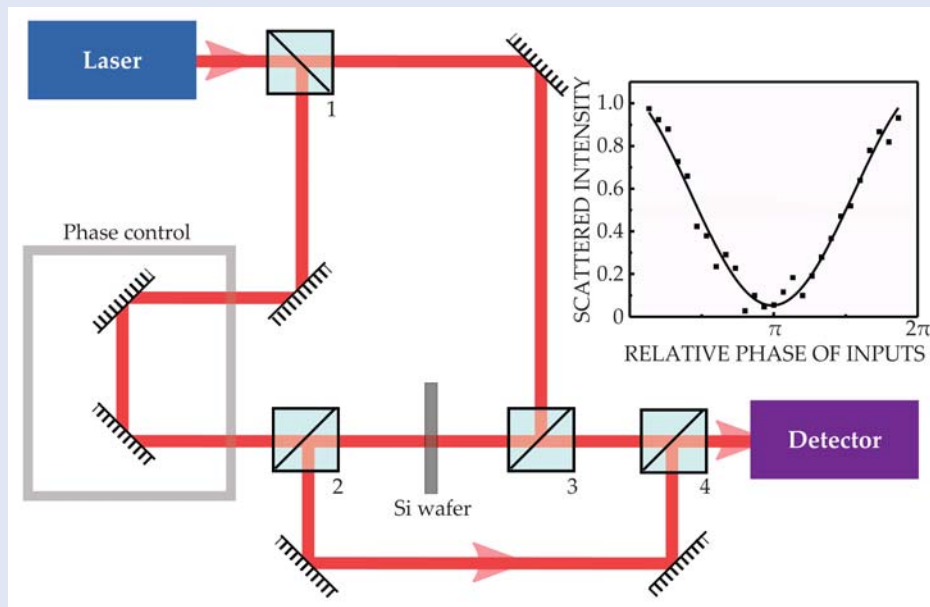
antilaser. The CPA will completely absorb incident radiation in a small frequency range, if the detailed spatial distribution of the radiation matches one that would be emitted by a corresponding laser. If the spatial pattern doesn't match—even if the radiation has the correct frequency—the same device may well absorb very little of the incident light and instead transmit or reflect most of it. To understand how a CPA performs that potentially useful trick, you first need to know how a laser works.

Although a laser can function as an amplifier, most of the devices we call lasers are used not to amplify light but to generate it. They do that by combining two key components. The first is a gain medium, which is simply a material with the appropriate quantum mechanical level structure. The second is a resonator, typically two parallel mirrors or facets bounding two sides of the gain medium. Energy supplied to the gain medium, often by electric current, causes the atoms or molecules of the medium to become excited. In time, the population is inverted, meaning that more atoms or molecules are in their excited state than in the ground state. Occasionally one of those excited entities emits a photon that travels in the gain medium. That solitary photon, according to the principle of stimulated emission discovered in a groundbreaking work by Albert Einstein in 1917, will cause more atoms or molecules to emit photons traveling in the same direction as the original photon.

Because of the resonator, the directions through the gain medium are not equal. The photons emitted in the directions perpendicular to the mirrors stay much longer in the medium, bouncing back and forth from mirror to mirror. The many passes create a positive feedback not unlike a nuclear chain reaction and cause exponential growth of a certain mode of the electromagnetic field. The mode is then emitted through one of the mirrors, which has been made partially transmitting. The specific narrow frequency band of the emission is determined mainly by the frequency that allows constructive interference to arise from the light generated inside the resonator.

Viewed from the outside, a laser is a resonator that emits a radiation field with a specific frequency and spatial distribution without the need of an input field. Ergo, by the generalized time-reversal symmetry of electromagnetics, it should be possible to generate a field that will be perfectly absorbed; the field must have the same frequency and distribution as the emitted laser field but be incoming rather than outgoing, and the gain medium of the laser must be replaced with a medium that absorbs at the same rate that the laser's gain medium amplifies.

Actually, the absorbing medium need not absorb particularly strongly. The time-reversed laser, the CPA, functions as a perfect constructive interference trap for radiation with a particular frequency and spatial distribution. So even if light can travel a long distance in the absorbing medium before it is absorbed, it *will* eventually get absorbed as it bounces back and forth indefinitely. On the other hand, a different radiation pattern, even one with the same frequency,



A backward-running laser.

In a 2011 experiment performed at Yale University, my colleagues and I demonstrated time-reversed laser action and control of absorption in a 100- μm -thick silicon wafer. When the laser action is reversed, the wafer functions as a coherent perfect absorber—informally, an anti-laser. Beamsplitter number 1 generates two laser paths that meet in the wafer. The intrinsic loss within Si varies with wavelength λ and, at $\lambda = 998.5\text{ nm}$, has just the right value to form a perfect interference trap provided the two beams are out of phase by π ; in that case the two beams are more than 99% absorbed. The absorbed beams correspond to the time-reversed version of the laser radiation the wafer

would emit if it contained an equivalent gain medium. When the phase offset of the beams is other than π , the Si wafer scatters light, which is diverted to a detector by beamsplitters 2–4. The plot at the upper right shows how the measured scattering intensity (normalized to its maximum value) varies with offset and demonstrates that we can tune the degree of absorption in the wafer simply by varying the interference properties of the input radiation.

will not be totally absorbed because the interference trap will not be created; in that case, a weakly absorbing medium will allow most of the light to escape. Thus the CPA concept highlights something not widely appreciated: How a medium absorbs depends not only on its atomic constituents and the frequency of the incident radiation but also on the detailed spatial distribution of the incident field. As a consequence, one can consider tuning the external field to either enhance or suppress absorption.

Two beams are better than one

Some 20 years ago, several research groups demonstrated CPAs in simple systems. In those and subsequent realizations, the CPA perfectly absorbs a single input beam. Inasmuch as most lasers are designed to emit a single, collimated output beam, those CPAs really did look like backward-running lasers, so it is perhaps surprising that no one seems to have realized their relation to lasers via time reversal.

The single-channel CPAs just described have a major limitation to their operation that arises because only a single mode of the electromagnetic field reaches the resonator: As long as the absorption of the medium within the CPA is tuned to the right value, the interference trap will be present; it cannot be controlled by modulating the input field. It is easy, however, to make a laser that emits two or more output beams—for example, by using two equivalent partially transmitting mirrors to bound the gain medium. In 2010 my colleagues and I presented the theoretical framework for time-reversed lasing and proposed a new two-channel experiment in which changing the field pattern can both enhance and suppress absorption in the CPA. A year later an expanded team realized the experiment, which is sketched in the figure. Due to the left–right symmetry of the system, to theoretically obtain perfect absorption we would need to illuminate the silicon wafer of our experiment with two oppositely directed beams that have the same amplitude but a phase difference

of π ; in practice we achieved better than 99% absorption. As the relative phase of the beams varies from 0 to π , the absorption by the silicon wafer continuously increases. For in-phase beams, the wafer absorption is 30%; by the time the phase offset is about $\pi/2$, the absorption has risen to 65%, the value that would be obtained if the wafer were illuminated with incoherent light.

Theoretical work on more complicated structures with alternating layers of silicon and silicon dioxide has shown that in principle the simple type of phase control we have demonstrated can turn absorption almost completely on or off. Thus the CPA could function as an optical switch, optical modulator, or optical detector and could see potential applications to silicon photonic devices and sensors. In even more complicated, random structures, the CPA concept points to methods for generating optical fields that can penetrate normally opaque surfaces to be absorbed in a specified subsurface region; if those methods come to fruition, they may see applications to biophysics or radiology.

A CPA is particularly good at converting a laser beam back to some other form of energy—thermal or electrical, for example. One thing the antilaser is not good for is defense against laser-energy weapons. Since it perfectly absorbs the incident energy, it would simply assist the attacker in melting the target into a molten puddle. A mirror would be a better choice.

Additional resources

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- E. Hecht, *Optics*, 4th ed., Addison-Wesley, Reading, MA (2002), chap. 13.