Vertical-Cavity Ring Laser

Betty Lise Anderson

Abstract— **A new type of laser diode structure is proposed, in which a ring type structure is implemented with the plane of the ring perpendicular to the surface of the semiconductor. Emitting beams both parallel and perpendicular to the surface, this structure could be useful for coupling into fiber or adjacent optoelectronic devices. By injection-locking a series of these lasers, a phased array of surface emitting lasers is made possible. Losses are expected to be significantly less than those reported for grating-coupled surface emitting arrays, with from 8% to 31% coupling plus absorption loss compared to 50%–73% refraction plus absorption loss for grating coupled arrays.**

Index Terms— **Ring laser, laser diode, surface-emitting laser, surface-emitting array.**

I. INTRODUCTION

THERE is a recognized need for high power, coherent diode laser sources. Various approaches have been used, including evanescently coupled 1-D arrays of edge-emitters [1], 2-D arrays of grating-coupled DBR surface emitting lasers, [2] and 2-D arrays of vertical-cavity Fabry-Perot lasers [3], [4].

In this letter, a new device structure which could be used to make coherent arrays is proposed: a ring laser whose resonator plane is perpendicular to the junction plane. This device emits beams both parallel and perpendicular to the wafer surface. By injection locking successive diodes in linear arrays, and using evanescent coupling or turning mirrors to couple multiple linear arrays, a 2-D coherent array may be achieved.

There has been some previous work investigating ring lasers in semiconductors. All of these devices, however, have the plane of the resonator in the same plane as the junction. Some employ straight paths with turning mirrors, [5, 6] and others use curved paths, which support whispering gallery modes [7]–[14].

As for surface emitting arrays, grating-coupling surface-emitting (GCSE) phased arrays have been demonstrated with good results [15], [16], but can suffer from high losses. Differential quantum efficiencies of 44%/surface (pulsed) have been reported, however [2]. This is compared to a DQE of 27% (pulsed) reported for an evanescently coupled gain-guided 8 × 8 vertical cavity Fabry-Perot array with patterned contact [4]. We will show that the proposed vertical-cavity ring laser (VRL) can potentially have lower losses than the GSCE arrays, at the expense of fabrication complexity.

II. PROPOSED DEVICE

The proposed ring laser structure, in which the plane of the ring is vertical, or perpendicular to the junction plane, is shown in Fig. 1. The active layer itself could be a double heterostructure, a set of quantum wells, a GRINSCH type structure, or some combination. Light generated in the active layer propagates around the ring both in the clockwise and counterclockwise directions. If M_4 is made to be partially reflecting, then the clockwise beam will emerge from the laser in a direction parallel to the surface, and the counterclockwise beam will emerge perpendicular to the surface.

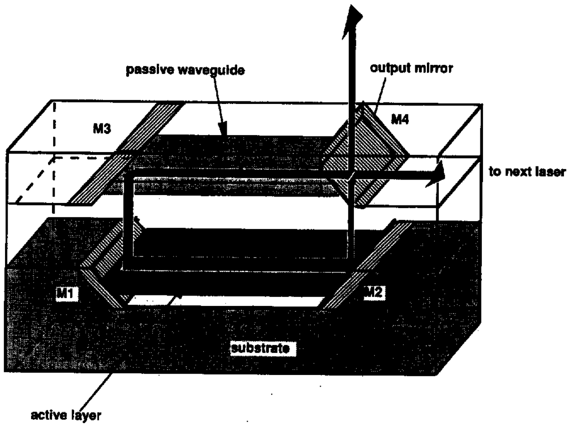

Fig. 1. Proposed vertical cavity ring laser structure consists of four turning mirrors, and two waveguides, of which one or both may have gain (one active, one passive shown here).

The cavity contains two planar waveguides; one or both may have gain. The figure shows the case of only one gain layer (the lower waveguide), but by placing a transparent conducting layer between the two waveguides (for example highly doped wide-gap material), one can pump both waveguides, potentially reducing cavity losses. On the other hand, the upper waveguide may be made passive and virtually transparent by careful choice of core material, by adjusting the dimensions of the quantum wells, if used, or by bleaching the quantum wells. Whether passive or active, the second waveguide helps reduce loss due to the beam divergence as it travels the cavity.

The two lower turning mirrors M_1 and M_2 are high reflectivity dielectric mirrors. The upper mirrors M_3 and M_4 would be totally internally reflecting even without dielectric layers if the areas outside these mirrors were left as air. The final path of the exit beam, however, would be refracted at some angle either to the surface or to the perpendicular. One would therefore coat the two upper 45° surfaces with dielectric mirror layers, and then fill in the area outside the cavity with semiconductor.

Manuscript received October 4, 1993; revised January 10, 1994.

The Ohio State University, Department of Electrical Engineering, 205 Dreese Laboratory, 2015 Neil Avenue, Columbus, Ohio 43210.

IEEE Log Number 9216742.

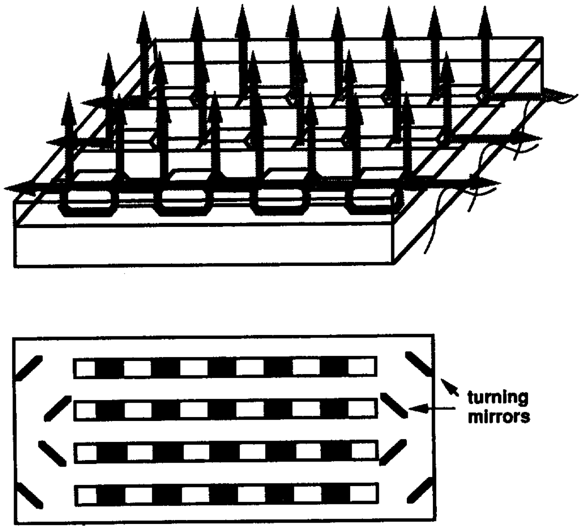

Fig. 2. Surface emitting coherent array of VRL's. Top: evanscently coupled. Bottom: Extended ring resonator, top view, after [17].

Each of the four mirror's reflectivities is individually controllable by mirror stack design. By making $M3$ partially transmitting, a controlled amount of energy of the incoming beam from an adjacent laser would be admitted into the cavity. These two lasers could then be mutually injection-locked. By adding independent phase control sections between devices, a mutually coherent, phased linear array of surface emitting lasers might be constructed having a single central lobe in the far-field. To create a two-dimensional array, Fig. 2, one could in addition either place several rows of the lasers close enough together for evanescent coupling, or create an "extended ring array" similar to that shown in Fig. 9 of [17].

A. Fabrication

The proposed device is process intensive. One would have to begin by etching a well with 45° sidewalls to create the lower two mirror surfaces $M1$ and $M2$, and apply the mirror coatings. Assuming the active layer to be GaAs, and the angle of incidence on the two lower turning mirrors to be 45°, a reflectivity of 99% could be achieved by a 10-period stack of alternating AlAs and $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ ($n = 2.99$ and 3.46, respectively, using values from [18]) for electric field polarized parallel to the plane of incidence, or perpendicular to the junction plane. Dielectric layers are routinely deposited on 90° surfaces, but just recently an impressive demonstration of deposition of AlGaAs/AlAs layers on the sloping sidewalls of a mesa by ultra-high vacuum MBE was reported in [19].

Next, a regrowth would be required to grow the lower waveguide layers in the well. This will require sufficiently good interfaces between the waveguide layers and mirror layers to avoid unnecessary leakage current. The upper waveguide layers would then be put down on a presumably planar surface.

Once all of the waveguide layers are grown, the top surface would have to be etched again to create the upper mirrors. After mirror stack deposition, another regrowth would be required to put down the filler material between adjacent devices; presumably these interfaces need only be of optical quality, as they will not be in the current paths.

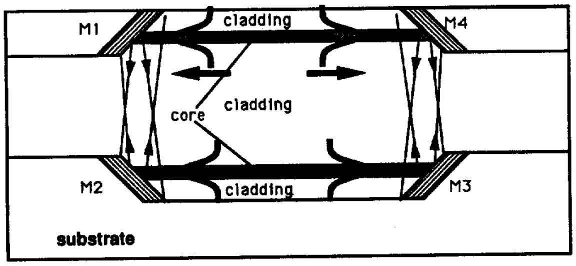

Fig. 3. The waveguides in the VRL, showing propagation of beam around cavity. Coupling losses result in the transmission of the light from one waveguide to the other.

B. Losses

In the vertical cavity ring laser, the beam sees gain only in one or possibly both of the two waveguide regions, which together represent some fraction of the total cavity length. In addition to the usual intrinsic losses (free-carrier absorption, scattering, absorption in the cladding), this laser would in addition experience mirror losses, coupling losses, and absorption losses during propagation through the passive regions.

The absorption losses in the two short legs of the cavity which do not have gain are small, since the material in the non-gain regions has a wide bandgap compared to the emission wavelength. The mirror reflection losses at the two bottom mirrors ($M1$ and $M2$) can be negligible, but the upper, or input/output mirrors $M3$ and $M4$ are partially transmitting and therefore constitute a loss to the cavity.

Once the beam leaves one waveguiding region, it diverges en route to the other, constituting a coupling loss. Assuming (arbitrarily) a bulk (non-quantum well) active layer thickness of 0.1 μm, and a short leg length of 0.4 μm, and a GaAs ($n_1 = 3.68$) core with $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ ($n_2 = 3.35$) cladding, the coupling coefficient is calculated to be 0.96 from one waveguide to the next. This is calculated by using a program developed by Marc Surette, now at Naval Research Labs, to compute the modes supported by the waveguides, and then propagating the beams across the short legs and performing an overlap integral between the expanding, traveling mode and the supported mode of the waveguide. The geometry is shown in Fig. 3. It should be noted that a grating surface emitting laser in a ring configuration has been demonstrated with high coupling [20]; the short legs of this cavity also provided no lateral waveguiding. In that structure transverse waveguiding was, however, present, unlike the proposed vertical ring laser structure.

Use of a passive upper waveguide could potentially introduce some absorption losses. These could be minimized, however, by the use of quantum wells. It has been shown that in devices with active and passive waveguide of the same composition, absorption losses are much less in multiple quantum well structures than standard double heterojunctions [21]. One could reduce this even further by varying the quantum well dimensions slightly. Alternatively, one could either pump the upper waveguide, simply bleach the quantum wells by injection, or perhaps reverse bias that waveguide and use the quantum confined Stark effect to reduce absorption.

Spreading in the plane of the junction will be less severe than beam divergence perpendicular to the junction, due to the presumably much larger lateral dimension. Although one might to tempted to correct for one or both of these diffractions by etching $M1$ and $M2$ to be curved in order to refocus the beams, and even though curved surfaces in each of the required planes have been fabricated before [22]–[24], a high enough degree of curvature would be impractical for focusing perpendicular to the junction plane.

In addition to coupling losses due to diffraction, additional losses can result if the mirrors are not perfectly aligned. Alignment losses can be made small for mirrors whose planes are perpendicular to the junction plane, since self-aligned techniques can be used for their fabrication [25]. For the geometry used here, however, in which the mirrors are tilted, we refer to Fig. 2 of [26], which shows that there will be a negligible change in coupling loss if the angle of the mirror can be controlled to within 2°, an easily achievable result.

III. DISCUSSION

The proposed vertical cavity ring laser structure has the potential for a) emission both perpendicular and parallel to the substrate, which can facilitate coupling both to fibers and other external devices and coupling into other device on the same chip, and b) integration into a coherent array.

Both of the these properties have already been demonstrated using GCSE lasers. Surface emitting phased arrays [2], [15], [16] have far-field patterns characteristic of coherent emission. Most loss mechanisms will be similar for the vertical cavity ring laser and the GCSE device, including cavity loss due to partially reflecting mirrors (gratings).

The GCSE arrays, however, have suffered in the past from high refraction loss into the substrate, 27% being reported in [15] and more than 50% in [16]. More recently, high-reflectivity coatings have been put on the grating side of the wafer and anti-reflection coatings on the substrate (output) side [2]. This has the effect of redirecting the previously lost light back up through the device. This in turn reduces the threshold and improves the power output, but it is not clear whether this recovered light adds to the array output in a coherent way. The vertical cavity ring laser has no grating losses, but does have internal coupling losses resulting from the circulating light expanding between the two waveguides. For the arbitrary geometry described earlier using identical bulk GaAs waveguides, we predict 8% coupling losses (two losses of $\approx$ 4% each).

On the other hand, absorption in the upper waveguide can be significant if both waveguides have the same composition and structure. The GCSE laser array is also reported to suffer from a 23% loss due to absorption in the grating regions [15] for a grating length of 300 μm, with single quantum well active regions in the laser and the external gratings of the same composition. The absorption loss in the upper waveguide of the vertical cavity ring laser would presumably be of this same order if no attempt is made to minimize it, either by pumping the upper waveguide (adds fabrication complexity), choosing a multiple-quantum well structure, varying the well dimensions to reduce loss even further (reduces coupling efficiency), or bleaching the quantum wells. Nevertheless, the worst case scenario discussed here would result in a total of 31% losses for a passive upper waveguide configuration of identical composition and dimensions as the active waveguide. For a transparent upper waveguide the total losses are 8%. These numbers (8%–31%) are compared to 50%–73% for the GSCE arrays.

ACKNOWLEDGMENT

I would like to thank the following people for helpful discussions: Gordan Jurasek, Stuart A. Collins, Jr., Dan Dapkus, Art Gossard, Steven A. Ringel, Brent Wagner, and Yih-Tyng Wu, and also Marc Surette for providing the mode analysis program. I also extend my heartfelt thanks to an excellent and constructive critique of the manuscript by the reviewers, many of whose suggestions have been incorporated into the final manuscript.

REFERENCES

[1] D. R. Scifres, R. D. Burnham and W. Streifer, "Phase-locked semiconductor laser array," *Appl. Phys. Lett.*, vol. 33, no. 12, pp. 1015–1017, 1978.

[2] G. A. Evans, et al., "Characteristics of coherent two-dimensional grating surface emitting diode laser arrays during CW operation," *IEEE J. of Quantum Electron.*, vol. 27, no. 6, pp. 1594–1608, 1991.

[3] M. Orenstein, E. Kapon, N. G. Stoffel, J. P. Harbison, L. T. Florex and J. Wullert, "Two-dimensional phase-locked arrays of vertical-cavity semiconductor lasers by mirror reflectivity modulation," *Appl. Phys. Lett.*, vol. 58, no. 8, pp. 804–806, 1990.

[4] R. A. Morgan, K. Kojima, T. Maullally, G. D. Muth, M. W. Focht, R. E. Leibenguth and M. Asom, "High-power coherently coupled 8 × 8 vertical cavity surface emitting laser array," *Appl. Phys. Lett.*, vol. 61, no. 10, pp. 1160–1162, 1992.

[5] A. Behfar-Rad and S. S. Wong, "A triangular-shaped GasAs/AlGaAs laser," *Technical Digest: International Electron Devices Meeting 1988*, pp. 319–322, 1988.

[6] S. Oku, M. Okayasu and M. Ikeda, "Low-threshold CW operation of square-shaped semiconductor ring lasers (orbiter lasers)," *IEEE Photon. Technol. Lett.*, vol. 3, no. 7, pp. 588–590, 1991.

[7] I. Ury, S. Margalit, N. Bar-Chaim, M. Yust, D. Wilt and A. Yariv, "Whispering gallery lasers on semi-insulation GaAs substrate," *Appl. Phys. Lett.*, vol. 36, no. 8, pp. 629–631, 1980.

[8] A. S.-H. Liao and S. Wang, "Semiconductor injection lasers with a circular resonator," *Appl. Phys. Lett.*, vol. 36, no. 15, pp. 801–803, 1980.

[9] A. F. Jezierski and P. J. R. Laubourn, "Integrated semiconductor ring lasers," *IEE Proceedings*, vol. 135, Part J, no. 1, pp. 1988.

[10] N. Bar-Chaim, K. Y. Lau, M. A. Mazed, M. Mittlestein, S. Oh, E. Ungar and I. Ury, "Half-ring geometry quantum well GaAlAs lasers," *Appl. Phys. Lett.*, vol. 57, no. 3, pp. 966–967, 1990.

[11] T. Krauss, P. J. R. Laybourn and J. Roberts, "CW operation of semiconductor ring lasers," *Electron. Lett.*, vol. 26, no. 25, pp. 2095–2097, 1990.

[12] H. Han, M. E. Favaro, D. V. Forbes and J. J. Coleman, "$\text{In}_x\text{Ga}_{1-x}\text{As}$-$\text{Al}_y\text{Ga}_{1-y}$-GaAs strained-layer quantum-well heterostructure circular ring lasers," *IEEE Photon. Technol. Lett.*, vol. 4, no. 8, pp. 817–819 1992.

[13] P. B. Hansen, G. Raybon, M.-D. Chien, U. Koren, B. I. Miller, M. G. Young, J. Verdielli and C. A. Burrus, "A 1.54 μm monolithic semiconductor ring laser: CW and mode-locked operation," *IEEE Photon. Technol. Lett.*, vol. 4, no. 5, pp. 411–413, 1992.

[14] J. P. Hohimer, G. A. Vawter, D. C. Craft and G. R. Hadley, "Improving the performance of semiconductor ring lasers by controlled reflection feedback," *Appl. Phys. Lett.*, vol. 61, no. 9, pp. 1013–1015, 1992.

[15] D. F. Welch, P. Parke, A. Hardy, W. Streifer and D. R. Scifres, "High-power grating-coupled surface emitters," *Electron. Lett.*, vol. 25, no. 13, pp. 819–820, 1989.

[16] G. A. Evans, *et al.*, "Coherent, monolithic two-dimensional (10 × 10) laser arrays using grating surface emission," *Appl. Phys. Lett.*, vol. 53, no. 22, pp. 2123–2125, 1988.

[17] G. A. Evans and J. M. Hammer, "Surface Semiconductor Lasers and Arrays," *Quantum Electronics-Principle and Applications,* ed. P. F. Liao. Academic Press, Boston, 1993.

[18] S. Adachi, "GaAs, AlAs, $Al_xGa_{1-x}As$: Material parameters for use in research and device applications," *J. of Appl. Phys.,* vol. 58, pp. 62–89, 1985.

[19] K. D. Choquette, M. Hong, R. S. Freund, S. N. G. Chu, R. C. Wetzel, J. P. Mannaerts and R. E. Leibenguth, "Vacuum integrated fabrication of vertical-cavity surface emitting lasers," *Journal of Vacuum Science and Technology B,* vol. 11, no. 5, pp. 1844–1849, 1993.

[20] D. J. Bossert, *et al.*, "Grating-surface-emitting lasers in a ring configuration," *Appl. Phys. Lett.,* vol. 56, no. 21, pp. 2068–2070, 1990.

[21] S. Tarucha, Y. Horikoshi and H. Okamoto, "Optical absorption characteristics of GaAs-AlGaAs multi-quantum-well heterostructures," *Japanese J. of Appl. Phys.,* vol. 22, no. 8, pp. L482–L484 1983.

[22] J. P. Donelly, R. J. Bailey, G. A. Lincoln, W. D. Goodhue, C. A. Wang and G. D. Johnson, "Monolithic two-dimensional surface-emitting arrays of AlGaAs horizontal-cavity diode lasers with etched facets and external parabolic reflectors," *Lincoln Lab Quarterly Report.* (Lincoln Laboratory, 1992).

[23] J. Salzman, T. Venkatesan, R. Lang, M. Mittlestein and A. Yariv, "Unstable resonator semiconductor lasers: Part 2: Experiment," *IEE Proceedings Part J,* vol. 134, no. 1, pp. 76–86, 1987.

[24] J.-I. Shimada, O. Ohguchi and R. Sawada, "Microlens fabricated by the planar process," *J. of Lightwave Technol.*, vol. 9, no. 5, pp. 571–576, 1991.

[25] R. v. Roijen, G. L. A. v. d. Hofstad, M. Groten, J. M. M. v. d. Heyden, P. J. A. Thijs and B. H. Verbeek, "Fabrication of low-loss integrated optical corner mirrors," *Appl. Opt.*, vol. 32, no. 18, pp. 3246–3248, 1993.

[26] F. R. Gfeller, P. Buchmann, K. Dätwyler, J. P. Reithmaier, P. Vettiger and D. J. Webb, "50 mW CW-operated single-mode surface-emitting AlGaAslasers with 45° total reflection mirrors," *IEEE Photon. Technol. Lett.*, vol. 4, no. 7, pp. 698–700, 1992.