EVALUATION OF P-N JUNCTION LASERS FOR COMMUNICATION PURPOSES

by:

ALP ÖNOL

Advisor:

PROF. MUSTAFA SANTUR

Department of Electrical Engineering
School of Engineering
Robert College
Bebek, Istanbul, Turkey

May 1967

This thesis has been prepared for the partial fulfillment of the requirements of the Robert College School of Engineering for the degree of Master of Sciences in Electrical Engineering.

ACKNOWLEDGEMENT

The author is pleased to acknowledge Dr. John Hofland for providi
he laser and helping with the set-up of the experiment. Appreciation
s also expressed to Dr. Mustafa Santur for his valuable help and
dvice in constructing the pulsing circuit, to Dr. Altan Ferendeci and
o Mr. Gültekin Yıldız for many helpful suggestions and discussions,
o Dr. Necmi Tanyolaç for financial support for the equipment, and to
r. Cevat Gül, who helped in constructing the circuit.

Alp Önol

May 1967, Istanbul

CONTENTS

IX. REFERENCES

PART I

INTRODUCTION

I. INTRODUCTION

Undoubtedly, light is the first electromagnetic radiation that has been generated by mankind, when the first fire was built. Light, along with the infrared, is the only radiation that can be detected and sensed by human beings throughout the electromagnetic energy spectrum. This fact is perhaps the reason why they have attributed such great importance to light.

A. Methods of Generating Light

Important as it is, the methods with which light was generated did not improve throughout the centuries. It stayed in the crude form of spontaneous radiation such as the random emission of incandescent sources. So have most other types of electromagnetic radiation: infrared, ultraviolet, or gamma rays. However, radio waves have been different. Electromagnetic radiation at these frequencies were produced with efficiency and precision that was unparalleled at other frequencies.

To appreciate the limitations of light waves as they are ordinarily found, let us consider how they are generated.

All light sources have a common origin: the random movement of electronic charges.

In incandescent lamps and other "hot" sources, electrons are accelerated by thermal energy and thus radiate. In gas discharge lamps, like the neon tube for example, the process is a little different: electrons are passed through the gas, where they excite the atoms to higher energy states. The atoms fall back to ground state randomly, and emit radiation which is in the visible spectrum.

The process characterizes the radiated wave: Firstly, the light output is not coherent, i.e. it differs in phase relationship, polarization and relative amplitude. Secondly, it is wide band (even the monochromatic sodium vapor lamp). Thirdly, the radiation produced thus, is not directional,(the sides of a beam produced by an arc lamp with a 6 foot parabolic mirror diverges about 1^{o}). Finally, and perhaps the most important limitation of ordinary light sources is their inherent low brightness. The maximum radiation intensity, or: the power radiated per unit area per unit solid angle per unit frequency band width have been controlled by Planck's blackbody law for radiation from hot objects. This sets the upper limit on radiation intensity, a limit which increases with increasing temperatures, but we have had available temperatures of only a few tens of thousands of degrees.

Let us see whether we can eliminate these disadvantages by using other methods. The method of generating radio waves by electronic oscillators could be applied here, but the basic problem now is that inevitably, some part of the device which requires careful and controlled construction has to be as small as the wavelength to be produced. This sets on a limit to the construction of operable devices. The wave length of the light being a fraction of a micron, electronic oscillators that generate light waves cannot be constructe
The upper limit of electronic oscillators is about 100 GHz.

B. Stimulated Emission Devices

Let us return back to gas-discharge lamps. Here, energy in the form of photons are released as a result of transitions of electrons from one energy level to the other, but the transitions are random, according to some probability function in time.

Organization of this process can lead to efficient sources of light. Briefly, let us see how this can be achieved.

As is well known from the quantum theory, atoms in all matter are allowed to occupy certain energy states or levels. Transitions from one of these levels to another is accompanied by either an emission of a photon through a downward fall or an absorbtion of a photon through an upward jump.

The frequency of the electromagnetic energy radiated is related to the difference of energy levels $E_2 - E_1 = \Delta E$ and given by Planck-Einstein relation:

$E = h\nu$ where h is Planck's constant
ν frequency of radiation

Transitions from upper energy levels to the lower ones can be classified into two parts. Spontaneous and stimulated transitions.

A spontaneous transition is the spontaneous falling of an atom from a higher energy level to a lower one. The atoms that have been raised to a higher level will rapidly drop back to the original level, emitting radiation according to Planck's law. This, however, is a purely random process.

Stimulated emission is rather a controlled version of this process: the atoms are forced down from the excited level by an external agent, by electromagnetic energy whose frequency satisfies the relation $\Delta E = h\nu$. The photon which is the result of this interaction is added to the original wave. In other words, an amplification process takes place.

This amplification is clearly proportional to the number of atom in the "excited" i.e. higher, level. Using this principle, a family of devices are made, named Maser after the first letters of Microwave

Amplification by Stimulated Emission of Radiation (or laser for Light Amplification of Stimulated Emission of Radiation).

C. Characteristic of Laser or Maser Output

The output of lasers are inherently coherent and monochromatic. The photon that is generated by the transition adds itself to the original wave in exactly the same phase and polarization and frequency.

A useful analogy may be used to make the idea of coherence clear. Let us consider a tuned RF amplifier. In the absence of an input signal and with no feedback between output and input, such an amplifier will have no output except a certain amount of noise which shall appear at the output terminals. This noise corresponds to the radiation that thermal sources produce. Now, if we introduce enough positive feedback, the amplifier will break into oscillation and its output becomes coherent at a frequency determined by the resonant circuit of the tuned amplifier. This corresponds to the coherent radiation of a laser.

D. History of the Laser

This idea of using stimulated emissions as methods of generating radiation occurred independently to several workers in the microwave field, notably C. H. Townes, J. Weber (U.S.A.) and N. G. Basov and A. M. Prokhorov (U.S.S.R.). However, Townes is the first one to make an actual device in 1954. This setup was using the two molecular states of gaseous ammonia molecules which can be physically separated by passing through an electrostatic focusing arrangement. However, the principle was painfully complicated and operated at a fixed frequency.

Subsequently, Bloembergen worked out in theory a Maser amplifier using a paramagnetic crystal with three energy levels and capable of operating continuously.

In 1956, H. E. D. Shovil constructed this solid state maser. Following this in 1958, A. L. Shawlow and C. H. Townes concieved the optical maser. In 1960, H. Maiman obtained the first laser action with a pink ruby. A year after, A. Javan, (U.S.A.) proposed the He-Ne laser, and built it with cooperation of W. R. Bennett and Herriot. This was the first laser to operate continuously. In 1962, a new class of lasers, P-N Junction Lasers were simultaneously made by several groups: R. N. Hall; G. E. Jenner, J. D. Kingsley, T. J. Soltys, R. O. Carlson of General Electric Company; M. I. Nathan, W. P. Dumke, G. Burns; F. H. Dill and G. Lasher of I.B.M. corporation and T. M. Amst; R. H. Rediker; R. J. Keyes; W. E. Krag; Blax and A. L. McWorther and H. J. Zeiger of Lincoln laboratories of M.I.T.

The P-N junction is perhaps not the last class of lasers to be concieved but they are the most compact and the cheapest. They convert d.c. power directly to coherent energy. These properties make this type of laser very attractive from the communications point of view.

E. The Need for High Frequencies

Before going into the details of the theory of operation of these devices, let us see why we want to use such high frequencies. One of the most extensive uses of electromagnetic radiation is in communications. The radio waves are used to convey information from one point to another.

This is the way all our communication systems operate. Let us take the Medium Wave band and calculate how many stations we can squeeze into this band. Allowing 9KHz for each station and taking

1160 KHz as the Medium Wave range, we shall have: 130 stations broadcasting simultaneously. If we had the means of doing the same thing with light frequencies, the band-width would be of the order of 000,000 GHz. For a rough approximation, we can assume that the number of stations is proportional to the frequency then, we potentially can have 10^9 stations broadcasting simultaneously using light frequencies. This is the primary reason why communication engineers for at least half a century have dreamed of generating light as efficiently and as precisely as radio waves. With the advent of lasers, this dream could be realized. However, there are some practical difficulties associated with the scheme.

Firstly, modulation should be possible either in the form of amplitude or frequency modulation. Generally speaking, all lasers except semiconductors, cannot be modulated internally. However, they can be externally modulated using various techniques such as the electrooptic effect[*](7), acoustooptical effect.[†](8) At any rate, the simplest modulation can be achieved in semiconductor lasers; this is done simply by the modulation of the current through the Diode. This is mainly the reason why P-N junction lasers are used in most of experimental laser communication systems.

---

[*] Kaminor and Turner, "Electro-optic Light Modulators," ProcIEEE (Oct. 1966), 1374-1378

[†] Gordon, "Acusto-optical Deflection and Modulation Devices," ProcIEE, (Oct. 1966), 1391-1401

PART II

THEORY OF OPERATION OF STIMULATED EMISSION DEVICES

II. THEORY OF OPERATION OF STIMULATED EMISSION DEVICES

Although the device which we shall concentrate on is the P-N junction laser and operates in a somewhat different fashion than an ordinary laser, it is useful to have a general idea as to how a laser works.

A. EINSTEIN EMISSION - ABSORBTION THEORY

The Quantum Theory predicts the existence of discrete energy levels of electrons in all matter. In the laser operation, we are interested in the transitions electrons make from one energy level to the other; as this involves either an emission or absorbtion of energy in the form of photons or phonons (heat). Long before the development of quantum wave mechanics, photon emission and absorbtion was treated thermodynamically by Einstein(2). He considered a system of independent atoms, each having two energy levels E_1 and E_2 $(E_2 > E_1)$. N_1 and N_2 are the respective numbers (or densities) of atoms in states 1 and 2. The stimulated transition probabilities S_{12}, S_{21} were assumed proportional to the thermal equilibrium radiation density which is given by the Base-Einstein statistics.

$$W(w_o) = \frac{\hbar w}{\pi^2 c^3 \left(e^{\hbar\omega/kT} - 1\right)} \quad \text{per unit frequency. 2-(1)}$$

Let $S_{12} = B_{12} W(w_o)$

$S_{21} = B_{21} W(w_o)$

where S_{12} S_{21} is the stimulated absorbtion probability.

The number of stimulated transitions per second from state 1 to state 2 is

$B_{12} W(w_0) N_1$ and from state 2 to 1.

$B_{21} W(w_0) N_2$.

Einstein added a second emission term $A_{21} N_2$ independent of thermal fields, which he termed spontaneous emission. Einstein did not, however, include in his analysis any non-radiative phonon transitions which we shall add later. In the steady state, emission and absorbtion rates are equal:

$$B_{12} W(w_0) N_1 = B_{21} W(w_0) N_2 + A_{21} N_2 \qquad (2\text{-}2)$$

At equilibrium N and N_1, the densities of states should be thermodynamically related. Boltzman Distribution applies requiring

$$\frac{N_1}{N} = e^{\frac{E_2-E_1}{kT}} \qquad (2\text{-}3)$$

Inserting this to (2-2), we get

$$W(w_0) = \frac{A}{B_{12} e^{\frac{(E -E_1)}{kT}} - B_{21}} \qquad (2\text{-}4)$$

At equilibrium, we must assume that the only radiation present is thermal. Thus the radiant energy density must satisfy the plancks law, given by (2-1). Therefore, equation (1) and equation (4) should be equal, giving

$$B_{12} = B_{12} = B \qquad (2\text{-}5)$$

and $$\frac{A}{B} = \frac{\hbar w^3}{\pi^2 c^3} \qquad (2\text{-}6)$$

The stimulated emission and absorbtion probabilities B_{21} and B_{12} are equal as expected. The spontaneous emission coefficient A_{21} is directly related to stimulated emission coefficient B

$$\frac{\text{Stimulated emission}}{\text{Spontaneous emission}} = \frac{BW(w_0)}{A} = \frac{1}{e^{hw_0/kT} - 1} \qquad (2\text{-}7)$$

$$= \text{thermal photons in the cavity mode}$$

Since the spontaneous emission equals to the stimulated emission divided by the number of photons which produce it, spontaneous emission is just that which would be produced by a single photon in the cavity mode.

From (2-6) we see that the spontaneous emission probability is proportional to the cube of emission frequency. Consequently, spontaneous emission becomes very important at optical wavelengths. It is by this way the excited state electrons relax to a lower state. Since A_{21} is the probability of spontaneous emission per second, its reciprocal is the upper state life time. This "natural life time", as the optical spectropists call it, will play quite an important role in our discussions later on.

As we have remarked above, Einstein did not consider the phonon induced transitions. This process along with spontaneous emissions reduce the density of higher states without producing useful output radiation.

Let P_{12} denote the probability per unit time of an atom in state 1, making a phonon induced transition to state 2 and P_{21} the converse probability of a 2→1 transition. Then, for thermal equilibrium, equating emission to absorbtion, we have:

$$N_2 B_{12} W(w) + AN_2 + P_{21} N_2 = N_1 B_{12} W(w) + P_{12} N_1 \qquad (2-8)$$

by extending this to a non-equilibrium situation and calling $S_{12} = B_{12} W(w)$ which is the stimulated absorbtion probability we have:

$$\frac{N_2}{N_1} = \frac{S_1 + P_1}{A_{21} + S_1 + P_{21}} \qquad (2-9)$$

As the incident radiation i.e., S_1 is increased, the ratio N_2/N_1 increases from its equilibrium value to approach unity. However, even with infinitely intense radiation, it is impossible to make $N_2 > N_1$ we can at best have $N_2 = N_1$.

We may determine the rate of energy absorbtion by a set of N electrons of which N_2 and N_1 are in states 2 and 1 respectively. Since $S_{21}N_1$ per second will begin a transition $E_2 \rightarrow E_1$ while $S_{21}N_1$ will begin a transition $E_1 \rightarrow E_2$ thus, the energy absorbed per second by the entire system is:

P absorbed $= S_{12}(N_1 - N_2)\,\hbar w_0$ (2-10)

As long as we have $N_1 > N_2$, radiation will be absorbed, but after $N_1 = N_2$ there'll be no absorbtion. Thus, by external incident radiation, N_2 cannot be made greater than N_1, a result which is also confirmed by eq. (2-9). Let us suppose that by some means we achieved a system in which $N_2 > N_1$. In this case, we shall have negative absorbtion or in other words, the power from the system will be emissive. This non-equlibrium situation in which $N_2 > N_1$ is termed population inversion or negative temperature because the normal Boltzman Distribution:

$\frac{N_1}{N_2} = e^{(E - E_1)/kT}$ will be reversed and from the equation, T has to be negative for this to happen.

An incident electromagnetic radiation of the energy gap frequency can be magnified by adding to itself the emission power. In other words, the photons coming to this active region will stimulate the atoms from the excited state to the ground state, thus they will increase in number which is an amplification process.

B. Requirements for Laser Operation

From the above discussion, we can draw the requirements for the essential elements of a laser or a maser

1. A pair of energy levels $E_2 > E_1$ spaced by the desired photon energy with a strongly radiative transition (not highly susceptible to release of energy via phonons.)

2. Means for elevating electrons into the upper state in large numbers via a path other than direct stimulated emission.

3. Electromagnetic system capable of retaining with low losses photons of energy (E_2-E_1).

4. Means for bringing useful electrons into the radiation field.

5. The system may require draining atoms out of the lower terminus state, a process named depopulation. Also, in systems that require pumping i.e. population inversion, by externally applied electromagnetic field, more than two states, a third state, even a fourth state is involved, which gives us three and four level masers respectively.

C. LASER SYSTEMS

Now that we have an idea of the requirements of laser operation, let us see the methods of achieving such a system.

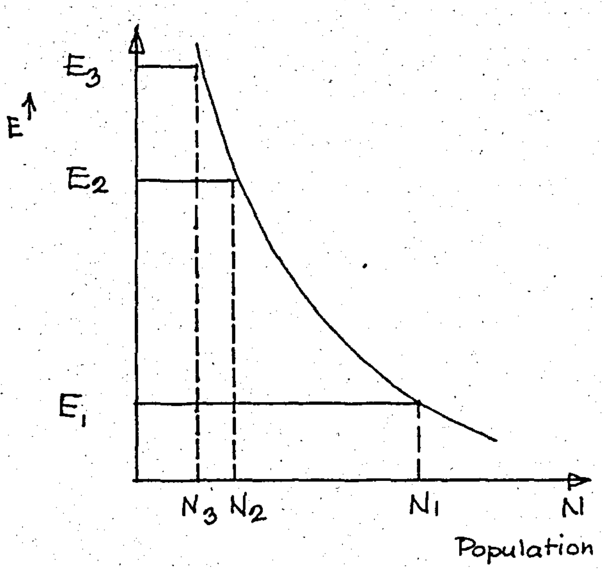
First, we shall examine the method of obtaining population inversion by external radiation. By eq. (2-9), we see that in a two-level system, this is impossible. However, if we have a three-level system, we could cause population inversion between the relative populations of a pair of levels.

Let us take a three-level system E_1, E_2, E_3. At thermal equilibrium, the populations N_1, N_2 and N_3 is given by the Boltzman Distribution:

$$\frac{N_3}{N_1} = e^{-\frac{\Delta E_{31}}{kT}} \quad \text{and} \quad \frac{N_2}{N_1} = e^{-\frac{\Delta E_{21}}{kT}} \qquad 2\text{-}(11)$$

and shown in Fig. (1) where $(\Delta E)_{nm} = En - Em$

Assuming that $(\Delta E)_{21} < (\Delta E)_{31} < kT$ and expanding the exponents into series and retain the first order terms we get



Three level system in thermal Equilibrium

FIG 2-1a

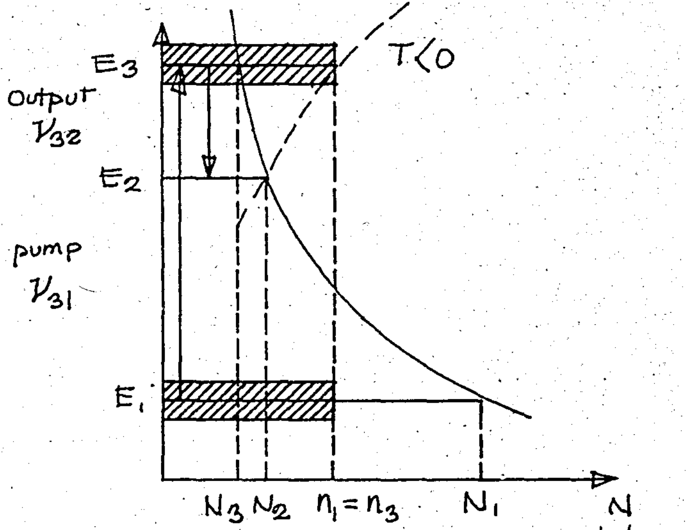
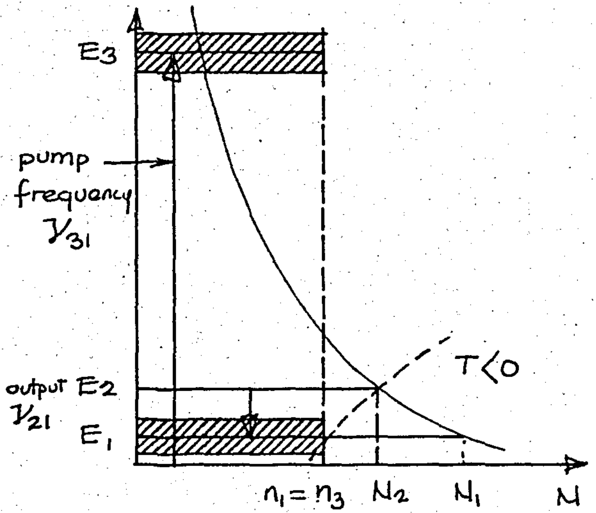


FIG-2-1b

$$N_3 = N_1 \left[1 - \frac{(\Delta E)_{21}}{kT}\right] \qquad 2-(12)$$

$$N_2 = N_1 \left[1 - \frac{(\Delta E)_{21}}{kT}\right] \qquad 2-(13)$$



Three Level system in negative temperature state.

FIG-2-1c

Let us now subject this system to an electromagnetic field whose frequency satisfies the condition

$$h\nu_{31} = (\Delta E)_{31}$$

and whose intensity is such that the transitions from E_1 to E_3 is saturated i.e. according to (2-9) the populations of the levels E_1 and E_3 are equal. Thus we can write

$$n_1 = n_3 \simeq \frac{N_1+N_3}{2} \simeq N_1 \left[1 - \frac{(\Delta E)_{31}}{kT}\right] \qquad 2-(14)$$

where n_1 and n_3 denote the new values of population levels 1 and 3.

Now, from eq. (2-10) we know that the condition system to be emissive is that the higher energy level population should exceed the lower level population. Therefore, if we have the population N_2 of the middle level differ from $n_1 = n_3$ i.e. $N_2 > n_1$ or $N_2 < n_3$ we shall have emission.

1. To utilize the transitions between levels 2 and 3 for amplification, we should have $n_3 > N_2$ (Fig 2b) substituting from eqs. (13) and (14), we get

$$\frac{1}{2}(\Delta E)_{31} > (\Delta E)_{21} \qquad 2 - (15)$$

This means that energy level E_2 (the middle level) should be nearer to level E_3 (the top level) than to E_1 (ground level). Also the frequency ν_{31} of the external field (called the pumping field because of the obvious analogy to a water pump), ν_{31} should exceed the frequency of the signal (the wave to be amplified, as depicted by Fig. 1b) by more than a factor of two.

2. If we want to utilize the transitions between 2 and 1, that is we want to amplify a signal of frequency ν_{21}, we have to have $N_2 > n_1$ which gives

$$(\Delta E)_{21} < (\Delta E)_{31} \qquad 2 - (16)$$

In this case, level 2 has to be closer to level 1 than to level 3. Again, the pump frequency should exceed the pumping field by a factor of two. (Fig. 2c)

What we have done up to now is the result of mathematical maniulations. Let us see what physical limitations these conditions impose.

First and most important is the method of population inversion. Usually, electrons are pumped from the lower level to the higher one by optical pumping. This limits the character of the energy level E_3. If E_3 were a sharp line it would be impossible to cause the electrons to make transitions from E_1 to E_3 as this would require a frequency $\nu = \frac{\Delta E}{h}$ as sharp as the line, no ordinary source can meet such a requirement. Therefore, level E_3 must be reasonably broad band so that conventional sources can be used to pump electrons to higher levels.

Secondly, the time the electron spends in the energy levels is important. If the electron that we have pumped to an excited state drops down back to E_1 instantly, we shall not be able to achieve population inversion. Thus, the relaxation time between levels 1 and 3 should be sufficiently large, otherwise large power levels are required to saturate the levels E_1 and E_3. This high pump power is undesirable for many reasons, the most important being, low efficiency

Also, the relaxation times $(\tau_1)_{32}$ and $(\tau_1)_{21}$ should satisfy some definite conditions. If the relaxation time between levels 1 and 2 is large, the population of level 2 will start to increase and the difference in population $(n_3 - n_2)$ will decrease. This is an undesirable effect which reduces the emissive power. The inverse is also tru a short relaxation $(\tau_1)_{21}$ assures the transitions of spent atoms from level 2 to 1 returning the system to its initial state. This is like filling the reservoir from which we can draw the atoms to be pumped to a higher state. An increase in this population allows one to obtain, at saturation, a large population n_3 of the third level. It is obviou that an increase in n_3 and decrease in n_2 will favorably effect the performance of the laser. Thus, for the laser represented in Fig. 2b, we should have $(\tau_1)_{32} > (\tau_{21}.)$

Analogous reasoning applies also for Fig. 2c. Here, the requirement is that the relaxation time $(\tau_1)_{32}$ be shorter than the relaxation time $(\tau_1)_{21}$.

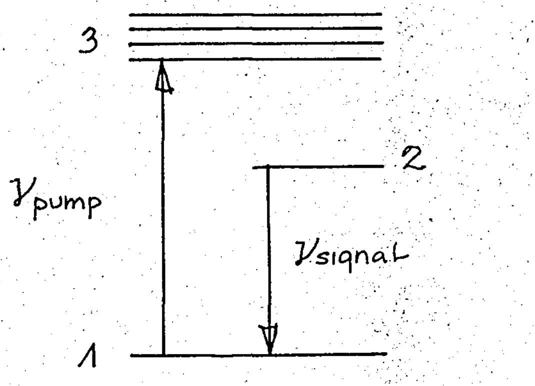
The relaxation time (τ_{32}) for Fig. 2b should be sufficiently long If this is not so, the number of non-radiative transitions from 3 → 2 will be large. Again, this will cause a decrease in population n_3 and an increase in the population of the second level. The difference $n_3 - n_2$ will decrease and once more, we shall have inefficient performance.

Besides three level lasers, four level lasers can be also achieved and in this case, the restrictions on the system parameters can be relieved.

Comparison between schemes of Fig. 2b and 2c favours that of 2c. The radiation emitted from 2b is inherently broad band because level E is broad band whereas that of 2c is coherent because the transitions are made between sharp energy levels.

D. Examples of Laser

1. Ruby Laser ⑨



Energy Levels of Cr^{+3} in AL_2O_3 (Pink Ruby)

FIG - 2 - 2

The best example of a working three-level system is the pink ruby. This material is Al_2O_3 with about 0.05% Cr^{+3} embedded in it. The energy levels used for laser action are that of Cr^{+3}. Because the concentrational Cr^{+3} is low, the energy levels of the free atoms are not distorted into bands, but retain their shape. The energy levels of Cr^{+3} is depicted in Fig. 2-2. The final level is a broad energy band suitable for optical pumping. The pumping is done by intense green light (5000 Å) focused on ruby, which excites chromium ions to level 3. The life time in the excited state is very short and ions drop back to 2 by a non-radiative transition. The transition form 2 to 1 is from a meta-stable state (relaxation time τ_{23} large), the atoms drop from this level to the lower one radiating a bright red. (6943) Å light.

2. Helium-Neon Gas Laser ⑩

Although the excitation method in gas lasers is not optical pumping, it will be of interest to touch.

In all gas lasers, there are two gases whose excited energy levels are close to each other. One of the gases, let us say gas A, cannot relax to a lower state by radiative processes, but only through a collision with an atom of another gas. If the atom of this gas can make transitions radiatively, we shall have emission of radiation.

This principle is applied in the He-Neon laser. The Helium-Neon atoms are exposed to an ionizing radio frequency voltage. This excites Helium atoms. Excited Helium atoms collide with neon atoms transferring their energy to these. The excited neon atoms drop back to ground state emitting radiation.

E. Gain, Power, Threshold Relations

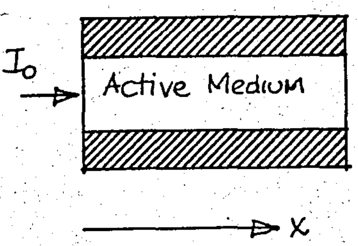


FIG 2-3

Consider a wave with intensity Io impringing on an active medium. This medium is in the state of inverted population appropriate for laser operation. After travelling a distance x, the wave will have an intensity given by

$$I = I_0 e^{-\alpha x} \qquad (2 - 17)$$

where α is the absorbtion or attenuation constant. The part of which is due to transitions between E_1 and E_2 (the energy levels where the laser action takes place) is given by (8).

$$\alpha(\nu) = \frac{(\lambda/\bar{n})^2}{8\pi} \; \frac{[N_1(g_2/g_1)-N_2]}{\tau} \; A(\nu) \qquad (2 - 18)$$

λ = wave-length in vacuum

$\bar{n}$ = index of refraction

g_1, g_2 = statistical weights of upper and lower levels

N_2, N_1 = number of atoms/cm^3 in upper and lower states

τ = lifetime of spontaneous emission from level 2--1

$A(\nu)$ = normalized line shape $\int g(\nu) d\nu = 1$

= frequency of radiation = $\frac{c}{\lambda}$

The absorbtion constant due to a particular line that can give rise to spontaneous and stimulated emission is at the frequency ν_0 where $g(\nu)$ is the largest, and where $A(\nu)$ is at its maximum given by $A = \frac{1}{\Delta\nu}$, $\Delta\nu$ here is the width of the emission line at half intensity

As far as equation (2 - 17) and (2 - 18) goes, let us see what the conditions that will make laser action easy will be.

1. As can be seen from (2 - 18), it will be easiest to use a system that has narrow spontaneous emission i.e. $A(\nu_0)$ large.

2. When lasing takes place, absorbtion constant will be negative. From eq. (2 - 17) we see that the intensity of the wave will be dependent on the length of the path, the beam traverses. Considering the values of α which is quite small, we shall have to have unreasonable lengths to have appreciable amplification. Since this is physically impossible, the active region is made part of fabry-perot cavity. The end plates are made parallel and reflecting so that light resonates back and forth inducing transition from level 2--1.

Since a fabry-parot cavity is used, only an integral number of wave-lengths can fit between reflectors

$$\frac{m\lambda}{\bar{n}} = 2L \qquad (2 - 19)$$

As we have mentioned earlier, to achieve laser action α has to be negative, but it must also be larger than certain magnitudes. This requirement is not something unique; every system in which amplification takes place, the amplification factor should be large enough to take care of the losses. Here we have end and internal losses.

Let

R = the reflectivity of the walls from inside the active region at $z = o$, L

β = the volume losses

α_t = the value of just at the threshold after which amplification takes place.

Here, the condition for threshold is that overall volume gain of the wave will just make up for the end, and other losses.

Thus,

$$R\,e^{(-\alpha_t - \beta)L} = 1 \qquad (2 - 20)$$

t is a negative number, since we have population inversion.

$$-\alpha_t - \beta = -\frac{\ln R}{L} \qquad (2 - 21)$$

The power required at threshold will be given.

$$P_t \geqslant \frac{N_2}{\tau} h\nu V \qquad (2 - 22)$$

using (2 - 21) and (2 - 22), one finds for the approximation $N_1 = o$

$$P_t \geqslant \frac{8\pi V h\, n_o^2 \nu^3 \Delta\nu}{\eta\, c^2} \left(-\frac{\ln R}{L} + R \right) \qquad (2 - 23)$$

where η quantum efficiency = photons at $h\nu$ emitted/photon absorbed.

From this discussion, we see that only population inversion is not enough for lasing, but $(N_2 - N_1)$ should have a certain minimum magnitude to take care of the losses before emission can take place.

PART III

SEMI-CONDUCTOR LASERS

III. SEMI-CONDUCTOR LASERS

A. Introduction

Having dealt with the basic theory of laser operation, let us now look for materials in which laser action can be achieved. The first criteria would be the presence of a pair of energy levels among which population inversion can be obtained. In He-Ne gas lasers and ruby lasers, the optical transitions responsible for the coherent light emission take place between energy levels that are similar to those of free atoms. They are sharply defined in energy and the energy levels are quantized. By using the techniques that we have discussed in the preceding part, population inversion has been achieved between some of these levels and lasing has been obtained.

Let us briefly review the energy level diagram of crystalline solids. An electron in a crystal is not in the force field of a single atom; but rather in the periodic potential field of many uniformly distributed atoms. Because of this interaction, each energy state of the single atom is split into a multitude of quasi-continuous band-like energy states. This splitting becomes more pronounced as the atoms are spaced more closely.

Thus, if we were to draw the familiar band picture, we would have allowed and forbidden energy ranges. This picture provides a useful explanation of electronic conduction. From this point of view, we can divide the solids into 3 groups: Insulators, conductors, and semi-conductors. In insulators, the lower energy range is full with electrons and the upper band has no electrons. The forbidden band is also very large (about 20 eV). It is very improbable for the electrons to make transitions from the lower band to the higher band. In conductors, these bands are located so closely to each other so that they overlap and the electron can occupy a large range of energy levels. In semi-conductors, the bands retain their identity, but the energy gap is not so large [about (1-3 eV)].

The probability of transition across the forbidden gap is reasonable. In fact, this is responsible for the conduction in intrinsic semi-conductors. Here, a question might arise: Can we induce these transitions by photons? The positive answer to this question might make laser action in semi-conductors possible. To solve the problem, let us look at the optical properties of semi-conductors.

B. Optical Properties of Semi-conductors

To determine the properties of semi-conductors, usually four phenomena are studied:

1. Absorbtion
2. Reflection
3. Photo-conductivity
4. Emission

For our purposes, the most important processes are absorbtion and emission. Absorbtion comes from four main processes:

1. Transitions between bands
2. Excitation and ionization levels of impurities
3. Excitation of lattice vibrations
4. Free carrier absorbtion

Process (1) is only effective at frequencies ν such that roughly $h\nu > \Delta E$, ΔE being the forbidden gap. This turns out to be for wavelengths shorter than 10 μm.

All the other processes take place at larger wavelengths and do not interest us for the purposes of this paper.

We have learned that at frequencies around infrared, we have absorbtion caused by transitions between bands. This was what we are looking for. Therefore, it shall be useful to analyze the situation.

Intuitively, we can see that this is a process in which an electro is raised usually from the valence band to the conduction band, by the absorbtion of a single photon.

1. Direct Interband Transitions

Let $E_V(k)$ energy of an electron in valence band

$E_c(k')$ energy of an electron in conduction band

where k and k' are wave vectors

$$k = \frac{2\pi}{\lambda}$$

The conservation of momentum will then give

$$E_c(k') - E_V(k) = h\nu \qquad 3-(1)$$

If the incident photon has a wave vector K, it has a momentum

$$hK \qquad \hbar|K| = \hbar\frac{2\pi}{\lambda} = \frac{h}{\lambda}$$

The principle of conservation of crystal momentum gives

$$k' = k + K \qquad 3-(2)$$

(It is one of the basic properties of the crystal momentum that it is conserved in a transition or collision). Since the transitions that we deal with occur in the infrared λ is large compared to lattice parameters and thus K can be neglected with respect to k and k'. Then equation 3 - (2) becomes

$$k = k' \qquad 3-(3)$$

which means that the wave vector does not change by the transition. The process is called a vertical transition. The reason for this is is not difficult to understand. Fig. 1 shows the energy picture of a direct semi-conductor (i.e. those semi-conductors in which lowest

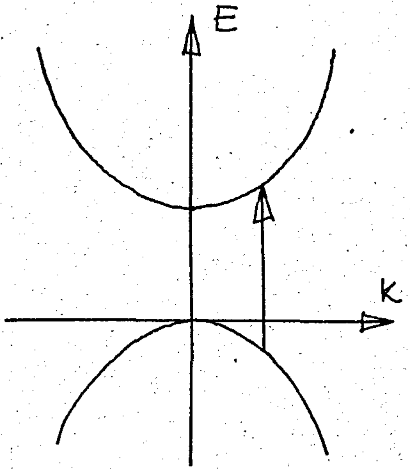


FIG 3-1
Energy picture of a Direct Semiconductor

conduction band minimum and highest valence band maximum are at the same wave vector in the Bruilloin zone). An electron makes a transition from the valence band to conduction band without changing the k vector. Thus, the transition is vertical. The transition probability is zero if $h\nu < \Delta E$ and $(h\nu - \Delta E)^{1/2}$ if $h\nu > \Delta E$. This can be calculated by means of the first order perturbation probability.

We should emphasize one point. The electron will not jump from valence to conduction band unless the frequency of the radiation is greater than the band gap frequency.

When such a transition takes place, a free electron and a hole are created near each other and they interact with a coulomb force. This interaction has important consequences. There is a possibility that the electron and the hole are bound together with a small but finite energy. Such a combination is called an "excitron"*. The concept of [illegible].

2. Indirect Interband Transitions

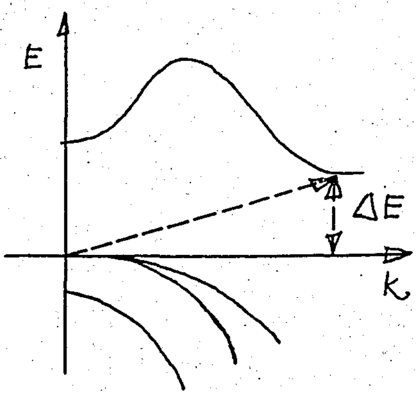


FIG 3-2
Energy picture of an Indirect semiconductor

In contrast with direct semi-conductors, we have indirect semi-conductors where the extrema of conduction and valence bands are at different wave vectors as shown in Fig. 2.

Here we cannot have vertical transitions. In order to satisfy the conservation of momentum we must introduce another quantity, the phonon, which is quantized lattice vibration or heat.

Calling the wave vector of phonon q, then

$k^{I} + q = k + K$ (3 - 4) if the phonon is emitted; or

$k = k + q + k$ (3 - 5) if the phonon is absorbed.

Before going on further, let us recapitulate on the two type[illegible] of transitions we have seen.

Suppose we are capable of achieving population inversion in the two types of semi-conductors we have seen. Which one should we choose as the more efficient system from the point of view of laser action?

Because the transitions between levels is only a photon process, direct semi-conductors should be chosen. Transitions in indirect semi-conductors are inefficient processes from laser point of view because of the emission of a phonon.

It seems once we have the electron in the conduction band, it shall have to fall to the lower level accompanied by an emission of a photon. The process is not so simple and does not occur in all direct semi-conductors. This was the reason why emission of photon was not experimentally detected in normal semi-conductors in early 1950. This observation was then attributed to the fact that: the requirement of conservation of the wave vector k permits only a single state of the valence band to serve as final state for the transition. It is extremely improbable that just this state is unoccupied. In order that such a situation to occur, we must have defects in the crystal.

C. Population Inversion in Semi-conductors

Having seen the absorbtion side of the story, we are ready to evaluate the other side: emission. However, since our aim is not to achieve spontaneous emission but stimulated emission, let us consider the concept of population inversion in semi-conductors.

Let E_{I} and E_{2} be two certain levels of semi-conductor situated in alence and conduction bands respectively; and let $f(E)$ describe the unction of distribution of electrons by energy levels. Then, for the ondition of population inversion between levels E_1 and E_2, we have

$$f(E_2) > f(E_1) \qquad 3-(6)$$

But, the distribution function $f(E_2)$ is related to $f(E_1)$. In fact, he first is the distribution of electrons and second is that of the oles, and

$$f_p(E) = 1 - f_e(E)$$

Thus, equation 3 - (7) becomes

$$f_e(E_2) + f_p(E_1) > 1 \qquad 3 - (8)$$

This calls for at least one of the levels (electrons or holes) to be degenarated. However, equation 3 - (8) holds only for direct transitions. In addition, the familiar fermi distributions of electrons and holes contradict eq. 3 - (8). Thus, the equation represents population inversion. In order to fulfill the condition 3 - (8), we must over-populate the upper level with respect to the lower level.

As we shall see later on, this can be done by (electric current fast electrons or optical) pumping. However, if we take the individual levels 1 - 2, neglecting others, then we shall not be able to achieve negative temperatures in any way. Only simultaneous excitation of several energy levels of the semi-conductor (a number of levels of the excitation and valency bands) will lead to population inversion. In order to make our following discussion easier, let us now introduce the concept of quasi-fermi levels.

Under equilibrium conditions, the probability of a state with energy E being occupied is given by Fermi-Dirac statistics.

$$f = \frac{1}{1 + e^{(E-F)/kT}} \qquad F \text{ fermi energy level}$$

If minority carriers, let us say electrons, are injected into a p-type semi-conductor and if they come to equilibrium among themselves in a time short, compared to the minority carrier lifetime, then the probability of an electron occupying a state in the conduction band is

$$f_c = \frac{1}{1 + e^{(E_c - F_c)/kT}} \qquad 3 - (9)$$

where F_c quasi-fermi level for electrons in the conduction band.

A similar expression holds for holes in the valence band.
To show the idea more clearly, let us take an intrinsic semi-conductor and draw its energy picture as in Fig. 3 - 3.

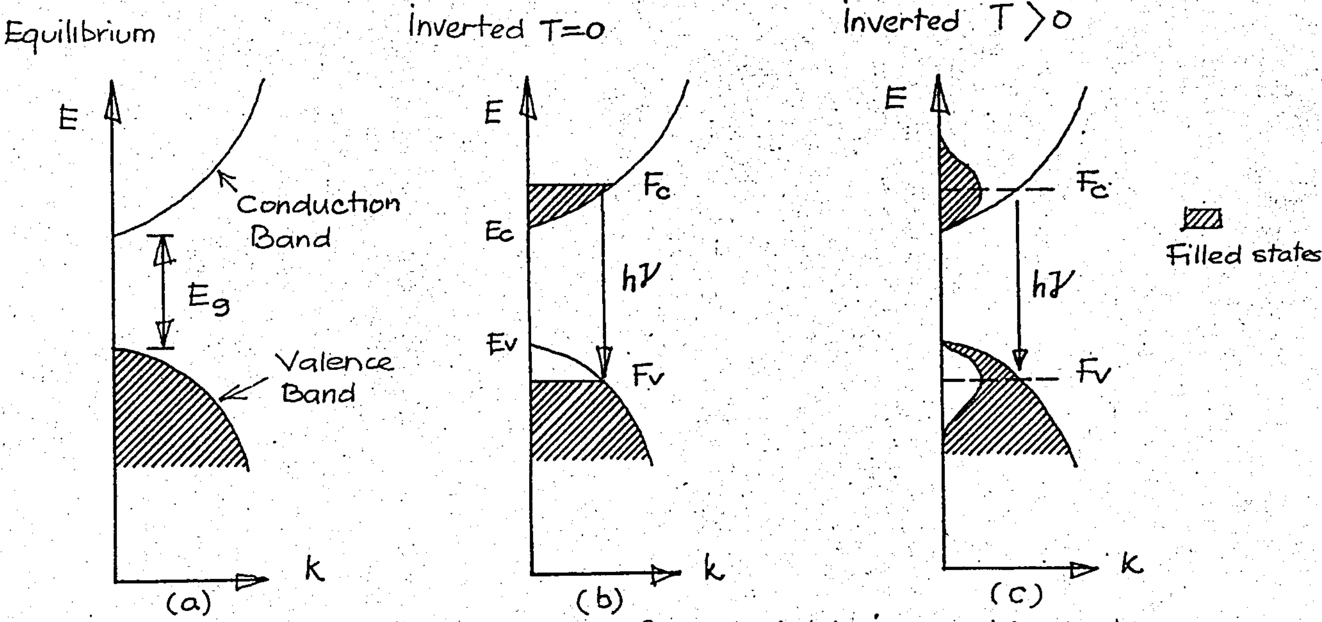


FIG 3_3 Energy Diagrams for an intrinsic semiconductor

The first figure depicts the semi-conductor at thermo-dynamic equilibrium, with a forbidden gap width Eg. at T = o. If a light wave of energy $h\nu > Eg$ is incident on the crystal, electrons will be making transitions from valence band to conduction band; exactly the same problem we dealt with in the preceding section. The resultant situation is given by Fig. b. The valence band is filled with holes or empty of electrons down to level E_V and the conduction band is full with electrons up to E_c (the quasi-fermi energy levels for holes and electrons). Now, photons with energy $h\nu$ such that $E_g < h\nu < (F_c - F_v)$ will cause downward transitions, and hence, stimulated emission. As can be expected at a finite temperature, there will not be a sharp energy distinction between filled and unfilled states. However, the distributions of carriers will be smeared as in Fig. 1c, as described by the equation 3 - (9). It is still possible to give conditions for stimulated emission. However, a question might arise. Equation 3 - (9) describes a system which is thermodynamically an equilibrium situation. However, Fig. 3 is a non-equilibrium situation: Overall thermal equilibrium does not exist, of course, but we assume that in a given energy band, the carriers will be in thermal equilibrium with each other.

Having the energy levels to work with, let us return to the population inversion and determine the physical conditions for this to happen. In the inversion region, the absorbed and emitted radiation quanta are given by

$$r_{abs.} = A\, S_{vc}\, f_v(1-f_c)\, \rho(\nu) \qquad 3 - (10)$$

$$r_{emit.} = A\, S_{cv}\, f_c(1-f_v)\, \rho(\nu) \qquad 3 - (11)$$

where $S_{vc} = S_{cv}$ the probability per unit time for a transition between a state in the valence band and a state in the conduction band separated by $h\nu$

$\rho(\nu) =$ density of states at energy h

A = a constant containing the density of states in valence and conduction bands.

f_c and f_v = probability of a state being occupied in the conduction and valence bands respectively and are given by 3 - (9).

At first sight, equation (10) and (11) don't say much, but they give simply the number of quanta of radiation absorbed depends on there being an electron in the valence band that can absorb the quantum in the presence of an empty state in the conduction band, i.e. the number is clearly proportional to $f_c\ (1-f_n)$. For the emitted radiation, the same principle can be applied.

For the emission to exceed absorbtion, we must have

$r_{emit} > r_{abs}$.

Substituting the value of f_c and f_v in equation (9), this condition becomes

$$\frac{1}{1+e^{(E_c-F_c)/kT}}\left(1-\frac{1}{1+e^{(E_v-F_v)/kT}}\right) < \frac{1}{1+e^{(E_v-F_v)/kT}}\left(1-\frac{1}{1+e^{(E_c-F_c/kt}}\right)$$

making the appropriate juggling, we shall get

$E_v - F_v > E_c - F_c$

$F_c - F_v < E_c - E_v$

but, $E_c - E_v = E_g$ the band gap energy, thus, finally we have

$F_c - F_v > E_g$ 3 - (12)

or from absorbtion phenomena, we can say that

$E_g = h\nu$

and equation 3 - (12) becomes

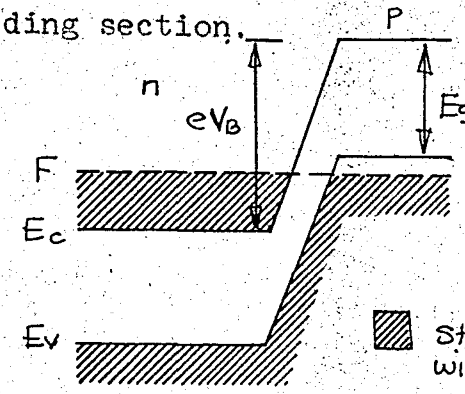
$F_c - F_v > h\nu$ 3 - (13)

What equation 3 - (12) does, is to relate the quasi-fermi energy levels of conduction and valence bands to the energy gap. In other words, it dictates the doping levels in P-N junctions necessary for laser action. Since $F_c - F_v$ cannot be greater than the built-in voltage, the condition can be stated as the built-in voltage must be greater than $h\nu$ or the energy gap, which means a degenerate junction like that of a Tunnel diode.

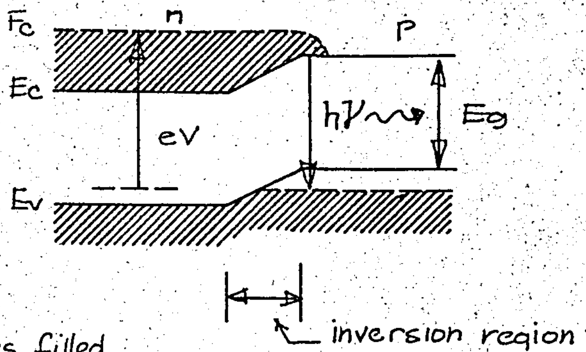
D. Methods of Excitation

1. Injection of Current

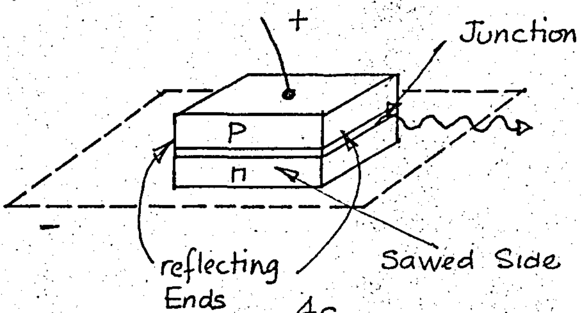
Let us take a semi-conductor junction as we have described in the preceding section.



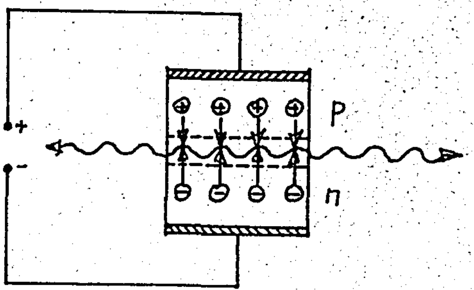
4 - a



4 - b



_ 4c



_4 d)

The semi-conductor on the left is doped with donor impurities that make it a degenerately n-type, that is, there are enough electrons added by the impurities to fill the conduction band up to the fermi level, F. On the right hand side, acceptor impurities are added, which deplete electrons from the valence band. In other words, add holes down to energy F.

When equilibrium is reached, a potential barrier V_b is built, which prevents further current flow. As discussed in the previous section, this built-in voltage is greater than the band gap, as shown in Fig. 3-4a. In fact, this picture is identical to that of a Tunnel diode. An application of voltage, in the forward direction, with a magnitude in the order of the energy gap, so as to remove this voltage results in the Figure of 3-4b. Upon removal of this potential V_B, concentration of minority carriers near the junction increases. In other words, as can be seen from the figure, electrons in the conduction band and holes in the valence band exist in the transition region. Electrons drop from the conduction band to an empty state in the valence band and emit photons of energy, approximately equal to h . In actual junctions, there are impurity levels in the gap near the band edges, and the photon energy can be less than E_g. It is also possible to have holes flow to the n side, where they recombine with electrons. The pre-dominant process is determined by relative impurity densities, the carrier lifetimes and carrier mobilities. In any case, we shall have a region in which population inversion can be achieved by high enough a voltage. Because the region is usually quite thin, the maximum optical gain over a reasonable distance will be in the plane of the junction. It is desirable to take advantage of this fact by constructing a resonant structure such as a Fabry Parot structure, as shown in Fig. 4c. This method was also discussed in one of the previous sections.

The phenomenon associated is not new, even in normal semi-conductor junctions, the problem of recombination is encountered, but, unlike in that case, radiative recombination is encouraged in this case.

Before we go on to other methods of excitation, let us briefly see some properties of injection excitation. The current density (electron component) is equal by order of magnitude to

$$I \approx -\left(\frac{e D n_p}{L}\right) e^{\frac{e\varphi}{kT}} \qquad 3 - (14)$$

where D is the diffusion coefficient

L diffusion length

n_p electron density in the p part of the semi-conductor.

φ

An analysis of this relation shows us that current density decreases with the increase of degeneration and with lowering the temperature of the sample.

From the discussion in part II D, we know that there is a threshhold of laser operation. Only after this value lasing occurs. If one were to write the efficiency relation for the semi-conductor laser,

$$= \frac{\text{Optical Power Output}}{\text{Electrical Power Input}} = \frac{\hbar\omega\,(I - I_o)}{e\varphi I} \qquad (3 - 15)$$

where I_o threshold current of which lasing starts

I total current passing through the sample

φ total voltage which is supplied to the sample.

If the condition of threshold is well-exceeded that the efficieny of such generators approach unity.

P-N junction is a very convenient method of pumping a semiconductor laser material, but it gives rise to some difficult problems in materials' preparation and structure fabrication. As we have discussed before, the semi-conductor junction should be degenerately doped in both sides of the junction, since a good source of holes and electrons will be needed. Many semi-conductors cannot be doped usefully, both n-type and p-type.

2. Electron Beam Pumping (12), (14)

Utilization of the electron beam for the excitation of semiconductor, as differed from the previous methods, makes it possible to attain the states with negative temperatures for the semi-conductors with a different width of the forbidden band, i.e. to obtain generation from an infrared region to the ultraviolet. The limit energy output at the electron excitation can be calculated under the assumption that process of the electron hole multiplication for carriers with energy sufficient for production pair is the fastest of all processes.

In this method, a beam of high energy electrons, 20 kV or greater, is directed at a flat face of the semi-conductor sample.

These electrons penetrate several microns into the material depending on the energy and lose a large fraction of energy by creating many low energy electron-hole pairs. It takes about two to four times the energy gap to create an electron hole pair, so that about 10^{14} electrons and holes are created per incident electron. They decay to conduction and valence band energies and form inverted population.

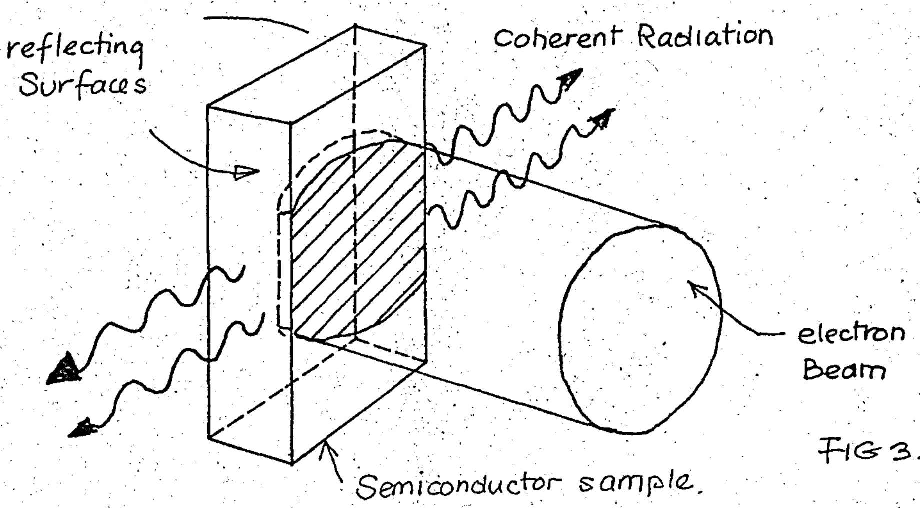


FIG 3-5. Electron Beam pumping

Coherent radiation is emitted perpendicular to the reflecting ends, as shown in Fig. 3-5.

3. Optical pumping (13)

Here, semi-conductor is excited with a radiation whose energy is larger than the band gap as we have discussed. The situation is identical to that of electron pumping.

4. Avalance Injection Methods

If the electrons or holes in a semi-conductor are accelerated to sufficiently high energy by an electric field they can ionize on electron across the energy gap and thus produce electron-hole pairs. This process which is called the avalanche break-down has been prepared as a method of obtaining population inversion in semi-conductors.

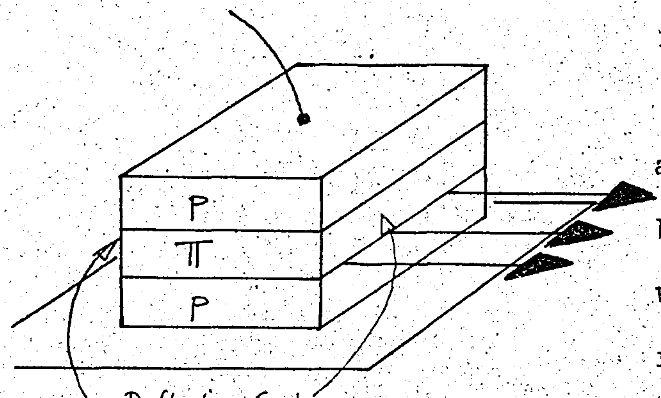


FIG 3-6

However, there are difficulties associated with the scheme. If a bulk crystal is used, the carriers will be very hot and they cannot form a degenerate distribution unless the field is turned off. Therefore, the field must be pulsed. Avalanche breakdown can also be observed in a reverse biased P-N junction.

In this case, the emission has a low quantum efficiency because the field is in the direction to push the electrons to the n side of the junction and holes to the p side where they are majority carriers and produce no radiation. These objections are overcome by a structure discovered by Weiser and Woods.(15)

The structure is essentially a p-π-p sandwich shown in Fig. 6. The Avalanche breakdown is initiated by holes in high resistivity π (low carrier concentration p) region where the field is high. The electrons are accelerated by the field into one of the p regions where the field is low. They form a degenerate distribution and laser action takes place perpendicular to the field direction.

In short, the characteristic advantages of a P-N junction laser are that it is compact and simple, that is, it requires only a low voltage, d.c. voltage power supply. It can easily be modulated by merely modulating the current, since output radiation is proportional to the current through the diode. However, the big disadvantage is that often P-N junctions are difficult or impossible to make.

Nevertheless, successful injection laser diodes have been constructed and occupy an important position in the field of coherent light generation.

PART IV

PROPERTIES OF INJECTION LASERS

IV. PROPERTIES OF INJECTION LASERS

We have started in search for a light source which is coherent and can be modulated easily. Injection lasers from this point of view, offer many advantages. Firstly, they convert, as we have emphasized earlier, d.c. elctrical power directly into light. The intensity of this light is directly proportional to the current passing through the diode.

A. Materials

To construct the real device, we must make a choice from the existing semi-conductors. As we have dealt before, there are two criteria for this. Firstly, the semi-conductor should be a direct type i.e. the maximum and minimum of valence and conduction bands should occur at the same wave vector, so that photon emission shall be a first order process. Secondly; we should be able to dope the semi-conductor degenerately both n and p-type.

Almost all direct band gap III-V compounds including several alloys satisfy these conditions.⑥⑦⑧⑨ GaAs①②③, however, was the first material to lase and it has had the most extensive study and development. Because of this fact, we will base our discussions on this material.

A second group to exhibit laser action is the lead salts.⑪⑫ These are also direct gap materials such as PbS, PbTe, PbSe.

The only elemental semi-conductor yet to lase is tellirium, at a wavelength of 3.4 . Several II-IV materials have been reported to lase.

As was mentioned in the previous paragraph, GaAs was the first semi-conductor laser, and most of the experimental work is done with this diode. Because of the high currents (~20 A) involved in achieving laser action, the measurements were made passing short pulses of current (1μ sec.) and observing the resulting recombination radiation, coming from the laser diode which is placed in a Liquid Nitrogen bath.

Later on, the advent of fabrication techniques of GaAs crysta quickly lead to the ability to operate them continuously at 2^{o}k and enabling lasing at room temperature operation for short periods (about 200 n sec).

B. Junction Fabrication⑤

The P-N junction laser is nothing more than an ordinary P-N junction diode in the form of appropriate cavity. The purpose of this cavity as discussed, is to select certain modes geometrically.

The P-N junction Laser is quite small by conventional laser standards. The typical dimensions are 250μ - 50μ - 50μ. Low threshold lasers can be obtained by epitaxial growth from liquid state(5). The Fabry Parot structure can be made by using the cleavage property of GaAs.

To form such small cavities with optically flat and parallel walls an n-type GaAs crystal(doped with Se, Si, Ge, Te, from about 3×10^{17} to 6×10^{18} carriers/cm^3) is cut into wafers whose plane is perpendicular to one or more (110) planes. These wafers are lapped and polished to remove surface damage and provide a smooth surface for diffusion.

Contacts are made to the P and N regions by conventional semiconductor techniques. The index of refraction of GaAs is high (3.6) so that it is unnecessary to put reflecting coating on the ends of a

Fabry Parot cavity. One has a reflectivity of about $0.32 = \frac{(n - 1)^2}{(n + 1)^2}$ for GaAs-air interface. However, silvering the ends lowers the threshold.

C. Spectral Properties of GaAs Lasers

1. Temperature dependance of the wavelength of emission. (15)

Since the frequency of the spontaneous emission is proportional to the band gap, for GaAs the spontaneous emission shifts to longer wavelength as the temperature is raised. At 77°k we have $\frac{d\lambda}{dT} = 0.46$ Å/degree. Because of this effect for GaAs at 77°K, the lasing radiation is about 8440 Å whereas at room temperature this shifts to about 9000 Å.

2. Pressure Dependance of the Recombination Radiation. (16) (23)

The pressure dependance of the recombination radiation at 77°K have been reported. The pressure dependance of the energy of the broad band spontaneous emission is

$$+1.1 \times 10^{15} \text{ev/Atm.}$$

which agrees with the pressure coefficient of the energy gap.

D. Spatial Properties

Spatial measurements are made on the Fabry Perot cavity, this being the most practical laser configuration.

Lasers, in addition to being highly monochromatic, are also spatially coherent. Thus highly directional beams of light can be produced. For a Fabry Perot-type laser structure, the angular spread of the beam θ (full included angle at half intensity) is determined by diffraction

$$\theta = \frac{\lambda}{d}$$

where d is the width of the emitting region in the plane where θ is measured.

Because of the small size of the P-N junction lasers, θ is much larger than in other types of lasers. Furthermore, P-N junction lase is an optically non-uniform structure: impurity densities near the junction are a function of position, so the index of refraction and absorbtion constant are not constant throughout the region.

To determine the spatial properties, tw experiments are done:

1. Near Field Patterns

This is the examination of distrinution of intensity at the surface of the diode with a microscope using an image converter.

2. Far Field Patterns

Examination of the distribution of intensity at large distances from the laser.

1. Near Field Patterns

The nature of these patterns give us a qualitative understanding of the real nature of the operation of the laser. Before the lasing occurs, there is fluorescence coming from the region less than 5 thick in the vicinity of the junction. The intensity of this light i fairly uniform along the junction. Because of the degeneracy of the junction, the usual P-N junction theory does not apply. It is difficult to predict where the recombination should take predominantl However, qualitatively, it is possible to arrive at some points:

1. Hole injection into the n side is favored by the heavier doping, usually encountered on the n side.

2. However, electron injection into the n side is favored by several factors. Firstly, the electron has a higher mobility than th hole. Secondly, the effective mass is much smaller in the conductio band than in the valence band. Thus, for a given carrier concentrati the Fermi level will be further into the conduction band on the n sid

than the valence band on the p side, causing the electrons to "spill" over to the p side first, as a potential barrier is reduced by the applied bias. Thirdly, the band gap in the heavily doped p side may be smaller, making it easier to inject to the p side.

Finally, the recombination time of the minority carriers is probably inversely proportional to the majority carrier concentration, thus electrons injected to the p side will dissappear very rapidly.

From these considerations it is, at least, not unreasonable to expect that the light comes from the p side of the junction.

2. Characteristics of the Emitted Radiation (Far Field Patterns)

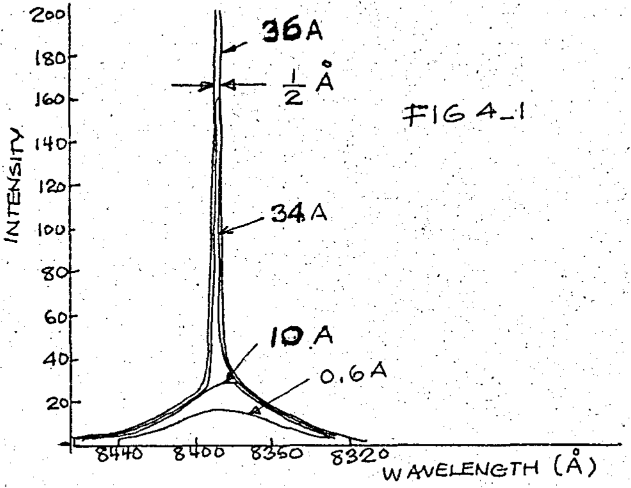


FIG 4-1

As the current is increased beyond the threshold, the width of the line decreases. For example, in one diode, as the current was increased from 10 to 34 amperes, the width of the emission decreases from 120 Å to 20 Å. As the current is further increased from 34 to 36 A, the emission width decreased to 0.5 Å. This is not hard to explain. At low intensity, the resonator is lossy and has poor mode discrimination. Although the stimulated emission is occurring, the feedback is too low for the system to oscillate. As the current is increased, the system breaks into oscillation.

The angular dependence of the emitted radiation is shown on Fig. 4 most of the radiation comes out at around 0°. As the current is increased above threshold, fluorescence stops and lasing starts, accompanied by the concentration of light in spots along the junction, instead of being uniform along the junction.

2. Far Field Patterns

Stimulated emission emerges more or less normally to the reflecting ends, but the details of the patterns can be quite complex: often fan shaped patterns are observed.

In good directional lasers, one beam is observed just above threshold, beam angles as low as 1° in the plane of the junction have been reported.

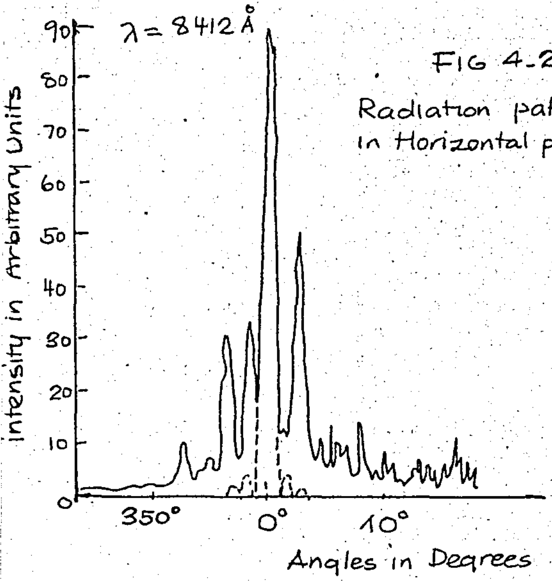


FIG 4-2
Radiation pattern in Horizontal plane

The polarization of the emitted radiation has been studied. Usually, but not always, the stimulated emission is polarized. Without any apparent order, different diodes are found to have plane of polarization in the junction plane, perpendicular to it or sometimes at an intermediate angle.

E. Temperature Effects ⑮ ⑰

As we have briefly touched before, the threshold lasing current is temperature-dependendent. There is, however, two regions at low temperatures, current is independent of temperature, but above 60°K, it can be represented as T^p where $p = 3$ As shown in the accompanying figure 4-3, the temperature at which T^3 begins, increases with increasing

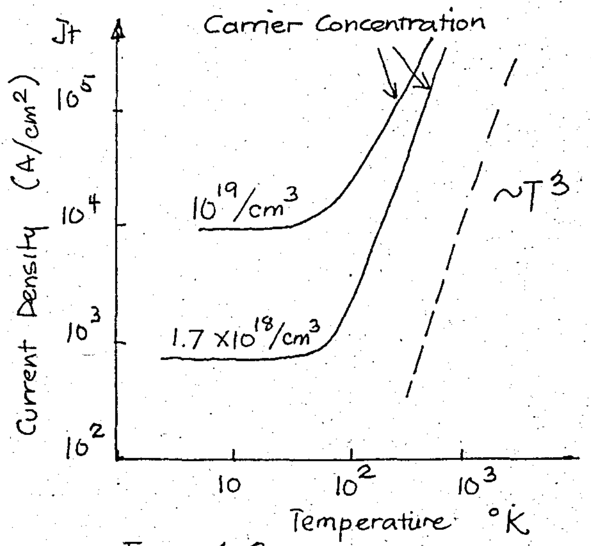


FIG 4-3
After Piltuhn & Rupprecht ⑤

substrate carrier concentration. Qualitatively, this behaviour is expected, since, as the temperature is increased, the distributions of electrons become non-degenerate, so that upward, as well as downward transitions can occur at the lasing photon energy in the active region Thus, the gain will be decreased for a given current density and it will have to be increased to take care of this.

Thresholds about a factor of three lower at room temperatures than those of ordinary diffused lasers have been found for solution regrown lasers.(5)

F. Operating Characteristics ⑭ ⑳ ㉒

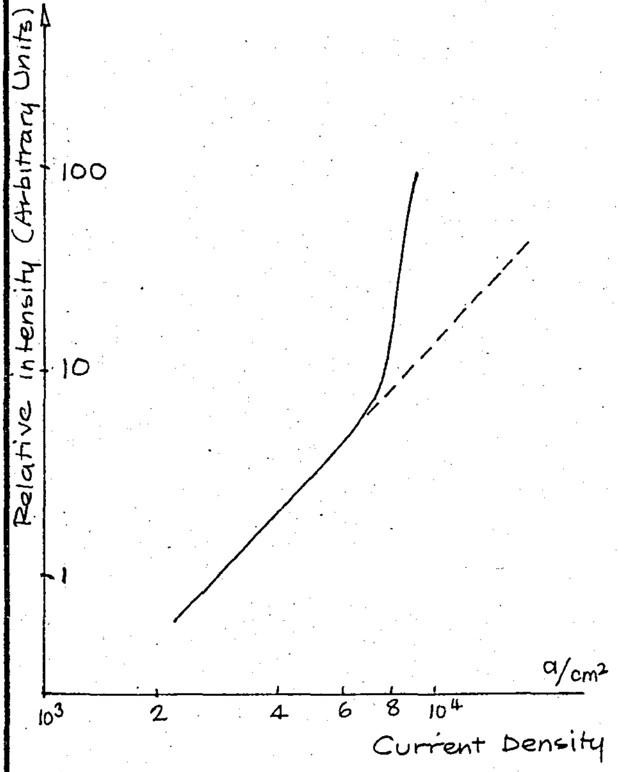


FIG 4-4
Dependence of radiation intensity on the current density

Although the internal quantum efficiency of the laser diode may be as high as 0.5 or higher (18), very little energy escapes from the diode laser below threshold, because most of the light is totally and internally reflected and absorbed in the inactive regions of the diode. At these current densities, the radiation is emitted isotropicly.

At and above threshold, the external efficiency (the number of photons escaping from the crystal per carrier crossing the junction) increases and the light output becomes coherent, as shown in Fig. 4-4. However, even above threshold, the external quantum efficiencies of 50 per-cent or less are observed at most temperatures, so that a good fraction of the light still remains in the laser. Dissipation of the heat produced by the absorbed light and series resistance is one of th major limitations on the operation of injection lasers. Because of th increase of the threshold and decrease of the thermal conductivity of the semi-conductor with increasing temperature above 30°K, the problem becomes more difficult as the temperature is increased. In order to operate an injection laser continuously, it is necessary to provide effective cooling. This can be done by placing the laser in contact with a large metallic heat sink, which is cooled by a cyrogenic liquid bath. CW operation with power outputs of several watts have been achieved, using GaAs using liquid helium(19), hydrogen(20), and nitrogen(21).

At room temperature only pulses of a few 100 nanoseconds or less can be used. For continuous-wave operation, it is desirable to make the laser very narrow, that is, with a high ratio of length to width in the junction plane. Keyes(22) has shown that in order to achieve CW operation at room temperature with currently available threshold current density, it would be necessary to make a laser with a length to width ratio of several hundred. This is beyond the present state-of-the art.

1. Heating Effects

Heat is generated by two processes in injection lasers.

1. Non-radiative combination of holes and electrons
2. Joule heating

Since the internal quantum efficiency is nearly unity, non-radiative recombination heating results mostly from re-absorbing light in the inactive part of the laser, rather than from non-radiative processes in the active region.

The rate of non-radiative heating is given by

$$P = (1-\eta_{ext})\ IV$$

The Joule heating comes from the contact heating mainly

$$P = I^2 R$$

Thus, for low levels, contact resistances is not important.

From measurements, it seems that the heat is generated throughout the diode. The thermal relaxation time of the diode is given by:

$$\tau_t = \frac{C\rho}{kT}\ W$$

where C = specific heat

ρ = density

kT = thermal conductivity

W = average distance heat must traverse to get out of the diode

For $W = 2 \times 10^{-3}$ cm. on finds

$$\tau_t \simeq 6\mu\text{sec}.$$

The experimental results agree on the order of magnitude and about 10 μsec. have been obtained through measurements.

For CW operation or for pulsed operation which repetition rates large compared to $\frac{1}{\tau_t}$ thermal conductivity is important.

In order to obtain high power or to operate at high temperatures, it is necessary to take special measures to get the heat out of the laser.

PART V

THEORETICAL TREATMENT OF THE P-N JUNCTION LASERS

V. THEORETICAL TREATMENT OF THE P-N JUNCTION LASERS

To treat the injection lasers theoretically, some simplifying assumptions have to be made. The validity of these assumptions, however, may be difficult to assess. The two important assumptions are as follows.

1. The form of transition probability as a function of energy and wave vectors of the initial and final states must be chosen arbitrarily. Since the effect of high impurity density on the energy states of the crystal is not known in detail, the transition probability is uncertain.

2. Minority carrier density vs. distance from the junction is important in calculations, but gradient near the junction is very steep, making the distance dependencies complex. Most calculations thus far have assumed homogeneity, i.e. if electrons are to be injecte into p side electrons are assumed to be uniformly distributed throughout the distance d in a material that has some given acceptor concentration.

A. Threshold Relation ①②

In the general treatment of laser, we have come out with a relation which gives power at the threshold for a system that is sharply defined in energy level scheme(Eg 2-23). The occupation of levels is completely determined by the knowledge of N_1 and N_2 since they are narrow compared to kT. In semi-conductors, the shape of the bands and the temperature determine the continuum of levels.

As we shall show later, this has important effects on the temperature dependency of the threshold current.

However, at T = 0, Eq.(2-23) can be applied because there is no thermal excitation. Writing Eq.(2-23) in terms of current density instead of power in the junction

$$P = IVg = \frac{(JA)\ (eVg)}{e} \qquad (5 - 1)$$

Vg = the voltage drop across the junction is essentially equal to the photon energy $\frac{E}{e}$ (Section 3a), then

$$P = (J)\ (E)\left(\frac{A}{e}\right)$$

$$P = \frac{(J)\ (h\nu)\ A}{e}$$

Solving for J and substituting (2-23), we shall get (9)

$$Jt = 6.3 \times 10^{4}\ \frac{n^2\ d\ E^2 \Delta E}{\eta}\ \left(-\frac{\ln R}{L} + \beta\right) \quad (5.2)$$

where E = energy of radiation

E = line width

Jt = A/cm.^{2}

η = efficiency

d = active region width (all lengths in cm.)

Let us calculate a typical current density for the junction

For a typical value of GaAs laser

$n = 3.6$

$d = 10^{-4}$ cm.

$E = 1.47$ eV

$\Delta E = 0.02$ eV

$\eta = 100\ \%$

$R = 0.32$

$L = 0.03$ cm.

$\beta = 0$

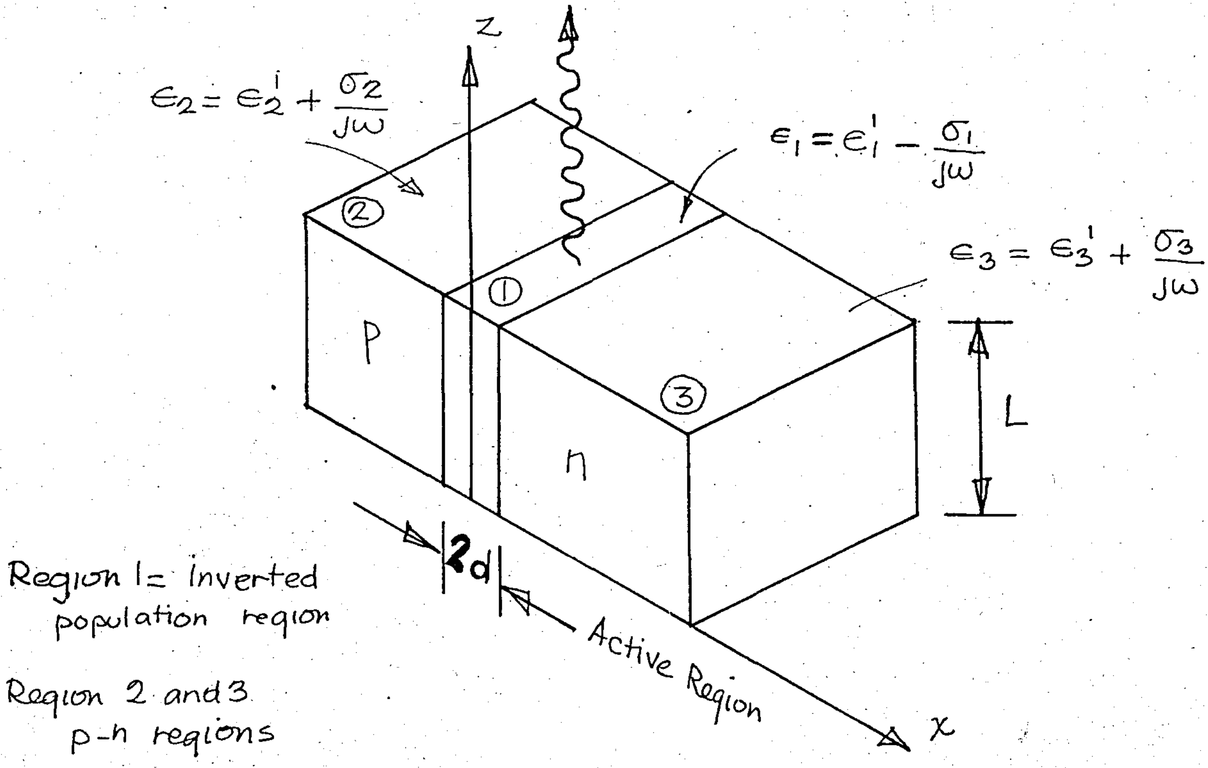
Then we shall get for the threshold current density 130 Amps/cm^2 at 0°K.

For typical cross section of 50μ x 50μ we would get about 2.75 m A. However, at room temperature, the order of the threshold curre density rises to 100,000 A/cm^2. This corresponds to roughly about 2 This, however, is not the case, because at higher temperatures, other effects come into consideration which are considered in 5.2. The experimental results for the threshold currents are as high as 20 A, at room temperature.

B. Generation of Light in the Junction Guiding of Modes ③④⑤

We have found out that the generation of coherent light takes place in the narrow transition region. To gain some idea on the propogation of light through this medium, let us treat this problem rigorously. In a few words, the problem is the propogation of electr magnetic wave along negative loss dielectric slab sandwiched between semi-infinite regions of positive loss dielectric slab.

To have a physical picture of the situation, let us take an idealized model of P-N junction laser for our calculations.



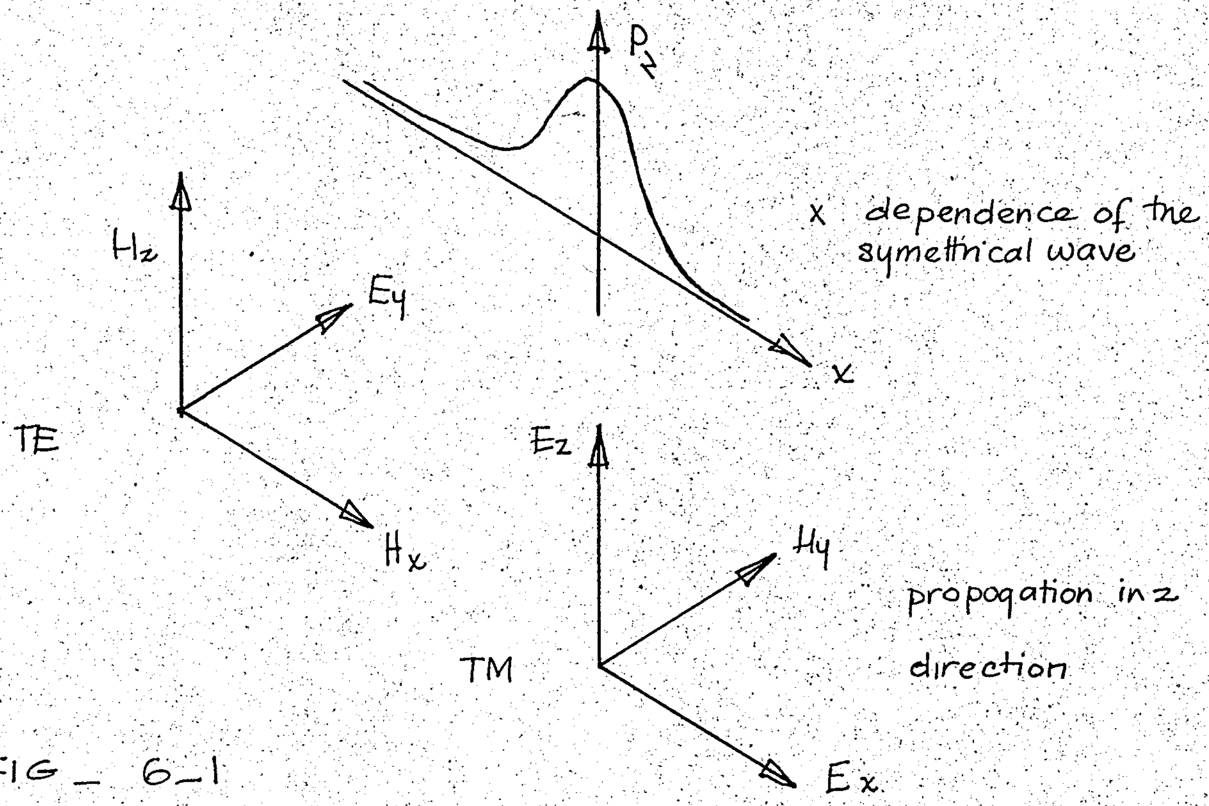


FIG _ 6_1

We know that surface waves of both TE and TM-type waves may be guided along a dielectric slab or sheet. The behaviour of electromagnetic waves in the gallium arsenide laser will follow this fact. In the semi-conductor laser, the lightis generated in the narrow junction region where the population is inverted. (Region 1 in Fig. 6-1). However, the energy is lost in the inactive parts of the region, namel the p and n regions (Regions 2 and 3) on either side of the junction.

These regions will be characterized by the following dielectric constants.

Junction Region 1 $\epsilon_1 = \epsilon_1' - \frac{\sigma_1}{j\omega}$ Negative conductivity

p-type Region 2 $\epsilon_2 = \epsilon_2' + \frac{\sigma_2}{j\omega}$ (5 - 3)

n-type Region 3 $\epsilon_3 = \epsilon_3' + \frac{\sigma_3}{j\omega}$

Now, we must solve the electromagnetic propagation problem, to determine how far the modes penetrate into the inactive regions and thus, determine how much energy is to be supplied by the inverted region before the net energy in this region is positive and is amplified as it propagates between the faces of the diode perpendicular to Z where Z is the direction of propogation.

The electromagnetic modes with the lowest threshold for maser operation are even TE and TM modes, guided along the plane of the junction like the waves bound to an electric slab. The TM modes will have a single component of magnetic field Hy and electric components Ex and Ez. The TE modes have the roles of electric field and magnetic field interchanged and hence have components Ey, Hx, and Hz.

The propogation of the modes in the Z direction will be with a propogation factor $e^{-Jk_z z}$. For both types of modes, the field will decay away from the active region, according to the factor $e^{-k(|x|-d)}$

Thus, we shall have for the electromagnetic wave variation

y, t variation $e^{jwt - k_y y}$

z, t variation

$$= e^{jwt - k_z z} \qquad (5 - 4)$$

and x variation will be

in Region 1 Active region

$$= A \operatorname{Cos} k_I x + B \operatorname{Sin} k_I x \qquad (5 - 5)$$

in Region 2 p-region

$$= e^{jk_2 x}$$

and in Region 3 n-region

$$= e^{-jk_3 x}$$

TM Modes

The solutions for Hy in the dielectric may be even or odd. The "even" and "odd" refer to the way Hz varies with x about the symmetry plane x = 0.

Matching the boundary conditions of transverse E and H at the two interfaces, x = ±d, we obtain

$$\frac{k_I}{E_I} \tan k_I d = J \frac{k_2}{\epsilon_2} \qquad (5- 6)$$

Doing the same thing for the TE mode, we get

$$k_I \tan k_I d = jk_2 \qquad (5 - 7)$$

From Maxwell's equations

$$k^2 + k_I^2 = w^2 \mu_o \epsilon_1$$
$$k^2 + k_2^2 = W^2 \mu_o \epsilon_2$$
$$k^2 = k_y^2 + k^2 z$$

Assuming

$\omega^2 \mu_o \quad (\epsilon_1 - \epsilon_2) \omega^2 \ll 1$ and

$\sigma_2, \sigma_3 \ll \sigma_1, \ll \omega\epsilon$ both of which are valid for junction lasers, one obtains the simple result, in terms of O_I for both TE and TM modes

$$k = k_o (1 + j\eta/2) \qquad (5 -11)$$

where

$$= \frac{\sigma_2 + \sigma_3}{2\omega\epsilon} - 2(k_o d)^2 \frac{(\epsilon_1' - (\epsilon_2' + \epsilon_3)/2}{\epsilon} \frac{\sigma}{\omega\epsilon} \qquad (5 -12)$$

Let us now try to interpret these in terms of experimental result

The real part of the k, k_o in equation (5-11), is approximately equal to the propogation constant in pure GaAs.

The imaginary part of k determines the growth of the wave and is expressed in terms of η. The first term of η in equation (5-12), gives the rate of decay due to losses in the p and n ragions. The second term gives the rate of growth due to the inverted population in region (1).

For the wave to grow, the negative conductivity σ_1 must be large enough so that the second term becomes larger than the first, i.e.

The penetration to the regions (2) and (3) are determined by

$$\epsilon_1' - \frac{(\epsilon' + \epsilon)}{2} .$$

If we look at the equation (5-12) only if this quantity is positi the wave will be able to grow as this quantity becomes larger, the penetration to the lossy regions becomes smaller.

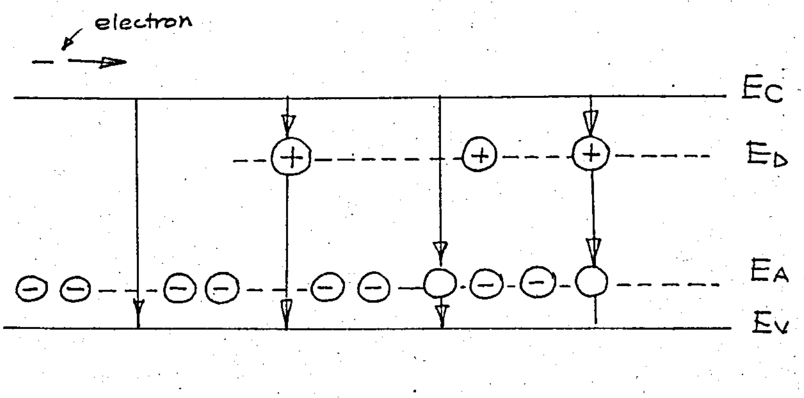
The reason for the confinement of the wave due to discontinuity in the real part of the dielectric constant between Region (1) and Region (2) has not been definitely established.

In practice, the guided TE and TM modes propogate in filaments along the junction plane rather than uniformly along the plane as suggested by the figure. The explanation of this behaviour is not very clear.

C. Spectral Analysis ⑧ ⑨ ⑩

To truly understand the injection laser, it is necessary to understand the levels or distorted bands that give rise to recombination radiation. It appears that, at least in heavily doped GaAs diodes, thetransitions are band to band, but bands have large tails (bands distorted by impurities). For more lightly doped diodes, the results are more contraversial. However, radiative transitions may be grouped in four, for an electron that is injected into the p-type material.

1. Conduction to valence band--Eand to band recombination.



Possible radiative transitions.

2. Donor to valence band, first captured by the donor, then make radiative transition.

3. Conduction band to acceptor

4. Donor to acceptor

In addition to these four processes, there is the possibility of bound excitron formation.

The spontaneous and stimulated emission functions has been calculated by assuming a parabolic distribution for the density of states in the conduction and valence band.*

---

*Lasher and Stern, "Spontaneous and Stimulated Line Shape in S.Conducto Lasers" Physics Review CXXXIII, (June, 1963), 2116-2119.

PART VI

PRACTICAL ASPECTS

VI. PRACTICAL ASPECTS

Having seen the theoretical side of the semi-conductor injection laser, let us review its practical aspects. Its advantages consist of:

1. Compact size
2. Direct conversion of d.c. electrical power to coherent radiation
3. Ease of modulation
4. Potential low cost of manufacture

However, it has some disadvantages which are

1. Relatively large beam angles. The beam angle is large compared to other lasers, which can be eleiminated by the use of lenses
2. Restriction to low temperature. This effectis the most important one to limit the application of the injection lasers. If techniques of producing semi-conductors improve, continuous wave operation might be achieved.

The most important practical aspect of the injection laser is the case with which it can be amplitude-modulated. A number of measurements to determine the frequency response have been made. However, these measurements are limited because of the difficulty of finding sensitive enough high-speed detectors. Once the laser radiation starts to turn on, it turns on very rapidly in less than 0.2 nsecs.

However, there is a delay between the onset of the current pulse and turn on the stimulated emission. This effect is caused by the fact that there is a finite time necessary to build up the population inversion with the current through the junction and at 77^oK it is of the order of InS. It decreases with increasing current above threshhold and can be shown to follow the relation *

$$t_d = \tau \, Ln \frac{I}{(I - I_o)}$$

For example, for $I = 5A$ and $\tau = 2ns$ td = 0.44ns. It should be noted, however, that this would not limit the response of a laser to microwaves,② the inversion will be built up when the microwaves are turned on and will be maintained even if it falls below threshold provided that the period of the microwaves is less than the spontaneous lifetime.

However, at room temperature, delays③ as long as 150 n sec. have been observed in some lasers and with improved fabrication techniques techniques have been eliminated. Amplitude modulation of GaAs laser at 11 G Hz have been achieved.④( ) The limitation on the frequency was imposed by the components of the system.

It is also possible to frequency-modulate the laser.⑤⑥ The index of refraction is dependent on the stress applied to the semi-conductor. This effect has been used to frequency-modulate a GaAs junction with ultrasonic techniques.

An important point to consider about frequency modulation is that frequency of each mode depends on the temperature through the index of refraction. At 77^oK, this effect produces 0.46 Å/K^o shifts in the modes which is equivalent to 20 GHz/K^o. Thus, the temperature should be controlled to stabilize the frequency.

---

*Goldstein and Wiegend, "Band Modulation of GaAs Lasers" Proc IEEE LIII (February, 1965), 195.

The case of high-frequency modulation makes GaAs laser attractive from communications stand-point. This is why we have chosen this laser in our study. However, because of the multi-mode operation (occurring above threshold), heterodyning cannot be used. The major advantage of the laser over an incoherent light emitting diode are its directionability and its high quantum efficiency, which gives high optical efficiency to the system. The frequency response is also better.

The major disadvantage, is that it must be refrigerated in order to take advantage of its frequency response.

PART VII

PROBLEMS OF OPTICAL COMMUNICATIONS

VII. PROBLEMS OF OPTICAL COMMUNICATIONS

A. Detection of Coherent Light ①④⑥

The problem of using optical frequencies for communications is not solved by generating coherent light only. There should be sensitive coherent detectors and detection techniques.

For our purposes it should be useful to have a brief review of these techniques and devices.

1. Basic Optical Detection Systems

The techniques of optical detection is identical in principle to the methods applicable in the RF or microwave regions.

However, there is a natural limit at these frequencies to the minimum amount of radiation that can be detected even in an ideal system that is in principle free of external noise sources. We can do no better than count individual photons. Technically speaking, this operation has been accomplished with cooled photo mulipliers in the short wave length visible and in the infrared. Therefore, the utmost limit of sensitivity has been reached.

The efficiency of the optical detectors is another problem. In the wavelength region from about 0.7 to 1.3 μm (7000A$^{\circ}$ - 13 000A$^{\circ}$) the efficiency of photoemissive surfaces drops to about 1% as compared to efficiencies of 20% in the blue and ultraviolet regions. As we go to wavelengths above 1.3 μm solid state devices predominate as the photoemission does not take place at longer wavelengths.

As we go to longer wavelengths it follows directly that we must use devices that will respond to low energy excitation. As the minimum energy for excitation decreases, there are many competing processes that interfere with the incoming optical signal. For example, thermal generation of the excited charge carriers can create problems. Many other noise sources are present such as optical excitation due to background. The room temperature blackbody radiation from the surroundings generates carriers that contribute to noise.

It is at these wavelengths incoherent detection begins to fail because it is increasingly difficult to achieve high sensitivity.

Let us now analyze a general photo-detector.

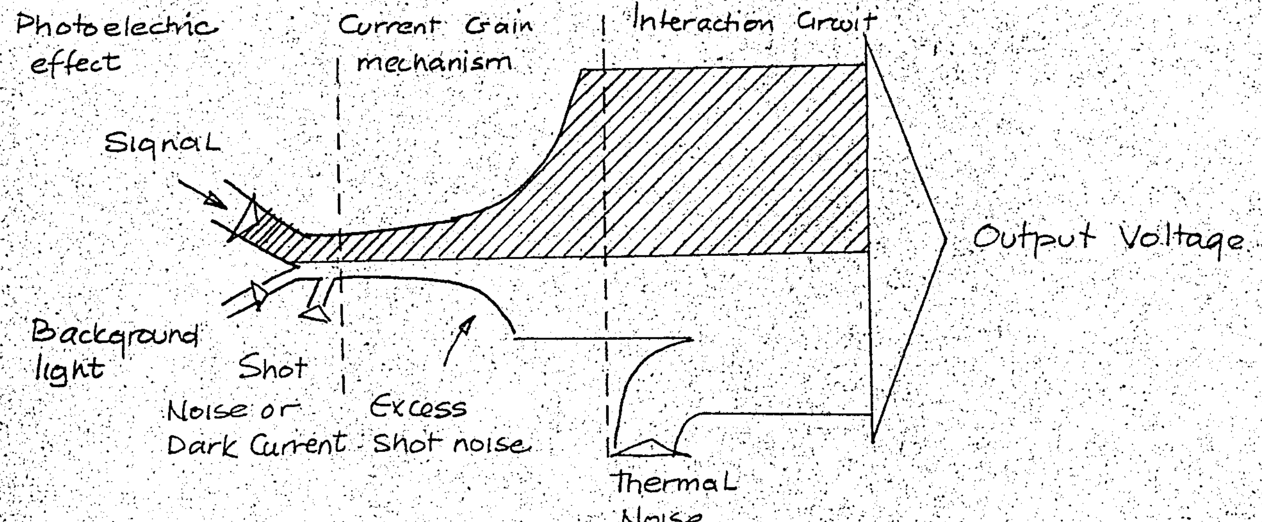


FIG 7. Generalized Photodetector

In all detectors, detection is a 3-step process. Firstly, free carriers are generated by the incident light in the second carriers are muliplied by whatever the current gain mechanism is and finally this current interacts with the circuitry to provide the output signal

The basic photo-electric process is characterized by a linear proportionality between the number of incident photons and the number of free electrons and holes that are produced. The process in the photo-emissive surfaces is clear; the similar process also takes place in semi-conductors: by the absorbtion of a photon, a free electron and a hole is produced. If an electric field is applied to the junction, it shall sweep these free charges thus an electric current will be generated.

In terms of optical power PL and primary photo-current Ip, the proportionality becomes

$$Ip = \eta \frac{ePL}{h\nu} \quad (7\text{-}1) \qquad \eta = \frac{\text{free carriers}}{\text{photons}} \quad \text{efficiency}$$

Current gain can be obtained in a number of ways, two of the most important are secondary emission multiplication as used in a photomultiplier and impact ionization (avalanching) as occurs in P-N junctions reverse biased close to breakdown.Of course these processes are characterized by a certain multiplicative excess noise.

2. Detection Methods.

a. Optical Superheterodyne Detection.

It is a well-known empirical fact that all photo detectors measure the intensity, not the amplitude. Using this principle, heterodyne detectors are made.

If we assume two electromagnetic light waves of different frequencies falling on the same area of the detector, the resultant amplitude of the waves are given by

$$Et = E_1 \mathrm{Cos}\ w_1 t + E_2 \mathrm{Cos}\ W_2 t \qquad (7\text{-}2)$$

We implicitly assume that the two waves are parallel and normal to the surface of the detector. If these conditions are not met, spatial phase cancellations may result.

The intensity if given by the square of the amplitude and thus,

$$E_t = E_1^2 \mathrm{Cos}^2 w_1 t + E_2^2 \mathrm{Cos}^2 w_2 t + E_1 E_2 \mathrm{Cos}(w_1 - w_2)t + E_1 E_2 \mathrm{Cos}(w_1 + w_2)t$$

(7-3)

We assume that for heterodyne detection, the detector can detect only the difference frequency $w_1 - w_2$ and it will not respond to frequencies w_1, w_2, $(w_1 + w_2)$.

It has been shown that there is a minimum time required for the generation of electron whole pairs(3), this is in the order of 3×10^{-1} seconds. The detector therefore, cannot respond to signals at optical frequencies. Thus, we can only detect the average power in these high frequency terms. The average of Cos wt is $\frac{1}{2}$, whereas the average of $\text{Cos}(w_1 + w_2)t$ is zero. The result is then simply

$$Et = \frac{E_1}{2} + \frac{E_2}{2} + E_1 E \text{ Cos}(w_1 - w_2)t$$

This equation means that if two coherent electro-magnetic waves are super-imposed on each other in space, the vector amplitudes of the two waves will add, giving rise to a single amplitude modulated wave at the difference of frequency. An optical detector placed in the path of these waves will detect simply the envelope of the modulated light wave, thus yielding an electrical signal that is modulated at the beat frequency.

Let us consider the problem of sensitivity. The signal power is given by the expression

$$S = 2\eta^2 I_L I_S f(w) \qquad (7\text{-}5)$$

where η = quantum efficiency

ηI_L ηI_S = currents generated by local oscillator and signal sourc respectively

$f(w)$ = frequency response of the detector

The factor 2 comes from the coherent nature of light.

The shot noise is given by the equation

$$N = 2e\,[(\eta I_s + \eta I_L + I_o)f(w) + I_R]\,\Delta f \qquad (7\text{-}6)$$

where I_D is the dark current of the device

I_R is the noise equivalent load of the following amplifier

Δf is the line width

Using a strong oscillator signal to noise ratio is reduced to

$$SNR = \frac{\eta I_s}{e\Delta f} \qquad (7\text{-}8)$$

If we let $I = ne$ where n is the number of incident photons, then we have simply

$$SNR = \frac{\eta n}{\Delta f} \qquad (7\text{-}9)$$

If I_L is sufficiently strong, it is possible to count the photons of the incident beam.

For the detector, both photo-emissive and solid state devices are used.

(1) Photoemissive Superheterodyne Detector

With photo-emissive devices, two modes of operation have been employed. Photo-multiplier type and the travelling wave type.

The frequency response in the photomultiplier is limited by the delays associated with the transit time of carriers.

In the TWT, there is no transit time limitation, since the beam and circuit waves are synchronous.

The band-width is limited by the band-width of the helix and its couplers.

(2) Solid State Superheterodyne Detection

The most succesful of these devices are the photodiodes rather than photoconductors. Here, again, the problem of transit time arises. The frequency limitation is directly a result of the transportation of carriers within the device. The speed with which the carriers can move is determined by the diffusion constant.

The most suitable semi-conductors for photodiodes are the III-V compounds such as GaAs, InAs, InSb.

b. Non-Linear Optical Detection

Non-linear optics , an entirely new area related to the detectio of radiation, has only recently become the subject of intensive study.

In general, a medium becomes polarized when it is struck by light. If the medium is transparent and therefore, lossless, the energy that induces the polarization is re-radiated. The original radiation and re-radiated emission combine to give the standard refractive effects.

If now the electric field associated with the incident radiation is so strong that it drives the polarization of the material out of the linear region, non-linear optics effects start to appear. These effects are made applied in the detection of coherent radiation, but detailed discussion of these effects is beyond the scope of this paper.

B. Optical Transmission ⑤⑦

As optical wavelengths are very short, this offers the possibilities of very broad band-widths and increased angular resolution.

In general what can be done with the centimeter and millimeter wavelengths can also be done by light waves. Hence, optical communication must compete with older means for accomplishing the same result.

As at lower frequencies there are two possible modes of transmission for a modulated light beam. The first is the radio, the unguided mode which uses the atmosphere as the propogating medium. However, the earth's atmosphere interacts with radiation at optical frequencies, causing difficulties. The approach has the advantage shared by all radio systems, namely the medium is free. The difficult may be overcome by using closely arranged repeaters.

This mode of operation offers the highest possibilities in space

PART VIII

EXPERIMENTAL

where there is no atmosphere to interact with, and where very high data rates are required.

A second possible mode of communication by light employs a transmission space shielded from the elements by some sort of a pipe, with suitable additional guiding or directing means to keep the light beam properly centered in the shield. There are two approaches to the problem.

1. Approach analogous to out lower frequency exprience passive EMN wave guidance. However, this seems to require severe tolerances.

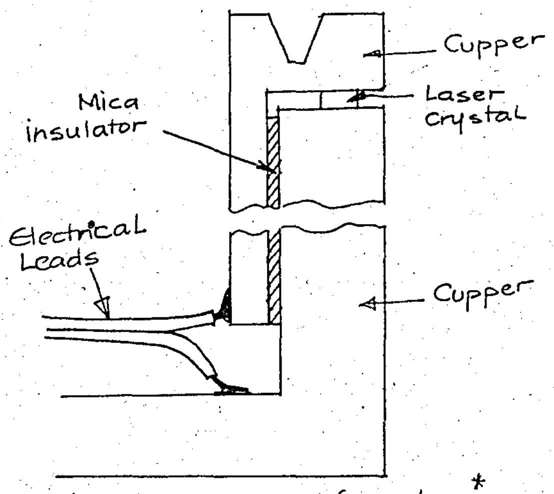
2. The other thought is creating a new type of guiding medium, one using active frequency elements to relieve mechanical requirements.

VIII. EXPERIMENTAL

INTRODUCTION. In the preceding sections we have tried to gain insight to the operation of the injection laser, particularly the gallium arsenide diode laser. We have now come to the stage where we have enough information to incorporate this device as a circuit component.

Because of the ease of modulation, there have been a number of attempts to utilize the gallium arsenide as a laser source.

The GaAs laser operation depends heavily on temperature: at very low temperatures, i.e. 2°K, it can be continuously operated. Goldstein and R.M.Wiegand (IV-4) have been able to modulate the GaAs diode at (M GHz) and at these temperatures. The percentage of modulation used was around 2. However, higher modulation percentages such as 25% were achieved. Recently, continuous wave operation at 77°K have also been achieved.(IV-21)(V-20) At this temperature, the same modulation techniques should be feasable.



Continious Wave configuration*
FIG 8-1

The room temperature operation eliminates the complexity of refrigeration and thus is advantageous. However, the scheme is inherently pulsed to cool the laser after a large pulse of current. This limits the use at room temperatures.

---

*Hergen Whorter and I.M. Feldmann, "Maximum CW Power from GaAs Lasers at 77°K." Applied Phys. Lett. XIX, 70.

The difficulty with the operation is not that of modulation; for pulse modulation techniques are available, but that of supplying the required pulse.

As we have emphasized earlier, at room temperatures, threshold currents for laser operation are as high as 15A to 20A, lasting very short: of the order of a fraction of a micro-second in order not to burn the junction. The limitation of the width of the pulse is also a result of the dependence of the threshold current on the temperature. As the current passes through the junction while lasing occurs, the diode is heated up to a higher temperature, which requires a higher threshold current for lasing. Consequently, lasing stops and non-radiative processes begin to take place, heating the diode further.

B. Pulse Power Supply. ④②

The problem of supplying a pulse of the required dimensions was first solved by employing electro-mechanical elements.⑤ This method is good for only a limited number of experiments concerning the characteristic of the laser. In this case, modulation is almost impossible.

To make modulation feasable, electronic ways of supplying the pulse should be sought. Usage of vacuum tube elements is not possible because of the inherent miller capacitances, rise times of the order of 10μsec. or so are encountered. Using the transistors as switches in the normal mode also has the problem of rise time. Transistors of the size to carry 10A have rise times about 10μsec.

The problem is solved by operating the transistor in the avalanche mode.①④③ To make the operation clear, let us take the arrangement as shown on Figure (8-2). The supply voltage Vcc is higher than the avalanche breakdown voltage. When the capacitor C is charged up to the breakdown voltage, avalanching occurs in the transistor and current builds up rapidly. Pulses with rise times of the order of a few nanoseconds develop across R_E. The fall time of of the pulse is directly proportional to the time constant R_E C. The pulse repetition rate can be changed by eithe changing the supply voltage Vcc or the charging time constant R_c C. Using thi method, rise time problem is eliminated The width of the pulse is dependant largely on the discharge time constant.

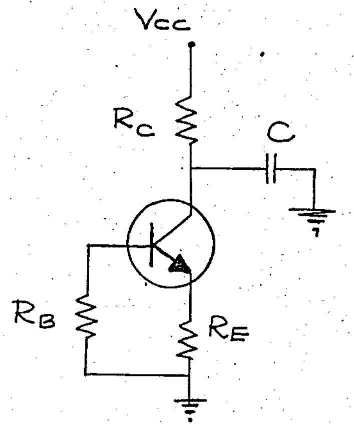


FIG 8-2
Basic Circuit

To have large currents, two stages are employed as depicted in Fig.(8-3) The first stage is the same as we have discussed in the preceding paragraph. The second transistor is biased at a lower voltage than its breakdown voltage. When the pulse, formed by the first transistor is injected to the base of Q_2, avalanching occurs and pulses of very narrow width of the order of 20 nanoseconds and as high as 50A can be obtained.

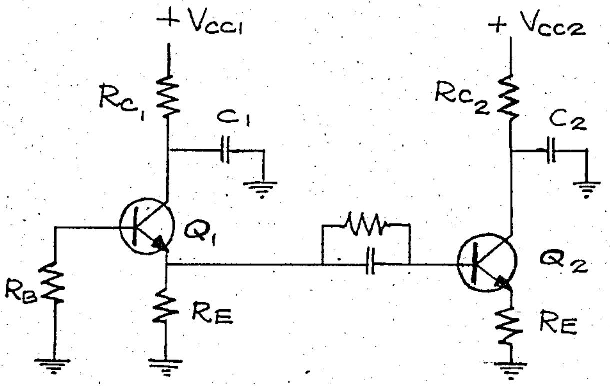


FIG 8-3

There are some difficulties associated with the circuits. Firstly silicon transistors have to be used because germanium transistors have rather high collector current flowing, when no signal is present at the base. This current prevents to attain breakdown voltages across the transistor with low Vcc. Nevertheless, a circuit using germanium transistors were constructed. The plan is shown in Fig(8-4) An additional diode was added to eliminate the oscillations. The set-up gave 250 Hz when Vcc, was -100 volts and 1 KHz at Vcc-250 V.

The height of the pulse was about 18 A. and the width 2 μ sec. Higher current pulses can be obtained by paralelling transistors in the second stage.

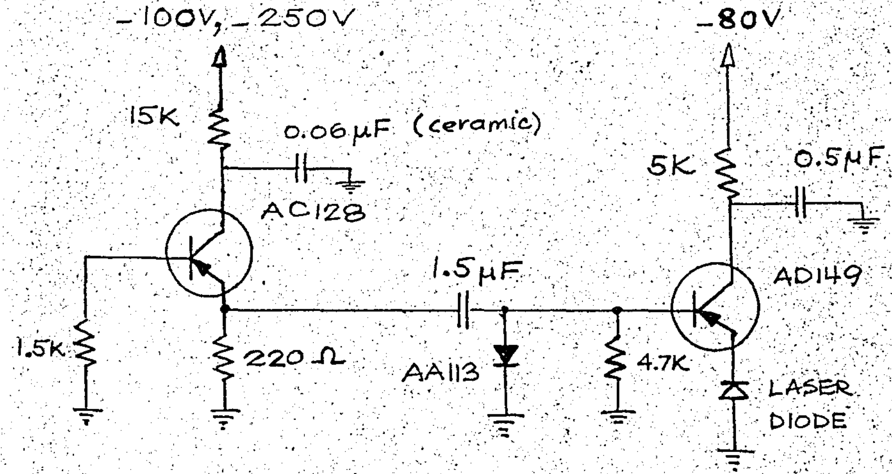


FIG 8-4: Pulsing circuit

Better results can be obtained by using silicon transistors, but these are not available in Turkey.

C. Modulation

Since the operation of the laser diode is inherently pulsed, pulse modulation techniques have to be used.

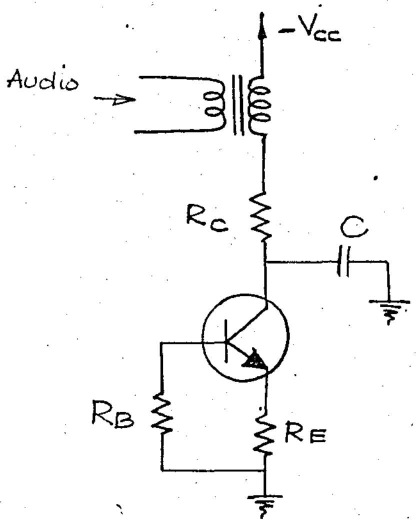
The basic types of modulation are pulse amplitude modulation(PAM), pulse duration modulation(PDM) and pulse position modulation(PPM).

Because of the nature of circuit, it is easier to use the PPM technique. Since the repetition rate is dependant on Vcc, modulating the supply voltage will modulate the output. Practically, this is done by adding a transformer in series with the charging circuit as shown in Fig.(8-5) The capacitor will be charged according to whether the voltage on the transformer adds to or cancels the Vcc, and the pulses will change their positions as shown in Fig.(8-5)

The repetition rate of the pulses is closely related to the frequency range of the information to be transmitted.

A voice communication system with a frequency range of 100 Hz.

to 3400 Hz will need pulse repetition rate greater than 6.8 KHz. This is determined by the nyquist sampling criterion which dictates that the repetition rate should be greater than 2 fm. Time multiplexing may be applied to squeeze in many channels depending on the pulse width. However, because of the pulse rate limitation of the laser diode at hand, this method is not used.



Modulating Circuit

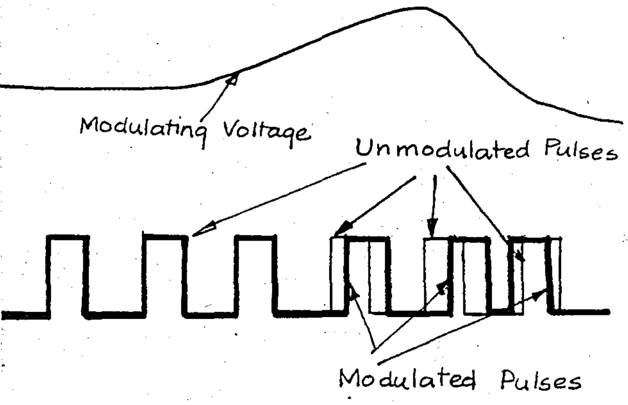


FIG 8-5. Pulse position modulation)

D. Laser Diode

The laser used in the experiment had been obtained through the courtesy of DR. R.N.Hall of General Electric Research Labs, Schenectady, New York. The following information was given:

GaAs laser

Designation: L2440

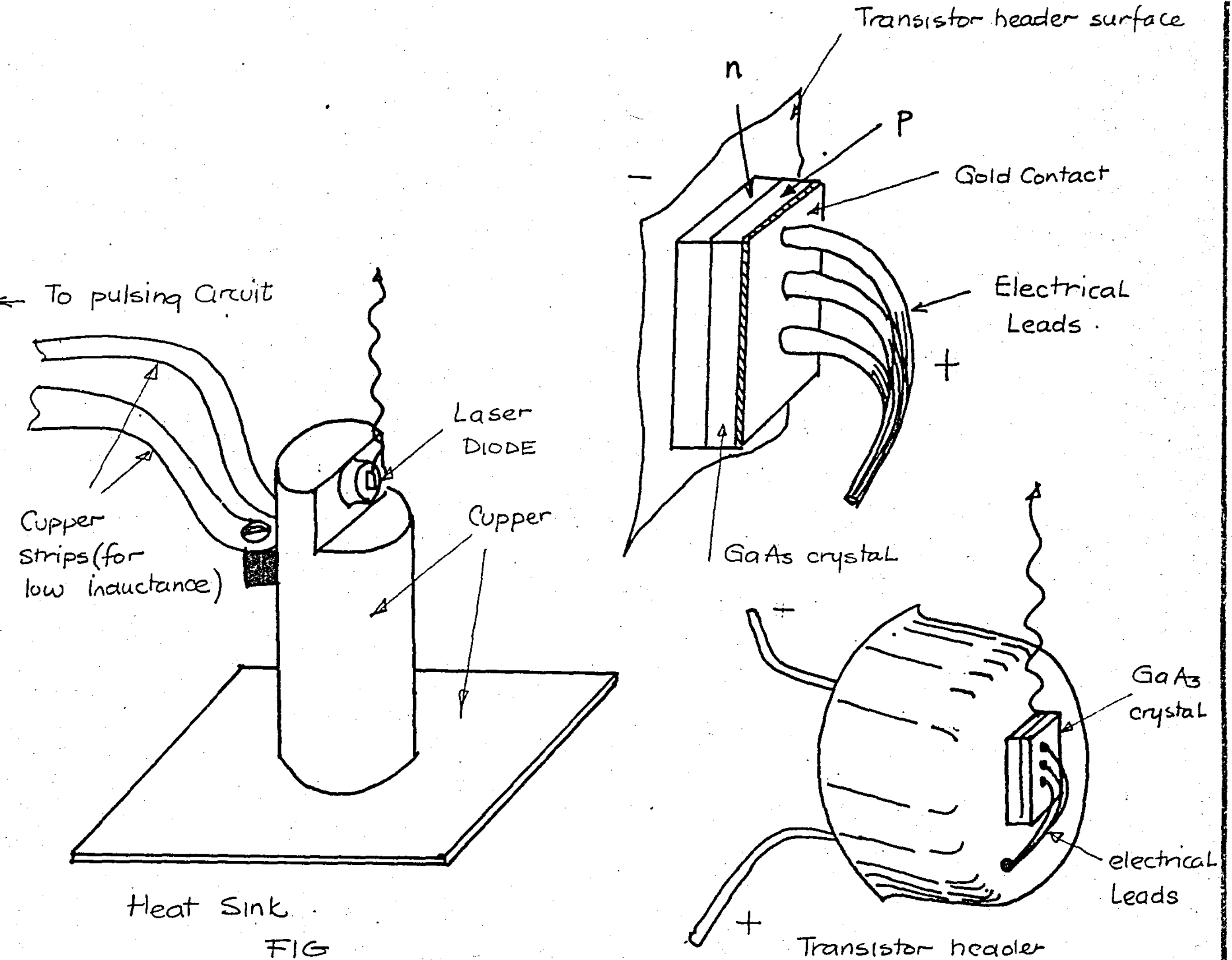
Threshold current: 1.63 A at 77^{O}K

Output wavelenth : 8440 A at 77^{O}K

The GaAs crystal was mounted on a transistor header, electrical eads were attached to the crystal in the manner shown in the figure.

The transistor header was mounted on a copper heat sink, so that he radiation was emitted perpendicularly with respect to the base of he mounting.

To have least inductance, copper strips were used to connect the aser to the pulsing circuit.

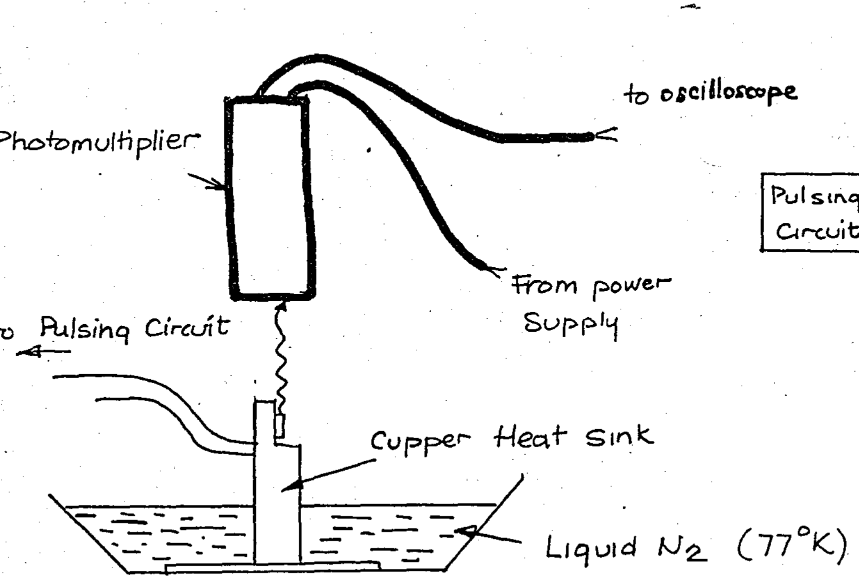


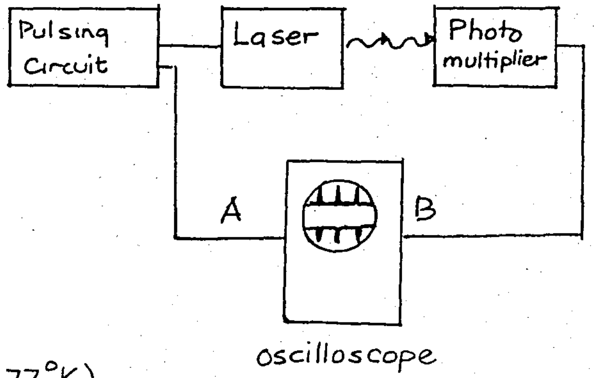
FIG

E. Detector

The detector used was a RCA-type 7010 photo-multiplier tube with peak sensitivity near 9000 A°. Because of this fact, type 7010 ubes have been used to detect radiation from GaAs lasers. The tube as loaded with a 1.5 M ohm resistance.

F. The Set-up.





The copper heat sink on which the diode was mounted was immersed n the liquid nitrogen bath. The photo-multiplier was placed directly n top of the diode.

Both the output of the photo-multiplier and the output of the ulsing circuit were simultaneously displaced on the oscilloscope.

G. Results

Due to the lack of time, the laser was operated a few times. The et-up was evaluated from the point of view of pulse repetition rate, ulse amplitude and duration.

The maximum repetition rate achieved was 3000 pps. However, at his repetition rate, the circuit components began to get hot. Thereore, at higher frequencies, better circuit components should be used.

The usual pulse width used was 2μSec The amplitude of the output f the laser could be varied from 0.35 volts to 7 volts(output of the hoto-multiplier).

Pulse position modulation was tried and succesful results were btained at 50 cps. Higher modulation frequencies are possible, but ith a better circuit and an improved laser. The pulse repetition rate of the diode limits the frequency of the information to be sent.

PART I

REFERENCES

1. Stepin L.D., Quantum Radio Frequency Physics (MIT Press: 1965).
2. Brotherton, Masers and Lasers (McGraw-Hill: 1964).
3. Weber, Opto-electric Devices (McGraw-Hill 1964)
4. Schawlov, "Optical Masers", Scientific American, (June 1961).
5. Townes, "Production of Coherent Radiation by Atoms and Molecules" 1964 Nobel Lecture, IEEE Spectrum, (August, 1965), 30-44.
6. Grivet and Bloembergen, "Quantum Electronics", Conference I, (Columbia Press: 1963), Paris.
7. Kaminov and Turner, "Electro-optic Light Modulators", Proc IEEE, (October, 1966), 1374-1388.
8. Gordon, "Accusto-optical Deflection and Modulating Devices", Proc IEEE, (October, 1966), 1391-1401.

PART II

REFERENCES

1. Beam W.R., Electronics of Solids, (McGraw-Hill: 1965).
2. Albert Einstein, Phys. Z. 18: 121-123 March 1917
3. Stepin L.D., Radio Frequency Physics, (MIT: 1965).
4. Brinbaum, "Optical Masers", (Academic Press: 1965).
5. Burns and Nathan, "P-N Junction Lasers", Proc. IEEE, (July, 1964), 771.
6. Nathan, "Semi-conductor Lasers", Proc IEEE, (October, 1966), 1276-1289.
7. Ramsey N.F., "Thermodynamics and Statistical Mechanics at Negative Absolute Temperatures", Phys. Rev. V 103 (July 1, 1956), 20-28.
8. Proc. IEEE (Journal of Quantum Electronics), (January, 1963)
9. Maiman T.H., "Stimulated Optical Radiation in Ruby Masers", Nature Vol 187 (August, 1960), 493-494.
10. Javan, Bennett, Herriot; "Population Inversion and Continuous Optical Maser Oscillation in a Gas Discharge Containing He-Ne. Mixture", Phys. Rev. Lett. Vol 6 (February, 1961), 106-110.

PART III

REFERENCES

1. Vavilov V.S., *Effects of Radiation on Semi-Conductors.* (Consultant's Bureau: 1965).
2. Smith R.A., *Optical Properties of Semi-conductors*, (Semi-conductors Academic Press: 1963).
3. Basov N.G., *Inverted populations in Semi-conductors*, (Conference on Quantum Electronics: 1963, Paris), VoL2 PP 1769-1786 Press: 1964).
4. Spenke E., *Electronic Semi-conductors*, (McGraw-Hill: 1958)
5. Burns and Nathan, Injection Lasers, *Opto-electronic devices*, (McGraw-Hill: 1964).
6. Burns and Nathan, "P-N Junction Lasers", *Proc IEEE*, (July, 1964), 770-794.
7. Nathan, "Semi-conductor Lasers", *Proc IEEE*, (October, 1966), 1276-1289.
8. Rediker, "Semi-conductor Lasers", *Physics Today*, (February, 1965), 42.
9. Lax, "Progress in Semi-conductor Lasers", *IEEE Spectrum* II, (July, 1965), 62-75.
10. R.N. Hall, "Coherent Light Emission from P-N Junctions", *Solid State Electronics* VoL:6, 405-416.
11. Lax, "Semi-conductor Lasers", *Science* VoL:141, (1963), 1247-1255.
12. Hurwitz, Keyes, "Electron Beam Pumped GaAs Laser", *Applied Physics Lett.* 5, (1964), 139-141.
13. Phelan, Rediker, "Optically Pumped Semi-Conductor Laser," *Applied Physics Letters* VoL:6 (1965), 70-71.

III

REFERENCES (Continued)

14. Hurwitz, Calawa, Rediker; "Electron Beam Pumped Lasers of PbS, PbTe, PbSe", *IEEE Journal of Quantum Electronics* QE-I, (May, 1965), 102-104.

15. Weiser, Woods, "Evidence for Avalanche Injection in P-type GaAs", *App. Phys. Lett.* Vol 6, (October, 1965), 225-228.

16. Dumke, "Interband Transitions and Maser Action", *Phys. Rev.* 127 (1962), 1559-1563.

17. Gremmelmaier, Henkel, "Gallium Arsenide Laser Diodes", *Siemens Review* XXXIII, (No. 3, 1963), 107-110.

PART IV

REFERENCES

1. Hall R.N., et al, "Coherent Light Emission from GaAs Junctions", Phys. Rev. Lett. 9. (1962), 366-378.
2. Keyes, Quist, "Recombination Radiation Emitted by Gallium Arsenide", Proc IEEE (Correspondence) 50, (August, 1962), 1822.
3. Nathan et al, "Stimulated Emission of Radiation from GaAs P-N Junctions", Appl. Phys. Letters 1, (1962) 62-64.
4. Quist, et al, "Semiconductor Maser of GaAs", Appl. Phys. Letters I, (December, 1962), 91-92.
5. Nelson, "Epitaxial Growth from Liquid State and Its Application to he Fabrication of Tunnel and Laser Diodes", RCA Review, (December, 1963), 603.
6. Holonyak, Bevacqua, "Coherent Visible Light Emission from Ga(As_{1-x} Px) Junctions", App. Phys. Letters I, (1962), 62-64.
7. Melngailis, "Maser Action in InAs Diodes", App. Phys. Letters 2, (1963), 176-178.
8. Weiser, Levitt, "Stimulated Light Emission from InP", App. Phys. Letters 2 (1963), 178-179.
9. Menlgailis, Strauss, Rediker. "Semi-conductor Diode Masers of (In_x Ga_{1-x})As", Proc IEEE 51, (August, 1963), 1154-1155.
10. Alexander, et al. "Spontaneous and Stimulated IR Emission from Indium Phosphide Arsenide Diodes", App. Phys. Lett. 4, (1964), 13-15.
11. Butler, et al. "PbTe Diode Laser", App. Phys. Lett. 5, (1964), 75-77.
12. Butler, "PbSe Diode Laser", Solid State Comm. 2, (1964), 303-304.

IV

REFERENCES(Continued)

13. MeIngailis, Phelan, Rediker. "Luminiscence and Coherent Emission in a large Volume "Injection Plasma in InSb", App. Phys. Lett 5, 99-100.

14. Bagaev, Basov, Wul, Kopylovsky, Krokhin, Popov Markin, Khvoshev, Shotov. Quantum Electronics Vol.2 Paris Conference 1963, (Columbia Press: 1964), 1890-1897.

15. Burns, Nathan. "Effects of Temperature on Properties of Semiconductor Laser", Proc IEEE 51, (June, 1963), 947-948.

16. Mayerhofer and Braunstein. "Frequency Tuning of GaAs by Uniaxial Stress", App. Phys. Lett. 3 (November, 1963), 162-163.

17. Dousmanis, Nelson. "Temperature Dependence of Threshold Current in GaAs", App. Phys. Lett. 5 (November, 1964), 174-176.

18. Hill, "Internal Quantum Efficiency of GaAs Laser", Journal of App. Phys. Vol.36:3435-3409.

19. Clifton and Debeye, "On Parameters Which Effect CW Output of GaAs Lasers", Applied Phys. Lett. (March, 1965), 120-122.

20. Engeler and Garfinkler, "Continuous High Power GaAs Laser", Journal of App. Phys. 35 (June, 1964), 1734-1741.

21. Marinice, "High Power CW Operation of GaAs Injection Lasers at 77°K", IBM Research and Development Journal 8 (Nol. 1964).

22. Keyes, "Thermal Problems of Injection Laser", IBM Research and Development Journal 9, (March, 1965), 303-314.

23. MeIngailis, Rediker, "Magnetically Tunable CW InAs Lasers", App. Phys. Lett. 2 (November, 1965), 198-199.

V

PART V

REFERENCES

1. Lasher, "Threshold Relations and Diffraction Loss for Injection Laser", IBM Research and Development Journal 7 (1963), 58-61.
2. Pilkuhn, Rupprecht. "A relation Between the Current Density at Threshold and the Length of Fabry-Parot-type GaAs Lasers", Proc IEEE 51 (September, 1963), 1243-1244.
3. Hall, Olecha. "Wave Propagation in an Active Dielectric Slab", Journal of Applied Physics 34 (September, 1963), 2565-2566.
4. McWhorter, "Electromagnetic Theory of Semi-conductor Junction Laser", Solid State Electronics 6 (September, 1963), 417-423.
5. Collin, Field Theory of Guided Modes, Chapter 2, (McGraw-Hill).
6. Yariv and Leite, "On the Propagation of Electromagnetic Radiation in P-N Junctions", Quantum Electronics, Paris Conference 1963, (Columbia Press), 1878-1882.
7. Quist, et al. "Semi-conductor Maser of GaAs", Ibid. 1833-1841.
8. Lasher and Stern, "Spontaneous and Stimulated Line Shape in Semi-Conductor Lasers", Bulletin of American Physical Society 8 (March, 1963), 201. Physics Rev. 133 (June 1963), 2116-2119.
9. Keyes, Quist, "Recombination Radiation in Gallium Arsendie", Quantum Electronics, 1963 Paris Conference, (Columbia Press: 1964), 1827-1831.
10. Stern, "Stimulated Emission in Semi-Conductors and Semi-metals", Physics of III-IV Compounds 2 (Academic Press: 1966), New York.

VI

PART - VI

REFERENCES

1. Carlsons, Soltys, "Low Threshold Room Temperature GaAs Diodes", <u>Bulletin of American Physical Society</u> 10 (June, 1965), 607.

2. Hilsium, Oliver, Tanner, "The Speed of Response of GaAs Lasers", <u>Phys. Lett.</u> 8 (February, 1964), 232-233.

3. Konnerth and Lanza, "Delay Between Current Pulse and Light Emission from a GaAs Laser", <u>App. Phys. Lett.</u> 4 (April, 1964), 120-121.

4. Goldstein and Wiegand, "X-Band Modulation of GaAs Laser", <u>Proc. IEEE</u>, (February, 1965), 195.

5. Mayerhofer, Braunstein, "Frequency Tuning of GaAs by Uniaxial Stress", <u>App. Phys. Lett.</u> 3 (November, 1963), 162-163.

6. Melngailis, Rediker, "Magnetically Tunable CW In As Lasers", <u>App. Phys. Lett.</u> 2 (November, 1965), 198-199.

VII

PART VII -

REFERENCES

1. Lasser, "Detection of Coherent Radiation", IEEE Spectrum, (April 1966), 73-78.

2. Anderson, McMurty, "High Speed Photo-detectors", Proc IEEE 54 No. 10, (October, 1966) 1335-1349.

3. Pershan Bloembergen, "Frequency Response of Photomixing Process", App. Physics Lett. 2 (1963), 117.

4. "Coherent Light Detection in Solid State Photodiodes", Proc IEEE 51 (January, 1963), 166-172.

5. Miller and Tillotson, "Optical Transmission Research", Proc IEEE 54 No. 11, (October, 1966), 1300-1311.

6. Jacobs, Stephen, "Optical Heterodyne", Opto-electronic Devices (McGraw-Hill: 1964), 72-74.

7. "Laser Wave Propagation Through Atmosphere", Proc. IEEE, (March, 1966), 368-375.

VIII

PART VIII

REFERENCES

1. Karlsons, Reno, Hannan, "Room Temperature GaAs Voice Communications System", Proc. IEEE 52, (1964), 1354-1355.
2. P.R.Prince, (Paralelling Avalanche Transistors", Proc. IEEE 53 (March, 1965).
3. Goldstein, Dalrymple, "GaAs Injection Laser Radar", Proc. IEEE, 55 (February, 1967).
4. Hansen, Schmidth, "A Fast Rise Time Avalanche Transistor Pulse Generator for Driving Injection Lasers", Proc. IEEE, (February, 1967).
5. Austin, et al, GaAs Radar Components and Techniques , Tech. Rept. 407, MIT Lincoln Lab., Lexington, Mass, (Oct. 1965), 54-65.
6. Schield, Bulwinkler, Weimer, "PCM Multiplex Transmission Over an Injection Laser Transmission System", Proc. IEEE 53 (December, 1965), 2140-2141.
7. Koehler, "Semi-conductor Switching at High Pulse Rates", IEEE Spectrum, (November, 1965), 51-66.
8. Henebry, "Avalanche Transistor Circuits", Rev. Sci. Instr. 32 (November, 1961) 1198-1208.