Superluminescence in InAsSb circular-ring-mode light-emitting diodes for CO gas detection

V. V. Sherstnev and A. M. Monahov
Ioffe Physico-Technical Institute, St. Petersburg, 195279, Russia

A. Krier
Physics Department, Lancaster University, Lancaster, LA1, 4YB, United Kingdom

G. Hill
III–V Central Facility, Electronic and Electrical Engineering Department, University of Sheffield, Mappin Street, Sheffield, S1 3JD, United Kingdom

(Received 19 June 2000; accepted for publication 26 October 2000)

We report on the superluminescence of an InAsSb light-emitting diode, operating at 4.6 μm, suitable for carbon monoxide gas detection. The source is based on an optical whispering (or circulating) mode which is generated near the edges of the mesa and which is responsible for the superluminescence. A pulsed optical output power in excess of 2.2 mW at room temperature has been measured, making these emitters suitable for use in cost-effective instruments for the environmental monitoring of carbon monoxide at 4.6 μm. © 2000 American Institute of Physics. [S0003-6951(00)04151-6]

The midinfrared (2–5 μm) spectral range contains the strong fundamental molecular absorption bands of a number of combustible and atmospheric pollutant gases. Currently, infrared gas detection techniques based on optical absorption are becoming increasingly popular as they are the only ones, which are truly gas specific and therefore reliable for gas sensor instrumentation.1,2 Consequently, there has been much research interest aimed at providing monochromatic optical output power in excess of 2.2 mW at 4.6 μm, as injection is increased, a whispering gallery mode is generated as injection is increased, resulting in superluminescence and a 300 K LED with an optical output power in excess of 2.2 mW at 4.6 μm.

The LEDs were all fabricated from III–V double heterostructures grown by liquid phase epitaxy (LPE). A conventional horizontal, multiwell graphite sliding boat was used for the LPE growth of the LED structures onto n-type InAs (100) substrates. These were 14 mm×14 mm square with a carrier concentration of 1×10¹⁸ cm⁻³ and were obtained from Wafer Technology Ltd. The LED structure, which has been described in detail previously elsewhere,7 consists of a rare earth gettering technique 8 to purify the active region, and subsequently, by using a rare earth gettering technique² to purify the active region, an improved device with a pulsed output power in excess of 1 mW has been achieved.⁹ The increase in optical output power in our recent investigations has come about largely through a careful reduction of the residual carrier concentration in the active region of mesa etched LEDs with a central dot contact. In this letter, we report on the fabrication of a superluminescent LED with a ring contact which produces a circular waveguide due to current crowding effects. A whispering gallery mode is generated as injection is increased, resulting in superluminescence and a 300 K LED with an optical output power in excess of 2.2 mW at 4.6 μm.

The LEDs were all fabricated from III–V double heterostructures grown by liquid phase epitaxy (LPE). A conventional horizontal, multiwell graphite sliding boat was used...
tire rear surface of the chip. Each of the contacts was deposited by thermal evaporation of Au:Zn alloy on the p side and Au:Te alloy on the n side of the diode, respectively. Once the LED chips had been prepared, they were mounted onto standard TO49 packages using Ag epoxy. Before testing, they were also equipped with a small parabolic reflector which was attached to the TO-49 header in order to help focus the LED output in the forward direction. The full width at half maximum of the resulting output beam obtained with this arrangement was about 12°. Since the LED chip was effectively placed at the focus of a parabola, the output beam was focused to a small spot, 1 mm diam., at a distance about 40 mm away, which is near optimal for many gas sensor instrument applications.

Figure 2 shows the electroluminescence emission spectra of the mesa etched LED I measured with increasing drive current. The distinctive feature of these spectral curves is their decreasing linewidth with increasing current. The half-width (FWHM) of the line at 15 mA is 880 nm whereas at 100 mA it is only 580 nm. The ratio of these halfwidths is 1.51. This spectral behavior shows that the device under consideration is a superluminescent diode. LED II also exhibited some line narrowing in the electroluminescence spectrum but the ratio of the halfwidths under the same drive conditions was only 1.17. The dip near 4.2 μm is due to CO₂ absorption from the atmosphere. The optical output power was also measured for the two different devices with a pulse duration of 2 μs at a repetition rate of 1 kHz in the current range from 0.2 to 3 A. The resulting optical output–current relationships are compared in Fig. 3. Both the curves have a linear portion in the current range from 0.2 to 1 A. The corresponding slopes were determined to be 1.05 for LED I and 0.88 for LED II. A value of the slope of the light–current characteristic which is greater than 1 is further evidence for superluminescence in LED I.

The above results demonstrate that LED I operates as a superluminescent diode unlike LED II. The LED I device has a ring contact with external and internal diameters much larger than the active layer thickness. The conductivity of the upper gold ring contact and the heavily doped n⁺ layer (and certainly the lower contact) are at least two orders of magnitude higher than the conductivity of the active layer. One can estimate the resulting current density distribution in the active layer by considering, as a model, a conductive layer between an infinite metal plate and a metal ring. The current density distribution on the lower plate is given by (units are chosen so that the layer width is a unit of length and the coefficient before the integral is equal to 1);

$$j_x(R) = \int_{r_1}^{r_2} \frac{E}{(1 + (R - x)^2)^{3/2}} dx,$$

where $r_1$ and $r_2$ are the internal and external radii of the ring,

FIG. 2. The room-temperature electroluminescence emission spectrum obtained from LED I, measured at increasing drive currents: 15 mA (curve 1), 50 mA (curve 2), and 100 mA (curve 3) at 560 Hz using a 50% duty cycle.
two dimensional solution which yields Bessel function solutions for the radial field distribution. The effective cavity length of $2\pi R$ imposed by the periodic boundary condition on the circulating wave results in the WG eigenmode condition: $2\pi R n = m \lambda$ for large integer $m$, where $R$ is the mesa radius, $n$ is the refractive index, and the mode spacing is simply given by $\Delta \lambda_{WG} = \lambda^2/2\pi R n$. This enables us to estimate a WG mode spacing of 4.6 nm which was too small for us to resolve with our low resolution spectrometer as is evident from the spectra of Fig. 2. Lasing is inhibited by the $Q$ spoiling effect of the rough circumference of the mesa. But, higher order modes are less affected since their intensity maxima reside further away from the perimeter, while the ring contact suppresses the modes in the central area of the device. Although the parabolic reflector collects light emitted at low angles, further measurements showed that light was emitted from both the surface and the edges of the mesa.

In summary, we have observed superluminescence in the midinfrared at 4.6 $\mu$m from a mesa etched LED. Spectral line narrowing was observed and the optical output power of these diodes was found to be more than two times greater than that of analogous diodes of a different configuration. The superluminescence was due to optical resonant mode behavior which we attribute to high order whispering gallery modes, previously not reported in LEDs operating at wavelengths as long as 4.6 $\mu$m. This result suggests the possibility of creating a whispering gallery mode semiconductor laser working at room temperature in the spectral range 3–5 $\mu$m.

The authors wish to thank EPSRC for the award of a visiting fellowship for V.V.S. One of the authors (A.M.) would like to thank the Ministry of Science of the Russian Federation for partial support of this work through the program “Optics and Laser Physics.”

---