Angle-Etched Facet Laser Arrays (Fan Laser Arrays)

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Abstract—We present a novel individually addressable diode laser array that uses angle-etched facets. By arranging the lasers in a fan-like structure, all lasers emit in different directions from a common effective aperture. Using this device design, we demonstrate lasers with beam directions that are fixed and distinct, stable, single mode, and capable of simultaneous and random access operation. We analyze both the effect of facet roughness on the performance of etched-facet diode lasers, as well as the thermal crosstalk characteristics of angle-etched facet lasers. Thermal crosstalk characteristics of angle-etched facet lasers are experimentally compared to parallel stripe lasers. The combination of the aperture and thermal crosstalk reduction allows us to reduce the effective thermal coupling between array elements by over one order of magnitude. We show a novel two-dimensional scanner built with a fan laser array: results demonstrate the feasibility of these novel arrays for multibeam applications.

Index Terms—COD, etched facets, facet roughness, fan laser, laser, laser array, micromachining, power density, thermal crosstalk modeling, two-dimensional laser scanner.

I. INTRODUCTION

INDIVIDUALLY addressable diode laser arrays are becoming the new source of choice to increase throughput in laser systems. Multibeam sources are being considered for applications such as CD players [1], [2] and laser printers [3], [4].

The optics used in consumer applications are low-cost and have limited numerical aperture. In order to take advantage of the low-cost optics, multibeam sources must be designed to fit within a restricted field of view. In a laser printer, the optics field of view is roughly 50 μm wide. The minimum allowable separation between lasers is limited by crosstalk. The maximum allowable crosstalk level, in printer systems, is 5%. These competing constraints have resulted in limiting the number of elements in individually addressable arrays to only 2 or 4 [3].

To increase the number of elements that can be used in an individually addressable diode laser array, we developed an angle-etched facet laser array: the fan laser array. In this paper, we show that the fan laser array out-performs parallel laser arrays because it simultaneously reduces the effective aperture of the laser array and the crosstalk between array elements.

We describe the design and fabrication of the fan laser array, present the far-field patterns, and show the light versus current characteristics. To the best of our knowledge, our results represent the highest power density obtained on uncoated etched facets to date.

As a result of our unique device geometry, we obtained thermal crosstalk reduction between angled array elements when compared to parallel array elements with similar minimum separation. We describe the enabling characteristics of the reduced laser aperture, and a system which uses the reduced aperture. The combination of the reduced aperture and reduced interelement crosstalk leads to one order of magnitude reduction in effective thermal crosstalk between array elements. This is the first demonstrated technique for reduction of thermal crosstalk between elements of an individually addressable laser array.

II. DEVICE DESIGN AND FABRICATION

Fig. 1 is a schematic of the fan laser array. The array is designed with all the elements displaced in a fan-like configuration. Each individual element has facets at preset angles. The micro facets were fabricated by dry etching. The lateral dimensions of the facet are 8 μm on one end and 70 μm on the other, with the former closer to the central point of the fan laser array. The active area is an 8-μm-wide stripe.

The minimum facet size in our design is effectively the minimum beam waist, and therefore determines the optical beam characteristics of the array elements. By tailoring the beam waist, one can design the array beams to completely fill the far-field without overlap, or to remain well focused when they cross the central point. The central point is used as an effective aperture for external optics. It is important
from a system point of view to have all the beams well
collimated at the central point to minimize the effective
aperture. The 8-μm-wide structure allows for single-mode
operation with pulsed drive current at all pump current levels.
Far-field measurements at different pump current levels have
been previously reported [5]. Single-mode operation could be
achieved in CW mode in the same manner as all other cleaved
facet ridge-waveguide structures.

Despite the fact that the lasers are only 8 μm apart at one
end, they are separated enough at the other end that it is
possible to directly wire bond onto the individual elements.
This bonding can be done without the need for complicated
metallization schemes as is required by closely spaced parallel
laser structures.

We fabricated proton-implanted and ridge-waveguide
(RWG) devices. The proton-implanted lasers are described
elsewhere [6]. Here, we describe the RWG fabrication.

We used graded-index separate-confinement-heterostructure
single-quantum-well (GRINSCH-SQW) material grown by
molecular beam epitaxy (MBE) with an InGaAs active region.
We fabricated laser arrays that operate at 850 and 950 nm.

The ridge formation of the RWG’s must be done with an
isotropic etch of the semiconductor. Because waveguides are
placed at finite angles from the natural crystal orientation,
chemistries that etch preferentially along certain crystal orien-
tations lead to corrugations along the side of the semiconductor
material. Lateral corrugations affect the waveguide and thus
the laser properties. Therefore, we used a low-temperature
material. Lateral corrugations affect the waveguide and thus
the laser properties. Therefore, we used a low-temperature
(0 °C) phosphoric acid etch. This etch is slow but controllable
and not crystal-orientation dependent.

Dry etching of the mirror facets is the crucial step in
the fabrication of the fan laser arrays. We used a reactive
ion etch (RIE) to generate the mirror facets. The active
chemical in the RIE was SiCl₄. The etch was done around
20 °C at 30-W power and 150 V of forward bias. Laser
performance depends directly on the etched facet quality.
The quality of the facets is defined in terms of the facet
roughness and the undercut angle. The key parameters for
the dry etching were: high etch contrast ratio between the
mask and the semiconductor; good thermal contact between
the substrate and the heat sink; and temperature stability
during the entire etch. The mask used was a 3000-Å layer
of silicon nitride (Si₃N₄). The contrast ratio between the
AlGaAs and the nitride was greater than 20:1. To get good
thermal contact, we mounted the etch wafer onto a 4- in Si
wafer. The Si wafer was placed on the cooling electrode. This
mounting process provided good thermal contact between the
etched piece and the heat sink. We found that temperature
variation from etch to etch on the order of 1 °C did not
affect the facet quality, only the etch rate. The temperature
stability, however, was critical in achieving straight vertical
sidewalls. We had better than 0.1 °C temperature stability by
using constant backside cooling of the wafer throughout the
etch.

In addition, it is important to ensure that the facets are
not compromised in subsequent processing, because the entire
fabrication process affects the facet quality. The etch must
be done on a thoroughly cleaned substrate; otherwise residue
from previous fabrication steps will lead to roughness on the
facet. One way to minimize surface residue is to perform the
etch early in the fabrication process. It is also important to
minimize the number of post-etch steps, because they to can
damage the facets. The solution is to keep the total number
of fabrication steps to a minimum and to use resist which is
thicker than the mirror etch depth.

Fig. 2 shows a SEM of an etched facet. We see that the
etched surface is very smooth and that the sidewalls are
perfectly vertical. The darker region above the surface is the
Si₃N₄ mask.

After the mirror etch, we opened contact holes over the
laser waveguides and evaporated Ti–Au is as a P contact. In
both steps, a 3.5-μm-thick resist was used to cover the facets,
protecting them from damage.

III. FAR-FIELD INTENSITY DISTRIBUTION

Given that the laser array elements are placed at discrete
angles, the far-fields shift according to laser facet orientation.
Using these angle-etched facets, we attained beam steering.
Fig. 3 is the far-field of one array [7]. The far-field mea-
surements show beam steering from −40° to 40° with 11
resolvable spots. All the beams are single-lobed and have beam
spreads in the far-field around 8° as designed.

The beam steering results we achieved have tripled all
previous beam steering results in both total steering angle
and in total number of resolvable spots [8], [9]. Furthermore,
we obtained single-lobed Gaussian beams at all angles. This
is important because previous methods, which result in non-
Gaussian beams, waste almost half of the optical power in
the beam pedestal. Using the angle-etched facet technique, it
is possible to obtain beam steering over any desired angular
range, the only limit is in the number of resolvable spots within
this angular range.
Fig. 3. The far-field of a fan laser array. The beams can address the far-field from \(-40^\circ\) to \(40^\circ\) with 11 resolvable spots.

IV. LIGHT VERSUS CURRENT CHARACTERISTICS

Pulsed and CW light versus current measurements of our devices are shown in Fig. 4. We were able to get up to 125 mW out of a single-stripe laser before contact failure. This corresponds to 5.2 MW/cm\(^2\), assuming an 8 \(\mu\)m by 0.3 \(\mu\)m emission aperture for a GRINSCH laser. To the best of our knowledge, this is the highest reported power density on an uncoated etched to date, and we did not observe catastrophic optical damage (COD) of the facet.

We attribute the high power densities to our design of noninjection regions near the mirror facets. This design is similar to the window laser approach which has shown great results for cleaved facet lasers [10], [11]. While fabricating cleaved facet lasers with noninjection regions can be quite cumbersome, it is easy to obtain in etched facet structures because the mirror and the contact placement are both lithographically defined. By coating the etched facet lasers and testing for lifetime, other groups have demonstrated 15 MW/cm\(^2\) and over 3000 h of operation of such devices [12], [13]. These results show that while etched facet lasers may not be able to sustain as high powers as cleaved facet lasers, they are well suited for low- and medium-power applications when cleaved facet lasers are unfeasible, such as in very closely spaced multi-element array sources.

The lasers fabricated have uniform \(L-I\) characteristics. Fig. 5 demonstrates the level of uniformity in both threshold and differential efficiency achieved for packaged lasers tested without heat sinking.

Fig. 4. The output power of an etched facet diode laser. Power is per facet. In pulsed operation, the laser was tested with 1 \(\mu\)s pulsed at 1% duty cycle at room temperature. In CW operation, the laser was tested at 15 \(^\circ\)C. In both cases, the lasers were tested with no p-side heat sinking.

V. ROUGHNESS OF ETCHED FACETS

One unfortunate down side of etching diode laser facets is that the facets can have a finite amount of roughness which affects the laser-diode performance. While cleaved facet diodes have, ideally, atomically smooth facets, the etched facet diodes may not, depending on the masks used in photolithography, on the etching process, and on the residue left by previous or subsequent processing steps. We modeled the effects of facet roughness on the performance of etched facet lasers to find the level of roughness that would lead to only negligible effects on laser performance.

The standard roughness assumed tolerable on laser facets is \(\lambda/100 \sim 0.03 \mu\)m in the material. By theoretically calculating the effects of facet roughness on the reflectivity of diode lasers, we show that the effects of additional facet loss for facets with \(\lambda/10\) roughness are in fact small for uncoated etched facet diodes; however, these effects become significant for high-reflectivity-coated (HR-coated) diodes. In HR-coated lasers, \(\lambda/10\) roughness leads to noticeably higher thresholds, decreased efficiencies, and shorter lifetimes. We conclude, from this study, that to have only negligible effects on laser performance, i.e., less than 1% increase in threshold current and less than 4% decrease in differential quantum efficiency, etched facet roughness must be on the order of \(\lambda/15\), 0.02 \(\mu\)m, in the material [14]. One implication of this result is that masks made for angle-etched facet lasers must have 0.02-\(\mu\)m resolution. While this required resolution means that the masks are expensive, it does not imply a significant increase in the cost of production of the laser, because the mask is a one-time cost.

VI. CROSS-TALK MEASUREMENTS

Multibeam sources are affected by three types of crosstalk: optical, electrical, and thermal. Optical crosstalk is usually not a problem, because the optical mode can be confined so that adjacent lasers are not affected. Electrical crosstalk can be avoided by ensuring that the resistance between elements is suitably high. Thermal crosstalk, until now, could only be reduced by increasing the separation between individual lasers, and by making each laser less temperature-sensitive [15], [16]. Presently, thermal crosstalk poses the dominant limitation: the minimum spacing between elements of laser arrays.

The fan laser array design addresses the thermal crosstalk limitation by proposing a different mechanism for crosstalk reduction. By placing lasers in a fan-out configuration, fan
lasers have much larger average separation than parallel lasers, and they maintain the same minimum facet separation. From the point of view of external optics, the only important parameter is the separation between array elements at the near facet. Therefore, we have effectively decoupled the optical and thermal array element separation and used this decoupling to reduce the thermal crosstalk. In this section, we show that with our laser design, thermal crosstalk between elements is reduced by over 50% when compared to parallel arrays with similar minimum element separation.

Thermal crosstalk causes threshold increases, power decreases, and wavelength shifts. Wavelength shifts are a precise measure of the temperature of a laser diode. We used the induced wavelength shifts to measure the thermal crosstalk between array elements.

We looked at the crosstalk level of pairs of lasers separated by similar facet spacing and compared sets of parallel and angled lasers. This was done by measuring the wavelength shift induced in one diode as a function of the operation of the next. One laser, the heating laser, was run in CW mode. The other laser, the test laser, was run in pulsed operation to avoid self-heating-induced wavelength shifts. The wavelength shifts observed in the test laser are our measured value of the interelement crosstalk.

It is important to compare devices with comparable performance characteristics. Fig. 6 shows the light versus current characteristics of two pairs of angled and parallel lasers. We tested lasers in pulsed operation at 15 °C with 1% duty cycle 1-µs pulses. They were found to have thresholds around 15 mA and efficiencies of 0.33 mW/mA. All lasers were mounted on TE coolers for temperature stabilization. The wavelength-shift characteristics of these devices were measured by sweeping the temperature of the TE cooler from 15 °C to 35 °C. The wavelength was found to shift by 2.14 Å/°C in this temperature range.

Fig. 7 is the laser wavelength shifts for lasers with 8-µm facet separation, tested at 1.2 Ith. The heating lasers were driven from 0 to 30 mA (2 Ith). We measured 8 nm of wavelength shift for parallel lasers. An angled laser with 8° between elements showed only a 3.3-nm wavelength shift. The angle-etched facet technique results in greater then 50% reduction in thermal crosstalk.

VII. THERMAL CROSS-TALK MODELING

We modeled the fan laser array to get the theoretically expected wavelength shifts. To obtain the correct functional form \( f(x) \) of the surface temperature profile, we numerically solved the heat equation for the semiconductor structure:

\[
\frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right). \tag{1}
\]

Here, \( t \) is time, \( x \) is the lateral dimension, and \( y \) is the vertical dimension. From (1), we get the functional form of

\[
f(x) = \frac{k}{\lambda} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right).
\]
the temperature $T$ and the surface temperature $T(x, y = 0)$:

$$T(x, y = 0) = T_h f(x).$$  \hspace{1cm} (2)

We used the experimentally measured wavelength shifts of the parallel diode lasers (with 8- and 15-$\mu$m separation) as a fitting parameter to determine steady-state temperature $T_h$ of the heating diode

$$T_h f(8 \, \mu m) = \frac{\Delta \lambda(x = 8 \, \mu m)}{\partial \lambda / \partial T}.$$  \hspace{1cm} (3)

In (3), we measured both the wavelength shift $\Delta \lambda$ and the wavelength dependence on temperature $\partial \lambda / \partial T$.

Using steady-state temperature of the heating laser, we found the surface temperature as a function of the distance from the heating laser $T(x)$. We calculated the gain as a function of temperature and wavelength. To get the total gain $G$ for the angled laser structures, we performed an integral along the length of the laser, taking into account the surface temperature as calculated from the device simulation. The total gain is given by

$$G(\lambda) = \int_{0}^{L} g(\lambda, T(x(t))) \cdot dt.$$  \hspace{1cm} (4)

In (4), $\lambda$ is the wavelength and $g$ is the material gain. $T$, the surface temperature, is a function of the distance from the heating laser $x$, and $x$ is a function of the distance along the laser structure $L$. The peak of the gain profile gives us the expected temperature shift for the angle-facet laser structure.

Fig. 9 shows the theoretically expected wavelength shifts for the laser structures. Theory overestimates the shifts according to our measurements. The discrepancy between the measured and calculated results can be attributed to two factors. First, we do not have a way of reliably measuring the temperature at large distances from the heating laser. We only have measures of the wavelength shifts at 8 and 15 $\mu$m. Second, we also used a simplified model of the quantum-well gain shift as a function of temperature. The simplicity of the model and the lack of extensive measurements could easily account for the small differences between the calculated and measured wavelength shifts.

From the analysis of the laser structures, we see that the measured crosstalk levels are in qualitative agreement with the expected theoretical values. Therefore, any further improvement in thermal laser performance would have to come from other mechanisms. We expect that the difference in thermal characteristics between angled and parallel lasers would be further increased with topside heat sinking.

VIII. Optical System Design

From a system point of view, the unique design of the fan laser array is advantageous because it is able to optically reduce the device aperture. The central point, the position where all the laser beams cross, is the minimum aperture. The central point of the fan laser array is within one Raleigh range of the laser facets. All the laser beams cross, at the central point, while still well collimated. Therefore, the central point is of comparable size to the individual elements, even though it is the aperture for all lasers. This reduction in device aperture by optical means is extremely useful, for one can effectively decrease the interelement spacing, without increasing the crosstalk.

To illustrate this point, we built a system where we reflect the beams of a seven-element laser array off of a microscanner, constructing a two-dimensional (2-D) laser beam scanner. The complete system results of this project will be shown elsewhere. Here, we discuss the enabling aspects of using the fan laser array as opposed to a parallel laser array.

In the 2-D laser scanner, one dimension is controlled by the fan laser array and the other by a silicon-surface micromachined microscanner. The fan laser array elements are displaced along the slow axis (lateral direction) of the diode lasers leaving the microscanner to control the fast beam axis (transverse direction). Given that the fast axis of a diode laser spreads at angles greater than 45°, the beam must be greatly collimated for the scanning to have any significant number of resolvable spots.

To best make use of a scanning system, one has to magnify the beams to fill the scanned mirror surface. The level of magnification at the mirror is directly proportional to the number of resolvable spots obtainable from the scanning.

The central point beamwidth for all the lasers is, according to calculations, 12 $\mu$m wide. We magnified this beam by a factor of 25 and reflected it off of the microscanner. This would restrict us to a much lower magnification factor. By using the fan laser array, we have increased the total number of resolvable spots obtained from the microscanner. Alternatively, one could get the same performance as the seven-element 8-$\mu$m spaced fan laser array by fabricating a parallel array of seven elements, all of which would fit into a 12 $\mu$m window, the effective aperture of the fan. This, however, would require less than 2-$\mu$m spacing between elements of the array, which is virtually impossible.

Fig. 10 shows a system schematic and one generated character. A seven-element laser with 8-$\mu$m center-to-center spacing was used. The microscanner has an optical aperture of 300 $\mu$m $\times$ 400 $\mu$m.

With this system, we demonstrated that the fan laser array not only reduces the thermal crosstalk between elements by the
geometric of the laser structure, but also effectively reduces the separation between elements of the array. The combination of the two effects corresponds to one order of magnitude reduction in the effective thermal crosstalk between array elements.

IX. DISCUSSION

We have demonstrated a novel device which can be used as a beam steering laser or as an independently addressable laser array. While we have made great progress toward solving the beam steering problem, monolithic beam steering is still far from competing with mechanical techniques in the total number of resolvable spots. This is a problem for in most well-established applications of beam steering, the total number of resolvable spots required is still more than an order of magnitude greater than we achieved. Beam steering sources and multi-element individually addressable arrays are, however, very useful in applications where one seeks to increase the throughput of optical systems by taking advantage of the small size, low cost, and high speed of diode lasers. Therefore, we believe that the fan laser array will be most applicable as a multibeam source. The fan laser array retains the favorable qualities of the diode lasers while reducing the interelement thermal crosstalk.

The device design is flexible in that it allows for fabrication of lasers of different widths and different angles. These parameters can be varied to conform to the specific requirements of a particular application. Therefore, the preset laser angles can be made much smaller to conform to the numerical aperture of the collecting optics. Similarly, the lasers can be made narrow to allow only for single-mode operation under all current pumping conditions. While the minimum spot size will be compromised because of the incidence angles of the angle-etched facet lasers, in many applications, such as printing, this is not expected to be a problem because the imaging requirements on the source are not very stringent.

The only way, until now, to reduce the thermal crosstalk between array elements was to increase the interelement separation. Here, we demonstrated a new technique to reduce the interelement crosstalk. This fan-out technique has the advantage that it can be coupled with any other techniques for reduction of the thermal crosstalk. One can, for example, increase the separation between lasers, make the lasers less temperature-sensitive, and at the same time fabricate them in a fan-out configuration.

X. CONCLUSION

We demonstrated an individually addressable laser array using angle-etched facets. With these devices, we obtained excellent laser beam steering results. We obtained optical power densities on an uncoated etched facet of up to 5 MW/cm² without observing COD at the facet. Using the device as an individually addressable laser array, we showed a reduction of the thermal crosstalk with respect to another parallel array of over 50%, and once aperture reduction of the laser array is taken into account, the thermal cross-talk between elements was reduced by one order of magnitude.

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Constance J. Chang-Hasnain (M’88–SM’92), for photograph and biography, see this issue, pp. 421.