Arizona State demonstrates first monolithic white lasers

Arizona State University has fabricated a monolithic multi-segment nanosheet of ZnCdSSe that is dynamically tunable over the full visible color range.

Arizona State University (ASU) has proven that monolithic semiconductor lasers are capable of emitting over the full visible color spectrum, which is necessary to produce a white laser ('A monolithic white laser', Fan et al, Nature Nanotechnology (2015); doi:10.1038/nnano.2015.149).

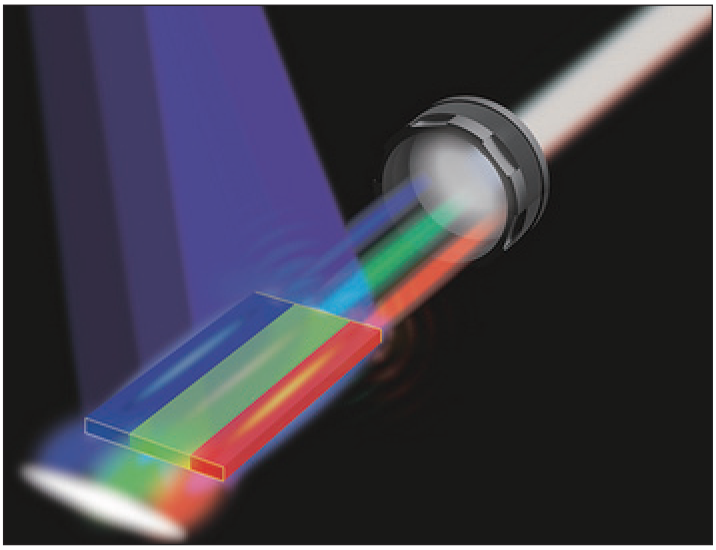
Researchers led by Cun-Zheng Ning, professor in the School of Electrical, Computer and Energy Engineering, have created a novel nanosheet based on a quaternary alloy of zinc, cadmium, sulfur and selenium (ZnCdSSe) with three parallel segments, each supporting simultaneously lasing in one of the three elementary colors red, green and blue. The device is therefore capable of lasing in any visible color, completely tunable dynamically over the full visible color range from red, green to blue, or any color in between. When the total field is collected, a white color emerges.

The development puts lasers one step closer to being a mainstream light source and potential replacement or alternative to light-emitting diodes (LEDs), it is reckoned, since lasers are brighter, more energy efficient, and can potentially provide more accurate and vivid colors for displays like computer screens and televisions. Ning's group has already shown that their structures could cover as much as 70% more perceptible colors than the existing standard for the display industry.

Another key application in the future could be visible light communications, in which the same room lighting systems could be used for both illumination and communication (Li-Fi for light-based wireless communication, as opposed to Wi-Fi using radio waves). Li-Fi could be more than 10 times faster than existing Wi-Fi technology, and white laser Li-Fi could be 10–100 times faster than LED-based Li-Fi currently still under development.

"The concept of white lasers first seems counter-intuitive because the light from a typical laser contains exactly one color, a specific wavelength of the electromagnetic spectrum, rather than a broad-range of different wavelengths," says Ning (who also spent extended time at China's Tsinghua University during several years of the research). "White light is typically viewed as a complete mixture of all of the wavelengths of the visible spectrum," he adds.

In typical LED-based lighting, a blue LED is coated with phosphor materials to convert a portion of the blue light to green, yellow and red light. This mixture of colored light is perceived as white light and can therefore be used for general illumination.



Schematic illustrating nanosheet with three parallel segments, each supporting lasing in one of three elementary colors. The device can lase in any visible color, completely tunable from red, green to blue, or any color in between. When the total field is collected, a white color emerges. Photo by ASU/Nature Nanotechnology.

In 2011, the USA's Sandia National Laboratories produced high-quality white light from four separate large lasers. The researchers showed that the human eye is as comfortable with white light generated by diode lasers as with that produced by LEDs, inspiring others to advance the technology.

"While this pioneering proof-of-concept demonstration is impressive, those independent lasers cannot be used for room lighting or in displays," Ning says. "A single tiny piece of semiconductor material emitting laser light in all colors or in white is desired."

The most preferred light-emitting semiconductor material is indium gallium nitride (InGaN), although other materials such as cadmium sulfide and cadmium selenide are also used for emitting visible colors.

The main challenge lies in the way light-emitting semiconductor materials are grown and how they work to emit light of different colors. Typically, a given semiconductor emits light of a single color — blue, green or red — that is determined by its unique atomic structure and energy bandgap. To produce all possible wavelengths in the visible spectral range, several semiconductors of very different lattice constants and energy bandgaps are needed.

"Our goal is to achieve a single semiconductor piece capable of laser operation in the three fundamental lasing colors," says Fan. "The piece should be small enough, so that people can perceive only one overall mixed color, instead of three individual colors," he adds.

The key obstacle is the lattice constant being too different for the various materials required. "We have not been able to grow different semiconductor crystals together in high enough quality, using traditional techniques, if their lattice constants are too different," says co-author Zhicheng Liu (a doctoral student at the time of the research).

The most desired solution would be to have a single semiconductor structure that emits all needed colors, says Ning. The key is that, at the nanometer scale, larger mismatches can be better tolerated than in traditional growth techniques for bulk materials. High-quality crystals can be grown even with large mismatch of different lattice constants.

Recognizing this unique possibility early on, Ning's group started pursuing the distinctive properties of nanomaterials such as nanowires or nanosheets more than 10 years ago. He and his students have been researching various nanomaterials to see how far they could push the limit of advantages of nanomaterials to explore the high-crystal quality growth of very dissimilar materials.

Six years ago, with funding from the US Army Research Office, the group demonstrated that nanowire materials could be grown in a wide range of energy bandgaps so that color-tunable lasing from red to green can be achieved on a single substrate about 1cm long. Later they realized simultaneous laser operation in green and red from a single semiconductor nanosheet or nanowires. These achievements triggered Ning's thought to push the envelope further to see if a single white laser is possible.

Blue, necessary to produce white, proved to be a greater challenge, due to its wide energy bandgap and very different material properties. "We have struggled for almost two years to grow blue-emitting materials in nanosheet form, which is required to demonstrate eventual white lasers," says co-author Sunay Turkdogan, fellow doctoral student at the time and now assistant professor at University of Yalova in Turkey.

The group finally devised a strategy to create the required shape first, and then convert the materials into the appropriate alloy contents to emit the blue color. "To the best of our knowledge, our unique growth strategy is the first demonstration of an interesting growth process called dual ion exchange process that enabled the needed structure," says Turkdogan.

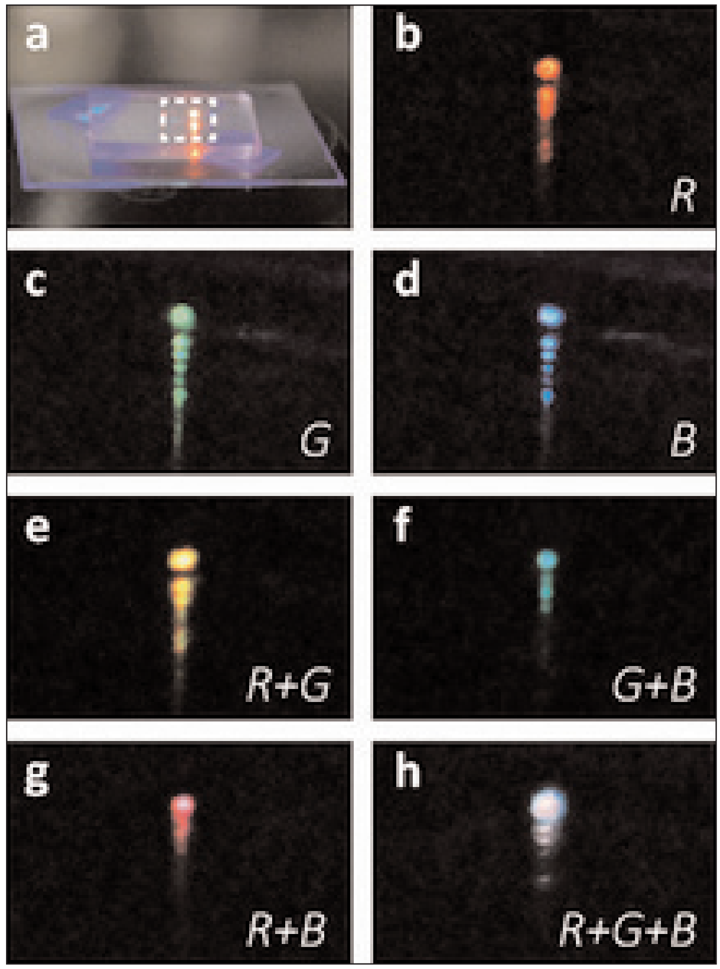


Photo collage showing mixed-emission red, green, blue, yellow, cyan, magenta and white colors from multi-segment nanosheet. The top dots in each photo are the direct image of laser emission, while the tails under these dots are the reflection from the substrate. Photo by: ASU/Nature Nanotechnology.

This strategy of decoupling structural shapes and composition represents a major change of strategy and the breakthrough that finally made it possible to grow a single piece of structure containing three segments of different semiconductors emitting all the required colors. "This is not the case, typically, in the material growth where shapes and compositions are achieved simultaneously," notes Turkdogan.

While this first proof-of-concept is important, significant obstacles remain to make such white lasers applicable for real-life lighting or display applications, says the researchers. One of crucial next steps is to achieve similar white lasers under the drive of a battery. For the present demonstration, the researchers had to use a laser light to pump electrons to emit light. This experimental effort demonstrates the key first material requirement and is expected to lay the groundwork ultimately for white lasers under electrical operation.

www.nature.com/nnano/journal/vaop/ncurrent/full/nnano.2015.149.html

http://nanophotonics.asu.edu