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MID-WAVE IR AND LONG-WAVE IR SEMICONDUCTOR LASER DEVELOPMENT

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14. ABSTRACT

Broad area quantum cascade lasers may preferentially operate in only a few high order modes rather than in a strongly multimode regime. We demonstrate that in such cases the high order mode can be converted into a single-lobed near diffraction-limited beam using an appropriate optic placed in the near field. Alternatively, high order modes can be strongly attenuated via slight sidewall etching. The result is to encourage fundamental mode lasing also leading to a very good far field beam. A third manner to influence the transverse modes is with feedback from an external mirror. The latter case can be used to create a plethora of modes albeit ones substantially less than the diffraction limit. The investigations demonstrate that broad area quantum cascade lasers (BA-QCLs) have the potential to simultaneously produce high power simultaneously with high brightness.

15. SUBJECT TERMS
Mid-wave infrared semiconductor lasers, long-wave infrared semiconductor lasers, quantum cascade lasers

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1.0 SUMMARY

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AFRL Program Manager: Dr. Chunte Lu

Statement of Objectives

To develop mid-wave infrared diode laser (DL) pump arrays with high average power, and long-wave infrared quantum cascade laser (QCL) array architectures that maximize average brightness.

Applications:

- Protection of aircraft from electro-optic/infrared (EO/IR) threats where compact laser sources are required.

Conduct laser structure growth and device process study to optimize DL efficiency and output power; improve QCL performance by optimizing the number of cascade stages, to reduce the heat per Watt of optical power that must be removed from the device. In this report, we detailed the technical approaches for enhancing the brightness of QCL.

2.0 INTRODUCTION

Infrared quantum cascade lasers are highly desirable for remote sensing, free-space communications, infrared countermeasures for aircraft self-protect and numerous other purposes. Naturally the end-user desires high power along with excellent beam quality. In the near-infrared DL universe such requests are usually mutually exclusive. Single transverse mode quantum well lasers lack power. Broad area diode lasers are only valuable as low brightness pump sources. Yet quantum cascade lasers may be able to overcome these limits. Broad area quantum cascade lasers (BA-QCLs) exhibit curious behavior such as a dual lobed "bat-ear" far-field pattern as would be produced by a single yet high order transverse mode[1]. Attracted by this phenomenon, our group has investigated BA-QCLs. Our ambition is to create a nearly fundamental transverse mode emitter for maximum brightness while simultaneously utilizing the broad area to maintain high power operation. In this paper, three methods of beam control are explored and described. These methods are the usage of an external optic to convert the beam, etching the sidewall of the cavity to disrupt high order modes and using feedback to create modes.

3.0 TECHNIQUE APPROACH

A key distinction between diode and QCL emission characteristics chiefly resides in the manner of processing the material. Wide stripe diode resonators are defined simply by placing an ohmic contact rectangle on the epitaxial side of the grown material. Current flows perpendicular to the growth plane modestly increasing the refractive index therein and creating a gain guided laser whose cleaved facets serve as the end mirrors. In contrast QCL resonators are defined by etching through the active region to prevent excessive current spreading parallel to the growth plane. Including the cleaved front and back facets, the result is a well-defined rectangle having a large refractive index difference on all sides. To first order, simple box cavity modes can adequately describe the electric field. A typical diode and QCL are compared in Figure 1. The QCL stripe width is established by the wet etched, ~6µm deep, trough subsequently covered in a very thin Silicon dioxide (SiO_2) dielectric followed by Ti/Au for electrical contact on the top surface. In the figure, the QCL active region can be observed by noting the thin light covered region across the facet.

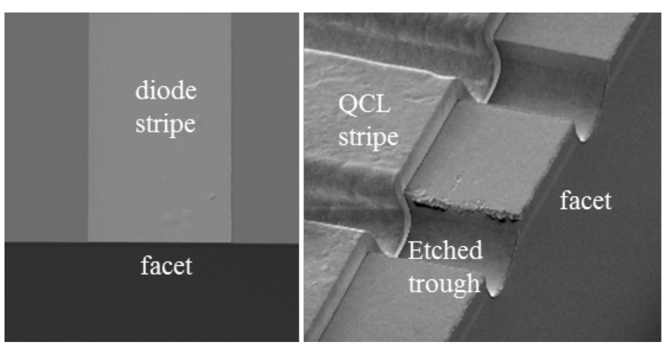

Figure 1. Typical DL (left) and QCL (right)

A second key component is the linewidth enhancement factor that incites refractive index perturbations in the material and leads to bright line filaments occurring in the diode beam. QCLs have a low linewidth enhancement factor[2] and are substantially less prone to filamentation[3]. The final factor is the very fast time scales of the QCLs so that gain recovery occurs rapidly.

Clearly power can be increased by broadening the waveguide to encompass a large gain area at the expense of exciting more transverse modes. And in diodes the result is a strongly multimode operation often with bright and dark regions due to filaments and other deleterious effects. Yet the investigation published in[1] suggests single mode operation. We observe this behavior in Figure 2, which is a plot of the far-field beam profile of a 25-emitter bar of 100μm wide QCLs with λ=4.6μm. Each emitter shows the same dual lobed far field pattern, which along with[1] is good empirical evidence that BA-QCLs prefer this state of operation. The resonator mode can be considered as two plane waves propagating in opposite direction reflecting from the cavity walls. At the facets the interference pattern creates a standing sine or cosine wave given by $\sin(M\pi x/w)$ (or cosine) where M is the mode number and w is the stripe width. The propagation of this mode into the far-field produces the beam shown in Figure 2. The divergence angle of each lobe goes as $\sin(\theta)=(\lambda M)/(2w)$ where λ is the wavelength. In fact a detailed analysis shows that it is not truly single mode. But the other oscillating modes are also high order modes with much less electric field amplitude than the dominant mode. One reason the preferential mode is high order is that the reflection coefficient increases with the internal incidence angle of the plane wave with the facet. Thus higher order modes reach threshold prior to the low order ones since mirror loss is reduced. Tantalizingly this single transverse mode characteristic suggests the savory possibility of converting the high order mode into the fundamental mode in similar manner to diode lasers[4] and optical fiber amplifiers[5].

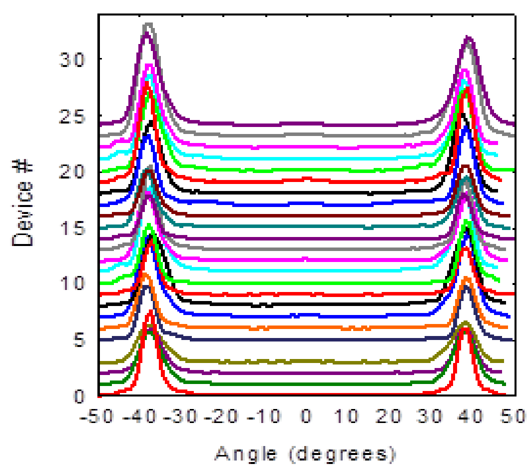

Figure 2. Far-field of a 25-emitter bar

3.1. The Axicon

Given that modes can be converted from higher to fundamental, the question is to what optic or phase plate will be necessary to do so. In this case, the answer comes from old optical propagation work converting Gaussian to Bessel beams. The optic is known as an Axicon and was first proposed in 1954 [6]. It remains useful today for a number of applications including eye surgery. When placed in the near field, approximately 20μm from the facet, the resulting beam propagates to the far field with nearly diffraction limited light, see Dente and Tilton[7] for a recent analysis.

In this work, the optic is manufactured from Indium phosphide (InP) using Focused Ion Beam Etching (FIB) and shown in Figure 3(a). Figure 3(b) shows the Axicon positioned adjacent to the QCL facet. When designed correctly, i.e. when matched to a single high order mode, the Axicon functions exceptionally well. Figure 3(c) is a comparison of the far-field beam from a true single transverse mode QCL and from a 100µm BA-QCL with Axicon included. The relative intensity is largely enhanced. But note that there are slight side lobes in the beam at ±35 degrees from other modes present.

We summarize the section by noting that the Axicon is effective but is rather cumbersome to manufacture, requires the QCL mode to be known (otherwise the conversion is imperfect), and is an additional optic requiring precise alignment in front of the facet.

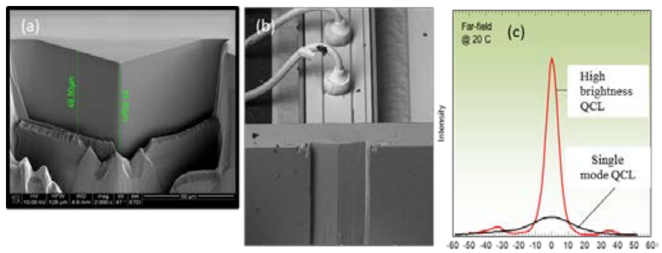

Figure 3. (a) FIB etched Axicon (b) Axicon aligned with QCL (c) Far-field

3.2. Lossy Metal Sidewalls (LMS)

Consider that mode overlap with the sidewalls increases with the mode number. Thus any loss introduced at the sidewalls that scales with a mode's overlap will act selectively in favor of lower order transverse modes[8]. Such a device is referred to as having LMS[9]. We now explore how this discrimination can be engineered to produce fundamental mode operation in a mid-infrared BA-QCL.

For our purpose of using metal to provide distributed loss to high-order transverse modes, we consider the following: First, the transverse magnetic (TM) polarization of optical modes in the QCL have an electric field component that is perpendicular to the plane of the epitaxial layers, and parallel with the sidewall of the device if the sidewalls are perfectly vertical. In this case the penetration of these modes will be very small as they will be "reflected" or "repelled" by the conducting boundary. However, the sidewalls are not vertical, but are significantly tilted as a result of chemical etching. Therefore, it is expected that a more significant ohmic loss will be incurred by the penetrating transverse modes. Second, the metal cannot be in contact with the active region because current will sidestep the cascade region to provide an electrical short. Therefore, the area of direct contact with metal must be limited to a portion of the sidewall adjacent to the top clad layer. Despite this constraint, we expect that the larger the metal contact area, the larger the ohmic loss to the transverse modes, and the larger the potential for discrimination. Finally, the overlap of each specific transverse mode with the sidewall is diminished as the cavity width is made larger and new transverse modes are allowed. Therefore, we expect the effectiveness of any mode filtering to be reduced if the cavity width is further increased.

Figure 4(a) is a scanning electron microscope (SEM) image of the etched ridge at the facet of a 60μm wide BA-QCL. The dotted circle shows where the SiO2 dielectric layer is etched away from the ridge while maintaining coverage over the active layer. The gold layer is thus in direct contact with the QCL material a couple of microns on each side of the mesa. Figure 4(b) shows the far field beam profile of the standard processed QCL and that of the LMS QCL. The high order mode is entirely replaced by a few low order modes. Fitting modes to the experimental data is shown in Figure 4(c) along with their evolution. The fundamental mode, M=1, is scaled to unity at each current level. At lower currents yet still well above threshold, Modes 3 and 5 exist but with intensity amplitudes 0.39 and 0.14 respectively of the fundamental mode. However as the current increases the M=3 component increases strongly while the M=5 component remains low. Continued development of the etch process may lead to better attenuation of the M=3 and higher modes.

Summarizing, LMS QCLs are especially attractive. The processing steps are not demanding with consistently positive results.

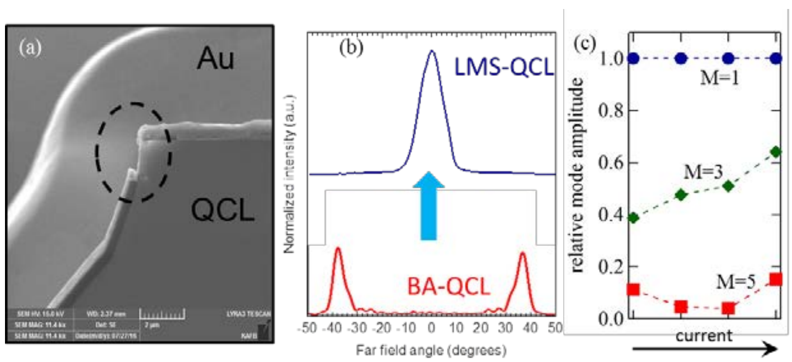

Figure 4. (a) SEM image of etched sidewall (b) LMS device becomes single lobed (c) Relative evolution of Modes 1, 3 and 5 with current

3.3. Engineered Sidewall Losses

In order to maintain high brightness conditions for broad area devices, the fundamental mode must be encouraged over higher order modes. There are two avenues for this: increasing the confinement factor of the fundamental mode relative to higher order modes, and the increase of losses for higher order modes relative to the fundamental.

It is impractical to selectively increase the confinement of the fundamental mode, as the index profile which confines that mode will also help confine others; confinement factors of many modes tend to be nearly identical to each other in a broad area waveguide. Providing selective losses to higher order modes is shown to be more feasible.

One straightforward approach to suppress higher order modes is to introduce losses through absorption at the sidewalls. The metallization layer required to electrically pump a QCL is separated optically and electrically from the laser core by an insulating layer, such as SiO_2 or Silicon nitride (SiN), that is typically hundreds of nanometers thick. In ridge waveguide configuration, the insulating layer acts as the immediate sidewall to the laser core, and generally is grown along the entire ridge wall and partially over the top of the device, with a small window etched out over the top epitaxial layer to allow for deposited gold contacts to make electrical contact with the device. The optical mode is then sufficiently insulated from the gold contact and has virtually no loss contributed by gold. If the gold were allowed to make direct contact with the laser core's sidewall, the supported waveguide modes would all demonstrate increased losses, with greater losses for higher order modes due to the greater modal overlap as previously discussed.

The problem with this approach is that gold deposited directly on the sidewalls would create a short circuit, circumventing some or all of the stages in the laser core. The insulating layer must be, at the minimum, retained on the laser core sidewalls, eliminating the chance of direct lateral interaction of the mode with gold. But this restriction does not rule out this approach entirely. The transverse mode is a two dimensional object, and extends beyond the limits of the laser core. If the insulating layer is partially removed to allow the deposited gold to nearly approach the top corners of the laser core to close proximity, say, within a micrometer, the portion of the mode existing directly above the laser core will have its lateral tails experience absorption loss from the gold. This technique, termed "distributed sidewall loss," was successfully demonstrated in (Kaspi, Luong et al. 2017) for the purpose of controlling transverse modes in broad area QCLs.

In this example, a 70 μm ridge, emitting 4.8 μm light, and processed with its insulating layer fully intact demonstrated a far field profile of two lobes separated by an angle of 76 degrees (± 38 degrees measured from the axis of propagation.) This angle can be used to calculate the dominant transverse mode order by the following relation:

$$\sin\theta_M = \frac{\lambda(M-1)}{2w} \tag{1}$$

Where M is mode order, with $M = 1$ indicating TM_{00} (fundamental) mode operation. It is immediately apparent that the fundamental mode would result in a 0 degree angle, giving a single lobed distribution expected from TM_{00}. Given the sensible limit of a ± 90 degree divergence angle, the upper limit for mode order capable of being projected out of a device is $M = \frac{2w}{\lambda}$.

This relation gives a dominant mode order of 19 for the 38 degree angle measured. This is no surprise, as the ridge width greatly exceeded the wavelength of the device. The same device design was then modified by over etching the insulating layer to variable depths, down to ~3.5 μm below the top of the ridge, or ~ 1 μm above the top of the laser core. Intermediate depths resulted in a multitude of lobes with divergence angles less than 38 degrees, indicating that the $M = 19$ order mode had been weakened in favor of the lower order modes. The multi-lobed far fields at intermediate depths indicated lower order modes were in close competition with no dominant mode to define the far field. At the insulator etch depth of 3.5 μm, far field of the 60 μm wide device become single lobed, indicating fundamental mode behavior. As a consequence of the increased loss from sidewall absorption, threshold current increased by ~10%, with slope efficiency also suffering slightly. The same 3.5 μm over etch was repeated for a 90 μm wide ridge, resulting in a dual lobed mixture of $M= 2, 3$ mode, with $M= 3$ being dominant. Given the ~1μm additional height left for the insulating layer, it is possible that further over etching could force fundamental mode behavior.

Figure 5 reflects the near and far field measurements of a broad area QCL with and without the implementation of the distributed sidewall technique from Kaspi[8]. Top shows the field profiles of the waveguide with a fully intact insulating layer. The bottom shows the field profile of the waveguide when 83 % (~3.5 μm) of the insulating layer removed, bringing gold in closer contact with the laser core. Note the divergent two lobed far field in the intact case with an intensity minimum in the center.

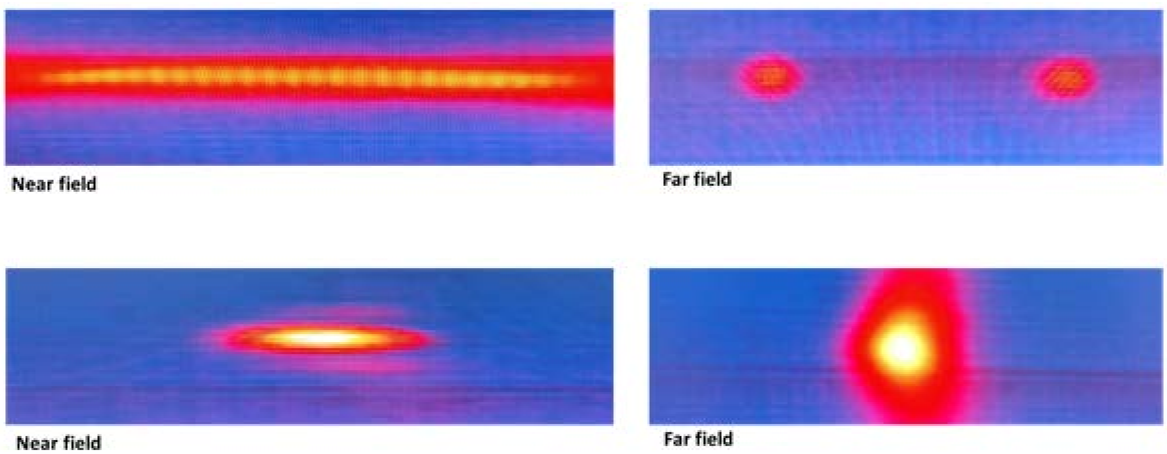

Figure 5. Near and far field measurements of a broad area QCL

4.0 CONCLUSION

The methods described in the report represent feasible ways to modify the behavior of BA-QCLs, which stem from the laser itself. That wide cavities, >40μm, lase preferentially on only a few high order modes is highly interesting and greatly beneficial. In fact, empirical yet uncorroborated experimental evidence suggests the wider the cavity the more likely it is that single mode behavior exists. Thus the door is opened for continued investigation both in fundamental physics (e.g. spatial hole burning, dynamics and mode coupling through the Third-order nonlinear optical susceptibility (χ3) nonlinearity[10] or other means) and applied engineering (e.g. Axicon design, etch process). Returning to the end-user, who desires high power and high beam quality, we believe that these techniques are capable of satisfying their demands.

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LIST OF SYMBOLS, ABBREVIATOINS, AND ACRONYMS

BA-QCLs	Broad area quantum cascade lasers
DL	diode laser
EO/IR	Electro-optic/infrared
FIB	Focused Ion Beam
InP	Indium phosphide
LMS	Lossy metal sidewalls
M	Mode number
QCL	Quantum cascade lasers
SEM	Scanning electron microscope
SiN	Silicon nitride
SiO_2	Silicon dioxide
W	Stripe width
TM	transverse magnetic
χ^3	Third-order nonlinear optical susceptibility
λ	Wavelength

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