Fine-tuned: A wholly new approach to tuning a laser's frequency

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Graphic: Christine Daniloff

(PhysOrg.com) -- For more than 30 years, scientists have been trying to harness the power of terahertz radiation. Tucked between microwaves and infrared rays on the electromagnetic spectrum, terahertz rays can penetrate clothing, plastic, and human tissue, but they're thought to be safer than x-rays. Since they're absorbed to different degrees by different molecules, they can also tell chemicals apart: a terahertz scanner at an airport checkpoint, for example, could determine whether a vial in a closed suitcase contained aspirin, methamphetamines or an explosive.

But practical ways to generate terahertz rays have been hard to find. Traditional gas lasers can operate in the right frequency band, but they’re big, expensive, and power-hungry. Semiconductor lasers — the kind you find in a DVD player — are small and cheap, but they're hard to nudge out of a limited spectral range: consider how long it took to get from the infrared lasers of the first CD players to the blue lasers of Blu-Ray discs.

In 1994, researchers at Bell Labs invented a new kind of small but powerful semiconductor laser called a quantum cascade laser, and in 2002, it was shown to be able to operate at terahertz frequencies. But accurately assessing an object's chemical composition requires exposing it to a continuous range of frequencies, which are absorbed to different degrees.

In a paper appearing in the most recent issue of *Nature Photonics*, Qing Hu, a professor of electrical engineering at MIT's Research Laboratory of Electronics, and his colleagues describe the first practical method for tuning terahertz quantum cascade lasers. What's more, the method is a fundamentally new approach to laser tuning that could have implications for other emerging technologies.

"Since the very beginning of terahertz development in the 1970s, people have been trying to make [high-power] sources that are compact and tunable, and so far, this is really the first example of such a source," says Peter Siegel, who leads the Submillimeter Wave Advanced Technology group at NASA's Jet Propulsion Laboratory at Caltech. "Qing deserves a lot of credit for all the work he put in and the groundbreaking ideas he pioneered and pushed through despite lots of setbacks and competition from other groups. He really, in the end, came through with a fantastic breakthrough."

Tuning an ordinary semiconductor laser usually requires changing the length of its light-emitting cavity; occasionally, if the laser doesn't need a broad frequency range, heating or cooling it will work instead. Hu compares these two approaches to changing the pitch of a guitar string by pressing down on it — changing its length — or screwing its tuning peg — changing its tension. Neither approach, however, works very well with terahertz quantum cascade lasers.

A third way to change the pitch of a guitar string, however, is to change its diameter: the lower-pitched strings on a guitar are thicker than the higher-pitched ones. And Hu's tuning technique is, roughly speaking, to change the diameter of the light beam.

A light beam traveling through space can be thought of as a wave, undulating up and down indefinitely until it strikes a physical object. But when the same light beam is confined — in, say, an optical fiber or a long, thin, quantum cascade laser — it exhibits an electromagnetic-field pattern called a "transverse mode." The transverse mode is kind of like another wave that's perpendicular to the first one, except that it dies off very quickly — its undulations rapidly get smaller — as it gets farther from the light beam. In fact, its undulations die off so quickly that it can be thought of as simply one big undulation perpendicular to the light beam but centered on it.

Hu's new tuning technique requires a particular type of quantum cascade laser called a wire laser, where the wavelength of the transverse mode — the width of the one big undulation — is actually greater than the width of the laser itself. Bringing a block of another material close enough to the laser deforms the transverse mode, which in turn changes the wavelength of the emitted light. In experiments, Hu and his colleagues found that a metal block shortened the wavelength of the light, while a silicon block lengthened it. Varying the proximity of the blocks also varies the extent of the shift.

Terahertz quantum cascade lasers have one big drawback: they need to be cooled with liquid nitrogen to very low temperatures. But Jerome Faist of the Swiss Federal Institute of Technology in Zurich, one of the inventors of the quantum cascade laser, says that while a roomtemperature version is a difficult and long-term project, “nothing actually tells us it is impossible.” And Siegel adds that, with Hu’s tuning technique, “I don’t see why it would matter what temperature the laser was operated at.”

Hu points out that his technique could also be applied to a new type of tiny laser that can be used for extremely fine-scale sensing. Ordinarily, visible-light lasers cannot be narrower than the wavelength of the light being used, but researchers have found ways around that fundamental limit by using a virtual particle called a plasmon, which is like a wave passing through a cloud of electrons. Some new types of plasmon lasers could also be tuned through manipulation of their transverse modes.

In its experiments, Hu’s group used a mechanical lever to bring a block of either silicon or metal close to a quantum cascade laser from a single direction. But they’ve designed and are now building chips that would use electronically controlled microelectromechanical devices to bring the silicon and metal blocks in from different directions, giving the laser a precise and continuous tuning range from short to long wavelengths.

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