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Light trapped in a layer thousands of times thinner than a sheet of paper

Scientists from the Faculty of Physics at the University of Warsaw, in collaboration with research groups from the Łódź University of Technology, the Warsaw University of Technology, and the Polish Academy of Sciences, have developed a structure that traps infrared light in a layer just 40 nanometers thick. To achieve this, they created a structure called a subwavelength grating using a special material – molybdenum diselenide ($MoSe_2$). They published their results in the prestigious journal "ACS Nano".

Controlling light at the micro- and nanoscale opens up opportunities for a better understanding of the world and the development of technology. As modern electronics approaches the limits of its capabilities, photonics comes into play. Instead of manipulating relatively heavy and slow electrons, we can use light and fast photons to encode information. This will make it possible to create devices that are not only faster but also even smaller than those currently in use.

There is only one problem – light is not only a particle but also a wave. A wave that has its own wavelength. For visible light, the wavelength – that is, the distance between successive maxima – is several hundred nanometers. For infrared light, it is a micrometer or more. Will this, then, be an obstacle to the miniaturization of photonic systems? Is it possible to trap light within a structure smaller than those few hundred nanometers?

Researchers from the Faculty of Physics at the University of Warsaw, in collaboration with research groups from the Łódź University of Technology, the Warsaw University of Technology, and the Polish Academy of Sciences, have found a way to do this, and they published their findings in the prestigious journal "ACS Nano". They developed a structure that traps infrared light in a layer just 40 nanometers thick. To achieve this, they created a structure called a subwavelength grating using a special material – molybdenum diselenide ($MoSe_2$).

What is a subwavelength grating? It is a type of diffraction grating, i.e., an array of parallel strips of material that bend and split light much like a prism. If we bring these strips closer together to a distance shorter than the wavelength, the grating can act as a perfect mirror. Furthermore, it can also confine light within its tiny volume.

Previously manufactured subwavelength gratings made from materials such as silicon, gallium arsenide, or gallium nitride had thicknesses on the order of several hundred nanometers. If they were thinner, the light would no longer be confined effectively. Therefore, in this case, it was decided to use a different material with a much higher refractive index than those previously used in photonics. In other words, one in which light travels at a lower speed than in other substances. Molybdenum diselenide proved to be the ideal material for this purpose. While light entering glass from air slows down by about 1.5 times, and by about 3.5 times when entering silicon or gallium arsenide, this value is 4.5 for $MoSe_2$. This has made it possible to reduce the thickness of the grating to a few dozen nanometers – a structure more than a thousand times thinner than a human hair.

Molybdenum diselenide is a promising material not only because of its light-refracting capabilities. It is a layered material, just like graphene. However, unlike graphene, it is a semiconductor. It also exhibits so-called nonlinear properties, including the generation of light at triple the frequency – third harmonic generation. This means that some of the light passing through it changes its frequency and thus its wavelength; for example, infrared light turns blue. This happens because three infrared photons "combine" into one, whose wavelength corresponds to the blue color. As the authors of the paper in "ACS Nano" show, because infrared light is strongly localized in the $MoSe_2$ grating, this nonlinear effect is more than 1,500 times stronger than if the phenomenon occurred in a $MoSe_2$ layer not formed into a grating.

It is worth noting that the work is groundbreaking not only because of the record-breaking performance achieved by this structure. The method of fabricating the $MoSe_2$ layer is innovative in itself. Until now, thin layers of this material have been obtained by exfoliation - the method also used in the production of graphene layers. It involves applying ordinary adhesive tape to a large crystal of the material in question, and then peeling it off along with a layer of graphene or MoSe2. The method is very simple and effective, but it has its drawbacks. It is somewhat random and therefore not very reproducible, and furthermore, it does not allow us to obtain large surface areas. The maximum area that can be achieved with exfoliation is on the order of ten square micrometers. This is not enough to consider practical applications such as photonic integrated circuits. Therefore, researchers from the Faculty of Physics at the University of Warsaw developed a method for producing MoSe2 layers via molecular beam epitaxy (MBE). This is one of the fundamental methods for producing semiconductor layers used in electronics, but it had not previously been applied to materials such as MoSe2. And the benefits of using it turned out to be enormous. The layer from which the subwavelength gratings were produced had an area of several square inches and a uniform thickness across its entire surface. And let's recall that this was a mere 40 nanometers, meaning the ratio of thickness to each of the other dimensions was one to a million. By comparison, these proportions for a standard A4 sheet of paper are only 1:2000.

The results published by Polish scientists show that molybdenum diselenide produced in this way is a material that could revolutionize our approach to manipulating light. Thick structures are no longer needed to trap and manipulate light. Just a few dozen nanometers are enough. At the same time, thanks to a scalable method for producing $MoSe_2$ layers, industrial applications are within reach.

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Faculty of Physics at the University of Warsaw

Physics and astronomy at the University of Warsaw appeared in 1816 as part of the then Faculty of Philosophy. Currently, the Faculty of Physics at the University of Warsaw consists of the following institutes: Experimental Physics, Theoretical Physics, Geophysics, the Department of Mathematical Methods in Physics. The research covers almost all areas of modern physics on scales from quantum to cosmological. The Faculty's research and teaching staff consists of over 250 academic teachers. About 1350 students and over 150 doctoral students study at the Faculty of Physics UW. The University of Warsaw is among the 200 best universities in the world, educating in the field of physics according to Shanghai's Global Ranking of Academic Subjects.

SCIENTIFIC PUBLICATION:

Emilia Pruszyńska-Karbownik, Tomasz Fąs, Katarzyna Brańko, Dmitriy Yavorskiy, Bartłomiej Stonio, Rafał Bożek, Piotr Karbownik, Jerzy Wróbel, Tomasz Czyszanowski, Tomasz Stefaniuk, Wojciech Pacuski, Jan Suffczyński, "Optical Bound States in the Continuum in Subwavelength Gratings Made of an Epitaxial van der Waals Material", ACS Nano 2026 20 (9), 7426-7437
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GRAPHIC MATERIALS:

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An artistic view of the subwavelength grating made of layered molybdenum diselenide. The red spheres represent molybdenum atoms, and the blue ones represent selenium atoms. Light is trapped within the grating, which enhances the generation of light at three times the original frequency.
(*Source: E. Pruszyńska-Karbownik, Faculty of Physics, University of Warsaw*).

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