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Optical bistability in semiconductor lasers

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Absorptive, dispersive and modal bistabilities are considered in semiconductor injection lasers. Previous work is briefly reviewed and the discussion is concerned with experimental work with transverse modal bistability in twin stripe injection lasers. A simple circuit analogy indicates how modal bistability can arise and how it is possible to have stronger light output on the side where the current drive is weakest. Experimental results are reviewed for an optical flip-flop with the use of twin-stripe lasers with three such lasers coupled together in an optical logic circuit. Various mode patterns that have been observed by using different geometries of twin-stripe lasers are discussed. Use is foreseen for active bistable devices in front-end optical signal processing.

1. Introduction

It has long been recognized that the semiconductor injection laser could form an active element for information processing (Lasher 1964; Basov 1968; Basov *et al.* 1972). Segmented lasers were considered that could switch between two states, with the bistable action arising because of saturable absorption. Initial work on such devices was often concerned with puslations between the two states (Nathan *et al.* 1965; Lee *et al.* 1970) and was used to study the undesirable effects of inhomogeneities within lasers for optical communications.

In communications, the need for stable injection lasers naturally led to experiments with external optical resonators, which can help frequency stability. However, such optical feedback can sometimes cause pulsations and hysteresis in the current–light characteristics (Broom *et al.* 1970; Lang *et al.* 1980) especially in lasers containing defects or saturable absorption. Hysteresis can indicate bistability, which with optical feedback can be caused by a complex range of mechanisms. Bistability with saturable absorption has been demonstrated by Lau *et al.* (1982). Dispersive bistability has been demonstrated by using frequency-selective optical feedback (Glas *et al.* 1982; Bazhenov *et al.* 1982).

In passive optical bistable devices the optical frequency is fixed, but in lasers the lasing frequency and mode can change. Modal bistability appears to be an important additional mechanism available in active devices. Mode hopping between longitudinal modes in lasers is well known and is a form of bistability or even multistability, when it is possible to switch to one of several modes. At present, stable longitudinal mode hopping is fraught with difficulties that need careful investigation. Transverse mode hopping looks more promising.

In a search for good structures that encourage stable transverse modes it is inevitable that structures are found that encourage modal instability. For example symmetrical twin-stripe lasers can encourage a high-power zero-order mode (Ripper *et al.* 1970), but asymmetry can lead to beam steering (Scifres *et al.* 1978) and instabilities (Kirkby 1978). Shore recognized the potential bistable action of twin-stripe lasers, and carried out extensive theoretical work on these structures (Shore *et al.* 1981, 1983; Shore 1982*a*). Bistable operation triggered by an external optical source was indicated (Shore 1982*b*). Later in this paper, experimental work (White *et al.* 1982, 1983) will be outlined demonstrating an optical flip-flop using twin-stripe lasers, along with new bistable results.

Injection lasers, then, exhibit absorptive bistability, dispersive bistability and modal bistability. Only a brief review is given of the first two effects.

2. Absorptive bistability

Figure 1 shows a schematic construction for an injection laser that will exhibit absorptive bistability (Lasher 1964; Basov 1968). Segment 1 is an active region on forward bias carrying a current I, and segment 2 acts as a saturable absorber. A simplified account of the bistable action is as follows: the total loss in both segments is too high to permit lasing action for the combined cavities, with the current I. Only spontaneous emission is then generated by I, as in a light-emitting diode. The device is 'off'. To switch into the 'on' state, I is momentarily increased, or light is injected, so as to increase the light intensity sufficiently to saturate the loss in segment 2. The total incremental loss in the two segments is then low enough to permit lasing action with the current I generating sufficient stimulated emission to keep the loss saturated in segment 2. Lasing action is maintained and the device is 'on'.

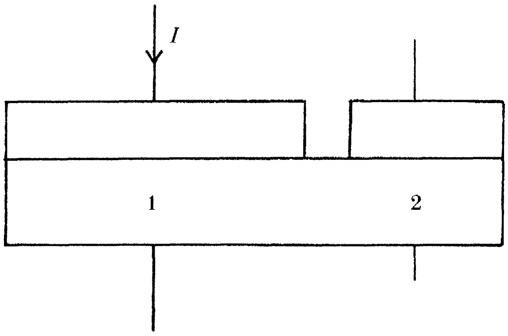

Figure 1. Segmented bistable injection laser (schematic). Segment 1 is the active region carrying current I; segment 2 is the saturable absorber.

Early experiments often exhibited pulsations rather than bistability. This may have been because of electrical feedback between the two segments. Harder *et al.* (1981, 1982) have shown that good bistable action requires an adequately high electrical resistance between segments 1 and 2 to prevent electrical feedback. Alternatively, it may have been that the nonlinearities were inadequate in the early work. Kawaguchi (1982*a*, *b*) has shown that bistability can occur with multiple unpumped segments and that it is possible to switch between bistable states by using external trigger pulses.

Different configurations have been demonstrated. Coupled cleaved cavities (Dutta *et al.* 1984) have exhibited a bistable frequency change. Lau *et al.* (1982) have found that feedback with an external mirror can help to enhance the bistability. However, the detailed mechanisms at work in these experiments may well be a mixture of dispersive as well as absorptive bistability.

3. Dispersive bistability

The refractive index of the material in an injection laser is affected by the electron density. Typically one finds for GaAs at the frequencies of laser action that a density of 10^{24} m^{-3} changes the refractive index by about 0.7 %. The electron density can be changed in nanoseconds through local current injection combined with diffusion and recombination. The electron density is also changed by the optical intensity stimulating recombination within a picosecond timescale. A laser that was 100 μm long would then require an optical input energy of about 2J per square metre of cross section to change the cavity's optical length by $\frac{1}{4}\lambda$. If the recombination time, τ, for the electrons were 1 ns then this optical energy, spread over τ, would require an input power around 2 mW per square micrometre of cross section of active region to effect a useful change in the laser's optical length.

Dispersive optical bistability can be demonstrated with an external feedback system, as shown in figure 2. There have been many experiments with optical feedback, but to establish *dispersive* bistability it is useful to make the feedback at a single frequency (Bazhenov *et al.* 1982; Glas *et al.* 1982). Bazhenov, for example, used a holographic grating to demonstrate such bistability. At low power levels the optical length of the laser was such that the feedback at the selected frequency had a phase that prevented oscillation. Changing the optical power level then altered the optical length of the laser so that laser action was possible. Optical bistability could be observed at the 1 mW level, in rough agreement with previous estimates.

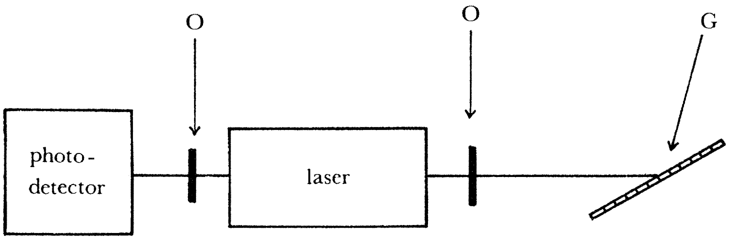

Figure 2. Schematic arrangement for observation of dispersive bistability in injection lasers. O, Lens or microscope objectives; G, grating or holographic element giving frequency-selective feedback into laser.

4. Modal bistability and twin-stripe lasers

To set the scene, we consider a simple model of coupled resonators (figure 3) with equal positive resistive loading but possibly asymmetrically distributed negative resistance. The circuit parameters are adjusted so that there are two modes that exhibit steady state oscillations with the same negative resistances but slightly different frequencies (see appendix). The mesh currents, i_1 and i_2, can differ markedly in amplitude so that in the power, $|i_1^2|\,R$ and $|i_2^2|\,R$, transferred to the positive resistance loads in each arm, can be asymmetrical and need not have the same sense of asymmetry as the negative resistance. The net power transferred to the positive resistances can be shown to be equal to the power given out by the negative resistances if and only if the system is oscillating in one or the other of the two permitted modes. Thus linear circuit theory, along with power conservation, shows that there is modal bistability; one mode

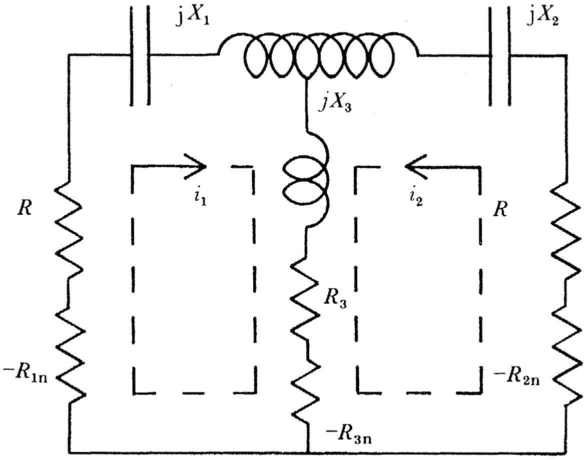

FIGURE 3. Equivalent circuit to demonstrate modal bistability. It is possible to have $|i_1| > |i_2|$ independent of whether $R_{1n} \lessgtr R_{2n}$. Only one mode at a time to give stable oscillation with the same negative resistances but different frequencies for the two modes: see Appendix.

or the other will oscillate but not both. Other conditions are possible where both modes may oscillate simultaneously, but these are not relevant for this discussion.

Transverse modal bistability of twin-stripe lasers exhibits various forms. The two laser stripes may be regarded as coupled oscillators as above. The optical gain in the medium provides the negative resistance while the facets radiate power and present positive radiation resistances to the circuit, with the resonator providing the reactance. A linear model combined with power conservation gives a helpful start to understand mode competition and the fact that the asymmetry need not correspond with the drive asymmetry (Mukai *et al.* 1983), but the model is not adequate for all cases because of the changes, within the resonator, of refractive index with electron density, which can in turn be changed by the optical intensity. Progress is being made elsewhere with theoretical models (Shore 1982*a*, *b*; Shore *et al.* 1983), but here we report experimental results.

Figure 4*a* shows a section for twin-stripe lasers using GaAs/GaAlAs heterojunctions made by Dr R. G. Plumb of Standard Telecommunication Laboratories. Three types of these lasers have so far been investigated. Closely coupled twin-stripe lasers ($s = d = 3$ μm) exhibit index guiding when the currents in the two stripes have similar values. A dip in the electron concentration between the two stripes gives sufficient increase in the refractive index to provide waveguiding. If the current in one of the stripes dominates over the other then the light–current characteristics are similar to the gain guided output from a single 3 μm stripe laser (White *et al.* 1982). At a critical ratio and level of the two current drives it is possible to have an index-guided mode that sits centrally between the two stripes, or alternatively to have a mode that is gain guided (figure 4*b*). This latter mode permits the peak optical intensity to cross from beneath one stripe at one facet to the other stripe at the other facet (White & Carroll 1983; Shore 1983), indicating beam steering, which could be useful for changing coupling to a fibre. At present the fastest time to switch between these two modes has been 800 ps, but this has not been optimized.

With these lasers both electrical bistability (applying an electrical pulse to trigger the laser from one mode to the other) and optical bistability have been demonstrated (White *et al.* 1983). Figure 5*a* gives a schematic layout of the latter experiment. The twin-stripe lasers exhibit

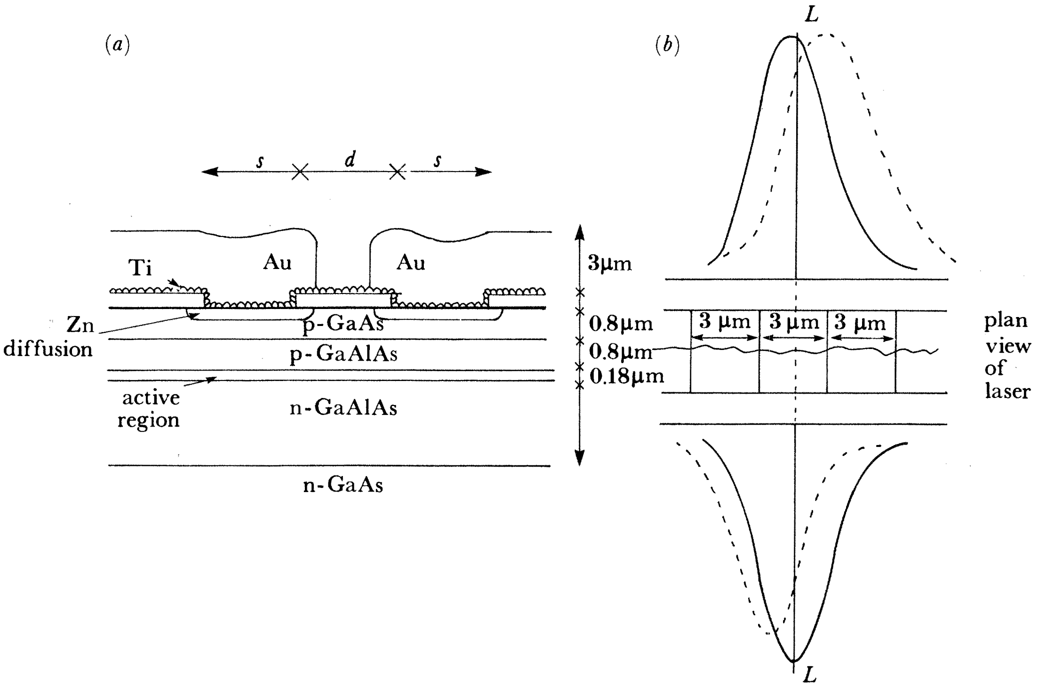

FIGURE 4. Twin-stripe laser: (*a*) schematic cross-section (*s*, stripe width, *d*, separation); (*b*) optical near-field distributions ($s = d = 3$ μm for bistable states A (——) and B (----) measured at each facet with $I_1 = I_2$, 10% above threshold.

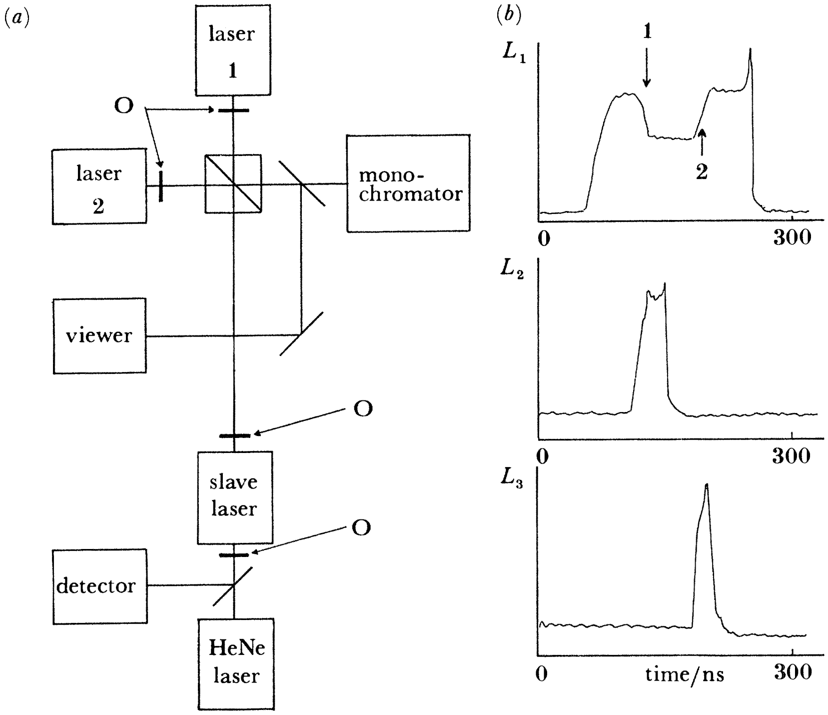

FIGURE 5. Optical flip-flop: (*a*) experimental layout (O, microscope (×50) objectives); (*b*) timing of optical outputs–inputs. L_1, Light output (relative units) at a point on the near field from bistable slave laser; L_2 and L_3, light outputs (relative units) from master lasers into slave laser to trigger bistable switching at 1 and 2 respectively.

sufficient tuning range, by small changes in the current drive, so that two master lasers could be tuned to the same frequency as a slave laser and their outputs focused onto different parts of the 'input' facet of the slave laser. By pulsing on one or the other master laser it was possible to change the mode of operation of the slave laser (figure 5*b*) and hence to demonstrate an optical flip-flop. The optical energy required to effect the switch of mode was estimated to be 1 pJ. The switching speed is limited here by the speed at which the master lasers can be turned on.

Recently, twin-stripe lasers with $s = 4$ μm and $d = 7$ μm have been examined. Although not so closely coupled, bistable transverse modes as shown in figure 6*a*, *b* have been observed. These modes appear to be a combination of zero-order and first-order modes operating simultaneously at different wavelengths, and even though $I_1 = 2I_2$ the peak field can be under either stripe. The differences in the width of the near-field pattern may be caused by the differences between gain guiding and index guiding.

Figure 6*c* shows results for a laser with $s = 2$ μm and $d = 2$ μm, indicating asymmetry in the light output even though $I_1 = I_2$. The interference pattern between the stripes probably arises because of curvature of the wavefronts from the two gain guided light output driven by each stripe. At the change of mode the different interference pattern indicates a different curvature of the wavefronts. Once again there is evidence that the light cross-couples beneath the two

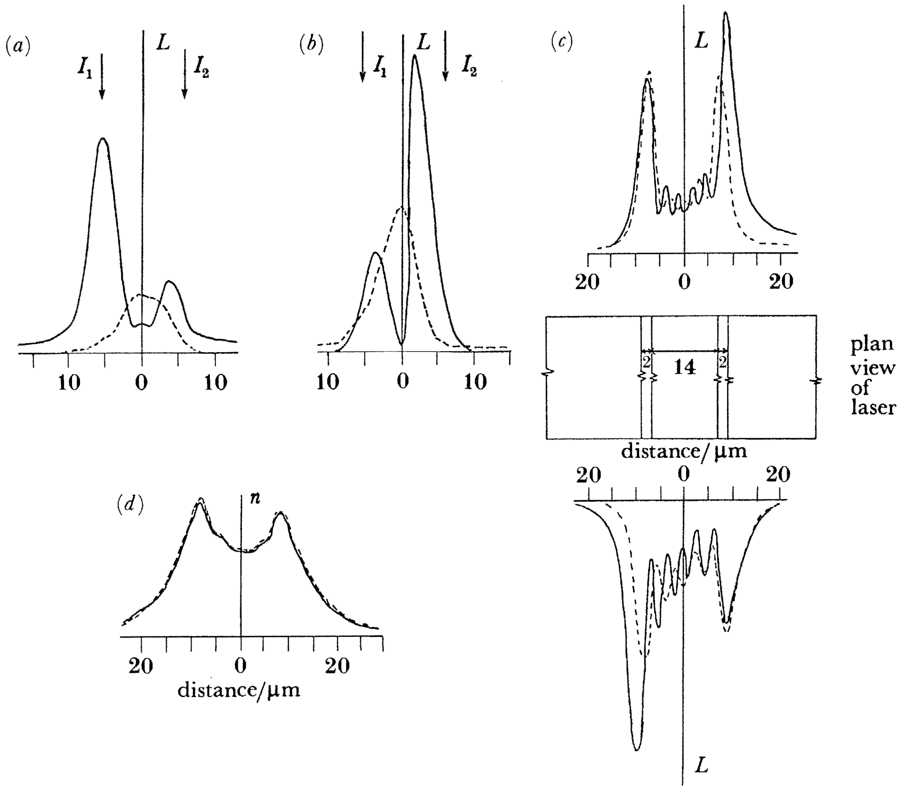

FIGURE 6. Bistable modes of twin-stripe lasers. (*a*) Spectrally resolved near-field patterns of a twin-stripe laser ($s = 4$ μm; $d = 7$ μm) biased to bistable state A ($I_1 = 2I_2$, 10% above threshold): ——, $\lambda = 865.7$ nm; ----, $\lambda = 863.8$ nm. (*b*) As above but for state B: ——, $\lambda = 860.4$ nm; ----, $\lambda = 865.2$ nm. (*c*) Spectrally resolved near-field patterns of a twin-stripe laser ($s = 2$ μm; $d = 14$ μm) biased to bistable state A (——) and state B (----). ($I_1 = I_2$, 10% above threshold.) (*d*) Charge carrier concentrations with conditions as in (*c*).

stripes. Within experimental error the electron density (figure 6*d*) has the identical transverse pattern for the two modes and it is suggested that the optical patterns are an 'in-phase' and an 'anti-phase' mode with bistability. Shore & Rozzi (1983) have suggested that it may be possible to achieve rapid switching between suitable transverse modes. On physical grounds one would expect that to achieve fast switching it is desirable to avoid changes in the electron density or the optical energy. A modal pattern such as that of figure 6*c* may then be close to the optimum for fast switching. Further experiments are under way to test this hypothesis.

5. Conclusions

Injection lasers have been shown to exhibit absorptive, dispersive and modal bistability. Modal bistability can be understood with a linear circuit model combined with power conservation. Different transverse near-field patterns for twin-stripe lasers have been measured indicating changes that could alter the coupling into an optical fibre or alter the coupling into another bistable laser. An all-optical flip-flop has been demonstrated. The full potential of switching between bistable modes has yet to be explored but there is hope that, with minimal change of either electron densities or optical energy, this switching can achieve picosecond speeds and require little energy to activate.

In active bistability, the element is biased into stimulated emission by an electrical current, though optical pumping should not be ruled out. The 'passive' device can be biased optically into a nonlinear régime by a 'floodlight'. It is therefore easier to envisage a two-dimensional 'passive' array of bistable switches. True two-dimensional active integrated arrays are probably further away from development and this remains a question for the future. However, some lasers have threshold currents in the milliampere range so that the bias power could be low enough for a modest amount of integration to form an all-optical signal-processing circuit at the sending or receiving end of a fibre. For such 'front-end' optical processing, active bistable elements may be a real competitor to other devices.

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Appendix

With the notation of figure 3, write

$$R-R_{1n}=(a+b)\,R;\quad R-R_{2n}=(a-b)\,R;\quad R_3-R_{3n}=cR;$$
$$\mathrm{j}X_1=\mathrm{j}(A+B)\,R;\quad \mathrm{j}X_2=\mathrm{j}(A-B)\,R;\quad \mathrm{j}X_3=\mathrm{j}CR;$$

where a, b, c, A, B and C may take positive or negative values and $\mathrm{j}=\sqrt{-1}$. Then from mesh analysis, eliminating the currents i_1 and i_2, the condition for steady oscillation is

$$\begin{bmatrix} (a+c)+\mathrm{j}(A+C)+(b+\mathrm{j}B) & c+\mathrm{j}C \\ c+\mathrm{j}C & (a+c)+\mathrm{j}(A+C)-(b+\mathrm{j}B) \end{bmatrix}=0.$$

Hence $$(a+c)+\mathrm{j}(A+C)=\pm\sqrt{\{b^2+c^2-B^2-C^2+2\mathrm{j}(Bb+Cc)\}}.$$

The condition that both modes have the same negative resistances assuming the same loads (same positive resistances) but different frequencies (different reactances) is satisfied if

$$a+c=0 \quad \text{and} \quad \mathrm{j}(A+C)=\pm \mathrm{j}K, \quad \text{where} \quad K^2=B^2+C^2-b^2-c^2,$$

with $$i_1/i_2=-(c+\mathrm{j}C)/(b+\mathrm{j}B\pm\mathrm{j}K) \quad \text{and} \quad bB+cC=0.$$

Hence $$|i_1/i_2|^2=G \quad \text{or} \quad 1/G,$$

where $G=(c^2+C^2)/(2B^2+C^2-c^2+2KB)$ is not, in general, unity. It may be checked that the power given out equals the power in,

$$|i_1|^2 R_{1n}+|i_2|^2 R_{2n}+|(i_1+i_2)|^2 R_{3n}=|i_1|^2 R+|i_2|^2 R+|(i_1+i_2)|^2 R_3,$$

for only one or other of the eigenmodes but not a mixture of both modes. In the twin-stripe laser, the asymmetry and level of the bias currents determines, through the asymmetry of the equivalent negative resistances, the asymmetry and level of total output power.

REFERENCES

Basov, N. G. 1968 *IEEE Jl Quantum Electron.* **QE-4**, 855–864.

Basov, N. G., Culver, W. H. & Shah, B. 1972 In *Laser handbook* (ed. F. T. Arecchi & E. O. Schulz-DuBois), pp. 1650–1693. Amsterdam: North-Holland.

Bazhenov, V. U., Bogatov, A. P., Eliseev, P. G., Okhotnikov, O. G., Pak, G. T., Rakvalsky, M. P., Soskin, M. S., Taranenko, V. B. & Khairetdinov, K. A. 1982 *Proc. Instn elect. Engrs* **129** (I), 77–82.

Broom, R. F., Mohn, E., Risch, C. & Salathe, R. 1970 *IEEE Jl Quantum Electron.* **QE-6**, 328–334.

Dutta, N. K., Agrawal, G. P. & Focht, M. W. 1984 *Appl. Phys. Lett.* **44**, 30–32.

Glas, P. & Muller, R. 1982 *Optics Quantum Electron.* **14**, 375–389.

Harder, C., Lau, K. Y. & Yariv, A. 1981 *Appl. Phys. Lett.* **39**, 382–384.

Harder, C., Lau, K. Y. & Yariv, A. 1982 *Appl. Phys. Lett.* **40**, 124–126.

Kapon, E., Lindsey, C., Katz, J., Margalit, S. & Yariv, A. 1984 *Appl. Phys. Lett.* **44**, 389–391.

Kirkby, P. A. 1978 Ph.D. thesis, University of Southampton.

Kawaguchi, H. 1982 *Proc. Instn elect. Engrs* **129** (I), 141–148.

Kawaguchi, H. 1982 *Appl. Phys. Lett.* **41**, 702–704.

Lang, R. & Kobayashi, K. 1980 *IEEE Jl Quantum Electron.* **QE-16**, 347–355.

Lasher, G. J. 1964 *Solid State Electron.* **7**, 707–716.

Lau, K. Y., Harder, C. & Yariv, A. 1982 *Appl. Phys. Lett.* **40**, 369–371.

Lee, T. P. & Roldan, R. H. R. 1970 *IEEE Jl Quantum Electron.* **QE-6**, 339–352.

Mukai, S., Yakima, H., Uekusa, S. & Sone, A. 1983 *Appl. Phys. Lett.* **43**, 432–434.

Nathan, M. I., Marinace, J. C., Rutz, R. F., Michel, A. E. & Lasher, G. J. 1965 *J. appl. Phys.* **36**, 473–480.

Ripper, J. E. & Paoli, T. L. 1970 *Appl. Phys. Lett.* **17**, 371–373.

Scifres, D. R., Streifer, W. & Burnham, R. D. 1978 *Appl. Phys. Lett.* **33**, 702–704.

Shore, K. A. 1982*a* *Quantum Electron.* **14**, 177–181.

Shore, K. A. 1982*b* *Quantum Electron.* **14**, 321–326.

Shore, K. A. 1983 *Elect. Lett.* **19**, 874–875.

Shore, K. A., Davies, N. G. & Hunt, K. 1983 *Optics Quantum Electron.* **15**, 547–548.

Shore, K. A. & Rozzi, T. E. 1981 *IEEE Jl Quantum Electron.* **17**, 723–731.

Shore, K. A. & Rozzi, T. E. 1983 *Optics Quantum Electron.* **15**, 497–506.

White, I. H. & Carroll, J. E. 1983 *Elect. Lett.* **19**, 337–339.

White, I. H., Carroll, J. E. & Plumb, R. G. 1982 *Proc. Instn elect. Engrs* **129** (I), 121–126.

White, I. H., Carroll, J. E. & Plumb, R. G. 1983 *Elect. Lett.* **19**, 558–560.