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Phase-locked arrays of vertical-cavity surface-emitting lasers

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ABSTRACT

Vertical-Cavity Surface-Emitting Lasers (VCSELs) are of increasing interest to the photonics community because of their surface-emitting structure, simple fabrication and packaging, wafer-level testability, and potential for low cost manufacture. Scaling VCSELs to higher power outputs requires increasing the device area, which leads to transverse mode control difficulties if devices become larger than about 5 microns. One approach to increasing the device size while maintaining a well controlled transverse mode profile is formation of coupled or phase-locked two-dimensional arrays of VCSELs that are individually single-transverse mode. Such arrays have unique optical properties, not all of which are desirable. This paper covers some of the basic principles of these devices and reviews recent work on device designs, fabrication and operation. A technique for improving the far-field properties of the arrays is demonstrated and performance limitations are discussed.

1. INTRODUCTION

The development of well-controlled epitaxy processes has made possible the vertical-cavity surface-emitting laser (VCSEL). This laser is based on the formation of a vertical optical cavity by epitaxial growth of high-reflectivity dielectric-stack mirrors and a short gain region. Although they are currently expensive because of the challenging epitaxy requirements, VCSELs are potentially very inexpensive devices. They do not require cleaving for mirror formation and can be probe tested on wafer. The packaging requirements are simpler than for edge-emitting lasers and their small size permits potentially very high device yields. The vertical cavity architecture has some intrinsic advantages over edge-emitting devices, including a relatively narrow, symmetric beam and surface-normal emission. If single transverse mode operation is needed, single, gain-guided VCSELs are limited to diameters of less than approximately 5 microns. This limits their power output and increases the beam divergence. One means of scaling VCSELs to higher power while controlling their transverse mode structure and beam properties is the fabrication of arrays of phase-locked lasers. The surface-emitting properties of VCSELs make them ideally suited for operation in two-dimensional arrays. The coupling of one-dimensional arrays of edge-emitting stripe lasers to make higher power sources has been very successful¹. The idea of similarly coupling two-dimensional arrays of VCSELs follows naturally.

2. VCSELs

The concept of the VCSEL started with the pioneering work of K. Iga². Electrically injected devices using the combination of epitaxial mirrors and thin quantum-well gain regions have been developed that can be readily fabricated and operate at room temperature^{3,4}. The field has grown rapidly and companies are now actively developing the technology and markets. Figure 1 shows an ion implanted VCSEL structure for gain-guided operation. The majority of the device is composed of the top and bottom mirrors. This is

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because the semiconductor alloys used for the mirrors have small differences in index of refraction and very high reflectivity mirrors are required due to the small gain-length product of the cavity. The cavity length is typically short to obtain single longitudinal mode operation and has only a few quantum wells inside the cavity. The epitaxial mirrors are doped in electrically-injected devices to facilitate current transport to the junction in the cavity. Because the mirror consists of a large number of heterointerfaces with an abrupt potential barrier at each interface, VCSELs have high resistive losses and require rather large operating voltages compared with edge-emitters. However, recent progress in the design of the mirror layers has greatly improved the current transport.^{5,6} The lateral size of the cavity is defined by ion implantation or by etching of an air post structure and can be further modified by apertures in the metallic contacts. The size of the cavity determines the transverse mode structure. Devices larger than about 5 microns will operate in multiple transverse modes as the output increases beyond threshold.⁷ The output power of a VCSEL will scale up approximately as the area of the device. However, with increasing area the device supports more modes and eventually device inhomogeneities will result in filamentation-like behavior with localized modes that are not coupled with the others. All this can have detrimental effects on the far-field intensity profile of the laser. There are applications where highly multimode behavior is not a problem and large area single VCSELs may be ideal. For the cases where single mode behavior is desired, there are strong limitations on the degree to which single devices can be scaled in size. The typical output power values obtained for single-transverse-mode VCSELs in the near IR are a few milliwatts.⁸

3. TWO-DIMENSIONAL PHASE-LOCKED ARRAYS

One approach to obtaining larger area VCSELs with single transverse mode operation is to fabricate them in coupled arrays with the elements of the array closely spaced. One key difference between phase-locked arrays of VCSELs and phase-locked edge-emitting devices is that the VCSELs can be easily fabricated in two-dimensional arrays. This allows for a symmetric beam with a large effective aperture and more efficient use of the wafer area than for one-dimensional arrays.

The basic coupling mechanism for the arrays is through the diffractive loss from a device interacting with its closely spaced neighbors. The individual devices are defined primarily by variation of the reflectivity of one mirror of the cavity so that individual devices would be single transverse mode. Typical arrays have edge-to-edge spacings of only 1 or 2 microns. Because of this, the array can be thought of as consisting of closely coupled individual lasers or as a large area device that has a high-order mode imposed on it by periodic variation of the cavity reflectivity.

Figure 2 shows a scanning electron micrograph of an array of coupled VCSELs. The reflectivity of the top mirror in this example is modulated by the etched grooves that remove some of the mirror layers. The etched grooves are obviously high loss regions and the remaining squares define the apertures of the individual lasers. It is intuitive that the mode favored by the structure will be one that minimizes the losses from the grooved area. This has been confirmed by modeling of the modes of the array.⁹ The model has predicted that phase-locked arrays formed with sufficient reflectivity modulation emit in an out-of-phase mode. This is entirely analogous to the behavior of phase-locked linear arrays of edge-emitting devices. As a consequence of this alternating phase near-field, the far-field of the arrays is a four-lobed, off-axis pattern. The first fabricated arrays did not show this clearly.^{10,11} As improved devices were fabricated, both optically pumped¹² and electrically injected¹³ arrays showed the four-lobed far-field as in figures 3b and 3c.

4. FABRICATION OF PHASE-LOCKED ARRAYS

There are some unique problems to consider in the fabrication of two-dimensional arrays of phase-locked VCSELs. These include the method of achieving the appropriate amount of reflectivity modulation in the array, and provision of uniform current injection across the aperture of the array. We have concentrated on fabricating top-emitting structures because of interest in modifying the near-field phase of the arrays and to utilize experience from optical pumping measurements.

4.1 Reflectivity modulation

Modulation of the reflectivity of one mirror of a large area VCSEL is necessary to define the elements of the array and provide mode selectivity. It is also important to obtain uniform current injection across the array aperture with some form of electrical contact that is compatible with the reflectivity modulation method. The first successful electrically injected phase-locked VCSEL arrays were substrate-emitting devices in which the top metallic contact fully covered the top epitaxial mirror and made a contribution to the reflectivity of the top mirror.¹⁴ The reflectivity modulation was then provided by a deposition and liftoff of gold in the form of a pattern of small squares that was then covered with a Cr/Au or Ti/Au covering layer that provided a smaller increase in reflectivity between the gold squares. The simplest top-emitting approach has been to pattern a VCSEL with a conventional epitaxial top mirror with a p-contact in the form of a grid to provide emitting apertures between the gold lines.¹⁵ This will in fact increase the reflectivity under the grid lines. However a high temperature anneal reduces the reflectivity at the metal interface sufficiently to provide enough modulation for defining an array. Versions of this device have produced more than one watt of pulsed power with multimode emission.¹⁶

Another approach to producing a metallic contact grid with a decrease in reflectivity is to put the contact under the top mirror.^{17,18} The grid contact then acts as an opaque mask in the cavity and the current injection completely bypasses the top mirror resistance. This approach requires use of a dielectric mirror that can be deposited on top of the contacted device. A modified version of this approach is to put a contact grid inside the mirror. The two types of devices we will describe in detail are based on this approach. One device structure uses etched grooves into a full epitaxial mirror that extend to a heavily doped GaAs layer midway inside the top p-doped mirror. A grid contact is formed in the etched grooves. The advantage of this approach is to utilize the removal of mirror layers to produce a reflectivity modulation as in our optically pumped devices while bypassing of some of the mirror resistance. The metallic grid does modify the reflectivity of the etched regions but the overall amount of reflectivity modulation can be controlled by placing the contact layer at a different position in the mirror stack. A second approach is to design the structure with a partial epitaxial top mirror. A grid contact is then formed on the mirror surface and a dielectric stack mirror is then deposited over the contact. This effectively buries the contact inside the mirror.

4.2 Arrays with etched contact trenches

The phase-locked array in figure 2 is fabricated with a grid contact to a layer inside the top p-doped epitaxial mirror. The structure is a top-emitting design with an InGaAs quantum well gain region. The AlGaAs mirrors are designed with linear piece-wise compositional grades that approximate a sinusoidal compositional profile to reduce the potential barriers at the mirror heterointerfaces.⁶ A unique feature of the top mirror design is the addition of a one-wave thick layer of heavily p-doped GaAs located in the 12th period from the top of the mirror. The top mirror has a total of 24 periods of high and low index quarterwave layers and the n-type bottom mirror a total of 32 periods. The buried contact layer adds a small amount of additional loss, but does not change the bandpass characteristics of the laser cavity near the design wavelength. The location of the contact layer was chosen based on the results from optical pumping experiments with VCSELs with etched array patterns¹². The fabrication process consists of first patterning the top mirror with a square array pattern in photoresist and etching to the contact layer with chlorine reactive ion beam etching (RIBE) with interferometric control.¹⁹ A Au/Be ohmic contact is then evaporated onto the sample and a self-aligned liftoff performed to leave a grid contact in the trenches between the square elements of the array. A proton implant is then performed to define a gain-guided region around the array. A pad-metallization is added on top for easier probing and the devices are isolated by a wet trench etch. Processing is completed with a backside n-metallization and a rapid thermal anneal.

Several different sizes of two-dimensional arrays have been fabricated. Device patterns available on the photomasks include 3X3, 5X5, 6X6, 10X10, 12X12 arrays of VCSELs and some single elements for comparison. The element sizes range from 3 to 8 microns across with spacings of 1, 1.5 and 2 microns

between the elements. For the etched trench devices, the largest patterns with good mode selectivity had elements 5 to 8 microns wide with 1 and 1.5 micron spacings. The patterns with 2-micron spacings between the elements have such large losses that they often operate as arrays of uncoupled lasers. The mode selectivity of the electrically injected arrays using the deeply etched and metallized array design is apparently much stronger than for optically pumped arrays with similar etch depths. This may be explained by the phase-shift induced by the gold layer and by losses from the heavily doped contact layer in the mirror. Figure 3b shows the far-field of a 12X12 array of 7 micron elements with a spacing between elements of 1 micron. The corresponding near-field of the device is shown in figure 3a. The measurements were made with a pulsed power supply, boxcar averager and calibrated photodiodes and current sensor. Typical pulse parameters are 200ns pulses at 800 Hz. We have not yet made CW measurements with heat sinking. Threshold currents for these devices are not well defined. Individual elements of an array will turn on at several tens of milliamps and additional elements will turn on with increasing drive current until the entire array is on. The current at which the entire array is on will vary with the element sizes and spacings and with the array area. The array in figure 3a was completely on at 350 mA and the data in figures 3a and 3b were taken at 580 mA. The far-field in figure 3c was observed at 1.4 A (with an output power of 50 mW). This particular array has very high mode selectivity as the far-field still indicates a single transverse mode at four times the current for complete array turn-on. This array also has a low differential quantum efficiency, starting at 0.05 and rolling over to 0.03 at high currents. The differential quantum efficiencies generally range from 0.04 to 0.10 for the coupled arrays. Although we have not done systematic variation of the reflectivity modulation with the injected devices, we see a tendency for better mode selectivity to correspond to lower quantum efficiency as was observed by Orenstein and coworkers.¹⁴ This trade-off between quantum efficiency and mode selectivity needs to be studied more thoroughly, as it is very important to the actual utility of phase-locked arrays. Maximum power output so far from our coupled arrays has been over 200 mW from the largest devices with a 12X12 array of 8-micron elements.

4.3 Arrays with dielectric / semiconductor mirrors

An alternative means of placing a grid contact midway inside a VCSEL mirror structure has been explored. This technique was originally considered for visible wavelength VCSEL devices as a means of simplifying the fabrication of the mirrors.²⁰ The concept is to grow part of the mirror structure as a conventional AlGaAs epitaxial structure. A grid contact can then be deposited on the surface which has a suitable heavily doped GaAs contact layer. The rest of the mirror is deposited on top of the contact grid in the form of additional quarterwave layers of amorphous dielectric materials such as those commonly used for optical coatings. Since the index of refraction differences available for these materials can be quite large, the number of additional quarterwave layers to be deposited is small. The advantages of this approach include reduced epitaxial growth time, an opportunity to bypass some of the semiconductor mirror resistance, lower energy ion implantation, no precise etching requirements and a process that preserves the planarity of device while still allowing adjustment of the reflectivity modulation of the array through the number of quarterwave layer periods above and below the contact metal. The device structure consists of 32 periods of n-type AlGaAs compositionally graded mirrors as used in the etched contact trench devices with a similar InGaAs quantum well cavity and a 9 period top p-type mirror with a p+ GaAs contact layer on top. The first step is liftoff of an ohmic p-metallization to form a grid contact. Subsequent steps include a current confining proton implant, pad-metallization, substrate-side n-metallization, isolation trench etch and anneal. The device is then coated with the dielectric mirror layers. The dielectric mirror structure is a 5-period quarterwave stack of SiO₂ and Nb₂O₅ deposited by reactive sputtering. The dielectric mirror is removed over parts of the contact pads by reactive ion etching in a CHF₃ plasma. The etch rate is higher for SiO₂ than Nb₂O₅, but both materials were found to etch well in this chemistry. A scanning electron micrograph of a cross section of a completed array is shown in figure 4.

A similar range of array sizes has been fabricated in the hybrid mirror devices as in the etched arrays. The results are comparable since the reflectivity modulation obtained in the two designs is very similar. Again, devices with smaller spacings between elements were well coupled, but the largest arrays with two-micron spaces had too much loss to phase-lock. The threshold current and operating power are

very similar to the etched array designs for devices of similar size. The hybrid mirror approach, however, seems to be very promising because of the simplified fabrication.

5. PHASE-CORRECTION OF COUPLED VCSEL ARRAYS

As shown in figure 3, the out-of-phase mode preferred for two-dimensional phase-locked arrays has a multilobed far-field with off-axis lobes. For some potential applications of such arrays this is not a matter of consequence. If a collecting system of sufficiently large field is used, then the light can be collected in the appropriate "bucket". Some applications may also have the detector or radiation utilizing region in such close proximity to the array that no optical system is needed at all. However, there are some applications, such as coupling into single-mode fibers or small multimode fibers and holographic systems for free space interconnects, where such a far-field profile would be a problem. One approach to obtaining an on-axis far-field with low divergence is to convert the near-field phase-profile to that of an in-phase mode by using an additional phase-shift layer on alternate elements of the array. This technique was proposed for linear arrays of edge-emitting devices by a number of groups²¹⁻²³ and was successfully demonstrated for a two-dimensional optically-pumped array²⁴. We have since extended that work to the electrically injected arrays described above²⁵.

5.1 Design of near-field phase-correctors

There are two constraints that determine the design of the phase-shift layer to be left on alternating devices. The first is that the optical path length through the phase shifter should be an odd multiple of one-half wavelength longer than the equal thickness path through air so that the elements will be in phase at a plane above the array. This is expressed as:

$$(n_{ps} - 1) d = m\lambda / 2 \quad (m \text{ odd}) \quad (1)$$

where n_{ps} is the index of refraction of the phase-shifter material, λ is the emission wavelength, d is the physical thickness of the phase-shifter and m is an odd integer. The second constraint is that the phase-shifter must have an optical thickness of an integer number of one-half wavelengths so as to not appreciably perturb the phase of the light reflected back into the cavity. This requires that the phase-shifter is an absentee layer on the mirror stack. To the extent that this condition is not met, the threshold of the array element with the phase-shifter will be increased and the coupling to adjacent elements reduced. The second constraint is :

$$n_{ps} d = i \lambda / 2 \quad (2)$$

where i is now an even or odd integer and a further physical constraint is that $i > m$. The simultaneous satisfaction of both these constraints yield a few refractive indices and physical thicknesses. Some possible choices that are appealing because of the availability of the material in thin film form and because processing, ie dry etching, techniques are developed are listed in the table below. Other material solutions are possible that might suit a particular application better.

n_{ps}	optical thickness	material
2	λ	SiN
1.5	$3\lambda / 2$	SiO ₂
3.5	$7\lambda / 2$	GaAs

Table 1. Some useful combinations of materials and thicknesses for phase-shifting of phase-locked VCSEL array elements that obey the constraints in equations 1 and 2.

5.2 Fabrication of phase-corrected arrays

Both of the array types described have been fabricated with near-field phase-shifters. The first optically-pumped devices were grown with an additional $7\lambda / 2$ layer of GaAs on top of the last top mirror period. The interferometrically monitored RIBE etch process was then used to etch away the GaAs layer on alternate elements by use of a checkerboard-like mask. Although well-controlled epitaxial growth can produce very precise layer thicknesses for quantum wells and mirror structures, the accurate growth of a thick layer is quite difficult and requires very careful calibration. For the electrically injected devices, we decided to use SiO_2 for the phase-shift layer. The lower index of SiO_2 relaxes the tolerance on the physical layer thickness, the material can be deposited after successful device fabrication and preliminary testing to increase the yield and selective dry etching is readily available to remove the SiO_2 from the underlying GaAs layer. The SiO_2 was deposited via the same reactive sputtering process used for the dielectric mirror layers. A checkerboard-like pattern was printed with careful alignment on the array and the SiO_2 layer etched by reactive ion etching in CHF_3 sufficiently long to remove it completely from the exposed elements of the array. A completed device, with etched array grooves and self-aligned gold grid contact is shown in figure 5.

A corrected far-field of a 5×5 array of 5 micron-wide elements is shown in figure 6b. The center lobe contains 36% of the total intensity in the far-field camera field of view. The central spot is about twice the angular width expected for a diffraction limited beam with the array aperture. The photo is taken at 5 times the single element threshold of the array. As the current was increased further, the center lobe increased in width as other modes become present. The far-field clearly shows the higher order beam lobes from the periodic nature of the array.

5.3 Performance limits for phase-corrected arrays

Clearly not all of the light emitted by the array is present in the on-axis lobe for these preliminary devices. What are the limits on the on-axis performance of a phase-corrected coupled array? We have performed some simple simulations using packaged FFT routines.²⁶ The limit for a uniformly illuminated array of 5 micron wide elements with 1 micron spacing is 64% assuming a top hat profile for each element. This fraction is decreased by a number of factors. The most dramatic effect results from changing the fill factor of the array, which is defined as the fraction of the array surface that is filled by the emitting elements. Going from a 5 micron wide element size to a 4 micron wide element size reduces the intensity in the central spot to 41%. The near-field photo in figure 6a shows that the modes of the elements are circular and do not fill the corners of the elements; and consequently contribute to a fill factor much less than the nominal value from the array dimensions. Of less effect is the mode profile, assuming a sinusoidal amplitude mode profile instead of a top hat decreases the on-axis intensity to 57%. The far-field distribution is surprisingly insensitive to errors in the phase-shifter optical thickness. A 20% phase-shift error decreases the on-axis intensity to 58% from 64%. More difficult to quantify are the effects of nonuniformity of the array's near-field intensity and decoupled elements of the array. These effects will show up as asymmetry in the far-field and broadening of the lobes. The far-field in figure 6b is certainly suffering from some of these effects. It should be possible to greatly improve the on-axis intensity by increasing the fill-factor of the array.

The utility of phase-correcting an array of emitters coupled in an antiphase mode has been criticized in a recent paper.²⁷ The criticism is that because the phase-corrected source still has a periodic amplitude modulation in the near-field, significant amounts of light are emitted into higher order diffracted lobes, as observed in figure 6b. Depending on the merit function used, one can argue that no improvement in beam quality has occurred. More intuitively, for some applications, such as ones in which the light is collected by a system with a moderate field of view into a detector, there is no improvement in collection efficiency. For some field values collection efficiency is actually decreased. There are however, some applications in which only a single, nearly diffraction-limited, lobe of the far-field can be effectively utilized. For example,

mode-matching into single-mode waveguides or use of diffractive optical elements for free space interconnects would both be greatly complicated by use of multiple, off-axis lobes. In such situations, phase-correction may be a worthwhile technique. The application of this technique is potentially much broader than demonstrated here. The elements of a coherent surface-emitting laser array can be arbitrarily phase-shifted by 180 degrees by this method. This allows one to fabricate a binary phase hologram into the surface of the array. As the realizable array sizes increase, the larger number of elements available may allow useful optical functions to be performed by a binary phase hologram integrated into the emitting surface.

6. FUTURE DIRECTIONS

There are other performance limitations that need to be addressed for phase-locked arrays in general. The most severe limitation on array performance at this time is the thermal loading that a large array experiences. Only limited CW measurements have been reported for coupled VCSEL arrays or other large-area VCSEL devices. The best performance reported for large-area single VCSELs is 113 mW CW for a 70 micron diameter device bonded p-side down to a diamond heat sink and emitting through the substrate.⁸ Improvements in device efficiency will be helpful in increasing the upper limit for CW operation. The apparent tradeoff between quantum efficiency and mode selectivity for phase-locked VCSEL arrays is very important as the primary appeal of phase-locked arrays is to provide a combination of increased power and transverse mode control.

If other factors are constant, the pulsed output power of an array scales as the emitting area. The sizes of the arrays that are practical at this time are probably limited by the uniformity of the VCSEL layers. Nonuniformity in the epitaxial layer growth results in shifts in the operating wavelength of the laser as a function of position. Larger arrays will eventually no longer phase-lock across their aperture because of the large energy loss to operate off resonance.

There are alternative approaches to the near-field phase-correction of arrays for situations requiring an on-axis lobe. In particular, the near-field phase-corrector is not applicable to substrate-emitting arrays. It may be possible to fabricate a beam transforming hologram on the substrate surface of an antiphase array that would produce a desired beam. An ingenious approach is to fabricate an array in which the supermode of the device has circularly symmetric zones. In such a device the reflectivity modulation is in a concentric ring pattern instead of a grid. Proper spacing of the modal zones produces a focused spot at a distance from the device surface.²⁸

7. CONCLUDING REMARKS

We have reported our results to date with two novel designs for phase-locked arrays of VCSELs. We have also demonstrated a near-field phase-correction scheme for modifying the far-field properties of the arrays. This method may have more general applications than producing an on-axis far-field. Although it is uncertain whether phase-locked arrays of VCSELs will become a practical device technology, VCSEL technology has progressed very rapidly and the potential for development and application of phase-locked arrays is improving with it. The physics of the two-dimensional VCSEL array coupling process has not been studied extensively and there are a number of device improvement issues remaining to be investigated.

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Figure 1. Drawing of a proton-implanted, gain-guided VCSEL with etched mesa isolation.

Figure 2. Scanning electron micrograph of a phase-locked array of VCSELs formed by etching partially through the top mirror layers.

Figure 3 a. Near-field image of a 12X12 array of 7-micron-wide VCSELs.

Figure 3b. Far-field image of the 12X12 array showing off-axis, 4-lobed pattern at 580 mA.

Figure 3c. Far-field image of the same 12X12 array at 1.4 A.

Figure 4. Cross section of a VCSEL array composed of partial semiconductor and dielectric top mirror with a gold grid contact. The bright regions inside the mirror are gold and the five dielectric quater-wave periods can be seen above the semiconductor layers and the gold.

Figure 5. A phase-locked VCSEL array with SiO₂ phase-shifters on alternating elements of the array for near-field phase-correction of the array.

Figure 6a. Near-field image of a 5X5 array of 5-micron wide VCSELs with phase-correctors as shown in figure 5.

Figure 6b. Far-field image of 5X5 phase-corrected array showing the on-axis emission with additional higher-order lobes. The spot to the left of the center lobe is a reflection artifact.

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