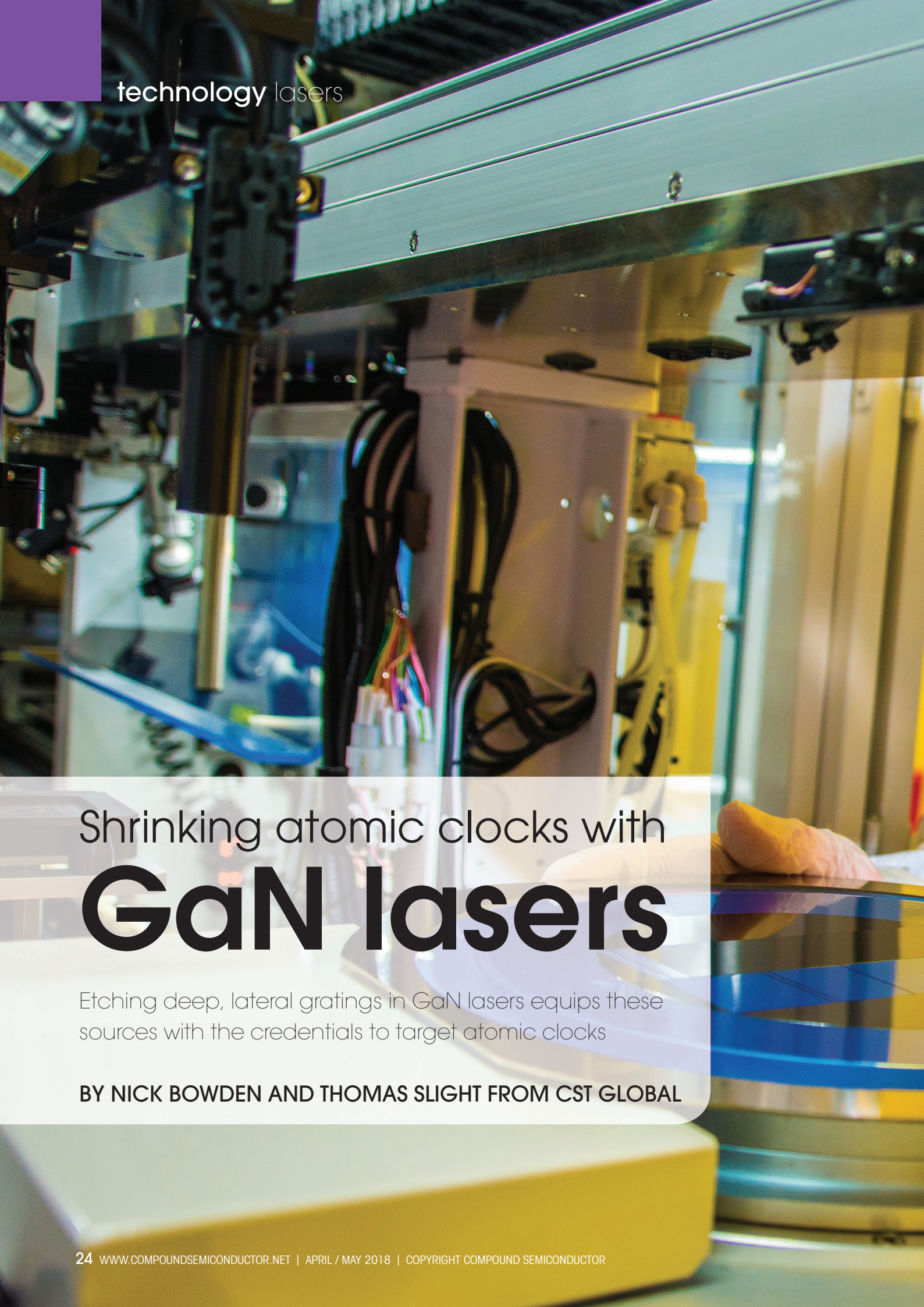

Shrinking atomic clocks with GaN lasers

Etching deep, lateral gratings in GaN lasers equips these sources with the credentials to target atomic clocks

BY NICK BOWDEN AND THOMAS SLIGHT FROM CST GLOBAL

WHAT WILL BE the legacy of the Blu-ray player? With the rise Netflix and other video-streaming services, sales of this player could rapidly decline. But the Blu-ray will still be cherished, in this industry at least, as the product that drove the commercialisation of the GaN-based laser.

The good news is that a second killer application is now emerging for this class of laser: illumination. GaN lasers are already being used in the headlights of high-end cars, and they are a very promising source for all forms of colour projector.

Other markets are also on the horizon. They demand GaN lasers with greater spectral purity and wavelength selectivity, characteristics that may be introduced by replacing the Fabry-Pérot cavity with a distributed feedback design. Making the switch allows the lasers to win deployment in plastic optical fibre networks and to provide communication through water, and last but by no means least, to serve in atomic clocks, where their blue emission is used to cool atoms.

At present, there are two common options for the optical source that is used in atomic clocks: bulky, solid-state lasers, which use frequency doubling to produce appropriate wavelengths; and blue laser diodes with external cavities, a combination that requires complex, vibration-sensitive mechanical assemblies. Replacing either of these sources with a GaN-based laser that features distributed feedback would deliver multiple benefits. It could simplify the design of the clock, slash its size, make it more robust, and ultimately underpin its transition from the lab to mainstream, commercial applications.

To try and turn this dream into a reality, our team at CST, the University of Glasgow, TopGaN Lasers and Aston University has been developing GaN lasers with the required attributes through a project known as CoolBlue. This effort, which is has the official title, *Quantum Cooling using Mode Controlled Blue Lasers*, has revealed that it is possible to produce a commercially viable, single wavelength, GaN laser diode for atomic-cooled, quantum sensors.

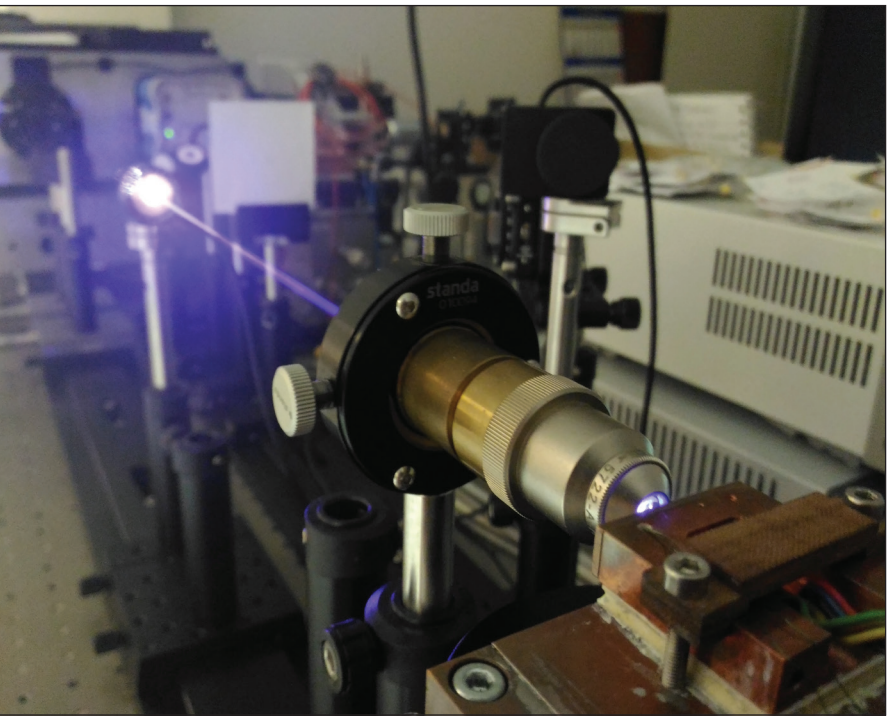

Figure 1.
A distributed feedback laser under test.

Credit:
S. Stanczyk, TopGaN Ltd.

While the market for this device may never be as big as that for the Blu-Ray player, it can still be significant. According to a 2015 report entitled *A roadmap for quantum technologies in the UK* (co-authored by Innovate UK, a leading UK Government research funding agency, and the Engineering and Physical Sciences Research Council) the global market for quantum technology is worth about $1 billion. If a third of this is quantum sensing, 10 percent of that is associated with sensing hardware, and one-tenth of that is the laser source, the market for this class of GaN laser diode is £3 million. Project a conservative annual growth of 10 percent, and that is a market of £5.3 million in five years.

Tapping into this market will require volume production of laser diodes that combine many of their well-known attributes – such as a small size and a robust packaging – with a high degree of spectral purity, ideally realised with a relatively simple approach. We are able to do this with our novel form of grating.

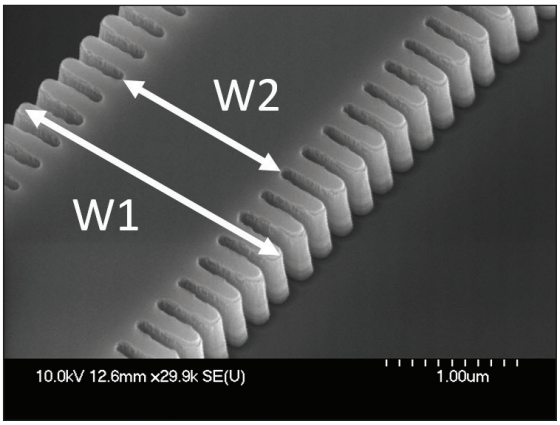

Figure 2.
A scanning electron microscopy image of the 'as etched' third-order grating, with waveguide widths W1 and W2 of 1.5 μm and 2.5 μm, respectively.

Grating design

Our approach differs from the two conventional ones that have been adopted for the production of distributed feedback laser diodes. One option is buried gratings, which are hampered by complex overgrowth steps that risk epi-defects. With the common alternative – surface gratings etched directly into the ridge top – the danger is a reduction of *p*-type contact quality, due to damage caused by reactive ion etching. Another impediment associated with surface gratings is a significant optical loss in the electrically un-pumped grating regions, an issue that may be mitigated with shallow-etched, lateral grating designs.

We avoid all of these pitfalls by pioneering deeply etched, lateral gratings. One of the merits of this approach is its reduced number of steps: most of the structure, including the waveguide and the grating, is formed in a single step. Additional advantages are a higher yield and a larger grating coupling coefficient, strengths that we particularly value for producing sources for atomic-cooled, quantum sensing systems, such as atomic clocks.

Fabrication of our lasers begins by taking commercially-available, MOCVD-grown GaN laser-grade wafer material that contains an active region with InGaN quantum wells with GaN barriers, and using an electron beam lithography tool at the University of Glasgow to define grating and ridge patterns. Reactive-ion etching transfers the pattern into a 100 nm-thick, hard mask before inductively coupled plasma etching forms the grating and the ridge. The resultant structures have a nearly vertical and smooth etch profile, to ensure optimal grating performance.

Completion of our devices involves the addition of an electrical contact to the cap layer, before the reverse of the wafer is mechanically-thinned and polished, before a conductive metal layer deposited on it. Finally, the devices are cleaved to different cavity lengths, with both front and back facets left uncoated.

Fabricating of first-order sidewall gratings is challenging, as it requires high aspect ratios and feature sizes as small as around 40 nm. So we use third-order gratings, which have minimum feature size of around 120 nm.

We have undertaken simple modelling to improve our grating design, and gain greater insight into the influence of grating dimensions on device performance. Using the beam propagation method, we have calculated the effective modal index. Then, using this value we have determined that for lateral grating waveguide widths of 1.5 μm and 2.5 μm and an etch depth of 0.5 μm, there is a refractive index difference within the laser of 0.0015. Using this value, and turning to couple mode theory, we can estimate a value for the coupling coefficient of 22 cm^{-1}. To ensure a single mode yield, the product of the coupling coefficient, κ, and

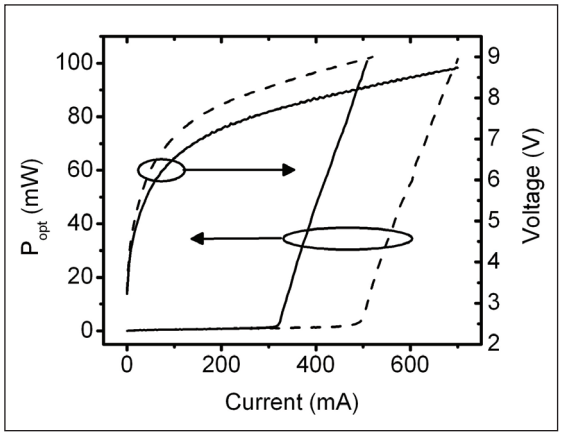

Figure 3. Optical power and voltage as a function of pulsed drive current for distributed feedback device (solid line) and the Fabry-Pérot device (dashed line).

cavity length should be around 1.5, implying that the optimal cavity length is around 700 μm.

To evaluate the performance of our devices, we have undertaken light-current-voltage and spectral measurements on distributed feedback lasers with a third-order grating that features lateral grating dimensions of 1.5 μm and 2.5 μm, a cavity length of 1000 μm and an etch depth of 520 nm. So that we can benchmark the performance of these devices, we have also fabricated Fabry-Pérot lasers with similar dimensions from the same wafer.

Pulsed drive measurements at 20 °C reveal that the slope efficiencies of both types of laser are similar. However, the distributed feedback laser has a lower threshold current, suggesting that the feedback from the grating is stronger than that from the cleaved facets. Both classes of laser have relatively high threshold currents, which is thought to be primarily due to sub-optimal epi material.

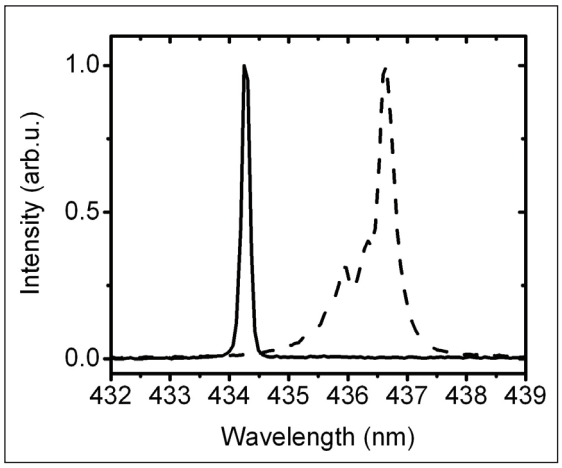

Figure 4. Single wavelength emission for distributed feedback device (solid line) and, for comparison, multi-mode spectra of the Fabry-Pérot device (dashed line).

Atomic aspirations

As expected, the emission from the distributed feedback laser is much narrower than that produced by the cousin with the Fabry-Pérot cavity. While the latter exhibits multi-mode emission, the distributed feedback laser produces a single wavelength emission spectrum (see Figure 4). At a drive current of 390 mA, which is 20 percent above threshold, this laser produces an output of 40 mW and has a spectral purity, judged in terms of the side-mode suppression ratio, of 22 dB. These values are sufficient for laser cooling within atomic clocks. However, meeting all the requirements for that application will require more work, including the realisation of continuous wave operation, and the shifting of the emission to 422 nm to target the Sr^+ ion.

While reaching an emission wavelength of around 422 nm will get in the right ballpark for the Sr^+ ion, temperature tuning is needed to hit the cooling line. To assess the capability for this, we have measured the performance of another distributed feedback laser, which has an emission wavelength of around 437 nm.

By varying the heat-sink temperature between 20 °C and 30 °C, we can tune the emission wavelength during pulsed operation. This device has a tuning coefficient of 0.013 nmK^{-1}, which compares well with published values for lasers of this type.

Thanks to the successes that we have had, we have won funding for a follow-up project, CoolBlue2. It started in April 2018 and runs for a year. All the partners in the first project are retained, and are joined by the National Physical Laboratory (NPL) and Helia Photonics. The role of NPL includes performing laser cooling system tests to demonstrate the efficacy of the technology, while Helia is offering expertise in laser facet coating, enabling improvements in laser performance.

We hope that the GaN technology that we develop in CoolBlue 2 will form the critical elements in many quantum applications. This effort should result in a stringent set of performance requirements for wavelength, stability, output power and linewidth, and will offer a clear understanding of how lasers can be deployed in many different applications.

Looking even further ahead, after CoolBlue 2 has finished, those of us at CST will continue to invest in product development, assuming sufficient visibility of market opportunity and maturity of the supply chain. This investment is likely to be at the chip or packaged device level, although clearly opportunities may exist for subsystem-based products.

This work was supported by the Innovate UK project Coolblue (project number 132543) and by The National Centre for Research and Development within the Eurostars 2 Programme (E10509/29/NCBR/2017)

Further reading

T. J. Slight *et al.* IEEE Photon. Technol. Lett. **28** 2886 (2016)