Fiber Optics and Laser Instruments

UNIT I -OPTICAL FIBRE AND THEIR PROPERTIES

Optical Communication History:

Alexander Graham Bell in 1880 reported the transmission of speech over 200 meter by modulating sunlight with a reflecting diaphragm ("photophone")

To avoid the degradation of optical signals in the atmosphere, Kao and Hockman in England (and simultaneously Wirt in France) in 1966 suggested the use of dielectric wave guides or optical fibers.

Historical reduction of optical loss - after Suzanne R. Nagel.

Increase in bit rate-distance product during the years 1850-2000. The emergence of a new technology is marked by a filled circle - after Govind P. Agrawal.

Progress in lightwave communication technology over the period 1974-1992. Different curves show the increase in the bit rate-distance product for five generations of fiber-optic communication systems - after Govind P. Agrawal.

Two Enabling Technologies:

Lasers: coherent sources of light
Glass: fibers with low optical attenuation

The Advent of the Laser - The Requisite Communication Resource

Human-made vs. Natural Sources of Electromagnetic Radiation (coherent *vs.* incoherent light sources)

The classical picture of light emission: Radiating lines of force from an oscillating charge

The quantum mechanical picture of light emission: Absorption and Emission of Radiation by an Atom

Coherent radiation: a continuous source (sharp spectral lines)

Incoherent radiation: a discontinuous or interrupted source (broad spectral lines)

Lasers: sources of fairly coherent radiation

Given the "quantum nature" of atomic emission, how do we get a fairly continuous source?
Answer: We induce a cooperative emission process. The key idea is that "population inversion" leads to "stimulated emission of radiation

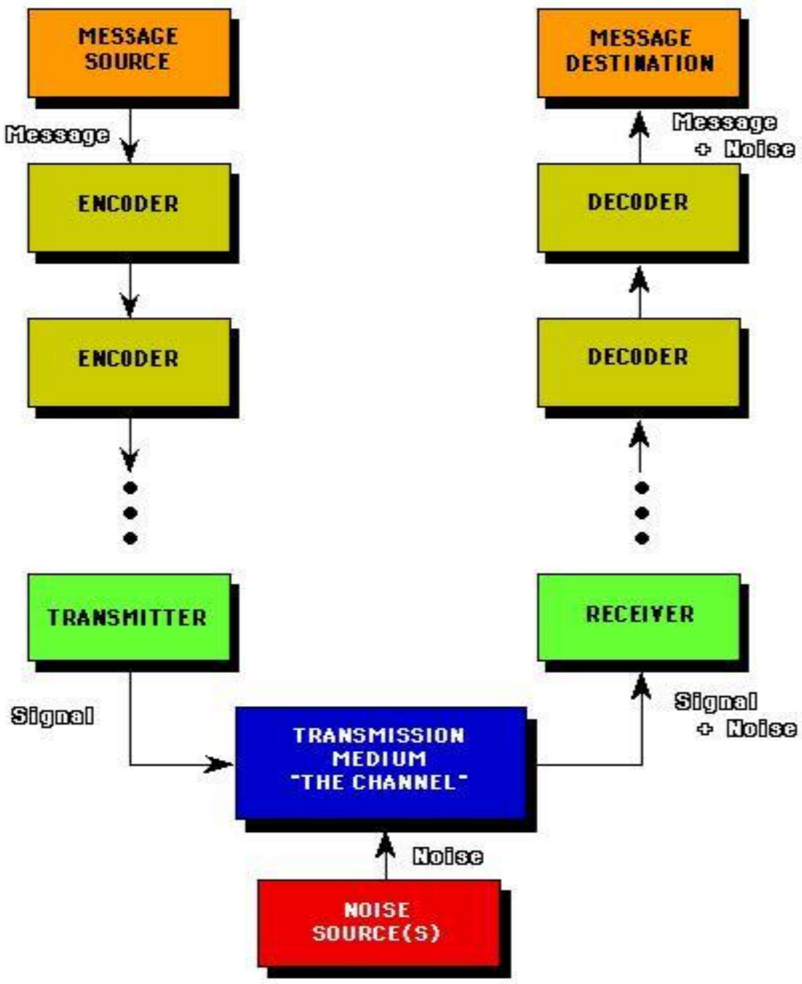
Communication media:

Visual Communication: torches, flares, smoke signals, semaphore, railroad signals and signal flags

Sonic or Auditory Communication: bells, sirens, horns, whistles, signal drums and Hooke/Wheatstone "Aconcryptophone"

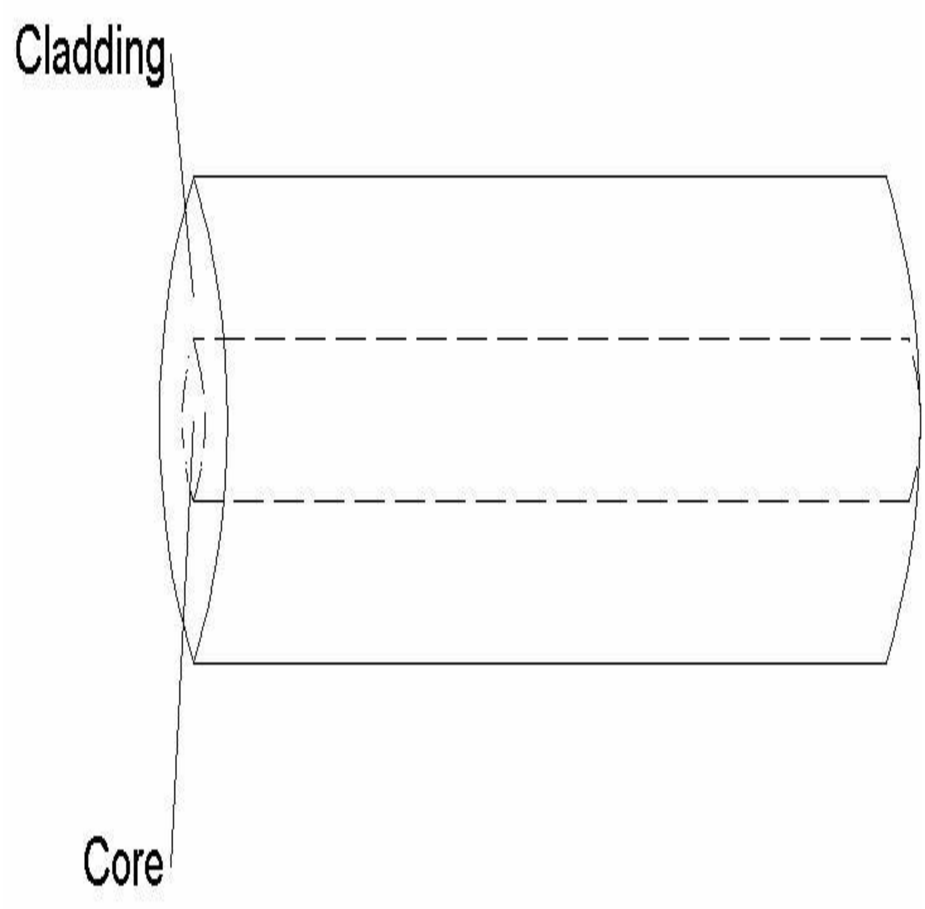
Shocking communication: communication by electric current flow on a electrical conductor.

The Shanon Diagram



Optical Fibers as Open-Boundary Waveguides

As indicated in **Figure** , an optical fiber is basically a two-layered structure comprised of dielectric material. It has a uniform circular cross-section along a straight longitudinal axis. The inner region is called the *core* and the outer region the *cladding.* We first analyze the electromagnetic fields present in optical fibers to derive several important propagation characteristics.



We study fields in phasor form, with ω the operating (radian) frequency. Assume the core is a perfect dielectric characterized by ϵ, μ, and define the parameter *k* as:

$$k = \omega\sqrt{\mu\epsilon} \qquad (1.1)$$

We also assume power flow is occurring along the longitudinal axis. Set this to be the *z*-axis and so the electric field has the form:

$$\vec{E} = \vec{e}(r,\phi)\,e^{-j\beta z} + e_z(r,\phi)\,e^{-j\beta z}\hat{a}_z \qquad (1.2)$$

where $\vec{e}$ lies in the transverse plane (has no *z*-component), and (r, ϕ) are the pola r coordinates for the transverse plane. Similarly, the magnetic field is given by:

$$\vec{H} = \vec{h}(r,\phi)\, e^{-j\beta z} + h_z(r,\phi)\, e^{-j\beta z}\hat{a}_z \qquad (1.3)$$

The parameter β is called the *phase constant.* It can be shown that real power flow in the +*z*-direction occurs when β is real and positive. The phase and group velocities of the field, v_p and v_g, respectively, are defined as:

$$v_p = \frac{\omega}{\beta}\,,\ v_g = \frac{1}{\frac{d\beta}{d\omega}} \qquad (1.4)$$

Moreover, the group velocity is the speed of propagation of energy or information along the optical fiber.
Define *q* as:

$$q = \sqrt{k^2 - \beta^2} \qquad (1.5)$$

Then Maxwell's equations for $\vec{E}$ and $\vec{H}$ are:

$$\begin{aligned} \frac{\partial^2 e_z}{\partial r^2} + \frac{1}{r}\frac{\partial e_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 e_z}{\partial \phi^2} + q^2 e_z &= 0 \\ \frac{\partial^2 h_z}{\partial r^2} + \frac{1}{r}\frac{\partial h_z}{\partial r} + \frac{1}{r^2}\frac{\partial^2 h_z}{\partial \phi^2} + q^2 h_z &= 0 \end{aligned} \qquad (1.6)$$

and:

$$\begin{aligned} e_r &= -\frac{j}{q^2}\left(\beta\frac{\partial e_z}{\partial r} + \frac{\omega\mu}{r}\frac{\partial h_z}{\partial \phi}\right) \\ e_\phi &= -\frac{j}{q^2}\left(\frac{\beta}{r}\frac{\partial e_z}{\partial \phi} - \omega\mu\frac{\partial h_z}{\partial r}\right) \\ h_r &= -\frac{j}{q^2}\left(\beta\frac{\partial h_z}{\partial r} - \frac{\omega\epsilon}{r}\frac{\partial e_z}{\partial \phi}\right) \\ h_\phi &= -\frac{j}{q^2}\left(\frac{\beta}{r}\frac{\partial h_z}{\partial \phi} + \omega\epsilon\frac{\partial e_z}{\partial r}\right) \end{aligned} \qquad (1.7)$$

The method of *modal analysis* seeks to represent the field as the superposition of several special types of fields. There are several types of modes. First, we must outright reject *TEM* (transverse electric and magnetic) modes, in which both $e_z = 0$ and $h_z = 0$, since no (nonzero) TEM modes can lead to real power flow in this situation. *TE* (transverse electric) modes have $e_z = 0$, while *TM* (transverse magnetic) modes have $h_z = 0$. Although TE or TM modes lead to a somewhat simplified analysis, there are several important fields which cannot be expressed as the superposition of such modes. Therefore, we must also consider more general *hybrid modes; HE* modes have $|h_z| \gg |e_z| > 0$ and *EH* modes have $|e_z| \gg |h_z| > 0$.

The geometry of the situation leads us to seek functions periodic in ϕ. Therefore, we assume the -dependence has the form $e^{j\nu\phi}$ where ν is an integer (possibly positive, negative or 0). Thus:

$$e_z(r,\phi) = AF_\nu(r)\, e^{j\nu\phi} \qquad (1.8)$$

and hence:

$$\frac{\partial^2 F_\nu}{\partial r^2} + \frac{1}{r}\frac{\partial F_\nu}{\partial r} + \left(q^2 - \frac{\nu^2}{r^2}\right)F_\nu = 0 \qquad (1.9)$$

Moreover, since this is in the core region, we impose that $F_\nu(r)$ to stay finite as $r \rightarrow 0$. Thus, the solution is the ν^{th} *order Bessel function of the first kind,* $J_\nu(qr)$. A similar result holds for. h_z

Now let us distinguish between the core $(r < a)$, characterized by ϵ_1, μ_0, and the cladding $(r > a)$ characterized by ϵ_2, μ_0. Define:

$$\begin{aligned} k_1 &= \omega\sqrt{\epsilon_1 \mu_0} \\ k_2 &= \omega\sqrt{\epsilon_2 \mu_0} \\ u &= \sqrt{k_1^2 - \beta^2} \\ w &= \sqrt{\beta^2 - k_2^2} \end{aligned} \qquad (1.10)$$

Imposing that the core function stays finite at r=0, that the cladding function decay to 0 at $r \rightarrow \infty$, and that $\beta > 0$ for real power flow, we have that u>0 and w>0. Thus, in particular, $k_1 > \beta > k_2$. Note, in particular, that this requires $\epsilon_1 > \epsilon_2$, which is the case in real fibers.

It may be convenient at times to express k_1 and k_2 in terms of the respective indices of refraction n_1 and n_2 and the wavelength λ in free-space:

$$k_1 = 2\pi n_1/\lambda \ , \ k_2 = 2\pi n_2/\lambda \qquad (1.11)$$

The longitudinal components in the core are given by:

$$\begin{aligned} E_z &= AJ_\nu(ur)\, e^{j\nu\phi} e^{j(\omega t - \beta z)} \\ H_z &= BJ_\nu(ur)\, e^{j\nu\phi} e^{j(\omega t - \beta z)} \end{aligned} \qquad (1.12)$$

and those in the cladding are:

$$\begin{aligned} E_z &= CK_\nu(wr)\, e^{j\nu\phi} e^{j(\omega t - \beta z)} \\ H_z &= DK_\nu(wr)\, e^{j\nu\phi} e^{j(\omega t - \beta z)} \end{aligned} \qquad (1.13)$$

In particular, we impose the same value ν characterize the fields in the core and cladding. This is necessary to achieve phase match conditions at r=a; for example, E_z must be continuous at r=a. Also, K_ν is the ν^{th} *order Bessel function of the second kind.* It can be shown that $K_\nu(wr) \sim e^{-wr}$ (asymptotically) as $r \rightarrow \infty$. In fact, $|J_\nu(j\alpha)| = K_\nu(\alpha)$ for real α.

To summarize, to have the field in the cladding decay we must have:

$$\beta > k_2 \qquad (1.14)$$

The condition $\beta = k_2$ is called *cutoff*. Additionally, if $F_\nu(ur)$ is not real valued, that is if $u^2 < 0$, then we have no real power flow. Hence we must also have:

$$\beta < k_1 \qquad (1.15)$$

with a corresponding cutoff condition $\beta = k_1$. To summarize:

$$n_2 k < \beta < n_1 k \tag{1.16}$$

where $k = 2\pi/\lambda$ is the free-space wavenumber.

The appropriate boundary conditions we must impose at *r*=*a* are:

$$E_{z1} = E_{z2} \ , \ E_{\phi 1} = E_{\phi 2} \tag{1.17}$$

These equations correspond to the property that the tangential component of the electric field must be continuous along a dielectric boundary. The first leads boundary condition leads to:

$$AJ_\nu(ua) - CK_\nu(ua) = 0 \tag{1.18}$$

and the second to:

$$-\frac{j}{u^2}\left(A\frac{j\nu\beta}{a}J_\nu(ua) - B\omega\mu u J'_\nu(ua)\right) - \frac{j}{w^2}\left(C\frac{j\nu\beta}{a}K_\nu(wa) - D\omega\mu w K'_\nu(wa)\right) = 0 \tag{1.19}$$

We must also impose:

$$H_{z1} = H_{z2} \ , \ H_{\phi 1} = H_{\phi 2} \tag{1.20}$$

These correspond to the fact that the tangential magnetic field is continuous along a dielectric boundary if there is no surface current present. We have a total of four homogeneous equations in *A*,*B*,*C*,*D*:

$$M\begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{1.21}$$

Since we seek nonzero fields, we cannot have all four constants *A*,*B*,*C*,*D* equal to zero; hence:

$$\det M = 0 \tag{1.22}$$

This condition *must* be met for a field to be present. Define:

$$\mathcal{J}_\nu = J'_\nu(ua)/uJ_\nu(ua) \ , \ \mathcal{H}_\nu = K'_\nu(wa)/wK_\nu(wa) \tag{1.23}$$

Then equation (1.22) becomes:

$$\left(\mathcal{J}_\nu + \mathcal{H}_\nu\right)\left(k_1^2\mathcal{J}_\nu + k_2^2\mathcal{H}_\nu\right) = \left(\frac{\beta\nu}{a}\right)^2\left(\frac{1}{u^2} + \frac{1}{w^2}\right)^2 \tag{1.24}$$

Given *k*, that is ω, the values *u*,*w* are known functions of β. Hence, (1.24) specifies β as a function of frequency ω, and as a function of the parameter ν. This equation has only discrete solutions, and in general for each ν there will be several roots, denoted as:

$$\beta_{\nu 1}, \beta_{\nu 2}, \cdots, \beta_{\nu N} \tag{1.25}$$

The corresponding modes are denoted as *TE*, $\mathbf{TM}_{\nu m}$, $\mathbf{HE}_{\nu m}$ or $\mathbf{EH}_{\nu m}$, as appropriate. Let us examine the TE and TM cases in particular. We obtain TE by setting *A*=*B*=0, and we seek nonzero *C*,*D*; and similarly TM is obtained by setting *C*=*D*=0 and we seek nonzero *A*,*B*. In each case, this req uires a 2×2 submatrix of *M* to have nonzero determinant, and in particular can be shown to require:

$$\nu = 0 \qquad (1.26)$$

Thus, there can be no ϕ-variation (there is radial symmetry) for TE and TM modes. The equation determining β for TE_{0m} is:

$$\frac{J_1(ua)}{uJ_0(ua)} + \frac{K_1(wa)}{wK_0(wa)} = 0 \qquad (1.27)$$

Similarly, the equation determining β for TM_{0m} is:

$$\frac{k_1^2 J_1(ua)}{uJ_0(ua)} + \frac{k_2^2 K_1(wa)}{wK_0(wa)} = 0 \qquad (1.28)$$

If $\nu \neq 0$, we do not have TE or TM modes, and the analysis becomes very complex. However, if $n_1 \approx n_2 (n_1 - n_2 \ll 1)$, we can apply an important class of approximations which lead to *weakly guided waves.*

The cutoff conditions $(w^2 \to 0)$ for lower order modes are summarized in **Table** below.

ν	Mode	Cutoff Condition
0	TE_{0m}, TM_{0m}	$J_0(ua) = 0$
1	HE_{1m}, EH_{1m}	$J_1(ua) = 0$
≥ 2	$EH_{\nu m}$	$J_\nu(ua) = 0$
	$HE_{\nu m}$	$\left(\frac{n_1^2}{n_2^2} + 1\right) J_{\nu-1}(ua) = \frac{ua}{\nu-1} J_\nu(ua)$

Table 1.1: Cutoff Conditions for Low Order Modes

We now discuss the *V*-number, also called the *V*-parameter or the *normalized frequency.* The value *V* is defined as:

$$V^2 = \left(u^2 + w^2\right) a^2 = \left(\frac{2\pi a}{\lambda}\right)^2 \left(n_1^2 - n_2^2\right) \qquad (1.29)$$

$2\pi/\lambda$

and is dimensionless. Note that the value is proportional to frequency (up to a factor equal to the speed of light), and hence *V* is called the normalized frequency. The value *V* is related to the number of modes a fiber can support. Also define the *normalized propagation constant b* as:

$$b = \frac{a^2 w^2}{V^2} = \frac{(\beta/k)^2 - n_2^2}{n_1^2 - n_2^2} \qquad (1.30)$$

Note that 0<*b*<1 corresponds to propagation.

A graph of *b* or β/k versus *V* shows, for fixed *V*, only several modes are possible. In particular, the HE_{11} mode exists (corresponds to a value *b* in the range 0 to 1) for all *V*, down to V=0. No other mode exists until V=2.405 (this is the smallest root of J_0). Hence, below this value of V, all modes other than HE_{11} are cutoff. For this reason, HE_{11} is called the *dominant mode.*

We define the *numerical aperture* of a fiber to be:

$$NA = \sqrt{n_1^2 - n_2^2} \tag{1.31}$$

so that:

$$V = \frac{2\pi a}{\lambda} NA \tag{1.32}$$

The physical significance of the numerical aperture can be obtained using the *ray theory* approximation to wave propagation. Refer to **Figure 1**. We assume light propagates in the fiber like a plane wave reflecting at top and bottom core-cladding boundaries according to *total internal reflection* (TIR); TIR occurs when the incidence angle at a dielectric boundary exceed the critical angle, that is when:

$$\sin\theta_i \geq \frac{n_2}{n_1} \tag{1.33}$$

It can be shown that the field in the cladding when TIR occurs has no real power flow associated with it, and is called *evanescent.* If we imagine launching a light wave into the fiber core from air, with an entry angle θ_{entry}, then:

$$\cos\theta_{\text{entry}} = \sin\theta_i \tag{1.34}$$

Thus, there is a maximum entry angle for which power will be launched in the fiber, and we define numerical aperture in terms of this maximum angle as:

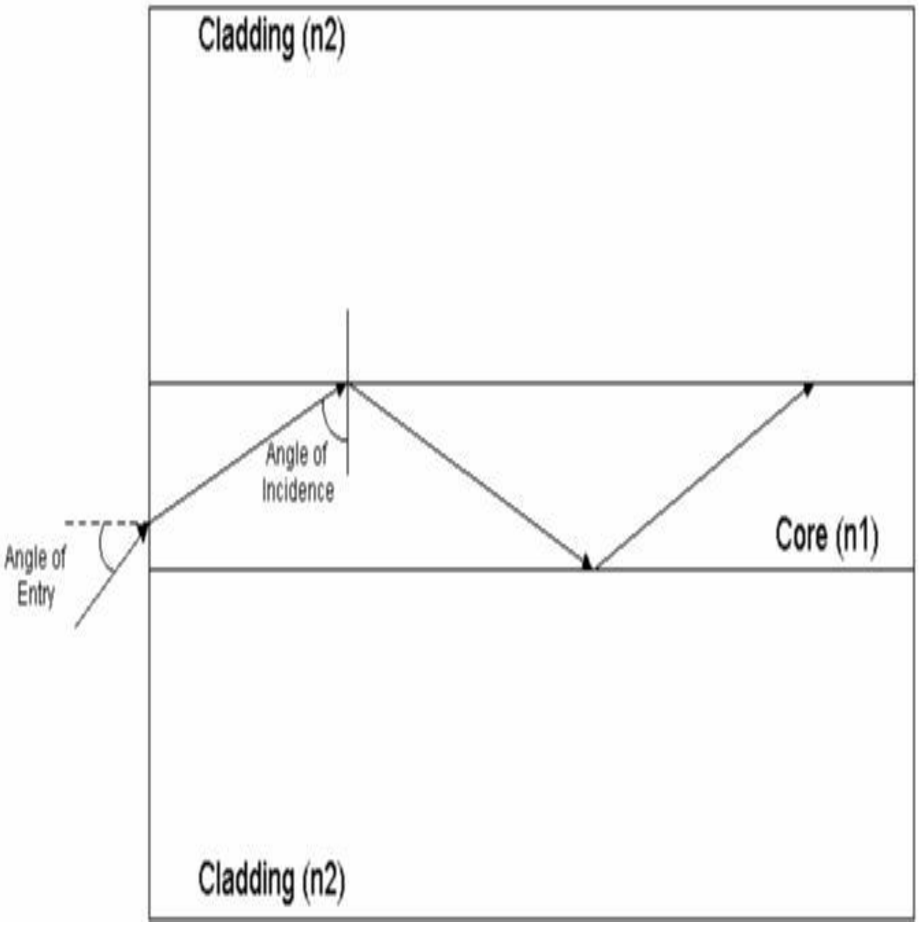
$$NA = \sin\theta_{\text{entry,max}} \tag{1.35}$$

The two definitions of numerical aperture coincide when $n_1 - n_2 \ll 1$.

Equation (1.32) implies two basic factors increase V, and hence increase the number of modes present in light propagating in a fiber. First, if the diameter a is increased (relative to wavelength) then V is increased. Hence, *single-mode* fibers have a narrow core diameter, and permit only one mode (the HE_{11} mode) to propagate; *multi-mode* fibers have a larger core diameter and permit many modes. Additionally, a large numerical aperture enlarges V. Now, equation (1.35) implies a larger NA corresponds to the ability of the fiber to accept a larger beamwidth of the input light signal. LED light sources produce much broader beams than semiconductor laser diodes, and hence LED sources must be used with larger NA fibers, and hence multi-mode fibers.

Let us consider multi-mode fibers (so that the total number of modes M) is large with a laser beam input. Approximate $\sin\theta$ by θ, so the solid acceptance angle for a light input (specified by (1.35)) is:

$$\Omega = \pi\theta^2 = \pi\left(n_1^2 - n_2^2\right) \tag{1.36}$$



For a waveguide or laser with radiation at λ, the number of modes per unit solid angle is approximately:

$$2A/\lambda^2 \qquad (1.37)$$

where $A = \pi a^2$ is the area; the factor 2 refers to two polarized orientations. Then:

$$M \approx \frac{2A}{\lambda^2}\Omega = \frac{2\pi a^2}{\lambda^2}\left(n_1^2 - n_2^2\right) = \frac{V^2}{2} \qquad (1.38)$$

Let us return to the weakly guided fiber approximation. Define Δ as:

$$\Delta = \frac{n_1}{n_2} - 1 \qquad (1.39)$$

and assume $\Delta \ll 1$. Two mode with the same value for β are said to be *degenerate.* We associate degenerate modes together since they have identical propagation characteristics, although different field distributions. In other words, we consider all linear combinations of a class of degenerate modes to be a mode unto itself. We group the primary lower order modes according to their degeneracies:

$$\begin{array}{l} HE_{11} \\ TE_{01}, TM_{01}, HE_{21} \\ HE_{31}, EH_{11} \\ HE_{12} \\ HE_{41}, EH_{21} \\ TE_{02}, TM_{02}, HE_{22} \end{array} \qquad (1.40)$$

Numerically, $\Delta \ll 1$ implies:

$$k_1^2 \approx k_2^2 \approx \beta^2 \qquad (1.41)$$

and we get:

$$\mathcal{J}_\nu + \mathcal{H}_\nu = \pm\frac{\nu}{a}\left(\frac{1}{u^2} + \frac{1}{w^2}\right) \qquad (1.42)$$

The positive sign leads to *EH* modes:

$$\frac{J_{\nu+1}(ua)}{uJ_\nu(ua)} + \frac{K_{\nu+1}(wa)}{wK_\nu(wa)} = 0 \qquad (1.43)$$

and the negative sign leads to *HE* modes:

$$\frac{J_{\nu-1}(ua)}{uJ_\nu(ua)} - \frac{K_{\nu-1}(wa)}{wK_\nu(wa)} = 0 \qquad (1.44)$$

To summarize:

$$\frac{uJ_{j-1}(ua)}{J_j(ua)} = -\frac{wK_{j-1}(wa)}{K_j(wa)} \qquad (1.45)$$

where:

$$j = \begin{cases} 1, & \text{TE and TM} \\ \nu + 1, & \text{EH} \\ \nu - 1, & \text{HE} \end{cases} \qquad (1.46)$$

Hence, all modes with the same *j* and *m* are degenerate; for example $HE_{\nu+1,m}$ and $EH_{\nu-1,m}$. This pair of degenerate modes are called *LP* (linearly polarized) modes, since they can be combined to yield fixed orientation. That is, in a complete set of modes, only one *E* and one *H* component are significant, say the $\vec{E}$ polarized along one axis and $\vec{H}$ perpendicular to it. Equivalent solutions are obtained with the polarization reversed.

These two cases can be combined with $\cos j\phi$ and $\sin j\phi$ so four mode patterns form one LP_{lm} mode.

Propagation in Optical Fibers

There are two primary system parameters which determine the characteristics of optical communication systems. Specifically, data is transmitted by a sequence of pulses, and the system must ensure these pulses are received with a sufficiently low probability of error, also called the *bit-error rate (BER).* Given a particular receiver, achieving a specified BER requires a minimum received power and a maximum data rate or signal bandwidth. An optical fiber introduces attenuation and dispersion in the system. Whereas attenuation tends to increase the power requirements of the transmitter needed to meet the power requirements at the receiver, dispersion limits the bandwidth of the data which may be transmitted over the fiber. We first examine dispersion. We recall the definition of index of refraction *n* as:

$$n = \frac{c}{v} \tag{2.1}$$

and hence *n*=1 for free-space. For silica glass $(\mathrm{Si}\,O_2)$, [illegible]. By placing impurities (dopants) in the material we can modify *n*. Optical fibers have a small core surrounded by a (relatively) thick cladding whose index of refraction is slightly less than that in the core.

Let n_0 denote the (nominal) value of *n* in the core, and n_c in the cladding. Let us denote the radius of the core as *a*.

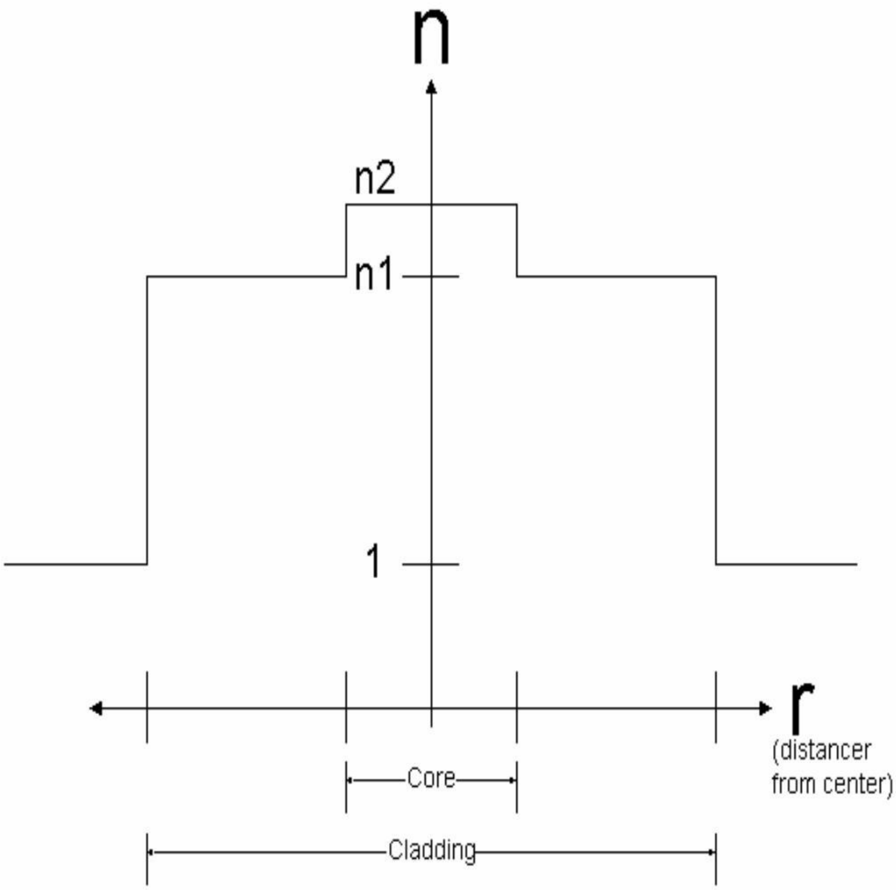
If *n* is constant in the core, it is a *step-index* fiber, and is otherwise a *graded-index* fiber. The value of *n* as a function of *r* for a step-index fiber is:

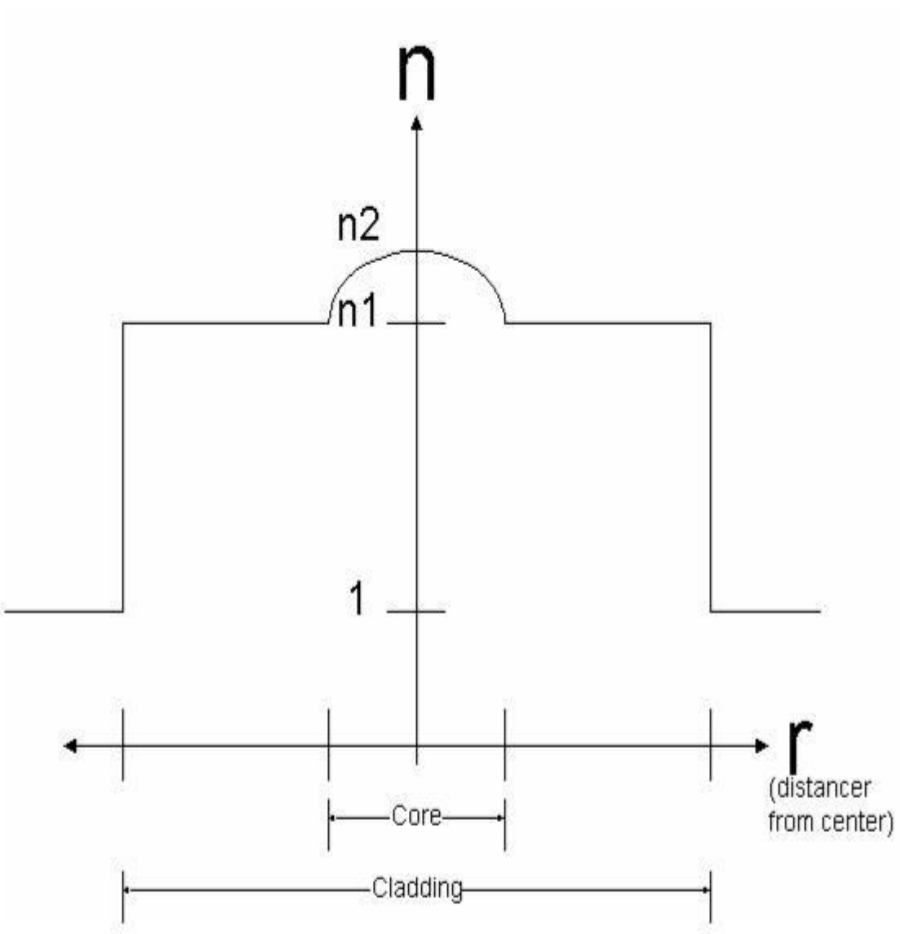
$$n = \begin{cases} n_0\,, & r \le a \\ n_c\,, & a \le r \le b \end{cases} \tag{2.2}$$

and is graphed in **Figure** , while the value of *n* as a function of *r* for a graded-index fiber is:

$$n = \begin{cases} n_0\left(1 - 2\Delta\,(r/a)^{\alpha}\right)^{1/2}, & r \le a \\ n_c\,, & a \le r \le b \end{cases} \tag{2.3}$$

where [illegible] and is graphed in **Figure** .


n
n2
n1
1
r
(distancer
from center)
Core
Cladding



If we define $\Delta = \frac{n_0 - n_c}{n_0}$, typically $\Delta \ll 1$; it is usually no more than a few percent. The numerical aperture can be approximated as:

$$NA = \sqrt{n_0^2 - n_c^2} \approx n_0\sqrt{2\Delta} \qquad (2.4)$$

A typical value is *NA*=0.2, which corresponds to a maximum entry angle $\hat{\theta} \approx 11^\circ$. *Dispersion* refers to the distortion of a propagating wave. Dispersionless transmission in general requires a constant group velocity. There are several types of dispersion. *Modal dispersion* is caused when a propagating wave is comprised of several different modes with different propagation characteristics. Modal dispersion can be eliminated (in principle) using single-mode fibers have cross-section close to λ, and are common at 1300*nm* and 850*nm*. The core typically has a diameter of $8 - 12\mu m$ and the cladding a diameter of $125\mu m$. Multimode fibers have core diameter $50 - 100\mu m$ and a cladding diameter of $125 - 140\mu m$. The purpose of graded index fibers is to reduce modal dispersion in multimode fibers. If we use the ray model for propagating waves, different modes correspond to different angles of incidence at the core-cladding boundary; those with steeper angles have lower group velocity. However, in a graded-index fibers, the index of refraction decreases away from the center, hence the speed of light increases as the cladding is approached, and this tends to compensate for the different paths taken by different modes.

Single mode fibers have $\Delta = 0.2 - 1\%$ and multimode fibers have $\Delta = 1 - 3\%$.
Material dispersion is caused by imperfect materials whose *n* depends on λ. This effect is usually an order of magnitude smaller than modal dispersion, and is typically quantified in terms of:

$$\frac{d^2 n}{d\lambda^2} \qquad (2.5)$$

A third type of dispersion is *waveguide dispersion,* caused by non-constant group velocity as a function of λ for a fixed mode.
One of the main consequences of dispersion is that a propagating pulse will broaden. We can quantify the pulse broadening in terms of the variance σ^2 of the waveform. That is, consider a pulse of light whose intensity as a function of time is $I(t)$; normalize the intensity so that:

$$\int_{-\infty}^{\infty} I(t)\, dt = 1 \qquad (2.6)$$

Define the mean time as:

$$\bar{t} = \int_{-\infty}^{\infty} tI(t)\, dt \qquad (2.7)$$

and the variance as:

$$\sigma^2 = \int_{-\infty}^{\infty} (t - \bar{t})^2\, I(t)\, dt \qquad (2.8)$$

If we input a pulse with variance σ^2_{in} to a dispersive system, then the output has variance σ^2_{out} given by:

$$\sigma^2_{\mathrm{out}} = \sigma^2_{\mathrm{in}} + \sigma^2_{\mathrm{modal}} + \sigma^2_{\mathrm{waveguide}} + \sigma^2_{\mathrm{material}} \qquad (2.9)$$

In quantifying dispersion, an important consideration is the *spectral width* of the light signal. The spectral width σ_λ is a measure of the purity of the light as a function of wavelength. If we consider the intensity as a function of wavelength, $I(\lambda)$, then the spectral width is defined as:

$$\sigma^2_\lambda = \int_0^{\infty} \left(\lambda - \bar{\lambda}\right)^2 I(\lambda)\, d\lambda \qquad (2.10)$$

where:

$$\bar{\lambda} = \int_0^{\infty} \lambda I(\lambda)\, d\lambda \qquad (2.11)$$

and the intensity is normalized as:

$$1 = \int_0^{\infty} I(\lambda)\, d\lambda \qquad (2.12)$$

Since dispersion causes pulse broadening, if we attempt to place too many pulses per second, they will spread and interfere with each other. Thus, a practical limitation is the available bandwidth, measured in *MHz* or *Mbps*. As we shall soon see, the bandwidth is inversely proportional to distance, so the *bandwidth-distance product* (in units of $MHz - km$) is approximately constant. For a multimode step index fiber, this is $20MHz \cdot km$, for a step index multimode fiber it is $2.5GHz \cdot km$, and it can be larger ($10GHz - km$or more) for single mode fibers.

To understand the effect of dispersion, consider the *group delay.* This is the time delay per unit length of energy propagating through a transmission system. We can assume each spectral component travels independently and undergoes its own time delay, τ_g. Let *L* be the transmission distance and v_g the group velocity. Then:

$$\frac{\tau_g}{L} = \frac{1}{v_g} = \frac{1}{c}\frac{d\beta}{dk} = -\frac{\lambda^2}{2\pi c}\frac{d\beta}{d\lambda} \qquad (2.13)$$

where:

$$k = 2\pi/\lambda \qquad (2.14)$$

If the spectral width σ_λ is not too big, the delay difference over the range of wavelengths comprising the light energy can be approximated by $d\tau_g/d\lambda$ at wavelengths $\lambda \pm \sigma_\lambda/2$. Thus, the delay difference between two such spectral components is:

$$\sigma_g = \frac{d\tau_g}{d\lambda}\sigma_\lambda = -L\frac{\sigma_\lambda}{2\pi c}\left(2\lambda\frac{d\beta}{d\lambda} + \lambda^2\frac{d^2\beta}{d\lambda^2}\right) \qquad (2.15)$$

We define the *dispersion constant D* as:

$$D = \frac{1}{L}\frac{d\tau_g}{d\lambda} \qquad (2.16)$$

Its units are typically given as picoseconds per kilometer per nanometer.

To quantify material dispersion, we use the ray model approximation, which in particular yields $\beta = \frac{2\pi n}{\lambda}$ where $n = n(\lambda)$ is a function of wavelength. This yields:

$$\tau_{\mathrm{mat}} = \frac{L}{c}\left(n - \lambda\frac{dn}{d\lambda}\right) \qquad (2.17)$$

and hence:

$$\sigma_{\mathrm{mat}} = -\frac{L}{c}\lambda\frac{d^2n}{d\lambda^2}\sigma_\lambda \qquad (2.18)$$

If we define the *material dispersion constant* D_{mat} as:

$$D_{\mathrm{mat}} = -\frac{\lambda}{c}\frac{d^2n}{d\lambda^2} \qquad (2.19)$$

Then:

$$\sigma_{\mathrm{mat}} = D_{\mathrm{mat}}L\sigma_\lambda \qquad (2.20)$$

We now quantify waveguide dispersion. We first write:

$$b = 1 - \left(\frac{ua}{V}\right)^2 \qquad (2.21)$$

For small Δ, we get:

$$\beta \approx n_2 k\,(b\Delta + 1) \qquad (2.22)$$

If n_2 is not a function of λ, then:

$$\tau_{wg} = \frac{L}{c}\frac{d\beta}{dk} \qquad (2.23)$$

Now, $V \approx kan_2\sqrt{2\Delta}$ and hence:

$$\tau_{wg} = \frac{L}{c}\left(n_2 + n_2\Delta\frac{d(Vb)}{db}\right) \qquad (2.24)$$

A detailed computation yields:

$$\frac{d(Vb)}{db} = b\left(1 - \frac{2J_v^2(ua)}{J_{v+1}(ua)\,J_{v-1}(ua)}\right) \qquad (2.25)$$

Then:

$$\sigma_{wg} = \sigma_\lambda L D_{wg} = -\frac{n_2 L \Delta \sigma_\lambda}{c\lambda} V \frac{d^2(Vb)}{d\lambda^2} \qquad (2.26)$$

For the type of material used in fibers, at lower wavelengths:

$$\frac{\sigma_{wg}}{L} \approx \frac{0.003\sigma_\lambda}{c\lambda} \qquad (2.27)$$

and:

$$\frac{\sigma_{mat}}{L} \approx \frac{0.02\sigma_\lambda}{c\lambda} \qquad (2.28)$$

and hence material dispersion dominates. At higher wavelengths (about $1.3\mu m$), waveguide dispersion dominates.

Modal dispersion in multimode fibers can be approximated as:

$$\sigma_{mod} = \frac{n_1 \Delta L}{c} \qquad (2.29)$$

Now we consider attenuation. Any optical fiber will attenuate a propagating signal. Given input power P_{in} over a fiber of length *L* and output power P_{out}, the mean attenuation constant α of the fiber, in units of *dB*/*km*, is defined as:

$$\alpha = \frac{10}{L}\log_{10}\left(\frac{P_{in}}{P_{out}}\right) \qquad (2.30)$$

The decibel unit (dB) is used to represent power ratios. However, it is sometimes convenient to represent absolute power levels on a logarithmic scale. The most commonly used unit is *dBm*, which corresponds to power referenced to 10*mW*:

$$P_{dBm} = 10\log_{10}\frac{P}{10 \times 10^{-3}} \qquad (2.31)$$

One of the main causes of attenuation is absorption of energy (or photons). Absorption is caused by atomic defects which result when the fiber is exposed to radiation, *extrinsic* absorption by impurity atoms, and *intrinsic* absorption by constituent atoms of the material. The dominant mechanism is extrinsic absorption, primarily by metallic ions (iron, cobalt, etc.) and OH^- ions.

In early optical fibers, the transmission distance was primarily limited by absorption by OH^- ions. These ions were introduced in the material from the presence of water or water vapor during the manufacture process. Attenuation caused by this ion is greatest at 1400, 950 and 725*nm*, leaving ``windows" for transmission between these wavelengths. The advent of the *vapor phase axial deposition (VAD)* manufacture method led to tremendous reduction in the OH^- concentration in fibers.

Losses in modern fibers are caused by ultraviolet absorption, infrared loss and scattering losses. The scattering losses, modeled by Rayleigh scattering, are caused by the interaction of the light wave with the constituent molecules which are on the order of the light wavelength. Rayleigh scattering loss is $\sim 1/\lambda^4$, so it can be reduced by increasing the wavelength. On the other hand, infrared absorption loss tends to increase with λ, and is usually worst above $1.5\mu m$. The point where this loss starts to increase to unacceptably large levels can be pushed out by doping the $\mathrm{Si}\,O_2$ with halides. In general, the combined effect of such losses is minimum at about $1.3\mu m$.

There are also losses caused by bends and microbends ; a microbend is a tiny ``crinkle" or imperfection in the surface of the fiber, on the dimensions of several wavelengths, and causes a perturbation in the field. Thus, microbends lead to coupling to higher order modes, which do not have the desired transmission characteristics, and also causes power loss. Bending and microbending can occur while the fiber is being manufactured, specifically during the spooling process. Spooling a fiber to minimize bends and microbends is not trivial when we consider that very long continuous fibers, of lengths 1*km* or more, are manufactured. The reason for manufacturing such long fibers is that splicing or coupling fiber segments together can introduce significant losses. The basic reason for loss when splicing fibers is the faces of the two segments are not properly aligned, so not all the output power of one segment is inserted to the other. Losses in modern fibers can be kept down to as little as 0.01*dB*/*km*.

If *BW* denotes the signal bandwidth and *L* the length of the fiber, then the bandwidth-length product is approximately constant. This constant depends on overall system parameters, such as total power loss, BER, etc. More precisely, an empirical result is:

$$BW \times L^{\gamma} \qquad (2.32)$$

is approximately constant, and the parameter γ is some value between 0.5 to 0.9. Usually, for *L*<1*km*, $\gamma = 0.9$ whereas for *L*>1*km*, $\gamma = 0.5$. Actually, this is not an entirely empirical result. What happens is that, as light travels over a longer and longer distance, energy at one modes tends to couple or induce energy at other modes, so that over long distances the modes are strongly coupled to each other, and do not propagate independently. In any case, the length 1*km* usually separates the applications of optical fiber transmission into *short-haul* and *long-haul* links.

UNIT 2 - INDUSTRIAL APPLICATION OF OPTICAL FIBRES

There are two commonly used types of optical modulators in fiber optic communication systems: the electro absorption modulator (EAM) and the Mach-Zehnder modulator (MZM).

Electroabsorption Modulator (EAM)

EAM is small and can be integrated with the laser on the same substrate. An EAM combined with a CW laser source is known as an electro absorption modulated laser.

An EML consist of a CW DFB laser followed by an EAM, as shown above. Both devices can be integrated monolithically on the same InP substrate, leading to a compact design and low coupling losses between the two devices.

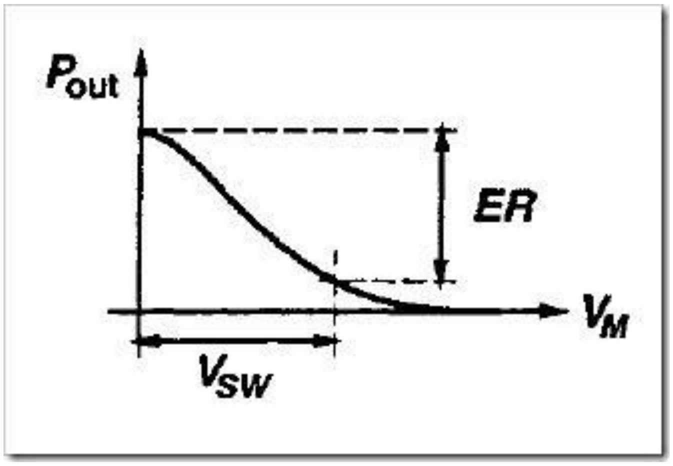
The EAM consists of an active semiconductor region sandwiched in between a p- and n-doped layer, forming a p-n junction. The EAM works on the principle known as Franz-Keldysh effect, according to which the effective bandgap of a semiconductor decreases with increasing electric field.

Without bias voltage across the p-n junction, the bandgap of the active region is just wide enough to be transparent at the wavelength of the laser light. However, when a sufficiently large reverse bias is applied across the p-n junction, the

effective bandgap is reduced to the point where the active region begins to absorb the laser light and thus becomes opaque.

In practical EAMs, the active region usually is structured as an MQW, providing a stronger field-dependent absorption effect (known as the quantum-confined Stark effect).

The relationship between the optical output power, Pout, and the applied reverse voltage, Vm, of an EAM is described by the so-called switching curve. The following figure illustrates such a curve together with the achievable ER for a given switching voltage, Vsw.



The voltage for switching the modulator from the on state to the off state, the switching voltage Vsw, typically is in the range of 1.5 to 4 V, and the dynamic ER usually is in the range of 11 to 13 dB.

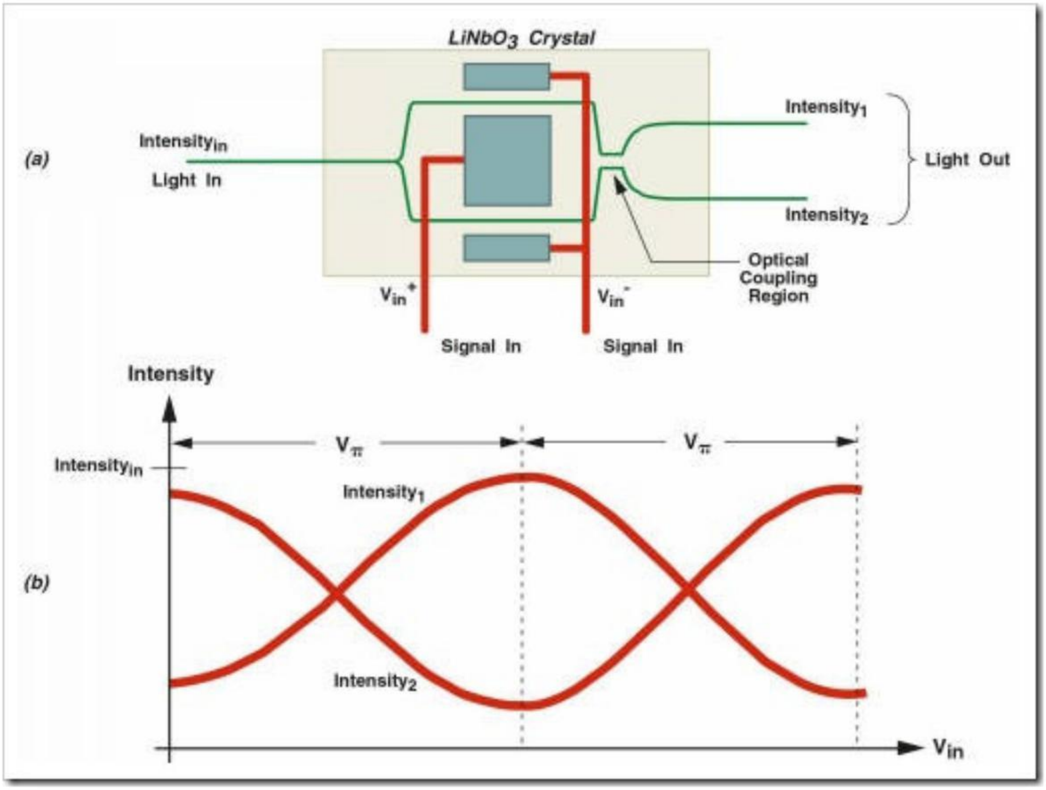
Because the electric field in the active region not only modulates the absorption characteristics, but also the refractive index, the EAM produces some chirp. However, this chirp usually is much less than that of a directly modulated laser. A small on-state (bias) voltage around 0 to 1 V often is applied to minimize the modulator chirp.

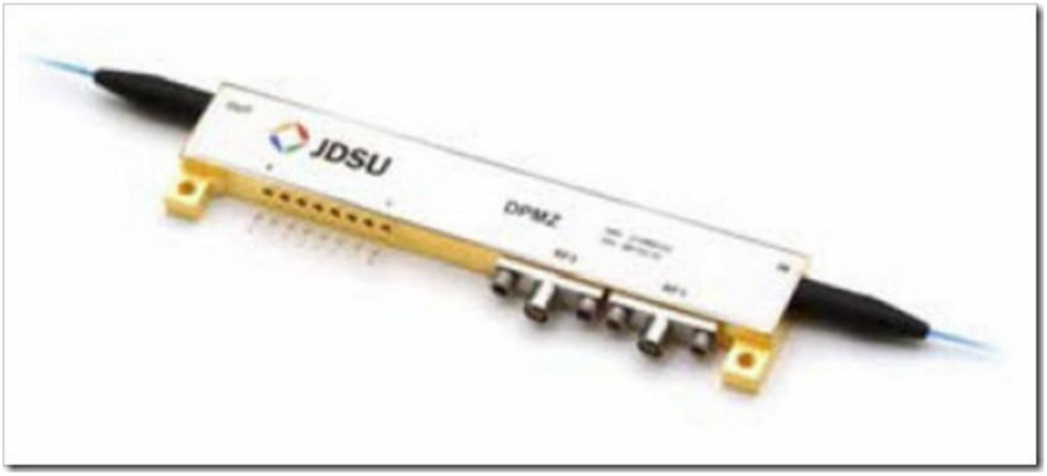
Lithium Niobate Mach-Zehnder Modulator (MZ Modulator)

Lithium Niobate Mach-Zehnder modulators are suited for use in metro, long-haul (LH) and ultra long-haul (ULH) optical transport applications.

The incoming optical signal is split equally and is sent down two different optical paths. After a few centimeters, the two paths recombine, causing the optical waves to interfere with each other. Such an arrangement is known as an interferometer.

If the phase shift between the two waves is 0°, then the interference is constructive and the light intensity at the output is high (on state); if the phase shift is 180°, then the interference is destructive and the light intensity is zero (off state).





The phase shift, and thus the output intensity, is controlled by changing the delay through one or both of the optical paths by means of the electro-optic effect. This effect occurs in some materials such as lithium niobate (LiNbO3), some semiconductors, as well as some polymers and causes the refractive index to change in the presence of an electric field.

The guided-wave LiNbO3 interferometers used to modulate laser beams was fabricated as early as 1980. LiNbO3 has been the material of choice for electro-optic MZ modulator because it combines the desirable qualities of high electro-optic coefficient and high optical transparency in the near-infrared wavelength used for telecommunications.

LiNbO3 MZ modulator can operate satisfactorily over a wavelength range of 1300 – 1550nm. It has been widely used in today’s high-speed digital fiber communication.

LiNbO3 MZ modulators with stable operation over a wide temperature range, very low bias-voltage drift rates, and bias-free operation are commercially available.

High-speed, low-chirp modulators are needed to take advantage of the wide bandwidth of optical fibers. Modulators have became a critical component both in the high-speed time-domain-multiplexing (TDM) and wavelength-division-multiplexing systems (WDM).

Modulators have been traditionally used to modulate a continuous wave (CW) laser to generate the digital signal to be transmitted through a fiber. High-speed modulator with >40GHz bandwidth has been fabricated. Low drive-voltage operation is the key to brining such modulators into practical use because this eliminates the need for high–power electrical amplifiers.

There is general a tradeoff between the speed and the drive voltage. The modulator chirp must also be taken into consideration in the link design. The design of the modulator and the associated chirp can be used as a degree of freedom to extend link distance.

Measurement of liquid level:

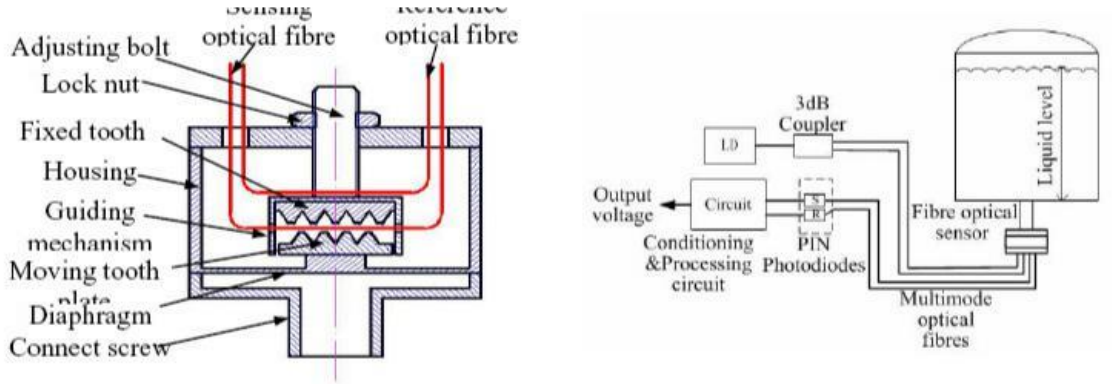
Continuous monitoring of liquid level in oil tanks is important in the petroleum and chemical industries where the measured data is useful in process control loops.Numerous types of sensors with various principles have been used for liquid level measurement of oil tanks [2]. Although most of them work well in practice, these sensors are limited by high cost or complicated configuration. Additionally, theatmosphere near the oil tanks is flammable and thus any electric spark is likely to cause severe disaster.

Optical sensors have a history of more than thirty years and have been successfully used in certain areas such as underwater acoustic sensing, strain monitoring, chemical substance detecting and so on. These kinds of sensors have many advantages including intrinsical safety in explosive or fire-hazardous environments, electrical insulation, electromagnetic interference (EMI) resistance, resistance to corrosive fluids, small size and weight, fast response and potential low cost [1][2]. They are very suited to measure physical parameters (pressure, temperature, density, etc.) in fields where safety is strictly required.

In this paper, a microbend-based fibre optical sensor, which is used for continuous monitoring of liquid level, and related signal processing circuit was designed and tested. Experimental results were given and discussed.

Principle of operation

Liquid level is obtained through hydrostatic pressure measurement with the fibre optical sensor. It is based on the principle that the hydrostatic pressure difference between the top and bottom of a column of liquid is related to the density of the liquid and the height of the column, n, i.e.,$p\ gH$,where p , , H and g are pressure, liquid density, column height and the gravity acceleration,respectively. Using pressure measurement to determine liquid level is particularly useful for applications with foaming or bubbling liquid, where other level measurement technologies have difficulties. The sensor head is actually a pressure sensor based on the small displacement of a diaphragm and microbend effect of optical fibres. It mainly consists of a sensing diaphragm with a hard center, a microbend modulator (a pair of tooth plates), sensing and reference fibres, adjusting bolts and stainless steel housing as shown in figure 1(a). The sensor is mounted at the bottom of an open liquid vessel and the sensing system configuration is illustrated in figure 1(b). Liquid pressure is converted into small displacement of movable tooth plate by the sensing diaphragm. Then the sensing fibre between two tooth plates is bent and the through light intensity is reduced. By detecting the output light power, the exerted pressure is obtained and the liquid level can be calculated with the specified density. The sensing diaphragm was directly fabricated instead of welded onto the steel housing to decrease additional stress caused by any temperature effects. Standard multimode fibres were used in order to lower the cost. Furthermore, two parallel optical fibres, one for sensing and the other for reference, were used to eliminate influence due to fluctuation of light source and other disturbance along the optical path.



(a) (b)

Figure 1. Structure of sensor (a) and system configuration (b).

Interferometric Methods

Laser-based distance measurements can be done using interferometric principles. Measurements of length using optical interferometry have been performed since the 19th century. But the limited intensity and coherence of conventional light sources restricted the measurements, which were difficult and suitable for used only over distances of a few centimeters. The development of lasers removed these restrictions. Lasers have allowed interferometry to develop into a fast, highly accurate and versatile technique for measuring longer distance.

Interferometric measurement of distance can be highly accurate. It offers a higher degree of precision than the pulsed time-of-flight or beam-modulation telemetry methods. However, it is best suited to measurements made in a controlled atmosphere (for example, indoors) over distances no greater than a few tens of meters.

Most laser-based interferometric systems for measurement of distance use a frequency-stabilized helium-neon laser. An unstabilized laser, operating in a number of longitudinal modes, will have a total linewidth around 10^9 Hz. This spread in the frequency (or wavelength) will cause the interference fringes to become blurred and to lose visibility as the distance increases. An unstabilized laser is suitable for measurement only over distances of a few centimeters. Stabilized lasers, usually in a temperature-controlled environment and operating in a single longitudinal mode, are used for longer distances.

We describe first the operation of a system based on the Michelson interferometer, because it is easy to understand the basic principles of interferometer distance measurement with reference to the Michelson interferometer. Later we will describe variations that provide better stability under conditions of atmospheric turbulence.

figure 15 shows the basic configuration for a Michelson interferometer. Review Course 5 on interference if necessary to understand the formation of an interference pattern. The beam from the laser falls on a beam splitter that reflects half the beam in one direction (the reference arm) and transmits the other half (the measurement arm). The two beams are each reflected by mirrors, a stationary mirror in the reference arm and a movable mirror in the measurement arm. In practice the mirrors are often cube corner reflectors (retroreflectors) which offer better stability against vibrations than conventional flat mirrors.

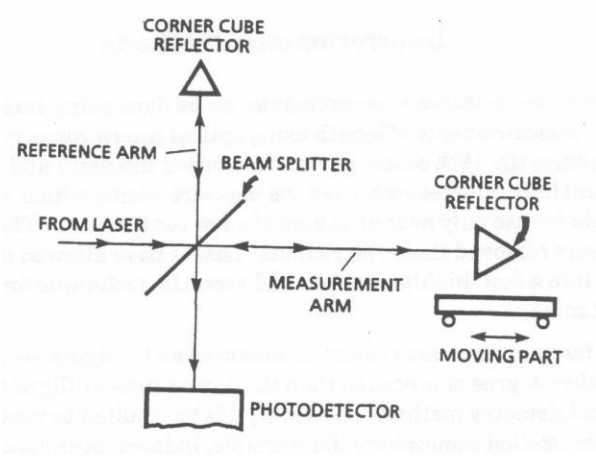


Fig. 15
Schematic diagram of the application of a Michelson interferometer to measurement of distance

The two reflected beams are recombined at the beam splitter to form an interference pattern that is viewed by an observer or measured by a recorder such as a photodetector. The character of the fringes is related to the different optical path lengths traveled by the two beams before they are recombined.

Suppose, for example, that the detector is viewing a bright fringe in the interference pattern when the movable mirror is at a certain position. If the movable mirror moves a distance equal to 1/4 of the wavelength of light, the round-trip distance traversed by the light in the measurement arm will change by 1/2 wavelength, and the fringe pattern will change so that the detector now views a dark fringe. The distance mesurement thus consists of counting the number of fringe variations as the mirror moves. Each complete fringe corresponds to a phase variation equal to 2p .The variation in phase d is determined by using the equation

$$d = 4p\ D\ x/l$$ Equation 20

where l is the wavelength of the light, and D x is the distance that the movable mirror has moved. It is apparent that this method offers high precision, allowing measurements of D x to be made with an accuracy of the order of a fraction of the wavelength of light.

The maximum distance D x that can be measured in this way is given by:

$$D\ x_{max} = c/D\ v$$ Equation 21

Where:

c = velocity of light.
D v = linewidth (i.e., spread in frequency) of the laser.

This equation shows the importance of using a frequency-stabilized laser with a small line width.

Note also that this measurement is a relative measurement which gives the distance that the mirror has moved from its initial position, rather than an absolute positional measurement.

Example D: Distance Measurement in a Michelson Interferometer	
Given:	A HeNe laser 50 cm long with two Longitudinal modes is used to measure distance in a Michelson interferometer. 2200 fringe changes are observed (bright to dark to bright) as the movable mirror is moved.
Find:	The distance the mirror moved. The maximum distance that could have been measured.
Solution:	Each fringe corresponds to a change in phase of 2p . So the total change in phase d is 2200 ? 2p . Using Equation 20:

	2200 ? 2p = 4p D *x*/l or D *x* = 2200 l /2 = 2200 ? 0.6328 ? 10^{-4}/2 = 0.0696 cm In a laser, the longitudinal mode spacing is *c*/2*L* where *L* is the length of the laser. So, a two-mode laser will have a linewidth D *v* equal to *c*/2*L*. Using Equation 21, we have: D x_{max} = $\frac{c}{\Delta\nu} = \frac{c}{c/2L}$ = 2*L* = 2 ? 50 = 100 cm.

The distance measured in an optical measurement is the optical path, which is the physical path multiplied by the index of refraction of the air through which the measurement is made. Since the index of refraction is close to unity, in some cases (for example, military ranging) it is not necessary to correct for variations in the index of refraction. But in interferometric measurements requiring a high degree of precision, one must correct for changes in the index of refraction that occur as a result of changes in air pressure, temperature, and so on. The index of refraction of dry air at a pressure of 760 Torr and a temperature of 15. C is1.0002765 at the helium-neon laser wavelength. As conditions in the air change, the index of refraction changes.
It increases by:

0.36 part per million for an increase of 1 Torr in atmospheric pressure.

0.96 part per million for an increase of 1Cin temperature.

0.06 part per million for an increase of 1 Torr in the partial pressure of water vapor.

So, a measurement system that requires high precision must include sensors for measurement of air temperature and pressure (an perhaps relative humidity) and a means (often an automated computer-based means) for correcting for the variable atmospheric parameters.

Measurement of Pressure

Worldwide a lot of research effort is carried out concerning new inspection techniques for the in-service monitoring of composite structures. This paper focuses on the use of optical fibre sensors. The sensor part of the optical fibre is a Bragg-grating. This is a periodic perturbation in the refractive index of the fibre core. When broadband light is coupled into the optical fibre sensor, a reflection peak will be obtained centered around a wavelength called Bragg-wavelength. The Bragg-wavelength depends on the refractive index and the period of the grating, which both change due to mechanical and thermal strain applied to the sensor. Optical fibres with Bragg-sensor have been embedded into filament wound pressure vessels.

A test setup has been implemented to demonstrate the ability of remote sensing. This is of great importance for the applicability of Bragg-sensors to mechanical and civil structures. The controlling computer and the test set-up are connected to an optical spectrum-analyser by means of independent optical links of 200m. In this way the relative positions of the different parts of the test set-up are irrelevant. The vessels have been subjected to static loading cycles as well as to slowly varying dynamic loadings. The measured shifts in Bragg-wavelength show excellent linear agreement with the pressure applied to the vessel. The combination of this measuring method and the test set-up is an essential step towards a continuous remote monitoring system for composite structures. It is also an important part in the total design of "smart" structures.

II. Introduction

There is an important international research work going on in the domain of non destructive evaluation techniques. And quite right, because there is a great necessity for techniques that are able to evaluate mechanical or civil constructions during their fabrication, installation and lifetime. This can be the detection of possible damage, the measurement of mechanical quantities, the measurement of pressures, temperatures, corrosion.

Today one can find many constructions made of fibre reinforced plastics that are in service since many years. Many of these undergo a gradual degradation and some are already in an advanced stage of deterioration. This can effect the safety of persons and installations. Therefore one wants to know the condition of a construction at every time and if possible correlate this with the remaining lifetime. This is even more true for constructions made of fibre reinforced plastics because of the lack of experience with the long term behaviour of this materials, notwithstanding the many constructions that yet have been built.

At this moment the observation of constructions under high load is mainly based on regular (but expensive and extensive) inspections. The constructions must therefore be put out of service during a certain period, causing serious financial implications for the user. This explains why permanent monitoring techniques arouse interest. The number of regular inspections can be reduced or even become totally unnecessary. Only at the time that some aberrant behaviour is recorded a more thorough inspection should be done. A monitoring technique could also be used to detect temporary or permanent overloads, inadmissible vibrations, abnormal temperatures, damage of the construction. A major advantage of monitoring is that in function of the measured load, fatigue cycles, overload, an estimation of the remaining lifetime of the construction can be made. The feedback from the recorded loads and deformations of (part of) the construction in real conditions can also lead to usable information in design or even the development or adaptation of standards and rules.

A monitoring technique is certainly eligible for mechanical and civil structures of which the integrity is of primordial importance. Examples of these are aeroplanes, pipelines, pressure vessels, chemical installations, bridges, dams, machine part.

In this paper some experiments on the use of optical fibre sensors for the permanent monitoring of pressure vessels and containers are reported. Pressure vessels find wide application in many different domains, such as transport, chemical industry, processing industry, food industry. These vessels work under high pressures, often under alternating stresses and ambient conditions (temperature, moisture. Therefore the aspect of safety is of major importance in the sector of pressure vessels. Because of the inadequate knowledge of the long-term behaviour of filament wound pressure vessels, high safety factors are applied in design rules, and there is often no consensus about the acceptability of certain damage patterns. The possibility of monitoring the condition of an in-service pressure vessel, should certainly elucidate these matters.

III. Optical fibre sensors

Table 1 gives a summary of the major advantages and disadvantages of the use of optical fibres in relation to more common monitoring techniques, such as electrical resistance strain gauges, accoustic emission[1-3].

Table 1: Advantages and disadvantages of optical fibre sensors.

Advantages	Disadvantages
○ high sensitivity for multiple quantities (temperature, strain) ○ possibility of measuring at multiple points with one optical fibre ○ insensitive to corrosion ○ ideally suited to be embedded in composite structures ○ does not affect the mechanical properties of the material in which it is embedded ○ withstands high temperatures	○ because of the high sensitivity, the measurement of one quantity can be influenced by other quantities ○ can't be repaired ○ because of the brittleness one has to be very cautious when handling these optical fibres ○ complex techniques often have to be used for the treatment of the signal

○ very small and light ○ can have a sensor function and be signal carrier (optical transmission) at the same time ○ insensitive to electromagnetic interference ○ geometrical versatile	○ high cost

The major efforts that take place in the development of optical fibre (sensor) technology will certainly have as effect that a number of the disadvantages cited above will disappear. There exist a lot of different optical fibre sensors, all suited for specific purposes (strain sensing, pressure sensing, chemical sensing, vibration sensing. The sensor studied in this project is a Bragg sensor that is ideally suited for strain measurements. A Bragg grating is a periodic perturbation in the refractive index of the fibre core. The realisation of a Bragg grating in an optical fibre is based on the photosensitivity of the Germanium doped fibre core. This means that the refractive index of the fibre core can be permanently changed by side illumination with ultraviolet light[4]. When light with a sufficiently broad spectrum is coupled into the optical fibre, a narrow band around a central peak wavelength will be reflected by the Bragg sensor. A typical reflected spectrum is shown in figure 1.

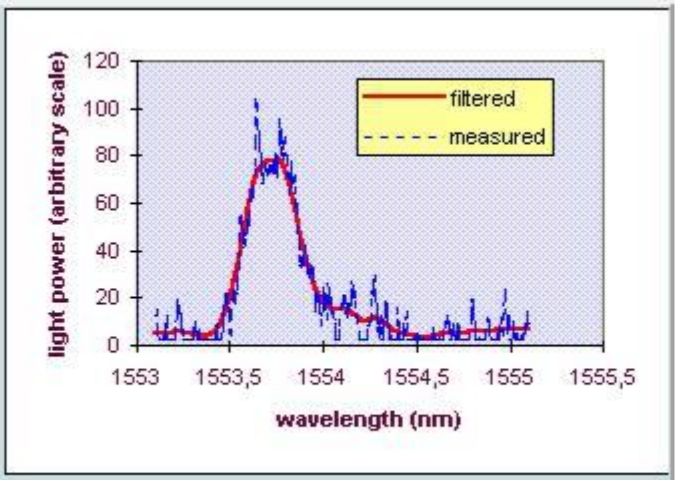


Fig 1. Measured and filtered spectrum of a Bragg sensor

This central peak wavelength, also called Bragg wavelength, is given by the Bragg condition:

$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda$$

Herein n_{eff} is the effective index of refraction and the period of the grating. When strain is applied to the sensor part of the optical fibre, the peak wavelength will change due to two reasons. Primary the period of the grating will change according to the applied strain, and secondly the effective index of refraction will change due to internal stresses. The strain can be caused by mechanical loads or by changes in temperature. By measuring the shift in Bragg wavelength, one can easily determine the applied strain according to formula 2:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P) \cdot \frac{\Delta L}{L}$$

Herein L is the length of the sensor and P is the optical strain coefficient which has a typical value of 0,22 for axial strain[5].One major advantage of a Bragg sensor is that the information is encoded directly into the wavelength, which is an absolute parameter. This means that the output does not depend on the total light level, nor on losses in the connecting fibres and couplers, nor on the power of the light source. The wavelength encoded nature of the sensor output also facilitates wavelength division multiplexing[6], by assigning each sensor to a different portion of the available source spectrum. The measurement of the optical signals is done with an optical spectrum analyser (OSA). The OSA has a white light source which is used to couple light into the optical fibre. The signal reflected from the Bragg sensor is coupled into the detection unit of the OSA via a 50/50-coupler.

The used light source has a relatively low light power and is liable to noise. Because of the coupler, splices and connectors the light power will also be attenuated when reaching the detector. This means that the influence of noise can be of importance and thus the reflected spectrum won't be of great quality. But for the measurements only the shift of the peak wavelength is of importance, thus a spectrum with a clear distinct peak wavelength is of importance. The measured spectra can also be mathematically filtered to reduce the influence of noise. There is obviously an important influence of noise on the recorded spectrum of figure 1.

As stated above this is inherent to the use of the white light source of the optical spectrum analyser (OSA). This means that the wavelength at which the maximum reflection occurs, will not necessarily be the wanted Bragg wavelength. Therefore the recorded spectra are mathematically filtered before extracting the peak wavelength. From this filtered spectra the two wavelengths at which half of the maximum reflection is recorded are determined and the mean value is defined as Bragg wavelength. One test also has been performed with a tunable laser source, which has more light power. With this source there is no longer influence of noise on the recorded spectra and thus the Bragg wavelength can easily be determined without the need of filtering the spectrum.

Unit 3 – LASER FUNDAMENTALS

Laser technology is one of the most rapidly developing areas in modern technology. When the laser was invented, in 1960, it was classified as a *solution in search of a problem*, and today laser technology is applied in many different areas such as: medicine, communication, daily use, military, and industry.

To explain how the laser can be applied in such diverse areas, we need to understand the basic physical principles of the operation of a laser.

In principle, the laser is a device which transforms energy from other forms into electromagnetic radiation. This is a very general definition, but it helps to understand the basic physics of the laser.

The energy put into the laser can be in any form such as: electromagnetic radiation, electrical energy, chemical energy, etc.

Energy is always emitted from the laser as electromagnetic radiation (which includes light beams).
From this light output, the laser got part of its name:

LASER = Light Amplification by Stimulated Emission of Radiation.

The terms used in this definition will be explained later in this course.

As we see, the word laser started as an acronym, but it is now accepted as a word, with other words derived from it: "to lase", "lasing" etc.

Energy States (Levels)

Every atom or molecule in nature has a specific structure for its energy levels.

The lowest energy level is called the ground state, which is the naturally preferred energy state. As long as no energy is added to the atom, the electron will remain in the ground state.

When the atom receives energy (electrical energy, optical energy, or any form of energy), this energy is transferred to the electron, and raises it to a higher energy level (in our model further away from the nucleus).

The atom is then considered to be in an excited state.

The electron can stay only at the specific energy states (levels) which are unique for each specific atom. The electron can not be in between these "allowed energy states", but it can "jump" from one energy level to another, while receiving or emitting specific amounts of energy.

These specific amounts of energy are equal to the difference between energy levels within the atom.

Each amount of energy is called a "Quantum" of energy (The name "Quantum Theory" comes from these discrete amounts of energy).

Energy transfer to and from the atom

Energy transfer to and from the atom can be performed in two different ways:

1. Collisions with other atoms, and the transfer of kinetic energy as a result of the collision. This kinetic energy is transferred into internal energy of the atom.
2. Absorption and emission of electromagnetic radiation.

Since we are now interested in the lasing process, we shall concentrate on the second mechanism of energy transfer to and from the atom (The first excitation mechanism is used in certain lasers, like Helium-Neon, as a way to put energy into the laser, and will be discussed in chapter 6 about the different kinds of lasers).

Summary

- The interactions between electromagnetic radiation and matter cause changes in the energy states of the electrons in matter.
- Electrons can be transferred from one energy level to another, while absorbing or emitting a certain amount of energy. This amount of energy is equal to the energy difference between these two energy levels (E_2-E_1).

We shall see later in this chapter that:

- When this energy is absorbed or emitted in a form of electromagnetic radiation, the energy difference between these two energy levels (E_2-E_1) determines uniquely the frequency (ν) of the electromagnetic radiation:

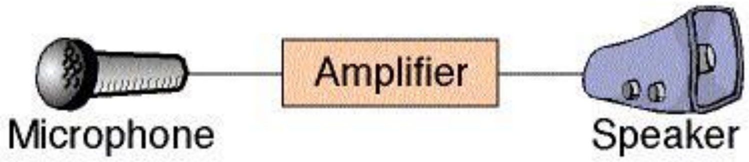
$$(\text{DeltaE}) = E_2-E_1 = h\nu = h(\text{bar})\omega$$

The laser is a system that is similar to an electronic oscillator.

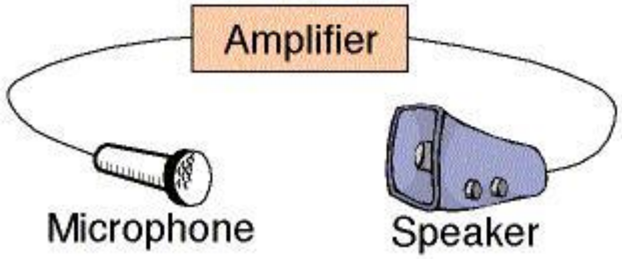
An Oscillator is a system that produces oscillations without an external driving mechanism.

To demonstrate an oscillator, we can use the familiar acoustic analog:

A sound amplification system has a microphone, amplifier and speaker.



When the microphone is placed in front of the speaker, a closed circuit is formed, and a whistle is heard out of the speaker.



The whistle is created spontaneously, without any external source.

Explanation: The speaker's internal noise is detected by the microphone, amplified and the amplified signal is again collected by the microphone. This positive feedback continues until a loud whistle is heard.

Every oscillator has 4 main parts (as seen in figure 3.1):

1. Amplifier.
2. Positive resonance feedback.
3. Output coupler.
4. Power source.

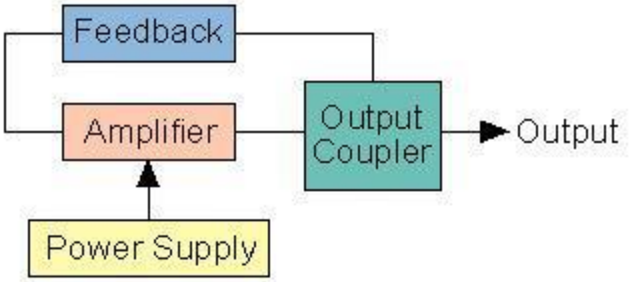


Figure 3.1: Electronic Oscillator

In analogy to the electronic amplifier, the laser can be described as composed of four structural units (see figure 3.2):

1. Active medium, which serves as an optical amplifier.
2. Excitation mechanism.
3. Optical feedback.
4. Output coupler, to allow electromagnetic radiation out of the laser device.

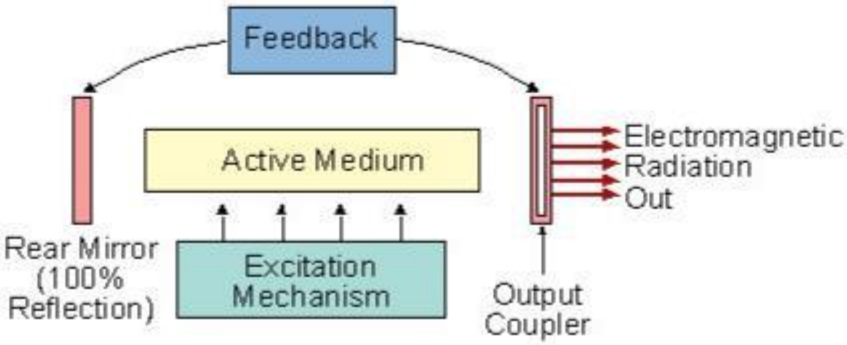


Figure 3.2: The Basic Laser System

Before explaining the details of each of the laser components, few terms must be understood:

- Active medium and its importance for the lasing process.
- Population inversion in the active medium, and the conditions for making it (Excitation of the active medium with an external source of energy).
- Stimulated emission and light amplification caused by it.
- Laser system and its components.

Lasers can be divided into groups according to different criteria:

1. The state of matter of the active medium: solid, liquid, gas, or plasma.
2. The spectral range of the laser wavelength: visible spectrum, Infra-Red (IR) spectrum, etc.
3. The excitation (pumping) method of the active medium: Optic pumping, Electric pumping, etc.
4. The characteristics of the radiation emitted from the laser.
5. The number of energy levels which participate in the lasing process

The active medium

The material used as the active medium determines:

1. Laser Wavelength.
2. Preferred pumping method.
3. Order of magnitude of the laser output.
4. The efficiency of the laser system.

We saw that the two basic requirements for laser action are:

1. Population Inversion between the upper and lower laser energy levels.

2. The active medium must be transparent to the output wavelength.

The active medium determines most of the laser properties, and that is why the laser name is derived from the name of the active medium

The number of applications of lasers is enormous.

In this chapter, the applications are divided into groups, and our hope is that with time we will fill the missing information on most of the well known applications of lasers. Some applications are already described in details, such as:

- Compact Disk (CD).
- Laser Printer.
- Bar Code Scanner.
- Inertial Fusion.

Properties of Laser Beams

Monochromaticity:

This property is due to the following two factors. First, only an EM wave of frequency n_0 = (E2-E1)/h can be amplified, n_0 has a certain range which is called linewidth, this linewidth is decided by homogeneous broadening factors and inhomogeneous broadening factors, the result line width is very small compared with normal lights. Second, the laser cavity forms a resonant system, oscillation can occur only at the resonance frequencies of this cavity. This leads to the further narrowing of the laser linewidth, the narrowing can be as large as 10 orders of magnitude! So laser light is usually very pure in wavelength, we say it has the property of monochromaticity.

Coherence:

For any EM wave, there are two kinds of coherence, namely spatial and temporal coherence.

Let's consider two points that, at time t=0, lie on the same wave front of some given EM wave, the phase difference of EM wave at the two points at time t=0 is k0. If for any time t>0 the phase difference of EM wave at the two points remains k0, we say the EM wave has perfect coherence between the two points. If this is true for any two points of the wave front, we say the wave has perfect spatial coherence. In practical the spatial coherence occurs only in a limited area, we say it is partial spatial coherence.

Now consider a fixed point on the EM wave front. If at any time the phase difference between time t and time t+dt remains the same, where "dt" is the time delay period, we say that the EM wave has temporal coherence over a time dt. If dt can be any value, we say the EM wave has perfect temporal coherence. If this happens only in a range 0<dt<t0, we say it has partial temporal coherence, with a coherence time equal to t0.

We emphasize here that spatial and temporal coherence are independent. A partial temporal coherent wave can be perfect spatial coherent. Laser light is highly coherent, and this property has been widely used in measurement, holography, etc.

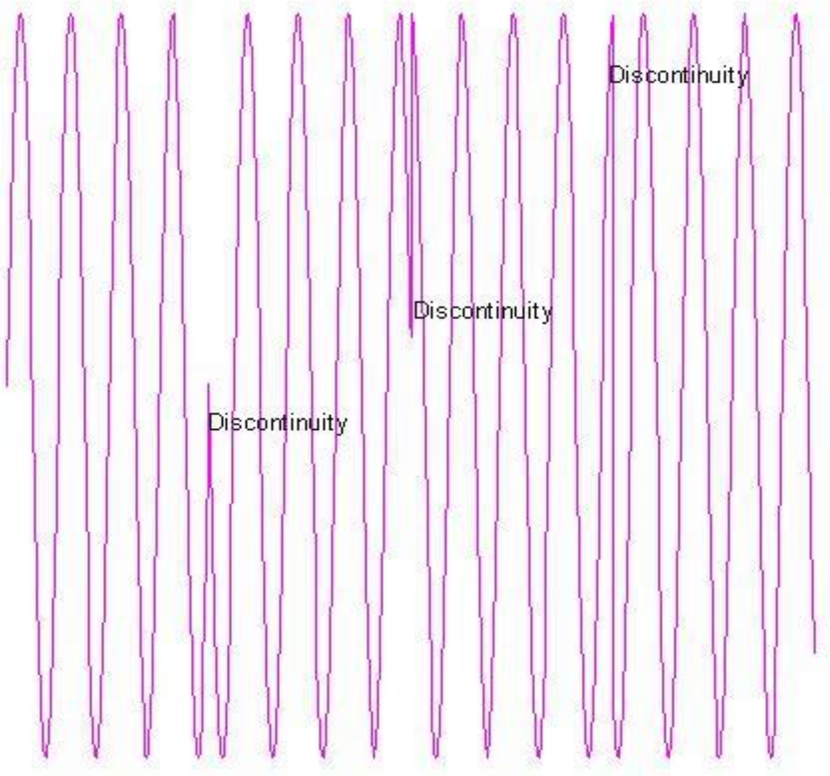


Figure 2.1: partial temporal coherence

Divergence and Directionality:

Laser beam is highly directional, which implies laser light is of very small divergence. This is a direct consequence of the fact that laser beam comes from the resonant cavity, and only waves propagating along the optical axis can be sustained in the cavity. The directionality is described by the light beam divergence angle. Please try the figure below to see the relationship between divergence and optical systems.

For perfect spatial coherent light, a beam of aperture diameter D will have unavoidable divergence because of diffraction. From diffraction theory, the divergence angle q_d is:

q_d= b l /D

Where l and D are the wavelength and the diameter of the beam respectively, b is a coefficient whose value is around unity and depends on the type of light amplitude distribution and the definition of beam diameter. q_d is called diffraction limited divergence. If the beam is partial spatial coherent, its divergence is bigger than the diffraction limited divergence. In this case the divergence becomes:

q = b l /$(Sc)^{1/2}$

where Sc is the coherence area.

Example: For laser light of wavelength l =$1.06*10^{-3}$ mm, D=3 mm, b =1.1, then

q_d= b l /D=$1.1*1.06*10^{-3}/3=0.3887*10^{-3}$ rad=0.022269° . Compare this value with a normal flashlight, the divergence is about 25° , a searchlight has a divergence angle of 10° , the high directionality of laser light is obvious.

Brightness:

The brightness of a light source is defined as the power emitted per unit surface area per unit solid angle. A laser beam of power P, with a circular beam cross section of diameter D and a divergence angle q and the result emission solid angle is p q^2, then the brightness of laser beam is:

B=4P/$(p\ Dq\ )^2$

The max brightness is reached when the beam is perfect spatial coherent.

Bmax=4P/$(p\ l\ b\ )^2$

In case of limited diffraction (q_d= l b /D, D=l b /q_d, q_d=q)

Do you know why Laser Ligh Source is much brighter than normal light? Click to listen to the answer.

LASER MODES:

Surely laser cavity is also very important for a laser in many other aspects, for example, its dimension decides the longitudinal laser modes. Then what is a laser mode?

Generally speaking light modes means possible standing EM waves in a system. The number of modes in this meaning is huge. Laser mode means the possible standing waves in laser cavity. We see that stimulated lights are transmitted back and forth between the mirrors and interfere with each other, as a result only light whose round trip distance is integer multiples of the wavelength l can become a standing wave. That is:

$m = 2L/(c/f) = 2L/l$, or $f = m\, c/(2L)$, $D\ f = c/(2L)$

Where L is the length of cavity, c is the light speed in laser cavity, f is the frequency of standing wave, l is the wavelength, m is an integer, D f is the frequency difference between two consecutive modes. The number of longitudinal modes may be very large, it can also be as small as only a few (below 10).

If we intersect the output laser beam and study the transverse beam cross section, we find the light intensity can be of different distributions (patterns). These are called Transverse Electromagnetic Modes (TEM). Three index are used to indicate the TEM modes— TEMplq, p is the number of radial zero fields, l is the number of angular zero fields, q is the number of longitudinal fields. We usually use the first two index to specify a TEM mode, like TEM00, TEM10, etc. Clearly, the higher the order of the modes the more difficult it is poor to focus the beam to a fine spot. That is why some times TEM00 mode or Gaussian beam is preferred.

. TEM Mode, Beam Diameter, Focal Spot Size and Depth of Focus

Modes are the standing oscillating electromagnetic waves which are defined by the cavity geometry. In the above section, we already computed the Longitudinal Modes frequencies for some simple cases. If the cavity is of closed form, i.e., both the mirrors and side walls are reflective, there will be large amounts of longitudinal modes oscillating inside the cavity, a typical value can be 10^9 modes for a He-Ne laser. People had thought closed form could improve the output power, but it turns out that the output beam can not be well focused for closed cavities with so many modes. So open oscillators are used, whose lateral walls are not reflective, light incident on this part will be absorbed. This can reduce the possible longitudinal modes to only a few, for example, as low as 6!

When these modes oscillate, they interfere with each other, forming the transverse standing wave pattern on any transverse intersection plane. This mechanism decides the Transverse Electromagnetic Modes (TEM) of the laser beam, which is the wave pattern on the output aperture plane. We use the sign TEM_{pql} to specify a TEM mode, where p is the number of radial zero fields, q is the number of angular zero fields, q is the number of longitudinal fields, and we usually use TEM_{pq} to specify a TEM mode, without the third index. A table of TEM patterns is shown below. Clearly, the mode pattern affects the distribution of the output beam energy, which will thus affect the machining process.

Then what is the diameter of a laser beam? Usually this diameter is defined as the distance within which $1/e^2$ of the total power exists.

The higher the order of the mode, the more difficult it is to focus the beam to a fine spot, since the beam of higher order is not from a virtual point, but from patterns as those in the table below.

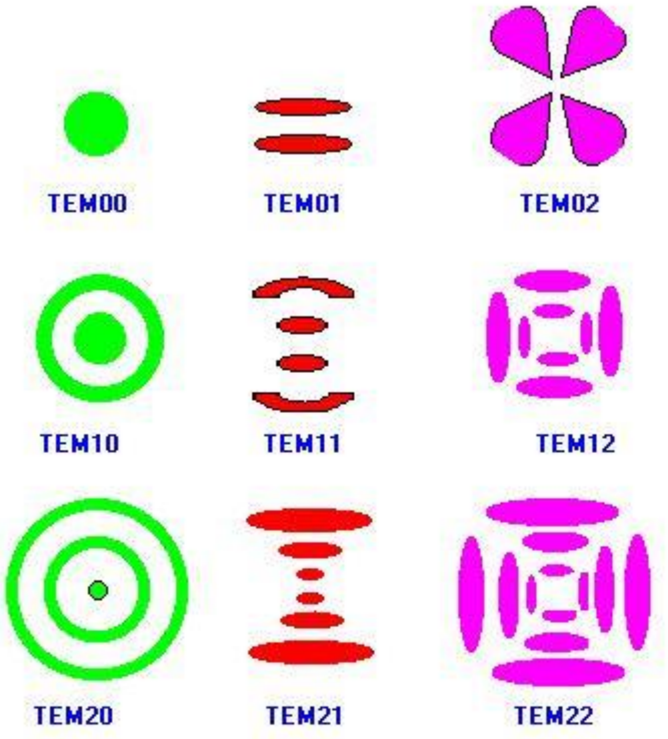


Table 2.14: Table of modes

Focal Spot Size:

Focal spot size determines the maximum energy density that can be achieved when the laser beam power is set, so the focal spot size is very important for material processing.

When a beam of finite diameter D is focussed by a lens onto a plane, the individual parts of the beam striking the lens can be imagined to be point radiators of new wave front. The light rays passing through the lens will converge on the focal plane and interfere with each other, thus constructive and destructive superposition take place, light energy is distributed as described in figure? below. The central maximum contains about 86% of the total power.

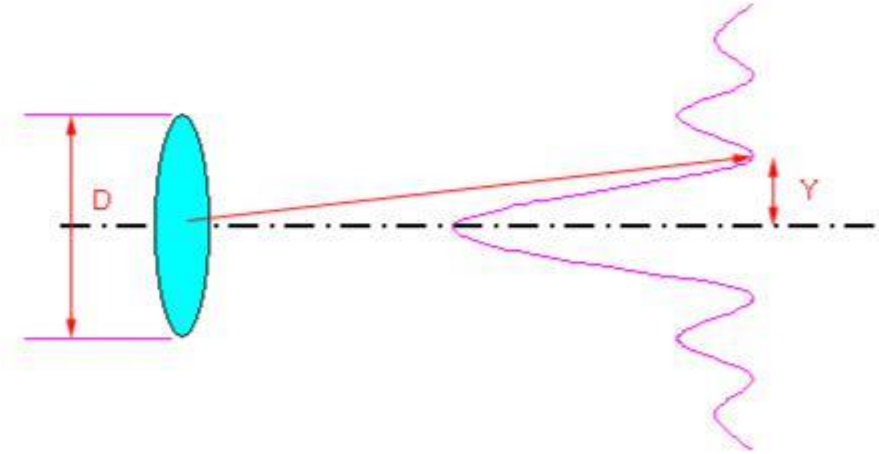


Figure 2.15: Focus pattern of parallel light

The focusing diameter is measured between the points where the intensity has fallen to $1/e^2$ of the central peak value. For a rectangular beam with a plane wave front, the diffraction limited beam diameter, which is the smallest focal diameter, is given by:

dmin = fl /D

For a circular beam, the equation is:
dmin = 2.44fl /D, you can try the interactive figure below to see the influnce of l and D on dmin.

For multi-mode beam TEMplq, the focal spot size is larger than the above two values. The smallest possible focal sopt size in this case is:

dmin = 2.44fl (2p+l+1)/D

Where f is the lens focal length, D is the beam diameter, l is wavelength of the light, p, l is the mode number. From this equation, we can clearly see the influence of modes to the focal property.

There are other factors that affect focal spot size, such as spherical aberration and thermal lensing effects. Most lenses are made with a spherical shape, but they cannot be of perfect shape, there exist spherical aberration. Lenses in laser systems transmit or reflect high power laser radiation, laser power variations can cause shape changes of the lenses, so the focal point will change when the radiation power changes, thus affect the focal spot size.

Depth of Focus (DOF):

The laser light is first converged at the lens focal plane, then diverges to wider beam diameter again. The depth of focus is the distance over which the focussed beam has about the same intensity, it is defined as the distance over which the focal spot size changes –5%~5%. The equation for DOF is:

$$DOF=(8l /p)(f/D)^2=2.44l (f/D)^2$$

Where l is the wavelength, f is the lens focal length, D is the unfocussed beam diameter.

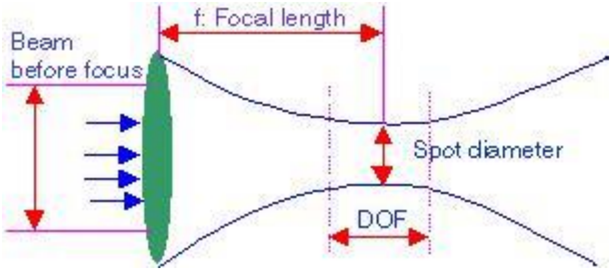


Figure 2.16: The DOF (Depth of Focus) of laser light

Usually longer depth of focus is preferred, because equal energy density along the beam is preferred when using the laser to process materials.

Various Laser Resonators

The most widely used laser resonators or cavities have either plane or spherical mirrors of rectangular or circular shape, separated by some distance L. There have appeared Plane Parallel Resonators, Concentric (Spherical) Resonators, Confocal Resonators, Generalized Spherical Resonators and Ring Resonators.

Plane Parallel Resonator consists of two plane mirrors set parallel to each other, as shown in the figure below. The one round trip of wave in the cavity should be an integral number times 2 , the resonant frequencies is = kc/(2L), k is an integral number, c is the speed of light in the medium, L is the cavity length. The frequency difference between two consecutive modes (possible standing wave in the cavity) is c/(2L). This difference is referred to as the frequency difference between two consecutive longitudinal modes; the word longitudinal is used because the number k indicates the number of half-wavelengths of the mode along the laser resonator, i.e., in the longitudinal direction.

Concentric resonator consists of two spherical mirrors with the same radius R separated by a distance L=2R, so that the centers are coincident. The resonant frequencies use the same equation as above.

Confocal resonator consists of two spherical mirrors of the same radius of curvature R separated by a distance of L such that their foci F1 and F2 coincident. In this case, the center of curvature of one mirror lies on the surface of another mirror, L=R. The resonant frequency cannot be readily obtained from geometrical optics consideration.

Resonators formed by two spherical mirrors of the same radius of curvature R and separated by a distance L such that R<L<2R, i.e., in between confocal and concentric, are called Generalized Spherical Resonators, which is also often used.

Ring Resonator is a particularly important class of laser resonators. The path of the optical rays is arranged in a ring configuration or more complicated configurations like folded configurations. We can compute the resonant frequencies by imposing the constraints that the total phase shift along the ring path or the closed loop path must be equal to the integral numbers of 2 . Then the resonant frequencies are = kc/Lp, where k is an integral number, Lp is the loop path length.

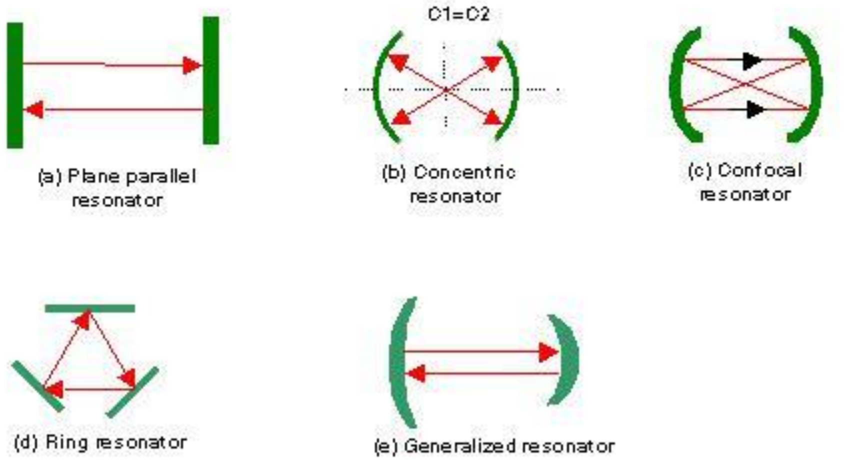


Figure 2.12: Various Resonators

(a) Plane parallel; (b) Concentric; (c) Confocal; (d) Ring; (e) General

Cavities can be identified as stable or unstable according to whether they make the oscillating beam converge into the cavity or spread out of the cavity. The output mirror of the laser resonator is finely coated to reach the required reflection into the cavity, if the beam is too intense, the mirror may suffer breakage. Breakage is serious because it causes shut down of the production. So for powers up to 2kW, lasers mainly use stable cavity designs(see figure ?a), laser output is from the center of optical axis. Stable cavity design allows the beam to oscillate many times inside the cavity to get high gain, the focal property and directionality are improved. For higher powered lasers, unstable cavities are often used (see figure ?b), laser output comes from the edge of the output mirror, which is often a totally reflecting metal mirror. The ring shaped beam reduces the intensity of the beam, thus reduces the risk of breakage. In the same time ring shaped beam is poor for focusing. Unstable cavities are suitable for high gain per round trip laser systems, which don't require large numbers of oscillation between the mirrors.

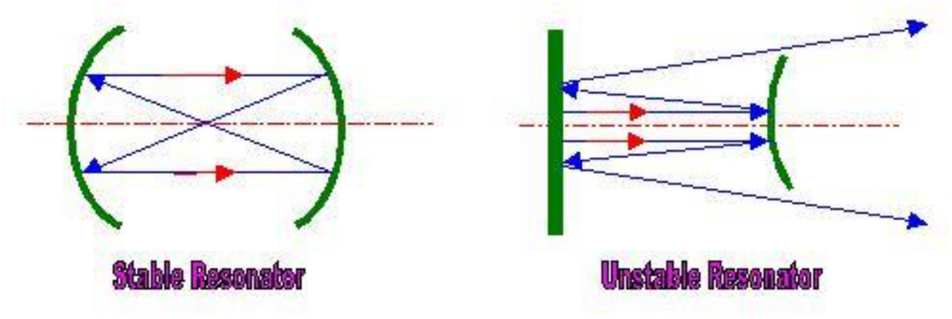


Figure 2.13: Stable and Unstable Resonators

Types of Lasers

Lasers can be divided into gas lasers, solid state lasers and liquid lasers according to the active medium used.

Gas Lasers:

Gas Lasers can be further divided into neutral atom, ion and molecular lasers, whose lasing mediums are neutral atoms, ions or gas molecules respectively.

Helium-neon (He-Ne) laser is a kind of neutral atom gas laser, the common wavelength of a He-Ne laser is 632.8 nm, it is tunable from infrared to various visible light frequencies. He and Ne are mixed according to certain percentage, pumping is by DC electrical discharge in the low pressure discharge tube. First He atom is excited. Because Ne atom has an energy level very near to an energy level of He, through kinetic interaction, energy is readily transferred from He to Ne, and Ne atom emit the desired laser light. The typical power of He-Ne laser is below 50 mW, it is widely used in holography, scanning, measurement, optical fiber communication, etc. It is the most popular visible light laser.

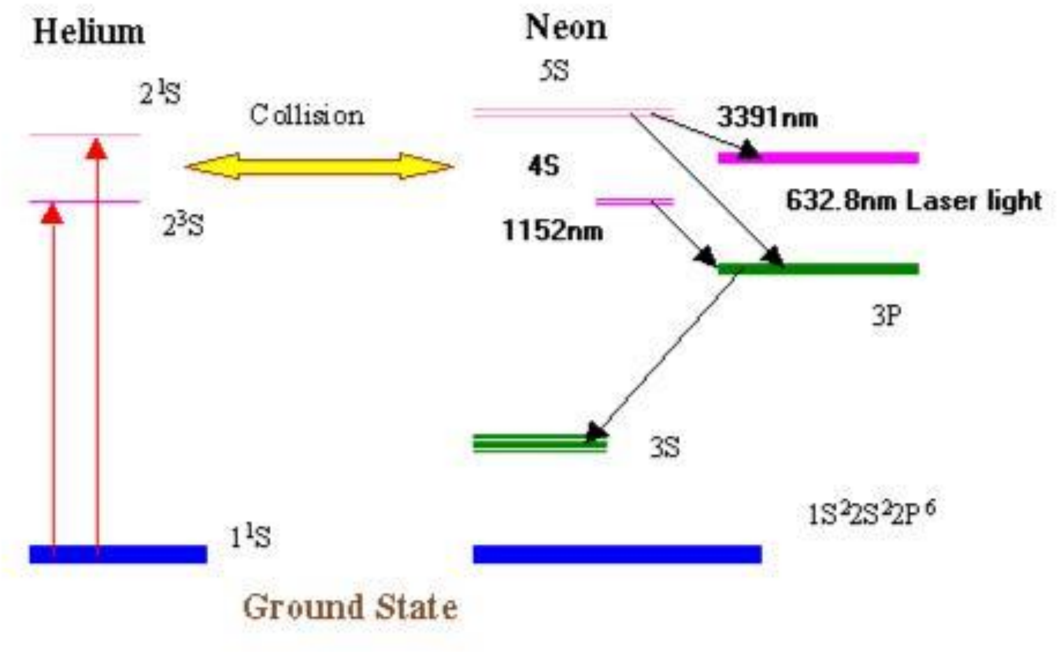


Figure 2.3: Scheme of energy levels of He-Ne laser

Carbon dioxide laser is a typical molecular gas laser, it emits laser light at a wavelength of 10.6 mm, its beam power ranges from several watts to 25 kW or even to 100 kW, so CO_2 laser is widely used in laser machining, welding and surface treating. For this reason, let's investigate it in detail.

The active medium of CO_2 laser is a mixture of CO_2, helium and nitrogen gases, the approximate constitute is CO_2:N_2:He::0.8:1:7. Pumping is realized by AC or DC electrical discharge. First most of the electrical discharge energy is absorbed by nitrogen gas, only a small part of the energy is absorbed by CO_2 molecules directly which raise them from ground state (000) to upper state (001). Large amounts of CO_2 molecules collide with the nitrogen molecules and gain the excitation energy. Once excitation is achieved, the CO_2 molecules at (001) state will give out energy and jump to lower energy state (100) or (020), thus giving out laser light at frequency 10.6m m or 9.6 m m respectively. The remaining decay from state (100) to (010), (020) to (010) or (010) to ground state (000) will dissipate energy in the form heat instead of light.

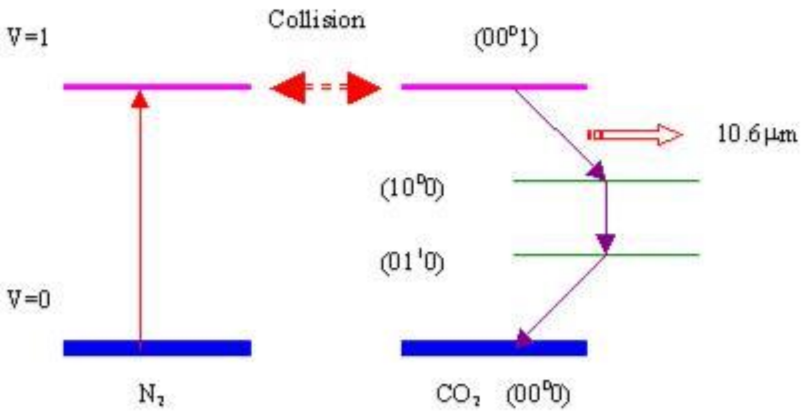


Figure 2.4: CO_2 laser energy level

Helium gas has high thermal diffusivity, while the thermal diffusivity of CO_2 is low. This combination makes CO_2 gas to have high lasing efficiency compared with other lasing materials and in the same time, the system also has good thermal diffusivity. Thus the role of helium is evident. The cooling of the carbon dioxide gas mixture becomes very important for the stable operation of CO_2 lasers, there are three basic cooling designs.

Slow Flow Lasers:

At too high temperatures, the lower energy levels of CO_2 molecules inside the laser can not be emptied to ground level fast enough, population inversion condition might be disturbed, and lasing might stop. Thus the lasing action is limited by a upper temperature, T_{lim}. For slow flow lasers, cooling is through the walls of the cavity, typically gas flow is about 20 l/min, coolant flow is about 7 l/min at room temperature.

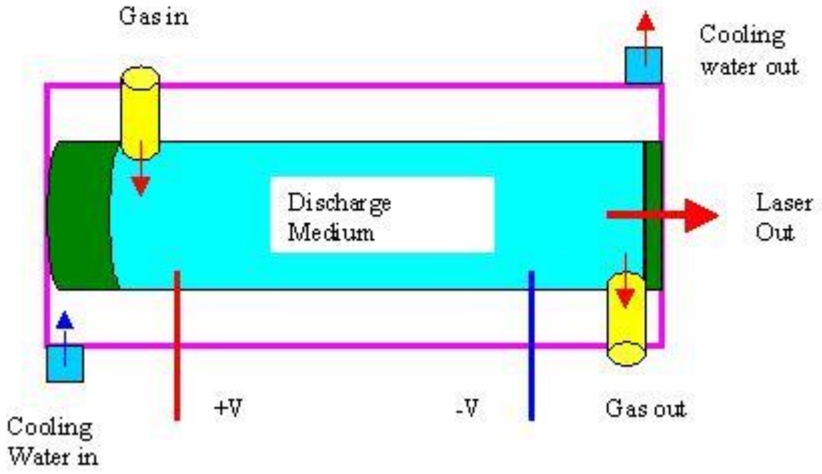


Figure 2.5: Cooling designs for CO_2 lasers

The highest power gain per unit cavity length can be computed as:

$P=4p\ h\ kL(T_{lim}-T_c)$

Where h is the energy conversion efficiency from pumping to optical, typical value 0.12; k is the heat conductivity of He, 0.14W/mK at 0 degree; L is the length of cavity, T_{lim} is the highest lasing temperature, 250° C, T_c is the coolant temperature, typical value 10° C.

For the above values, P is around 50W/m, not very high. To reach a higher power, the cavity has to be very long.

Fast Axial Flow Lasers:

Such lasers use gas convection for cooling, gas flows at the speed of 300~500 m/s through the discharge zone, the flow, discharge and optical oscillation are all along the optical axis, which favors the symmetrical power distribution of the laser beam. The typical power gain is about ten times more than the slow flow lasers. The output power is also decided by the cooling efficiency.

Transverse Flow Lasers:

The axial convection cooling is good for symmetrical beam energy distribution, but the transverse flow design is more effective, thus compact high power lasers are designed in this way. The disadvantage is the lack of symmetry.

There are many other flow patterns, for example, using spiral flow around the cavity. Since the flow pattern has so close relation with the quality of lasers, this area is a big concern in laser design.

Solid State Lasers

In solid state lasers, ions are suspended in crystalline matrix to generate laser light. The ions emit electrons when excited, the crystalline matrix spread the energy among the ions. The first solid state laser is ruby laser, but it is no longer used because of its low efficiency. Two common solid state lasers are Nd:YAG lasers and Nd:glass lasers, there structures are very similar. Both use krypton or xenon flash lamps for optical pumping.

For Nd:glass lasers, the glass rod has the advantage of growing into larger size than YAG crystals, but the low thermal conductivity of glass limits the pulse repetition rate of Nd:glass laser. So Nd:glass lasers are used in applications which require high pulse energies and low pulse repetition rates. It is suitable for hole piercing and deep keyhole welding operations.

YAG crystal has a higher thermal conductivity than glass, so the thermal dissipation in Nd:YAG laser cavity can be improved, operation power can be up to several hundred watts in continuous mode, and high pulse rates (50kHz) can be reached. YAG is a complex crystal of Yttrium-Aluminium-Garnet with chemical composition of $Y_3Al_5O_{12}$, it is transparent and colorless. About 1% Nd^{3+} ions are doped into the YAG crystal, the crystal color then changed to a light blue color. The wavelength of Nd:YAG laser is 1.06m m.

Solid state lasers are widely used in laser machining.

Note: the following is the construction of our Q-Switched Nd-YAG laser. For a common Nd:YAG laser, QWP, QS, GL-C, UV-C are not included. The signs in the picture are as follows. Circ:circuit board; RM:rear mirror; QWP:Quarter wavelength plate;QS:Quick switch;Ap/Sh:aperture and shutter;T-S:temperature test sensor; L-C,UV-C:green light crystal and UV light crystal; FM:front mirror.

Click on the figure to listen to a brief description on it.

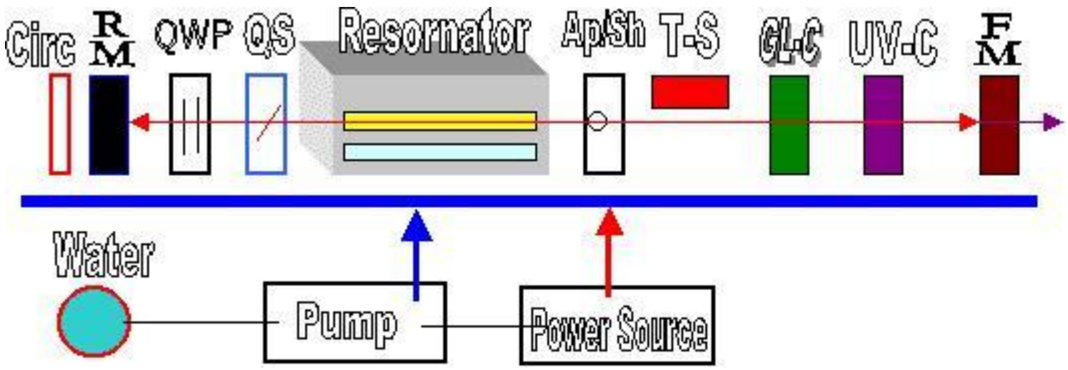


Figure 2.6: Construction for our Q-Switched UV Nd-YAG laser

Liquid Lasers

Liquid Lasers use large organic dye molecules as the active lasing medium. These lasers can lase in a wide frequency range, i.e. they are frequency tunable. The spectral range of dyes covers infrared, visible and ultraviolet light. Pumping is by another pulsed/continuous laser, or by pulsed lamp. These lasers are used in spectroscopic investigation and photochemical experiments.

UNIT 4 – INDUSTRIAL APPLICATION OF LASERS

There are literally thousands of references on the theory and practical uses of lasers. They are used in everything from portable CD players to sophisticated weapons systems. The term LASER is an acronym for "Light Amplification by Stimulated Emission of Radiation," and is defined as "any of several devices that emit highly amplified and coherent radiation of one or more discrete frequencies." At Northeast Laser & Electropolish, we utilize pulsed Nd:Yag (Neodymium-Doped Yttrium-Aluminum-Garnet) type lasers for welding. The Nd:Yag rod, when stimulated by a flash lamp, emits light in the ultraviolet range with a wavelength of 1.06 microns. This light is then focused and delivered to the workpiece, where the high energy density beam is used to weld.

Interferometric Methods

Laser-based distance measurements can be done using interferometric principles. Measurements of length using optical interferometry have been performed since the 19th century. But the limited intensity and coherence of conventional light sources restricted the measurements, which were difficult and suitable for used only over distances of a few centimeters. The development of lasers removed these restrictions. Lasers have allowed interferometry to develop into a fast, highly accurate and versatile technique for measuring longer distance.

Interferometric measurement of distance can be highly accurate. It offers a higher degree of precision than the pulsed time-of-flight or beam-modulation telemetry methods. However, it is best suited to measurements made in a controlled atmosphere (for example, indoors) over distances no greater than a few tens of meters.

Most laser-based interferometric systems for measurement of distance use a frequency-stabilized helium-neon laser. An unstabilized laser, operating in a number of longitudinal modes, will have a total linewidth around 10^9 Hz. This spread in the frequency (or wavelength) will cause the interference fringes to become blurred and to lose visibility as the distance increases. An unstabilized laser is suitable for measurement only over distances of a few centimeters. Stabilized lasers, usually in a temperature-controlled environment and operating in a single longitudinal mode, are used for longer distances.

We describe first the operation of a system based on the Michelson interferometer, because it is easy to understand the basic principles of interferometer distance measurement with reference to the Michelson interferometer. Later we will describe variations that provide better stability under conditions of atmospheric turbulence.

Figure 15 shows the basic configuration for a Michelson interferometer. Review Course 5 on interference if necessary to understand the formation of an interference pattern. The beam from the laser falls on a beam splitter that reflects half the beam in one direction (the reference arm) and transmits the other half (the measurement arm). The two beams are each reflected by mirrors, a stationary mirror in the reference arm and a movable mirror in the measurement arm. In practice the mirrors are often cube corner reflectors (retroreflectors) which offer better stability against vibrations than conventional flat mirrors.

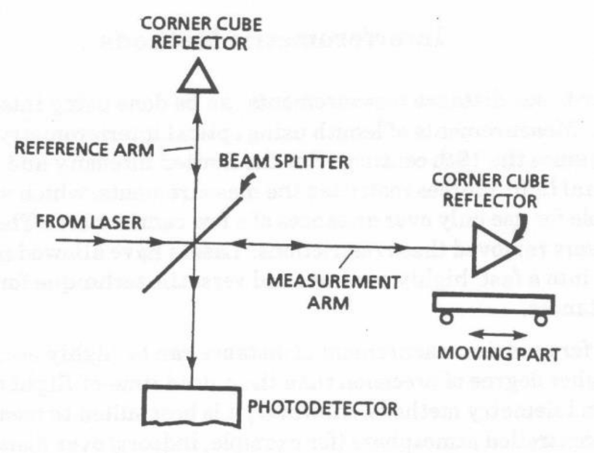


Fig. 15

Schematic diagram of the application of a
Michelson interferometer to measurement of distance

The two reflected beams are recombined at the beam splitter to form an interference pattern that is viewed by an observer or measured by a recorder such as a photodetector. The character of the fringes is related to the different optical path lengths traveled by the two beams before they are recombined.

Suppose, for example, that the detector is viewing a bright fringe in the interference pattern when the movable mirror is at a certain position. If the movable mirror moves a distance equal to 1/4 of the wavelength of light, the round-trip distance traversed by the light in the measurement arm will change by 1/2 wavelength, and the fringe pattern will change so that the detector now views a dark fringe. The distance mesurement thus consists of counting the number of fringe variations as the mirror moves. Each complete fringe corresponds to a phase variation equal to 2p . The variation in phase d is determined by using the equation

$$d = 4p\ D\ X/l$$

where l is the wavelength of the light, and D X is the distance that the movable mirror has moved. It is apparent that this method offers high precision, allowing measurements of D X to be made with an accuracy of the order of a fraction of the wavelength of light.

(55)The maximum distance D X that can be measured in this way is given by:

$$D\ X_{MAX} = C/D\ V$$

WHERE, C = velocity of light.
D V = linewidth (i.e., spread in frequency) of the laser.

This equation shows the importance of using a frequency-stabilized laser with a small line width.

Note also that this measurement is a relative measurement which gives the distance that the mirror has moved from its initial position, rather than an absolute positional measurement.

Example D: Distance Measurement in a Michelson Interferometer	
Given:	A HeNe laser 50 cm long with two longitudinal modes is used to measure distance in a Michelson interferometer. 2200 fringe changes are observed (bright to dark to bright) as the movable mirror is moved.
Find:	The distance the mirror moved. The maximum distance that could have been measured.
Solution:	Each fringe corresponds to a change in phase of 2p . So the total change in phase d is 2200 2p . Using Equation 20: 2200 2p = 4p D *X*/l or D *X* = 2200 l /2 = 2200 ? 0.6328 ? 10^{-4}/2 = 0.0696 cm In a laser, the longitudinal mode spacing is *C*/2*L* where *L* is the length of the laser. So, a two-mode laser will have a linewidth D *V* equal to *C*/2*L*. Using Equation 21, we have: D X_{MAX} = $\frac{c}{\Delta\nu}$ = $\frac{c}{c\,/\,2L}$ = 2*L* = 2 ? 50 = 100 cm.

The distance measured in an optical measurement is the optical path, which is the physical path multiplied by the index of refraction of the air through which the measurement is made. Since the index of refraction is close to unity, in some cases (for example, military ranging) it is not necessary to correct for variations in the index of refraction. But in interferometric measurements requiring a high degree of precision, one must correct for changes in the index of refraction that occur as a result of changes in air pressure, temperature, and so on. The index of refraction of dry air at a pressure of 760 Torr and a temperature of 15? C is 1.0002765 at the helium-neon laser wavelength. As conditions in the air change, the index of refraction changes. It increases by:

? 0.36 part per million for an increase of 1 Torr in atmospheric pressure.
? 0.96 part per million for an increase of 1C in temperature.
? 0.06 part per million for an increase of 1 Torr in the partial pressure of water vapor.

So, a measurement system that requires high precision must include sensors for measurement of air temperature and pressure (an perhaps relative humidity) and a means (often an automated computer-based means) for correcting for the variable atmospheric parameters.

LASER DOPPLER VELOCITY

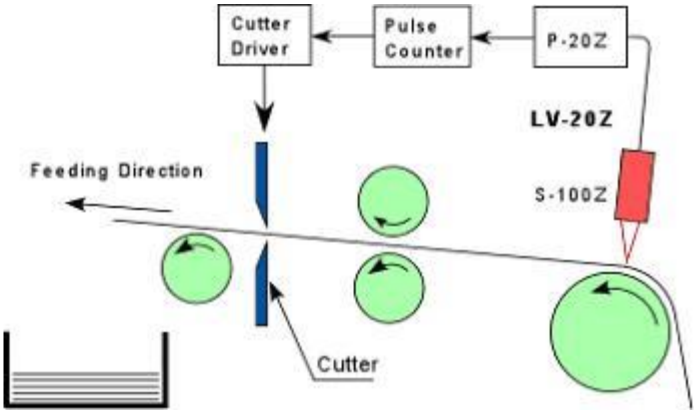
High-Precision, Compact, Low Cost, Next Generation of Non Contact Laser Doppler Velocimeters

Canon laser Doppler velocimeters, equipped with diffraction gratings, take advantage of an optical (diffraction laser light Doppler method) that will not dependent on the laser wavelength. Therefore measurement precision is unaffected by fluctuations in the semiconductor laser wavelength due to c in temperature. Not only are these sensors environmental stability they can be used for a wide applications; since we use an E/O frequency shifter, they are capable of taking measurement from a still as a running state.

THEORY by movie

LV-20Z, LV-50Z

Application example for non-contact length measurement.



Laser Tracking:

Detecting the 3D state vector of a space object remains a key issue for aerospace and satellite navigation. The solution for this problem is sought in both radio (RADAR) and optical spectral domains (LADAR), but the latter is more attractive as it provides better resolution due to the shorter wavelengths involved. In both cases, a critical problem is the low level of the return signal from the remote target. In addition, atmospheric turbulence is a significant factor that reduces signal fidelity for LADAR.

Compensation of atmospheric turbulence can be achieved by introducing perturbations in the wavefront of the propagating beam exactly opposite to those introduced by the torellence.

This compensation of the perturbations may result in an increase of the power density on the target and therefore in the returned signal intensity, leading to an improved system Resolution and improved tracking efficiency.

To meet these requirements, Metro Laser is developing several new system concepts with operating principles based on the unique features of reflection by optical phase-conjugation (OPC), which allow us to maximize the return signal from a target .

For operation of a LADAR system with OPC, it is essential to ensure mutual coherence between the signal and at least one of the pumping beams. For the Four Wave Mixing (FWM) scheme of OPC, this condition implies that the pumping beams should have temporal coherence equal to the time required for a round trip from the LADAR to the target.

We have demonstrated that a coupled-cavity configuration [1, ,] (see Figure 1) automatically solves the problem of mutual coherence between the pump (1,2) and signal (3) beams. As a result, the laser operates using the target (mirror M3) as the output coupler.

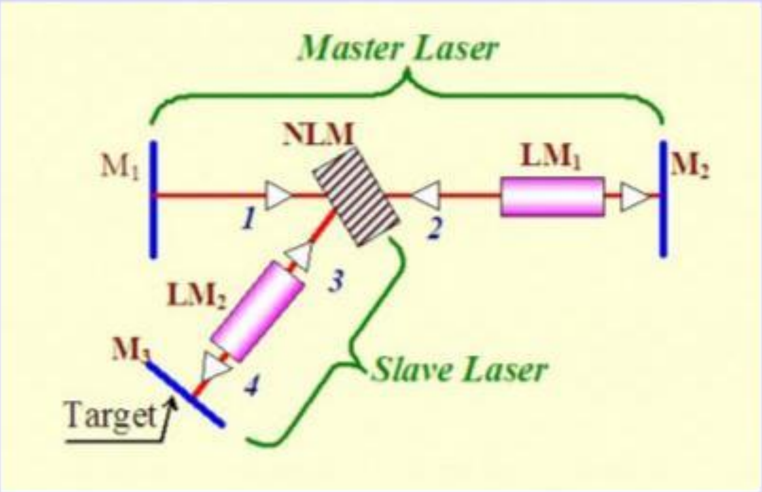


Figure 1 - Scheme of the coupled-cavity laser system with phase conjugation. M1,2 mirrors of the master laser. Target is described by mirror M3. LM1,2 are the laser media in the master and slave leg, respectively. NLM is the nonlinear medium of the FWM OPC Mirror, which uses the beams 1 and 2 as the pump source. Beam 3 is the signal beam and 4 is the PC beam.

When the target is moving, the laser automatically back-traces the angular position of the target due to the changing direction of beam oscillation in the slave laser (Figure 1). Measurement of angular characteristics of this direction and its variation give us the Angular position of the target.

Measurement of the time-delay of laser beam propagation and its frequency shift due to the Doppler effect allow us to determine the range and velocity of the target.

The actual implementation of systems based on this idea is of course quite complex (a field prototype may be seen below), involving an array of sophisticated subsystems, but MetroLaser is meeting this challenge and taking the once largely academic field of non-linear optics into the real world to meet real aerospace needs.

Delivery of Laser Energy

There are two ways that the laser beam is delivered to the workpiece. The first involves the use of "hard optics," and the second involves the use of a fiber optic cable. "Hard optics" basically means that the laser beam is deflected and focused through the use of mirrors and lenses only. This method has practical limitations in the distance of the workpiece from the laser source and dictates that it be moved into the correct position and angle to perform the weld. This type of workstation is ideal for many small or delicate items that require manual or single "spot" welds. The second delivery method involves the use of a fiber optic cable. The laser energy can be focused into one end of the cable and emerge at the other end (tens of meters away), with a minor loss of energy. The beam can then be "collimated" and refocused onto the workpiece. This method allows for the beam to be delivered precisely to the needed area, and even allows for movement of the focusing optics instead of, or in addition to the workpiece itself. At Northeast Laser, we have both "hard optics" and fiber delivered laser systems to suit just about any application.

Welding with Laser Energy

Up to the point that the laser beam contacts the workpiece, all the components that direct it are either transparent, refractive or reflective, absorbing only small amounts of energy from the ultraviolet light. The laser power supply is capable of delivering a "pulse" of light that has accurate and repeatable energy and duration. When the "pulse" of laser energy is focused into a small spot (adjustable anywhere from approximately 0.1 to 2.0 mm in diameter) onto the workpiece, the energy density (energy/area) becomes quite large. The light is absorbed by the (metal) workpiece, causing a "keyhole" effect as the focused beam "drills" into, vaporizes and melts some of the metal. As the pulse ends, the liquefied metal around the "keyhole" flows back in, solidifying and creating a small "spot" weld. The entire process takes only milliseconds. The laser has the ability to fire many pulses per second, and moving the workpiece or optics allows anything from separate "spot" welds to a series of overlapping "spot" welds to create a "seam" weld that can be structural and/or hermetic.

Similarities and Differences to Other Welding Processes

When compared to other welding processes, laser welding has some similar as well as some unique characteristics Like GTAW (Gas Tungsten Arc Welding), laser welding is a fusion process performed under inert cover gas, where filler material is most times not added. Like electron beam welding, Laser welding is a high energy density beam process, where energy is targeted directly on the workpiece. Laser differs from both GTAW and EB (electron beam) welding in that it does not require that the workpiece complete an electrical circuit. And since electron beam welding must be performed inside a vacuum chamber, laser welding can almost always offer a cost advantage over EB in both tooling and production pricing.

Advantages of Laser Welding

One of the largest advantages that pulsed laser welding offers is the minimal amount of heat that is added during processing. The repeated "pulsing" of the beam allows for cooling between each "spot" weld, resulting in a very small "heat affected zone". This makes laser welding ideal for thin sections or products that require welding near electronics or glass-to-metal seals. Low heat input, combined with an optical (not electrical) process, also means greater flexibility in tooling design and materials.

Joint Types and Tooling Concerns

Whether through part design, tooling design, or a combination of both, one of the most important factors for a successful laser weld is that components be held in intimate contact along the weld area. The ideal weld joint should have no gap between components. This is especially true in a lap weld joint configuration. Even the slightest space between parts can be the difference between a consistently strong weld, and no weld at all. Butt or seam weld joints are slightly more tolerant, where successful welding can be performed with up to 0.025mm (0.001 inch) separation, and in some cases (depending on section thickness and joint design) with gaps as large as 0.05mm (0.002 inch). Fillet welds can also offer challenges, especially when welding two parts at a 90-degree angle. Since laser welding is most often done without the benefit of filler metal, the material that forms the fillet must be "drawn" from the two sections being welded. This can often cause stress cracking that starts at the toe of the weld and propagates through the joint, causing weakness or creating a "leak path" through joints that need to be hermetic. There are several weld joint design features that should be avoided/exploited in order to ensure a consistent weld in production situations. The engineers at Northeast Laser are available to discuss these various features and suggest which ones may be suited to your application.

Materials Overview

Although laser welding is applicable to a large range of both ferrous and non-ferrous metals, there are some materials and combinations of materials that perform better than others. For instance, 304 and 304L series stainless weld extremely well, while 303, 316, and 316L stainless are crack-sensitive. Since 303 stainless is often used because of its machine ability, it is sometimes possible to make one component from 303, and the (less complex) mating component from 304L. The resulting alloy is usually less sensitive to cracking during welding. The laser process can also be applied to titanium, kovar, copper and certain aluminums, though copper and aluminum require much more energy due to their reflective and heat transfer characteristics. Laser welding can be used to join dissimilar metals as well, such as copper to stainless, or stainless to certain types of phosphor bronze. There are many combinations that work well, while others should be avoided.

UNIT 5 – HOLOGRAM AND MEDICAL APPLICATIONS

Introduction:
In everyday life we see everything in 3-D, and we accept it as obvious.

However, when we look at a hologram which show a 3-D image of something, we are impressed.

Holography enables looking at a 3 dimensional scene, where the perspective and parallax are kept as in real life. (Parallax is the relative position of the bodies in the picture as seen from different points of view).

The medium on which the 3-D image is recorded is called "Hologram"

The name Hologram comes from the Greek language, and means "whole message (picture)".

Looking at a hologram from different angles, show different perspectives of the scene.

All the information on the 3 dimensional scene is retained in the hologram.

Hologram is based on interferometry.

What is recorded on the hologram is not the image (as in standard film photography), but the interference pattern created by the waves from all parts of the bodies in the scene.

Interference pattern is created between two beams of light (waves) occupying the same place in space at the same time.

Holographic nondestructive testing techniques (HNDT) are used to locate and evaluate cracks, disbonds, voids, delaminations, inhomogeneity and residual stresses in a test sample without destruction of the sample. The holographic interferometry techniques are

Applied for nondestructive testing of materials.

The HNDT techniques can be used for the testing of laminated structures, turbine blades, solid propellant rocket motor casings, tyres and air foils. These techniques are also useful in medical and dental research. In HNDT techniques, the test sample is interferometrically compared with the sample after it has been stressed (loaded). A flaw can be detected if by stressing the object it creates an anomalous deformation of the surface around the flaw. The holographic interferogram will show up the anomalous deformation by an abrupt change in the shape of the interference pattern.

The object can be stressed by mechanical stressing, pressure or vacuum stressing, thermal stressing, vibrational stressing and magnetic stressing. The stressing of the object can create gross deformation and rigid body motion of the object. This will produce fine interference fringes in the interferogram if the test area is large. In such a situation, the interference fringes around the flaw will be very fine and it would not be detected by unaided eye. By using fringe control methods, the effects of gross deformation and rigid body motion can be compensated.

Applications of holographic interferometry

Field	Applications
Aerospace	Defect in In honeycomb plates testing of construction materials Testing of welding methods Inspection of rocket bodies Flow visualization in wind tunnels Vibration modes of turbine blades
Automobiles	Testing of oil pressure sections testing of welding methods Research in construction of automobile bodies Construction of engines
Machine tools and precision instruments	Measurement of deformations of machine parts, jigs And tools Measurement inside cylinders Measurements of stiffness (heat, static or dynamic) Analysis of construction of instruments and tools
Electrical and electronic industries	Vibration modes of turbine blades, motors, transformers, loudspeakers testing of Welding and adhesion Testing of circuit parts Analysis of audio equipments Leak test of batteries
Civil Engineering	Analysis of constructions Design of pipes Research in concrete.
Chemical industry	Measurement of mixed fluids. Tyre, rubber and NDT Of tyres, plastics Testing of molded products Measurement of adhesion defects

Medicine	Measurement on living bodies Chest deformation due to inhalation Measurement on teeth and bones Testing materials for dental surgery Testing of urinary track
	Measurement on eyes, ears, etc.
Musical instruments	Measurement of vibration modes
Cultural articles and paintings	NDT and restoration.

Medical Uses of Lasers :

The highly collimated beam of a laser can be further focused to a microscopic dot of extremely high energy density. This makes it useful as a cutting and cauterizing instrument. Lasers are used for photocoagulation of the retina to halt retinal hemorrhaging and for the tacking of retinal tears. Higher power lasers are used after cataract surgery if the supportive membrane surrounding the implanted lens becomes milky. Photodisruption of the membrane often can cause it to draw back like a shade, almost instantly restoring vision. A focused laser can act as an extremely sharp scalpel for delicate surgery, cauterizing as it cuts. ("Cauterizing" refers to long-standing medical practices of using a hot instrument or a high frequency electrical probe to singe the tissue around an incision, sealing off tiny blood vessels to stop bleeding.) The cauterizing action is particularly important for surgical procedures in blood-rich tissue such as the liver.

Lasers have been used to make incisions half a micron wide, compared to about 80 microns for the diameter of a human hair.

Medicine has two prime objectives; first to detect disease at an early stage before it becomes difficult to manage and second, to treat it with high selectivity and precision without any adverse effect on uninvolved tissues. Lasers are playing a very important role in the pursuit of both these objectives. Due to their remarkable properties, lasers have made possible ultraprecise, minimally invasive surgery with reduced patient trauma and hospitalization time. The use of lasers in surgery is, by now, well established and spans virtually the entire range of disciplines: ophthalmology, gynaecology, ENT, cardiovascular diseases, urology, oncology, etc. The use of lasers for biomedical imaging and diagnostics and for phototherapy using photoactivated drugs is receiving considerable current attention and is expected to have profound influence on the quality of health care. Laser spectroscopic techniques have the promise to provide sensitive, *IN SITU*, near real time diagnosis with biochemical information on the disease. These developments have the potential to change the way medical diagnosis is presently perceived.

Instead of a means of solving an already known clinical problem, the diagnosis may in future screen people for problems that may potentially exist. Further, any potential risk factor so detected can be corrected with high selectivity by the use of drugs that are activated by light. Because these drugs are inert, until photoexcited by radiation with the right wavelength, the clinician can target the tissue selectively by exercising the control on light exposure (only the tissue exposed to both drug and light will be affec-ted). A good example is the fast-developing photodynamic therapy of cancer. There are indications that selective photoexcitation of native chromophores in the tissue may also lead to therapeutic effects.