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Mode Control in Semiconductor Lasers

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Since the introduction of a double heterostructure a decade ago, the technology of the semiconductor laser has made a remarkable progress. The operating lifetime of GaAs-AlGaAs DH lasers has increased from several tens of minutes to tens of thousand hours; it may well be over 10^6 hours at room temperature if one can rely on the extrapolation based on high-temperature accelerated aging tests. A variety of stripe-geometry lasers have been devised, leading to improvements of the device performance and much deeper understanding of the physics of the semiconductor laser.

These improvements, coupled with the progress in optical fiber technology and its related disciplines, have accelerated the effort to realize practical fiber-optic communications systems. When the semiconductor laser began to be closely examined from the systems point-of-view, however, it has become increasigly clear that the performance of "conventional" stripe lasers is not satisfactory in many respects.

Most "conventional" lasers exhibit more or less "well-behaved" optical properties just above threshold. When the output power is increased to several mW or more, however, they tend to reveal a number of peculiarities such as enhanced power fluctuations, beam direction shifts and lateral displacements of the near-field spot. These anomalies have been found to be associated with "kinks" or nonlinearities in the output-vs-current characteristic curves.

Theory and experiment have shown that the kink phenomenon is not a sporadic but rather an intrinsic property of those lasers whose transverse mode in the junction plane is guided by its gain profile. In these lasers, the lateral transverse mode is determined by the gain profile, which in turn is influenced by the mode profile through a spatial hole-burning effect. This interaction between electromagnetic fields and population inversion, coupled with the carrier concentration dependent refractive index and an inevitable slight asymmetry in the device parameter, gives rise to transverse mode instabilities and associated anomalies.

Quite a number of ideas have been proposed to eliminate or alleviate the kink phenomena. One may simply reduce the stripe width down to several um, which is comparable to the minority carrier diffusion length, thus minimizing hole burning. The most straightforward scheme is to introduce a built-in (complex) refractive index profile along the junction plane. The built-in refractive index step has to be larger than the gain-induced refractive index change, which is on the order of 10^{-3}. Some of the laser structures designed along these lines are a transverse-junction stripe laser, a buried heterostructure laser, a channeled substrate planer laser, a strip-buried heterostructure laser, a terraced substrate laser, a rib-guide laser and a plano-convex stripe laser.

In spite of different geometries and fabrication processes, all these new lasers exhibit more or less similar optical characteristics which are much superior to those of "conventional" stripe lasers: they are kink-free at least up to 10 mW and lase in single transverse mode. The power fluctuation is quantum-noise limited and the linearity is even better than that of light emitting diodes. The buried heterostructure may be cited as a representative example. Its active region is surrounded by passive lower-refractive-index material and hence the carrier and optical confinement is complete. Typically it begins to lase at 20 mA and maintains funda-

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mental transverse mode up to its catastrophic failure limit, which is more than 50 mW (pulsed). The beam half power width is 25°x35°, parallel and perpendicular to the junction plane, respectively and its differential quantum efficiency is 60-70 % (from both facets).

Somewhat unexpectedly, most of the transverse-mode stabilzed lasers, except for narrow-stripe gain-induced mode lasers, oscillate in a single longitudinal mode as well. This behavior is not fully understood, although it may be quite natural for a homogeneously broadened laser. The spectral half width has been measured to be narrower than 10 MHz.

The concept of mode control developed for GaAs-AlGaAs lasers should be equally valid for other materials, notably loger-wavelength lasers. The geometrical tolerances here are expected to be less stringent because of larger dimensions involved.

There still remain some problems in connection with the stability of lasing mode. One is the onset of self-sustained oscillations during the course of operation observed in not-negligible fractions of laser that were initially very well-behaved. This behavior may ultimately limit the device reliability in many applications. Another problem is concerned with the longitudinal mode instability induced by the optical feedback. This phenomenon is essentially an external cavity effect and may be very troublesome in fiber-optic communications, although it may find applications in optical disc play-back systems. In principle, this problem is expected to be solved by developing a suitable optical isolator or by incorporating frequency selective elements such as distributed feedback and Bragg diffraction reflectors.

In conclusion, the major problems of mode instabilities of semiconductor lasers are now solved. Mode-stabilized lasers oscillate in a single transverse and logitudinal mode, delivering output powers of more than 10 mW. These improvements should lead to much wider applications of semiconductor lasers.