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Whispering gallery lasers on semi-insulating GaAs substrates[a]

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Double heterostructure lasers are described in which light is guided by total internal reflection along a dielectric interface formed by the perimeter of an etched mesa. By means of the crowding effect, injection current is restricted to a narrow strip adjacent to the edge of the mesa. This results in the preferential excitation of optical modes which are localized in the vicinity of the dielectric interface. Both half-ring lasers formed at a single cleaved facet and quarter-ring lasers formed at a cleaved corner were fabricated.

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Recently, monolithically integrated optoelectronic circuits consisting of injection lasers, optical detectors, and active electronic devices have been fabricated on semi-insulating GaAs substrates. The circuits which were reported have been an injection laser integrated with a Gunn diode oscillator,[1] a laser with an integral transistor modulator,[2] and an integrated optical repeater.[3] In each of these progressively more complex circuits, the integrated laser relied in the conventional way on two opposite cleaved facets to provide the optical feedback necessary to support lasing. When one considers constructing significantly more complex circuits than those which have been fabricated until now, one is faced by a limitation imposed by the length of the laser cavity on one of the chip dimensions. Injection lasers are typically not made much longer than $\sim 300\,\mu$ because any increase in length results only in a larger value of the threshold current and a smaller differential quantum efficiency. To eliminate this rather serious restriction on chip size one can consider replacing one of the cleaved mirrors with either an etched mirror[4] or a DFB/DBR reflector.[5] An alternative solution, which is the topic of this letter, is to curve the optical path in the laser cavity so that a resonator may be formed at either a single cleaved facet or at a cleaved corner.

Light can be made to follow the curve of a dielectric interface by the mechanism of total internal reflection in much the same way that sound waves can be made to propagate along the curved walls of a whispering gallery, as was first correctly explained by Lord Rayleigh.[6] Dielectric discs have been proposed for use as high-Q optical resonators,[7] and injection lasers based on this principle have been fabricated on n^+-GaAs substrates.[8]

The structure which we have used is shown in Fig. 1, and the parameters of the layers are given in Table I. Current in the devices passes between the p-type contact surrounding the mesas and the n-type contact at the top of the mesas. When a device is forward biased, the current which crosses the p-n junction sets up a lateral voltage drop along the resistive p layers in the mesa. This causes the bulk of the injected current and hence the optical gain to be restricted to a region lying within just a few microns of the mesa edge. We have previously demonstrated how this "crowding effect" can be used to form lasers on semi-insulating substrates.[9]

The GaAs-air boundary at the edge of the mesa forms the dielectric interface which guides the optical mode along the curve. Solution of Maxwell's equations yields TE-like and TM-like waves whose radial dependence is given by a high-order Bessel function inside the mesa, and a Hankel function of the second kind in the region outside the mesa.[7] The presence of the Hankel function corresponds to radiation loss from the curved structure. Owing to the large index step which exists at the GaAs-air interface, one finds upon matching boundary conditions at the interface that ra-

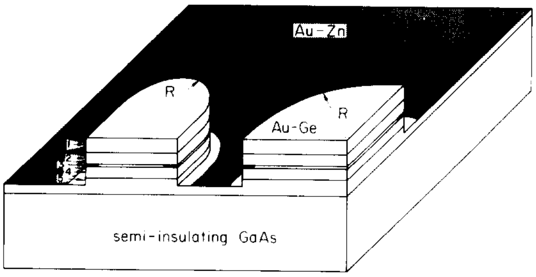

FIG. 1. Schematic diagram of a quarter-ring and a half-ring whispering gallery laser.

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TABLE I. GaAs substrate layer parameters.

Layer	Composition	Doping (cm^{-3})	Thickness (μ)
1	n-GaAs	5×10^{18}	2.5
2	n-$Ga_{0.6}Al_{0.4}As$	10^{17}	2.0
3	undoped GaAs	···	0.25
4	p-$Ga_{0.6}Al_{0.4}As$	10^{17}	2.0
5	p-GaAs	10^{17}	2.5

diation loss from the perfectly smooth curve is entirely negligible for all reasonable radii.

A useful expression for for the radial dependence of the modes can be obtained by noting that the Bessel function asymptotically approaches an Airy function in the vicinity of the interface.[10] The width W of the mth radial mode, as defined by the distance away from the perimeter at which the intensity has decayed to 10% of its peak value, can be determined with reasonable accuracy by locating a zero of mode at the mesa edge. Using an approximation for the zeros of the Airy function,[11] we obtain

$$W \simeq \{(0.19) + (0.65)[m + (0.75)]^{2/3}\}(R\lambda^2/n_{\mathrm{eff}}^2)^{1/3}, \quad (1)$$

where R is the radius of curvature, λ is the free-space wavelength, and n_{eff} is the effective index of refraction for propagation in the active layer. For values of the parameters typical for our devices, W is on the order of several microns for the lower-order modes. This means that both the optical modes and the gain region are restricted to the immediate vicinity of the mesa edge.

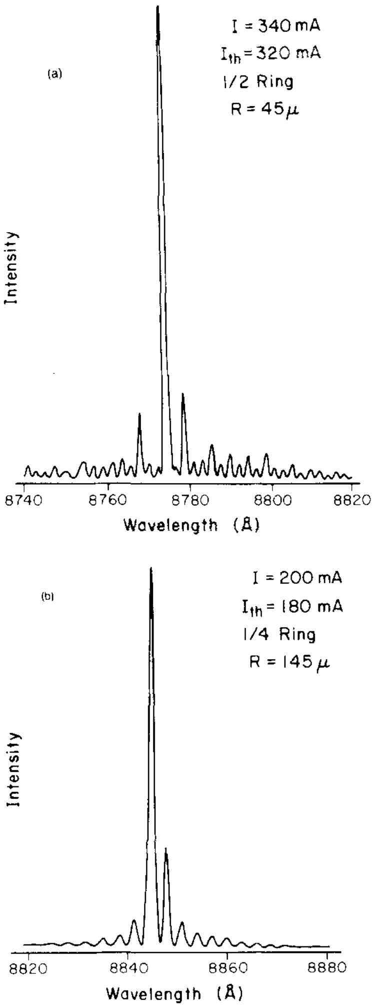

FIG. 2. Spectrum of a whispering gallery laser for (a) a half-ring and (b) a quarter-ring device.

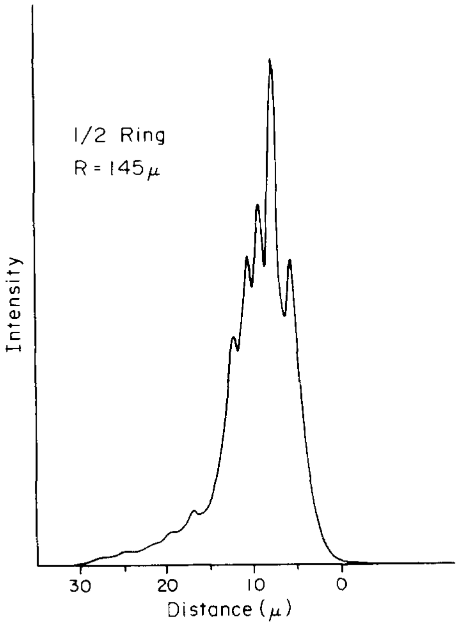

FIG. 3 Near-field pattern of a half-ring laser. The origin is at the mesa edge.

The devices were fabricated beginning with a liquid-phase epitaxy growth of the layers, followed by a deposition of Au-Ge and Au to a thickness of 1 μ. Resist patterns were

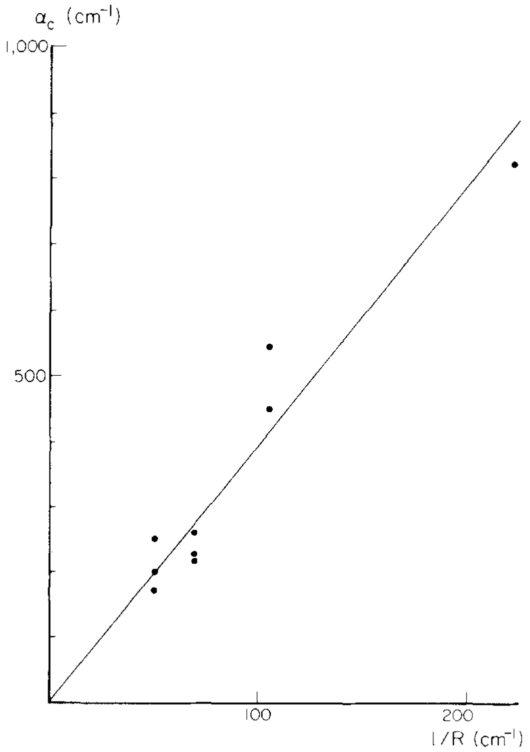

FIG. 4. Loss constant vs reciprocal radius for guiding along the curved interface.

photolithographically defined, and metal was etched in the exposed areas. The Au patterns were used as an etching mask for mesa definition. The mesas were etched using 3 methanol:1 phosphoric acid:1 H_2O_2, which is known to etch GaAs in a very smooth fashion.[4] The metal overhang which resulted from lateral etching was used as a shadow mask for the evaporation of the Au-Zn p-type contact. Both half-ring and quarter-ring lasers were fabricated with radii ranging from 45 to 195 μ. Straight control lasers were also fabricated from the same wafer.

The straight lasers displayed low threshold currents, with the lowest room-temperature pulsed threshold current being 36 mA for a 100-μ-long device. The best differential quantum efficiency obtained for these lasers was 32%. The best performance for a curved laser was observed in a 145-μ-radius quarter-ring laser, which had a threshold current of 180 mA and a differential quantum efficiency of 10%. The spectra of a half-ring and a quarter-ring laser are shown in Fig. 2. The spacing between the modes corresponds to the sum of the arc length of the curve and the length of the straight sections. The near-field pattern for a half-ring laser is shown in Fig. 3, where lasing is seen to occur in several radial modes.

Although a perfectly smooth ring suffers negligible radiation loss, in any practical device scattering will occur from imperfections at the dielectric interface. Some scattering will occur from the gain-guided modes of the straight lasers, but we can expect the scattering to be strongly enhanced in the curved lasers because the curvature of the interface acts to concentrate the modes close to the mesa edge. We can deduce the value of the loss constant α_c along the curve from the threshold current by means of the oscillation condition

$$g(L_s + L_c) = \ln(1/\mathscr{R}) + \alpha^0(L_s + L_c) + \alpha_c L_c, \quad (2)$$

where g is the optical gain, L_s and L_c are the lengths of the straight and curved sections, $\mathscr{R}$ is the mirror reflectivity, and α^0 represents all other optical losses. If we assume that the width of the gain region does not vary much with injection current, we can take the gain to vary linearly with pumping current density[12] (A/cm), which we express as

$$g = A^{-1}\{[I/(L_s + L_c)] - J_0\}, \quad (3)$$

where A and J_0 are constants to be determined. Equations (2) and (3) taken together predict a linear dependence of the threshold current on length for the straight lasers. By analyzing our data we obtain the values $A = 18$ mA and $J_0 = 1.0$ A/cm, assuming a loss constant $\alpha^0 = 50\ \text{cm}^{-1}$. We now have all the information needed to determine α_C from the value of the threshold current by means of Eq. (1). The values of α_c determined in this way are shown in Fig. 4.

A theoretical calculation of scattering of power from the lasing mode to other bound modes and to radiation modes caused by small imperfections at the interface predicts for α_c a $1/R$ dependence.[13] The straight line in Fig. 4 represents a least-squares fit to the data passing through the origin.

In conclusion, whispering gallery lasers suitable for incorporation into integrated optoelectronic circuits have been demonstrated. The performance of these devices is limited by the scattering introduced by surface roughness at the dielectric interface. An improvement in the performance of these devices could be obtained by improving the smoothness of the mesa edge, or by reducing the index step at the interface.

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