Stabilization of lateral mode transients in high-power broad area semiconductor lasers

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The lateral modes in high-power broad area gain-guided semiconductor lasers suffer from instabilities that can lead to self-focusing of the optical modes resulting in the formation of beam filaments. The introduction of cold-cavity index guiding, by means of etched holes, has been previously shown to reduce filament formation in the optical near field. In this work, a simple measurement technique is presented and utilized to characterize the behavior of local intensity fluctuations in the time domain. The use of etched holes to provide index guiding is shown to provide a significant improvement in the temporal stability of the lateral optical modes. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3067866]

High-power broad area semiconductor pump lasers are key components for laser systems used in material processing and medical applications. However, due to the lack of cold-cavity index guiding in the lateral direction, the lateral modes of gain-guided semiconductor lasers suffer from both temporal and spatial instabilities. These instabilities can be especially problematic when scaling the optical mode volume and injection level for high-power operation. In addition, beam filaments can contribute to degraded efficiency, increased threshold current, and reduced lifetime through early catastrophic optical mirror damage in semiconductor lasers. Various mechanisms control the spatiotemporal properties of the lateral optical mode profile including carrier-induced (linewidth-enhancement factor), thermally induced, and intensity-dependent variations in the refractive index profile.[1] Due to the spatial and temporal fluctuations of all of these terms, the lateral modes in high-power gain-guided semiconductor lasers are often unpredictable and unstable.

Spatial control of lateral modes enables the reduction in filamentation and smoothing of near- and far-field profiles. A variety of methods have been theoretically proposed and experimentally demonstrated in prior works.[2–7] Evidence of carrier-induced instabilities in the measured intensity noise spectrum of broad area laser diodes has also been found.[8,9] In this work, spatially localized fluctuations of lateral modes in high-power broad area semiconductor lasers under steady state conditions are investigated and characterized in the time domain. Index guiding (in the form of etched holes) is introduced as a method of stabilizing the lateral modes and is shown to also suppress the temporal transients arising from the intermodal instability.

The GaAs-based laser structure in this work is grown by metalorganic chemical vapor deposition. The devices are processed following a standard broad area laser fabrication procedure, and the fabricated lasers operate at 808 nm. Prior to cleaving, a pattern of holes is milled through the *p*-contact into the optical cavity of the laser stripe using a focused ion beam (FIB).[6] The holes are 5 μm wide and with 20 μm separation between their centers, thus are uniformly distributed across the 100 μm wide laser stripe. Three aligned rows of holes are employed to improve the index guiding to the optical mode, but the induced index perturbation is located within the laser cavity, away from either laser facet,[7] to avoid possible mirror damage. Other design considerations can be found in Ref. 6. These holes are milled to a sufficient depth to allow some interaction with the optical mode, but not so deep as to introduce significant losses or penetrate the active region. The laser die is then cleaved, and high reflectivity/antireflection coatings are deposited on the front and back facets, respectively. The single emitters are then bonded junction down using AuSn solder on standard Cu *c*-mount packages with CuW inserts providing coefficient of thermal expansion matching between the die and heat sink. The diode lasers operate continuous wave at 25 °C. Figure 1(a) illustrates the measured light-current-efficiency characteristics of the patterned laser, as well as for an unpatterned reference laser taken from the same wafer. Figure 1(b) shows a top view scanning electron microscope (SEM) image of the laser stripe with the etched mode-stabilizing holes. The laser with etched holes shows improvement in slope efficiency due to the increased overlap of the optical mode with the lateral gain profile.[6]

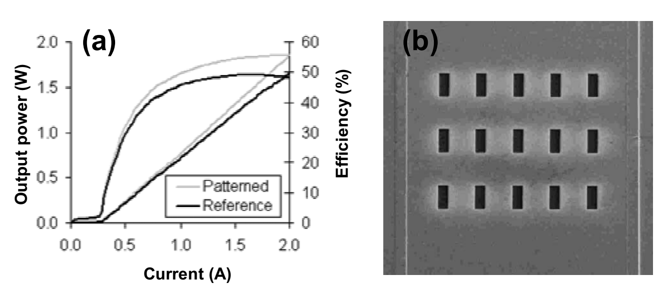

FIG. 1. (a) Light-current-efficiency characteristics of the etched and unetched reference broad area semiconductor lasers. (b) SEM image of the FIB-etched hole pattern in the laser stripe.

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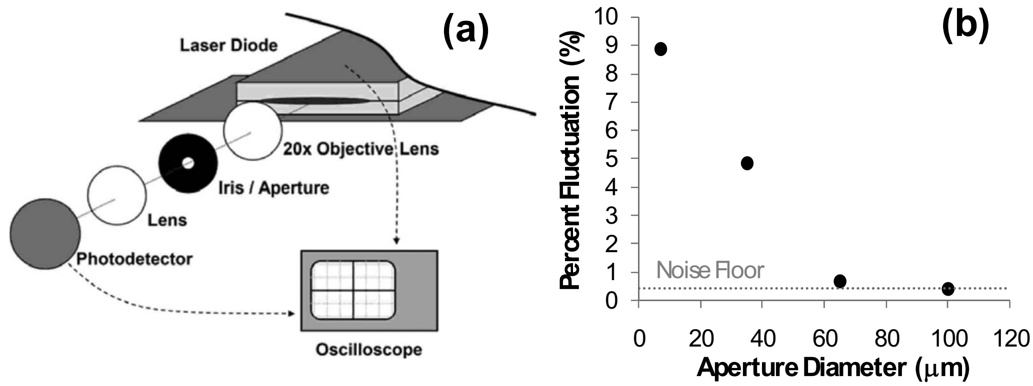

FIG. 2. (a) Schematic of the free-space optical setup used to monitor the stability of the local optical field. (b) Measured optical power fluctuation vs the effective aperture size.

Figure 2(a) illustrates a schematic of the measurement setup used to characterize the spatially localized intensity fluctuations. A high-magnification microscope objective lens is used to image the laser facet. Pinhole apertures of various sizes (as well as an adjustable iris) are placed at the image plane to spatially filter a spot along the laser facet. A beam splitter (not shown) is placed behind the aperture and a second lens is used to reimage the facet onto a charge coupled device camera. By back illuminating the aperture with a light-emitting diode light source and comparing it to the known dimensions of the emitter facet, the effective sampling spot area (as a function of pinhole aperture size) is obtained. Next, the camera is replaced by a Si photodetector (with adjustable neutral density filter to prevent detector saturation), which is monitored by an oscilloscope. In this way, local optical power variation from a region of controllable size can be monitored in the time domain. The oscilloscope is set to capture a single waveform, and the trigger level is manually lowered to the point of the first waveform capture, effectively taking a snapshot of a local random power fluctuation. The process is repeated multiple times to ensure the reported waveforms are representative of typical fluctuations. The diode current is monitored on a separate oscilloscope channel to verify its stability over the same timeframe.

Using a fully open iris as the spatial filter, the setup is calibrated to known light versus current curves for the lasers under test. The intensity excursions are characterized using the ratio between the peak-to-peak power ($P_{\mathrm{max}} - P_{\mathrm{min}}$) and the minimum power (P_{min}). Figure 2(b) plots the characterized intensity fluctuation as a function of effective spatial filter aperture diameter for an unpatterned reference laser operating at 5 A, producing 5.5 W of output power. The relative intensity noise floor fundamentally arises from the contribution of spontaneous emission. As shown in Fig. 2(b), while the total laser output integrated across the entire 100 μm facet stripe shows good stability, significant temporal intensity fluctuations become evident as the sampling region is reduced in size.

Figure 3 compares captured output waveforms from a 7 μm spot measured at a single point along the facet for an unpatterned reference laser and the laser with the etched holes (both taken at 5 A corresponding to ~5.5 W of laser output). The unpatterned laser exhibits a significantly larger power variation (9%) than the laser with etched holes (3%). The measured characteristic time scale (~6 ms) suggests the physical origin of these transients to be thermally induced changes to the refractive index profile in the lateral direction. The introduction of cold-cavity index guiding by means of the etched holes serves to dominate the refractive

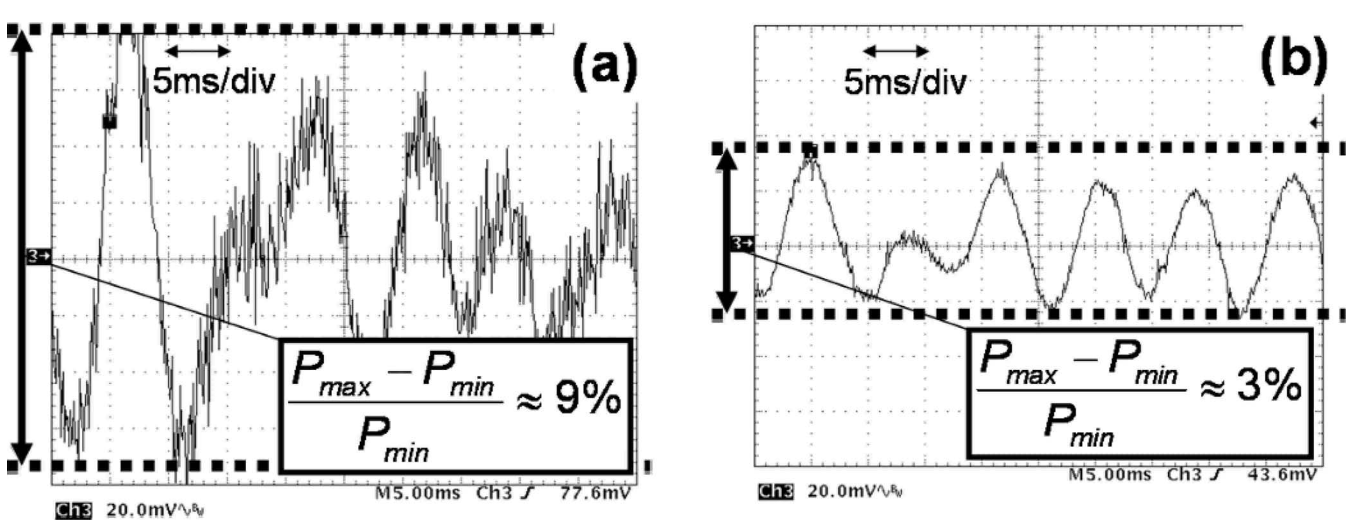

FIG. 3. Measured photodetector waveforms for the unpatterned broad area semiconductor laser (a) without and (b) with etched holes measured through an effective 7 μm aperture. The data are taken at the same current injection level, with the dc component of the signal removed for illustration purposes.

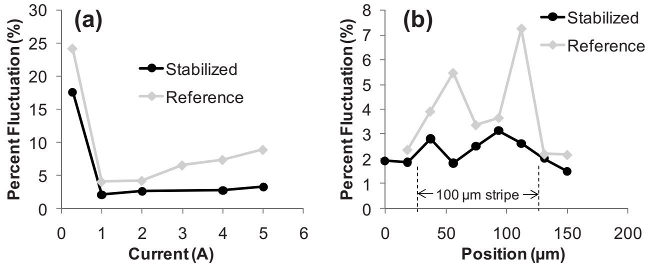

FIG. 4. Measured power fluctuation through an effective 7 μm aperture for the etched and unetched reference devices as a function of (a) drive current and (b) position along the facet.

index profile, thereby reducing the effect of thermal fluctuations on the local optical field.

Figure 4(a) illustrates the measured fluctuation as a function of drive current at a single point along the facet. As shown below threshold (<1 A), large excursions are measured; these are attributed to incomplete/unstable formation of the lateral optical waveguide at such low drive conditions. Above threshold, the fluctuations are found to increase with drive current, with the etched holes providing improvement at all drive currents. Figure 4(b) illustrates the measured fluctuation in the near field as a function of position along the facet, with the etched device again showing a considerable improvement over the unetched reference.

In summary, a simple technique is utilized to characterize the spatiotemporal characteristics of lateral modes in broad area semiconductor lasers. While the total integrated power of diode lasers is stable in time and is limited by the relative intensity noise, significant intensity fluctuations are found to occur in localized regions along the facet stripe. These excursions are observed on millisecond timescales, suggesting the physical origin to be thermally induced instabilities of the refractive index profile in the lateral direction. Etched holes are shown to provide stability to the lateral modes through the introduction of a cold-cavity refractive index profile that dominates the other nonlinear effects such as the carrier- and intensity-dependent refractive index variation. It is expected that with faster electronics, this technique could be similarly used to probe beam filament transients occurring on faster timescales, presumably caused by similar variations in the refractive index profile due to local carrier/gain-dependent fluctuations. By replacing the Si photodetector with a suitable high-speed mid-IR detector (such as HgCdTe), similar monitoring of local temperature oscillations might also be observed.

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