effective for the criterion of eqns. 3, |k_e - k_a| is nearly equal to |k_a - k_b|, the energies of the wave vectors of electrons diminished by k_a are therefore an effective criterion. They can be calculated by the relation \(|k^2/2m_e^* - \epsilon + a_1 + \epsilon_q| = \frac{a_1}{2} + \epsilon_q + \epsilon_q\) for the \(\Gamma\) valley, where \(m_e^*\) and \(\epsilon_q\) are the effective mass and nonparabolicity, respectively. Define an energy denoted by \(\epsilon_q(r, t)\). This is a mean energy averaged over the energies of the wave vectors substracted by \(k_a\) for all the \(\Gamma\) valley electrons. It can be given by the following expression:

\[
\epsilon_q(r, t) = \frac{\epsilon_q}{d^2/2m_e^*} \int_0^1 \frac{d\epsilon_q}{d\epsilon_q} \left( \epsilon, \epsilon / d \epsilon \right) d\epsilon \]

Using the approximation

\[
(1 + \frac{a_1}{2} + \epsilon_q + \epsilon_q) \epsilon_q = 1 \quad \frac{a_1}{2} + \epsilon_q + \epsilon_q
\]

eq k_a T_{\epsilon_q}(r, t)

eqns. 2 and 5 are rewritten as

\[
n_{\epsilon_q}(r, t) = A[T(\epsilon)T_{\epsilon_q}(r, t) + \frac{a_1}{2} + \epsilon_q + \epsilon_q]T_{\epsilon_q}(r, t)FN_{\epsilon_q}(r, t)
\]

where

\[
A = \frac{2m_e^*}{2m_e^* + \epsilon_q + \epsilon_q} \frac{(2\pi \hbar)}{2m_e^* + \epsilon_q + \epsilon_q}
\]

\[
y_\epsilon = \frac{\epsilon_q}{\epsilon_q}
\]

\[
y = \frac{\epsilon_q}{\epsilon_q} T_{\epsilon_q}(r, t)
\]

\(\Gamma\) is the Gamma function, and \(F_j\) is the Fermi-Dirac integral of order \(j\) defined by

\[
F_j(y) = \frac{y^j}{1 + \exp (y - \epsilon_q)}
\]

From eqns. 6a and b, an equation for \(y_\epsilon\) may be obtained namely \(\epsilon_q(r, t)\), which can be numerically solved. \(T_{\epsilon_q}(r, t)\) is calculated by eqn. 6b.

To show effectiveness of eqns. 6a and b, simulation results under a uniform electric field are presented. The carrier-carrier interaction is not taken into consideration for simplicity. In the figures the results are obtained for the carrier concentration of \(2 \times 10^{18} \text{cm}^{-3}\) and the electric fields of 2kV/cm and 7kV/cm at 300K. Fig. 2 shows the time responses of the mean velocity. Good agreement between the present method using eqn. 5 and the exact algorithm of Lugli and Ferry are observed. The previous method using eqn. 4 produces a larger mean velocity than the exact algorithm. There is not a large difference among the three methods for the mean energy. The electron distribution function, specified as a function of \(k_a\), which is the component of \(k\) along the electric field, has also been studied. It has been confirmed that the distribution function obtained by the present method agrees well with that obtained by the exact algorithm. The distribution function obtained by the previous method was, however, shifted by a small amount to the positive direction of \(k\), which corresponds to the larger mean velocity shown in Fig. 2. The present method is a better approximation than the previous one for a wide range of the carrier concentration. It may therefore be effective for device simulation.

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PERFORMANCE CHARACTERISTICS OF GaInAs/GaAs LARGE OPTICAL CAVITY QUANTUM WELL LASERS

Indexed terms: Semiconductor lasers, Fiber optics, Optical fibers

The fabrication and performance characteristics of ridge-waveguide GaInAs/GaAs quantum-well lasers with large optical cavity (QW) designs are reported. As expected, lasers with very large optical cavity have narrow far-field width (22°) perpendicular to the junction. However, due to small confinement factor, they also have higher threshold current (36 mA). The LOC design has been optimised to produce lasers with low threshold current (12 mA), high efficiency (0.35 mW/Wfacet) and narrow far field divergence (12°). These lasers operate in the fundamental transverse mode to output powers of 130 mW/facet.

Semicontact laser diodes emitting near 0.98 m fabricated using GaInAs/GaAs multi-quantum-well (MQW) structures are of considerable interest for pump lasers for erbium-doped glass fibre amplifiers. Thus, in addition to high power output, high fibre coupling efficiency is an important parameter for the design of these lasers. High fibre coupling efficiency requires narrow far field. We have used a large optical cavity design to reduce the far field (by a factor of 2) normal to the junction plane of these lasers. This Letter reports the fabrication and performance characteristics of a large optical cavity ridge-waveguide laser emitting near 0.98 µm.

The schematic cross-section of the GaInAs/GaAs/MQW ridge-waveguide laser is shown in Fig. 1. The active regions in these laser structures have one or many quantum wells with cladding layers of different composition around them. Three active region structures are shown in Fig. 1. They are grown by molecular beam epitaxy (MBE) growth technique on an n-GaAs substrate.

The MBE grown layers for Fig. 1a are (i) n-GaAs buffer layer, 0.5 µm thick, (ii) N-AlGaAs, GaAs cladding layer, 1.5 µm thick, (iii) N-AlGaAs, GaAs cladding layer, 400 Å thick, (iv) MQW active region with three 80 Å thick GaAs,AlInAs wells and three 400 Å thick GaAs,AlInAs barrier layers.

Fig. 2 Time responses of mean velocity under uniform electric fields

300K, 2kV/cm, 7kV/cm

- Lugli and Ferry
- proposed method
- Fischetti and Laux

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four 60 Å thick GaAs barrier wells, (v) P-Al$_{1-x}$Ga$_x$As layer, 400 Å thick, (vi) P-Al$_{0.4}$Ga$_{0.6}$As cladding layer 2.6 µm thick, and (vii) P-GaAs contact layer, 0-1 µm thick. The Al$_{0.15}$Ga$_{0.85}$As layers on either side of the MQW GaInAs active region are needed to form the large optical cavity. The different structures of active regions in Figs. 1b and c are self-explanatory.

![Diagram of ridge-waveguide laser](image)

**Fig. 1** Schema of ridge-waveguide laser, showing the three active-layer designs

After growth, 5 µm wide mesas are etched on the wafer using a photoreist etching mask and wet chemical etching. The mesas are oriented along the (110) direction. The wafer is then processed using standard dielectric deposition and metallisation techniques to produce 500 µm long laser chips.

The intensity profile of the fundamental mode can be calculated by solving the wave equation for the three structures shown in Fig. 1. The calculated full width at half maximum values for the three structures shown in Fig. 1 are 0.94 µm, 1.7 µm and 0.57 µm, respectively. The calculated mode profiles are shown in Fig. 2.

![Mode profiles](image)

**Fig. 2** Calculated field intensity distribution normal to junction plane for three designs of Fig. 1

The far field of a laser normal to the junction plane can be obtained from the intensity distribution of the propagating mode. For a Gaussian intensity profile of the form $e^{-2y^2}$ for the propagating mode, the full width at half maximum (FWHM) of the far field is approximately given by

$$
\theta = 2 \sin^{-1}(0.222/\theta_0)
$$

(1)

The $\theta_0$ values are obtained by equating the FWHM obtained from Fig. 2 to that of a Gaussian distribution. The calculated $\theta_0$ values, using eqn. 1 and calculated $\theta_0$ values, are 44°, 24° and 77° for Figs. 1a, b and c, respectively. The measured values for our devices are somewhat smaller, are discussed later. Note that the field intensity for the structure of Fig. 1b is significantly more spread out and can reach the contact metallisation, causing some absorption and therefore higher threshold and lower differential quantum efficiency unless the cladding layer is very thick.

The light/current characterisation of ridge-waveguide lasers fabricated using the three active layer designs of Fig. 1 is shown in Fig. 3. The designs a, b and c have threshold currents of 12, 36 and 16 mA, respectively. The carrier spreading was estimated to be ~10 µm from the measurement of spontaneous emission. Hence a threshold current of 12 mA corresponds to a threshold current density of 240 A/cm$^2$. The external differential quantum efficiencies of designs a and c are comparable and are higher than that for b. The threshold currents for the designs a and c are similar. However, that for b is significantly larger. This may be due to small mode confinement for b compared with that for a and c. The mode confinement factor for b can be increased (by about a factor of 3) using three GaInAs quantum wells for the active region. This would increase the transparency current density by a factor of 3. But since the relationship of gain to current density is sublinear, the net effect may result in lower threshold than that shown in Fig. 3b. The absence of a kink in the plot of $dL/dI$ against I indicates no change in transverse mode pattern.

The measured intensity distribution of the far field along and normal to the junction plane is shown in Fig. 4 for the three designs. The far field along the junction plane for the three designs is similar (FWHM ~ 12°) because it is primarily determined by the weak index guiding provided by the ridge. However, normal to the junction plane the far-field widths vary significantly. The design 1c has the largest far-field width (FWHM ~ 68°) and design 1a has a FWHM far field width of 32° normal to the junction plane. The narrow far-field width is important for high fibre coupling efficiency. The light/current characteristics of design a at high currents are shown in Fig. 5.
In summary, we have optimised the design for a GaAs/ 
GaAs multi-quantum-well laser emitting near 0.98 μm. Lasers 
with large optical cavity have narrow far-field width perpen-
dicular to the junction plane. The optimised design has 
narrow far-field width (32° x 12°), low threshold current 
(12 mA) and high efficiency (0.45 mW/mA/facet). The lasers 
emit in a fundamental transverse mode to output powers of

![Fig. 4 Measured far-field intensity profile along and normal to junction plane for three laser designs of Fig. 1](image)

130 mW/facet. With a high reflectivity coating (> 95%) at the 
back facet and a low reflectivity coating (~ 5%) on the front 
facet, the output power can be increased by almost a factor of 
two.

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EFFICIENT, NARROWBAND LP_{01} → LP_{02} 
MODE CONVERTERS FABRICATED IN 
PHOTOSENSITIVE FIBRE: SPECTRAL 
RESPONSE

Indexing terms: Converters, Optical fibres

LP_{01} → LP_{02} mode converters have been fabricated by pho-
toinducing index gratings within the fibre core by means of 
internally or externally applied light fields. The mode conver-
tors have conversion efficiencies of over 75% and simple 
spectral response curves with one or two peaks. The mode 
conversion linewidths range from 0.2 to 10 nm.

Introduction: A promising approach for fabricating fibre mode 
converters is to create a periodic index grating in the cladding 
of an optical fibre using the fibre's photosensitive properties. 1 
Mode converter gratings fabricated using fibre photo-
sensitivity have been demonstrated in a special two-mode 
eliptical core optical fibre. 2 In this case, high power 514.5 nm 
CW Ar-ion laser light is launched into the two modes of the 
fibre to produce a two-mode interference pattern that pho-
toinduces an index grating of the correct period and cross-
sectional shape. Since the writing light is guided within the 
fibre core, the procedure is referred to as the internal writing 
technique.

A drawback of the external writing technique is that mode 
converters cannot be designed to operate at preselected wave-
lengths that are relevant to optical fibre communication 
systems. This drawback has been overcome by using an exter-
nal writing technique. 3 In this method, each element of the 
index grating is written point-by-point by photoinducing with 
ultraviolet light (249 nm) a small index perturbation in the 
fibre core. The technique is called external writing because the 
writing light irradiates the optical fibre from the side. Refer-
ence 3 reports the fabrication of an LP_{01} → LP_{02} mode 
converter operating in the 600 to 900 nm wavelength region. 
Efficient intermodal coupling requires not only a grating of 
the correct period but also that the individual index perturba-
tions be blazed. 2 That is, the interface plane between per-
turbed and unperturbed index regions is tilted (blazed) at 
about 2 degrees to the optical fibre axis. The internal writing 
technique has the advantage that mode converters can be 
fabricated in standard optical fibre and operated at wave-
lengths appropriate to optical communication systems.

The externally written LP_{01} → LP_{02} mode converters have 
however, a complicated multiwavelength spectral response. 
The single peak is a result of the LP_{01} approximate mode 
corresponding to four true modes in a fibre, i.e. the fibre is not 
really bimodal. In the fabrication of practical two-mode 
ofibres, the mode converter operates in a narrow bandwidth of 
around a single wavelength. Single peak spectral responses 
require two-mode fibres in which the higher order mode has only 
one mode constituent. This may be accomplished by using 
a special two-mode fibre as described in Reference 2 or by writing 
gratings that couple the LP_{01} to the LP_{02} mode whose 
according two true 
mode 
degenerate. The purpose of the paper is to report 
the fabrication of LP_{01} → LP_{02} mode converters using both 
the internal and external writing techniques.

Internal writing: Fig. 1 shows the experimental configuration 
for fabricating the mode converter grating. Light (488 nm) 
from an Ar-ion laser operating in a single longitudinal mode 
is launched into a fibre (normalised frequency v = 6.35) and 
passed through a mode filter to leave only the LP_{01} mode in

![Fig. 1 Schematic diagram of experimental arrangement used to write mode converter gratings using the internal writing technique](image)