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A semiconductor laser for information read-out

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Semiconductor lasers only became efficient lasers when they were made in the form of 'double heterojunctions': an active layer in which the laser radiation is produced, between two layers of another composition. In the first lasers of this type the active layer consisted of GaAs. The laser radiation from this material has a wavelength of about 890 nm. Since then the development of semiconductor lasers has moved simultaneously in two opposing directions. On the one hand there is a clear need for laser radiation at longer wavelengths for optical communication by glass fibres, since Rayleigh scattering in the fibres is lower at these longer wavelengths. On the other hand there is a need for semiconductor lasers that produce radiation at shorter wavelengths for applications in which the radiated power is concentrated in the smallest possible area. This article describes a laser of this shorter-wavelength type that Philips is putting on the market. The wavelength of the emitted radiation is 780 nm.

Introduction

The information on a 'VLP' disc is recorded in a spiral track 25 km long, with a pitch of 1.66 μm and consisting of pits 0.6 μm wide and 0.12 μm deep. This form of information storage also has its attractions for applications such as audio discs and data filing, mainly because it can provide a very high information density — of the order of one bit per μm^2. Philips are active in the development of such systems ('Compact Disc'; 'DOR' = Digital Optical Recording).

The information stored in this way is read out by scanning the track of pits with an optical system; a photodiode converts the intensity variations of the reflected light into an electrical signal (*fig. 1*). The requirements imposed on the light source (*L*) for this system can only be met by lasers: the radiation must have a radiation density of about 2500 W per cm^2 per steradian for a detected signal with an acceptable signal-to-noise ratio to be generated by the variations in reflection from an area of about 1 μm^2 [1]. The light source in the 'VLP' system is at present a helium-neon laser [2].

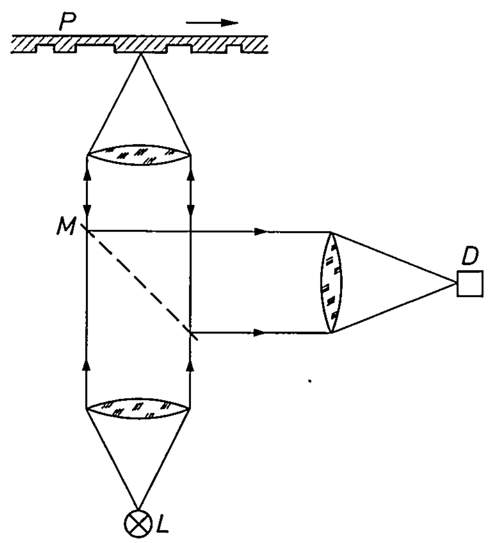

Fig. 1. Optical system for read-out from the track of pits on a 'VLP' disc. *L* laser. *M* half-silvered mirror. *P* 'VLP' disc. *D* photodetector.

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[1] J. P. J. Heemskerk, Appl. Optics **17**, 2007, 1978.
[2] A description of the Philips 'VLP' system is given in the series of articles on this subject in Philips tech. Rev. **33**, 177-193, 1973, and Appl. Optics **17**, 1993-2042, 1978.

In this article we shall discuss an alternative to the HeNe laser in this application: the 'CQL10', a semiconductor laser based on the AlGaAs system. Lasers of this type have already proved to be highly suitable as light sources for optical communication by glass fibre [3]. A further development of this kind has now led to the CQL10.

The CQL10 differs greatly in many respects from the HeNe laser. For example, it does not produce a parallel beam, but a highly divergent beam, which requires a different optical system. The coherence length is relatively small; this is an advantage for the intended application; it reduces the chance of undesirable wave interference. Other advantages are that it is small, mechanically strong and only requires a low supply voltage. The HeNe laser is 20 cm long and requires a supply voltage of 1500 V, whereas the CQL10 measures about 1 cm and requires a voltage of 2 to 3 V. In quantity production the CQL10 will also be cheaper.

When we were designing the CQL10, the two main requirements were that it should be capable of faithful read-out from the existing 'VLP' discs and that it should work well even at a temperature of 60 °C. The last requirement relates to using the 'Compact Disc' in an ambient temperature of 45 °C (as in the tropics). Because of the compact construction of the unit the cooling capacity must necessarily be relatively small, so that the temperature of the encapsulation of the laser could rise as high as 60 °C.

The AlGaAs laser

The construction and principle of operation of a 'semiconductor laser with double heterojunction' will be outlined briefly with the aid of *fig. 2* [4]. The laser consists of three layers with different types of conductivity and different energy gaps E_g. In layers *1* and *3* E_g is greater than in the 'active' layer *2*.

A photon of the correct frequency ν ($h\nu \approx E_{g2}$) passing through layer *2* may generate a hole-electron pair or 'stimulate' an electron that may be present in the conduction band to recombine with a hole in the valence band. In a generation process the photon disappears ('absorption'), while in a recombination process a photon of the same phase is added ('stimulated emission').

If the semiconductor is in thermal equilibrium ($I = 0$ in *fig. 2a*), a current of such photons is strongly attenuated because there are few electrons in the conduction band and few holes in the valence band: virtually the only process that occurs is electron-hole generation (with absorption); recombinations (with emission) hardly occur at all. If there is an electric current (I) in the diode in the forward direction, however, electrons flow from layer *1* and holes from layer *3* into layer *2*. If this current is high enough the energy-level diagram takes the form shown in fig. *2b*. As a result of the presence of the barriers ΔE_c and ΔE_v the electrons and holes collect in layer *2* and a *population inversion* arises, in which there are 'effectively' more occupied than unoccupied states in the conduction band, which means that on average the stimulated recombinations outnumber the excitations for every incident photon. A light wave that passes through this medium is amplified. This 'amplification by stimulated emission' is proportional to the 'excess' of electrons in the conduction band.

The grey region in fig. *2a* is therefore an amplifier for light in the *z*-direction. By means of partially

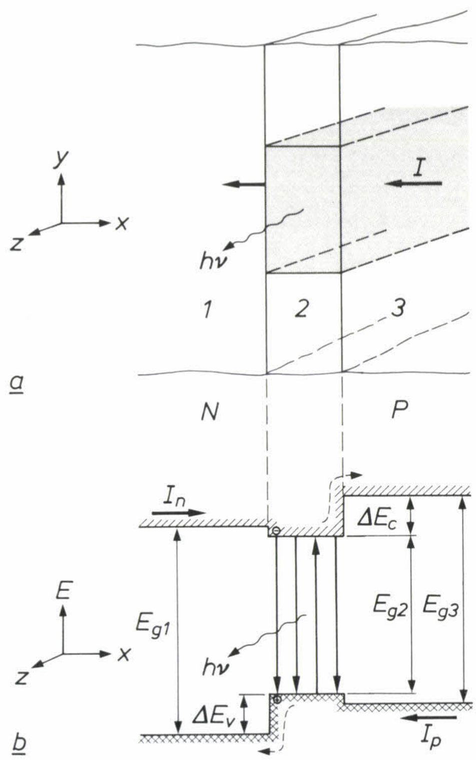

Fig. 2. Structure and principle of operation of the semiconductor laser with double heterojunction. *a*) The laser consists of three layers *1*, *2* and *3*; layer *1* has *N*-type conductivity, layer *3* has *P*-type conductivity and both have a larger energy gap than layer *2*, which is undoped (almost intrinsic). When a sufficiently large current (I) flows in the forward direction the grey part of layer *2* becomes 'active', i.e. becomes an amplifier for wavelengths of frequency ν ($h\nu \approx E_{g2}$). The semiconductor/air interfaces perpendicular to the *z*-axis at the front and back of the active region act as half-silvered mirrors, providing feedback in the amplifier. If the gain can compensate for the losses the resonator thus obtained will start to oscillate. 'Laser radiation' will then be emitted from the front and rear mirrors. *b*) A simplified energy-level diagram for a large value of the current I. Because of the presence of the barriers ΔE_c and ΔE_v the electrons and holes flowing towards layer *2* collect in this layer and readily cause a 'population inversion'. The layer is then active because the stimulated recombination processes with emission of coherent photons outnumber the generation processes with absorption. I_n is the electron current, I_p the hole current. E_{g1}, E_{g2}, E_{g3} are the energy gaps of the layers *1*, *2* and *3*.

transmitting mirrors at the front and back, feedback is provided and a resonator is produced. When the current I is gradually increased, the amplification on one pass through the resonator becomes greater at some instant than the internal losses and the losses at a mirror, and the resonator starts to oscillate: laser action occurs. The current at which this starts is known as the threshold current (I_{th}). For larger values of I the laser emits an intense coherent light beam from the two end mirrors. *Fig. 3* gives the light/current characteristic (optical power plotted against current) of the laser. For currents below the threshold the holes and electrons recombine *spontaneously*, with the emission of incoherent photons; the diode then behaves like an LED.

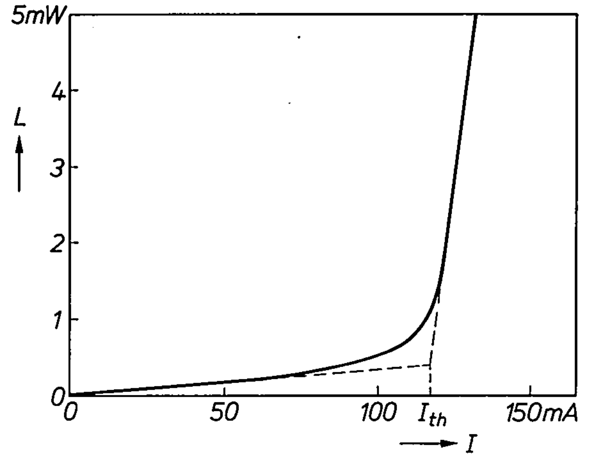

Fig. 3. Light/current characteristic of a laser, i.e. the power L of the emitted radiation as a function of the current I. Below the threshold I_{th} the diode acts as an LED (spontaneous emission) and above it as a laser (stimulated emission).

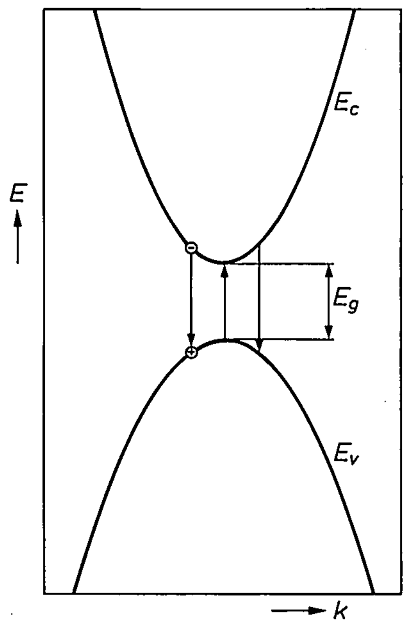

Fig. 4. Energy E as a function of the momentum (the wave number) k of the electrons in a 'direct' semiconductor. The minimum of the conduction band E_c and the maximum of the valence band E_v have the same value of k. Consequently an electron at the bottom of the conduction band can recombine 'directly' — i.e. without transfer of momentum to the lattice — with a hole at the top of the valence band. Because of this, the probability of a recombination or generation process for each incident photon is much greater than in 'indirect' semiconductors such as Ge and Si in which the maxima and minima of the bands are not directly opposite one another.

The secret of the 'semiconductor laser with double heterojunction' lies in the difference in energy gap between layer *2* and layers *1* and *3*. Not only does this create the barriers ΔE_c and ΔE_v (fig. 2*b*) that 'trap' the holes and electrons thus making it easy for a population inversion to occur, but it also creates a jump Δn in the refractive index that traps the photons in the x-direction. This is because an increase in the energy gap implies a reduction in the refractive index; layers *1* and *3* therefore have a lower refractive index than layer *2*, so that light waves travelling close to the z-direction are totally reflected at the interfaces.

The AlGaAs system — or to be more accurate the $Al_xGa_{1-x}As$ system — is particularly suitable for making a laser of this type. In the first place, GaAs is a 'direct' semiconductor (see *fig. 4*), which means that there is a high probability of absorption and stimulated emission. In the second place the Al ion in the zinc-blende lattice of $Al_xGa_{1-x}As$ is of about the same size as the Ga ion, so that layers of different composition can be epitaxially applied on top of one another without causing stresses. Because the energy gap and the refractive index have a marked dependence on x in accordance with the empirical relations [5]

$$E_g = 1.424 + 1.247x \text{ eV}, \qquad (1)$$

$$n \approx 3.59 - 0.71x, \qquad (2)$$

there is considerable freedom in the choice of these quantities. Relation (1) is only true for values of x between 0 and about 0.46. In this entire region the material is a direct semiconductor, outside this region it is not.

The front and back mirrors are in fact cleavage planes of the crystal and are consequently ideally plane and parallel. No special measures are taken to entrap the photons in the y-direction. However, no current is allowed to flow through layer *2* outside the active region (grey in fig. 2*a*), so that population inversion only occurs inside this region. Light waves in the z-direction derive the greatest effective gain from the inversion ('gain guiding').

[3] See for example G. A. Acket, J. J. Daniele, W. Nijman, R. P. Tijburg and P. J. de Waard, Philips tech. Rev. 36, 190, 1976.
[4] A detailed discussion is given in the article of note [3]; heterojunctions are also discussed in L. J. van Ruyven, A. Rev. Mat. Sci. 2, 501, 1972.
[5] H. C. Casey Jr. and M. B. Panish, Heterostructure lasers, Part A, pp. 45 and 192; Academic Press, London 1978.

The laser crystal of the CQL10

Fig. 5 gives a cross-section of the laser crystal of the CQL10. It consists of a substrate *S* with four layers *1*, *2*, *3*, *4*, which are applied to it by means of liquid-phase epitaxy (LPE) [6], and two metallic contact layers. The substrate and layer *4* are of pure GaAs. In the other layers some of the Ga has been replaced by Al: 16 at % in layer *2*, and 46 at % in layers *1* and *3*. We shall return later to the choice of these compositions, particularly for layers *1*, *2* and *3*. In the epitaxy, wafers of about 2 cm^2 are formed. These are cleaved into wafers of about 1 cm^2 which are then processed as described briefly below before being cleaved again into the individual laser crystals.

The thickness chosen for the active layer, 0.2 μm, is an optimum. As the thickness decreases, the threshold current generally decreases, because a population inversion has to be maintained in an ever-decreasing volume. However, if the layer becomes thinner than 0.2 μm, I_{th} increases again because the radiation is no longer effectively confined between layers *1* and *3*.

In the lateral direction (y) the current flow is limited to a stripe 5 μm wide, since the layers *3* and *4* outside this stripe have been made into insulators by proton implantation of the wafer (grey shading in fig. 5). During the implantation a metal mask protects the 5 μm stripes from the proton bombardment. The implantation front comes to within about 1 μm of the active layer. This provides adequate definition of the current flow, while disturbances of the crystal lattice in advance of the front still do not reach the active layer.

Pure GaAs has been chosen for the substrate (*S*) and the top layer (*4*), because Al at the surface oxidizes very readily and this makes it extremely difficult to apply good metal contacts. To help form good contacts the substrate is heavily *N*-doped with Si and the top layer is partly made into a degenerate *P*-semiconductor by a strong Zn diffusion. Before the substrate is metallized, it is ground and etched to a thickness of about 100 μm, to remove the Zn diffused into the substrate and make the cleavage easier.

A wafer is cleaved into about 30 'bars', each of which is broken into about 30 laser crystals, so that a wafer yields about 1000 lasers. The width of the bars, i.e. the distance between the mirror planes of the active region, is 250 μm.

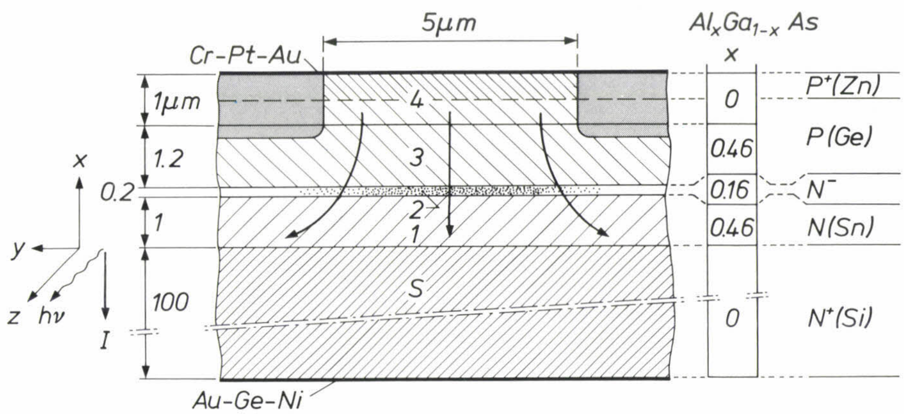

Fig. 5. Cross-section through the laser crystal of the CQL10. The thickness of the layers is given on the left and the Al content x (the composition is $Al_xGa_{1-x}As$) and the conduction type and dopant are given on the right. The undoped layer *2* is weakly *N*-type because of residual impurities. The upper part of layer *4* is doped to make it very strongly *P*-type (degenerated) by giving it a strong Zn diffusion. The upper layers are made into insulators by proton implantation (dark grey area), except for a narrow stripe (5 μm) that determines the passage of current and hence the width of the active region in layer *2*. The difference in composition between layer *2* and layers *1* and *3* provides the desired difference in energy gap. The heavy doping of the substrate *S* and the upper layer permits good electrical contact between the crystal and the metallic layers (Cr-Pt-Au and Au-Ge-Ni).

The composition of the active layer and the 'cladding' layers

As we shall now briefly explain, the selection of the values of 16% for the Al content x_2 of layer *2* and 46% for the Al content x_1 of layers *1* and *3* is directly linked to the requirement that this laser must be able to read the internationally standardized 'VLP' discs reliably even when the temperature of the laser encapsulation is 60 °C. In normal operation this means that the temperature of the active region is about 70 °C.

The wavelength of the HeNe laser now used for scanning 'VLP' discs is 630 nm. If a laser with a longer wavelength is to be used, the permissible variations in disc thickness become smaller. For a GaAs laser ($x_2 = 0$, $\lambda = 890$ nm) the tolerances would become unacceptably small. An analysis has shown that the wavelength can be increased to about 780 nm for standard 'VLP' discs [7]. This wavelength corresponds to an energy gap of 1.62 eV, and hence to $x_2 = 0.16$ for an AlGaAs laser (see eq. 1). Since λ increases as x_2 decreases, this is a minimum value for x_2.

If the laser in a given 'VLP' unit is replaced by a laser of longer wavelength, the resolution decreases; the diameter (d) of the light spot increases. This can be compensated for by increasing the numerical aperture A ($d = 1.2\ \lambda/A$). However, this reduces the tolerance for the disc thickness. On the face of it this would be expected: the tolerance for a 'blunt' beam (large value of A) is smaller than for a sharp beam (small value of A). The relationship, however, is more complicated than this because of refraction effects at the edges of the pits. For standard 'VLP' discs the analysis gives a maximum of 780 nm for the wavelength, as mentioned above.

The use of a longer wavelength also means that crosstalk between adjacent tracks occurs more readily because of coma of the light spot. This problem arises because of 'sag' at the edge of the disc, which has the effect that the axis of the laser optical system is not always perpendicular to the disc. This problem can in principle be avoided by using an arrangement in which the optical axis follows the curvature of the disc.

To obtain high barriers and a large jump in the refractive index, the difference Δx between x_1 and x_2, and hence x_1, should be made as large as possible. The maximum temperature at which the probability of holes and electrons escaping across the barriers is still sufficiently small would then be as high as possible. However, if x_1 exceeds the value 0.46, there is a fundamental change in the band structure [8], which has an important consequence for the laser design: the depth of the donor levels (Sn) in layer *1* increases suddenly. This considerably reduces the concentration of electrons at the junction and injection suddenly becomes much more difficult. We note that raising x_1 above 0.46 would in any case not be very effective in raising the height of the barriers because equation (1) is no longer valid and the energy gap only increases slowly for $x_1 > 0.46$. For our laser design 0.46 is therefore a practical maximum for x_1.

With the jump in x thus limited to a value of 0.30, the probability of charge carriers escaping thermally from the active layer is still sufficiently small even at a somewhat higher temperature. An increased escape probability means a higher threshold current I_{th}. With $\Delta x = 0.30$, the threshold current I_{th} does not increase by more than 30% if the temperature rises 30 degrees. For a typical laser with a threshold current of 120 mA at 30 °C, the threshold current therefore remains below 160 mA at 60 °C, a very acceptable value. The value $\Delta x = 0.30$ also implies a jump of 0.2 in the refractive index, which is sufficient to trap the light in the x-direction.

Assembly and encapsulation of the crystal

To keep the manufacturing costs of the CQL10 as low as possible, we tried to make good use of well-proven standard components for the design of the encapsulation. *Fig. 6* is a diagram of the encapsulation. It consists of an assembly block *B* specially made for the laser, and two standard components: the baseplate *P* and the cap with window *C*. A *PIN* photodiode (*D*) of silicon attached to the baseplate is used for stabilizing the optical power from the laser crystal by feedback to the power supply. *Fig. 7* shows the components and the assembled laser.

The assembly block (fig. 6*b*) enables the laser crystal (*L* in fig. 6*a*) to be accurately located in the equipment. It is mainly cylindrical and is made with very close tolerances, particularly for the outside diameter (8.991-9.000 mm) and the relative position of the mounting surface (*A*) for the crystal. Two slots in its base permit the block to be accurately oriented in the equipment. It also functions as a heat sink for the heat generated in the crystal. (The electrical energy supplied is converted almost entirely into heat: the optical efficiency is 1 to 5%). The shape and

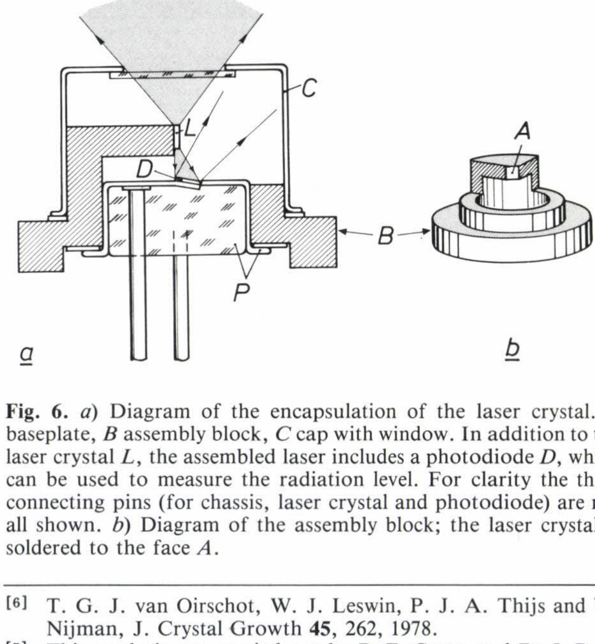

Fig. 6. *a*) Diagram of the encapsulation of the laser crystal. *P* baseplate, *B* assembly block, *C* cap with window. In addition to the laser crystal *L*, the assembled laser includes a photodiode *D*, which can be used to measure the radiation level. For clarity the three connecting pins (for chassis, laser crystal and photodiode) are not all shown. *b*) Diagram of the assembly block; the laser crystal is soldered to the face *A*.

[6] T. G. J. van Oirschot, W. J. Leswin, P. J. A. Thijs and W. Nijman, J. Crystal Growth 45, 262, 1978.

[7] This analysis was carried out by P. F. Greve and Dr J. P. J. Heemskerk of the Philips Audio Division, and Ing. W. G. Ophey of Philips Research Laboratories, Eindhoven.

[8] See for example R. Dingle, R. A. Logan and J. R. Arthur Jr., in: Gallium arsenide and related compounds (Edinburgh) 1976 (Inst. Phys. Conf. Ser. No. 33a), p. 210.

material (oxygen-free copper) of the block are chosen so as to minimize its thermal resistance, which is about 5 kW.

When the crystal is being attached it must not be exposed to mechanical stresses resulting from differences in the expansion coefficients of crystal and block. It is therefore soldered with indium, which is very ductile and has a melting point of 156 °C.

The crystal is soldered with a special soldering jig to a tolerance of ± 50 μm in the transverse direction, ± 1° in the angle to the vertical and 4 μm in the vertical direction. The vertical tolerance is so small for the following reasons: firstly, the exit mirror must not lie below the edge of the block because the beam then reflected by it would interfere with the main beam, giving inadmissible variations in the intensity some distance away from the laser as a function of the angle to the optical axis. Secondly, the crystal should also not project more than 4 μm beyond the edge because the cooling of the mirror would then be inadequate. A great deal of heat is generated at the mirror itself because the cleavage plane is a crystallographic 'injury' that induces substantial non-radiative heat-generating recombination processes.

The baseplate has three connecting pins sealed in glass, for connection to the chassis, the laser crystal and the photodiode. It is a standard Philips product, the TO-18, which can have up to seven pins. The photodiode is soldered in an indentation in the baseplate at an angle of 10° to prevent the reflected light from affecting the laser or emerging within the aperture angle of interest in the application.

The window in the cap (*C* in fig. 6) must not affect the emergent wavefront. It has been found that a standard microscope cover glass meets the requirements for application in 'VLP' equipment, i.e. that its flatness must be such that it will give no more than two Newton's rings over the diameter. The window is hermetically sealed into the cap. Interference measurements are made to test the windows for flatness both before and after the cap is welded to the block. To protect the crystal, the encapsulation is filled with dry nitrogen (max. 100 ppm H_2O). A layer of gold (2 μm) protects the encapsulation from oxidation.

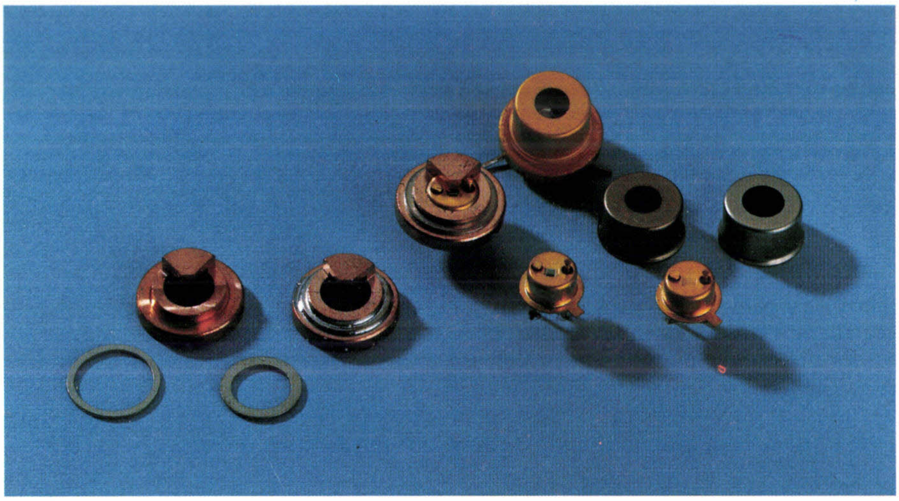

Fig. 7. The encapsulation components and the assembled laser. The various components and the assembled laser can be identified from fig. 6. The second assembly block from the left has the welding rings for baseplate and cap.

Characteristics and use of the CQL10

Fig. 8 shows an example of the spectrum of the laser for a current above the threshold value. As noted earlier, the laser can be considered as an amplifier of light waves in the z-direction (see figs 2 and 5), which has become a resonator because of the mirrors. The envelope of the peaks in fig. 8 gives the gain profile of the amplifier (width about 3 nm). The peaks represent longitudinal modes of the resonator cavity; they occur where the resonance condition $l = m\lambda/2n$ is satisfied (l is the length of the resonator, m an integer, λ the wavelength of the light, n the refractive index of the resonator material). With $l = 250$ μm, $\lambda = 780$ nm, $n = 3.59$ the number of half-wavelengths m in the resonator will be about 2300 and the distance $\Delta\lambda$ between two adjacent peaks ($\Delta m = 1$) will be about 0.3 nm, as in fig. 8. Closer inspection reveals that within the gain profile $\Delta\lambda$ increases significantly with λ, owing to the dependence of n on λ (i.e. dispersion). The width of the envelope and the number of peaks decrease as the current increases. At a high current there is clearly one dominant mode. A spectrum with many modes implies a short coherence length.

The exit beam from this laser, unlike that from the HeNe laser, is strongly divergent. This is because the exit aperture is of the order of magnitude of the wavelength, so that there is considerable refraction. *Fig. 9* gives the measured intensity as a function of the angle to the optical axis both in the plane of the active layer and perpendicular to it. The aperture of the laser is least, and the divergence therefore greatest, in the plane perpendicular to the active layer. The peak at $-20°$ in fig. 9 is from light that is reflected by the photodiode, which is at an angle of 10° (page 42); it falls completely outside the angle of aperture of interest for read-out applications.

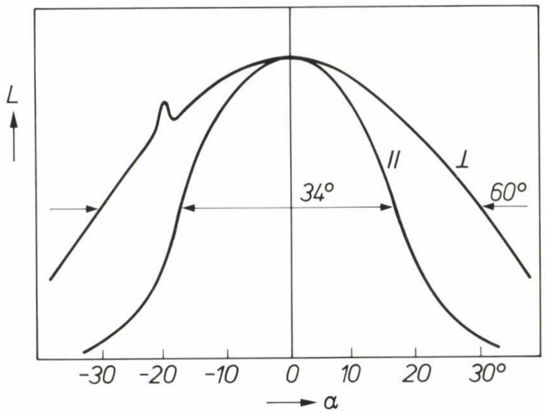

Fig. 9. The power L of the emitted radiation as a function of the angle α to the optical axis of the laser, for radiation in the plane of the active layer (||) and for radiation in the plane perpendicular to it (⊥). The peak at $-20°$ is caused by reflection at the photodiode. The 'half-power angles' are 34° and 60° respectively.

In addition, the laser light is 'astigmatic': the emergent wavefront is more strongly curved in the x-direction than in the y-direction (*fig. 10a*). The centre of curvature for the x-direction lies in the exit mirror, and the centre of curvature for the y-direction is about 25 μm behind it in the laser. Astigmatic laser radiation is a characteristic of lasers with 'gain guiding' (page 39) in the lateral direction (y in fig. 10). The gradual transition from 'amplification' to 'absorption' in the y-direction at the edge of the active region is linked with a decrease in this same direction in the velocity of light (i.e. with an increase in the refractive index). The light therefore lags somewhat at the edge so that the wavefront is already curved inside the laser (fig. 10b). After refraction at the exit plane,

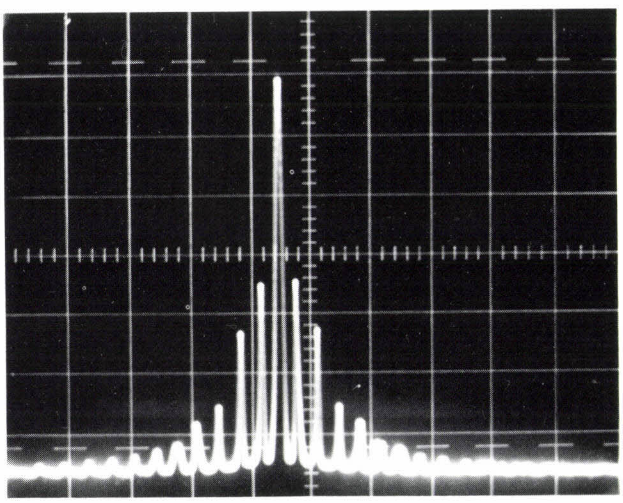

Fig. 8. Example of a spectrum of the light produced by the CQL10. The horizontal scale represents the wavelength; 0.85 nm per scale division. The peaks correspond to 'longitudinal modes of vibration' of the light in the laser cavity.

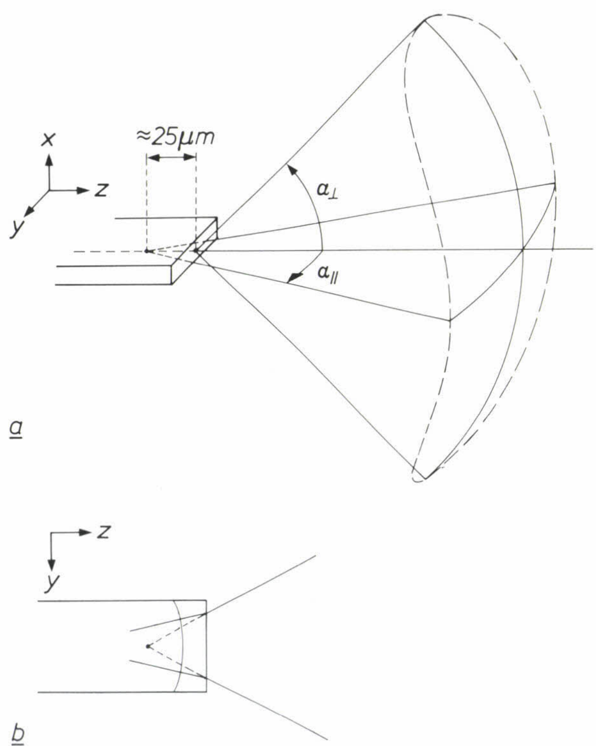

Fig. 10. The astigmatism of the laser light. *a*) The centre of curvature of a wavefront in the x-direction lies in the plane of the exit mirror and the centre of curvature in the y-direction is about 25 μm behind it. *b*) The astigmatism of the light arises inside the laser, where a wavefront is curved in the y-direction because of 'gain guiding'.

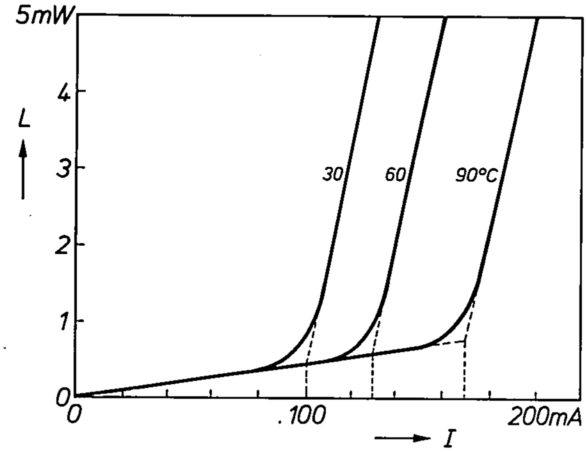

Fig. 11. Temperature dependence of the light/current characteristic. The threshold current increases as the temperature increases. In this example the increase is 30% per 30 K.

the wavefront of fig. 10*a* is produced. The astigmatism can be corrected by a cylindrical lens.

The light/current characteristic (fig. 3) is dependent on the temperature of the laser crystal (*fig. 11*). The threshold current increases with temperature; the variation is expressed empirically by

$$\frac{I_{th2}}{I_{th1}} = \exp \frac{T_2 - T_1}{T_0} .$$

In the temperature range of fig. 11 the effect must be attributed to the higher probability of electrons and holes escaping across the barriers ΔE_c and ΔE_v (fig. 2) at a higher temperature. The quantity T_0, which characterizes the temperature behaviour, depends therefore to a large extent on ΔE_c and ΔE_v. T_0 is at least 115 K for the CQL10. This means that the threshold current increases by no more than 30% for a temperature rise of 30 K.

To limit the threshold current the temperature of the active region must be kept as low as possible. For this reason the laser crystal has been soldered with the upper layer on the assembly block; the active layer is then as close as possible to the block. The thermal resistance between the active region and an external heat sink is then about 25 K/W; about 5 K/W of this is due to the block, as we saw earlier. If for one reason or another the active region is not cooled adequately the laser may go into 'thermal runaway'; this is explained in *fig. 12*.

In measuring the thermal resistance we make use of the temperature dependence of the refractive index. The position of the spectrum is determined for one temperature (T_1) of the block and one current, then the temperature of the block is reduced to $T_1 - \Delta T$ and the current is adjusted so that the spectrum comes back to the same place. The active region then has the same temperature as before. The thermal resistance is $\Delta T/\Delta W$, where ΔW is the increase in the electrical power supplied (which is almost completely converted into heat).

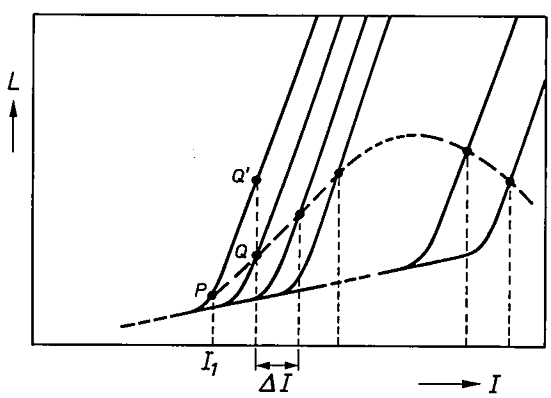

Fig. 12. 'Thermal runaway' of a laser. If the active region is insufficiently cooled — because the thermal resistance between this region and block is too high, too much heat is developed in the active region or the block is insufficiently cooled — the temperature of the active region rises and its characteristic curve (the solid lines) shifts to the right when the current is increased. Starting from a current I_1 a current increase ΔI does not take the operating point to Q' as it would have done if the temperature in the active region had remained the same, but to Q. Initially, therefore, the characteristic is less steep. As the current is increased, the shift for each step ΔI becomes increasingly larger so that in the end even *less* light leaves the laser and it goes into thermal runaway.

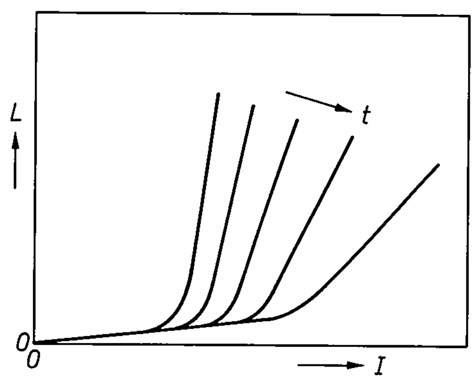

Fig. 13. Deterioration of the laser. With the passage of time the characteristic curve becomes less steep and the threshold current becomes higher. If the light level is too high or too much heat is generated in the laser this deterioration takes the form of instantaneous damage, but when suitable precautions are taken the effect is not measurable even after several thousands of hours of operation.

The laser gradually deteriorates during use; the threshold current increases and the light/current characteristic above the threshold becomes less steep (*fig. 13*). The rate of deterioration, however, depends strongly on the temperature; a rise of 30°, for example, reduces the life by a factor of about 15. If care is taken to keep the temperature under control, the laser will have a long life; life tests have shown that at a light level of 5 mW and an ambient temperature of 30 °C the quality of many lasers has hardly changed after 10 000 hours of operation.

There are various reasons for the deterioration in performance. In the first place, crystal defects that have formed outside the active region during growth or during assembly may grow into this region. Defects may also change position under the action of the injection current and so penetrate into the active region. (It may also happen that defects leave the active region, as is evident from the improvement in the light/current characteristic that is sometimes observed during 'burning in'.) Finally, as noted earlier, the mirrors are sensitive elements since they contain many crystallographic defects because they are cleavage planes. These defects induce non-radiative heat-producing recombination processes that cause chemical changes in the material, and they can also induce a kind of punch-through effect at very high light intensities. These various effects rarely occur at room temperature but are activated by the light and heat developed in the operating laser.

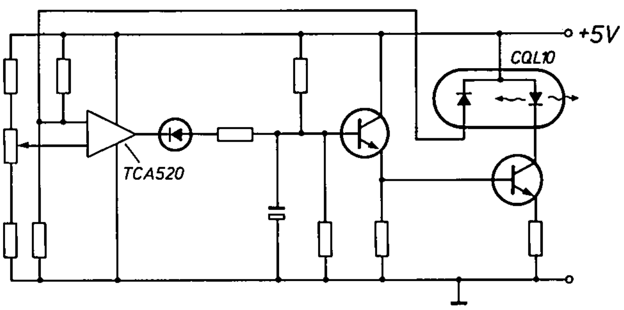

Fig. 14. Circuit for stabilizing the light flux from the laser. In the diagram of the laser (*CQL10*), the diode symbol on the right represents the laser crystal, the one on the left represents the photodiode. The circuit contains feedback; the photodiode records the light flux from the laser and controls the supply current so as to correct for variations in the light flux.

Electrically, the CQL10 is a diode with a knee voltage of about 1.6 V and a series resistance of about 2Ω. To obtain a current in the forward direction, it is preferable, because of the steepness of the *I-V* characteristic at the operating point, for such a diode to be supplied from a current generator. However, if the laser is directly connected to a current generator, the light level will tend to fluctuate because the *L-I* characteristic is also very steep and may vary as a result of temperature fluctuations or ageing. The photodiode behind the laser crystal in the CQL10 can be used for stabilization of the light level, which is required in many applications. *Fig. 14* gives an example of a power-supply circuit that will keep the light level constant with the aid of the photodiode.

When in use, the laser must be carefully protected from current surges that produce excessively high optical fluxes; in such cases deterioration is so fast that it is more accurate to speak of instantaneous damage. Such damage may even be caused by relatively small current peaks of very short duration (nanoseconds) because the characteristic curve is so steep, and the laser is also so fast that it can follow variations at frequencies in the gigahertz region. It is therefore of primary importance to protect the laser from voltage peaks, e.g. from the mains supply. Precautions should also be taken when switching on or off, since this can often cause large variations in current; it is recommended that the power supply should be turned down and the laser short-circuited before switching on or off.

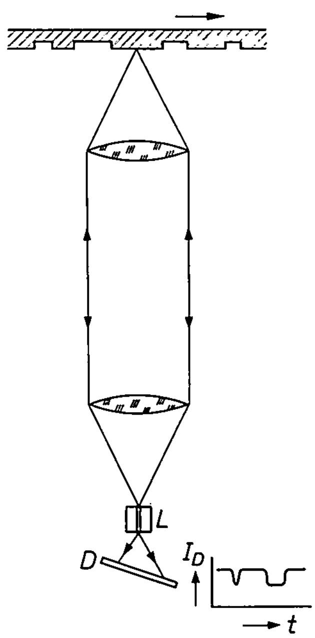

Fig. 15. Diagram illustrating detection with feedback. The light that is reflected by the disc is fed back to the exit mirror of the laser crystal (*L*). The laser reacts to this by an increase in the emitted power. Fluctuations in the reflected light are therefore reproduced in the current I_D in the detector *D* behind the laser crystal.

Detection of the information signal by feedback

Finally, we shall discuss the possibility of detecting the information in the reflected light by means of the laser itself. In this case the reflected light is not coupled out (see fig. 1), but fed back to the exit mirror of the laser (*fig. 15*). The laser crystal then reacts to variations in the light reflected by the disc with variations in the emitted power; these are detected by the photodiode [9]. (When a stabilizing circuit like the one shown in fig. 14 is used, the variations should of course be fast compared with the response time of this circuit.)

On closer examination of the 'feedback effect' it appears that the laser reacts to feedback with a shift of the light/current characteristic towards lower current values (*fig. 16a*); for a given current intensity, therefore, more power is obtained from the laser with feedback than without. In the first instance this is quite understandable: because radiation is fed back, the laser has effectively smaller radiation losses (a higher Q) and — for the same current — it therefore starts to oscillate at a higher level. The feedback effect is really a very complicated effect: the laser cavity is coupled to an 'external cavity' (laser mirror, optical system and reflector) and this coupling results in a fine structure for every laser mode [10]. We shall not go into these complications in detail, but merely point out that the reaction of the laser here is relatively simple because the coherence length is much smaller than the optical pathlength.

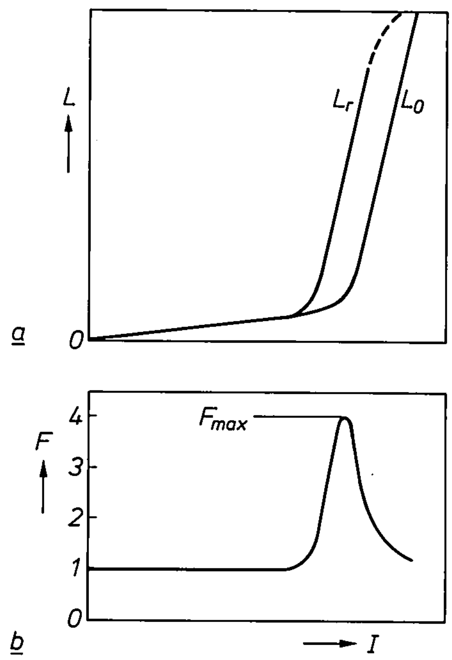

Fig. 16. *a*) The *L-I* characteristic without feedback (L_0) and with feedback (L_r). In the main the effect is to decrease the threshold current: *b*) 'Feedback factor' F (= L_r/L_0) as a function of I. It can be seen from (*a*) that F must have a maximum when the current is close to I_{th}.

In detection we are concerned with the 'feedback factor' F, i.e. the ratio L_r/L_0 of the optical power with feedback to that without feedback. It follows from fig. 16*a* that F plotted as a function of the current will have a maximum (F_{max}) in the vicinity of I_{th} (fig. 16*b*). F is also highly dependent on the external optical system, of course.

We use the arrangement of *fig. 17a* to test laser crystals for sensitivity to feedback. When the mirror S is located in the image of the laser mirror ($z = 0$) about 2% of the light is fed back. This is reduced to zero by even a very small shift in S. The photodiode signal as a function of z thus provides the feedback factor directly for this arrangement (fig. 17*b*). The mirror is attached to a vibrating loudspeaker cone and the curve of fig. 17*b* can be read off an oscilloscope. With this arrangement we find values for F_{max} that vary from 5 to 20 depending on the dimensions and composition of the wafer from which the laser crystal originates.

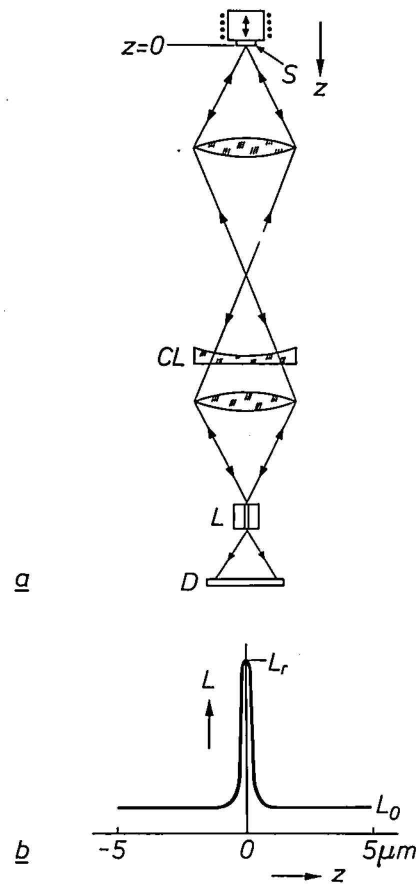

Fig. 17. *a*) Arrangement for measuring the feedback factor. *L* laser, *D* detector. The mirror *S* is placed on a vibrating loudspeaker cone. *CL* cylindrical lens. *b*) The radiated power as a function of the position *z* of the mirror.

A device for reading out information stored in

[9] See for example the article of note [1].

[10] Y. Mitsuhashi, T. Morikawa, K. Sakurai, A. Seko and J. Shimada, Optics Comm. **17**, 95, 1976.
C. H. F. Velzel and R. P. Brouwer, IEEE J. **QE-15**, 782, 1979.
C. H. F. Velzel, Ned. T. Natuurk. **A45**, 54, 1979.

tracks of pits as on a 'VLP' disc is a very complex unit. Whether the detection method outlined here will be used for this purpose depends on a complex of factors that we shall not discuss here. In the CQL10, however, this possibility has been taken into account in the sense that the photodiode that detects the laser power is fast enough to follow the variations that represent the information flow.

Summary. The CQL10 is a semiconductor laser for read-out of the information on a 'VLP' disc, a 'Compact Disc', a 'DOR' disc or similar devices. It is about 1 cm in size and operates from a voltage of 2 to 3 V. The laser crystal is a substrate of GaAs with epitaxial layers of $Al_xGa_{1-x}As$. With $x = 0.16$ for the 'active' layer the wavelength obtained is short enough (780 nm) for the intended application. The value of x for the 'cladding' layers is 0.46. Proton implantation is used to limit the flow of current and the laser activity to a narrow stripe 5 μm wide. The end mirrors of the laser cavity are formed by cleavage planes. The crystal, in good thermal contact with a heat sink, is mounted in an encapsulation with a window and connecting pins. The threshold current for laser operation is about 120 mA at 30 °C and has not increased by more than 30% at 60 °C. The light/current characteristic is very steep above the threshold. The spectrum consists of lines at a spacing of about 0.3 nm. The beam is strongly divergent and is slightly astigmatic. Laser deterioration is not usually noticeable even after 10 000 hours of correct operation, but care must be taken to avoid voltage peaks so as to protect the mirrors. A photodiode in the encapsulation can be used for electronic stabilization of the light flux and for detection of the information signal by feedback to the laser.