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Laser Reliability

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Catastrophic Optical-Damage in High-Power, Broad-Area Laser-Diodes

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ABSTRACT

A detailed description of the phenomenon of catastrophic optical-damage (COD) in short (380μm cavity-length), 12μm aperture, proton-bombarded, double-heterostructure laser-diodes with uncoated facets was first presented in 1974. In these devices, COD generally initiates at the facets due to high optical-power density and propagate along transverse-mode filaments. To achieve reliable operation at high optical-power, broad-area laser-diodes have evolved to long (several-millimeter cavity-length), wide-aperture (50-200μm), dielectric-defined, broadened-waveguide, separate-confinement, double-heterostructure, quantum-well laser-diodes with coated, passivated facets. COD in these devices involve both transverse modes and ring-cavity modes.

INTRODUCTION

COD description

For modern, high-power laser-diodes, the remaining failure-mode is reported to be catastrophic optical-damage (COD). A brief description of the COD phenomena is as follows [1, 2]. A local region of the laser diode, generally at the front facet, is heated by absorption of the laser light so that the material melts. Since heat is generated by absorption of the laser light, the molten region is substantially confined to the active layer of the laser cavity. The surface of the molten region is optically reflective. Lasing is sustained in the optical cavity defined by the surface of the molten region and the back facet. The molten region propagates towards the back facet as the material exposed to the laser light continues to melt whereas the material on the opposite side, no longer heated by laser light, solidifies. Propagation of the molten region continues until there is insufficient gain in the optical cavity to maintain a liquid state.

COD refers to the track of melted-resolidified material which is highly non-radiative because it contains a high density of material defects. This track of defective material appears dark in any image that maps the minority-carrier lifetime, e.g. photoluminescence imaging, electroluminescence imaging, electron-beam induced-current.

While COD of single-mode lasers involves only transverse modes, we recently discovered [3, 4] that COD of modern, broad-area, multi-mode laser-diodes involves both transverse modes and ring-cavity modes. The presence of the ring-cavity modes accounts for many of the unusual features of COD, some of which have been reported but not explained [5-8]. This report provides a description of COD formation and propagation, with and without ring cavity modes, in broad-area laser-diodes.

Device structures

COD formation and propagation depends on the device structure which is under constant evolution as device engineers attempt to improve performance and reliability or to adapt to new applications. Discussion of various device structures is beyond the scope of this paper. The features of recent broad-area laser-diodes that significantly affect COD formation and propagation are:

- the separate-confinement, broadened-waveguide, quantum-well epitaxial-structure [9] that defines electrical and optical confinement perpendicular to the p-n junction
- facet passivation [10] that forms a facet with low optical absorption and maintains the facet quality during device operation
- gain-guided lateral-confinement that defines electrical and optical confinement parallel to the p-n junction.

Variations on facet formation and electrical and optical confinement do not significantly change the COD phenomenology described in this report.

Ring cavity modes

In 1972, Ettenberg et al. [11] first proposed the presence of internally-circulating modes in sawn-cavity, broad-area laser-diodes as an explanation for an observed bi-modal distribution in the efficiency of lasers that are fabricated in an essentially-identical fashion. The internally-circulating modes are the ring-cavity modes described by Chin et al. [3] in 2009.

To the best of our knowledge, there is only one report of internally-circulating modes as a cause of catastrophic degradation of broad-area laser-diodes [12] prior to our report in 2009 [3]. The likely reasons for this long hiatus are related to better understanding of ring-cavity modes [11-13] leading to changes in laser structures that suppressed this specific failure-mode.

The gain of internally-circulating modes relative to the transverse modes depends on a number of device parameters:

- ratio of the emission aperture divided by the cavity length [11]
- front-facet and back-facet mirror-loss [13]
- side-wall reflectivity [11, 12].

The ratio (R) of the emission-aperture width divided by the cavity length in lasers reported by Ettenberg et al. [11] is in the range of 0.20 to 0.34. Internally-circulating modes are suppressed in lasers with low values of R. Recent broad-area lasers generally have emission-aperture widths in the range of ~50μm to ~100μm and a cavity length in the range of ~1mm to ~5mm. For these devices, values of R are in the range of 0.01 to 0.10 and thus ring-cavity modes should be suppressed by the device geometry.

The optical loss for transverse modes in a Fabry-Perot cavity depends on the front-facet and back-facet mirror-reflectivity whereas reflection of ring-cavity modes at the facets is due to total internal reflection [3]. Ring-cavity modes appear for values of $\{F = (1/2L) \ln (1/R_1R_2)\}$ more than ~50cm^{-1}, where L is the cavity length and R_1 and R_2 are the front and back reflectivity, respectively [13]. Recent broad-area lasers generally have R_1 ~0.05, R_2 ~0.95 and L in the range of 1mm to 5mm. For these devices, F is in the range of 3cm^{-1} to 15cm^{-1} and thus ring-cavity modes should not appear.

The reflection of the ring-cavity modes at the front and back facet is due to total internal reflection [3,11-13]. The reflection at the side walls of sawn-cavity broad-area laser diodes is believed to be due to micro-facets ~6μm in dimension [11].

Henshall [12] increased side-wall reflection losses to suppress internally-circulating modes by proton bombarding the sides. Proton bombardment affects both the electrical and optical properties of GaAs [14], but Henshall [12] did not state the specific effect leading to optical loss. We believe that the major effect is the reduction of free carriers [3].

Ettenberg et al. [11] was able to control the appearance of the ring-cavity modes by the use of a clever dual-electrode structure which allowed electronic control of the optical loss at a virtual side-wall of the optical cavity. This virtual side-wall is the interface between an electrically-pumped lasing-region and an electrically un-pumped non-lasing region. In a casual view, it appears that both side walls of the optical cavity of recent gain-guided broad-area laser-diodes are equivalent to the virtual side-wall with high optical-loss incorporated by Ettenberg et al. [11] in their custom dual-electrode structure. However, whereas Ettenberg et al.[11] evaluated their lasers at approximately twice the threshold current, COD failure of present broad-area lasers with passivated facets occurs at more than an order-of-magnitude above threshold. The higher optical side-emission produces a high density of free carriers at the side wall that results in sufficient reflectivity for propagation of the ring-cavity modes [3].

RESULTS AND DISCUSSION

Location of COD

Bou Sanayeh et al. [6] have reported that the temperature profile of the laser facet is proportional to the near-field intensity-profile since the elevated temperature at the facet is due to optical absorption as a result of non-radiative surface-recombination. During normal device-operation, surface recombination increases as a result of thermally or photo-thermally associated chemical processes. COD initiates at locations of the laser facet where the near-field intensity and consequently the local temperature are highest.

While the results of Bou Sanayeh et al. [6] make logical sense, our examination [3] of numerous failed lasers indicates that COD often initiates at locations on the facet unrelated to the near-field intensity profile. In these devices, the COD initiates at facet locations where ring-cavity modes internally reflect.

Figure 1 shows the near-field profile of a 100μm aperture, 2mm cavity-length, 808 nm laser-diode measured during failure by COD using a high-speed camera. The device was driven to failure by increasing the operating current at the rate of ~1 A/hr. Failure occurred at ~4A. Frames were taken every 3μs. Selected frames are shown in Fig. 1. Frames 180 and 182 are almost identical and show the near-field of the diode just prior to failure. Frame 183 captures the near-field as the device begins to fail. Frame 184 is the near-field after device failure. Based on the study by Bou Sanayeh et al. [6], failure by COD is expected at a location of high near-field intensity. Frame 180 identifies four peaks of high near-field intensity, labeled a-d. However, COD occurs near the center of the emission region as indicated by the heavy black vertical line in Frame 183 where the intensity is actually a local minimum.

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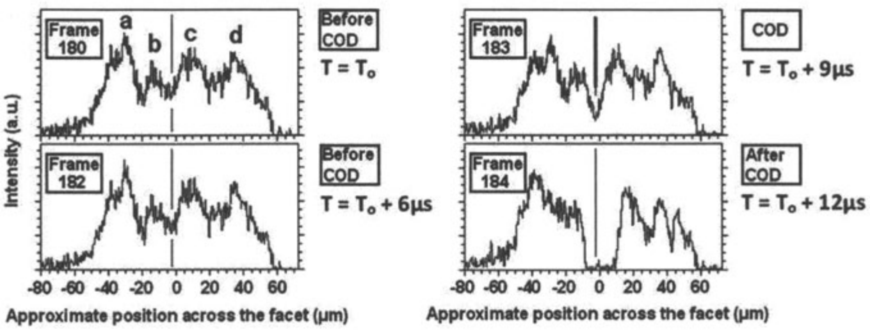

Figure 1: Four frames of time-elapsed near-field profiles of an 808nm laser diode. Consecutive frames are 3μs apart. The heavy vertical dark line in Frame 183 indicates the position on the facet where the COD initiates. The fine vertical dark line in the other frames also indicates the same COD position.

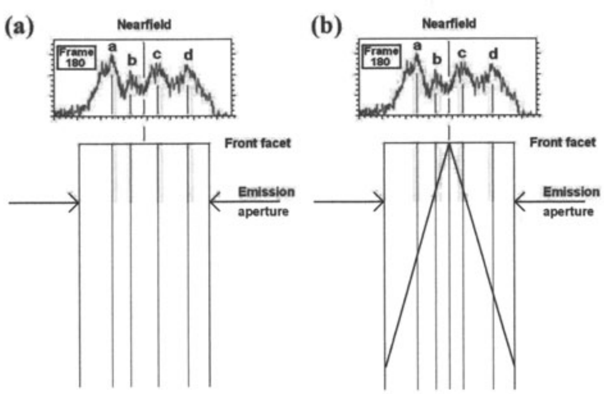

Figure 2: (a) The laser near-field profile and the associated transverse-mode filaments in the optical cavity. (b) The laser near-field profile, the associated transverse-mode filaments and a ring-cavity mode in the optical cavity.

Figure 2 illustrates how we believe the COD in Fig. 1 initiates. In Fig. 1a, the near-field intensity profile is shown. Below the near-field, a plan view of the front portion of the laser cavity is shown to illustrate the transverse-mode filaments responsible for the peaks in the near-field. Figure 2b illustrates a ring-cavity mode [3] reflecting off the front facet at the location of the COD. The ring-cavity mode has an angle of incidence of 16° to the front facet and is totally internally reflected so that it is not revealed in the near-field profiles of Fig. 1. We believe it is the combination of the transverse-mode intensity and the ring-cavity mode intensity that initiates the COD.

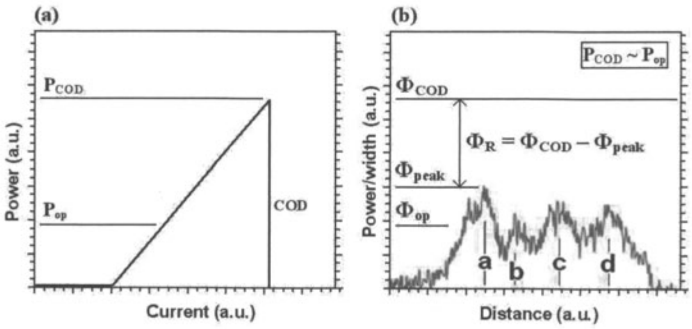

Figure 3: (a) Light vs. current characteristic of a laser diode driven to failure by COD at an output power value of P_{COD}. The recommended operating CW power, P_{op}, is approximately set at $P_{COD}/3$ to $P_{COD}/2$. (b) Φ_{op} and Φ_{COD} are indicated on a sample, non-uniform, near-field intensity-profile of a broad-area laser-diode. Φ_{op} is an average intensity value whereas Φ_{peak} is the peak intensity value. The device is reliable as long as $\Phi_{COD}>\Phi_{peak}$.

For a laser diode that is not thermally limited, the output power as a function of operating current is illustrated in Fig. 3a. As the drive current is increased, the device eventually fails by COD at a power level of P_{COD}. Device manufacturers typically specify a CW operating power, P_{op}, of $P_{COD}/3$ to $P_{COD}/2$ to ensure reliable operation.

Figure 3b shows the near-field profile of the broad-area laser-diode shown in Fig. 1. The power per unit width of the near-field is represented by Φ. The area beneath the near-field profile is P_{op}. The near-field profile is non-uniform and thus Φ_{op} represents an average value. Typically, the peak value Φ_{peak} is no more than 1.2 Φ_{op}. Φ_{COD} is generally more than $2\Phi_{peak}$.

If the facet is ***not passivated***, Φ_{COD} degrades over time due to chemical processes accelerated by heat and light [15]. The laser diode fails by COD when $\Phi_{peak} = \Phi_{COD}$ at peaks in the near-field profile [6]. This failure process is sudden but not random. For a given aging time at constant current, Hashimoto et al. [15] has determined that the values of Φ_{COD} follow a Weibull distribution

If the facet is ***passivated***, Φ_{COD} is relatively stable and the device should not fail by COD. However, extensive studies of passivated broad-area laser-diodes show the occurrence of random failures [16, 17]. The initiation of these random failures is believed to be mainly related to the ring-cavity modes.

The appearance of ring-cavity modes are clearly temporary, otherwise the slope efficiency would be anomalously low [11-13]. The pulse power at which a broad-area laser fails by COD depends on the pulse duration. Figure 4 illustrates the general trends of P_{COD}-pulsed as a function of pulse duration [18]. For pulse durations more than ~1μs, the COD power is approximately constant. However, COD power increases with shorter pulses, increasing approximately an order-of-magnitude as the pulse duration decreases from ~1μs to ~1ns.

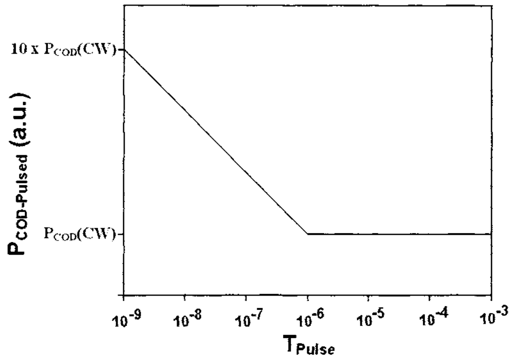

Figure 4: The power at which COD occurs in a broad area laser as a function of pulse width.

Figure 3 indicates that a local power density of $\Phi_R = \Phi_{COD} - \Phi_{peak}$ is required to cause COD. The intensity of transverse filaments has spatial-temporal fluctuations at the relaxation oscillation frequency (Ω_{rel}) and a filament frequency (Ω_{fil}) [19]. The changes in intensity as well as Ω_{rel} and Ω_{fil} depend on the pump level. For present laser diodes that operate at more than ten times the threshold current, Ω_{rel} and Ω_{fil} have values of ~1.0GHz and ~5GHz, respectively. At these frequencies, the intensity fluctuations of transverse filaments would have to exceed ten times the CW value of P_{COD} to cause COD.

The appearance of ring-cavity modes depend on the ring-cavity gain relative to the gain of the transverse modes. During certain transverse-modes fluctuations, ring-cavity modes appear. At the front facet, the intensity of the ring-cavity mode adds to that of the transverse modes at ***only*** the location where it reflects off the front facet. If the optical intensity at this location is sufficiently high, a COD initiates.

Most combinations of transverse mode and ring-cavity mode will lack either the intensity or duration to cause COD. However, as the operating current is increased, there will certainly be a value of operating current where COD will occur. Additionally, at a lower value of operating current, after sufficient time, a fluctuation in transverse mode/ring-cavity mode, sufficient to cause COD, should also occur. This is clearly a random process and likely accounts for the observed random failures in life-test of passivated, broad-area, laser-diodes [16, 17].

There are several additional pieces of evidence that supports our model of COD formation in present broad-area laser-diodes.

1. CODs initiate very near the center of the emission region or at locations symmetrical about the center of the emission region. These locations are the expected locations where a ring mode reflects from the front facet [3].
2. The COD track spreads within an angle confined by ±16° since the ring mode reflects from the front facet due to total internal-reflection [3]. The critical angle for optical transmission in the infrared spectral region from GaAs to air is ~16°.
3. Single mode lasers which cannot support a ring-cavity mode have higher reliability relative to broad-area lasers. Van de Casteele et al. [20] has demonstrated an ~5400 FIT

failure-rate, based on over 900khrs of device testing, for single-mode 980nm laser-diodes operated at 83°C junction temperature (65°C sub-mount temperature) and a peak facet power-density of ~340mW/µm (850mW output power). This reliability result greatly exceeds that of two 96µm aperture lasers, operated at output powers of ~20W (~208mW/µm) and a heat-sink temperature of 21°C for a period of ~4000 hours [5].

COD propagation

As described in the Introduction, after initiation, the COD propagates into the optical cavity. In some cases, the COD damage track is roughly linear, propagating along high optical-intensity, transverse-mode filaments [7]. Figure 5a is an example of a linear COD track. Figure 5a is an electroluminescence image of the optical cavity of a failed laser diode. The device is a custom 3.6mm cavity-length, 100µm aperture, 9.8nm laser diode with an aperture fabricated in the n-contact to enable viewing of the optical cavity during device operation.

The COD in Fig. 5a was formed using fault-mode protection to suppress ring-cavity modes as described previously [6]. The current to the laser diode was ramped at the rate of 1A/hr until device failure by COD at an optical power of ~10W (~11.6A). The current was stopped when a 5% drop in optical output was detected. Due to the response time of the electronic circuitry and the extremely-rapid propagation-speed of the COD discussed below, the output power had dropped ~20% and the COD had propagated ~20µm before the current was finally stopped as shown in Fig. 5b. The COD initiated at location B on the front facet. After obtaining the electroluminescence image in Fig. 5b, the device was operated at a current of 3A for a period of three hours. While there was a small further decrease in the slope efficiency, the COD had propagated a distance of ~1100µm during the 3hrs as shown in Fig. 5a.

Figure 5c is an electroluminescence image of the optical cavity of another failed laser-diode from the same manufacturing run as the device in Fig. 5a. The current to the laser diode was ramped at the rate of 1A/hr until device failure by COD at an optical power of ~11W (~22A). The higher operating current relative to the device in Fig. 5a is a result of thermal roll-over. The ring-cavity modes were ***not*** suppressed and as a result, both transverse and ring-cavity modes contribute to COD propagation.

The ring-cavity modes reflect off the front facet at an angle-of-incidence of 16° due to total internal reflection [3]. The transverse modes cause the COD to propagate along the optical axis whereas the ring-cavity modes cause the COD track to spread at angles ≤16° to the optical axis as it propagates. Figure 6a is a magnified view of the front facet of the device in Fig. 5c. Figure 6b is the same image as in Fig. 6a with lines drawn to indicate the effect of the ring-cavity modes. The horizontal line is perpendicular to the front facet. The two oblique lines are at incidence angles of ±16° to the front facet. The COD tracks are spreading parallel to the oblique lines due to the ring-cavity modes.

Finally, it should be noted that the distance AB in Fig. 5a is approximately the same as the distance CE in Fig. 5c. As discussed above, the location of COD in failed devices is determined by the location where the ring-cavity mode reflects off of the facet. For devices from the same manufacturing group, i.e. the same bar, where the cavity length is near identical, the COD location is either at the center of the emission region or symmetrical about the center of the emission region as in Fig. 5.

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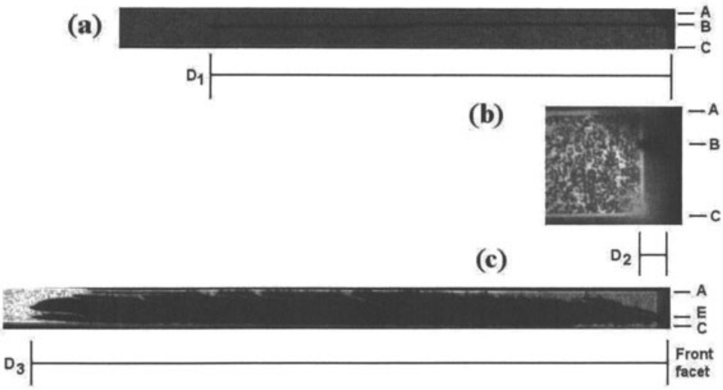

Figure 5: (a) Planar IR-image of the optical cavity through a window in the n-contact for a 3.6 mm cavity length, 980nm laser that has failed by COD. The emission width (A-C) is 100μm. The COD initiates at position B on the front facet and propagates a distance D_1 during device degradation to 50% of the original output power. (b) Planar IR-image of the front facet region of the optical cavity through a window in the n-contact for the laser in (a). Current was stopped when the output power decreased by 20% resulting in a short linear COD initiating at position B and extending a distance D_2 into the optical cavity. (c) Planar IR-image of the optical cavity through a window in the n-contact for another laser from the same manufacturing group as the device in (a). The COD initiates at position E on the front facet and propagates a distance D_3 during device degradation.

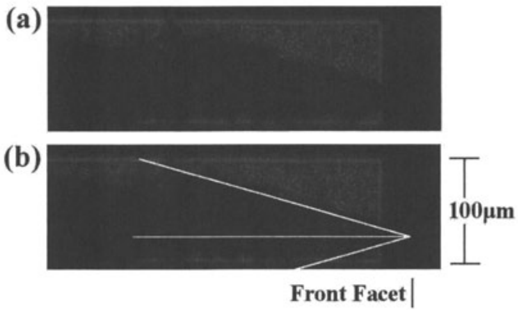

Figure 6: (a) Magnified front-facet portion of laser in Fig. 5c. (b) Same image as in Fig. 6a. The horizontal white line is along the optical axis and is perpendicular to the facet. The two other drawn lines are at angles of ±16° to the optical axis.