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mise the transit time, reference to Figs. 3*a* and *b* shows that, for a channel length greater than $\simeq 0\cdot4\,\mu$m, the transit time is shorter in InP than GaAs; the converse is marginally true for channel lengths less than $0\cdot4\,\mu$m. For this particular channel length, the corresponding f_T, given by $(2\pi \times \text{transit time})^{-1}$, is 114 GHz. The recent results of Maloney and Frey[4] do not show this behaviour, with InP always having a higher f_T than GaAs for a given channel length. Moreover,

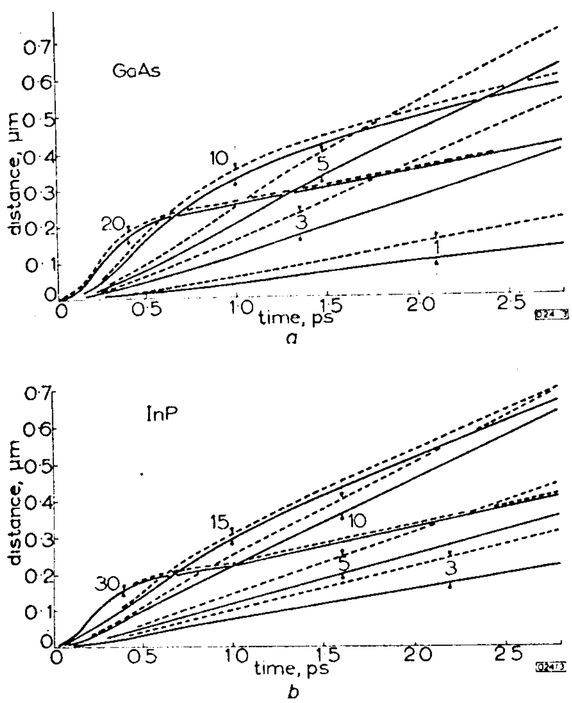

Fig. 3 *Variation of drift distance with time*
a GaAs
b InP
——— $N_D = 10^{17}$ cm^{-3}, - - - - $N_D = 0$
Fields in kV/cm

their cut-off frequencies are also significantly lower than the values we calculate, 50 GHz compared with 114 GHz for a $0\cdot4\,\mu$m-long channel GaAs f.e.t. being one example. The reason for this discrepancy is because they assume that the channel field E is limited by the inequality $2\text{ V} \leqslant EL \leqslant 7\text{ V}$, where L is the channel length, as recently pointed out by Shur.[7] There is, however, no reason *a priori* why the source-drain voltage should not be less than 2 V in very-short-gate devices.

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References

1 RUCH, J. G.: 'Electron dynamics in short channel field effect transistors', *IEEE Trans.*, 1972, **ED-19**, pp. 652–654
2 MALONEY, T. J., and FREY, J.: 'Electron dynamics in short-channel InP field effect transistors', *Electron. Lett.*, 1974, **10**, pp. 115–116
3 MALONEY, T. J., and FREY, J.: 'Frequency limits of GaAs and InP field effect transistors', *IEEE Trans.*, 1975, **ED-22**, pp. 357–358
4 MALONEY, T. J., and FREY, J.: 'Frequency limits of GaAs and InP field effect transistors at 300K and 77K with typical active layer doping', *ibid.*, 1976, **ED-23**, p. 519
5 FAWCETT, W., and HERBERT, D. C.: 'High field transport in gallium arsenide and indium phosphide', *J. Phys. C.*, 1974, **7**, pp. 1641–1653
6 RUCH, J., and FAWCETT, W.: 'Temperature dependence of the transport properties of GaAs determined by a Monte Carlo method', *J. Appl. Phys.*, 1970, **41**, pp. 3843–3850
7 SHUR, M.: 'Influence of nonuniform field distribution on frequency limits of GaAs field-effect transistors', *Electron. Lett.*, 1976, **12**, pp. 615–616

LONGITUDINAL FIELD CONTROL IN STRIPE-GEOMETRY LASERS

Indexing term: Semiconductor junction lasers

The theory of optical confinement by a gain-guiding mechanism in stripe-geometry lasers has been extended to include the effects of longitudinal inhomogeneity of the optical field and the gain coefficient. A proposal is made for utilising these effects to improve field control and efficiency in lasers with a.r.-coated facets.

In the injection laser, a stripe geometry[1] is usually employed to define the active width and provide a reasonably uniform lasing region. There is now evidence, at least for narrow stripes, that confinement of the lasing emission to the region of the stripe occurs primarily via a gain-induced guiding mechanism[2,3] although in larger stripe widths a real index guidance may also occur.[4] Conventional theories of these effects[2–4] assume a uniform distribution of gain and loss along the cavity length, allowing variations only in the transverse directions. Although this is a reasonable approximation for the facet reflectivity corresponding to a GaAs–air interface (0·32), it becomes progressively worse for lower reflectivities. This is because the photon field distribution along the cavity becomes less uniform for decreasing mirror reflectivities,[5–7] and this produces corresponding changes in the gain distribution. In view of the interest in the use of antireflecting coatings on the mirrors to inhibit catastrophic degradation[8] and possibly assist in long-term reliability,[9] we present here an extension of the gain-guiding theory[2,3] to include longitudinal inhomogeneity of optical field and gain. In addition, a suggestion is made for achieving longitudinal field control at low reflectivities by the use of specially-shaped stripe geometry.

To illustrate the extension of the theory, we consider here the case of gain-guiding only; the corresponding extensions to the case of real index antiguiding[3] or guiding[4] should be obvious. We shall ignore the effect of stimulated emission on the transverse gain profile, since this assumption has been shown to be reasonable for narrow stripes ($\sim 10\,\mu$m) by the analysis of Hakki.[10] Hence we consider a dielectric profile $\varepsilon(x, z)$ of the form

$$\varepsilon(x,z) = \varepsilon_0(z) - 2ia^2(z)x^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where z denotes the direction along the cavity length, x is the transverse direction in the junction plane and $x = 0$ occurs at the centre of the stripe. The origin of the z-axis is taken at the cavity symmetry point, where the amplitudes of forward and backward travelling waves are the same. $\varepsilon_0(z)$ is the relative permittivity at $x = 0$, and is given, in the notation of Cook and Nash,[3] by

$$\varepsilon_0(z) = n_e^2 + \frac{in_e}{k} g_p(z) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where k is the wave number in free space, $g_p(z)$ is the gain per unit length at $x = 0$ and n_e is an effective refractive index[11] determined by the waveguide provided by the heterostructure layers perpendicular to the junction plane. The real parameter $a(z)$ appearing in eqn. 1 is given by

$$a^2(z) = \frac{n_e}{2k}\left(\frac{2}{S}\right)^2 (g_p(z) + \alpha) \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where S is the stripe width and α the loss at the stripe edges.[3]

To relate the gain $g_p(z)$ to the electric field $E(x, z)$, the usual equilibrium rate equations[12] at $x = 0$ may be used. If we consider (for simplicity) only the situation far above threshold, and include both forward and backward travelling waves, we find

$$g_p(z)\left(|E(0,z)|^2 + |E(0,-z)|^2\right) = \frac{jn_e}{edc} \quad . \quad . \quad . \quad (4)$$

where j is the current density (assumed uniform), d is the active-layer thickness and the other symbols have their usual meaning. At threshold and above, the modal gain is determined from the photon rate equation[12]

$$\int (g_p(z) - a(z)/n_e)dz = \ln(1/R_1 R_2) \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where the integral is over one round trip of the cavity and R_1, R_2 are the facet reflectivities.

In addition to eqns. 4 and 5, a further relation between the unknowns $E(x,z)$ and $g_p(z)$ is furnished by the scalar wave equation with relative permittivity given by eqn. 1.

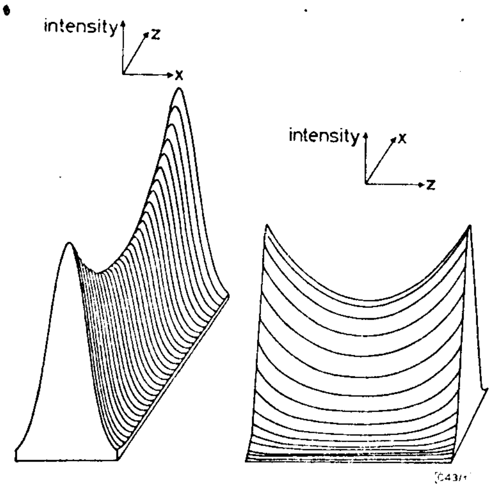

Fig. 1 *Front and side views of calculated power distribution for a 10 μm stripe-geometry GaAs d.h. laser*

Facet reflectivities 0·1, cavity length 500 μm, loss $\alpha = 10\ \mathrm{cm}^{-1}$

Although a completely self-consistent solution of these equations would require lengthy numerical computation, a reasonable 1st-order approximation may be achieved by an iteration technique commencing with the known solution[2,3] for $E(x,z)$ obtained by ignoring the z-dependence of ε and g_p in the equations. Inserting this result in eqn. 4 yields, for a cavity length L,

$$g_p(z) = \frac{g_p(0)}{\cosh\left[\dfrac{z}{2L}\ln(1/R_1 R_2)\right]} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

whence the threshold equation (eqn. 5) may be solved for $g_p(0)$. Eqn. 6 provides a 1st-order approximation for the dielectric distribution $\varepsilon(x,z)$ via eqns. 1–3. Hence we seek solutions of the wave equation with the resultant expression for $\varepsilon(x,z)$. Following Kogelnik,[13] we write

$$E(x,z) = \exp[-i\phi(z) - i(P(z) + Q(z)x^2/2)] \quad . \quad . \quad (7)$$

where $\phi'(z) = k(\varepsilon_0(z))^{\frac{1}{2}}$ and $P(z)$, $Q(z)$ are complex beam parameters. The resulting equation for $Q(z)$ is[13]

$$Q^2(z) + k(\varepsilon_0(z))^{\frac{1}{2}}\,Q'(z) + 2ik^2 a^2(z) = 0 \quad . \quad . \quad . \quad (8)$$

where $\varepsilon_0(z)$ and $a(z)$ are given by eqns. 2 and 3, together with eqn. 6. Solution of eqn. 8 is effected most simply by a series in ascending powers of z with complex coefficients. Similarly, the complex phase $P(z)$ may be obtained as a series from the relation given in Kogelnik's paper.[13]

Solutions for the case $R_1 = R_2 = 0{\cdot}1$ are given in the form of 3-dimensional intensity plots in Fig. 1. These results illustrate the main features of gain-guided fields in laser cavities with low facet reflectivities. As expected from simple physical considerations, the fields are best confined in the lateral direction near the centre of the cavity and spread to their maximum breadth at the mirrors. We may draw the following conclusions for stripe-geometry lasers, especially those with a.r.-coated facets:

(*a*) In the situation considered here, where the guiding action is accomplished by the variation of gain and loss across the stripe, the fields are spread at the facets, hence giving a lower power density, which may assist in inhibiting both catastrophic and long-term degradation.

(*b*) In the opposite situation of real index guidance produced either by dips in the carrier concentration (spatial hole burning)[4,10] or by a particular fabrication process,[14] the behaviour will be reversed in that the fields will be strongly focused at the facets; detailed calculations not presented here support this. An analogous situation may exist in the direction normal to the junction planes in single heterostructure lasers.

(*c*) Experiments designed to study guidance mechanisms in a.r.-coated lasers[3] should be interpreted with caution.

In conclusion, we note that the field distributions of Fig. 1 do not make the most efficient use of the available gain which could be provided by the stripe geometry. A more optimal distribution could, however, be achieved by a measure of longitudinal field control. For this, it is merely necessary to provide shaped stripe contacts, as opposed to the conventional rectangular stripes. For example, to encourage a field distribution with constant beam width, it follows from eqns. 3, 6 and 8 with $Q'(z) = 0$ that the required variation of stripe width $S(z)$ should be

$$\frac{S^2(z)}{S^2(0)} = \left[\frac{g_p(0)}{\cosh\left[\dfrac{z}{2L}\ln(1/R_1 R_2)\right]} + \alpha\right][g_p(0)+\alpha]^{-1} \quad . \quad . \quad . \quad (9)$$

where $g_p(0)$ may be found from eqns. 5 and 6. Provided the guidance mechanism is well established and likely values for α determined, the fabrication of such a stripe, e.g. by photolithographic techniques, should present no special technological problems.

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References

1 D'ASARO, L. A.: 'Advances in GaAs junction lasers with stripe geometry', *J. Luminescence*, 1973, **7**, pp. 310–337
2 NASH, F. R.: 'Mode guidance parallel to the junction plane of double-heterostructure GaAs lasers', *J. Appl. Phys.*, 1973, **44**, pp. 4696–4707
3 COOK, D. D., and NASH, F. R.: 'Gain-induced guiding and astigmatic output beam of GaAs lasers', *J. Appl. Phys.*, 1975, **46**, pp. 1660–1672
4 GOODWIN, A. R., KIRKBY, P., and THOMPSON, G. H. B.: 'The effect of stripe width on the optical gain-guiding properties of oxide-insulated stripe-geometry lasers'. Presented at IEEE international semiconductor laser conference, Nemu-no Sato, Japan, 1976, Paper L-II-4
5 NANNICHI, Y.: 'Variation of the gain factor of GaAs lasers with photon and current densities', *J. Appl. Phys.*, 1966, **37**, pp. 30091–3012
6 ULBRICH, R., and PILKUHN, M. H.: 'Influence of reflectivity on the external quantum efficiency of GaAs injection lasers', *IEEE J. Quantum Electron.*, 1970, QE-6, pp. 314–316
7 GOOCH, C. H.: 'Theory of high-power operation of GaAs lasers'. Proceedings of international symposium on GaAs (Institute of Physics, 1966), pp. 62–67
8 ETTENBERG, M., SOMMERS, JUN., H. S., KRESSEL, H., and LOCKWOOD, H. F.: 'Control of facet damage in GaAs laser diodes', *Appl. Phys. Lett.*, 1971, **18**, pp. 571–573
9 KRESSEL, H., and LADANY, I.: 'Reliability aspects and facet damage in high-power emission from (AlGa)As CW laser diodes at room temperature', *RCA Rev.*, 1975, **36**, pp. 230–239
10 HAKKI, B. W.: 'GaAs double heterostructure lasing behaviour along the junction plane', *J. Appl. Phys.*, 1975, **46**, pp. 292–302
11 KNOX, R. M., and TOULIOS, P. P.: 'Integrated circuits for the millimeter through optical frequency range'. Proceedings of symposium on submillimeter waves (FOX, J., Ed.) (Polytechnic Press, Brooklyn, NY, 1970), pp. 497–516
12 CARROLL, J. E., ELDON, S. G., and THOMPSON, G. H. B.: 'Incremental efficiency enhancement and r.f. response of GaAs-GaAlAs double heterostructure stripe lasers', *Electron. Lett.*, 1976, **21**, pp. 564–565
13 KOGELNIK, H.: 'On the propagation of Gaussian beams of light through lenslike media including those with a loss or gain variation', *Appl. Opt.*, 1965, **4**, pp. 1562–1569
14 YONEZU, H., MATSUMOTO, Y., SHINOHARA, T., SAKUMA, I., SUZUKI, T., KOBAYASHI, H., LANG, R., and HAYASHI, I.: 'High quality lasing characteristics by horizontal mode stabilization with a built-in refractive index profile'. Presented at the IEEE international semiconductor laser conference, Nemu-no Sato, Japan, 1976, Paper L-II-8