David.R.Gilson

OPTICAL COMMUNICATIONS

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Reading

"An Introduction to optical fibres" (Cherin), McGraw Hill, (out of print now).
"Fibre Optic systems" (P Halley), Wiley

Introduction

It was recognised about 30 years ago that the high frequency of optical light signals allowed a huge bandwidth for the transmission of information. Optical communications has the asset of a very high carrier frequecnies (around 3.10^{14} Hz). This allows wide bandwidth, high information rate communications.

Fig one
(schematic system)

The schematic system is bascially a transmitter transmitting to a reciever through some channel.

Transmitter
Diode laser or light emitting diode (LED)

Channel
Free space or a **fibre optic link**

Reciever
PIN (p-type, insulator, n-type) photodiode or avalanche photodiodes (APD's)

We will concentrate on the basis of fibre links. Free space propagation is limited by; attenuation, scattering, divergance loss, obscuration, etc. However, there are interests in using this for satellite to satellite communications (this tends to use high power lasers, Nd:YAG or diode laser array with beam expansion/low divergance beams.).

Fibre optic transmission

This has many attractive features:
* Low loss, high bandwidth
* Small size and light weight (devices, channels)
* Low interference with other equipment and therefore immunity from electromagnetic noise.

* Secure and safe
* Growth capability (eg capacity can be increased after commissioning).

Basic Principal of fibre

Light is trapped and propagated by total internal reflection.

fig 2

It can be shown from figure 2 that the external angle for total internal reflection to occur can be expressed as,

$$\sin(i_{ec})=(n_1^2-n_2^2)^{1/2}$$

So if $n_1>n_2$ i_{ec} is real and for $i<i_{ec}$ the beam is 'trapped'.

The *numerical aperature* of fiber (NA) is defined as $n_o.\sin(i_{ec})$ (for this there is no external index, it is air here) and is,

$$NA=(n_1^2-n_2^2)^{1/2}$$

writing,

$$n_1-n_2=dn$$

and

$$n=(n_1+n_2)/2$$

(and noting $n_1=n_2$ for telecomms fibres)

$$NA=(2ndn)^{1/2}$$

The condition that the beam comes in along one of the cross-sectional axes and passes through a central point. it is said that this condition applies to meridional rays. Rays which are not meridional rays a called *scewed rays*, (off-axis) because of the path they take around the fibre. Also note that "modes" not trapped in the core can propagate in the cladding.

fig 3

These however, are usually rapidly damped by the jacket.

Loss

Loss in the fibre limits transmmission range (ie signal/noise drops) and has it's origin in:

I. Material absorbtion (intrinsic to the pure material).
   A) Ultraviolet absorbtion tails ('wings').
   B) Infrared absorbtion tails.
   SiO_2 (fused silica) wins out because UV absorption (8.9 eV) is at a short wavelength and infraed (fundamental 8 μm) is a long wavelength.

II. Absorption due to impurities that are deliberatley added (they are added so that $n_1>n_2$) or undesirable impurity (OH^- "water" can severely inmfluence loss).

III. Rayleigh scattering (intrinsic, unavoidable. Thermal fluctuations from manurfacture are frozen into the fibre which cause density fluctuations, which changes the refractive index).

IV. Waveguide and microbending loss.

The loss (attenuation) coefficient is written as,

$$\alpha=Sum(\alpha_i)+C(lambda)+B+A/lambda^4 \text{ (per unit area)}$$

The first term comes from intrinsic absorption and deliberate dopants. The second term is impurities, the third term is waveguide/microbending and the last term is from Rayleigh. We can also say,

$$P_{out}=P_{in}.\exp(-\alpha L)$$

Expressing this is dB per unit length,

$$10.\log_{10}(P_{out}/P_{in})=10.L\alpha.\text{Log}_{10}(e) \text{ (dB)}$$
$$dB/L=4.3\ .\alpha$$

(See sheet about loss). There is an advantage working at 1.3 and 1.5 μm

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<u>Loss comparison with other transmission techniques.</u>

fig 1

See fig one for a comparison between co-ax, twisted pair and optical fibre for losses for varying frequencies. What can be seen with this plot is that the capacity of fibre can be raised without a loss penalty, unlike electrical conduction transmission.

Glasses for fibres

There are two types of glass of fibres. HIGH SILICA GLASS, which is SiO_2 plus doped SiO_2. Common dopants can be GeO_2, P_2O_5 or B_2O_3. The other type of glass (which is not used in telecommunications (because of lower transmissions)) is silicate Borosilicate/soda lime glass.

Manufacture

The "preform" is produced with a higher index centre and lower index on the outside, e.g. using modified chemical vapour deposition (MCVD) (see sheet).

The tube of preform is coated with "glass" inside as the various silicate vapours are passed into it. The torch finally collapses the tube producing the doped preform. The preform is then heated and pulled to make a fibre. Material compatibility issues are very important. They have to be mechanically, thermally and optically similar. For example if one index region expanded more with temperature than another index area it would crack away.

As the new "pulled" fibre is formed, it is accreted with a plastic *jacket* to protect it from surface damage/imperfection.

To form multigradred preform the manufacture process is the same but the rate of dopant addition can be changed with respect to time. This means we can have a distrobution of index, linear or non-linear.

Modes

The ray approach is valid for large fibre core diammeters, but we need wave theory for low diammeter cores with the diammeter at the same order as the wavelength. We will look at propagation using Maxwell's equations with appropriate boundary conditions.

See "Modes in a slab dielectric waveguide" Sheet

Points

(See sheet mentioned above)
(1) Only discrete set of propagation constants are allowed. i.e. discrete set of 'modes' (field configurations).
(2) For $\underline{K}d<=pi/2$ then only one mode propagates (TE_o), this condition requires,

$$k_o d(n_1^2-n_2^2)^{1/2}<=pi/2$$

i.e. single mode slab waveguide

(3) The number of modes is proportional to,

$$R=k_o d(n_1^2-n_2^2)^{1/2}$$

(a quantity for fibres called the V number is calculated in a similar way.)

(4) Near cut-off for a mode, y->0, Therefore damping is weak and radiation spreads further and further into the cladding.

Explanation ?

Consider the equation for propagation in the slab (or the core of the fibre),

$$E_y(x,y,z)=A.\cos(\underline{k}x).\exp(-j\beta z) \text{ (in slab)}$$
$$=A((\exp(j\underline{k}x)+\exp(-j\underline{k}x))/2).\exp(-j\beta z)$$
$$=(A/2)[\exp(j(kx-\beta z))-\exp(-j(kx+\beta z))]$$

This shows us plane waves propagating with components ±k with with respect to x axis and ß along z axis.

fig 2

From fig2, **tan(theta)** is discrete because k is discrete. The planewaves interfer to produce modes with discrete constants.

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(continued from "Modes in a slab dielectric waveguide" Sheet)

$$2.(2d/lambda_o)(n_1^2-n_2^2)^{1/2}<=1 \text{ (m=1)}$$

multiply by pi

$$2pi(2d/lambda_o)(n_1^2-n_2^2)^{1/2}<=pi \text{ (m=1)}$$
$$=k2d(n_1^2-n_2^2)^{1/2}<=pi$$
$$=kd(n_1^2-n_2^2)^{1/2}<=pi/2$$

Satisfy this and get one mode : single mode slab optical waveguide.
Similar arguments apply to circular cross section fibres where the v-number is defined.

$$v=(2pi/lambda_o)a(n_1^2-n_2^2)^{1/2}$$

Where a is the core radius.
A fibre will support one mode if,

$$v=(2pi/lambda_o)a(n_1^2-n_2^2)^{1/2}<=2.4$$

Then only one mode will propagates (EH_{11}). This is a single mod fibre.

Fibre Bandwidth

This is important for fibre comunnications. Short pulses of digital information can be broadened by three mechanisms;

1) MODAL DISPERSION: Different modes have different group velocities.

2) MATERIAL DISPERSION: Index varies with the wavelength.

3) WAVEGUIDE DISPERSION: Guide is dispersive for single mode (theta is a functio of n)

1) Modal dispersion

fig 1

Transit time for LO mode,

$$t_{LO}=L/v=n_1L/c$$

Transite time for HO mo,

$$t_{HO}=L'/v=n_1L/(c.sin(theta_c))$$

Differencce in transit times,

$$dT=tHO-tLO=(n_1/c)\{(1/sin(theta_c))-1\}\ L$$

but,

$$sin(theta_c)=n_2/n_1$$

Hence,

$$dT/L=(n_1/c)((n_1-n_2)//n_2)$$

or taking,

$$1/dT=d\upsilon$$

(bandwidth)

Then,

$$L.d\upsilon=cn_2/(n_1(n_1-n_2))$$

(usually quoted in GHz.km). This increases as n_1-n_2 decreases.

EG,
n_2=1.46
n_1=1.48 (step index)
Then, $d\upsilon$.L=1.47*10^7 Hz.km = 0.0147 GHz.km. i.e. pulse sprading is approximately 67ns/km.

GRADED INDEX (GRIN) fibre attempts to overcome modal disperion by equalising mode optical paths.

fig 2

The optical path remains constant for all mode paths beause the lowest order path has the highest index and higher paths have lower indicies, which causes all modes to propagate at the same average speed (hence taking the same time to travel down the fibre). The properties of the graded fibre causes modes to be periodically focus and defocus along the path. All this gives ***low modal dispersion***. Another advantage of this is that we get a fibre large apperature with good light collection which is multimode capable. As a side note, it can be described by,

$$dT/L=(n_1(n_1-n_2)^2)/(2cn_1^2)$$

Eg,
n_1=1.48
n_2=1.46
$d\upsilon$.L=2.2*10^9 Hz.Km
=2.2 GHz.Km
Therefore, pulse spreading is of the order 450ps/Km

Note, for single-mode fibre (EH_{11}) modal dispersion is of course absent. This requries that,

$$(2\pi a/\lambda_0)(n_1^2-n_2^2)^{1/2}<=2.4$$

(a is as before).
Therefore, we need small diammeter and/or small index difference (n_1-n_2=dn). If a is small it is difficult to get light into the fibre. If dn is small the manufacture is difficult to control pratically.

fig 3

Single mode fibre is favoured for "long-haul" applications.

2) Material Dispersion

Material dispersion plays a role in broadening optical pulses even for single-mode fibres. Any pulse has a finite spectral width and n is a function of lambda (n dictates how fast different wavlengths propagate). This influences the group velocity ie how information is transmitted. The group velocity,

$$v_g = \partial w / \partial k$$
$$w = 2\text{pi} f$$
$$k = 2\text{pi}/\text{lambda}$$

The *group delay* is defined as the reciprol of the group velocity (see sheet).

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Fibre Gratings

fig 1

In-fibre gratings have application in telecommunications and sensors. One technique for forming these gratings is based on producing periodic variations in in the refreactive index. This acts to reflect the guided mode in the structure ie

fig 2

Suppose the spacing is **S**
When the reflected waves add in pphase the reflected wave becomes strong because of constructive interference. This is BRAGG grating.

$$2Sk = 2\text{pi}m$$

Where m is an integer and,

$$k = 2\text{pi}/\text{lambda} = 2\text{pi}.n_1/\text{lambda}_o$$
$$S = m*\text{lambda}_o/2n_1$$

or the resonant wavelength is,

$$\text{lambda}_o = 2n_1S \text{ (for m=1)}$$

EG for S=533 nm, n_1=1.47 (fused silica) then the resonant wavelength is 1.56 μm (for near IR).

For a large number of elements (peaks in refractive index) the resonance becomes very sharp.

fig 3

Production of gratings

The periods are very small and optical techniques are needed. By exposing a photosensitive fibre to an interference patteren it is possible to induce index changes (eg, germano-silica fibre, it can be enahnced by hydrogen loading (high pressure diffusion)). The technique to carry this out is Holographic Interferometry.

fig 4

Irradiance disstrobution at **A** formed as follows;
Beam **1** propagates as,

$$E=E_o.\sin(\omega t+k\sin(theta)x-k\cos(theta)y)$$

Beam **2** propagates as,

$$E=E_o.\sin(\omega t-k\sin(theta)x-k\cos(theta)y)$$

Adding give us,

$$E_R=E_o\omega t-k\cos(theta)y)*\cos(k\sin(theta)x)$$

We know that,

$$\text{Irradience}\ \alpha\ \langle E^2\rangle$$
(time average)

Therefore,

$$E_R^2=E_o^2*4*\sin^2(\omega t-k\cos(theta)y)*\cos^2(k\sin(theta)x)$$

$$\langle E_R^2\rangle=2E_o^2*\cos^2(k\sin(theta)x)$$

So the irradence varies as $\cos^2$ along x.
The period of the peaks is given by,

$$k\sin(theta).x_p=pi$$

$$x_p=lambda/2\sin(theta)=lambda/2\sin(psi/2)$$

Where Psi is the angle between the beams.

EG, if x_p=533 nm and lambda is 244 nm. This requires that theta is 13.2 degrees (psi=26.4 degrees).

This works by shinging the laser along the side of the fibre, known as side writing. The laser can goe straight through the cladding but the plastic jacket has to be removed.

So in summary laser holographic techniques can *write* Bragg grating in fibres. The requirements are,

- Photosensitivity i the fibre
- UV laser to induce index change. eg, frequency doubles Ar^+ laser at 244 nm OR excimer laser AF at 193 nm.

Applications of fibre gratings

Communications: Wavelength division multiplexing

fig 5

From figure 5, lambda's 1,2 and 3 enter the fibre, G1 made to reflect lambda-1 and so on.

Sensors: Strain sensors are straining (stretching) fibres alters **S** and reflection of lambda changes.

Sources of optical signals

(See sheet for some schematics)

We are concerened here with; Light Emitting diodes (LEDs) and Diode Lasers. Lasers are used for most communications applications. But LED's are usuful for short distance work. Both have the advantage for being compact and making use of emission occuring due to electron-hole recombination in a forward biased PN junction semiconductor. They are low power consumption, compact solid state devices.

LEDs are incoherent emitters and LASERs are (reasonably) coherent emitters.

LEDs

(See sheet) These are surface emitters.

fig 6

Modulation can be achieved to some 100 MHz.

Fibre Coupling

Using the concept of RADIANCE ie, power per unit area per solid angle.

S = Power/(area*solid angle of emission)
S= Watts/cm^{2}sr
(sr-solid radians)
fig 7

How much power goes into the core ?. LEDs are *Butt-Coupled.*

dP(into fibre)=S * solid angle(set by the numerical apperature of the fibre) * Core area

fig 8

Sin(theta)=theta=$(n_1^2-n_2^2)^{1/2}$=NA (approx)
$\delta\omega$=pi*l^2/r^2=pi(theta*r)^2/r^2=pi*theta^2=pi*(NA)^2

Hence the core radius is Ø then area is piØ^2

dP=Spi(NA)^{2}piØ^2

If radiance, S=0.5 W/cm^2/sr and NA=0.1 and Ø=25 µm. Then dP=3*10^{-7} W into the core. This is very low and is why people prefare to goto Lasers.

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Laser Source

The main advantages stem form the characteristics of;
High radiance (W/cm^2/sr),
small emission area / high power,
small linewidth,
fast switching.

fig 1

From figure one, diode lasers behave like LEDs below a particular threshold laser and above that current it behaves like any other laser. For diode lasers, the DC bias is held at the threshold value and modulation for fast switching pushes it above the threshold for lasing events to transmit information in shor pulses.

Detectors

See sheets

Bit Error rate

See sheets

Modulation format

See sheets

Future developments

Ebrium fibre amplifiers

fig 2

Wavelength division multiplexing fibre gratings

Narrow linewidth lasers
This gives us coherent detection

Now follows some examples and revisions

Attenuation

fig 3

Signal out at D_1 is 01. μW. The cut off at 0.5 Km and measured at D_2=0.3 μW,

$$Loss=10*\log_0(0.1e-6/0.3e-6)=4.7\ dB$$
$$Loss/Distance=4.7\ dB\ /\ 0.5\ Km=9.4\ dB/Km$$

Bit Error rate (BER)

fig 4

Suppose the input power is 5 mW, and we are using a 5Km fibre at 6 dB/Km loss (we assume $ò_{RMS}$=3μA and R_o=0.4 A/W. The latter being the responsivitiy). The BER needs S/N and this needs P_o of fibre.

(1) Loss is 30dB (5Km*6dB/Km)
$$30=-10*\log_0(P_o/P_{in})$$
$$10^{-3}=P_o/P_{in}$$
Therefore,
$$P_o=5*10^{-3-3}=5*10^{-6}\ W=5\ \mu W$$

Detector signal current = ð R
=5µW*0.4A/W
I_s=2*10^{-6}
I_s/ò=0.66

This would give intollerable noise. This indicates that the length of the fibre is too great. If we reduce the length of the fibre down to 3 Km, then the loss is 18 dB.

$$-18=10*\log_{10}(P_o/P_{in})$$
$$P_{out}=8*10^{-5}\ W$$
$$I_s=8*10^{-5-5}$$
$$S/N=3.2*10^{5}/3*10^{-6}=10.66$$
$$dB=20*\log_{10}(10.66)=20.5\ dB$$

Dispersion - Example

Suppose we launch into a fibre two pulses simultaneously at different wavelengths, at 900nm and 910 nm say. But what is the time difference of the avarival at the end of the fibre ? It has been shown earlier that,

$$dT_g=-(\text{lambda}^2/c)(\partial n^2/\partial\text{lambda}^2)(d\text{lambda}/\text{lambda})$$

So,

$$\text{lambda}^2(\partial n^2/\partial\text{lambda}^2)\ @\ \sim 905\ nm$$
$$\text{lambda}^2(\partial n^2/\partial\text{lambda}^2) = 0.02$$

$$dT_g=(-0.02/3e8)(10nm/905nm)=7.3e-13\ s/m$$

For 1Km we get 730 ps (0.73ns) of spreading

end of course - thanks for reading
:-)