Physicists propose perfect material for lasers

May 8 2019

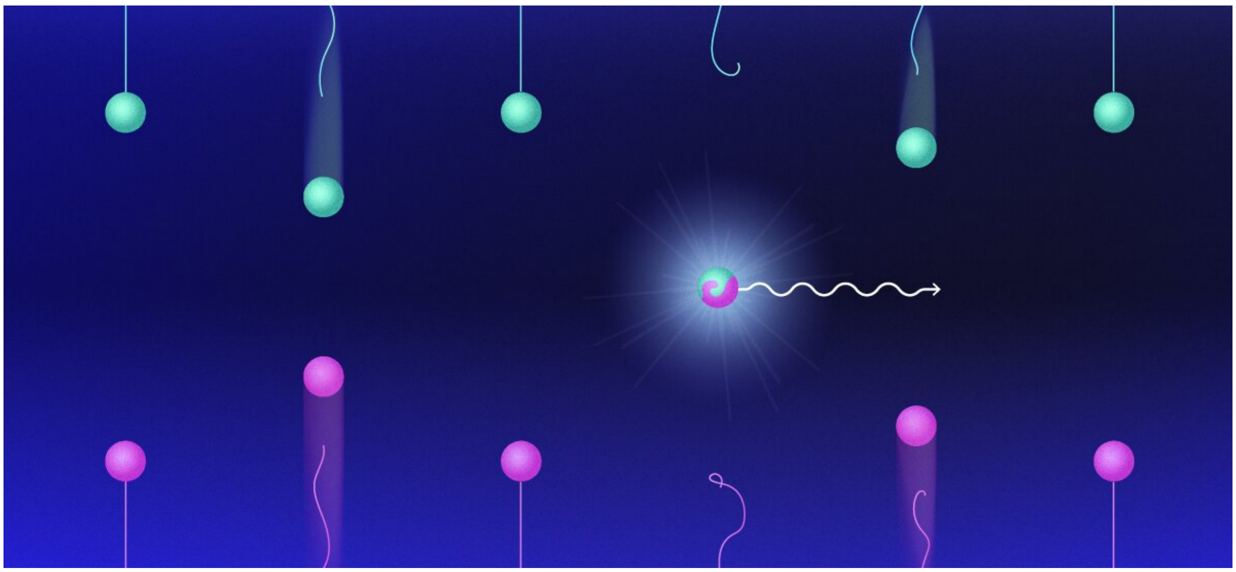

Illustration. Light emission resulting from a mutual annihilation of electrons and holes is the operating principle of semiconductor lasers. Credit: Elena Khavina/MIPT

Weyl semimetals are a recently discovered class of materials in which charge carriers behave the way electrons and positrons do in particle accelerators. Researchers from the Moscow Institute of Physics and Technology and Ioffe Institute in St. Petersburg have shown that these materials represent perfect gain media for lasers. The research findings were published in *Physical Review B*.

21st-century physics is marked by the search for phenomena from the world of fundamental particles in tabletop materials. In some crystals, electrons move as high-energy particles in accelerators. In others, particles even have properties somewhat similar to black hole matter.

MIPT physicists have turned this search inside-out, proving that reactions forbidden for elementary particles can also be forbidden in the crystalline materials known as Weyl semimetals. Specifically, this applies to the forbidden reaction of mutual particle-antiparticle annihilation without light emission. This property suggests that a Weyl semimetal could be the perfect gain medium for lasers.

In a semiconductor laser, radiation results from the mutual annihilation of electrons and the positive charge carriers called holes. However, light emission is just one possible outcome of an electron-hole pair collision. Alternatively, the energy can build up the oscillations of atoms nearby or heat the neighboring electrons. The latter process is called Auger recombination, in honor of the French physicist Pierre Auger.

Auger recombination limits the efficiency of modern lasers in the visible and infrared range, and severely undermines terahertz lasers. It eats up electron-hole pairs that might have otherwise produced radiation. Moreover, this process heats up the device.

For almost a century, researchers have sought a "wonder material" in which radiative recombination dominates over Auger recombination. This search was guided by an idea formulated in 1928 by Paul Dirac. He developed a theory that the electron, which had already been discovered, had a positively charged twin particle, the positron. Four years later, the prediction was proved experimentally. In Dirac's calculations, a mutual annihilation of an electron and positron always produces light and can not impart energy on other electrons. This is why the quest for a wonder material to be used in lasers was largely seen as a search for analogues of the Dirac electron and positron in semiconductors.

"In the 1970s, the hopes were largely associated with lead salts, and in the 2000s—with graphene," says Dmitry Svintsov, the head of the Laboratory of 2-D Materials for Optoelectronics at MIPT. "But the particles in these materials exhibited deviations from Dirac's concept. The graphene case proved quite pathological, because confining electrons and holes to two dimensions actually gives rise to Auger recombination. In the 2-D world, there is little space for particles to avoid collisions."

"Our latest paper shows that Weyl semimetals are the closest we've gotten to realizing an analogy with Dirac's electrons and positrons," added Svintsov, who was the principal investigator in the reported study.

Electrons and holes in a semiconductor do have the same electric charges as Dirac's particles. But it takes more than that to eliminate Auger recombination. Laser engineers seek the kind of particles that would match Dirac's theory in terms of their dispersion relations. The latter tie particle's kinetic energy to its momentum. That equation encodes all the information on particle's motion and the reactions it can undergo.

In classical mechanics, objects such as rocks, planets, or spaceships follow a quadratic dispersion equation. That is, doubling of the momentum results in four-fold increase in kinetic energy. In conventional semiconductors—silicon, germanium, or gallium arsenide—the dispersion relation is also quadratic. For photons, the quanta of light, the dispersion relation is linear. One of the consequences is that a photon always moves at precisely the speed of light.

The electrons and positrons in Dirac's theory occupy a middle ground between rocks and photons: at low energies, their dispersion relation is quadratic, but at higher energies it becomes linear. Until recently, though, it took a particle accelerator to "catapult" an electron into the linear section of the dispersion relation.

Some newly discovered materials can serve as "pocket accelerators" for charged particles. Among them are the "pencil-tip accelerator—graphene and its three-dimensional analogues, known as Weyl semimetals: tantalum arsenide, niobium phosphate, molybdenum telluride. In these materials, electrons obey a linear dispersion relation starting from the lowest energies. That is, the charge carriers behave like electrically charged photons. These particles may be viewed as analogous to the Dirac electron and positron, except that their mass approaches zero.

The researchers have shown that despite the zero mass, Auger recombination still remains forbidden in Weyl semimetals. Foreseeing the objection that a dispersion relation in an actual crystal is never strictly linear, the team went on to calculate the probability of "residual" Auger recombination due to deviations from the linear law. This probability, which depends on electron concentration, can reach values some 10,000 times lower than in the currently used semiconductors. In other words, the calculations suggest that Dirac's concept is rather faithfully reproduced in Weyl semimetals.

"We were aware of the bitter experience of our predecessors who hoped to reproduce Dirac's dispersion relation in real crystals to the letter," Svintsov explained. "That is why we did our best to identify every possible loophole for potential Auger recombination in Weyl semimetals. For example, in an actual Weyl semimetal, there exist several sorts of electrons, slow and fast ones. While a slower electron and a slower hole may collapse, the faster ones can pick up energy. That said, we calculated that the odds of that happening are low."

The team gauged the lifetime of an electron-hole pair in a Weyl semimetal to be about 10 nanoseconds. That timespan looks extremely small by everyday standards, but for laser physics, it is huge. In conventional materials used in laser technology of the far infrared range, the lifetimes of electrons and holes are thousands of times shorter. Extending the lifetime of nonequilibrium electrons and holes in novel materials opens up prospects for using them in new types of long-wavelength lasers.

More information: A. N. Afanasiev et al. Relativistic suppression of Auger recombination in Weyl semimetals, *Physical Review B* (2019). DOI: 10.1103/PhysRevB.99.115202

Provided by Moscow Institute of Physics and Technology

Citation: Physicists propose perfect material for lasers (2019, May 8) retrieved 23 June 2024 from https://phys.org/news/2019-05-physicists-material-lasers.html