Single quantum well laser with vertically integrated passive waveguides

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The condition for the fundamental mode operation in a single quantum well laser with vertically integrated passive waveguides has been studied. With proper choice of parameters, transverse beam divergence as low as 19° has been achieved.

Semiconductor lasers are proving useful in a variety of applications. A limiting factor sometimes encountered is the large beam divergence in the transverse direction, which is characteristic of conventional laser structures. For example, the collection efficiency can be poor for conventional lasers launched into even high-numerical aperture lenses systems. Reduction of the transverse divergence can be achieved by increasing the source size in waveguides with smaller refractive index steps or thinner active layer. Examples of the this type of structure include the large optical cavity (LOC),[1] the thin active layer,[2] and the thin tapered-thickness(T^3)[3] active layer lasers, all using the conventional double-heterostructure materials as the active layers. To the extent that the reduction in optical confinement does not lead to additional carrier losses, the threshold current of the laser should be inversely proportional to the confinement factor. This is not the case, however, in single quantum well (SQW) lasers, such as the graded-index separate-confinement (GRINSCH) SQW lasers, because the reduced energy barrier may result in higher rates of carrier leakage[4,5] and lower carrier collection efficiency in the wells.[6] While the question concerning the carrier collection efficiency in single quantum well lasers has not been fully clarified, the carrier leakage loss is indeed an important consideration since the operating carrier densities of single quantum well lasers are on the order of $10^{19}/\text{cm}^3$.[4]

Recently it has been demonstrated that by monolithic stacking two or three GRINSCH single quantum well lasers within the minority-carrier diffusion length of a *p-n* junction, inversion can be achieved in all wells.[7,8] The operating voltage and the threshold current density per quantum well are comparable to those of the typical discrete single quantum well lasers. If the separation between the wells is larger than 1 μm, the individual GRINSCH elements operate independently (incoherently), resulting in a 45° far-field angle which is equal to that of the discrete single quantum well laser. If the well spacing is $< 1\ \mu$m, optical coupling among the elements can occur. Both the in-phase mode with a low-divergence single-lobed far-field pattern, and the out-of-phase mode, with a two-lobed far-field pattern, have been observed. In this approach, the reduction of beam divergence is achieved through the interference of three optically and electrically coupled graded-index separate-confinement single quantum well lasers. Since the source size is expanded without reductions in the carrier confinement, carrier losses caused by excess leakage and reduced carrier collection efficiency can be prevented. To achieve the fundamental (in-phase) mode operation, it is necessary to properly control the spacing and the relative gains in the wells so that the modal gain of the fundamental mode is the highest. However, it is difficult to accurately predict the gains in the individual wells. In general, the relative gains in the wells are not equal because the carrier density in the central well is always higher than those in the subordinate wells due to carrier diffusion. The variations in the well thicknesses also affect the relative gains. These factors could lead to uncertainty in the mode selection.

In this letter, we report the fundamental mode operation in a GRINSCH single quantum well laser with vertically integrated passive waveguides. Far-field beam divergence as low as 19° has been achieved. The laser structure, as shown in Fig. 1, consists of three graded-index waveguide symmetrically placed about a *p-n* junction. The center-to-center spacing of the waveguides is 1 μm. The central waveguide consists of a 120-Å-thick single GaAs quantum well sandwiched between two linearly graded $\text{Al}_x\text{Ga}_{1-x}\text{As}$ regions with $0.3 < x < 0.6$. The two subordinate waveguides have the same graded-index profile except that the GaAs quantum well is replaced by a transparent $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ layer. The laser material was grown by atmospheric pressure metalorganic chemical vapor deposition (MOCVD).

By eliminating the quantum well active regions in the two subordinate waveguides, the mode selection mechanism is simplified. The operation mode is solely determined by the confinement factor in the central well. The calculated near-

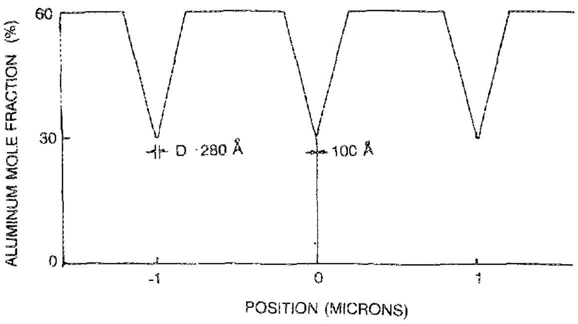

FIG. 1. Structure of the single quantum well laser with vertically integrated passive waveguides.

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and far-field light intensity distributions of the three eigenmodes for the coupled-waveguide structure are shown in Fig. 2. The calculation is based on the real part of the refractive index profile because the imaginary part has a negligible effect on the waveguiding properties. There exist three eigenmodes in the coupled waveguides, each being a linear combination of the fundamental modes of the individual waveguides. The operating mode is the one with the largest confinement factor with the gain medium. The confinement factors can be controlled by the waveguide parameters. Mode C is eliminated because its overlapping factor with the gain region is nearly zero. To determine waveguide parameters for the in-phase mode operation, we have calculated the confinement factors for the in-phase mode (A) and the out-of-phase mode (B) by varying the widths of the valley of the subordinate waveguides, D, for a fixed waveguide spacing of $1\ \mu$m. The results are shown in Fig. 3. The in-phase mode has a larger confinement factor for $D < 355\ \mu$m. In this region, the beam divergence, ranging from 20° for $D = 200$ Å to 19° for $D = 350$ Å, is quite insensitive to D. This large tolerance makes it easy to discriminate against the out-of-phase mode by the layer thickness control. However, the power in the side lobes of the far-field pattern increases for smaller D. In our experiment D is chosen to be 280 Å as a compromise between low threshold current and higher power in the central lobe. This corresponds to a calculated confinement factor of 2% and a beam divergence of 20°, compared to a confinement factor of 3.8% and a divergence of 45° in single quantum well lasers. We note that the reflectivity at the mirrors plays no role in the mode selection since all three modes have comparable reflectivity. This is also different from the case in the conventional LOC lasers in which the higher order modes, despite their lower confinement factors, may become dominant due to their higher modal reflectivities.

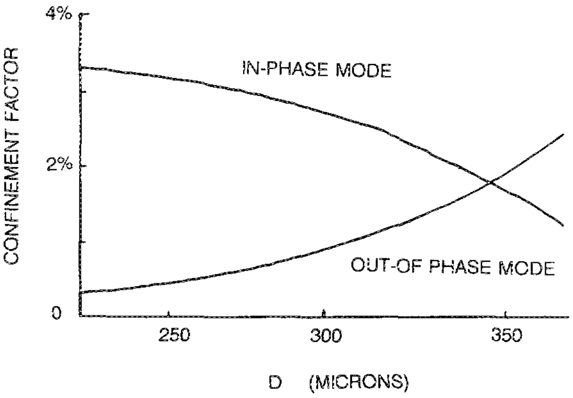

FIG. 3. Calculated confinement factors of the in-phase and out-of-phase modes as a function of the width of the valley of the passive waveguides.

The MOCVD-grown material was processed into conventional oxide stripe lasers 60 μm wide by 600 μm long which were mounted junction side up on copper heat sinks. Typical devices display room-temperature cw threshold currents of 230 mA and external efficiencies (uncoated) of 0.4 mW/mA. The threshold current is higher than that of the typical discrete GRINSCH SQW lasers due to the lower confinement factor. The characteristic temperature T_0 of the devices is 150 K at room temperature, lower than 180 K for the discrete single quantum well lasers. The lower T_0 is caused by the higher carrier losses that occur at higher carrier densities. The measured near- and far-field intensity distributions are shown in Fig. 4. The near-field measurement was carried out by using an oil immersion microscope objective with a numerical aperture of 1.3 giving rise to a resolution of 0.4 μm. With this resolution, three coupled-waveguide emitting elements are clearly resolved. The far-field pattern is single lobed exhibiting a full width at half maxima divergence of 19°, compared to 44° in the conventional GRINSCH SQW structure. The far field is stable to at least three times the threshold. We note that to reproduce the same beam divergence using a single-element GRINSCH SQW laser with a modified index profile, it would result in a

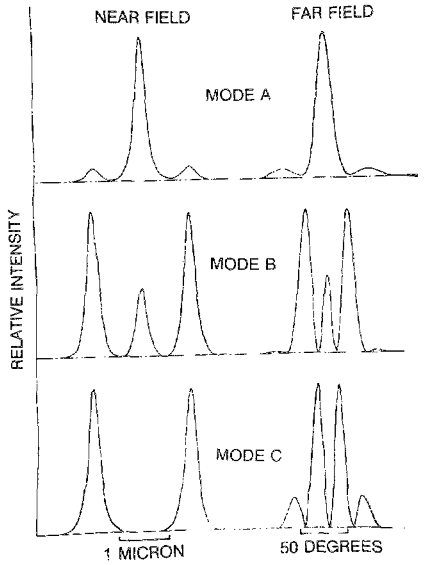

FIG. 2. Calculated near- and far-field patterns for the three eigenmodes of the coupled waveguides. The confinement factors in the wells are 2%, 0.67%, and 0 for modes A, B, and C, respectively.

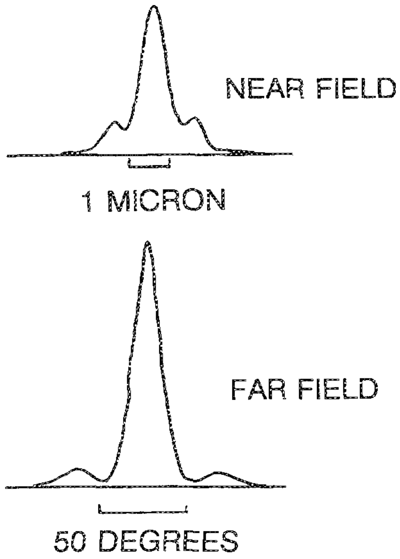

FIG. 4. Measured near- and far-field pattern perpendicular to the junction plane.

significant reduction in the confinement and a prohibitively high threshold current.

In summary, we have demonstrated the operation of a single quantum well laser with vertically integrated passive waveguides. The waveguide parameters for the in-phase mode operation are determined. The beam divergence as low as 19° has been achieved.

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