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LASERS

To make a mirrorless laser

Periodic temporal modulation of a photonic crystal can be used to produce laser light

By **Daniele Faccio**[1] *and* **Ewan M. Wright**[2]

Inside any laser is a cavity with a "gain medium" that gives the laser its energy to emit light. A typical gain medium contains atoms that can be excited by using an external energy source and is sandwiched between a pair of mirrors. The mirrors impose a periodicity on the light inside the cavity—similar to how the length of a guitar string limits what musical notes can be played—and allows the medium to pack more energy into the light each time it passes through the gain medium. On page XXX of this issue, Lyubarov *et al.* (*1*) propose a radically new approach to making a laser in which the cavity is replaced by a medium with no mirrors. Instead, the optical properties of the medium are periodically modulated in time.

The laser device of Lyubarov *et al.* contains no mechanism for recirculating the light at all. Its operation relies on a slab of transparent material with a refractive index that varies periodically in time. Because the wavelength of light in a medium varies inversely with the refractive index—the shorter the wavelength, the higher the effective refractive index—the medium modulation produces an effect that is akin to periodically compressing light waves. Lyubarov *et al.* take advantage of this periodic temporal compression and show that it can be used to amplify light that will also be coherent, as is laser light.

Time-modulated systems and amplification of light from temporal modulation are not completely new. Although different research fields may trace the origins of these ideas back to different sources, they all connect to a series of ideas proposed in the mid-20th century. In 1970, physicist Gerald Moore explained how a temporally modulated yet otherwise empty cavity can lead to the creation of photons (*2*). This is commonly referred to as the dynamical Casimir effect, which was not experimentally verified in a superconducting circuit until 2011 (*3*). In general, any system that has a time-dependent parameter can exhibit some form of amplification, similar to how a child can increase the amplitude of a swing by shifting their weight periodically and strategically. A common feature of temporally periodic systems is a typical resonance frequency at which the energy transfers from the time-varying parameter—for example, the child periodically and strategically shifting their center of mass twice per period, first by bending their legs backward as they swing backward and then later extending their legs forward as they swing forward. In technical terms, the greatest amplification in energy for any periodic system occurs for light waves with a frequency equal to twice the parameter modulation frequency.

Researchers have been investigating how to use temporally modulated materials. For example, can such materials control the frequency of light or can magnet-free materials made of nonreciprocal elements be created in which light can only propagate in one direction (*5*)? One can draw on analogies between the spatial and temporal cases of photon modulation in crystals to understand the physics of periodic time crystals. Spatial photonic crystals are crystal-like materials with periodic structures that modulate the propagation of light (*5*). These crystals behave for light in a way similar to what atomic crystals do for electrons, in that they lead to the formation of periodic bandgap structures—forbidden "gaps" in the frequency range where the propagation of waves is strongly suppressed. This suppression of waves occurs when the wave vector of the light is equal to half of the periodicity of the modulation and can be used to confine light, similar to the mirrors of a standard laser.

To observe the formation of "gaps" with a temporal modulation, one may use a block of material that can change its refractive index with the right periodicity. For such a system, one can expect a bandgap where the frequency is equal to half of the temporal modulation frequency of the material. When this happens, the energy of the system is no longer conserved, which allows its energy to be amplified. Although this was known for a wave propagating inside a periodic time crystal, Lyubarov *et al.* provide detailed classical and quantum models for an atom placed inside such a crystal. When stimulated with a flash of light, an atom inside the medium remains essentially in a so-called "transparent" state in which there are an equal number of electrons in the ground and excited states. In this state of balance, the stimulation causes the atom to absorb and emit equal amounts of light. The periodic modulation can then lead to exponential amplification for the emitted light with a narrowed spectrum that is characteristic of a laser beam. In this view, the "transparent" atom acts as a conduit for energy transfer between the periodic modulation of the medium and the emitted light. Moreover, this behavior does not appear to depend on the specific initial excitation of the atom. The initial stimulation with a flash of light can be at a substantially different frequency from the bandgap frequency as long as the light is emitted across a broad range of frequencies. Eventually, the exponential amplification at the bandgap will take over and pin the system to emission at the resonant frequency at half the modulation frequency.

Although the periodic time crystal laser does not rely on cavity mirrors or a gain medium, it does rely on a modulation of the medium that needs to be extremely fast because of the resonance condition, with the exponential amplification rate depending on the amplitude of the modulation. Typical photonic materials exhibit small modulations of the refractive index at the femtosecond or picosecond time scales required for lasers at visible to terahertz wavelengths. Recent progress in so-called epsilon-near-zero or index-near-zero materials offers a possibility for ultrafast switching of the medium with near-unity refractive index modulation (*7*, *8*), but this typically also has large losses that may make it harder to achieve laser-like behavior.

The mechanism presented by Lyubarov *et al.* may also be applied for producing light at much longer wavelengths by transducing different forms of energy into electromagnetic radiation. For example, a periodic temporal mechanical modulation in the form a periodic pressure applied to the medium could be used to amplify electromagnetic waves, akin to the original proposal by Moore, albeit not with a cavity but through a photonic time crystal—more than half a century since the idea was first proposed.

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