Novel grating boosts brightness

Alfalight's top-emitting laser produces far higher output powers than edge-emitters thanks to a curved grating that runs along the underside of the chip. This radical design allows beam-focusing with simple optics and is ideal for pumping fiber lasers, say Manoj Kanskar and François Brunet.

High-power laser diodes serve many tasks. These include cutting metals, welding plastics and solders, and pumping solid-state lasers, fiber lasers and amplifiers, which can all be accomplished with single emitters, bars and arrays.

Many applications prefer to employ a circular beam emitted from the end of a fiber, rather than the more complex emission profile that comes from an edge-emitting laser. However, the costs of fiber-coupled laser diode manufacturing are high – almost an order of magnitude more than those for laser diode chips and bars, in terms of dollars per watt.

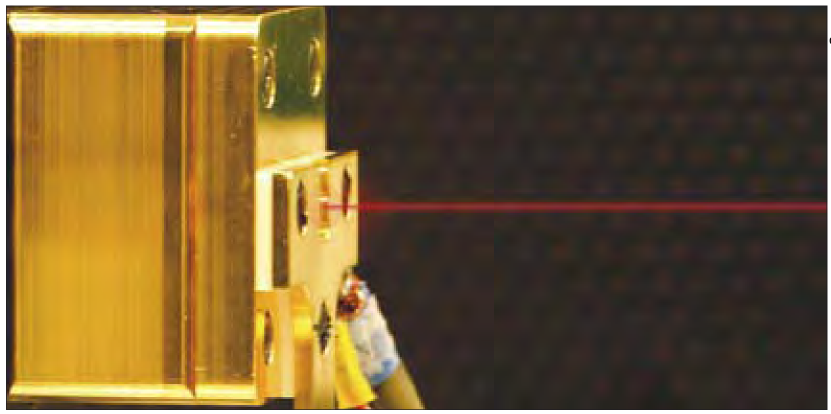
The increased cost of the fiber-based laser stems from the inferior beam quality of edge-emitting broad-area diode lasers and bars. Expensive beam-formatting optics with tight tolerances are needed to transform the output from these emitters into a form that can be coupled into a fiber, and this propels the dollar-per-watt figure to a level that is unattractive for many applications. But the cost-per-watt can be driven down with bright diodes built with low-cost manufacturing techniques that produce an output that is easy to couple into a fiber. At Alfalight, which is based in Madison, WI, we have developed a design that does this – a curved-grating surface-emitting distributed feedback (SE-DFB) laser (figure 1, p22).

Empowering the fiber

Coupling substantial power into a small-core fiber requires a laser with high spatial brightness. This means that the device has to produce a high power in a given entendue (a metric that reflects the size of the source and the spread of the beam, in terms of the solid angle).

One way to generate a high-power source is to couple the emission from several single-mode lasers into a single fiber. But this approach is impractical because each diode produces no more than 1 W of useful power, and an unwieldy number of lasers would have to be coupled together for power-hungry industrial applications. So numerous 100 µm wide, multimode broad-stripe lasers in bar and stack forms are used instead, which can deliver hundreds of thousands of watts needed for pumping applications.

By utilizing a relatively simple coupling scheme, about 10 W of power can be launched into a 100 µm diameter, 0.15 numerical aperture fiber. However,



Alfalight

Alfalight's surface-emitting distributed feedback laser produces a collimated longitudinal beam that can be used for cutting, welding and the pumping of fiber and solid-state lasers.

power scaling is a significant challenge. Combining chips boosts power, but at the expense of higher costs and increased complexity. Multiple bars offer an alternative route to power scaling, but they require expensive micro-optics for collimation and complex, high-tolerance configurations for beam transformation. Once again, costs are an issue.

A far better source for fiber coupling is our SE-DFB laser, a novel emitter with a curved grating that is analogous to an unstable resonator. This design draws on a well known approach to establishing good lateral-beam quality over a large area, and enables fabrication of high-power, high-brightness lasers that can form an ideal source for power scaling, particularly in the form of arrays.

Our SE-DFB lasers have several advantages over their edge-emitting cousins: the absence of facet coatings; greater tolerances for bonding to a heat sink; better array yields; and simplified coupling optics. These four strengths create a laser with lower manufacturing costs than an edge-emitter, whether it is in the form of a single chip or an array.

Edge-emitters require a facet coating, which is a time-consuming, cumbersome step. SE-DFB production avoids this. It employs a wafer-level batch process to add an anti-reflection coating to the device's output window. Out-of-spec dies can then be discarded with wafer mapping techniques, leading to minimal yield losses at expensive downstream steps.

The SE-DFB design also simplifies bonding of

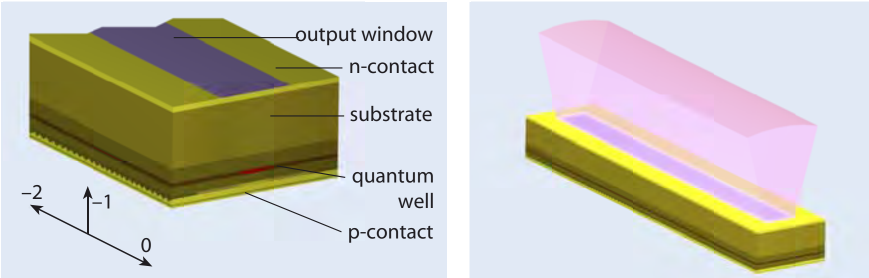


Fig. 1. The SE-DFB laser produces emission through the substrate via the surface-normal mode (–1). The fundamental (0) and feedback (–2) modes propagate along the length of the waveguide.

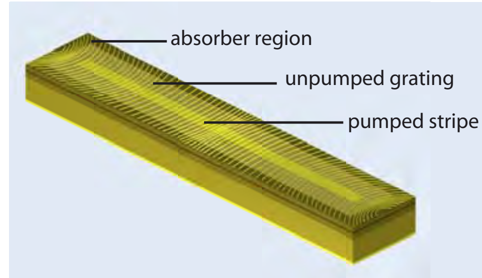


Fig. 2. The underside of a curved-grating SE-DFB laser has a central pumped stripe, grating and absorber regions.

the chip to a heat sink. Edge-emitters have to be precisely placed at the knife-edge of an expensive heat sink, whereas SE-DFB lasers can simply be picked and placed on an inexpensive flat heat-sink surface, using far higher alignment tolerances.

Fabricating arrays is more successful with SE-DFBs because failure can be eliminated by selecting burned-in, pre-tested, known-good-devices. In comparison, entire stacks of edge-emitting arrays have to be scrapped after most of the value-adding has occurred if a handful of faulty elements are found.

Lastly, SE-DFBs simplify fiber coupling. Output can be collimated straight out of the chip in one direction, eliminating the need for an expensive diffraction-limited, fast-axis microlens, which is an indispensable component for collimating edge-emitters. Collimation along the perpendicular optical axis can be realized with a relatively inexpensive cylindrical lens. In fact, one aspherical lens can focus the output of a two-dimensional array of SE-DFBs, which cuts the cost of focusing optics.

The strengths of the SE-DFB laser stem from the curved second-order grating that is etched into the p-cladding and subsequently coated with gold (figure 1). Adding a patterned p-contact defines the pumped stripe dimensions, and the parts of grating outside of this region remain unpumped (figure 2).

A zero-order mode propagates along the waveguide, which has two diffraction orders: one for feedback and another for surface emission. Feedback only occurs from the grating, thanks to suppression of Fresnel reflections from the ends and sides of the chip by an absorbing layer above this structure. Surface emission is produced from transmission through the substrate via an anti-reflection-coated window aperture in the n-side metallization. Laser output is emitted from the device's top surface, with the beam collimated in the longitudinal direction and diverging in the lateral direction, with a full angle of 8º.

The SE-DFB's curved grating produces an unstable resonator with modes that are governed by the phase of the grating (i.e. its shape). This phase-related information is incorporated into the SE-DFB laser by taking a glass plate and encoding an array of phase-height patterns on this surface. This information is transferred to the device with an interference pattern that follows the curved wavefront phase, which can be defined on a wafer that's coated with a photoresist using a holographic exposure system. High volume production is easy, because a single exposure can record the grating pattern over the whole wafer.

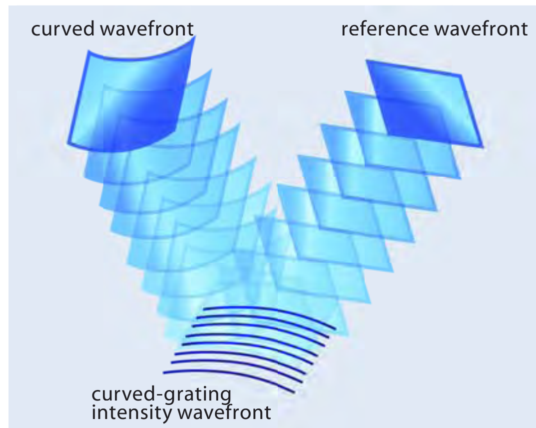


Fig. 3. Curved gratings that feature in the SE-DFB laser are formed by interference of a reference plane wavefront and curved wavefront. The reference wavefront comes from a collimated laser beam and the curved wavefront is generated by the collimated beam exiting the phase plate surface.

The curved grating is responsible for the SE-DFB's cylindrical wavefront in the output beam. This profile makes it appear that the beam emanates from a narrow virtual line source, even though a much wider stripe is pumped (figure 4). In fact, the ratio of the pump source widt to that of this virtual line waist is approximately equal to the increase in brightness produced by the curved grating design. This grating also suppresses filamentation in the wavefront propagation – a common issue in broad stripe lasers – which stems the combination of spatial-hole burning and carrier-index coupling.

We have demonstrated that the theoretical strengths of the SE-DFB design can be realized in real devices, such as a single stripe emitter with a $7500 \times 500\,\mu m$ active area. This chip produces a record power of 73 W from a single laser diode, thanks to the freedom to scale the pumped stripe area while maintaining the current density at a relatively low, constant value. With a well designed grating it is possible to suppress filamentation and control the lateral mode for a much larger size of

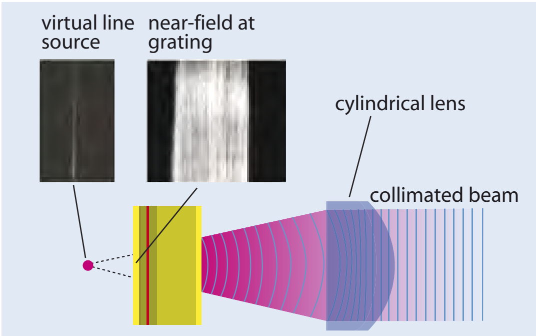


Fig. 4. The SE-DFB laser produces a lateral beam with a cylindrical wavefront that appears to emanate from a narrow virtual line source behind the grating surface. The wide stripe is an image captured at the grating surface and the narrow stripe is a virtual line source formed at the focus behind the chip.

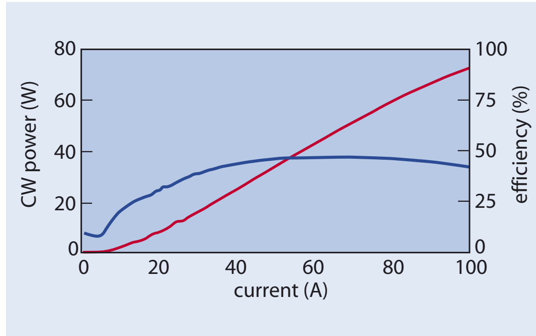


Fig. 5. Alfalight's SE-DFB laser can produce a continuous-wave output of 73 W, which is a record for a single chip. The efficiency of this source is 50%.

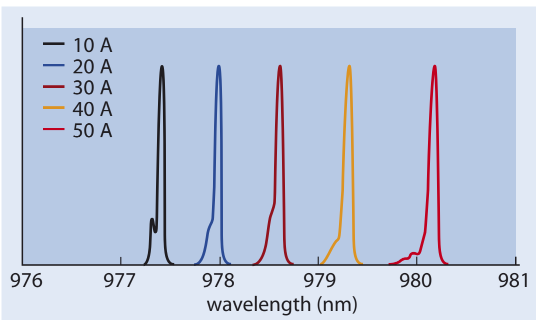


Fig. 6. Wavelength shifts with temperature for the SE-DFB laser are just 0.07 nm/°C, which makes this an ideal source for pumping narrow absorption lines of fiber and solid-state lasers.

gain stripe compared with edge-emitters.

The emission bandwidth of this SE-DFB laser is just 0.3 nm, which makes it 10 times as bright as an edge-emitter (figure 5). Our chip also produces a five-fold reduction in wavelength shift with temperature to 0.07 nm/°C, removing the need for chip cooling in certain applications. Immunity to catastrophic optical mirror damage – a common failure mechanism for high-power edge-emitters – is another strength of our laser that results from the absence of any facet. Due to the relatively large emission area of our SE-DFBs, the output beam of our laser at the exit window is 1000 times less than that of an edge-emitter.

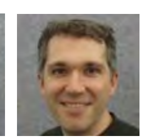
In some applications, edge-emitters suffer from a back reflection that damages the source. This is not an issue for SE-DFBs because coupling light back into the cavity would require precise matching of the wavelength and the incident angle, which is very unlikely. Instead, incident light is reflected by the chip, preventing damage from parasitic beams.

We are developing a two-dimensional tiling of SE-DFBs can realize multi-kilowatt arrays, through the interleaving and polarization combining of individual sources. Further power scaling should be possible with wavelength beam combining. A key advantage of the two-dimensional tiling approach is that it allows devices to be "voltage-added", which means that they can be driven with an inexpensive low current supply that cuts the overall system cost.

The SE-DFB's narrow spectral width and minimal shift in wavelength with temperature make it an ideal source for pumping narrow absorption peaks of solid-state gain media. This includes the 975 nm band of ytterbium-doped and ErYb co-doped fiber lasers, which has a relatively high absorption coefficient. Shorter fiber lengths can then be employed in the laser, which mitigate deleterious nonlinear effects, such as stimulated Brillouin scattering and stimulated Raman scattering. Another benefit of pumping at this wavelength is that it leads to a lowering of the quantum defect – the difference in energy between the pump source and the emitted light. Gain media can then run cooler, reducing the likelihood of thermal lensing. This is a significant benefit for solid-state lasers, such as slab and thin disc lasers.

It is impractical to use edge-emitting Fabry-Pérot lasers for pumping the 975 nm transition because their spectral width is too broad. In addition, the wavelength drift with temperature is too fast and expensive thermal management systems are needed to maintain the resonance wavelength. What's more, increases in pump current that detune the wavelength from resonance produce a substantial amount of power that is not absorbed, which has to be managed without causing failure to downstream components. This adds to the challenge of building reliable, kilowatt-class fiber lasers and amplifiers.

Our SE-DFB laser's desirable characteristics, such as incredibly high brightness and a very small shift in emission wavelength with temperature, make them great sources for pumping fiber-coupled arrays that generate kilowatt powers. However, they can also be employed as direct-diode sources for plastic welding, sintering, heat treatment, soldering, engraving and some cutting applications. Armed with bulk cylindrical optics, simple, low-cost collimation is possible and the SE-DFB can then be used as an inexpensive source for other applications, such as security illumination, sensing and designation. By operating this laser in pulsed mode, it can produce nanosecond pulses that have a five-fold increase in power, which makes this source a low-cost option for transmitters in range finders. With such a broad range of applications, it is clear that the SE-DFB laser has a bright future.

About the authors

Manoj Kanskar (left) is Alfalight's vice-president of research and development, and **François Brunet** (right) is product manager.