INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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H4.SMR/453-1

TRAINING COLLEGE ON PHYSICS AND CHARACTERIZATION OF LASERS AND OPTICAL FIBRES

(5 February - 2 March 1990)

SOURCES for Fiberoptic Communications

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SOURCES

FOR

FIBEROPTIC COMMUNICATIONS

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In this chapter we discuss the optical sources that are extensively used in fiber communications. We show their geometry, electrical and optical characteristics, the electronic circuits to drive them and their interaction with the fiber.

Introduction

The most important sources for optical communications are light emitting diodes (LED's) and laser diodes (LD's). Both are semiconductor pn junction devices that emit light of a few milliwatts power when an electrical current flows in the forward direction of the diode. These solid-state devices must fulfill some important requirements if they are to be used in reliable fiber systems. A number of these requirements is listed below:

* size, weight and cost. The source must be small and light because it is to be used with fibers with small core (some µm radius for monomode fibers) and low numerical aperture. Also mass production for lowering the cost is necessary
* reliability. Long operating life and good stability of the performance are very important prerequisits for reliable fiber links
* output power and efficiency. What is important is the power coupled into the fiber core. As a consequence, not only enough light power must be generated by the source but the optical beam must have low divergence for better coupling efficiency. The power efficiency should be as good as possible, preferably at least 10%, and the waste heat should be kept low.
* wavelength. The light should be emitted at a wavelength where the fiber has low optical loss and low dispersion. The glass fibers employed usually today have their best values for loss and dispersion at wavelengths around 1.3 and 1.55 µm. Older systems, however, and also optical links for short distances, typically up to a few hundred meters, may use sources at 0.85 µm.
* spectral properties. The most important parameter is the spectral width because it affects the transmission bandwidth.
* Modulation. Practically all fiber systems use direct current modulation of the LED or LD. The light source must thus permit efficient current modulation up to the desired frequency.

THE LIGHT EMITTING DIODE LED

A LED for fiber communications works on the same principles as the visible LED's used as indicator lamps and in the electronic displays, Fig. 1. A shallow semiconductor pn junction is formed, the device is biased in the forward direction and the flowing current produces light which is generated near the junction. The portion of the light which escarpes the diode from the upper or front surface is used to transmit the information contained in the signal current.

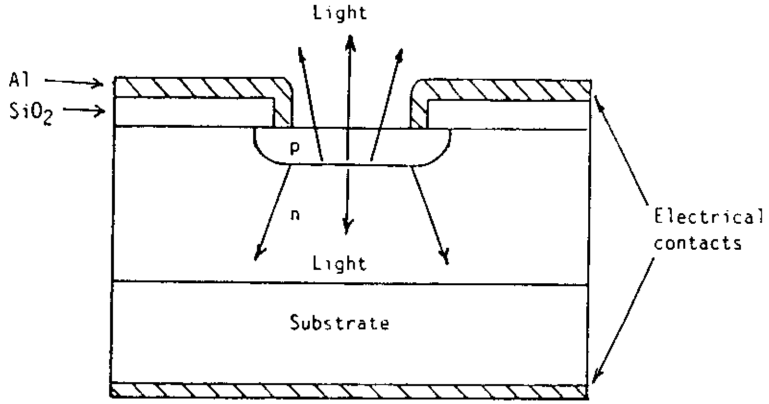

Fig. 1. Construction of a typical LED. The light emerging from the upper surface can be partially coupled into a fiber.

The main differences between LED's for displays and for communications are, apart the obvious difference in the wavelength of the emitted radiation, their geometry and the materials used. As a consequence, the LED's for communications have special characteristics that are unknown to the display LED's. They will be discussed later in this section.

The light emission process

But, let us first consider the fundamental question which pertains to the physical mechanism responsible for the light emission in a semiconductor diode. As is known from semiconductor physics, the energy states in a semiconductor form so-called energy bands. The band with the highest energy levels for electrons is called the conduction band which is followed, in decreasing energy direction, by the valence band, Fig. 2. These two bands are separated by an energy gap E_g. Now, in a semiconductor we have two kinds of electric charges that carry the electric current, electrons and the positively charged holes. The electrons that can be used for the current flow, so-called free electrons, are found in the conduction band which they partially fill, especially the botom levels. On the contrary, the holes are found in the upper levels of the valence band.

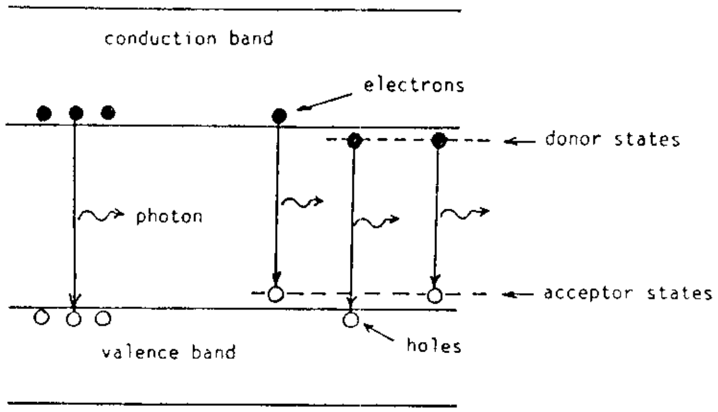

Fig. 2. Principle of light emission in semiconductors.

Electrons in the conduction band can now make transitions to the valence band where they recombine with holes. In this process, energy corresponding to the energy difference between the levels involved can be released in form of quants of light or photons. The energy of such a photon is

$h \cdot \nu$ h is the Planck's constant $6.626 \cdot 10^{-34}$Js,
ν the optical frequency

or

$\frac{hc}{\lambda}$ c is the velocity of light in vacuo
λ the light wavelength.

Since the energy levels involved are situated at the band edges, we write for λ

$$\lambda = \frac{hc}{E_g} \approx \frac{1.24}{E_g(eV)} \ \mu m, \ E_g \text{ given in electron-volt (eV)}$$

The formula shows that we can obtain the desired wavelength λ by choosing a semiconductor materials with the appropriate E_g. In the course of development of LED's for fiber optics, a number of semiconductors has been investigated and a few of them are now in wide use. Unfortunately, the principal material in the electronics industry, silicon, cannot be used as a light source. This is because the rate of radiative recombinations electron-hole in silicon is very low. The physical reason behind this fact is illustrated in Fig. 3a where the dependence of the conduction and valence band edges on the wave vektor $\vec{k}$ or momentum of the electron is depicted for a material like silicon. The transition of electrons from the lower levels of the conduction band to

the higher levels of valence band involves a change of the momentum.

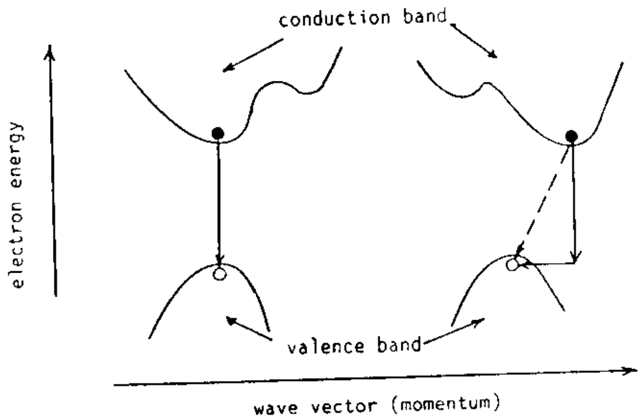

Fig. 3. Types of interband transitions, a) direct band gap semiconductor like Si, Ge, b) indirect band gap semiconductor like GaAs.

It can be shown that such transitions are quite improbable whereas they have a high probability in semiconductors having a band diagram given in Fig. 3b. Here the momentum is conserved during the transition as is the case in the compound material Gallium Arsenide (GaAs) which forms the basis for the industrial fabrication of many LED's.

LED structures

We now turn our attention to some basic geometric structures for LED's. The most widely used one is the double heterostructure (DH) LED, the principle of which is depicted in Fig. 4. A thin layer of a semiconductor, here the compound GaInAsP, is sandwiched between two layers of another semiconductor, here InP, doped as p- and n-type respectively. When current flows in the forward direction, electrons and holes meet and recombine in the middle layer. This is so because the middle layer has a smaller energy gap than the outer layers. Consequently, electrons and holes are forced to recombine in the middle layer (we call this a "carrier confinement") where the light is

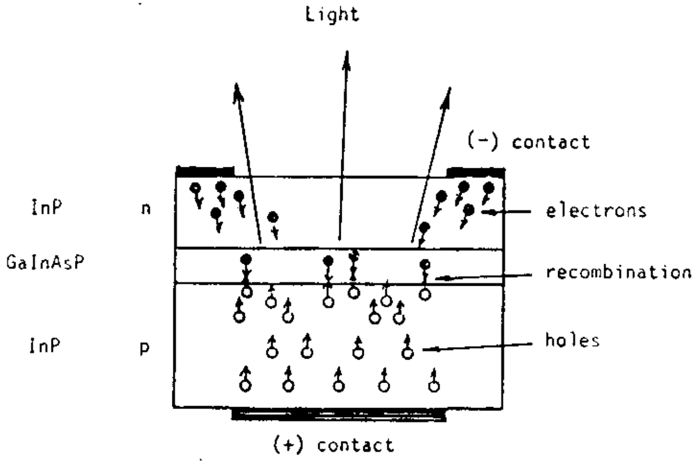

Fig. 4. Principle of the light emission in a double heterostructure LED

generated almost isotropically. The actual structure is, of course, somewhat more complicated. A possible structure is given in Fig. 5 where the light energing from the front (or upper) surface ("surface emitter") is focused through a microlens onto a fiber. These diodes can be made to generated light at 1.3 or 1.55 µm and have usually a circular light emitting area of 30-50 µm diameter for coupling into multimode fibers. Another example is the <u>double heterostructure GaAlAs/GaAs/GaAlAs</u> which is used as light emitter at 0.85 µm.

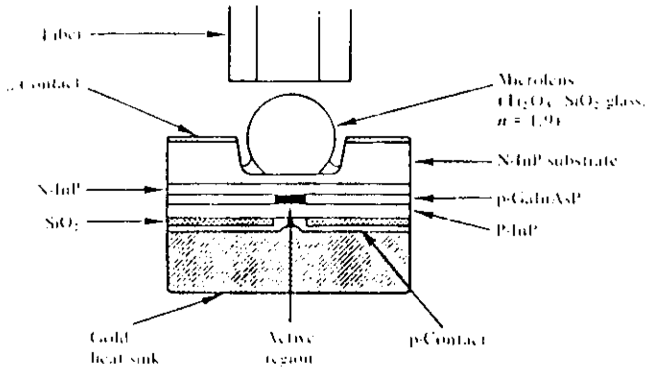

Fig. 5. Schematic cross-section of a double heterostructure LED for emission at 1.3 or 1.55 µm /2/.

Characteristics

Let us now turn our attention to the most important characteristics of LED's. The <u>current-voltage relationship</u> is that of a diode and given by the relation

$$I = I_s \ [\exp \left(\frac{eU - IR_s}{kT}\right) - 1]$$

I is the current, I_s the saturation current, U the applied voltage, R_s the sum of series, contact and lead-wire resistance, k the Boltzmann's constant $1.38 \cdot 10^{-23}$ J/K and T the temperature of the junction in Kelvin. The I-V relationship for a commercial DH LED emitting at 1.3 µ is given in Fig. 6. We see that if the applied voltage exceeds approximately 0.9 volts a current of a few mA begins to flow. Typical operating currents for LED's are between 50 and 150 mA.

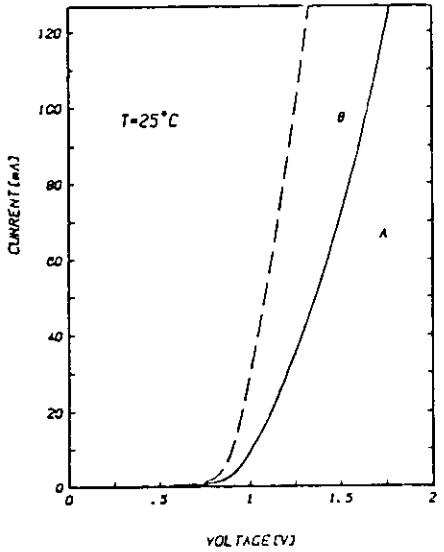

Fig. 6. Current-voltage relation for two DH InP/GaInAsP/InP LED's emitting at 1.3 µm (surface emitters).

The optical power of a DH LED at 1.3 µm as a function of diode current is shown in Fig. 7. The relationsship is more or less linear up to about 30 mA but heating effects deteriorate the light emission efficiency at higher currents.

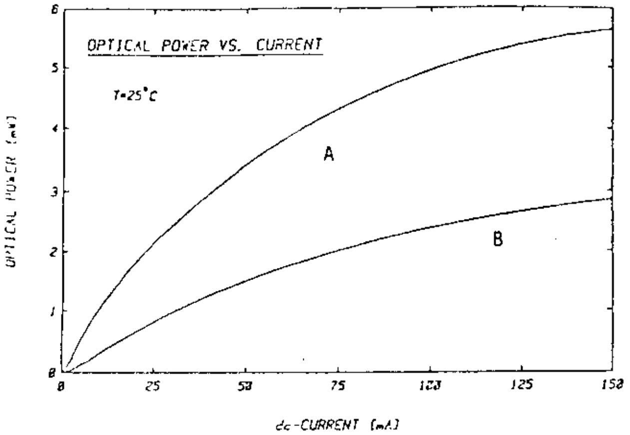

Fig. 7. Optical power versus dc diode current for two 1.3 µm DH LED InP/GaInAsP/InP, (surface emitters)

By pulsing the current, the linearity of the light-current characteristic can be extended to still higher currents. The same can be achieved by carefuly cooling the diode by means of a Peltier cooling element.

Spectrum

The spectrum of the LED radiation has a peak value at the characteristic wavelength of the device and a more or less broad spectral width at half peak intensity Δλ, as shown in Fig. 8 for two 1.3 DH LED's.

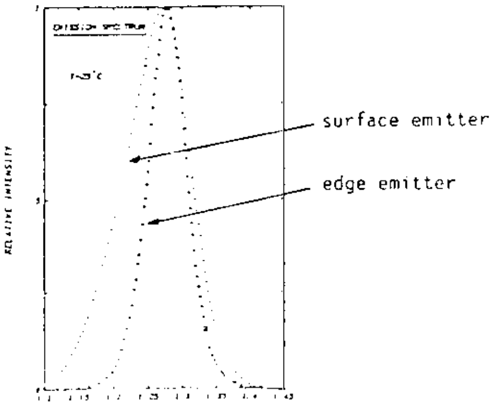

Fig. 8. Spectrum of two 1.3 µm DH LED's (surface emitter and edge emitter).

The values for Δλ depend strongly on the materials used for LED fabrication. At 1.3 µm a typical surface emitter LED has Δλ around 110 nm and at 1.55 µm Δλ increases to about 150 nm. These values are indeed very large compared to laser diodes (Δλ < 2-3 nm) and represent a severe bandwidth limiting factor because of the light dispersion in the fiber. This characteristic together with the low optical power coupled into a fiber have usually restricted the application of LED's to systems that have small bandwidths (some tens of MHz) or bit rates up to about 100 Mb/s.

LED-fiber coupling

Several methods have been investigated for coupling the light of an LED to an optical fiber. The simplest method is to place the fiber end in front of the LED as near as possible to the emitting surface, and to fix this arrangement with index-matching epoxy resin, Fig. 9.

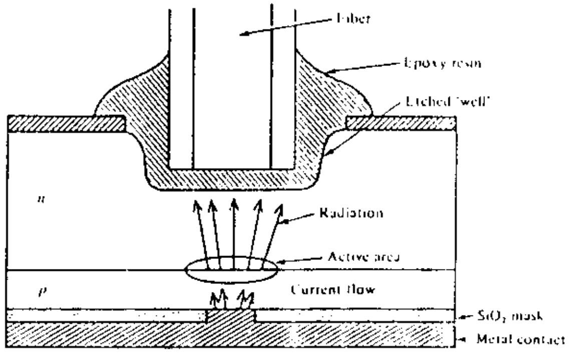

Fig. 9. LED-fiber coupling arrangement ("Burrus-type") /1/

The coupling efficiency is, unfortunately, very low. Only about 1% of the LED light will be coupled into a 50 µm core graded-index fiber and for monomode fibers the efficiencies are much lower. The reasons for these low efficiencies are a) the relatively large size of the emitting surface (about 30-50 µm diameter) and b) the wide angle beam because the radiation pattern is practically diffuse so that only a small portion can enter the fiber.

An improvement of the coupling efficiency is obtained by using a microlens on the LED as in Fig. 5 or by using a fiberend which is tapered and rounded to form a lens. Still, the efficiency remains low, around 2% for a 50 µm core fiber. A somewhat smaller beam angle can be achieved with structures where the light is not emitted perpendicularly to the junction plane but more or less parallel to it, as shown in Fig. 10. This device is called a "edge-emitting LED" and its geometry is similar to a laser diode. The emissive area is now small, typically 0.2x10 μm^2, and the full beam width of the light is narrow perpendicularly to the junction typically about 30°. The spectral width is about 70 nm and 100 nm for 1.3 and 1.5 µm diodes respectively. Better coupling efficiencies are now possible, around 10% with a 50 µm fiber. The power injected into a monomode fiber can reach about 50 to 100 µW.

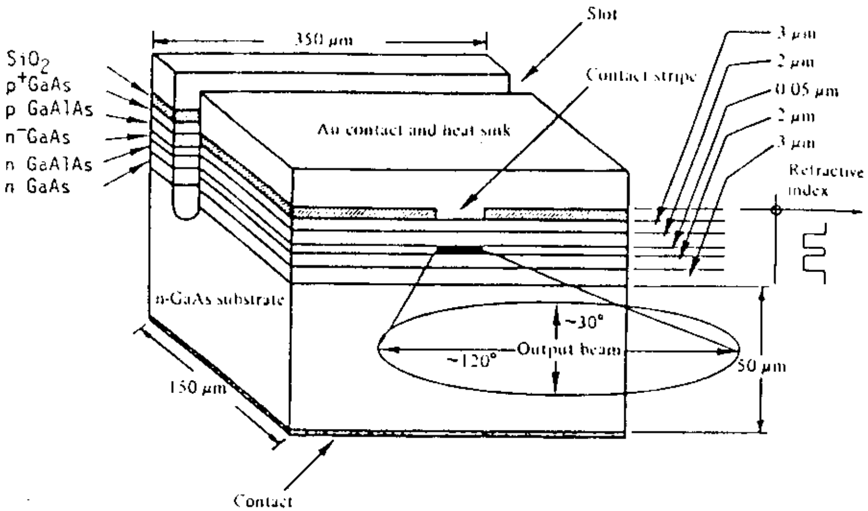

Fig. 10. Schematic illustration of a DH edge-emitting LED at 0.85 µm /2/

Temperature

The temperature has a significant effect on the LED. At constant diode current an increase in temperature results to a decrease of optical power. The additional current needed to maintain the optical power is 0.8% per °C in 0.85 µm LED's and around 2% per °C in 1.3 µm LED's.

Frequency response

The frequency response of an LED may be modelled quite well by the equivalent circuit in Fig. 11. R and L represent the total resistance resp. inductance of the leads to the device, the contacts and the bulk semiconductor. C_j is the junction capacitance - resulting from the charge stored in the depletion layer - but its effect on the frequency response can be neglected. This is so because C_j dominates the reverse bias behavior and the LED is always forward biased. On the contrary, the contribution of the diffusion capacitance C_d and of the resistance r_d to the frequency behavior is significant. C_d and r_d depend on diode current and represent the effect of the additional carriers that are stored outside the depletion layer so that a current I can flow.

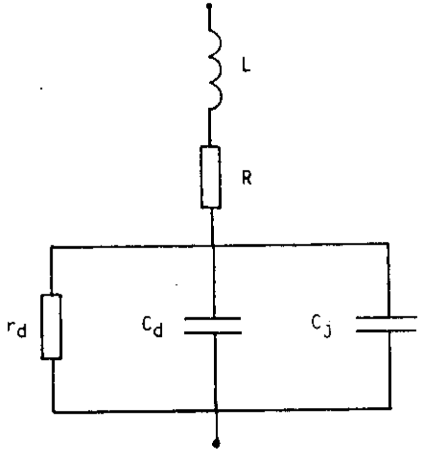

Fig. 11. Equivalent circuit of LED.

$$r_d \approx kT/eI \qquad \text{and } C_d \approx eI\tau/2\,kT$$

e is the electronic charge and τ the minority carrier lifetime. For a high-frequency response the product

$$r_d\, C_d \approx \tau/2$$

i.e. the factor τ must be made small. In practice, the modulation bandwidth (3 dB points) of LED's for fiber communications is usually less than 100 MHz but some special LED's have been fabricated with bandwidth exceeding 1000 MHz.

LED driver circuits

Practical circuits for LED modulation are shown in Fig. 12. In Fig. 12a the LED is switched on and off with the collector current of the transistor. When the switch is open, the transistor is switched off and no current flows through the LED. By closing the switch, the baseemitter diode becomes forward biased and a collector current flows through the LED. In Fig. 12b the resistors R_1 and R_2 bias the transistor at about the middle of its load line, i.e. into its linear region, so that a dc current flows through the LED when the

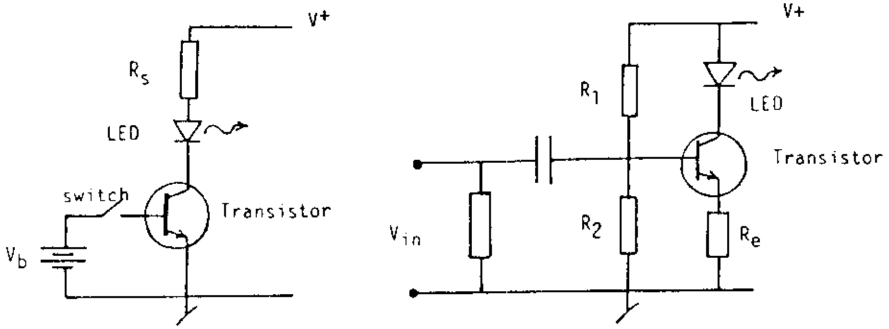

Fig. 12. LED modulation circuits. a) on-off modulation via a switch,
b) modulation of the LED optical power by the voltage V_{in}

voltage V_{in} is zero. The voltage V_{in} is then used to modulate the light of the LED by modulating the collector current of the transistor.

Newest reports from the research front indicate that LED's with modulation bandwidths around 1 GHz have been fabricated. The light coupling efficiencies into monomode fibers are being steadily improving. Also the optical bandwidth $\Delta\lambda$ has been significantly reduced, i.e. around 10 nm at 1.3 µm using "super-radiant" LED's. All these developments make the LED an attractive source for transmission of information in the Gbit/s range and for repeaterless distances in the order of 10 tO 20 km. This is a technological breakthrough because, up to now, these transmission capacities have exclusively been served by laser diodes.

THE LASER DIODE

In this chapter the characteristic performances and typical geometries of laser diodes (LD's) for optical communications will be outlined. The basic laser theory will not be presented but the important results pertaining to the operation of a LD will be briefly summarized.

The principle of laser operation

Let us consider a hypothetical atomic system with two energy levels E_1 and E_2, where $E_2 > E_1$, Fig.13, and an electron which is normally at level E_1 ("ground state"). This electron can absorb a photon that impinges onto the system and it can make a transition from E_1 to E_2 (Fig.13a). This process is only possible if the energy hv of the absorbed photon equals exactly the difference $E_2 - E_1$

$$h\nu = E_2 - E_1$$

After a short time τ (lifetime if the electron in the "excited" state) the electron will fall down spontaneously to its ground state E_1 by releasing the energy $E_2 - E_1$ as a photon of energy hv (Fig. 13b). This is the "spontaneous emission" process. There is, however, another possible electronic transition. The excited electron can be "triggered" to undergo the transition by a photon of energy hv (Fig. 13c). What is remarkable here is that the photon triggering the electronic transition $E_2 \rightarrow E_1$, is not annihilated in this process but continues its path whereas a new photon is generated. Moreover the two photons have identical frequencies, phases and states of polarization. This is the "stimulated emission" process and it gives us the possibility to amplify the number of photons, i.e. to amplify light power. The term "laser" is an acronym for light amplification by stimulated emission of radiation.

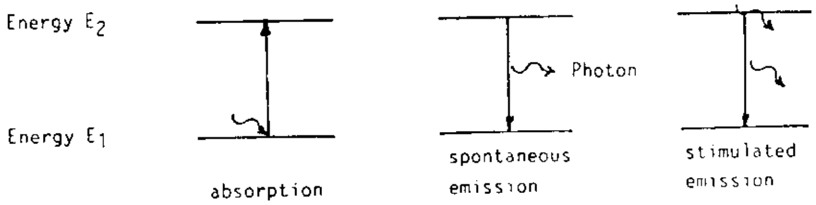

Fig. 13. Energy level diagram illustrating absorption (a), spontaneous emission (b) and stimulated emission (c).

But how can we construct a device that acts as a laser oscilator? If we borrow the idea from the classical electronic oscillator circuit, we need a light amplifier and a feedback mechanism for coupling part of the light output power back into the amplifier and which should incorporate some means for frequency tuning. Fig. 14 shows how all this can be accomplished with a DH diode. The electrons and holes that recombine in the middle layer ("active layer") produce spontaneously emitted rediation, just like in a LED. The difference with a LED lies in the fact that the two opposite end surfaces perpendicular to the active layer are formed as mirrorlike planes strictly parallel to each other. This configuration is called an optical resonator or Fabry-Perot resonator. Of all photons created in the active layer only those parallel to the junction can reach a mirror and be reflected back into the active layer. The number of these photons can be amplified as they travel back and forth between the mirrors provided that the rate of stimulated emission is greater than that of absorption. This can be the case if we inject through the diode current enough electrons into the active layer so that a condition known as "population inversion" is fulfilled. When the amplification of the light in the layer exceeds the losses (absorption, scattering, mirror losses and other losses) the laser oscillator starts operating. When this situation is reached a standing wave is created between the mirrors. Optical power that leaves the layer from the (partially reflecting) mirrors forms the laser beam.

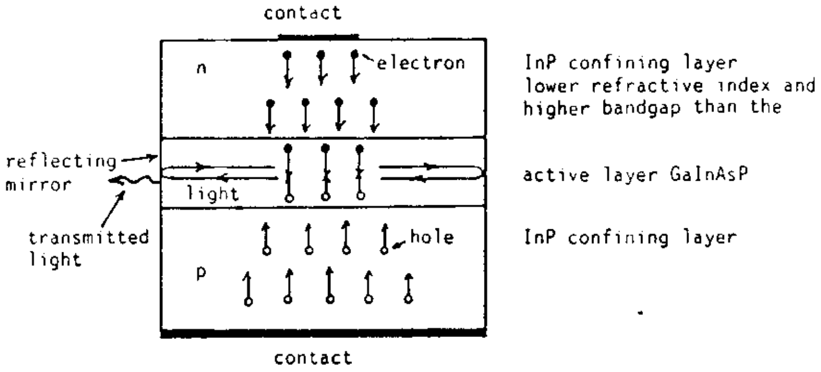

Fig. 14. Principle of a semiconductor laser with a double heterostructure.

The standing wave is illustrated in Fig. 15. It obeys the condition

$$\frac{\lambda}{2n} \cdot q = L$$

where L is the length of the layer (cavity length) perpendicularly to the mirrors, n the refractive index, λ the wavelength and q an integer. However, only a limited number of wavelengths can exist in the laser beam.

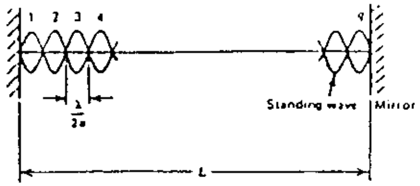

Fig. 15. Standing wave in a laser oscillator /3/

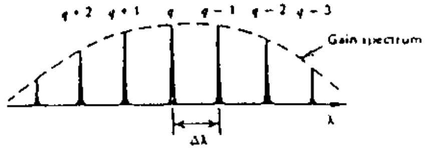

Fig. 16. Spectrum of longitudinal modes /3/

These wavelengths are called longitudinal or axial modes and are determined by the gain spectrum of the laser, Fig. 16 . They are closely spaced, the wavelength difference, so-called mode spacing, between them being:

$$\Delta\lambda = -\lambda^2/2nL$$

For example, in a 1.3 µm diode laser having n ≈3.4 and L = 300 µm, Δλ becomes 8 Å. The number q itself is very large, q ≈ 1615.

LD structure

The actual geometry of a typical 1.3 µm DH LD is given schematically in Fig. 17. Starting from a InP substrate, four thin layers are grown on top of it, the active layer GaInAsP being embeded between two layers of InP. This growth can be accomplished by a number of technological processes, like LPE (liquid phase epitaxy), MBE (molecular beam epitaxy) and MOCVD (metallorganic chemical vapor deposition). On the top of the last layer an isolating layer of SiO_2 is deposited that has a 5-10 µm wide groove in the middle so as to allow the application of a stripe metallic contact on the top of the laser. With this method the current distribution in the transverse direction is confined in the central region of the laser chip.

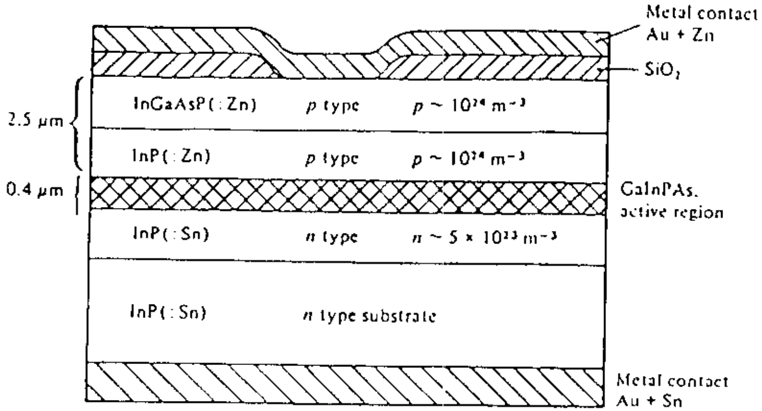

Fig. 17. Structure of DH diode laser with stripe geometry emitting at 1.3 μm /1/

In a DH diode the active layer has a higher index of refraction than the two adjacent layers. Oblique rays which originate in the active layer and are incident on the interfaces suffer total internal reflection. They are guided along the layer by multiple reflections until they reach the end mirrors where they are again reflected back into the layer. We call this an "optical confinement".

In the laser above the lateral confinement of the active zone is achieved by the current flow ("gain guided" laser). It is also possible to confine the zone by using lateral material of lower refractive index ("index guided" laser). In both types typical zone dimensions are 5-10 μm width and 0.1-0.3 μm thickness.

Practically all commercial LD's have a geometry that restricts the diode current to a small region along the junction plane. The simplest current restricting mechanism is the oxide stripe laser where a SiO$_2$ layer on the p-material confines the current flow through an opening in the dielectric. Fig. 18i. Another widely used method is to create regions of high resistivity by implanting protons or deuterons and to let an opening for the current flow. Fig. 18ii. Also, by Zn-diffusion one can convert a small region of a top n-type layer into a p-type, thus providing a current path. Fig. 18iii.

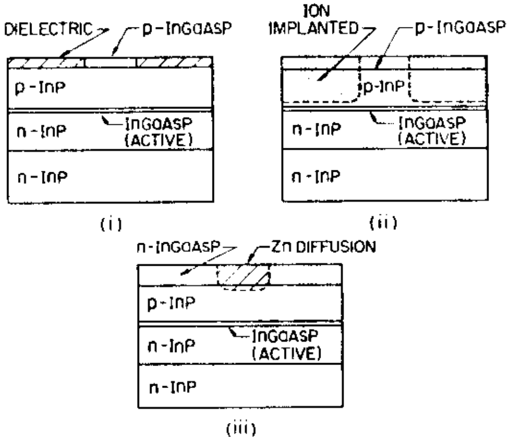

Fig. 18. Gain-guided laser structures, see text [5].

In the above structures, the stimulated emission is determined by the carrier distribution which provides a gain distribution along the junction. They are called gain-guided lasers. Although these LD's are used in many applications, they may present some problems as optical communication transmitter devices. They have the tendency for self-pulsations and they show non-linearities in the light-current characteristics, called kinks. The mode guiding in the lateral direction is poor because the effective optical index depression caused by the flow of carriers is weak, about 4 10^{-3}.

The index-guided LD is broadly used in optical communications, especially above 1 μm. There are two sub-families. The weakly index-guided laser is shown in Fig. 19 for different geometries.

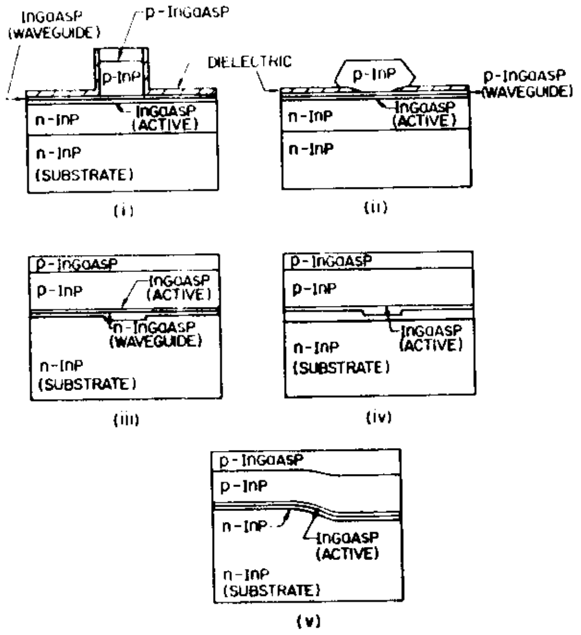

Fig. 19. Weakly index-guided lasers, see text [5].

The most studied LD's of this type are: the ridge waveguide laser (RWG), Fig. 19i; the heteroepitaxial ridge overgrown laser, Fig. 19ii; the channeled substrate planar laser (CSP), Fig. 19iii; the rib waveguide laser, Fig. 19iv; and the terraced substrate laser, Fig. 19v. In those lasers, the lateral index step is about 10^{-2} and so the lateral mode confinement is much better than in the gain-guided type. They are, however, more difficult to fabricate.

The strongly index-guided laser allows a much larger index step in the lateral direction, about 0.2. The active region is buried in high band-gap, lower index material (burried heterostructure laser (BH). Fig. 20 shows some of the geometries with planar active layer: (i) etched mesa buried heterostructure EMBH; (ii) double channel planar buried heterostructure DCFBH; (iii) planar buried heterostructure; and (iv) strip buried heterostructure. Buried heterostructure lasers have low threshold currents, 10 to 15 mA, output powers of lo to 15 mW in the fundamental transverse mode and can be current modulated in the multi-GHz region

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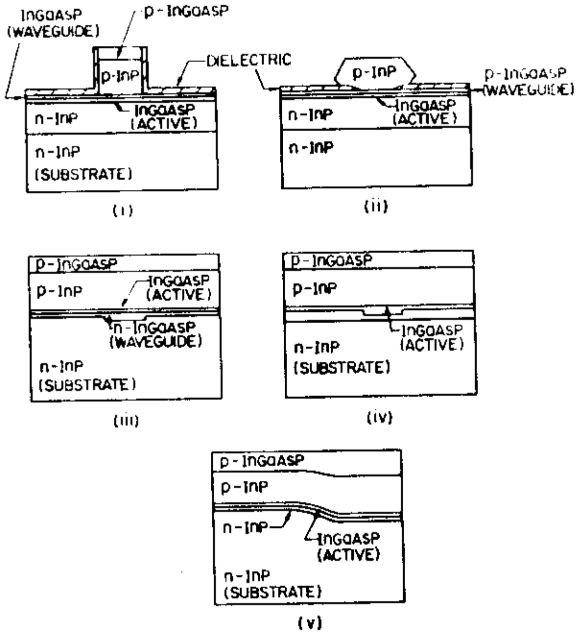

Fig. 19. Weakly index-guided lasers, see text [5].

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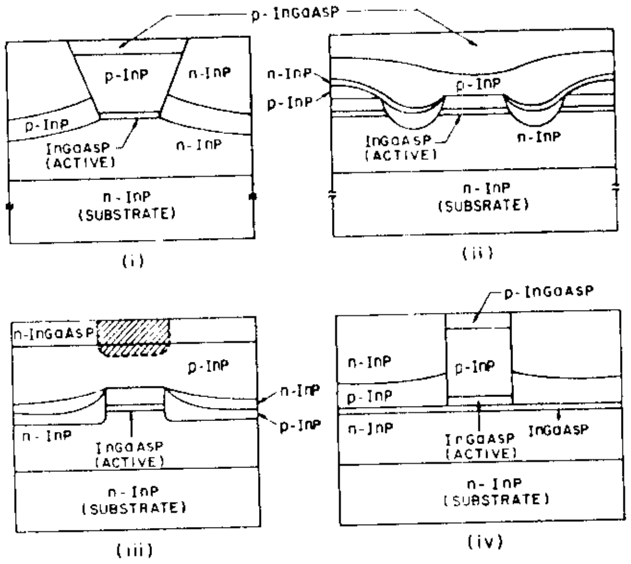


Fig. 20. Planar buried heterostructure lasers, see text [5].

LD characteristics

At low currents, electrons and holes recombine in the active region and create predominantly spontaneous rediation. At a certain current, the optical gain exceeds the losses in the resonator and predominantly stimulated radiation is created.

This point is called threshold of oscillation and the corresponding bias current the threshold current, Fig. 21.

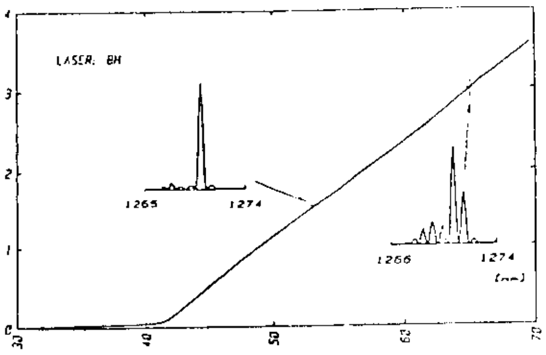


Fig. 21. Light-current characteristic of a 1.3 µm laser diode. The spectrum is also given at two operating points.

The differential gain in the stimulated (laser) region is about 0.2 mW/mA for 0.85 µm and 0.15 mW/mA for 1.3 µm LD's.

Temperature

The gain of the LD decreases with temperature. The threshold current rises by about 1% per °C heatsink temperature in 0.85 µm lasers and by 2% per °C in 1.3 µm lasers, Fig. 22.

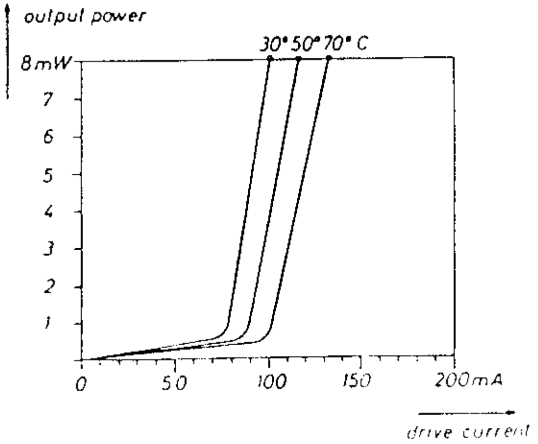


Fig. 22. Effect of temperature on the laser diode.

Also the wavelength is temperature dependent. It increases by 1 nm per 3 °C for 0.85 lasers. For these reasons LD's are in practice temperature stabilized by using Peltier-type thermoelectric coolers.

Spectrum

Gain guided lasers typically show multi-longitudinal mode behavior. Their spectrum consists of 10-20 axials modes, as seen in Fig. 23 for a 0.85 µm laser.

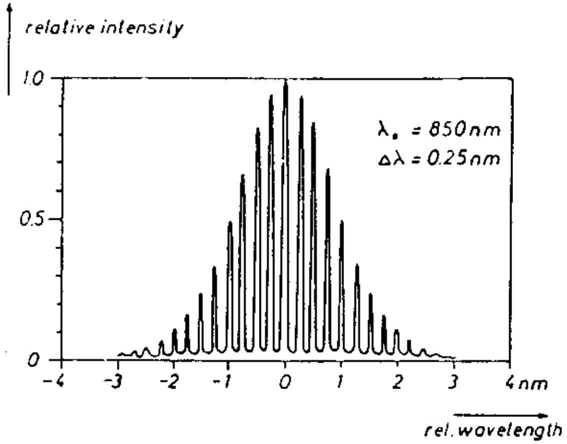


Fig. 23. Multimode spectrum of a gain guided 0.85 LD.

The overall spectral width is about 2-5 nm and the mode spacing about 0.2 - 0.3 nm. The line spacing of 1.3 µm LD's is about 0.8 nm, Fig. 24.

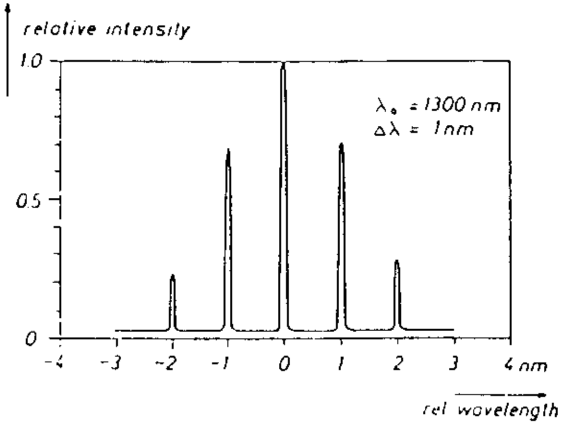


Fig. 24. Spectrum of a gain guided LD at 1.3 µm.

Index guided lasers typically have fewer axial modes than gain guided lasers or even only one mode (monomode laser), Fig. 25. The problem with monomode

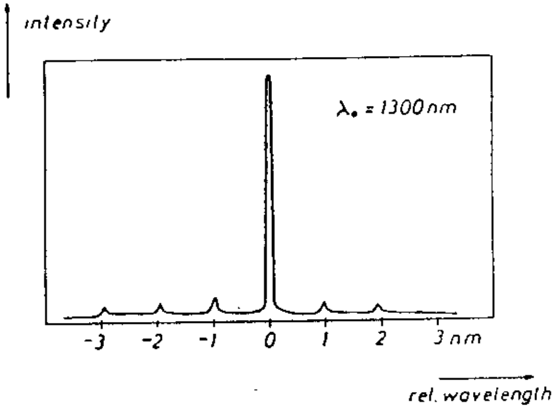


Fig. 25. Spectrum of a monomode laser at 1.3 µm, dc operation.

lasers is that they tend to become multimode when they operate under pulsed current conditions. This decreases the performance of high-speed long-haul digital systems because of chromatic dispersion and of added noise. The chromatic dispersion is due to the wavelength dependese of the speed of light in the fiber and causes pulse broadening and intersymbol interference.

LD noise

The noise of the laser is associated with the random fluctuations of the optical power and has several reasons. It is well known that when classical "white" light, i.e. light from an incandescent lamp, is detected by a semiconductor detector diode, so-called "shot noise" is generated in the photocurrent. When light from a LD is detected, additional noise arises caused by the laser emission process. This noise increases with increasing optical lasing threshold and decreases at higher currents, Fig. 26.
There is another reason for laser noise that is seen when the light signal is detected at the end of the fiber. This is the mode competition noise, also called mode partition noise. In a multimode laser all modes are always competing with each other and the spectrum is time dependent. The spectra of Figs. 23 and 24 are time averaged. If one mode is isolated from the others, its noise increases dramatically and is 30-40 dB higher than the noise of all the modes taken together. This effect does not exist in monomode lasers.

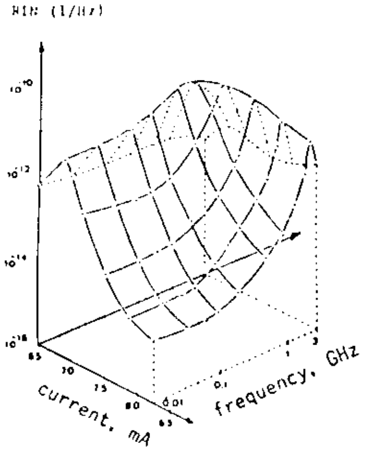


Fig. 26. Laser noise dependence on diode current and on frequency. RIN means the relative intensity noise and is the ratio of the optical intensity noise density to the square of the mean optical intensity.

Under pulsed conditions however, a monomode laser becomes multimode, the dispersion of the fiber separates the modes and consequently higher noise is measured at the fiber end.

One of the main development efforts is the fabrication of LD's with truly monomode radiation even under high pulse repetition rates and large on/off ratios ("dynamic monomode laser"). Fig. 27 shows one of the several device geometries that have been proposed to that effect. It is called the distributed feedback laser (DFB) and it incorporates a corrugated region which

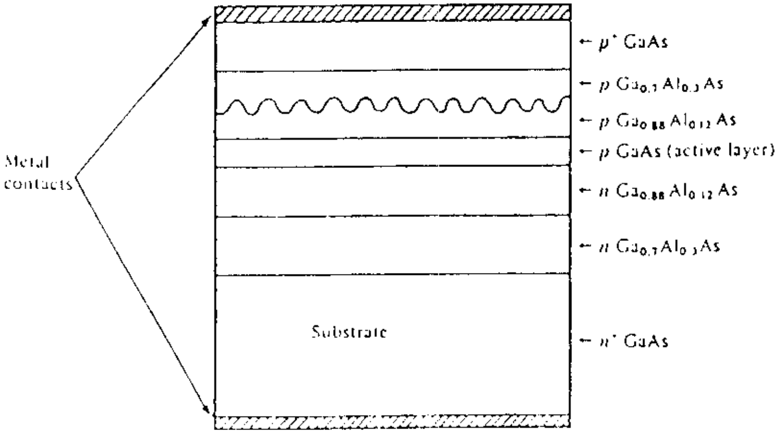


Fig. 27. Cross-section of a DH distributed feedback laser device based on GaAs/GaAlAs /1/

acts as a sharp tuning mechanism for a single axial mode.

Another noise source in a LD is the optical feedback noise. Its origin is the light reflected back into the laser from the fiber input face or from other interfaces. This light disturbs the laser oscillation causing random, sometimes wild fluctuations of the light power. Usually, monomode lasers are more sensitive to it than multimode lasers. One way to avoid it is to use antireflex-coating fiber faces, tapered fiber inputs or optical isolators.

Coherence

Laser radiation is said to be coherent. The degree of coherence reflects the ability of different parts of the light wave to interfere with each other. The coherence is called temporal if the phases of the waves are stable within the coherence time or spatial if it relates to the interference ability between two portions of the wave in a surface transverse to the direction of propagation. The temporal coherence length, i.e. the length over which interference in the axial direction may be achieved is

$$l_c = \lambda^2/2\pi n\Delta\lambda$$

where n is the index of refraction in the propagation medium. A 0.85 μm multimode GaAs/GaAlAs LD with $\Delta\lambda$ = 3 nm has only l_c = 38 μm (n = 1, air). In contrast a well stabilized monomode laser could have $\Delta\lambda$ = 0.01 Å and l_c becomes 11.4 cm. In this case the coherence time t_c would be

$$t_c = l_c/C \simeq 400 \text{ ps}$$

c is the velocity of light in the air.

Multimode operation reduces the temporal coherence but the spatial coherence remains practically the same.

Radiation pattern

The radiation pattern of a LD, i.e. the space distribution of the light intensity away from the laser diode ("far-field") has typically an elliptical shape which is due to optical diffraction effects at the boundaries of the resonator cavity, Fig. 28.

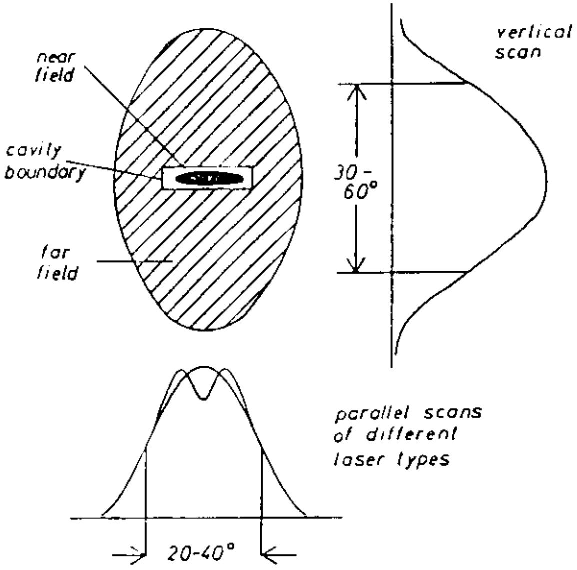


Fig. 28. Far-field and near-field radiation pattern of LD /4/

The full angle at half peak intensity is quite large, 30-60° in a plane vertical to the junction and 20-40° in a plane parallel to the junction. The "near-field", i.e. the light intensity distribution on the radiating surface of the LD is also more or less elliptical in shape. The problem with the near-field is that it has an astigmatism and may cause difficulties when imaging the laser facet through a lens to a fiber core. The use of cylindrical lenses may ease the difficulty.

Polarization

The light from LD's is partially polarized. This contrasts with LED's that emit non-polarized light. The direction of polarization is parallel to the junction and the degree of polarization can be better than 90% when the LD is operated well into the lasing region.

Bandwidth

The modulation bandwidth of LD's is much larger than that of LED's and exceeds usually 500 MHz reaching as far as 3 GHz. Lately, some new laser structures have been proposed that show modulation bandwidths greater than 15 GHz.

Optical power

The optical power of LD's is also much higher as compared to LED's. The usual power levels of LD's at dc operation are between 5 and 20 mW, although LD's having more power have also been constructed.

Coupling to fibers

What is important in a transmission system is the power coupled into the fiber. Also in this resped LD's are superior to LED's because the laser beam is narrower which results to a higher coupling efficiency. Some typical methods of coupling between a LD and a graded-index multimode fiber (50 µm core diameter) are illustrated in Fig. 29. Direct coupling (butt-joint) results to about 35% efficiency (a). If the fiber end is molten as a spherical lens, about 50% efficiency is obtained (b). Still higher efficiency (about 60%) is achieved, when a tapered fiber is used (c). High efficiencies of about 60% are also reached, if a "selfoc" lens is placed between LD and fiber.

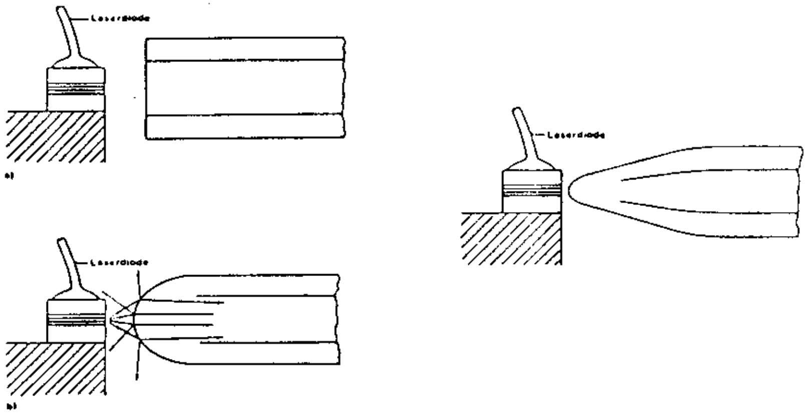


Fig. 29. Some coupling methods between LD and multimode fiber.

Care must be taken when coupling LD's to monomode fibers because of the small dimensions (a few µm core diameter) of the latter. The use of taperlensed fiberends has been very successful. Coupling efficiencies of about 45% can be achieved.

For further reading

[1] J. Wilson and J.F.B. Hawkes, Optoelectronics: An Introduction, Prentice-Hall Intern. Series in Optoelectronics, 1983

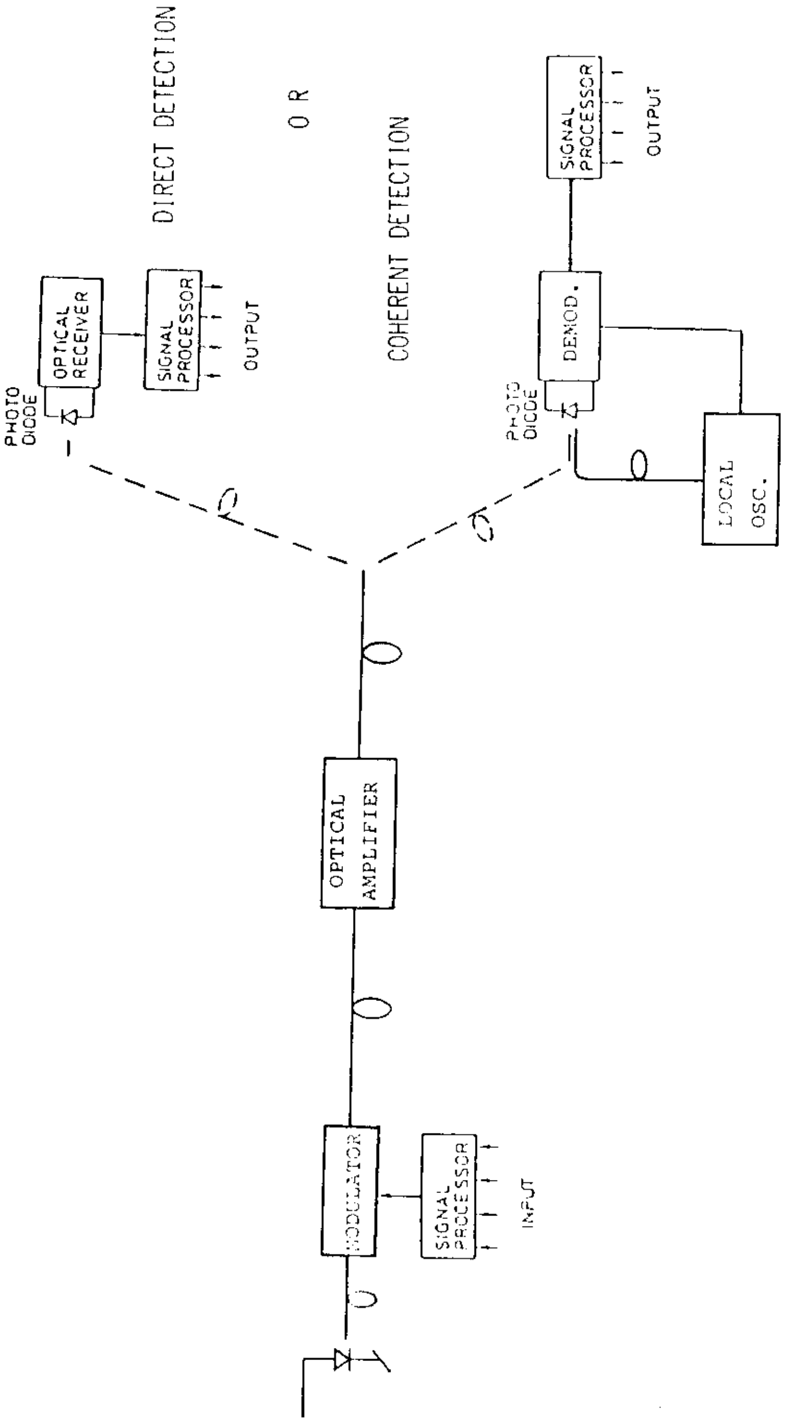
[2] John Gowar, Optical Communication Systems, Prentice-Hall Intern. Series in Optoelectronics, 1984

[3] Y. Suematsu and K.-I. Iga, Introduction to Optical Fiber Communications, John Wiley, 1982

[4] Hewlett-Packard, Fiber Optics Handbook, published by Hewlett-Packard GmbH, Boeblingen, 1983

[5] G.P. Agrawal and N.K. Dutta, Long Wavelength Semiconductor Lasers, Van Nostrand, 1986

ADVANCED HIGH-CAPACITY POINT - TO - POINT COMMUNICATION LINK



LINK DISTANCE LIMITATIONS

OPTICAL POWER LIMIT:

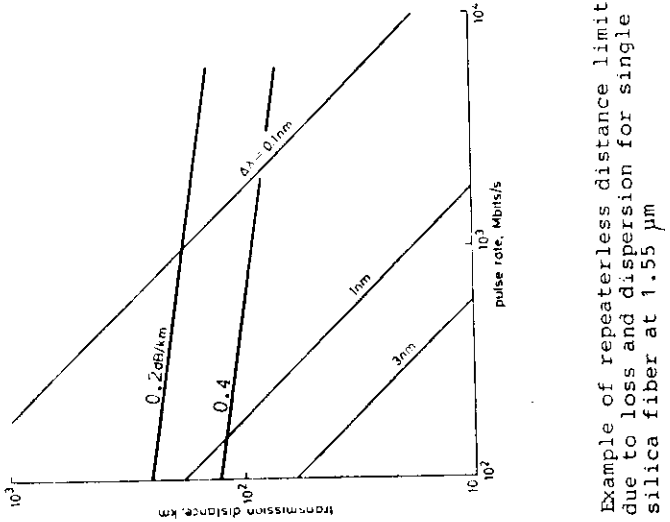
$L = (P_L - P_R - M) / \alpha$

P_L: POWER INTO FIBER
P_R: POWER AT RECEIVER FOR BER 10^{-9}
M: MARGIN
α: FIBER LOSS

DISPERSION LIMIT:

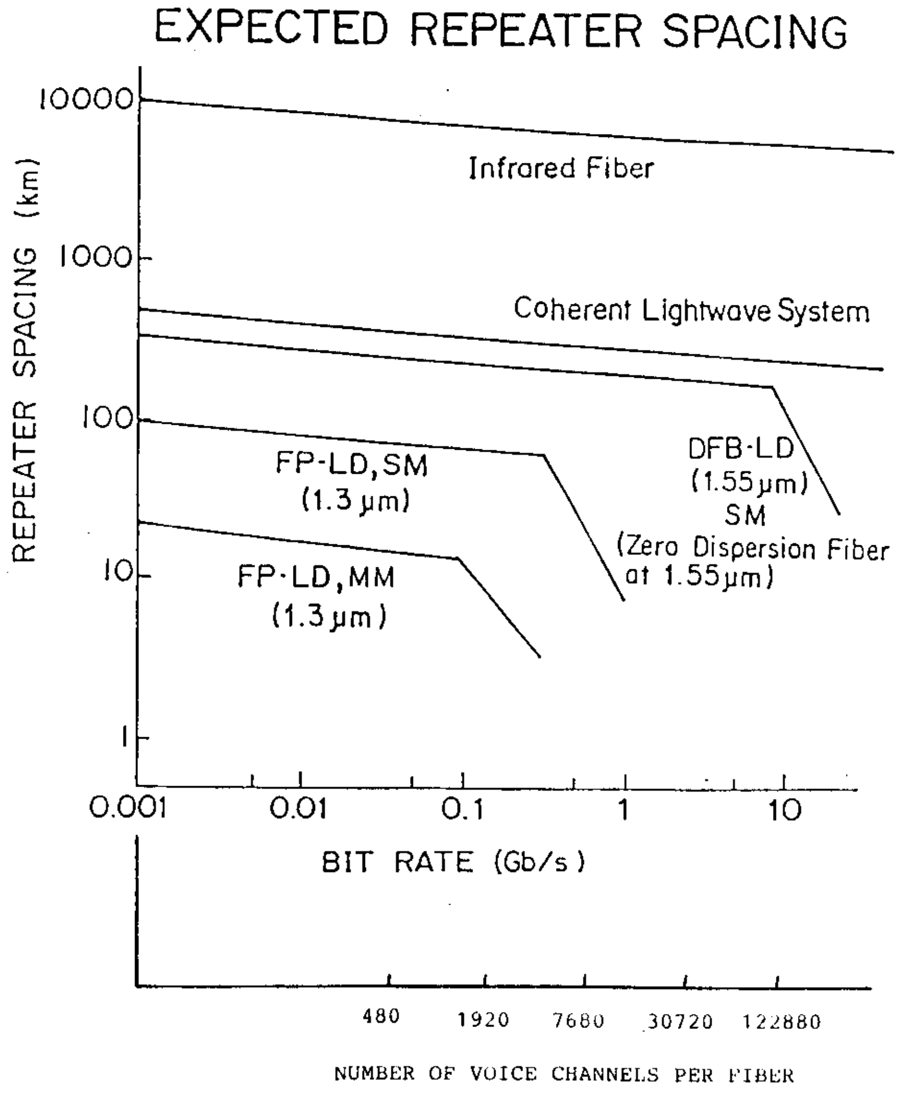
$L = 1 / 2 B \sigma \Delta\lambda$

B: BIT RATE
σ: FIBER DISPERSION
$\Delta\lambda$: SOURCE LINEWIDTH

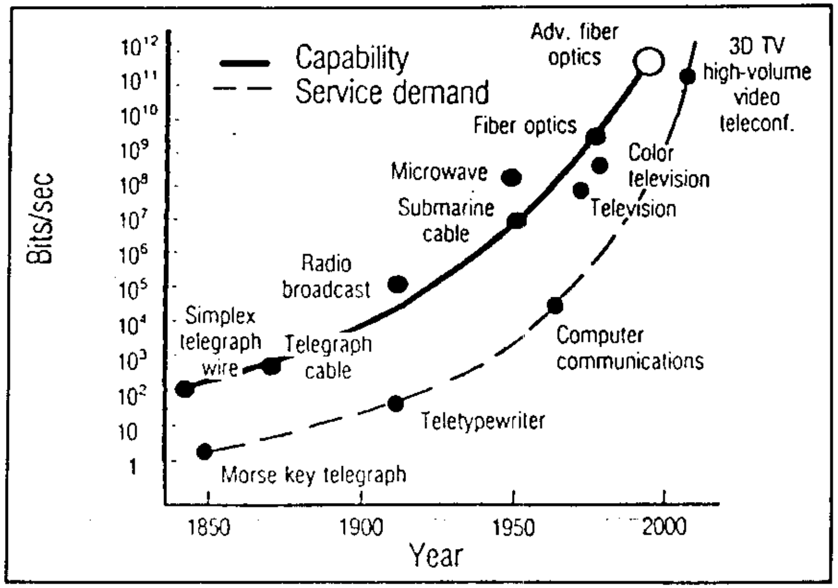


Example of repeaterless distance limitations due to loss and dispersion for single mode silica fiber at 1.55 μm

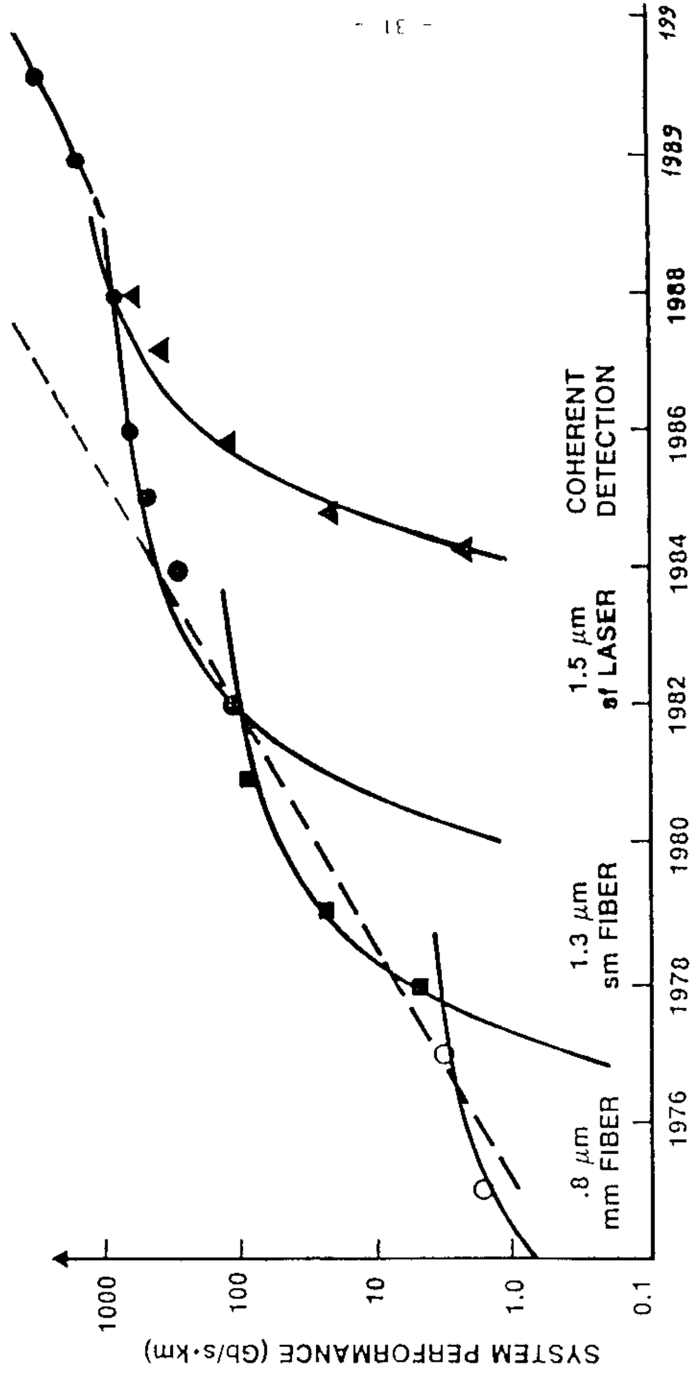
FIBEROPTIC POINT-TO-POINT LINKS



DEVELOPMENT OF TELECOMMUNICATION CAPACITY AND SERVICE DEMAND



LIGHTWAVE PROGRESS

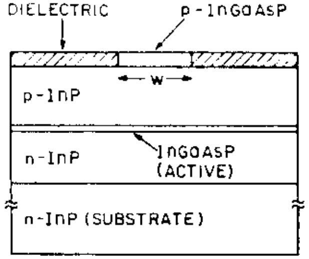


(Adapted from R.Linke, AT&T Bell Labs, 1988)

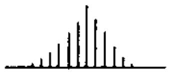
LASERS FOR FIBER COMMUNICATIONS

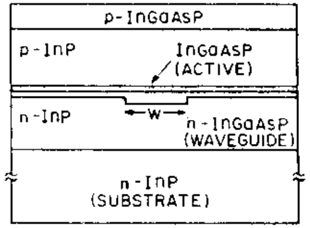
LASER STRUCTURES

SPECTRA

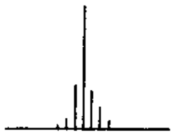


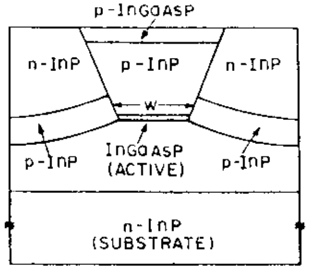
GAIN GUIDED





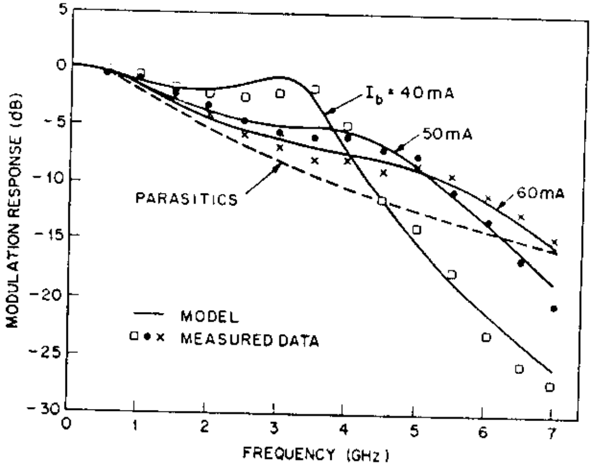
WEAKLY INDEX GUIDED





STRONGLY INDEX GUIDED

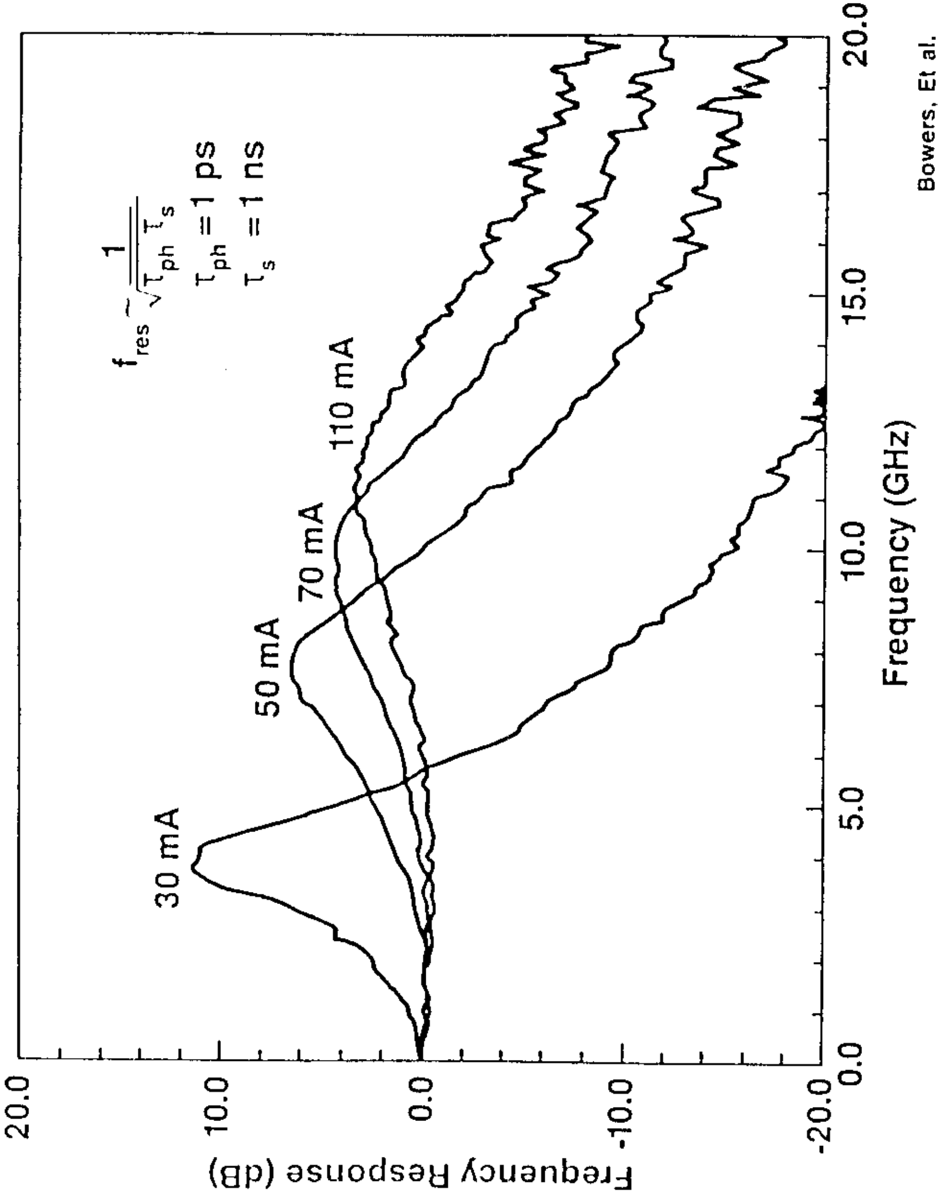
SMALL SIGNAL MODULATION RESPONSE, BH LASER



Tucker, LT 84

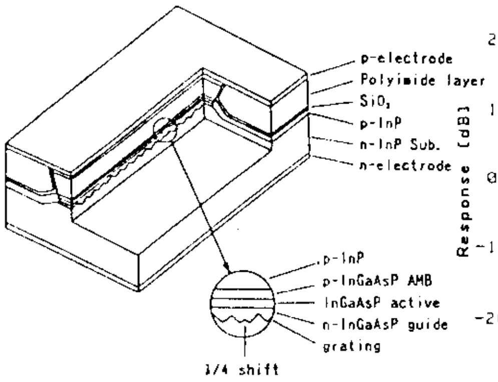
PARASITIC ELEMENTS DEPEND ON STRUCTURE

- EXTERNAL, LIKE BOND WIRE INDUCTANCE
- INTERNAL, LIKE CAPACITANCE FROM OXIDE AND CURRENT BLOCKING LAYERS

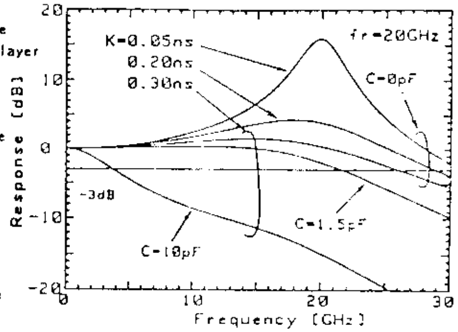


Bowers, Et al.

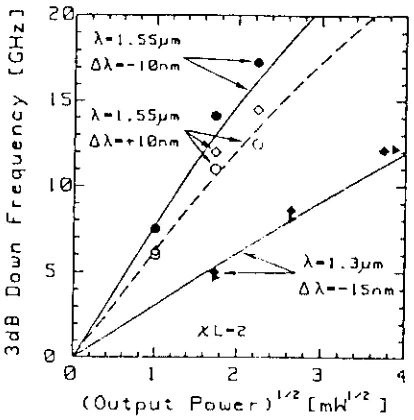
HIGH-SPEED SEMICONDUCTOR LASERS

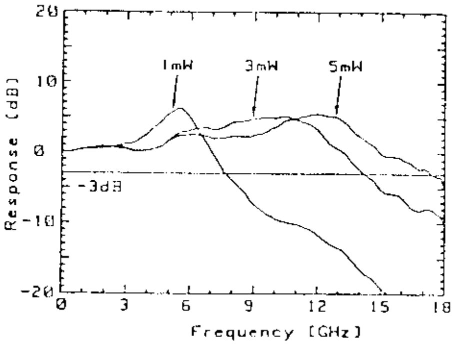


Schematic structure of high speed PIQ-BH λ/4-shifted DFB lasers



Calculated



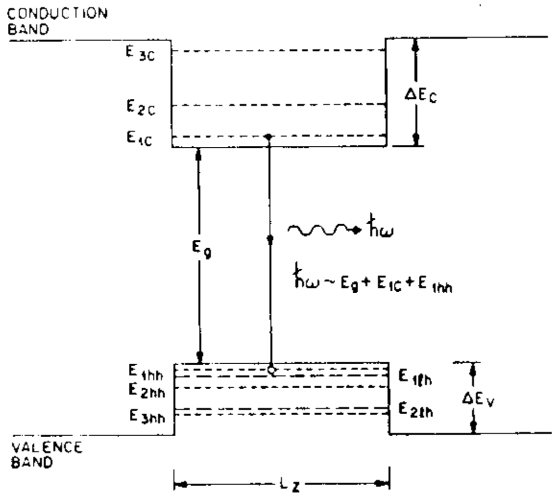


Small signal modulation

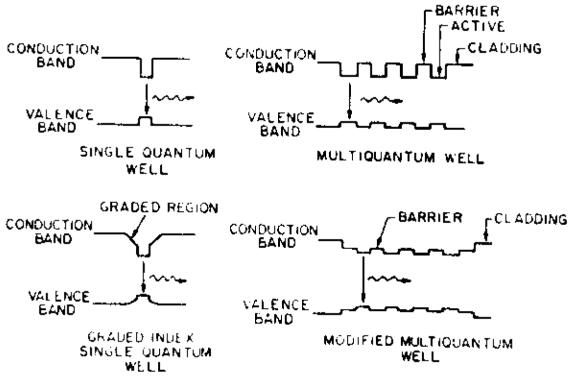
QUANTUM WELLS

ACTIVE LAYER THICKNESS OF A DH-STRUCTURE COMPARABLE TO THE DE BROGLIE WAVELENGTH (h/p).

CONFINEMENT OF CARRIERS TO FINITE POTENTIAL WELLS.



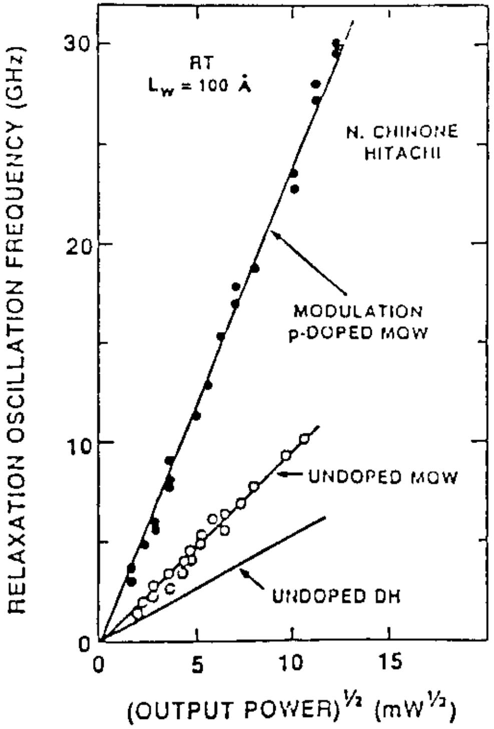
Holonyak, QE 80



G. Agrawal, 86

RELAXATION OSCILLATION FREQUENCY

AlGaAs MODULATION p-DOPED MQW-LD

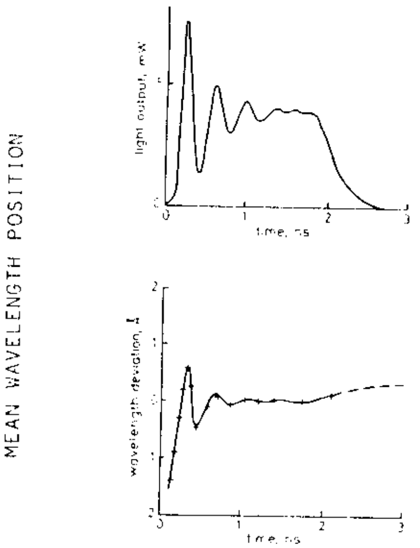


K.Uomi et al., ECOC'87(1987)29(vol. III)

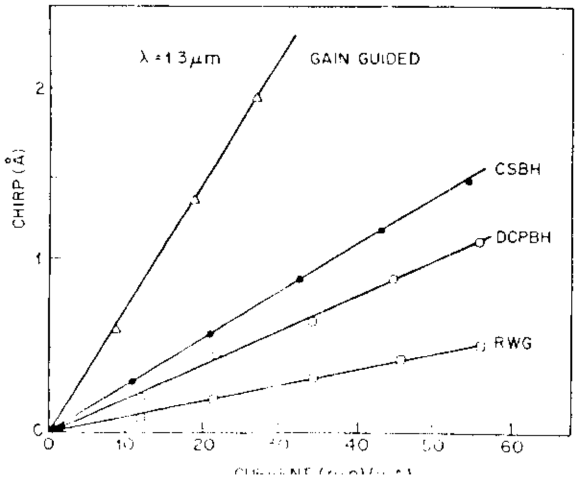
LASER UNDER DIRECT CURRENT MODULATION

- NUMBER OF MODES CHANGES DURING PULSE
- MODES SHIFT BACK AND FORTH
- SPECTRAL LINES BROADEN

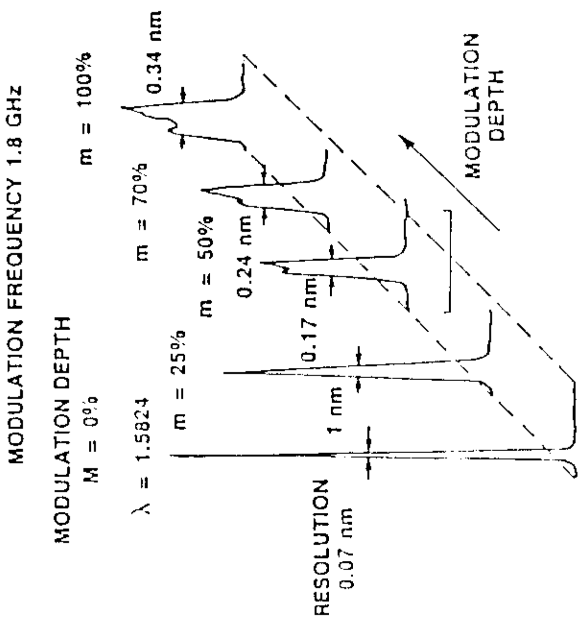
" CHIRP". RESULT: BANDWIDTH LIMITATION DUE TO DISPERSION

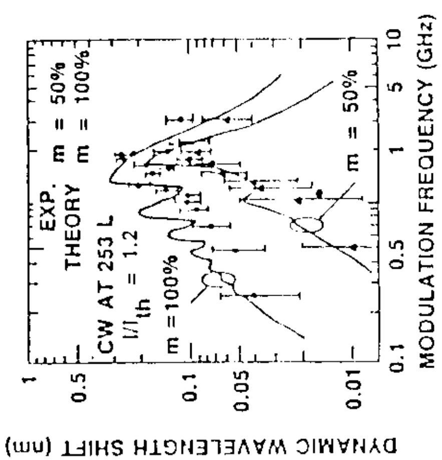


M.Adams, 87



WAVELENGTH "CHIRPS" UNDER MODULATION

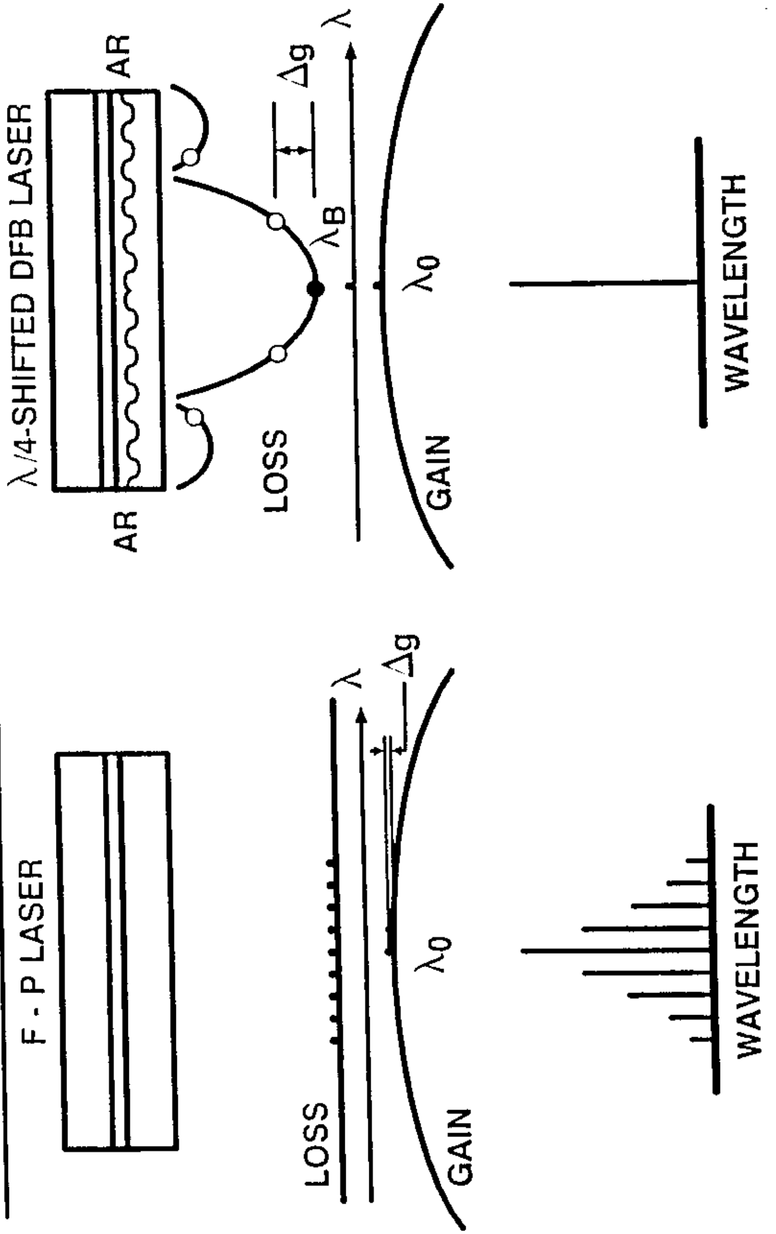




Introduces dispersion penalty at multigigabit data rates and maximum distances (50–200 km)

Koyama et al. (1983)

Single Frequency Operation Of DFB Lasers

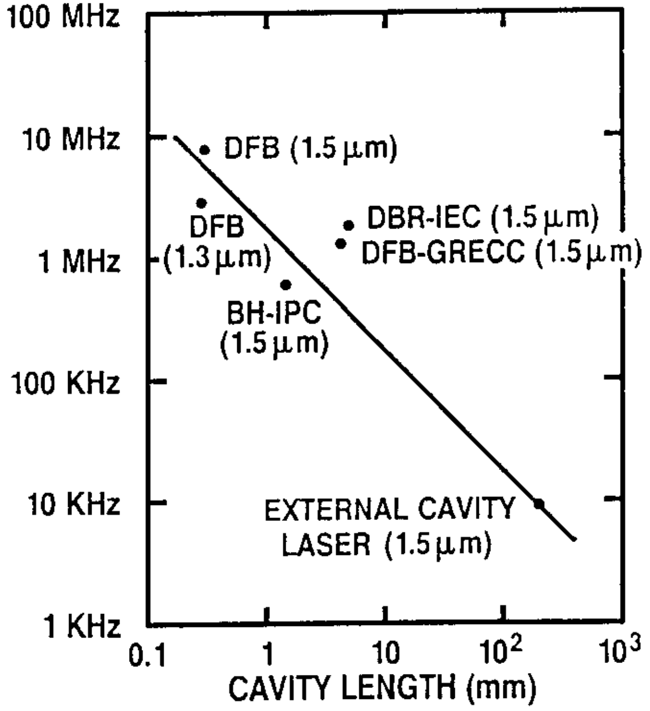


LINEWIDTH OF SEMICONDUCTOR LASERS

LINEWIDTH IS FINITE BECAUSE OF:

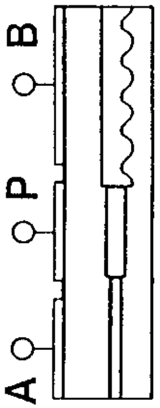
- PHASE NOISE DUE TO
  PHASE FLUCTUATIONS RESULTING FROM SPONTANEOUS EMISSION
  ELECTRON DENSITY FLUCTUATIONS WHICH MODULATE THE INDEX OF REFRACTION THUS INDUCING PHASE FLUCTUATIONS
- CURRENT NOISE AT LOW FREQUENCIES, 1/F-NOISE

MINIMUM LINEWIDTH OF VARIOUS TYPES:



T.P.Lee,OFC 88

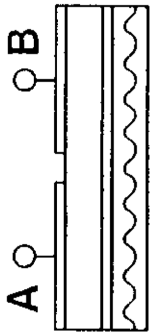
Tunable Wavelength Semiconductor Lasers



3.1 nm (380 GHz)
CONTINUOUS

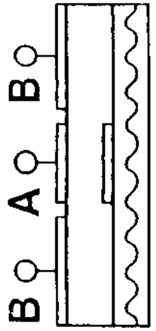
5.8 nm (720 GHz)
FULL RANGE

NEC



2.1 nm (250 GHz)
CONTINUOUS

NTT

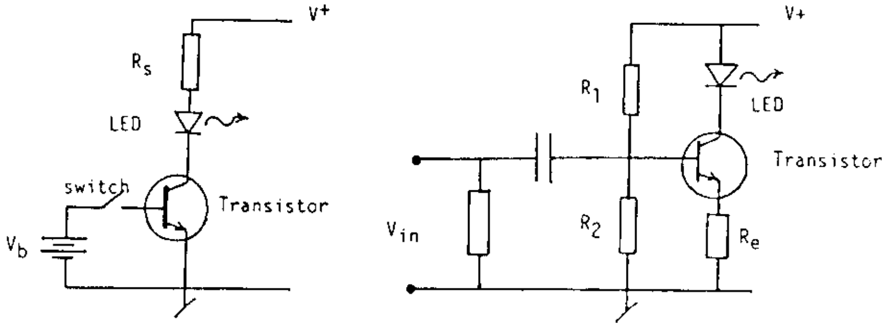


1.2 nm (150 GHz)
CONTINUOUS

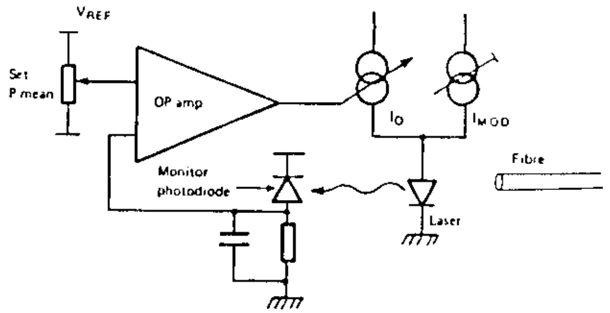
TIT

T.P.Lee, OFC 88

LED AND LASER DIODE DRIVER CIRCUITS

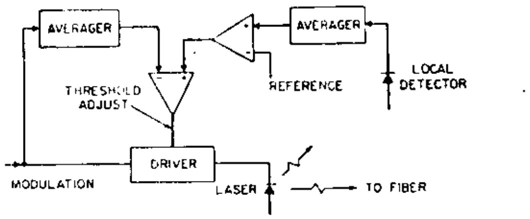


LED modulation circuits. a) on-off modulation via a switch, b) modulation of the LED optical power by the voltage V_{in}

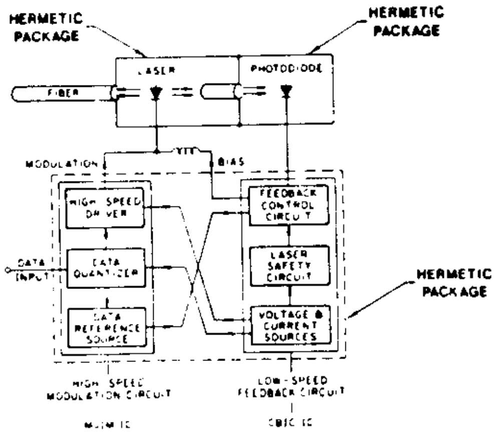


A LD drive circuit providing a dc and a modulation current to the LD and a feedback for stabilization of the mean optical power.

LASER DRIVER AND TRANSMITTER



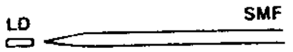
Laser drive circuit that monitors the modulating signal to provide a reference for the feedback loop.



F.Bosch, 86

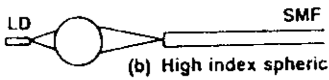
Schematic of an optical transmitter. The circuit has a high-speed modulation section with subnanosecond switching times and a low-speed automatic optical feedback control section with ms response times. The entire transmitter circuit contains only two silicon IC's and is capable of bit rates up to about 1 Gbit/s.

SINGLE MODE FIBER-LASER COUPLING



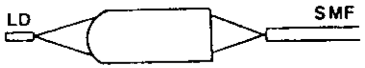
(a) Tapered hemisperical fiber

3-6 dB



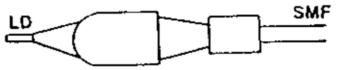
(b) High index spherical lens

2-3 dB



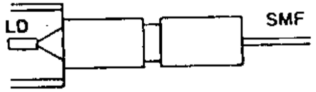
(c) Plano-convex grin lens

3 dB



(d) Confocal lens system

3 dB



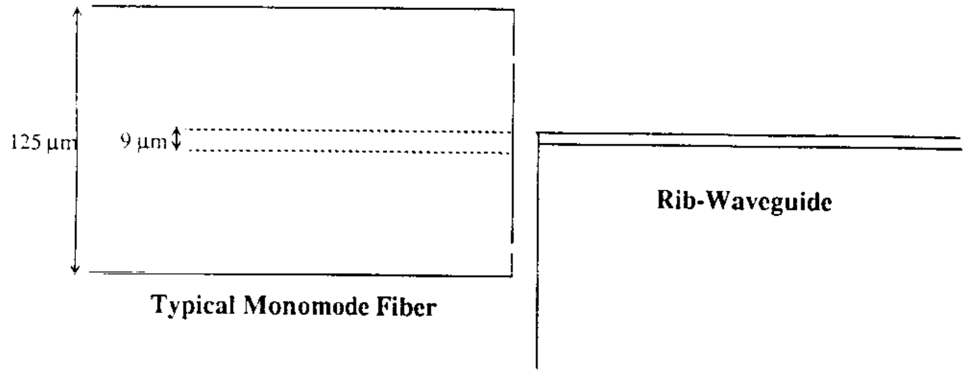
(e) Compact disk-grin lens

12 dB

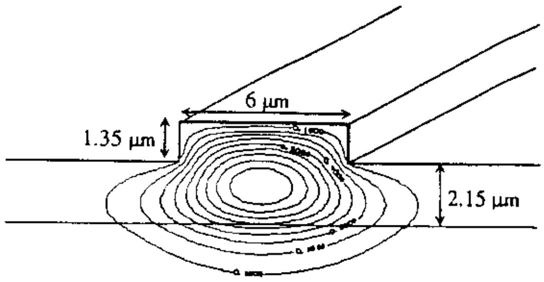
(b) R. Nelson (1986)
(c) Makita et al. (1985)
(d) Kawano et al. (1985
(e) Reith et al. (1986)

Butt joint coupling

between III-V Rib-Waveguides and Monomode-Fibers



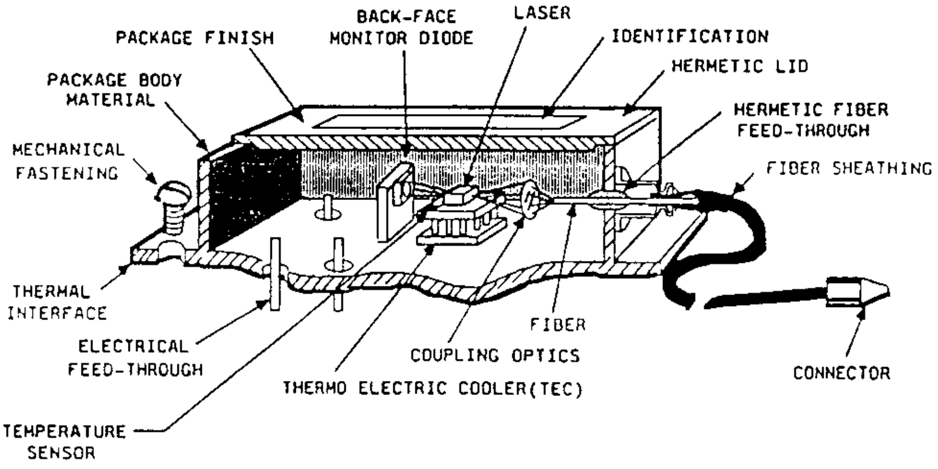
Coupling Loss with
typical Monomode-
Fiber ca -2.5dB



Rib-Waveguide
with Modeshape

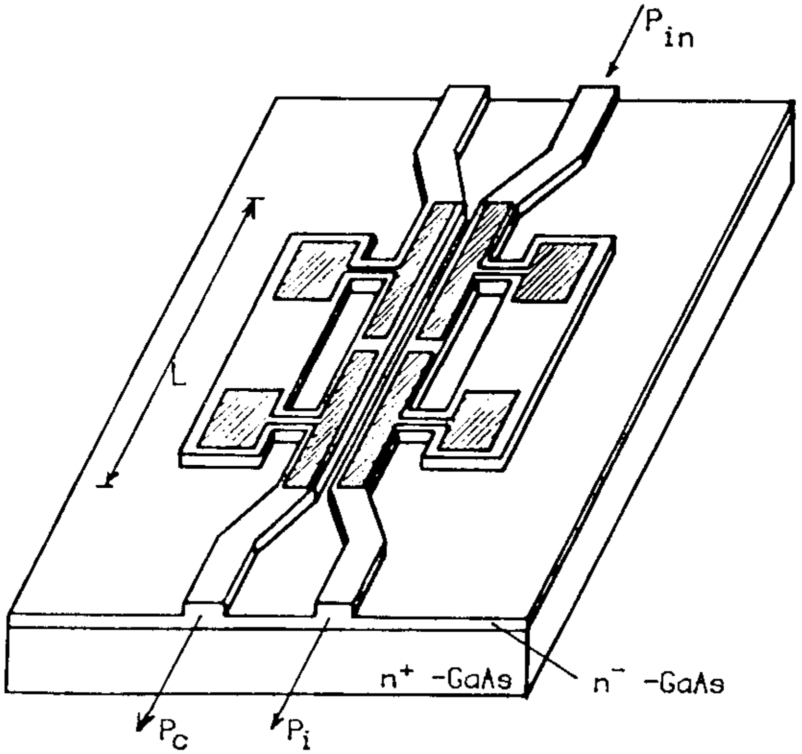
ETH ZURICH, 1989

ELEMENTS OF A DEVICE PACKAGE

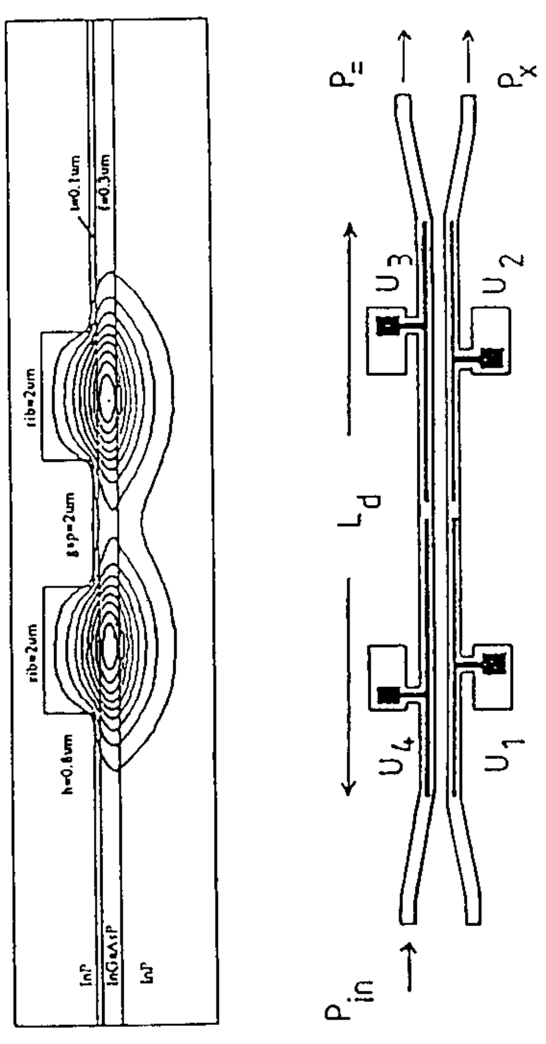


INTEGRATED OPTIC DEVICE FOR FIBER-COMMUNICATION

GaAs STEPPED Δβ DIRECTIONAL COUPLER

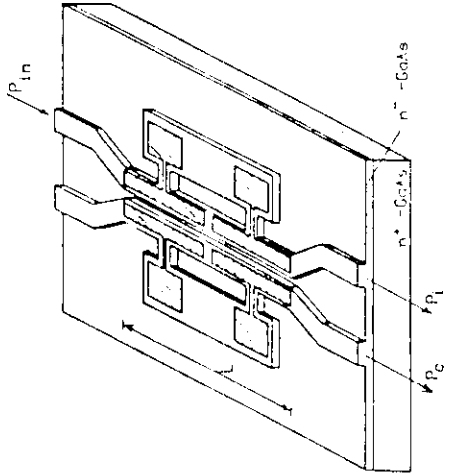


Single mode laser light entering one of the input waveguides can be made to appear at the output of the left or right waveguide depending on the voltage applied between the electrodes.

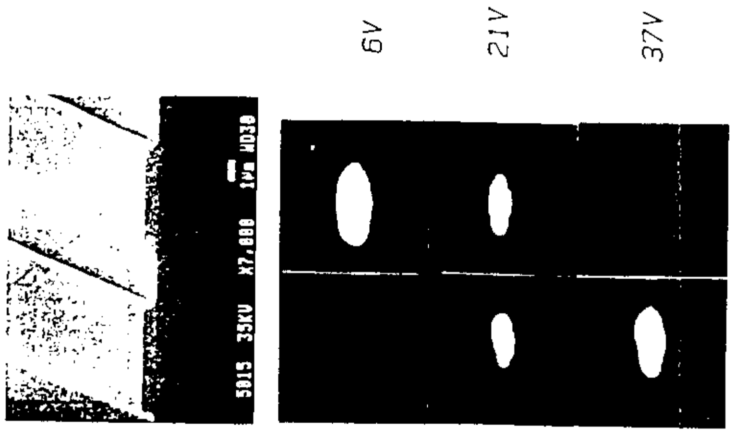


Double heterojunction InP/InGaAsP/InP rib-waveguide switch. The cross sectional view shows the equipotential lines of the field amplitude of the first supermode (amplitude spacing is 0.1 ranging from 0.1 to 0.9 of the maximum fields. The schematic layout of the mask includes the four electrodes needed for the operation of the $\Delta\beta$ - switches. The overall length of the coupling regions L_d is typical 3 - 5 mm.

Electrooptic Waveguide Modulator/Switch using n- - n+ GaAs Coupled Rib-Waveguides in Steped Δβ Configuration
(Buchmann, Kaufmann, Guekos, Melchior 1985)

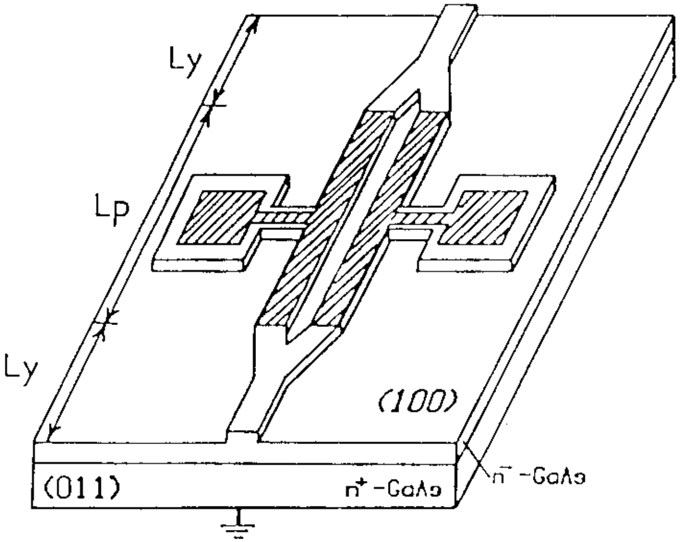


Electrooptic Waveguide Modulator/Switch using n- - n+ GaAs Coupled Rib-Waveguides



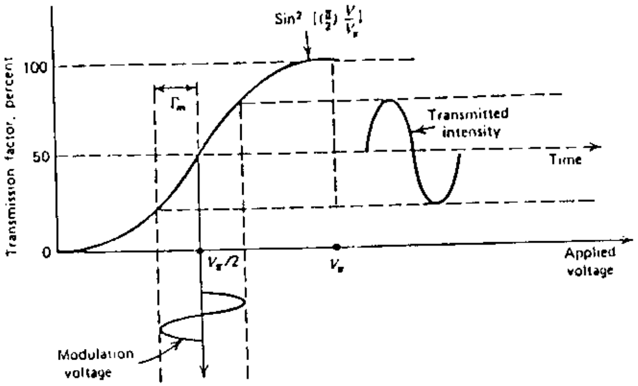
INTEGRATED OPTIC DEVICE FOR FIBER-COMMUNICATION

GaAs MACH-ZEHNDER INTERFEROMETER

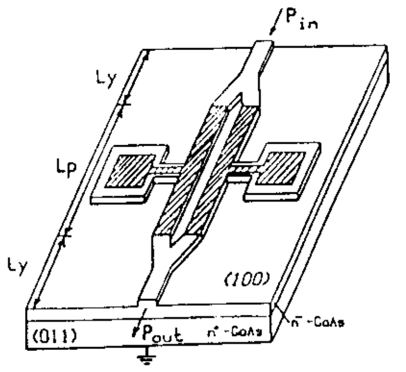


Single mode laser light entering the device splits evenly between the two parallel waveguides. An electrical voltage applied across the waveguides changes the refractive index of the semiconductor. At the output waveguide interferences produce a modulation of the light intensity in synchronism with the applied voltage.

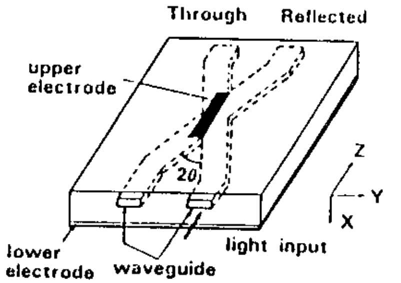
Light Modulation in Mach-Zehnder Interferometer

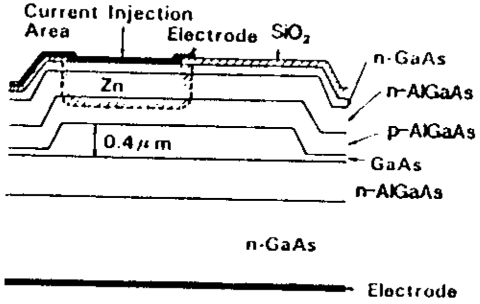


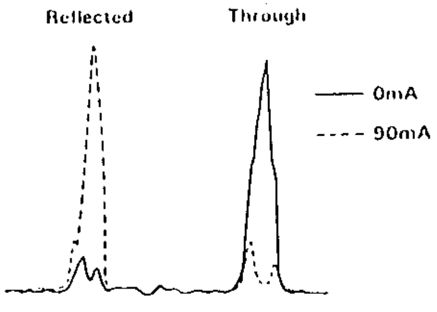
Electrooptic Mach-Zehnder Waveguide Modulator using n⁻ - n⁺ GaAs Rib-Waveguides (Buchmann, Kaufmann, Guekos, Melchior 1985)



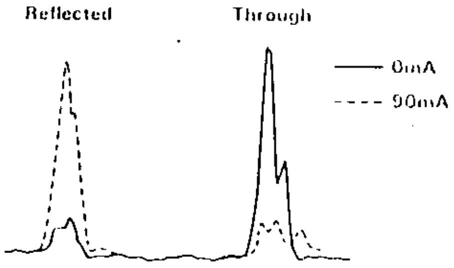
Carrier Injection-Type Optical Switch in GaAs for 1.06 to 1.55 μm Wavelength Range (Ito and Tanifuji 1989)







λ = 1.3μm



λ = 1.55μm

AMPLIFER COMPARISON

	SEMICONDUCTOR	RAMAN	ERBIUM
GAIN	>30dB	>30 dB	>30 dB
PUMP POWER	-	0.03dB/mW	0.4 B/mW [1]
COUPLING	-7dB	0	0?
P_{sat}	+10dBm	+20dBm ?	10dBm
BANDWIDTH	300A	300A [2]	30A [3] (200A)
TUNABILITY	YES	YES	NO
POLARIZATION DEPENDENCE	PROBLEM	NO	NO
NOISE (Nsp)	~1.5	<1	~1.5
CROSSTALK	-	+	+

[1] 0.15-2dB/mW @ 1.48 um
2 dB/mW @ 0.98um
0.3dB/mW @ 0.528 um
[2] TAILOR WITH PUMP LASER
[3] 1.48 um PUMP LASER

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