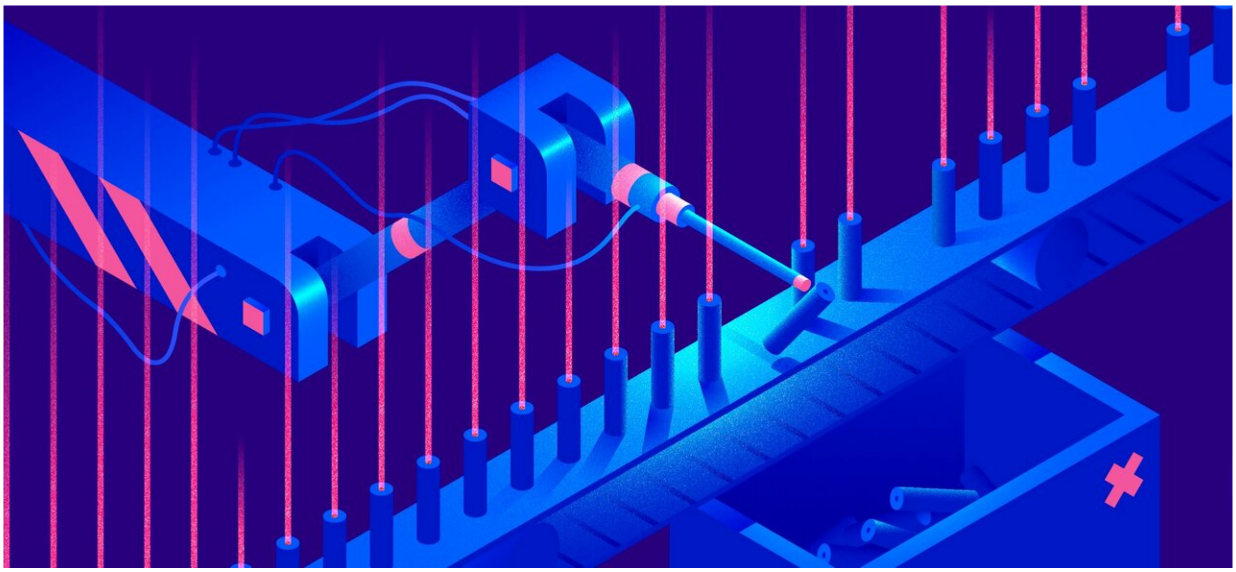
Physicists take big step in nanolaser design

February 7 2019



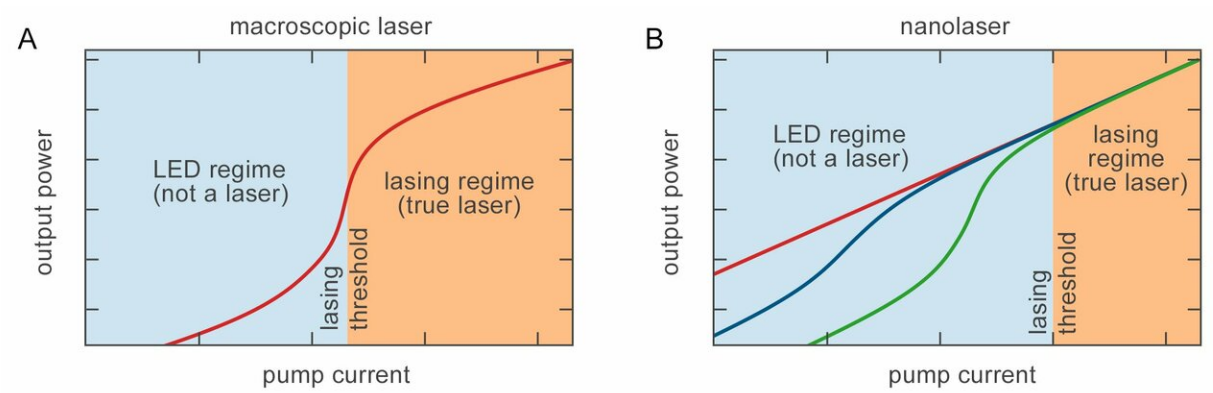
Nanolaser test. Credit: @tsarcyanide/MIPT

Lasers are widely used in household appliances, medicine, industry, telecommunications and more. Several years ago, scientists introduced nanolasers. Their design is similar to that of the conventional semiconductor lasers based on heterostructures in common use for several decades. The difference is that the cavities of nanolasers are exceedingly small, on the order of the wavelength of the light they emit. Since they mostly generate visible and infrared light, the size is on the order of one millionth of a meter.

Nanolasers have unique properties remarkably different from those of macroscopic lasers. However, it is almost impossible to determine at what current the output radiation of the nanolaser becomes coherent; additionally, for practical applications, it is important to distinguish between the two regimes of the nanolaser: the true lasing action with a coherent output at high currents, and the LED-like regime with incoherent output at low currents. Researchers from the Moscow Institute of Physics and Technology developed a method to determine under what circumstances nanolasers qualify as true lasers. The research was published in *Optics Express*.

In the near future, nanolasers will be incorporated into integrated optical circuits, where they are required for a new generation of high-speed interconnects based on photonic waveguides, which would boost the performance of CPUs and GPUs by several orders of magnitude. In a similar way, the advent of fiber optic internet has enhanced connection speeds, while also boosting energy efficiency.

And this is by far not the only possible application of nanolasers. Researchers are already developing chemical and biological sensors, mere millionths of a meter large, and mechanical stress sensors as tiny as several billionths of a meter. Nanolasers are also expected to be used for controlling neuron activity in living organisms, including humans.



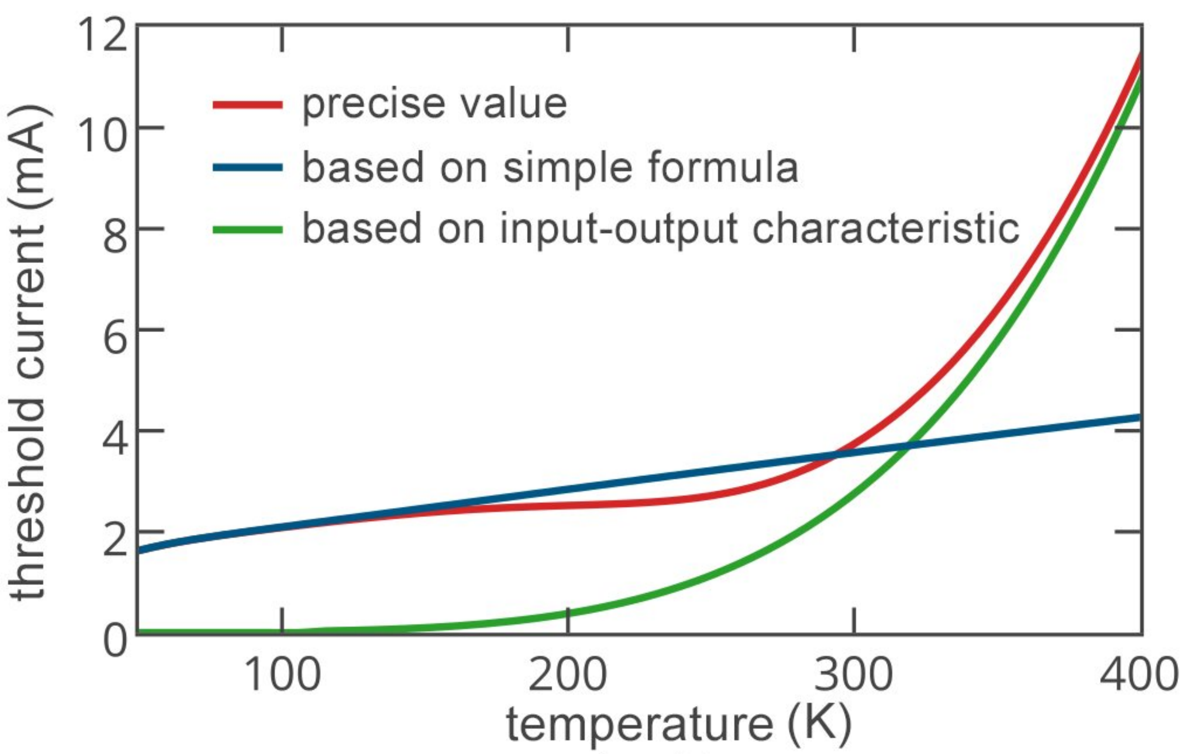
Dependence of the output power on pump current for a conventional macroscopic laser (A), and for a typical nanoscale laser (B) at a given temperature. Credit: A.A. Vyshnevyy and D.Yu. Fedyanin, DOI: 10.1364/OE.26.033473

For a radiation source to qualify as a laser, it needs to fulfill a number of requirements, the main one being that it has to emit coherent radiation. One distinctive property that is closely associated with coherence is the presence of a so-called lasing threshold. At pump currents below this threshold value, the output radiation is mostly spontaneous and no different in its properties from the output of conventional light-emitting diodes (LEDs). But once the threshold current is reached, the radiation becomes coherent. At this point, the emission spectrum of a conventional macroscopic laser narrows down and its output power spikes. The latter property provides for an easy way to determine the lasing threshold—namely, by investigating how output power varies with pump current (figure 1A).

Many nanolasers behave the way their conventional macroscopic counterparts do, exhibiting a threshold current. However, for some devices, a lasing threshold cannot be pinpointed by analyzing the output power versus pump current curve, since it has no special features and is just a straight line on the log-log scale (red line in figure 1B). Such nanolasers are known as "thresholdless." This presents the question: At what current does their radiation become coherent, or laserlike?

The obvious way to answer this is by measuring the coherence. However, unlike the emission spectrum and output power, coherence is very hard to measure in the case of nanolasers, since this requires equipment capable of registering intensity fluctuations at trillionths of a second, which is the timescale on which the internal processes in a nanolaser occur.

Andrey Vyshnevyy and Dmitry Fedyanin from the Moscow Institute of Physics and Technology have found a way to bypass the technically challenging direct coherence measurements. They developed a method that uses the main laser parameters to quantify the coherence of nanolaser radiation. The researchers claim that their technique allows to determine the threshold current for any nanolaser (figure 1B). They found that even a "thresholdless" nanolaser does in fact have a distinct threshold current separating the LED and lasing regimes. The emitted radiation is incoherent below this threshold current and coherent above it.



Nanolaser threshold current versus device temperature. The blue and green curves give a very good approximation of the exact value shown by the red line.

Credit: Andrey A. Vyshnevyy and Dmitry Yu. Fedyanin, DOI: 10.1364/OE.26.033473

Surprisingly, the threshold current of a nanolaser turned out to be not related in any way to the features of the output characteristic or the narrowing of the emission spectrum, which are telltale signs of the lasing threshold in macroscopic lasers. Figure 1B clearly shows that even if a well-pronounced kink is seen in the output characteristic, the transition to the lasing regime occurs at higher currents. This is what laser scientists could not expect from nanolasers.

"Our calculations show that in most papers on nanolasers, the lasing regime was not achieved. Despite researches performing measurements above the kink in the output characteristic, the nanolaser emission was incoherent, since the actual lasing threshold was orders of magnitude above the kink value," Dmitry Fedyanin says. "Very often, it was simply impossible to achieve coherent output due to self-heating of the nanolaser," Andrey Vyshnevyy adds.

Therefore, it is highly important to distinguish the illusive lasing threshold from the actual one. While both the coherence measurements and the calculations are difficult, Vyshnevyy and Fedyanin came up with a simple formula that can be applied to any nanolaser. Using this formula and the output characteristic, nanolaser engineers can now rapidly gauge the threshold current of the structures they create (see figure 2).

The findings reported by Vyshnevyy and Fedyanin enable predicting in advance the point at which the radiation of a nanolaser—regardless of its design—becomes coherent. This will allow engineers to deterministically develop nanoscale lasers with predetermined properties and guaranteed coherence.

More information: Andrey A. Vyshnevyy et al, Lasing threshold of thresholdless and non-thresholdless metal-semiconductor nanolasers, *Optics Express* (2018). DOI: 10.1364/OE.26.033473

Provided by Moscow Institute of Physics and Technology