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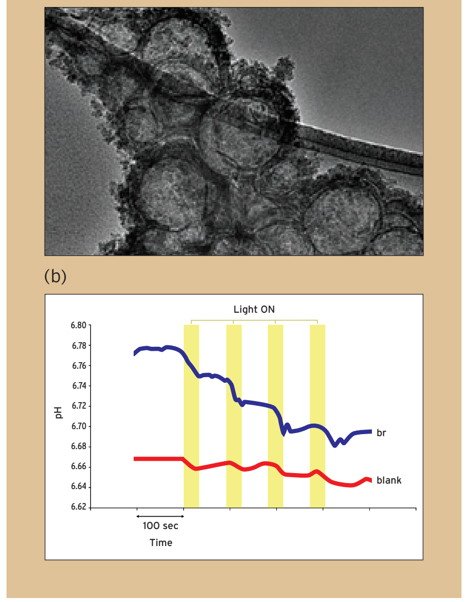
López's group has also petrified liposomes containing bacteriorhodopsin protein and the antibiotic peptide gramicidin to demonstrate that not only structure, but function is also preserved (See Figure 7). The researchers hope that these thin films will serve as highly selective and perhaps active transport membranes in devices that approach the fidelity of biological membrane function.

Figure 7. Even though these liposomes are entrapped in silica (a), light-activated proteins in the membranes still pump protons out of the vesicles (lowering the pH) when the light is on (b).


(a)

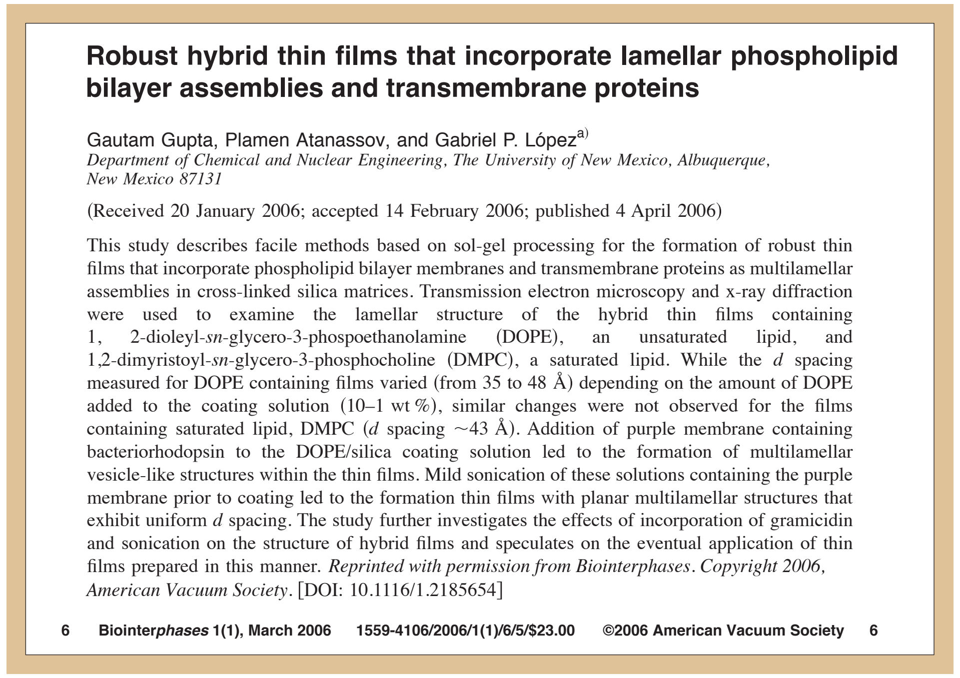
(b)

Currently López and coworkers are working to stabilize chlorosomes, the highly-efficient, light-harvesting "antennas" found in green sulfur bacteria living in low-light hotsprings and near sea vents. Chlorosomes differ from other antenna complexes because of their large size and their lack of a protein matrix supporting the photosynthetic pigments. If a chlorosome is put in water or a solvent, it falls apart as evidenced by the fading of its characteristic green color. Using the soft petrification technique, López' student, Gautam Gupta, succeeded in encapsulating chlorosomes in a hard material that stayed stable for at least 30 days. His collaborators at Sandia National Laboratories and Washington University are interested in this material for building photovoltaic or photoconversion devices.

Science and the Humanities

Contrary to romantic visions of a scientist shouting "eureka" in the lab, the working life of an academic engineer is filled with meetings, budgets, proposal writing, teaching, and research group management. Moreover, in both the administrative and basic research milieu, it's easy to lose sight of the significance of one's work, of who one is ultimately working for.

López is working for the diabetic patient needing a smart polymer implant that monitors glucose and metes out insulin just like a healthy pancreas. He's working to help a pharmaceutical company sorting through millions of compounds for targeted cancer drugs. For the diagnostician trying to quickly narrow down the causes of an epidemic. For the aid worker needing a simple blood test that is stable without refrigeration. For solutions to these problems and more, we have Mother Nature to thank. And, of course, Gabriel López's inspired biokleptomania. ■



Robust hybrid thin films that incorporate lamellar phospholipid bilayer assemblies and transmembrane proteins

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This study describes facile methods based on sol-gel processing for the formation of robust thin films that incorporate phospholipid bilayer membranes and transmembrane proteins as multilamellar assemblies in cross-linked silica matrices. Transmission electron microscopy and x-ray diffraction were used to examine the lamellar structure of the hybrid thin films containing 1, 2-dioleyl-*sn*-glycero-3-phospoethanolamine (DOPE), an unsaturated lipid, and 1,2-dimyristoyl-*sn*-glycero-3-phosphocholine (DMPC), a saturated lipid. While the *d* spacing measured for DOPE containing films varied (from 35 to 48 Å) depending on the amount of DOPE added to the coating solution (10–1 wt %), similar changes were not observed for the films containing saturated lipid, DMPC (*d* spacing ~43 Å). Addition of purple membrane containing bacteriorhodopsin to the DOPE/silica coating solution led to the formation of multilamellar vesicle-like structures within the thin films. Mild sonication of these solutions containing the purple membrane prior to coating led to the formation thin films with planar multilamellar structures that exhibit uniform *d* spacing. The study further investigates the effects of incorporation of gramicidin and sonication on the structure of hybrid films and speculates on the eventual application of thin films prepared in this manner. *Reprinted with permission from Biointerphases. Copyright 2006, American Vacuum Society.* [DOI: 10.1116/1.2185654]

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The Laser Trailblazer

Luke Lester's bright ideas set records in quantum dot lasers and other optoelectronic devices.

Luke Lester's Career Brief

$11.5 M	venture capital funding raised
>$10 M	research funding attracted
26	h number
182+	papers
14	invited talks (most in Europe)
21	Ph.D. and M.S. students graduated
8	current students

First. Fastest. Best.

DURING HIS 16 year career in semiconductors and photonics, Luke Lester has consistently pushed technology to set new records:

- In 1988 he fabricated the world's fastest transistor, a record that stood for over a decade as noted by the *Guinness Book of World Records*. This device is found today in many cell phone receivers.
- Two years later he made the first quantum well (QW) laser diode whose operation speed was greater than any previous semiconductor laser. Today's industry standard is based on his design. In 1993, Lester created the fastest long-wavelength photodetector, with a 1.3 picosecond response time that has yet to be beat.
- In 2000, Lester and his colleagues at UNM's Center for High Technology Materials (CHTM) produced the first quantum dot (QD) laser whose properties surpassed those of QW devices.
- A year later he spearheaded the first commercial foray into QD laser diodes, co-founding Zia Laser, Inc., which was recently acquired by Germany's NL Nanosemiconductor and then merged with Innolume.

In spite of these pioneering efforts, however, QD lasers have yet to become commercially viable. So this is also a story of why even the first, fastest, and best in the lab doesn't always make that quantum jump into marketplace success.

Laser diodes are ever-present in our world. Watch a DVD or scan a barcode, and there is a laser diode to thank. Lester, a professor of electrical and computer engineering, has focused on lasers whose qualities make them especially attractive for telecommunications—lasers whose brightness can be modulated to transmit data across vast fiber optic networks. In particular, Lester was searching for a "tunable" laser that offers a wide range of distinct wavelengths. This kind of device would enable simultaneous transmission of many different data streams in the same optical fiber.

In 1998 Lester was handed a new gallium arsenide (GaAs) wafer on which a layer containing millions of nanometer (nm)-sized dots of Indium Arsenide (InAs) had been grown. None of Lester's students seemed interested in making it into lasers and testing them, so it languished for weeks. But when Lester finally got a look at the spectrum it produced, he knew in an instant this was something big. He had been searching for it for the past five years.

ABCs of LASERS

The active region of the earliest lasers was a gas. Gas atoms have discrete energy states, so when an electron is first excited and then drops down to a lower energy state, a photon of a very specific wavelength is emitted. Gas lasers can produce high quality, stable optical beams of essentially one wavelength. Unfortunately they were big and expensive, couldn't be modulated quickly, and operated at dangerous high voltages. When semiconductor lasers debuted in the early 1960s, they offered the potential of much smaller, more efficient, and cheaper devices.

Semiconductor lasers are basically a sandwich of two materials: an "n-type" layer that contains an abundance of electrons, and a "p-type" that is missing electrons and is conceptualized as containing positively charged "holes." This p-n junction is called a diode. When a current is injected across the diode, the electrons and holes flow towards one another, and if they meet and recombine they generate a photon. If that photon stimulates another excited electron-hole pair to combine and emit light at the same wavelength, phase, and direction, a cascading process is begun, with specific wavelengths getting built up and amplified as the photons bounce back and forth in the cavity. This is lasing.

One disadvantage of these "bulk" lasers is that they require a lot of current to make them lase. The active region of a bulk laser is so large, with a plethora of atoms that can absorb light, it is necessary to pump in a lot of electrons and holes to overcome this photonic reabsorption and generate light in a self-sustaining way. More current means greater power and more performance problems due to heat. A large active region also means a greater number of uncontrolled spontaneous (as opposed to stimulated) emissions of photons, which create optical noise.

Another big problem was a large "linewidth enhancement factor." As the current and gain increased, the index of refraction varied as well, which altered the wavelength of the standing waves inside the laser cavity. The end result was that the output wavelength and intensity danced around.

Calculations in the 1980s indicated that reducing the size of the active region would lower the threshold current density and stabilize the output. The hope was to make a laser that combined the best of both worlds: the inexpensive production and small size of bulk lasers and the cleaner, more atomic-like properties of gas lasers. Indeed, the next technological step was to thin the active layer so much that the electrons and holes are confined to two dimensions and become trapped in energy potential wells where they have a greater chance of meeting and combining. As a result, quantum wells (QW) concentrate more electrons in energy states that contribute to laser action, making them more efficient and faster than bulk devices.

Lester, while still in graduate school at Cornell, was the first person to demonstrate the predicted increase in speed by making the first high-frequency QW laser diode that performed better than bulk.

The efficiency and linewidth could be improved even more by further restricting the active area to a sea of small islands called quantum dots (QD). These dots, measuring 20 nm wide and 10 nm high, are so small that they have quantized energy levels somewhat like that of an individual atom. A QD laser has about 10 million dots in its active region.

And that's what Lester was looking at in his UNM lab in 1998 when he got so excited. It was the first QD laser with properties superior to QW devices. It could operate at room temperature and had a low threshold current density of 26 Amperes/centimeter^2 (A/cm^2), 10 times lower than most QWs. (The current record, still held by UNM, is 10 A/cm^2.) Its spread of distinct wavelengths spanned 190 nm, twice as broad as QW lasers. (The UNM team ultimately upped the span to 201 nm.) This wide range is due to the range of dot sizes (bigger dots produce longer wavelengths). Early tests also indicated the device exhibited the lowest linewidth enhancement factor measured to date. Figure 1 is a schematic of the device.

The Zenith of Zia

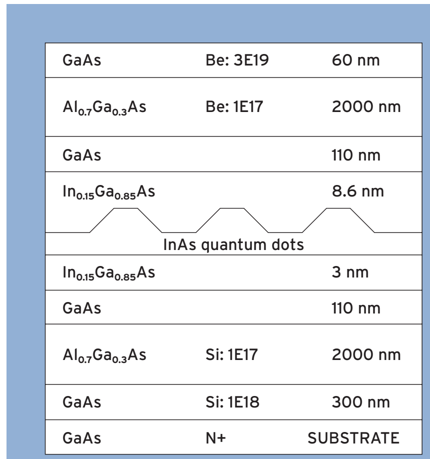
The laser wafer was designed and grown at CHTM by Research Assistant Professor Andreas Stinz and Electrical and Computer Engineering Professor Kevin J. Malloy, who came up with a new molecular beam epitaxy recipe for assembling their quantum dot structure through a judicious choice of materials. They surrounded the InAs dots with GaInAs, which exhibited a greater bandgap energy than InAs but less than the GaAs substrate. This meant that electrons and holes were more attracted to the dots than the surrounding materials, and photons emitted from the dots were less likely to be absorbed or scattered by the GaAs. Lester coined the now trademarked term DWELL (dots-in-a-well) to describe this structure. The group's first three papers announcing the DWELL laser and a later paper explaining the physics have been cited over 521 times and their work resulted in 5 patents (4 US and 1 Japanese), which are the only patents issued to date for this laser technology. Other groups subsequently demonstrated that DWELLs afford high speed, high efficiency and temperature-insensitive operation. Almost everyone in the laser community now makes QD devices this way.

But it wasn't only scientists who were interested in the new devices. They piqued the interest of venture capitalists who were visiting Zia Laser, the start-up incorporated in May 2000 by Lester, Malloy, Stinz, and former UNM graduate student Petros Varangis. The VCs nixed Zia's original plan for producing eye-safe QW lasers in favor of the much trendier and unique QDs. Lester, who was Zia's Chief Technology Officer and then Chief Research Officer, eventually raised $11.5 million (out of a total of $22.5 Zia was to receive) from investors while at the company. Zia's work also attracted the press. Its R&D was covered by *Laser Focus World, Photonics Spectra, The Economist*, and other popular and trade periodicals.

Zia's first device was a specialty laser, tunable around 1.55 microns for long-haul communications, which typically require a pure signal at each wavelength. This laser was made of InAs deposited on indium phosphide. Under an atomic force microscope, the InAs initially looked like dots, but it turned out that they were elongated, more like dashes. The lasers still provided a broad spectrum for tuning, but the gain spectrum wasn't symmetric and the threshold current was higher than that of QDs. Lester wanted to investigate growing the InAs dots differently. However, it was market forces that ultimately determined the laser's fate. By the winter of 2001, there were indications that the telecommunication boom was starting to go bust.

Zia's second product, a single wavelength (1.3 micron) DWELL laser, was aimed at the relatively short distances (less than 10 km) of data communication for which lasers had to be inexpensive and insensitive to temperature fluctuations.

It's with respect to the latter that DWELLs, with their discrete, isolated energy states, are expected to have an edge. But this market supersaturated as well. Plus there was resistance to the 1.3 micron wavelength since many data systems were designed around 1.55 microns. QWs were so entrenched, it's questionable whether companies understood the benefits of QD well enough to make the switch. But again, this issue was never resolved as decreased demand kept shelves of QW lasers sitting idle. By early 2003 it was clear Zia had to find another niche.



GaAs	Be: 3E19	60 nm
$Al_{0.7}Ga_{0.3}As$	Be: 1E17	2000 nm
GaAs		110 nm
$In_{0.15}Ga_{0.85}As$		8.6 nm
InAs quantum dots		
$In_{0.15}Ga_{0.85}As$		3 nm
GaAs		110 nm
$Al_{0.7}Ga_{0.3}As$	Si: 1E17	2000 nm
GaAs	Si: 1E18	300 nm
GaAs	N+	SUBSTRATE

Figure 1. Schematic of the quantum dot laser structure

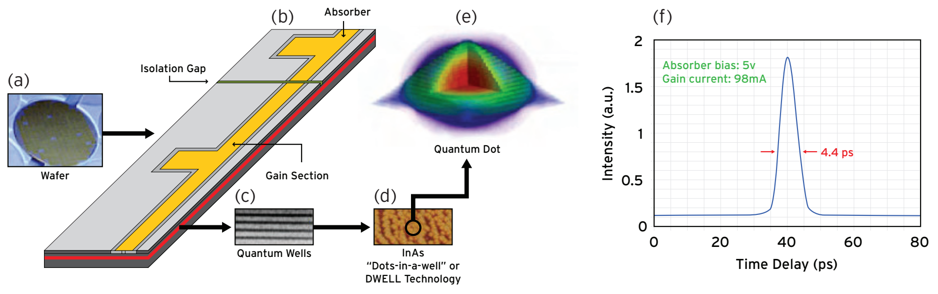


Figure 2. Grown on wafer (a), this mode-locked laser (b) has an 8 millimeter active gain length and contains four layers of indium arsenide dots-in-a-well (c). The dots, which self-assemble during molecular beam epitaxy growth are about 15 nanometers wide and 7 nanometers tall (d). Depending on how a section is biased, it can act as either an absorber or emitter. The calculated quantum mechanical wavefunction for an electron inside a quantum dot is shown in (e). The time domain is seen in (f). This mode-locked laser has an 5 Ghz repetition rate.

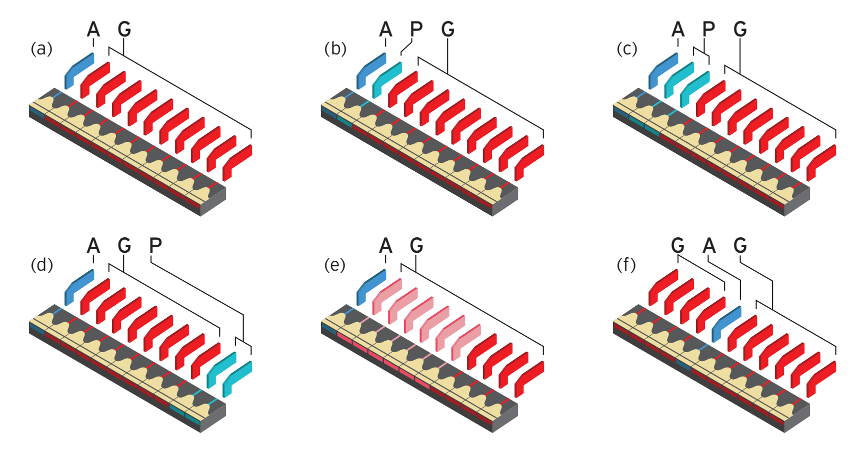


Figure 3. This quantum dot photonic integrated circuit consists of eleven 0.5 millimeter (mm) sections, each of which can be made into an Absorber (blue), Gain region (red), or Passive waveguide (cyan) depending on how that section is biased. With this flexibility, many kinds of devices can be configured. For example, laser (a) has a 0.5 mm absorber and a 5 mm gain region. With an absorber in the 5th section and a 2 mm and a 3 mm gain region on either side, the device (f) produces higher order harmonics.

Unlocking Mode-Locking

Lester turned to mode-locking, a task QD lasers excel at better than any other semiconductor laser. Mode-locking produces very short light pulses that are ideal for clock applications. Lester was hoping mode-lock lasers could replace electronic clocks in silicon microprocessors.

In addition to the atomic structure of the semiconductor and dot size, the length of the resonance cavity determines the pulse interval of a laser's emitted light. Mode-locking puts all the standing waves in the cavity in phase with one another so that periodically they constructively interfere, producing an intense pulse of light. Quantum dots are ideal for what's known as passive mode-locking, because all they require is the placement of a saturable absorber in the cavity. This non-linear element blocks low intensity waves, while letting high intensity ones pass through, and since the highest intensity light is at the center of the pulse, it gets amplified while other frequencies are filtered out.

The saturable absorber in a DWELL is exactly the same material as the gain section, only reversed biased, so the dots absorb light rather than emit it. A quantum dot's emission and absorption wavelengths are the same.

In a 2001 *Applied Physics Letters* article, Lester, Malloy, Stintz, and others reported the first mode-locking QD laser, fabricated from the same wafer as their earlier work. They were two years ahead of any other group.

Their mode-locked device had two parts: a 4.73 millimeter (mm)-long active gain region and a 0.85 mm absorber. The device produced fully mode-locked pulses 17 picoseconds long with a repetition rate of 7.4 GHz at 1.3 microns. (A similar device is shown in Figure 2.) However Zia ran out of money before it could develop a viable product focused on optical clocking, and by the 2003–2004 time frame the technology lost out to "dual-core" and "quad-core" microprocessor technology. To some extent, QD mode-locked lasers remain a technical solution looking for a problem to solve.

QDPIC

Lester returned to UNM full time in 2003. Shortly thereafter he became the Associate Director of CHTM and recently was given an Endowed Chair in Microelectronics. But he didn't give up on QDs or mode-locking. In fact, he designed a novel system for studying and developing QD passively mode-locked lasers. Called a quantum dot photonic integrated circuit (QDPIC), the device consists of up to 30 linked, independently controlled 0.5 mm-long optical waveguide sections made of GaAs embedded with InAs QDs. Depending on how a segment is biased or injected with current, it can be made into an absorber, a saturable absorber (absorption stops over a threshold), a passive wave guide, an active laser medium, or a spontaneous LED emitter.

In a 2007 *Optics Express* paper, Lester's group demonstrated how it optimized an 11-segment device by measuring the output of different geometric configurations of absorber, gain and passive sections. (See Figure 3.) For example, in going from a two-part laser to a three-part device, the researchers narrowed the pulse width from 9.7 to 6.4 picoseconds and increased the peak pulsed power by 49 percent. The group reports a record peak power of 224 mW for QD mode-locked lasers operating over 40 GHz.

They also systematically explored how moving the absorber section to different positions produces harmonics. For instance,

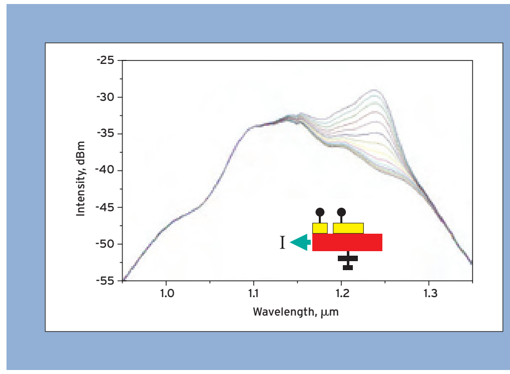


Figure 4. Emission spectra of a three segment quantum dot photonic integrated circuit consisting of an absorber, a front gain section biased to emphasize high energy emissions, and one that favors the lowest emissions. As the bias of the back gain section is increased in steps of 10 milliamperes, the bandwidth broadens.

when the 6th section is the absorber and the rest is gain, the frequency between pulses changes from 7.2 GHz to 14.4 GHz, the second harmonic. They observed higher-order harmonics at frequencies up to 115 GHz. Lester, who plays the cello, says this is analogous to harmonic generation on a stringed instrument. He is developing a paper for *Nature Photonics* studying very high laser harmonics in more depth and comparing them to the work of Jean-Louis Duport, a renowned cellist who wrote a treatise on very high "false harmonics" in the early 19th century.

The ability to produce different frequencies and rapidly switch between them—in effect, creating an arbitrary waveform—is of special interest for military laser sensing and ranging (LADAR) where high resolution is needed to identify often obscured targets. Seeing how a precisely modulated laser signal is reflected back provides more detailed information than that from a single waveform.

Pulsed lasers are also useful as diagnostic tools for characterizing very high speed optical devices and for "optical time division multiplexing" that could enable communication at very high speeds up to 100 gigabits per second. With Dan Kane at Southwest Sciences in Santa Fe, NM, Lester's group is exploring other applications including two-photon high-resolution microscopy, laser cutting that eliminates the bead produced by current laser cutters, and terahertz sensing for homeland security. For all applications, QD lasers promise more compact designs than existing technologies.

In its studies, Lester's lab has employed Frequency-Resolved Optical Gating or FROG (co-invented by Kane) to characterize laser pulse width. Conventional autocorrelation techniques suffer from ambiguities in pulse shape. The researchers think that with FROG, they can very accurately measure the non-linear chirp that broadens the pulse and compensate for it with an external grating or pulse compressor. They hope to compress the pulse down to the theoretical limit of 200 femtoseconds in a hand-held device.

Another possible application of a QDPIC is optical coherence tomography (OCT), which images tissues in medicine and paintings in art conservation. OCT is a non-invasive technique that penetrates 2–3 millimeters and produces images interferometrically. With the introduction of wide bandwidth light sources emitting wavelengths over a 100 nm range, researchers have achieved micrometer resolution, better than ultrasound or magnetic resonance imaging. However, these original sources lack power.

QDs are a good candidate to broaden the bandwidth further due to their range of sizes and to boost power. With its QDPIC, Lester's group is the first to simultaneously achieve a bandwidth of greater than 150 nm at a power greater than 1 milliwatt. In the April 1, 2007 *IEEE Photonics Technology Letters*, they report that their design can be adjusted to independently change the power and bandwidth, and unlike other methods, does not require a complex growth regime. (See figure 4.) One gain section is biased to saturate the low energy states in favor of high energy emission, while the other segment encourages low energy emission. By adjusting the length of each section, the researchers can saturate the lower energies sooner and use proportionately more dots to generate higher energy emission, producing more power than other technologies which continue to dump more energy into lower transition states even as they pump higher ones.

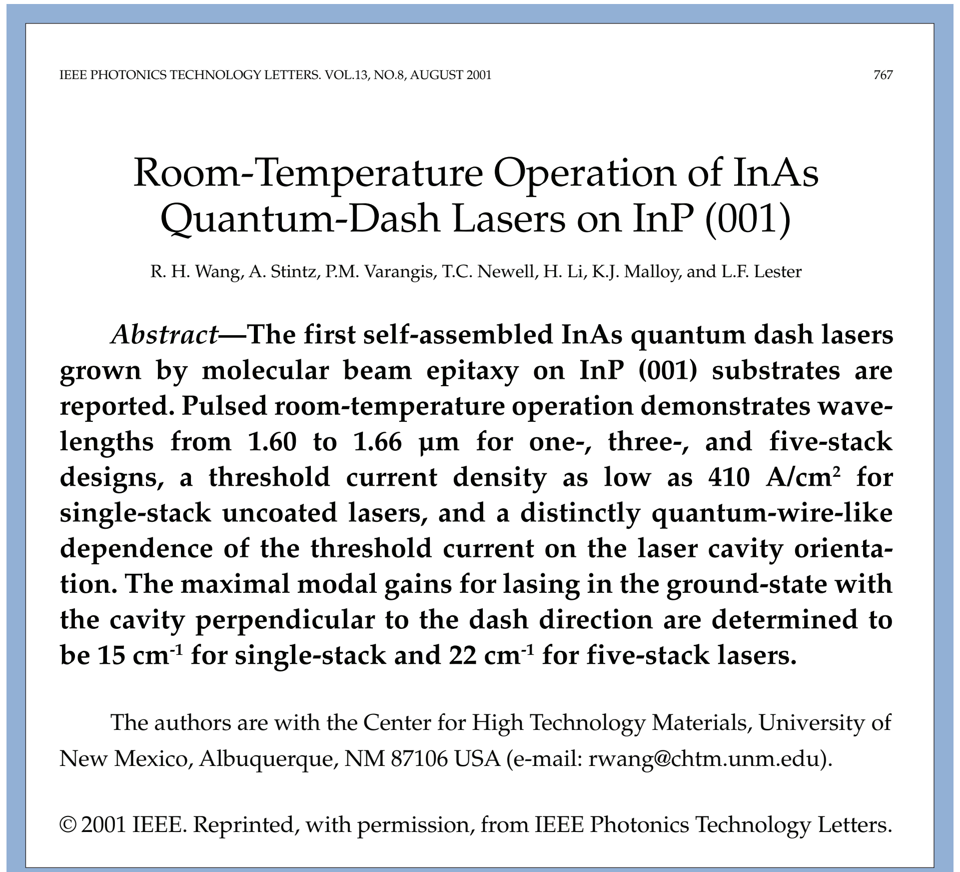
Rerouted to Telecom

It turns out this interplay between the filling of lower energy transitions and higher ones is also important to the line width enhancement factor, α, or chirp parameter. For ultrashort laser pulses, chirp means the pulses spread out due to the dispersion of the material through which they propagate, with some wavelengths moving faster than others. This is a big problem for telecommunications.

Lester and colleagues developed a theory to explain why: as the injection current increases, α balloons from 4 to 60 as the lower energy states of the QDs are saturated. Frederic Grillot of the National Institute of Applied Sciences in Rennes, France and now visiting CHTM, saw Lester's paper and extended it, showing that after ballooning, the factor plummets to negative 30. The researchers think this happens when higher excited energy states begin "stealing" electrons and holes from the filled lower states. In a paper accepted by the *Journal of Quantum Electronics*, they elucidate the factors that control chirp, holding out the prospect for chirpless optical transmission over much greater distances. A laser with a negative α value could counteract the positive chirp of optical fibers, allowing signals to travel much farther without degrading.

Even if the telecommunications market doesn't rebound, Lester is sure to be investigating some relevant QD or optoelectronic device. With a high h number of 26, over 182 papers under his belt (14 of which were invited especially in Europe where QD research is thriving), Lester will continue to make an impact.

"Luke is an extremely respected member of the optoelectronics community," says Pallab Bhattacharya, Charles M. Vest Distinguished University Professor of Electrical Engineering and Computer Science and James R. Mellor Professor of Engineering at the University of Michigan. "I have been aware of Luke's work since he was a graduate student at Cornell working on high-speed quantum well lasers. At UNM, Luke is considered as one of the pioneers in the development of QD lasers. In fact, he is credited for demonstrating the *lowest* threshold current (16 A/cm^2—nearly zero!) in a QD laser. Later he went on to demonstrate extremely low chirp and linewidth enhancement factor in these lasers. Luke has been a true pioneer." ■



IEEE PHOTONICS TECHNOLOGY LETTERS. VOL.13, NO.8, AUGUST 2001 767

Room-Temperature Operation of InAs Quantum-Dash Lasers on InP (001)

R. H. Wang, A. Stintz, P.M. Varangis, T.C. Newell, H. Li, K.J. Malloy, and L.F. Lester

Abstract—The first self-assembled InAs quantum dash lasers grown by molecular beam epitaxy on InP (001) substrates are reported. Pulsed room-temperature operation demonstrates wavelengths from 1.60 to 1.66 µm for one-, three-, and five-stack designs, a threshold current density as low as 410 A/cm^2 for single-stack uncoated lasers, and a distinctly quantum-wire-like dependence of the threshold current on the laser cavity orientation. The maximal modal gains for lasing in the ground-state with the cavity perpendicular to the dash direction are determined to be 15 cm^{-1} for single-stack and 22 cm^{-1} for five-stack lasers.

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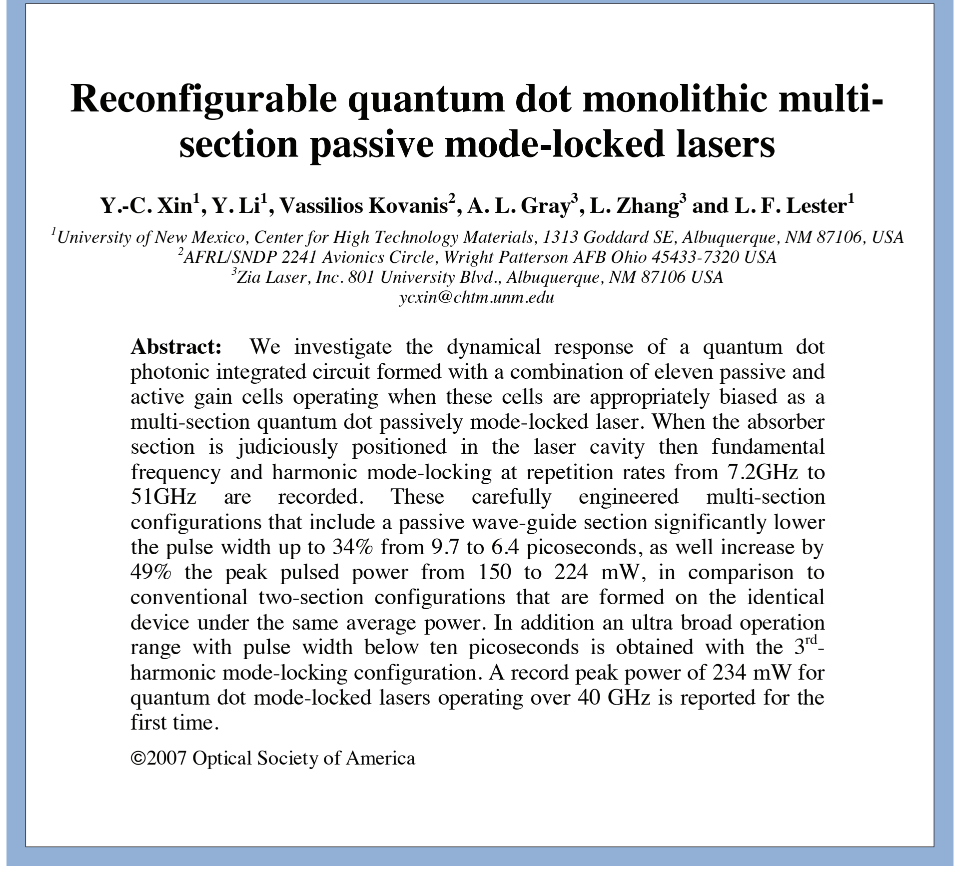

Reconfigurable quantum dot monolithic multi-section passive mode-locked lasers

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Abstract: We investigate the dynamical response of a quantum dot photonic integrated circuit formed with a combination of eleven passive and active gain cells operating when these cells are appropriately biased as a multi-section quantum dot passively mode-locked laser. When the absorber section is judiciously positioned in the laser cavity then fundamental frequency and harmonic mode-locking at repetition rates from 7.2GHz to 51GHz are recorded. These carefully engineered multi-section configurations that include a passive wave-guide section significantly lower the pulse width up to 34% from 9.7 to 6.4 picoseconds, as well increase by 49% the peak pulsed power from 150 to 224 mW, in comparison to conventional two-section configurations that are formed on the identical device under the same average power. In addition an ultra broad operation range with pulse width below ten picoseconds is obtained with the 3rd-harmonic mode-locking configuration. A record peak power of 234 mW for quantum dot mode-locked lasers operating over 40 GHz is reported for the first time.

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For Further Reading

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