Numerical Investigation of Leaky-Mode Coupling in VCSELs

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ABSTRACT

We investigate various aspects of leaky-mode coupling behavior in VCSELs using a 2D finite difference model to simulate two coupled pixels. Phase-locking is shown to occur in a manner consistent with previous simple models.

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SUMMARY

Recent advances in Vertical-Cavity Surface-Emitting Laser (VCSEL) technology that have led to higher efficiencies and lower thresholds have opened up a new realm of applications for these devices. In particular, phase-locked arrays of VCSELs[1], previously thought to be impractical due to thermal considerations, now look extremely attractive as high-power and high-brightness sources. In addition, a new understanding of waveguiding in VCSELs[2] has led to practical methods for designing phase-locked arrays employing either evansecent or leaky-mode (antiguided) coupling. The latter type of coupling is particularly attractive in light of previous calculations[1] that predict especially strong mode discrimination against higher-order lateral modes. In this paper we report the first detailed simulation of leaky-mode coupling between two VCSEL pixels performed without the use of simplifying assumptions such as the effective index model. The results of this simulation are, however, found to be in good agreement with previously-developed simple theories[3] of leaky-mode coupling.

The structure chosen for examination consists of two 3-μm-wide pixels in rectangular geometry (of infinite extent into the page) connected by a coupling region of varying width as shown in Fig. 1. The coupling region is assumed to be fabricated by etching prior to regrowing the upper mirror stack and may be of either higher or lower effective index than the pixel region (Fig. 1 shows a high-index, antiguided coupling region). Electrical and optical confinement at the outer edges is provided via a tapered oxide layer although this aspect of the device is inconsequential to the present study. The active region of the structure contains 5 quantum wells with spatial gain profiles that may be chosen arbitrarily. We calculate the in-phase and out-of-phase modes near threshold for this structure with the use of a fourth-order-accurate finite difference model[4] in an attempt to investigate the properties of both evanescent and leaky-mode coupling. The fundamental (in-phase) leaky mode for a coupling width of 0.75 μm is shown in Fig. 2. This optimum width for in-phase operation was chosen using the effective index model and a simple formula developed previously to describe leaky-mode coupling in edge-emitting geometries[3]. The calculated mode discrimination against the out-of-phase mode was found to be

about 3 times the mirror loss. As the width was increased to 1.1 μm, the threshold gain became equal for the two modes, again in agreement with simple theory[3]. *These calculations confirm the ability to engineer in-phase or out-of-phase operation for leaky-mode-coupled pixels by varying the coupling width and/or index step.*

Next, the strength of leaky-mode coupling in VCSELs was investigated by introducing a strong quantum well gain asymmetry between the two pixels and watching for changes in mode shape. Even for a gain imbalance of 100%, no discernable changes in mode shape were observed. This result implies that the coupling was sufficiently strong so that gain introduced into the right pixel was equally shared by the left pixel. This further implies that *leaky-mode-coupled arrays may be pumped peripherally without a significant degradation of the far-field pattern.* In contrast, a similar calculation was performed for two evanescently-coupled pixels with similar index step by merely reversing the direction of the etch shown in Fig. 1. The resulting in-phase amplitudeprofile is shown in Fig. 3 for the same case of 100% gain imbalance. As is seen, the un-pumped left pixel has diminished considerably in intensity because its mirror losses are not replenished efficiently by light coupled over from the right pixel.

In conclusion, these calculations confirm our previous understanding of leaky-mode coupling for the case of VCSELs fabricated using cavity length modulation to affect variations in effective index. The coupling strength has been shown to be high, and preference for the in-phase or out-of-phase mode may be engineered into the mask layout. As is the case for edge-emitters[3], the resulting operation is expected to be insensitive to thermally-induced index changes because of the large magnitude of the index step. Numerous applications are envisioned for leaky-mode coupling in VCSELs, including optical logic gates and high-power high-brightness arrays.

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4. G. Ronald Hadley, "Low-truncation-error finite difference equations for photonics simulation II. Vertical-cavity surface-emitting lasers", to be published in the Journal of Lightwave Technology, January 1988.

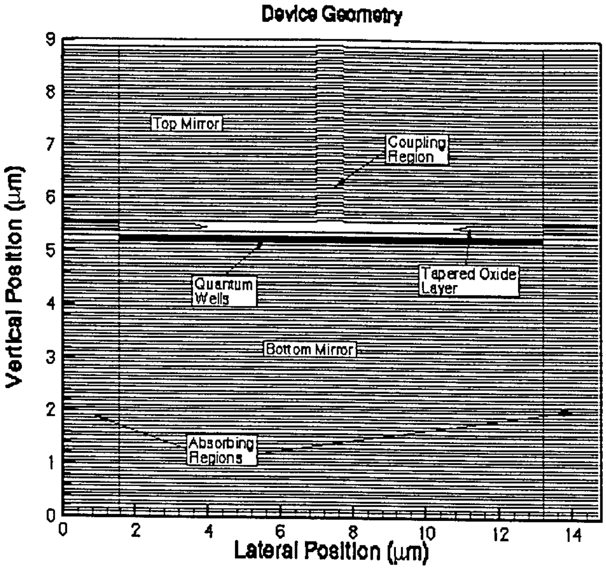

Figure 1. Device geometry for leaky-mode coupling

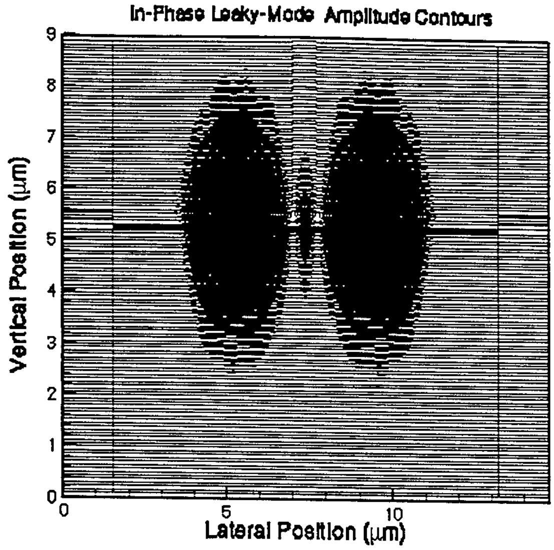

Figure 2. Amplitude contours for in-phase leaky mode at a coupling width of 0.75 µm

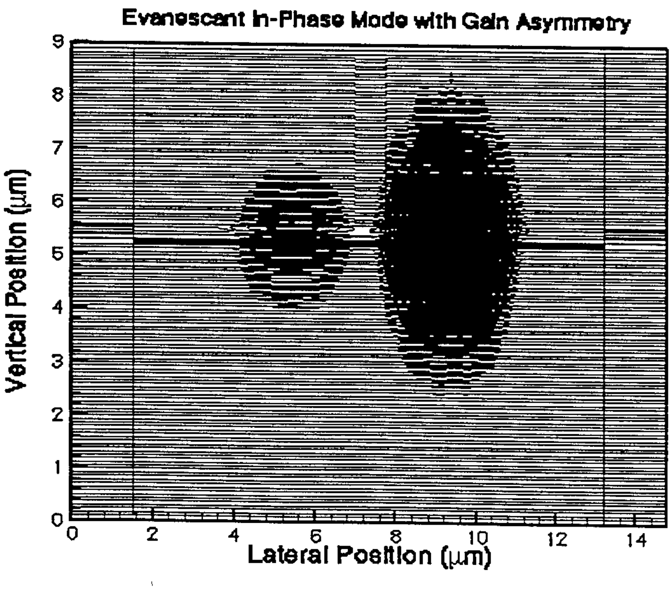

Figure 3. Amplitude contours for the in-phase evanescent mode with 100% gain imbalance; i.e. zero gain in the left pixel and twice the normal gain in the right pixel.

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