One- and Two-Dimensional Coherently Coupled Implant-Defined Vertical-Cavity Laser Arrays

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***Abstract*—Loss between elements of coherently coupled vertical-cavity surface-emitting laser (VCSEL) arrays typically causes out-of-phase operation with on-axis intensity nulls in the far-field. We show that in-phase evanescently coupled VCSEL arrays may be defined by proton implantation. An advantage for implanted in-phase coherently coupled VCSEL arrays is that this approach employs a simple and reliable fabrication process where the absence of loss between elements leads to in-phase coupling. We present data for 2, 3, and 4 element in-phase implant-defined coherently coupled VCSEL arrays.**

***Index Terms*—Coherent arrays, vertical-cavity surface-emitting laser (VCSEL).**

ARRAYS OF vertical-cavity surface-emitting lasers (VCSELs) have been studied extensively for coherent optical coupling between lasers [1]–[11]. Coherent coupling allows for increased power in the far-field at a single frequency, which may be used in applications such as optical logic, image processing, and beam steering. Because of the optical loss between evanescently coupled VCSELs, a phase shift of 180° is typically observed between neighboring lasers [1]. Previous work with implanted VCSEL arrays specifically included elements of optical loss such as an air gap [2] or metal [3]–[7] between lasers. These geometries create an out-of-phase array mode with an on-axis null in the far-field which is undesirable for most applications. Phase-adjusted arrays [8] and anti-guided VCSELs [9], [10] can bypass or compensate for this mode at the cost of a complicated fabrication process. It is also possible to achieve in-phase coupling with photonic crystal VCSELs, however, the hole(s) between lasers frequently promote the out-of-phase mode [11]–[13].

In this work, we show that proton implantation isolation in the top distributed Bragg reflector of VCSELs emitting at nominally 850 nm may be used to define individual elements in the array. The implantation pixelates the gain region without adding optical loss between neighboring lasers. One of the main attractions of these arrays is that there is no additional fabrication complexity to that of a conventional implant-defined VCSEL [14]. The devices studied have 27 top distributed Bragg reflector (DBR) periods, 35 bottom DBR periods, and GaAs quantum wells to provide gain. A cross-sectional sketch of this device is shown in Fig. 1. To begin, a thick resist process is used to define the round, unimplanted regions inside the contact ring of each VCSEL. The energy and dose of the proton-implantation were 340 keV and 4×10^{14} cm^{-2}, respectively. The wafer was tilted at 7° from normal during implantation to prevent channeling. Following implantation, a standard VCSEL fabrication process is followed.

Data from three array geometries are presented: a 2 × 1 array with 5.3 μm diameter implant apertures at a center to center pitch of 9.3 μm, a 3-element array with 6.3 μm diameter implant apertures at a pitch of 9.5 μm in a triangular arrangement, and a 2 × 2 array with 5.0 μm diameter apertures at a pitch of 9.0 μm. These dimensions correspond to mask dimensions used for photolithography to define the implant apertures. These specific dimensions are chosen because an individual implant diameter of approximately 5 μm or less is expected to create a single-transverse-mode laser, and the pixelation separation needs to be sufficient to allow for a single lasing fringe between implanted regions and, thus, in-phase operation of the array elements.

Lasing near-field images under continuous wave operation of the 2 × 1, 3-element, and 2 × 2 arrays are shown in Fig. 2. Images of the lasers below threshold show the spontaneous emission is primarily located within the unimplanted regions, in spite of the effects of current spreading and the approximate few micron diffusion length of carriers in the quantum wells.

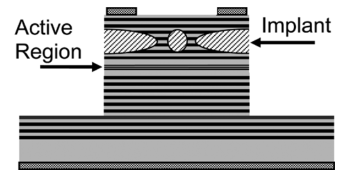

Fig. 1. A cross-sectional sketch of a 2 × 1 implant-defined VCSEL array.

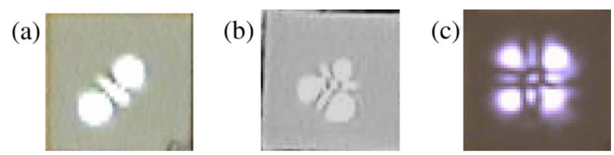

Fig. 2. Lasing near-field images of an (a) 2 × 1, (b) 3-element, and (c) 2 × 2 array.

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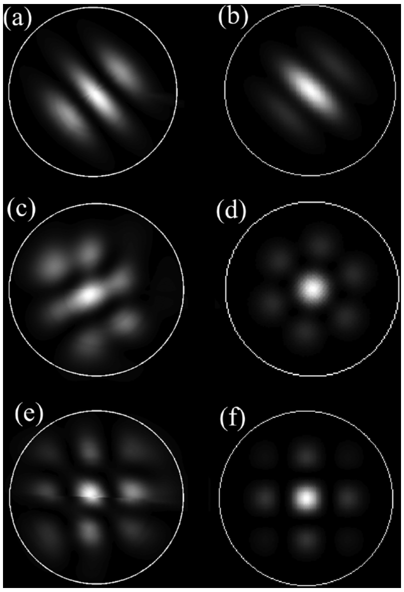

Fig. 3. Intensity-coded far-field patterns for a: 2 × 1 array (a) measured and (b) simulated; a 3-element array: (c) measured and (d) simulated; and a 2 × 2 array array: (e) measured and (f) simulated.

Since the implant provides electrical confinement without adding optical loss, the lasers tend to lock in-phase, producing a low-order mode. In the near-field images of Fig. 2, the minor lobes located between the major, implant-defined lobes of the array elements are out-of-phase with the major lobes but do not contribute significantly to the far-field beam pattern. The odd number of fringes enables the in-phase mode, similar to the previous anti-guided leaky-mode array approach [9]. The implant-defined lasing regions are expected to have a slightly higher refractive index under continuous wave operation due to thermal lensing [15], thus leaky coupled modes are not expected. In addition, the near-field optical mode patterns are unchanged under pulsed operation. The image in Fig. 2(c) corresponds to the lowest order evanescently coupled mode calculated by Hadley [1] for a 2 × 2 leaky-mode array.

Measured and calculated intensity encoded far-field beam patterns for each of the array types just above lasing threshold are shown in Fig. 3. In these plots, the circle represents emission 10° from perpendicular to the laser facet. As expected for in-phase operation, all three measured far-field patterns demonstrate an on-axis maximum and show general agreement with our simulation. The minor differences between our calculated and measured results are likely due to a difference in intensities between lasing regions, the lobes between emitting regions, and the noncircular emission centers as apparent in the near-field. Specifically, the subsidiary lobes seen in Fig. 2 result in additional power to the peripheral far-field lobes in Figs. 3(a), (c), and (e). The spectra for the arrays with near fields in Fig. 2 show a single emission peak. This verifies that each array's operation is single-mode. Increasing current injection further above threshold leads to the lasing of multiple transverse modes.

In order to further probe the optical coupling mechanism, a 2 × 1 array was operated under pulsed conditions with 100 ns

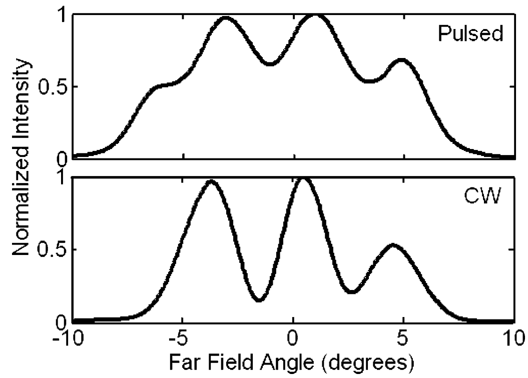

Fig. 4. Normalized far-field intensity patterns for pulsed (top) and continuous wave (bottom) operation of a 2 × 1 implant array.

pulses and 1 μs period. Although the coherence between elements of the array (as measured in the far-field) [16] decreases as compared with continuous wave operation, an interference pattern with an on-axis maximum is still visible, as seen in Fig. 4. For both pulsed and continuous wave operation, this 2 × 1 array operates with a slight nonzero phase difference between the lasing elements as evidenced by the major far-field lobe having near normal emission in Fig. 4. The presence of the interference pattern under pulsed conditions indicates that in the presence or absence of a thermal lens, optical coupling between array elements persists in these arrays.

In conclusion, we have demonstrated one- and two-dimensional implant-defined coherently coupled VCSEL arrays. These arrays operate in-phase and, thus, produce an on-axis maximum in the far-field. Further work is needed to suppress higher order array modes, which turn on with increasing injection current and, thus, limit the single-mode power from these arrays. Efforts are also continuing on larger array sizes where a principle challenge is achieving uniform current injection to each element of the array.

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