an SiO_2 layer only 700 Å thick. With the fact, we have made a passive polariser with $\sim 1{\cdot}5$ dB fibre-waveguide-fibre insertion loss and > 13 dB extinction ratio.

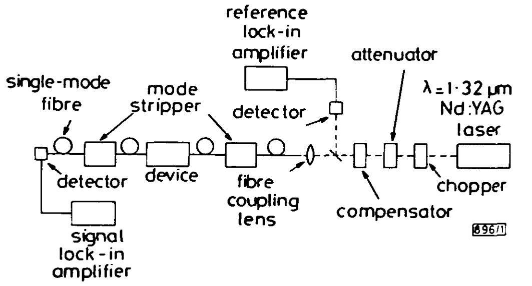

Fig. 1

Waveguides of various strip widths were fabricated by diffusing 800 Å-thick thermally evaporated titanium metal strips into a Z-cut, Y-propagating $LiNbO_3$ crystal at 1050°C for 9 h in an H_2O-rich atmosphere. These conditions are sufficient for low propagation loss and good mode match[2] to the single-mode fibre used in the experiment. The total fibre-waveguide-fibre insertion loss with no buffer layer or metallic overlay, measured with the apparatus shown schematically in Fig. 2,

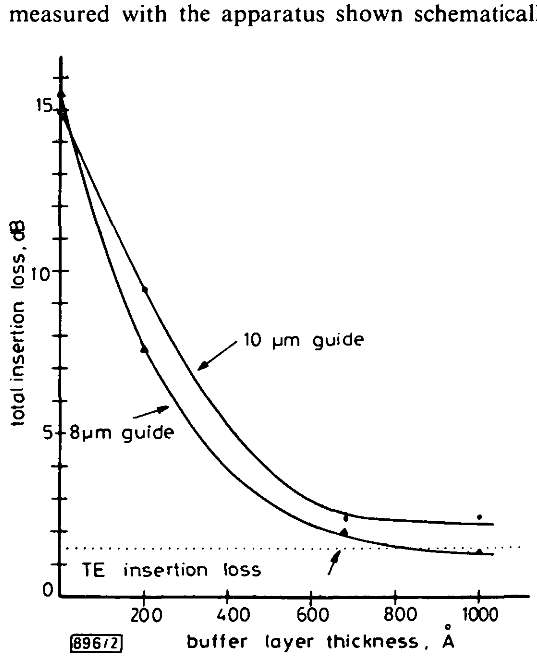

Fig. 2 *TM insertion loss against buffer-layer thickness*

was $-1{\cdot}5$ dB and $-2{\cdot}5$ dB for the TE and TM modes, respectively.

Then the loss by electrode without an intermediate buffer layer was measured. A 1 cm-long, 1000 Å-thick CrAl patch, a typical thickness used in electrode fabrication, was evaporated over the waveguides. The total insertion loss was measured and found to be $-1{\cdot}5$ dB for the TE polarisation and -15 dB for the TM polarisation for the 8 μm and 10 μm waveguides.

Finally, the insertion loss for this sample with the above electrode and several values of SiO_2 thickness were measured. The buffer layers were deposited in a CVD Silox Reactor*[,3] at $T = 460$°C using SiH_4 (3% in N_2), O_2 and N_2 dilutant. The deposition rate was ~ 170 Å/min. The SiO_2 layer, under visual inspection, appears uniform over the $0{\cdot}75$ cm × 3 cm area used in the experiment. After each measurement, the aluminium electrode was removed using a $KMnO_4$/NaOH etch and the buffer layer removed using a 5% solution of HF in deionised H_2O before depositing a new buffer layer and electrode. Repolishing of the ends of the substrate was not necessary. Fig. 2 shows the results of these measurements. As shown, the excess loss introduced by the electrode decreases as SiO_2 buffer layer thickness increases and is essentially eliminated for thicknesses greater than ~ 700 Å. Further increase in the thickness of the SiO_2 layer yields only minimal changes in the loss. These measurements show that typical SiO_2 buffer layers[4] are thicker than required. The 1 dB difference in loss between the unloaded, no buffer layer and the 700 Å buffer-layer loss measurements for the TM mode is of the order of, but slightly higher than, our experimental uncertainty. It may be that the buffer-layer-clad waveguides are slightly lower-loss than the air-clad waveguides, but more measurements will have to be made to support this conclusion.

It is interesting to note that the total insertion loss of 1·5 dB for the TE mode was not affected by the presence of the metal electrode. Consequently we have demonstrated with a simple, 1 cm metallic overlay a passive polariser with a total fibre-coupled insertion loss of 1·5 dB and extinction ratio > 13 dB. Although this extinction ratio is acceptable for most cases, the polarising effect may perhaps be accentuated by resonant effects as seen in GaAs.[5]

Because of its higher conductivity and lower electrical losses than aluminium, gold electrodes are important for very-high-speed modulators.[6] For the same waveguides, a 1000 Å-thick SiO_2 buffer layer was required to eliminate the loss to the TM polarisation introduced by a gold overlay. Again the TE loss was essentially unaffected by the metallic overlay.

In conclusion, we have performed an experimental investigation of the excess loss of metal and SiO_2-clad Ti:$LiNbO_3$ waveguides. Under low-loss diffusion conditions for operation at $\lambda = 1{\cdot}32$ μm, to eliminate the electrode loss a minimum buffer layer thickness of 700 Å and 1000 Å is required for aluminium and gold electrodes, respectively. A low-loss passive polariser has been demonstrated with a total fibre coupled insertion loss of 1·5 dB and an extinction ratio of > 13 dB.

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FAR-FIELD DISTRIBUTIONS OF SEMICONDUCTOR PHASE-LOCKED ARRAYS WITH MULTIPLE CONTACTS

Indexing terms: Lasers and applications, Semiconductor lasers

Experimental results of far-field patterns of semiconductor laser arrays with multiple contacts are reported. It is found that, by tailoring the distribution of the currents through the array elements, narrow single-lobe patterns—which are more useful in most applications—can be obtained from arrays that usually operate in a double-lobe mode. A diffraction-limited 1·8°-wide far-field pattern was obtained from a three-element array.

Phase-locked interactions among semiconductor laser diodes fabricated on the same substrate in close proximity to each other have been investigated recently by several research groups.[1-9] Besides the prospect of obtaining higher power levels, one of the important parameters of the arrays is their far-field pattern in the junction plane. This pattern consists of peaks with an angular separation inversely proportional to the spatial separation of the array elements and whose widths are inversely proportional to the overall width of the array. The envelope of these peaks has the shape of the far-field pattern of a single element of the array. The phase between two adjacent phase-locked lasers determines the relative positions of the peaks with respect to the forward direction (i.e. 0°). When all the lasers operate in phase, the far-field will usually have a main lobe in the forward direction, which is useful for most applications. However, when adjacent lasers operate in antiphase, as is theoretically favoured and practically obtained in most cases,[4-6,9] the far field will have the characteristic double-lobe pattern, which is a disadvantage in some applications (for example, optical recording, optical communications etc.). Clearly, a control on the near-field distribution of the array and on the mutual interaction between the array elements may help ensure the desirable far-field distribution.

In all the monolithic arrays demonstrated to date, all the diodes were connected in parallel, i.e. a common contact was applied to all of them. Thus virtually no control can be exercised over their operational characteristics. Recently, we have demonstrated the operation of a monolithic phase-locked laser array where a two-level metallisation technology is used to obtain a separate contact to each of the 9 μm-spaced elements of the array. The isolation between the lasers was obtained by proton-implantation, and the isolation between the two metallisation levels was achieved with an SiO_2 film. More details on the configuration and fabrication procedure are given in Reference 10.

In this letter we report on the results of far-field measurements conducted on groups of elements of this array. Figs. 1*a* and *b* show the near-field pattern near threshold and at the operational current level, respectively, of a group of three adjacent lasers. It should be noted that, owing to nonuniformities inherent to the growth process, different currents had to flow in each laser in order to obtain the uniform pattern. Fig. 1*c* shows the resulting far-field pattern, exhibiting the double-lobe feature expected in antiphase operation. The separation between the two peaks is 5·5°, which agrees very well with the 5·6° value corresponding to the 9 μm separation between the lasers.[4] The minor peak at the centre is also predicted theoretically.[4] The main advantage of the separate-contact configuration is that, by tailoring the currents through the lasers, the same 3-element array can be operated with a far-field pattern in which most of the energy is concentrated in a single lobe in the forward direction, as shown in Fig. 2. The FWHM of the pattern is 1·8°, to be compared with a calculated value of 1·74°.[4] As also seen in Fig. 2, the mode is stable within a range of emitted power levels.

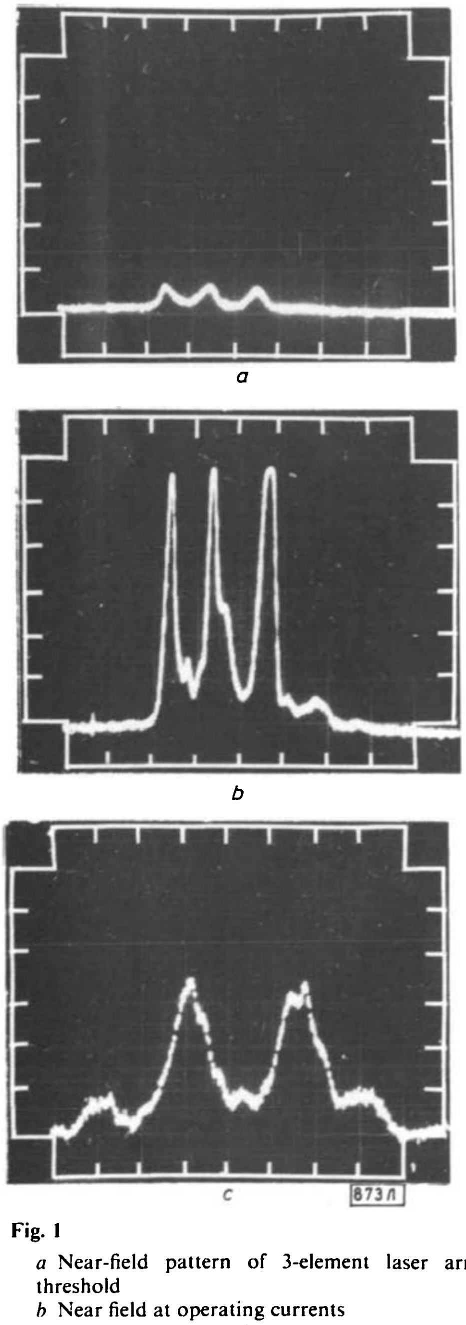

Fig. 1

a Near-field pattern of 3-element laser array operating near threshold

b Near field at operating currents

c Far field corresponding to near field of *b*

Horizontal scales: 8 μm/div. (*a* and *b*); 2 degrees/div. (*c*); vertical scales: arbitrary units

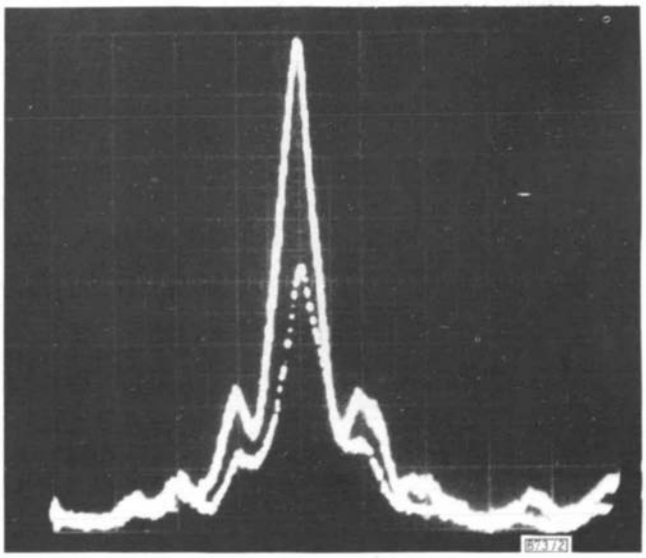

Fig. 2 *Far-field pattern of 3-element array with currents adjusted to produce single-lobe distribution*

Horizontal scale: 2 degrees/div.; vertical scale: arbitrary units

Similar results were obtained in arrays with four elements. In Fig. 3*a*, we see the far-field pattern of a typical laser, which is approximately 8° wide. In Fig. 3*b* we see the double-lobe far field of the 4-element array with lasers operating at comparable levels of peak near-field intensity, and in Fig. 3*c* the same array with the near-field distribution tailored to yield a 1·8°-wide single-lobe far-field pattern. The theoretically predicted value for the FWHM of the single lobe of a 4-element array is 1·28°.[4] The somewhat wider lobe obtained in this work may be the result of incomplete phase-locking among the interacting lasers.

In conclusion, we have demonstrated the control of far-field patterns obtained from monolithically integrated phase-locked laser arrays with multiple contacts. This control may be useful in applications such as optical recording and optical communications, where, in addition to increased power levels, stable radiation distributions where most of the energy is emitted in the forward direction are desired.

The research described in this letter was performed jointly by the Jet Propulsion Laboratory and the Applied Physics Department, California Institute of Technology, under con-

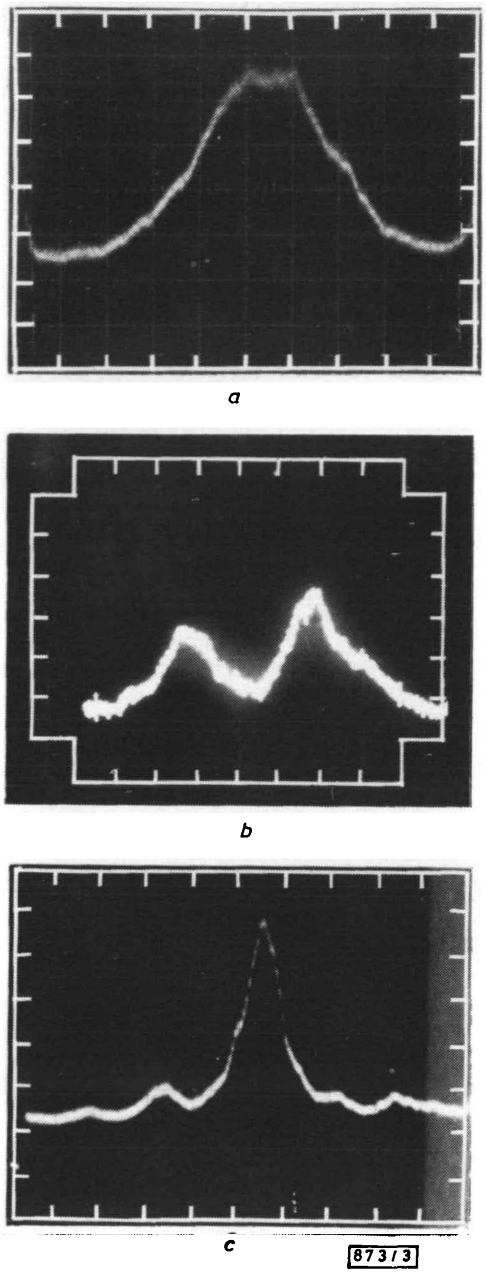

Fig. 3

a Far field of a single laser operating by itself
b Far field of a 4-element array with laser operating in anti-phase mode
c Far field of a 4-element array with lasers operating in in-phase mode
Horizontal scale: 2 degrees/div.; vertical scale: arbitrary units

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INCIDENT WAVELENGTH DEPENDENCE OF PULSE RESPONSES IN InP/InGaAsP/InGaAs AVALANCHE PHOTODIODES

Indexing terms: Optoelectronics, Avalanche photodiodes

Pulse responses of InP/InGaAsP/InGaAs APDs have been studied at 1·3 and 1·55 μm. A faster response rise-up characteristic was observed at 1·55 μm than at 1·3 μm. This result indicates that response speed depends on the hole generating region and hole pile-up at the heterojunction is decreased by introducing a hole-acceleration layer such as InGaAsP.

InP/InGaAs(P) heterostructure avalanche photodiodes (APDs) are suitable detectors for use in optical-communication systems in the wavelength range up to 1·6 μm. To obtain a high avalanche gain and to reduce a tunnelling dark current, these diodes have been realised in the heterostructure, where InGaAs(P) layers were used as light absorption regions and InP layers as multiplication regions.[1,2] Recently, it has been found that photogenerated holes pile up at the heterointerface in these APDs and their response speeds are degraded by the slow thermionic emission of these holes.[3,4] While the frequency response of this diode has been improved by inserting a thin InGaAsP layer between the InP and the InGaAs layer, the wavelength dependence of pulse response has not been studied.[5] Pulse response is important in fibre-optic-communication systems using intensity-modulated light. In this letter we report on rising-up characteristics of pulse responses for wavelengths of 1·3 and 1·55 μm in InP/InGaAsP/InGaAs APDs.

A cross-sectional structure of the diode used is shown in Fig. 1. The carrier concentration of the *n*-InGaAsP and *n*-InGaAs layer was 8×10^{15} cm^{-3} and the thicknesses were 0·8 μm and 2 μm, respectively. The upper InP layer has a carrier concentration of 1×10^{16} cm^{-3} and a thickness of 1·5 μm. The absorption edges of InGaAsP and InGaAs layers

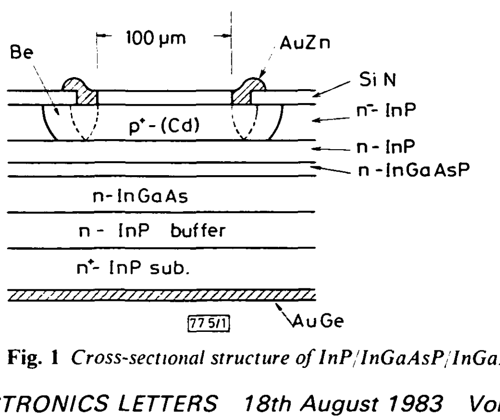

Fig. 1 *Cross-sectional structure of InP/InGaAsP/InGaAs APD*