or

$$p(t) = 2\pi cr \int_0^t \exp(-ct'/r) f(t - t')\, dt' \qquad (14)$$

which show, in principle, that the magnetic field waveform observed at a distance r can be 'inverted' to give the source dipole moment $p(t)$ as a function of time.

To deal with the electric field case we employ eqn. 9 to yield

$$P(s) = 2\pi r\varepsilon_0 c^2 sG(s)/[s^2 + sc/r + (c/r)^2] \qquad (15)$$

Using a little algebra we note that

$$\frac{s}{s^2 + sc/r + (c/r)^2} = \frac{s}{(s + a)(s + b)} = \frac{a}{a - b}\frac{1}{s + a} + \frac{b}{b - a}\frac{1}{s + b} \qquad (16)$$

where

$$a = (1 + j3^{1/2})c/2r$$

and

$$b = (1 - j3^{1/2})c/2r$$

The transform is evaluated to give

$$L^{-1}\frac{s}{s^2 + sc/r + (c/r)^2} = q(t)u(t) \qquad (17)$$

where

$$q(t) = \exp(-ct/2r) \times [\cos(3^{1/2}ct/2r) - 3^{-1/2}\sin(3^{1/2}ct/2r)] \qquad (18)$$

has the form of a damped sinusoid.

Now an application of the convolution theorem to eqn. 15 gives

$$p(t) = 2\pi r\varepsilon_0 c^2 \int_0^t q(t - t')g(t')\, dt' \qquad (19)$$

which has a form similar to eqn. 13. Of course eqns. 13 and 19 should both yield the same results for $p(t)$.

Practical implementation of the inversion scheme would seem to be well worth while. We are currently investigating a more realistic propagation model which, unfortunately, leads to inelegant convolution integrals.

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HIGH EFFICIENCY SURFACE-EMITTING DISTRIBUTED BRAGG REFLECTOR LASER ARRAY

Indexing terms: Lasers and laser applications, Semiconductor lasers, Integrated optics

A surface-emitting distributed Bragg reflector laser array with three stripes were fabricated. The external differential quantum efficiency was 32% and the maximum output power was 500 mW.

There has been considerable interest in surface-emitting laser diodes, because they are potentially very important for one- and two-dimensional monolithic laser arrays. There are several approaches to the realisation of surface-emitting lasers, such as the vertical resonator cavity,[1,2] 45° mirror,[3] parabolic mirror,[4] and the grating-coupler.[5–9] Among these, grating-coupled lasers have the advantages of a narrow beam divergence and dynamic single mode operation. Although the quantum efficiencies of grating-coupled lasers were very low, there has been considerable progress recently in various aspects. Continuous wave operation in a distributed Bragg reflector (DBR) laser[7] and a distributed feedback (DFB) laser[8] were reported with differential quantum efficiencies of 9% and 8% respectively, and a differential quantum efficiency of 20% was obtained in a DBR laser under pulsed conditions.[9] Since grating-coupled surface-emitting lasers do not require cleaved facets, the ultimate maximum output power will be limited by internal heating, and very high output power is expected with one- and two-dimensional laser arrays. In this letter, we report a three-stripe surface-emitting multiquantum well (MQW) DBR laser array with a very high differential quantum efficiency of 32% and a high output power of 500 mW.

Fig. 1 shows the schematic diagram of a surface-emitting MQW-DBR laser array. The wafer consists of an n-GaAs buffer layer (0·2 μm), an n-$Al_{0.6}Ga_{0.4}As$ cladding layer (1·3 μm), an n-$Al_{0.2}Ga_{0.8}As$ guiding layer (0·25 μm), an undoped MQW layer (three 10 nm-thick GaAs well layers and two 5 nm-thick $Al_{0.2}Ga_{0.8}As$ barrier layers), a p-$Al_{0.2}Ga_{0.8}As$ guiding layer (0·15 μm), a p-$Al_{0.6}Ga_{0.4}As$ cladding layer (1·3 μm), and a p-GaAs contact layer (0·5 μm) on an n-GaAs substrate by molecular beam epitaxy. The main difference from previous work on a single stripe MQW-DBR laser[7] is that n- and p-guiding layers were introduced to form the separate confinement structure, and that the number of well layers was reduced from five to three. The optical power is mainly confined in the guiding layers, and the modal absorption loss in the unpumped MQW layer in the DBR section reduced. Moreover, the guiding layers increase the coupling efficiency between the active and the DBR sections, since the vertical electric field distribution is less affected even though the p-guiding layer is deeply etched. The residual thickness of the p-guiding layer before grating formation was 0·05–0·1 μm, which is thinner than in the previous work and increases the diffraction efficiency. The stripes were formed by etching the p-guiding layer by about 0·05 μm. One chip consists of three stripes, and both the width and the separation of each stripe were 4 μm. The length of the DBR section, the active section, and the window section were 300, 300, and 17 μm, respectively. The window section was introduced to increase the catastrophic optical damage level. The facet of the window

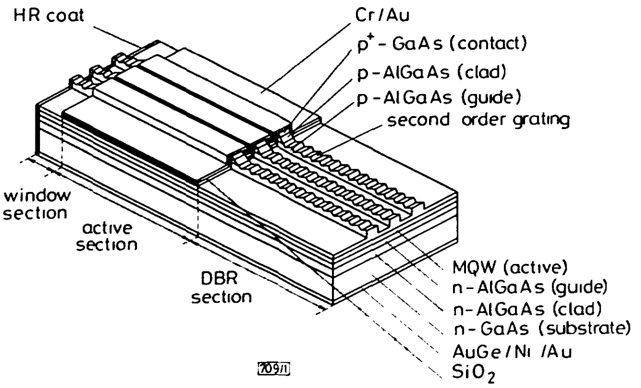

Fig. 1 *Schematic diagram of a surface-emitting MQW-DBR laser array*

section was high reflection coated (86%) to increase the surface-emitting output, while the DBR section facet was scratched to suppress Fabry–Perot modes.

Fig. 2 shows the surface-emitting power/current characteristics at room temperature. The pulse width was 100 ns and the repetition frequency was 100 kHz, so the duty ratio was 1%. The threshold current was 105 mA and the maximum output power was 500 mW. The maximum differential quantum efficiency was as high as 32%, and the total quantum efficiency was 25%. This very high quantum efficiency is probably due to the introduction of the guiding layers and the reduction of the *p*-guiding layer thickness. The lasing wavelength was about 879 nm, and two or three modes were usually observed. The beam divergence in the direction normal to the grating lines was about 0·2°, although the beam pattern was slightly deformed when a multimode oscillation occurred.

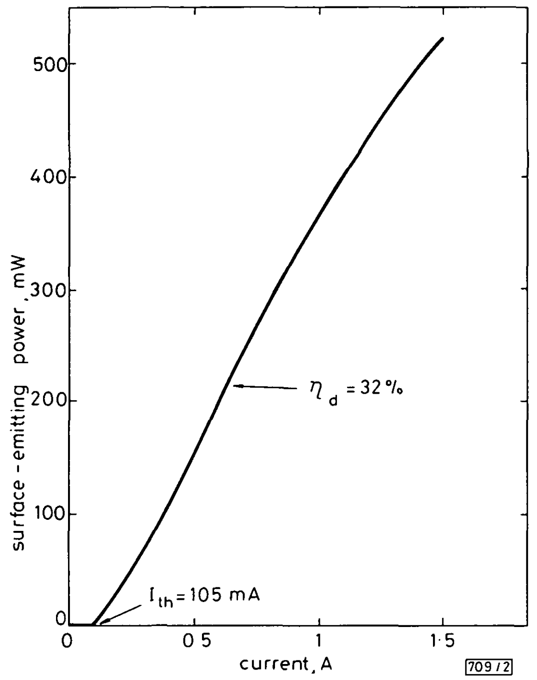

Fig. 2 *Current against surface-emitting power at room temperature*

In these laser arrays, phase locking has not been observed, and the measured beam divergence in the direction parallel to the grating lines was 18°. However, phase-locked operation with narrower beam divergence will be possible by increasing the optical coupling between the elements.

To conclude, we fabricated a surface-emitting MQW-DBR laser array with three stripes. The threshold current was 105 mA, and the maximum differential quantum efficiency and the output power were 32% and 500 mW, respectively. This shows that grating-coupled surface-emitting lasers offer great potential for high power laser arrays with narrow beam divergence.

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FABRICATION OF TAPERED COUPLERS IN GaAs/GaAlAs RIB WAVEGUIDES

Indexing terms: Optical connectors and couplers, Optical fibres, Integrated optics

Tapered couplers have been fabricated in GaAs/GaAlAs single-mode rib waveguides. A new etching technique has been used to fabricate transitions of 1 μm over lengths of approximately 160 to 300 μm. Losses for the TE and TM fundamental modes have been measured at a wavelength of 1·3 μm.

Introduction: There is a need for coupling efficiently from single mode optical fibres to thin guiding layer GaAs rib waveguides. High coupling efficiencies may be obtained with relatively thick guiding layers. However, for rib waveguide optical phase modulators it is desirable to have a thinner guiding layer so that the required drive voltage is reduced. To optimise both insertion loss and the required drive voltage properties, tapered transitions have been studied. By fabricating a tapered coupler, the design of an optical modulator may be improved in terms of the future to-device coupling efficiency without increasing the required drive voltage.

Fabrication: The material structure used for preliminary evaluation of the taper fabrication technique is shown in Fig. 1. The tapered coupler was fabricated by first depositing a tapered titanium film on the GaAs substrate using a novel shadow masking technique. An electron beam evaporation

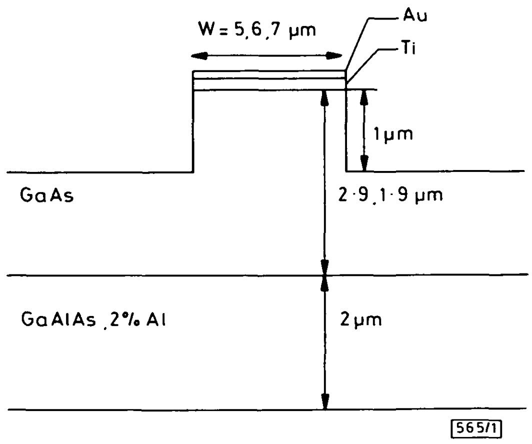

Fig. 1 *Material structure*

2·9 μm guiding layer before taper, 1·9 μm guiding layer after taper