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1218-1

"Fiber Optics: An Introduction"

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FIBER OPTICS
An Introduction

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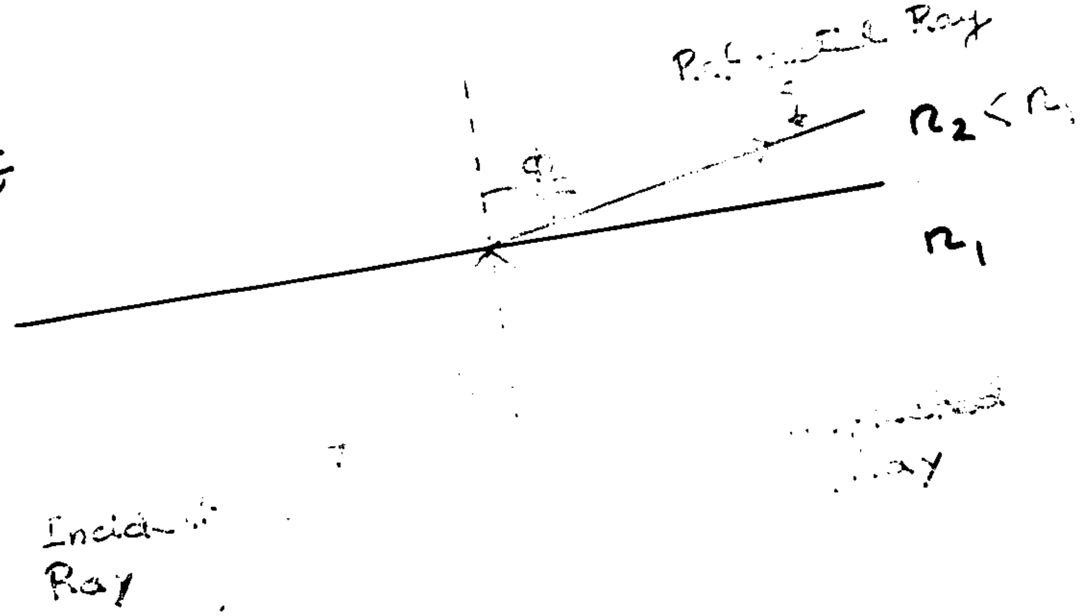
Light Frequencies (~ 10^{14} Hz) - much

- **Radio w**

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

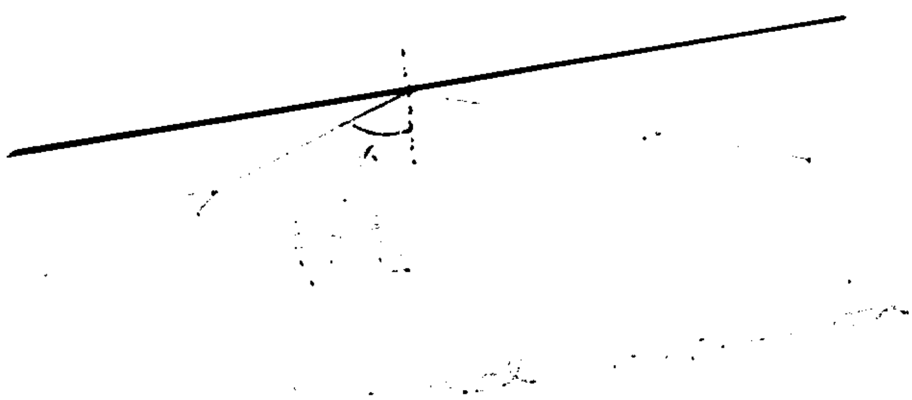


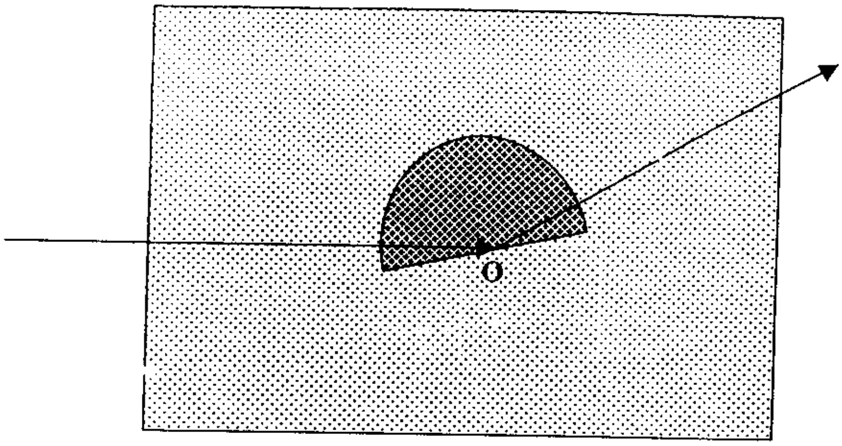
Snell's Law: $n_1 \sin \phi_1 = n_2 \sin \phi_2$

If $n_2 < n_1$

then $\phi_2 > \phi_1$

When $\phi_2 = 90^\circ$, $\phi_1 = \phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

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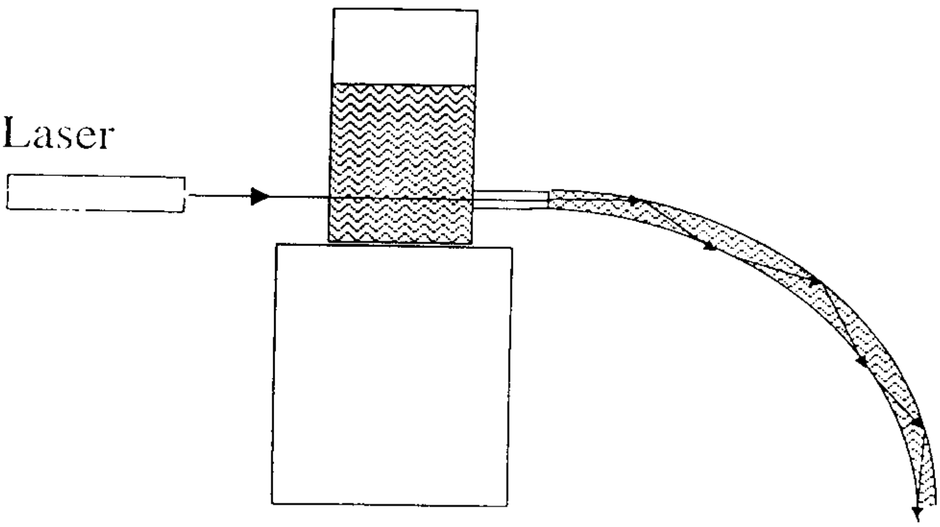
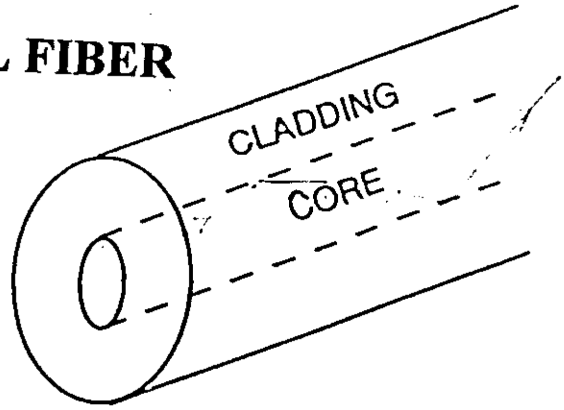
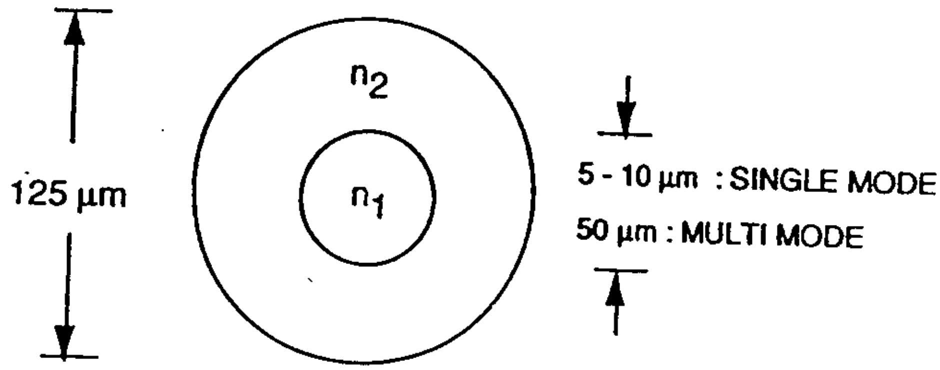

Laser

OPTICAL FIBER





MATERIAL : DOPED SILICA

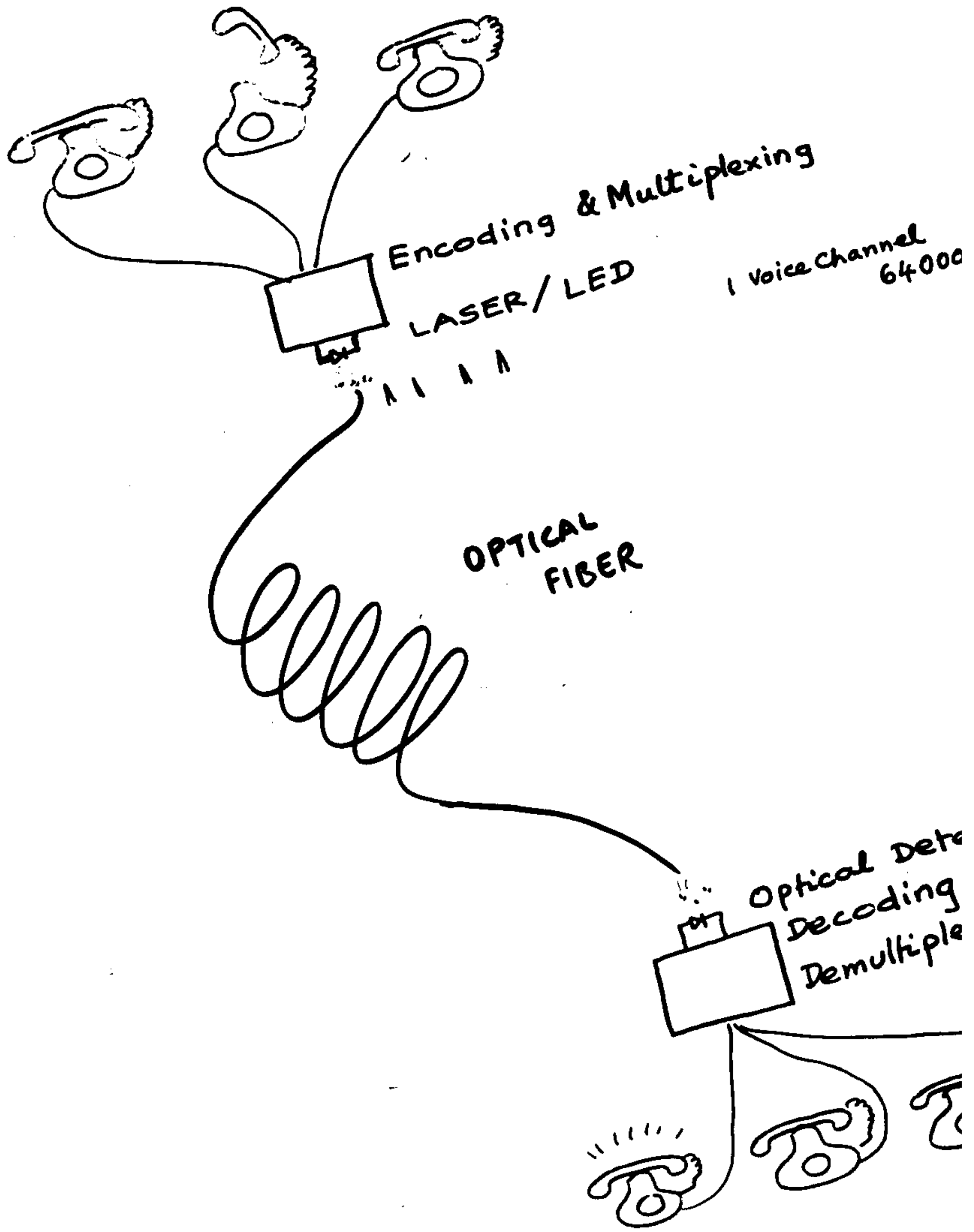
I-6

2 Gbits ⇔ 68.5

⇒ 2 M voice channel-km

x 10

I-6



Typical bit rates required

Service	Bit requirement
Telephone circuit	64×10^3 bits/s
1000 words of text	60×10^3 bits
20 Volume ncyclopaedia	3×10^8 bits
dard TV	100×10^6 bits/s
	1.2×10^9 bits/s

A typical SMF can carry

1 G bit/s for 40 km

without any repeater

To transmit 1 voice channel

$\Longrightarrow$ 64000 bits/s

Thus one fiber can carry

$$\frac{10^9}{64000} \simeq 15,000$$ voice channels for 40 km

To transmit 1 TV channel

$\Longrightarrow$ 100 M bits/s

Thus one fiber can carry

$$\frac{10^9}{100\times10^6} \simeq 10$$ TV channels for 40 km

ADVANTAGES

Very large information carrying capacity:
10 GBits / Sec over 9000 Km
= 1.4 Billion voice channels. kilometer

Very low loss

* Large repeater spacing

* With optical amplifiers 10,000 km repeater spacing possible

Light weight and low volume

Very little cross talk and secure

Little electromagnetic interference .

•

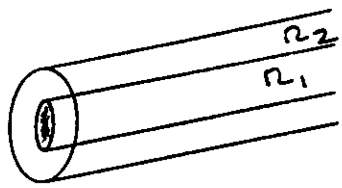
•

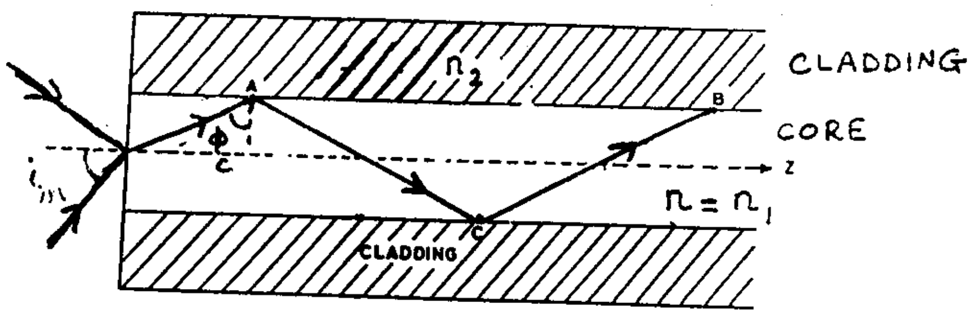
Two important characteristics of any digital communication system

LOSS

PULSE BROADENING

Numerical Aperture: NA

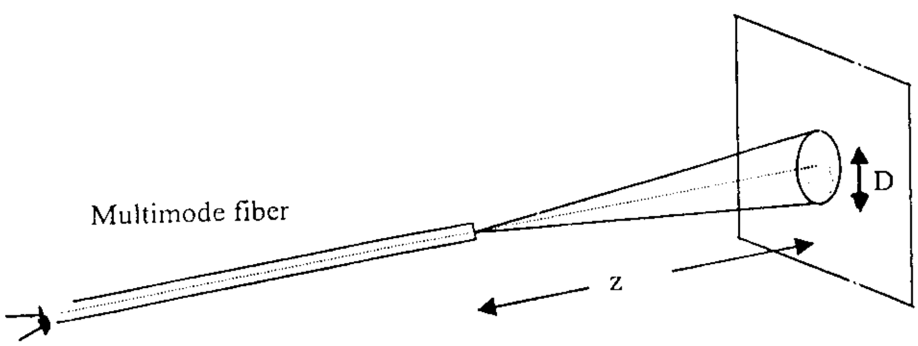


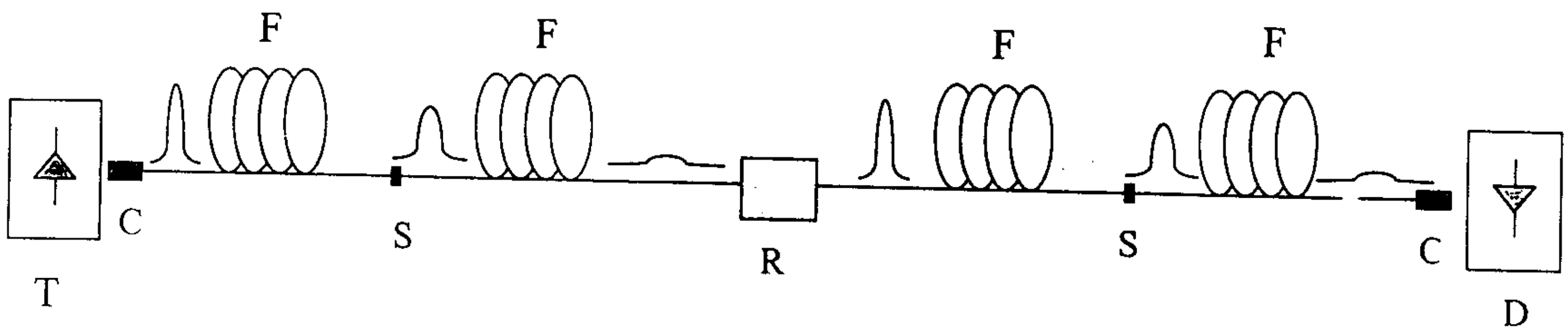


$$NA = \sin i_m = \sqrt{n_1^2 - n_2^2}$$

$n_1 = 1.48$; $n_2 = 1.46$

$\Rightarrow NA = 0.24$ & $i_m \simeq 14^\circ$





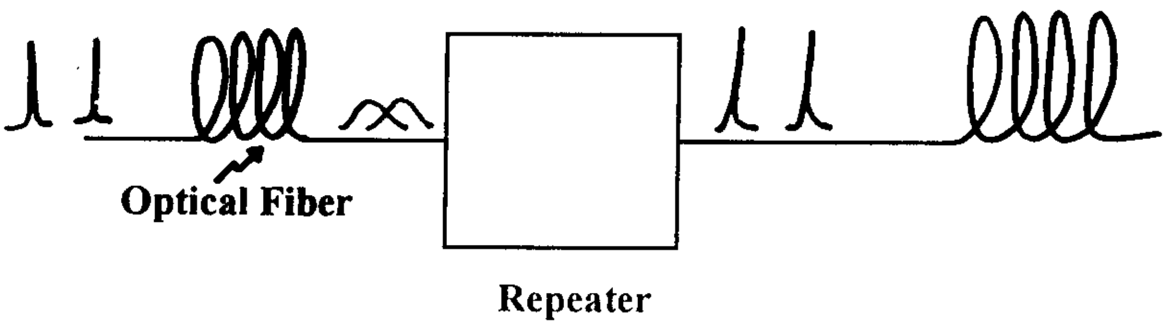
T	Transmitter
C	Connector
F	Fiber
S	Splice
R	Repeater
D	Detector

- Optical fibers have revolutionized the field of communication

- More than 80 million kilometers of fibers world wide carrying traffic

- Two important characteristics of any digital communication system

1. **LOSS**
2. **PULSE BROADENING**



To reduce cost

Repeater spacing should be large

$\Rightarrow$

Attenuation should be small

&

Pulse Broadening should be small

Loss of power in decibels

$$\alpha = 10 \log_{10} \frac{P_1}{P_2}$$

P_1: input power
P_2: output power

If $P_2 = \frac{1}{2} P_1$

$\Rightarrow \alpha = 10 \log 2 \approx 3$ dB

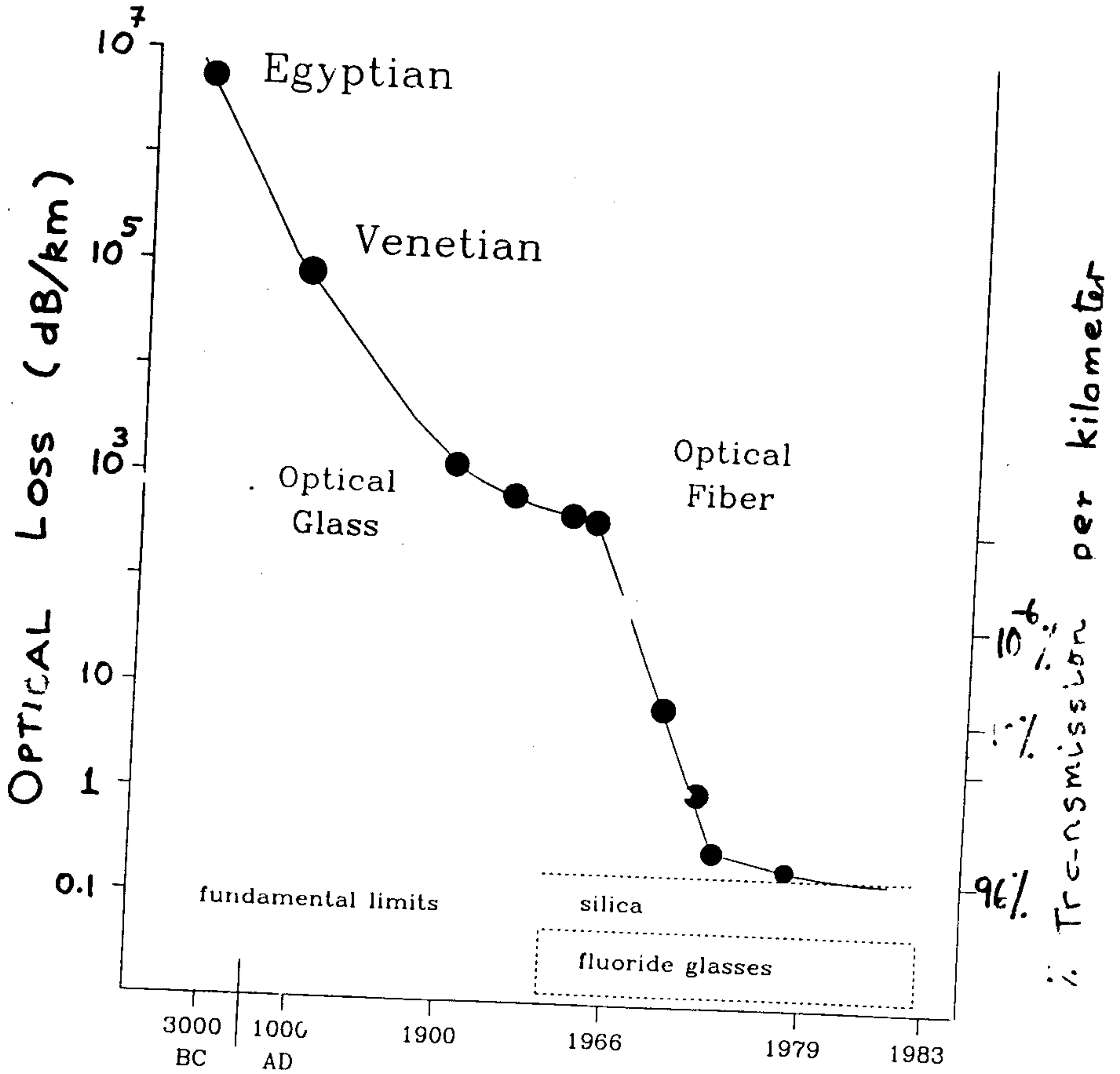
$\Rightarrow$ 3 dB loss ≡ 50% Power loss

If $P_2 = \frac{1}{1000} P_1$

$\Rightarrow \alpha = 10 \log 1000 = 30$ dB

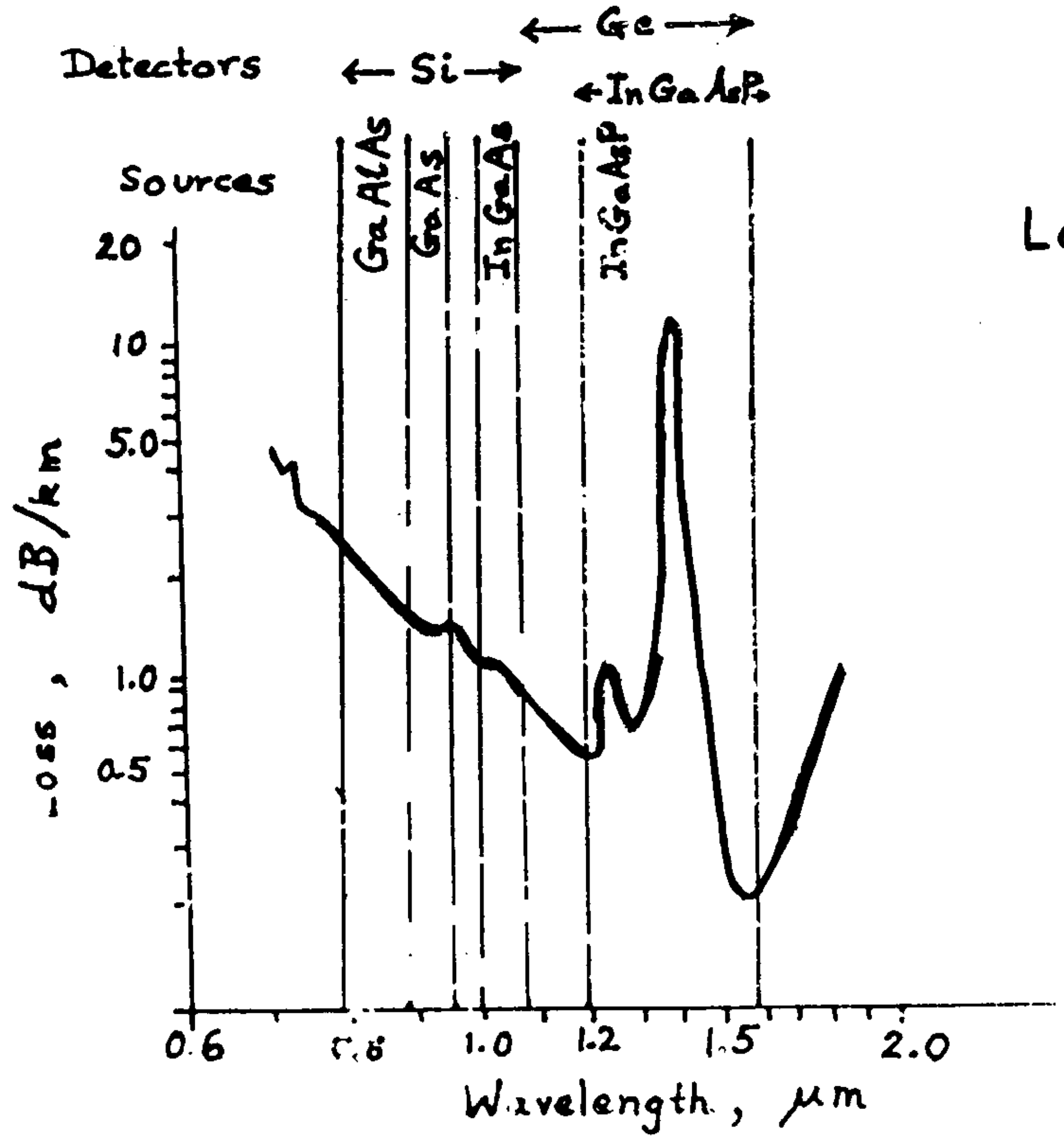
Thus

30 dB loss ≡ Power loss by a factor of 1000



Egyptian
Venetian
Optical Glass
Optical Fiber
OPTICAL LOSS (dB/km)
10^7
10^5
10^3
10
1
0.1
fundamental limits
silica
fluoride glasses
3000 BC
1000 AD
1900
1966
1979
1983
% Transmission per kilometer
96%

3 dB ⇔ 50% power loss



Loss (dB) $= 10 \log \frac{P_{in}}{P_{out}}$

0.2 dB/km ⇔ 96% transmission in 1 km

Why Glass Fibers ?

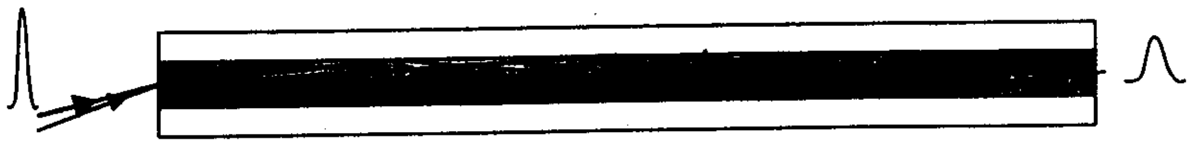
Glass is a remarkable material which has been use for at least 9000 years. The three most important properties of glass are:

1. Glass does not solidify at a discrete freezing temperature but gradually becomes stiffer and stiffer and eventually becomes hard. In the transition region it can be easily drawn into a thin fiber.

2. Highly pure silica is characterized with extremely low light transmission loss. Today, in most commercially available silica fibers, 96% of the power gets transmitted after propagating through 1 km of optical fiber.

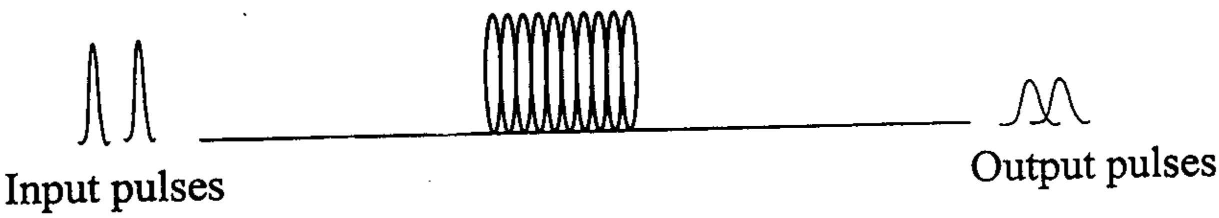
3. The third most remarkable property is the intrinsic strength of glass. Its strength is about 2,000,000 lb/in^2 so that a glass fiber of the type used in the telephone network and having a diameter of about 125 μm can support a load of about 40 lb.

What is pulse dispersion ?

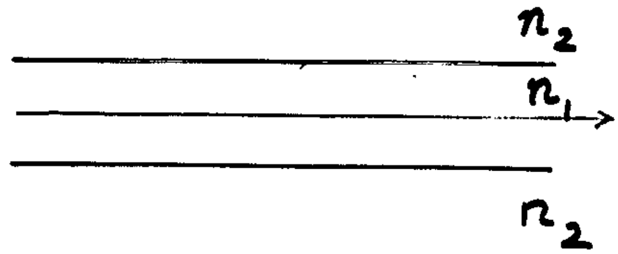


The two rays of light propagating in the fiber take different times to reach the other end

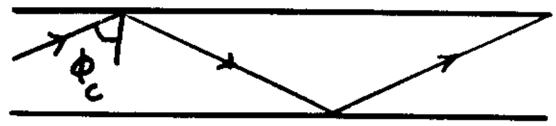
PULSE DISPERSION



Larger pulse dispersion ➡ Smaller possible bit rate



$$\tau_{min} = \frac{L}{c/n_1} = \frac{n_1 L}{c}$$



$$\tau_{max} = \frac{L/\sin\phi_c}{c/n_1} = \frac{n_1^2 L}{c\, n_2}$$

$$\sin\phi_c = \frac{n_2}{n_1}$$

Pulse dispersion

$$\Delta\tau = \tau_{max} - \tau_{min} = \frac{n_1 L}{c}\left[\frac{n_1 - n_2}{n_2}\right]$$

$$\Delta = \frac{n_1 - n_2}{n_2} \simeq 0.01 \; ; \quad n_1 \simeq 1.5 \; ; \quad L = 1\,km$$

$$c = 3 \times 10^8\ m/s$$

$$\Longrightarrow \quad \Delta\tau \approx 50\ ns/km$$

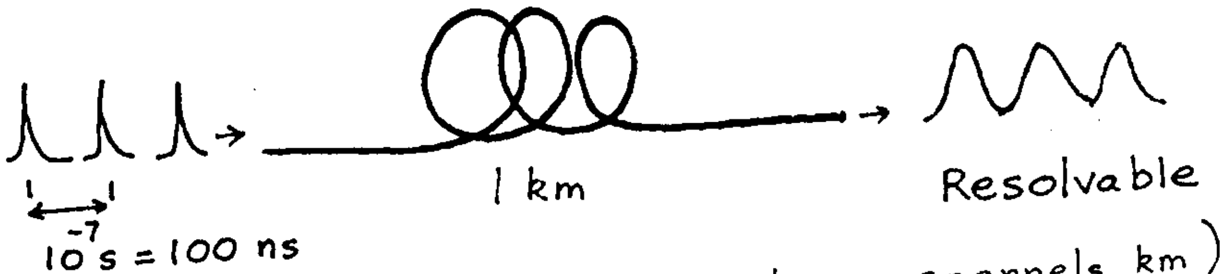
Intermodal Dispersion.

Pulse Dispersion $\Delta\tau = \frac{L}{c} n_1 \left(\frac{n_1 - n_2}{n_2} \right)$

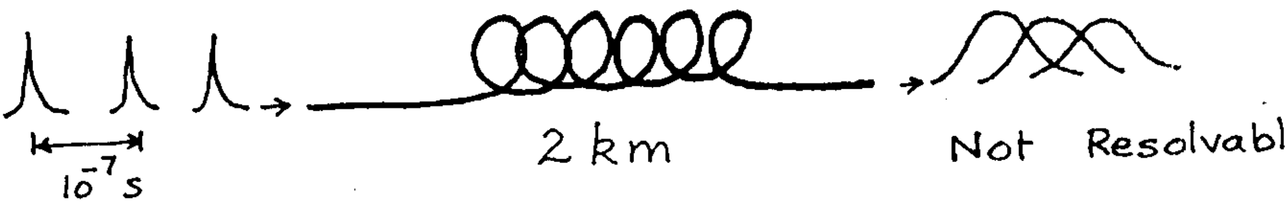
Typical Values

$n_1 = 1.46$, $\Delta = \frac{n_1 - n_2}{n_2} \simeq 0.01$, $L = 1\,km$

$$\Rightarrow \quad \Delta\tau = 50 \ ns/km$$



$\Rightarrow$ 10 Mbits/s ($\equiv$ 150 telephone crannels km)



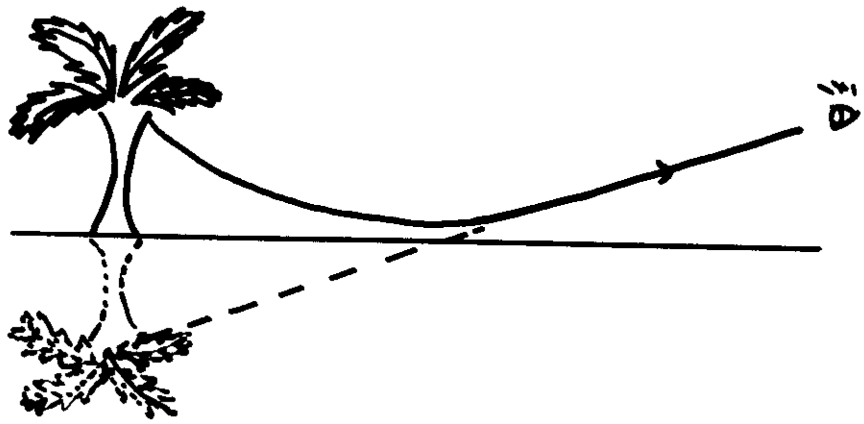
For large information carrying capacity, one must reduce pulse disper

Two alternative solutions:

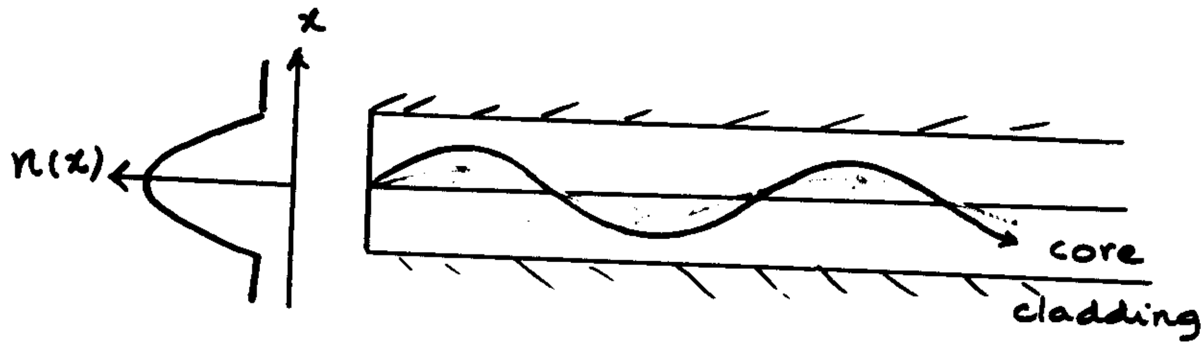
(a) G'ADED INDEX \Multimode) Fibers

(b) S NGI E MODE Fibers

Graded index medium



Graded index fiber



Greater path lengths almost compensated by an increased velocity of propagation

=> Less pulse dispersion

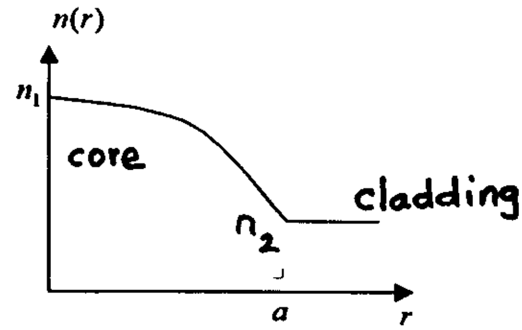
reduction by almost a factor of 1000 as compared to step index fibers

Optimum profile => Nearly parabolic

Parabolic Index Fiber

$$n^2(r) = n_1^2\left[1 - 2\Delta\left(\frac{r}{a}\right)^2\right] \qquad 0<r<a$$

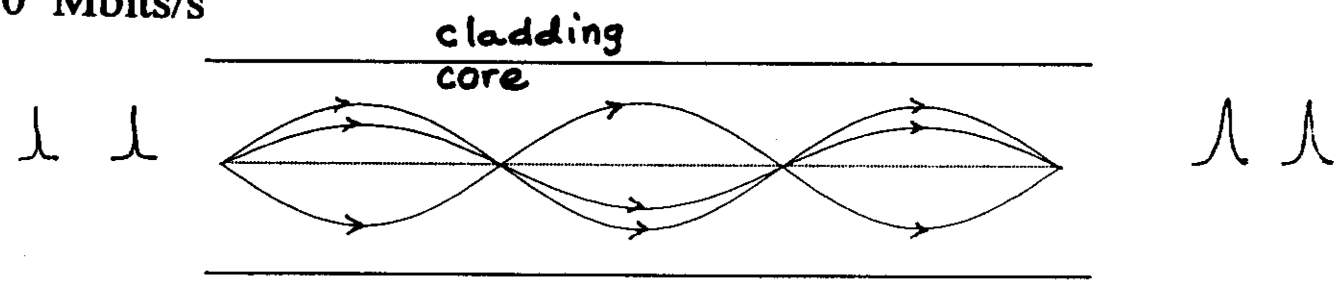
$$= n_2^2 = n_1^2(1-2\Delta) \qquad r>a$$



Intermodal dispersion : $(\Delta\tau)_i = \frac{n_1 L}{2c}\Delta^2$

$$n_2 \approx 1.5,\ L = 1\text{ km},\ \Delta \approx 0.01 \Rightarrow (\Delta\tau)_i \approx \frac{1}{4}\text{ ns/km}$$

50 Mbits/s



Pulses will remain resolvable even after about 10 km length of the fiber.

Greater path length is compensated by greater average velocity leading to smaller pulse broadening.

2-6

[redacted]

2-6

Figure B.3 shows a typical refractive index profile, obtained by Pearson *et al.* (1969), in a 30 mole% Li_2O, 15 mole% Al_2O_3, 55 mole% SiO_2 glass rod of 1.90 mm diameter, during an ion exchange in a 50 mole% $NaNO_3$, 50 mole% $LiNO_3$ fused salt bath at 470°C for 50 hr. As can be seen from the figure, the refractive index profile is very nearly parabolic. The refractive index at the axis of the rod is approximately 1.539.

The details of the experimental procedure can be found at many places; see, for example, Kitano *et al.* (1970) and Pearson *et al.* (1969).

B.2. *The New SELFOC Fibers*

The manufacturing process of the SELFOC fibers as discussed in Sec. B.1 is not only time consuming but it also cannot be used for continuous fabrication of fibers. In a recent paper Koizumi *et al.* (1974) have reported the fabrication of SELFOC fibers by a single continuous process, which makes mass production feasible. Further, the refractive index gradient (i.e., the value of a_2) is so large that even if the fiber is bent randomly the

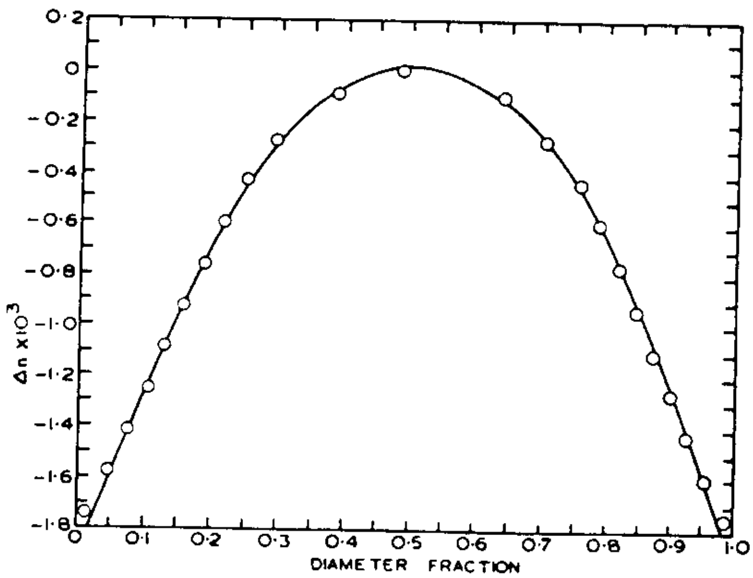
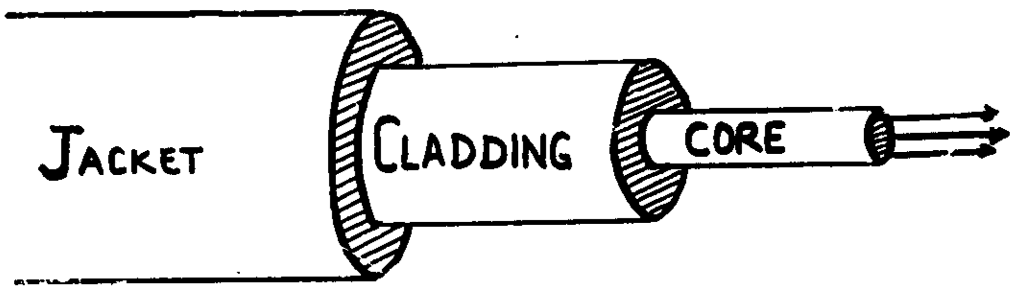
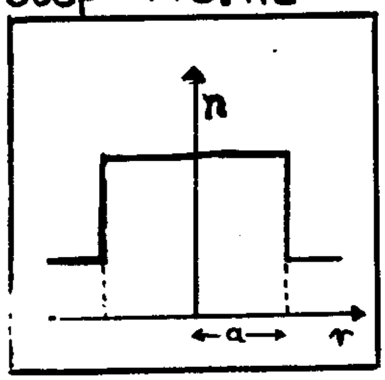


Fig. B.3. Measured refractive index profile of an ion-exchanged rod, normalized to a maximum of zero. The solid line is a parabola fitted to the experimental points by the least-squares method (after Pearson *et al.*, 1969; reprinted by permission).

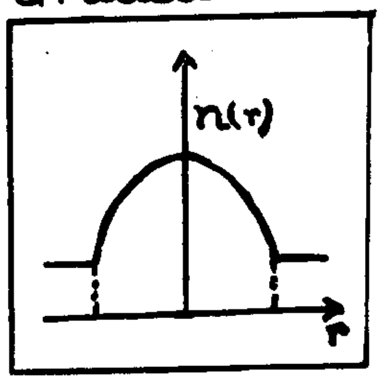
OPTICAL FIBERS



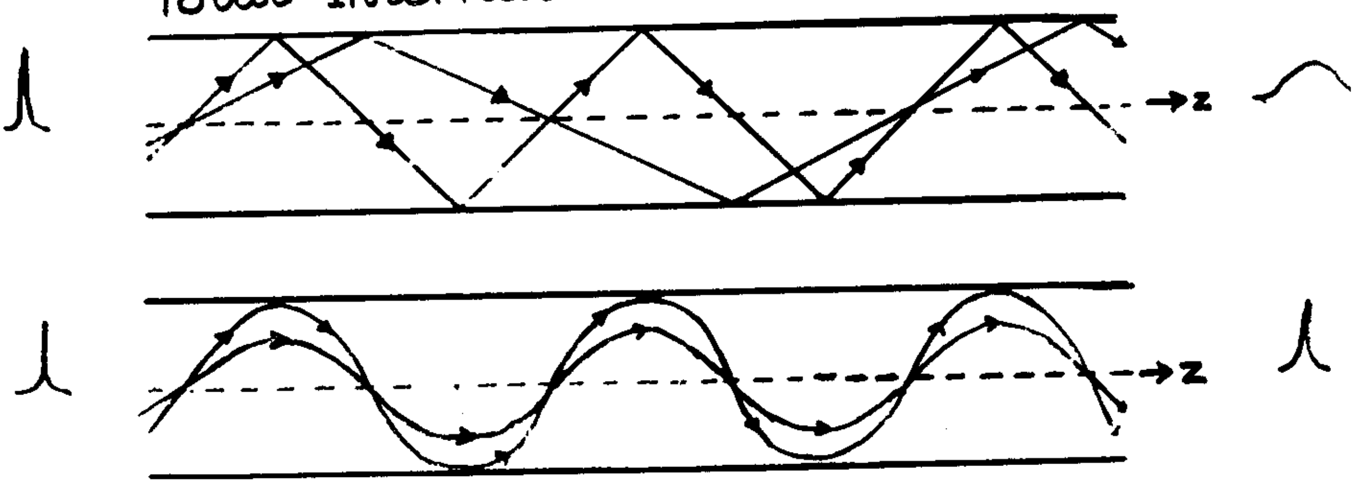
Step Profile



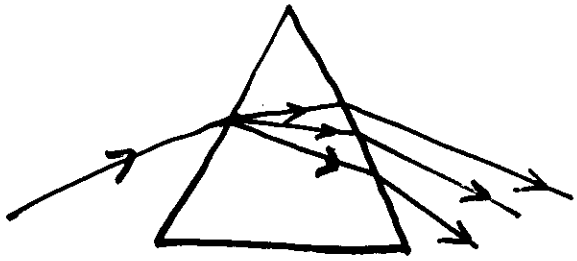
Graded Profile



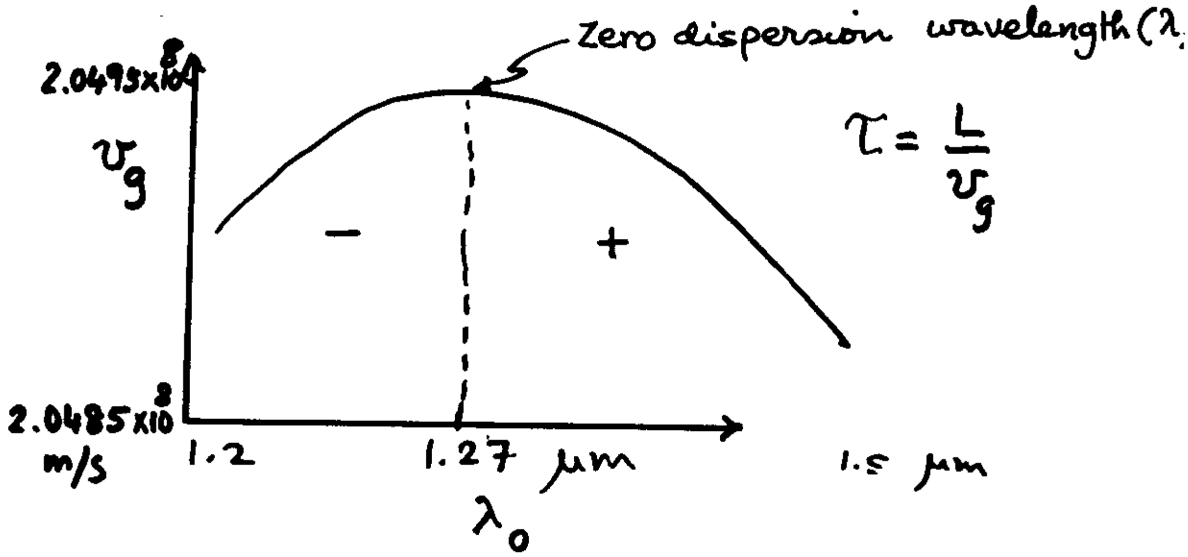
Total Internal Reflections



Material Dispersion [$n(\lambda)$]



Finite spectral width of a source $\Delta\lambda_0$



$$\tau = \frac{L}{v_g}$$

$$\Delta\tau_m = -\frac{\lambda_0}{c}\frac{d^2 n}{d\lambda_0^2} L \Delta\lambda_0$$

$c \simeq 3 \times 10^8$ m/s

Material Dispersion

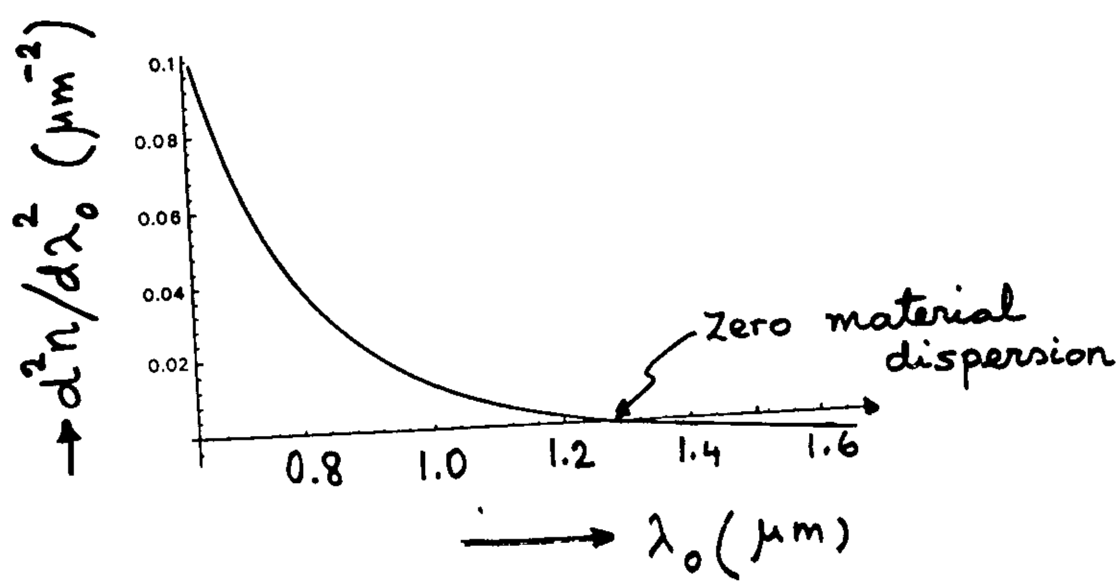
Plane Wave: $\Psi = A\ e^{i(\omega t - kz)}$

$$k(\omega) = \frac{\omega}{c}\, n(\omega) \quad ; \quad \omega = \frac{2\pi c}{\lambda_0}$$

$$\frac{1}{v_g} = \frac{dk}{d\omega} = \frac{1}{c}\left[n(\omega) + \omega \frac{dn}{d\omega} \right]$$

$$\tau = \frac{L}{v_g} = \frac{L}{c}\left[n(\lambda_0) - \lambda_0 \frac{dn}{d\lambda_0} \right]$$

$$(\Delta\tau)_m = \frac{d\tau}{d\lambda_0}\Delta\lambda_0 = -\frac{\lambda_0 L}{c}\ \frac{d^2 n}{d\lambda_0^2}\ \Delta\lambda_0$$



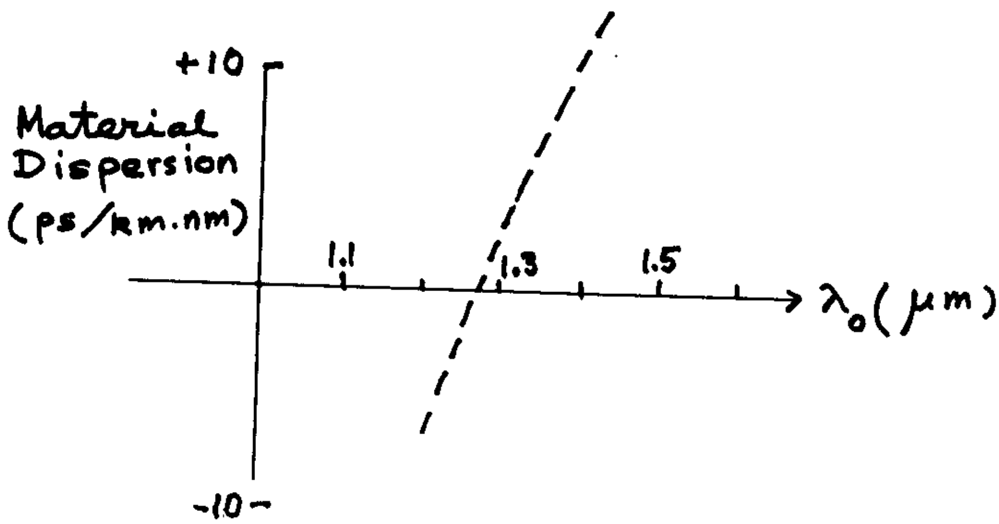
$$\Delta\tau_m = -\frac{\lambda_0 L}{c}\frac{d^2 n}{d\lambda_0^2}\Delta\lambda_0$$

Material Dispersion parameter

$$D_m \equiv \frac{\Delta\tau_m}{L\,\Delta\lambda_0} = -\frac{1}{\lambda_0 c}\left(\lambda_0^2\frac{d^2 n}{d\lambda_0^2}\right)$$

$$\approx -\frac{10^4}{3\lambda_0}\left(\lambda_0^2\frac{d^2 n}{d\lambda_0^2}\right) \quad \text{ps/km.nm}$$

(λ_0 is measured in μm)



For pure silica

$D_m \sim -84.2$ ps/km.nm ($\lambda_0 \approx 0.850\ \mu$m)

$\sim +2.4$ ps/km.nm ($\lambda_0 \approx 1.3\ \mu$m)

$\sim +21.5$ ps/km.nm ($\lambda_0 \approx 1.55\ \mu$m)

I Generation Optical Communication Systems (~ 1977)

Parabolic Index Multimode Fibers $\Delta\tau_i \gtrsim \frac{1}{4}$ ns/km

LED's at 0.85 μm ($\Delta\lambda_0 \approx 25$ nm) Loss ~ 3 dB/km

$\Delta\tau_m \approx$ 84 ps/km.nm x 25 nm $\approx$ 2.1 ns/km

Bit rate ~ 45 Mbits/s $\Rightarrow$ Repeater Spacing ~ 10 km

II Generation Optical Communication Systems (~ 1981)

Parabolic Index Multimode Fibers $\Delta\tau_i \sim \frac{1}{4}$ ns/km

LED's at 1.3 μm ($\Delta\lambda_0 \approx 25$ nm) Loss ~ 1 dB/km

$\Delta\tau_m \approx$ 2.4 ps/km.nm x 25 nm $\approx$ 0.06 ns/km

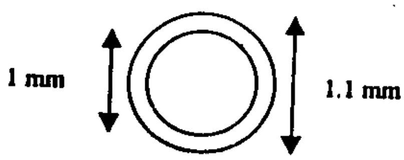
Bit rate ~ 45 Mbits/s $\Rightarrow$ Repeater Spacing ~ 30 km

Table 13.1. *Typical characteristics of fiber optic communication systems at different stages*

Generation	Date	Bit rate	Type of fiber	Loss (dB/km)	Repeater spacing (km)
I (0.8–0.9 μm)	1977	~45 Mbit/s	Multimode (graded index)	~3	~10
II (1.3 μm)	1981	~45 Mbit/s	Multimode (graded index)	~1	~30
III (1.3 μm)	At present	~2.5 Gb/s	Single mode	≤0.5	~40
IV (1.55 μm)	At present	≥10 Gb/s	Single mode	<0.3	≥100

Note: Futuristic system: WDM, solitons. Infrared fibers ($\lambda_0 > 2\ \mu m$); extremely low loss ($<10^{-2}$ dB/km); ⇒ repeater spacing >1000 km.

Plastic Optical Fibers (POF)



$n_1 = 1.49$ (PMMA)

Polymethyl Methacrylate

$n_2 = 1.40$

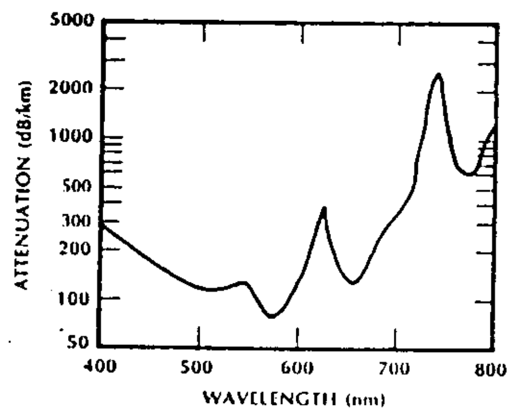
$$NA = \sqrt{1.49^2 - 1.40^2} \approx 0.51$$

$$\Rightarrow i_m \approx 31^\circ \text{ (very large NA)}$$

Easy splicing/alignment

Low loss windows at 570 nm, 650 nm & 780 nm

At 650 nm : Loss ≈110 dB/km



POF's are expected to provide low cost solution to short distance communications (LAN's)

GI POF → ~ few hundred Mbits/s

Schrodinger equation solutions

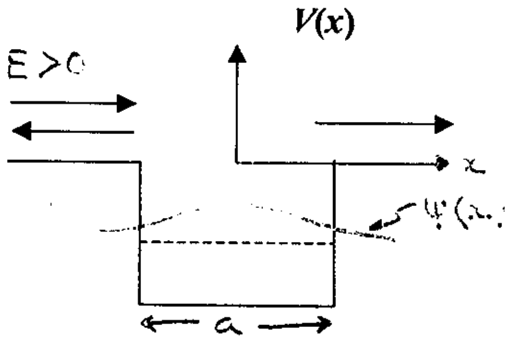
$$V = V(x)$$

$$\Psi(x,t) = \psi(x)e^{-iEt/\hbar} \quad \text{stationary states}$$

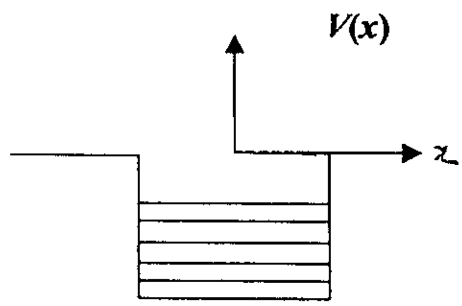
$$\frac{d^2\psi}{dx^2} + \frac{2\mu}{\hbar^2}[E - V(x)]\psi(x) = 0$$

$$V(x) = -V_0 \qquad |x| < a/2$$

$$= 0 \qquad |x| > a/2$$



$\Psi(x)$: $e^{+\gamma x}$ $\cos\kappa x$ $e^{-\gamma x}$



$\hbar \to 0$

For $\sqrt{\frac{2\mu V_0 a^2}{\hbar^2}} < \pi$ only one bound state

In general,

$-V_0 < E < 0$ finite number of bound states

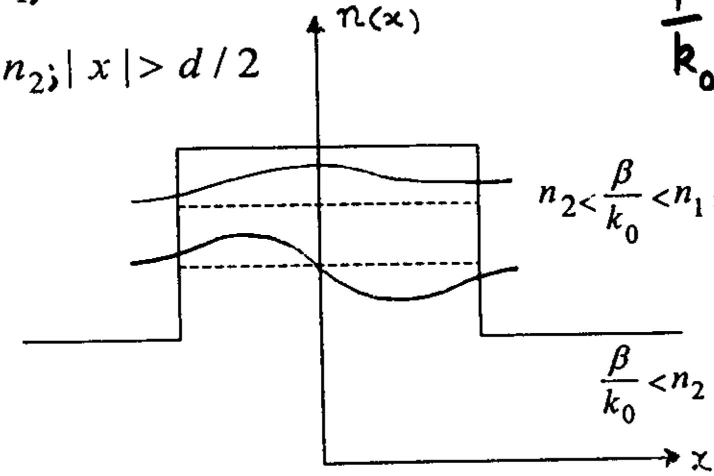
$E > 0$ continuum scattering states

$$n = n(x) \Rightarrow E_y = \psi(x)\, e^{i(\omega t - \beta z)} \qquad \text{(TE modes)}$$

$$\frac{d^2\psi}{dx^2} + [k_0^2 n^2(x) - \beta^2]\psi(x) = 0 \qquad k_0 = \frac{2\pi}{\lambda_0} = \frac{\omega}{c}$$

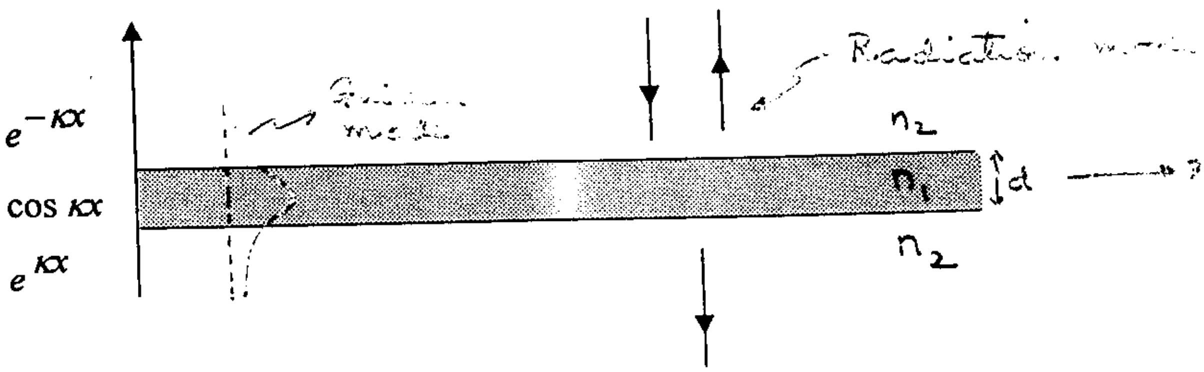
$$n(x) = n_1;\ |x| < d/2$$
$$= n_2;\ |x| > d/2$$

$$\frac{\beta}{k_0} = n_{eff}$$



$n_2 < \frac{\beta}{k_0} < n_1 \Rightarrow$ Discrete Guided Modes

$\frac{\beta}{k_0} < n_2 \Rightarrow$ Continuum Radiation Modes



$n_1 = 1.50, \quad n_2 = 1.48, \quad d = 3.9\ \mu m$

For $\lambda_0 = 1\ \mu m$; $\quad \frac{\beta}{k_0} \approx 1.497$ (symm TE modes)

$\frac{\beta}{k_0} \approx 1.488$ (antisymm TE modes)

Field in the core

$$E_y = A \cos \kappa x \; e^{i(\omega t - \beta z)}$$

$$= 2\, A\, e^{i(\omega t - \beta z + \kappa x)} + 2\, A\, e^{i(\omega t - \beta z - \kappa x)}$$

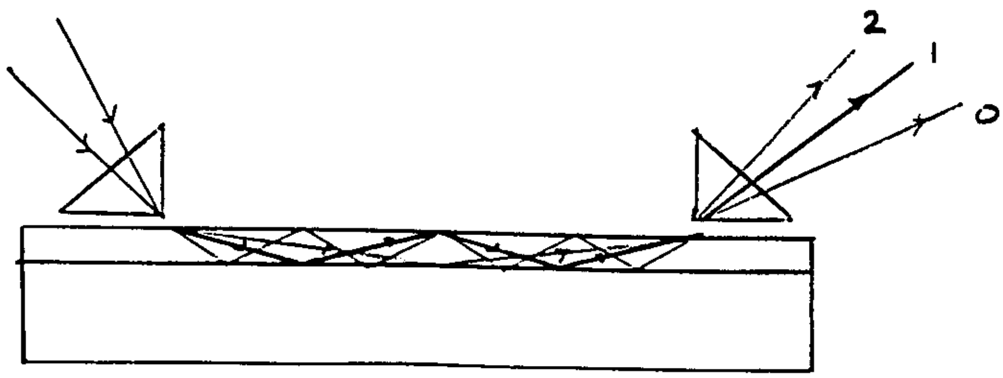
Plane Wave: $e^{i(\omega t - \mathbf{k.r})} = e^{i(\omega t - k_x x - k_y y - k_z z)}$

$$k_x = \mp \kappa \quad ; \quad k_y = 0 \quad ; \quad k_z = \beta$$

$$\cos \theta = \frac{k_z}{k} = \frac{\beta}{k_0 n_1} \Rightarrow \theta \approx 3.6^\circ \quad \text{(symm TE mode)}$$

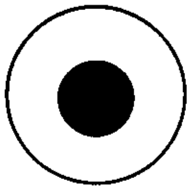
$$\approx 7.1^\circ \quad \text{(Antisymm TE mode)}$$

Prism film coupling experiment



Fiber Types

Step Index Multimode

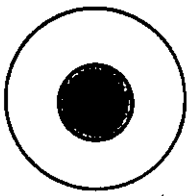


Core dia.: 100 - 200 μm

Cladding dia.: 140 - 240 μm

NA: 0.2 - 0.5

Graded Index Multimode

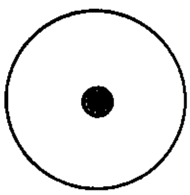


Core dia.: 50 - 85 μm

Cladding dia.: 125 μm

NA: 0.2

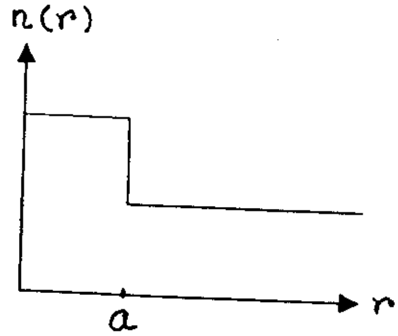
Singlemode



Core dia.: 9 μm

Cladding dia.: 125 μm

Step Index Fiber



$$n = n_1 \qquad 0 < r < a$$
$$\;\; = n_2 \qquad r > a$$

$$E(r,\phi,z,t) = R(r) \begin{Bmatrix} \cos & l\phi \\ \sin & l\phi \end{Bmatrix} e^{i(\omega t - \beta z)} \qquad \text{LP}_{lm} \text{ modes}$$

$$\beta = \beta_{lm}$$

$$R(r) = A \; J_l\left(U \frac{r}{a}\right) \qquad 0 < r < a$$

$$\;\;\;\; = B \; K_l\left(W \frac{r}{a}\right) \qquad r > a$$

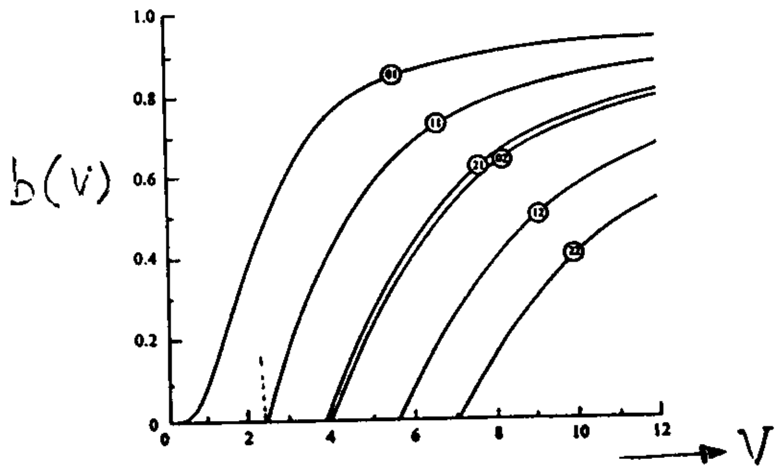
$$U \equiv V\sqrt{1-b} \quad ; \quad W \equiv V\sqrt{b}$$

$$V = \frac{2\pi}{\lambda_0} a \sqrt{n_1^2 - n_2^2} \qquad b \approx \frac{\frac{\beta}{k_0} - n_2}{n_1 - n_2}$$

$$U \frac{J_l'(U)}{J_l(U)} = W \frac{K_l'(W)}{W}$$

$$\Rightarrow \qquad b = b(V)$$

$$b \;=\; b(V) \;;\qquad 0 < b < 1 \quad \left(n_2 < \frac{\beta}{k_0} < n_2\right)$$



$$V \;=\; \frac{2\pi}{\lambda_0}\, a\sqrt{n_1^2 - n_2^2} < 2.4048 \qquad \text{SMF}$$

For the fundamental mode

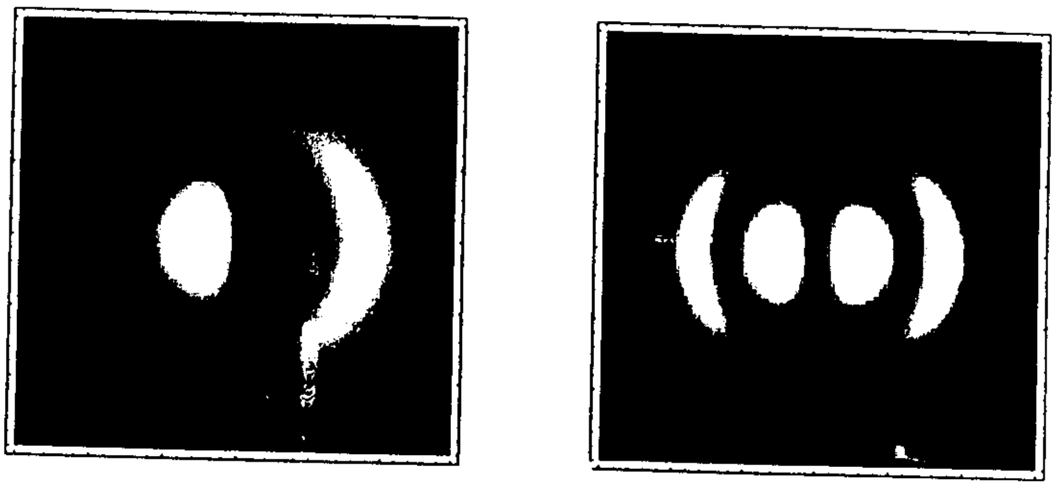
$$b(V) \;\approx\; \left[1.1428 \;-\; \frac{0.996}{V}\right]^2 \;;\quad 1.5 \;\le\; V \le 2.5$$

$$b \;\approx\; \frac{\frac{\beta}{k_0} - n_2}{n_1 - n_2} \Rightarrow \beta \;=\; \frac{\omega}{c}\left[n_2 + b(V)(n_1 - n_2)\right]$$

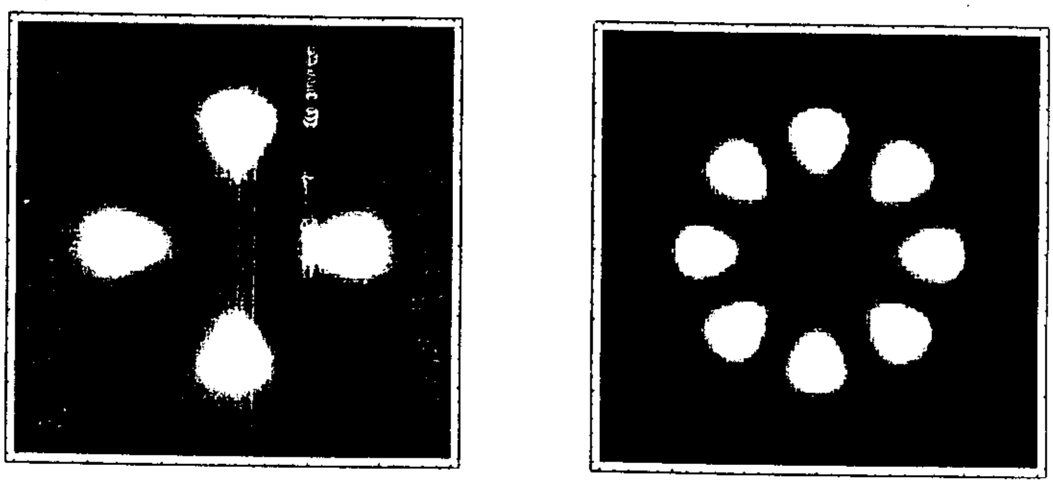
$$b \;=\; b(V) \;\Rightarrow\; \frac{d^2\beta}{d\omega^2} \neq 0$$

$$(\Delta\tau)_w \approx -\frac{L}{c}(n_1 - n_2)\left(\frac{\Delta\lambda_0}{\lambda_0}\right)\left(V\,\frac{d^2(bV)}{dV^2}\right)$$

LP_{12}



LP_{41}



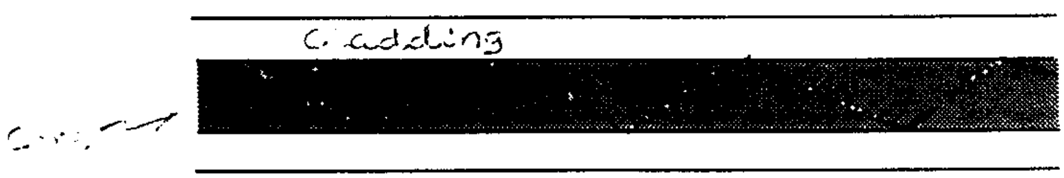
SINGLE MODE FIBERS

SIF : $$V = \frac{2\pi}{\lambda_0} a \, n_2 \sqrt{2\Delta} < 2.4048$$

$$\Delta \approx \frac{n_1 - n_2}{n_2}$$

Example: $a \approx 4.8\ \mu\text{m},\ n_2 \approx 1.45,\ \Delta \approx 0.002$

$\lambda_0 > 1.15\ \mu\text{m} = \lambda_c$



Fundamental Mode:

$$E \approx A\, e^{-r^2/w^2} \; e^{i(\omega t - \beta z)}$$

Phase Factor

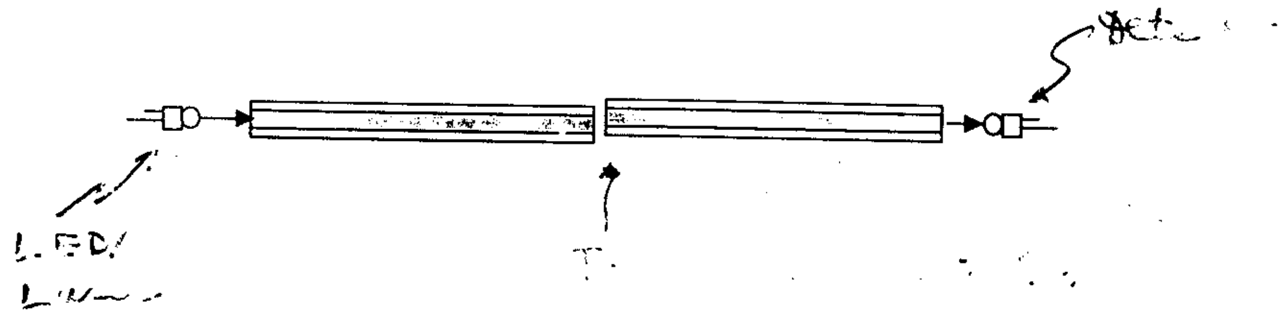
$$\frac{w}{a} \approx 0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6}\ ; \ 0.8 \le V \le 2.5$$

Example : $a \approx 4.8\ \mu\text{m},\ n_2 \approx 1.45,\ \Delta \approx 0.002$

$\lambda_0 = 1.1\ \mu\text{m} \Rightarrow w \approx 4.4\ \mu\text{m}$

$\lambda_0 = 1.3\ \mu\text{m} \Rightarrow w \approx 5.0\ \mu\text{m}$

Splice loss at joints



$$\alpha(\text{dB}) \approx 4.34\left(\frac{u}{w}\right)^2$$

$$w \approx 5\ \mu\text{m}$$

For $\alpha < 0.1\ \text{dB}$

$u < 0.76\ \mu\text{m}$

6-40

3-10

MODE **PLANE WAVE**

$$E = \psi(r)\, e^{i(\omega t - \beta z)}$$

$$\beta(\omega) = \frac{\omega}{c}\, n_{eff}$$

$$\frac{1}{v_g} = \frac{d\beta}{d\omega}$$

$$E = E_0\, e^{i[\omega t - k(\omega) z]}$$

$$k(\omega) = \frac{\omega}{c}\, n(\omega)$$

$$\frac{1}{v_g} = \frac{dk}{d\omega}$$

$$b = \frac{\beta / k_0 - n_2}{n_1 - n_2} \Rightarrow \beta = \frac{\omega}{c}[\underbrace{n_2 + (n_1 - n_2) b(V)}_{n_{eff}}]$$

$$V = \frac{\omega}{c}\, a \sqrt{n_1^2 - n_2^2}$$

$$\frac{1}{v_g} = \frac{d\beta}{d\omega} = \frac{n_2}{c} + \frac{n_1 - n_2}{c}\, \frac{d}{dV}(Vb)$$

Waveguide Dispersion

$$\tau = \frac{L}{v_g} \Rightarrow \Delta\tau_w = L \frac{d}{d\lambda_0}\left(\frac{1}{v_g}\right)\Delta\lambda_0 \approx -\frac{L}{c} n_2 \Delta\left[V \frac{d^2}{dV^2}(bV)\right]\frac{\Delta\lambda_0}{\lambda_0}$$

$$D_w = \frac{\Delta\tau_w}{L\Delta\lambda_0} \approx -\frac{n_2\Delta}{3\lambda_0} \times 10^4\ [V \frac{d^2}{dV^2}(bV)] \qquad \text{ps/km.nn}$$

(λ_0 in micrometers)

$$D_w \approx -\frac{n_2 \Delta}{3\lambda_0} \times 10^4 \left[V \frac{d^2}{dV^2}(bV) \right] \quad \text{ps/km.nm}$$

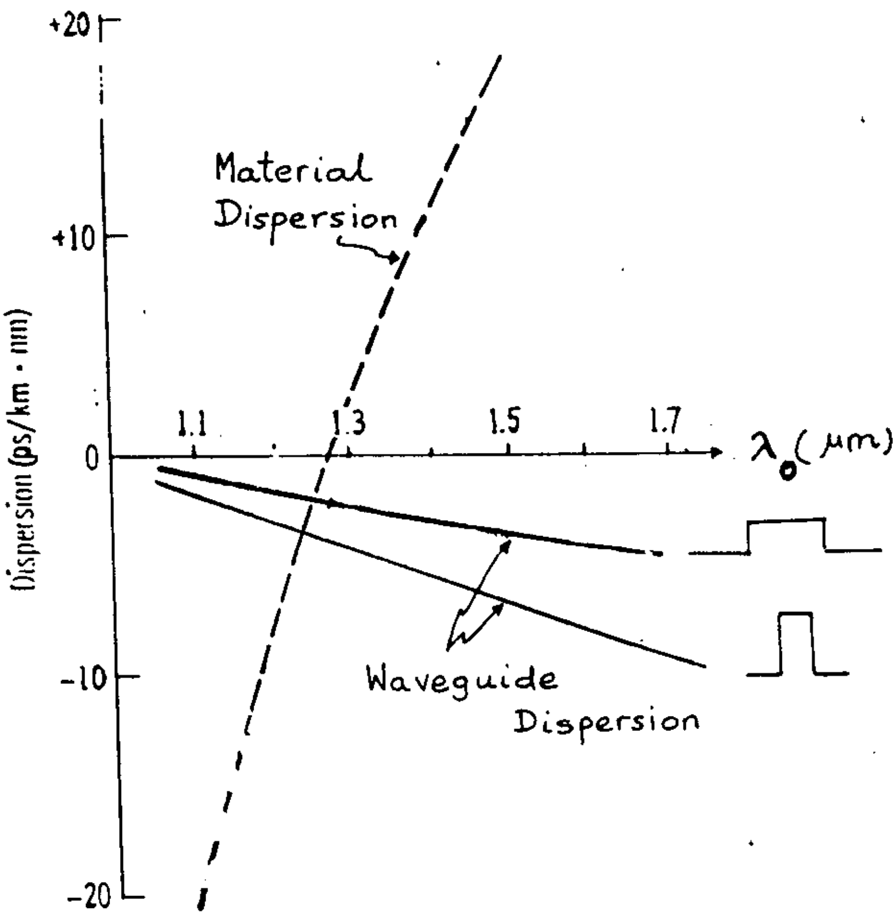
$$b(V) \approx \left(A - \frac{B}{V} \right)^2 \quad ; \; 1.5 \lesssim V \lesssim 2.5$$

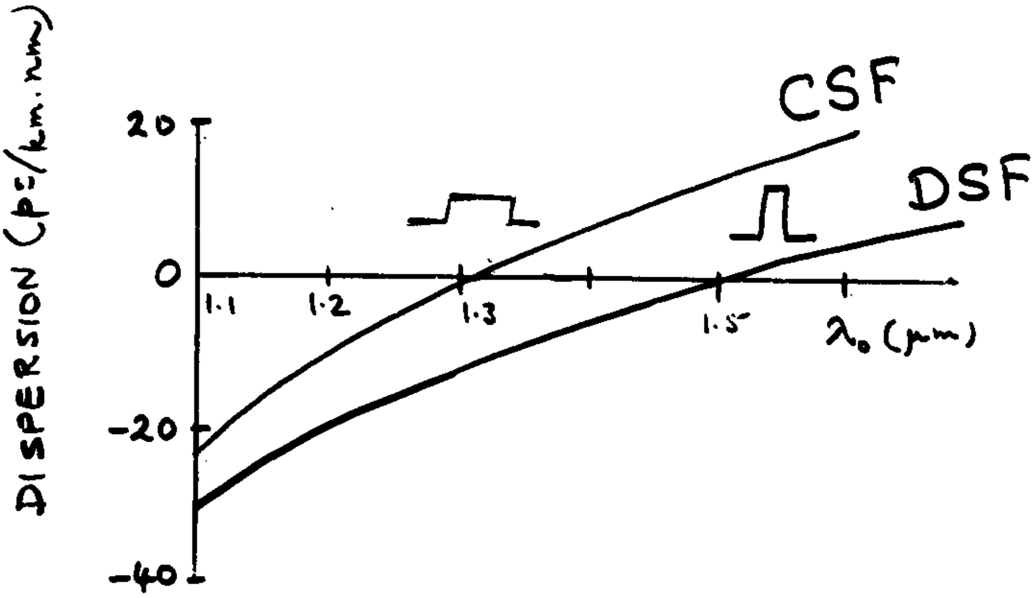
$$\Rightarrow \quad V \frac{d^2}{dV^2}(bV) \approx \frac{2B^2}{V^2} \quad ; \quad [\, V \approx \frac{2\pi}{\lambda_0} a n_2 \sqrt{2\Delta}\,]$$

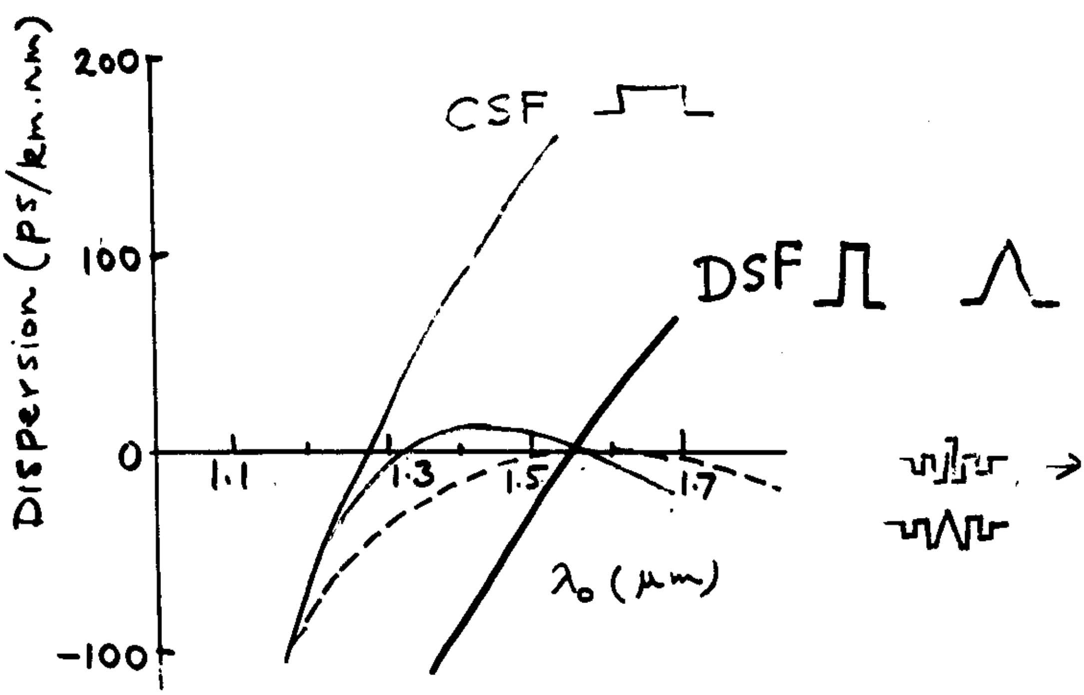
$$\approx \frac{\lambda_0^{\,2}}{2\pi^2 a^2 n_2 (2\Delta)} \quad (V \approx 1.9)$$

$$D_w \approx -\frac{\lambda_0}{12\pi^2 a^2} \times 10^4 \quad \text{ps/km.nm}$$

$a \approx 4\ \mu\text{m}$, $\lambda_0 \approx 1.3\ \mu\text{m}$ $\Rightarrow$ $D_w \approx -7$ ps/km.nm

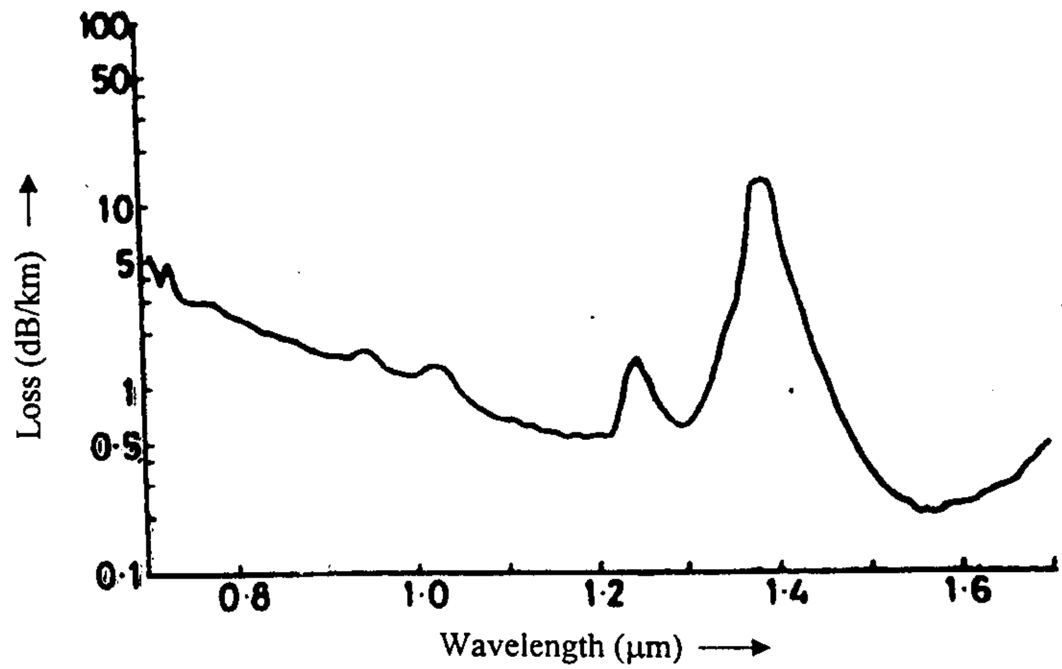

+20
+10
0
-10
-20
Dispersion (ps/km · nm)
1.1
1.3
1.5
1.7
λ_0 (μm)
Material Dispersion
Waveguide Dispersion

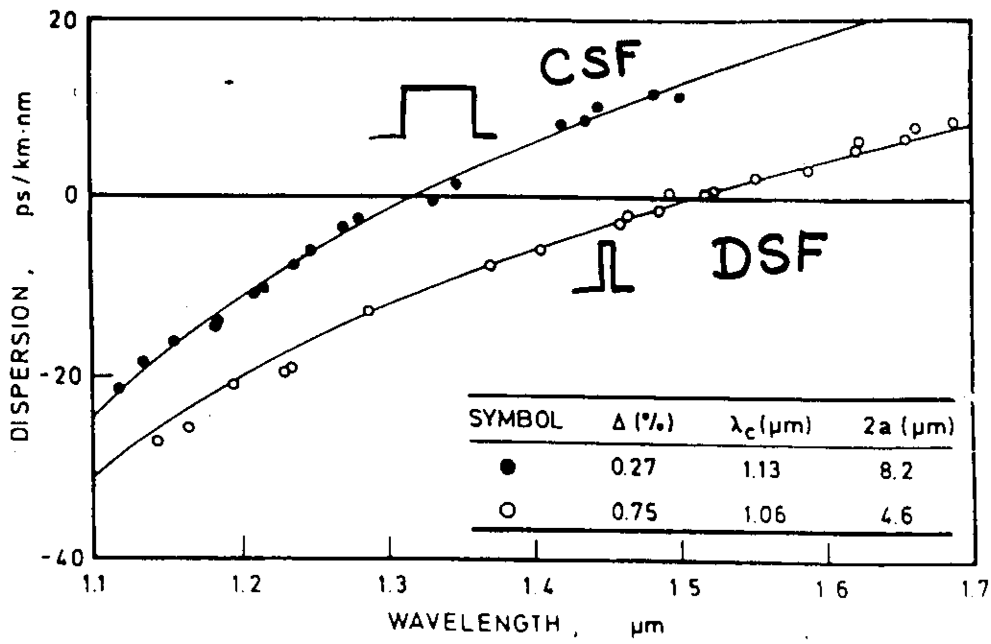




—— DISPERSION SHIFTED

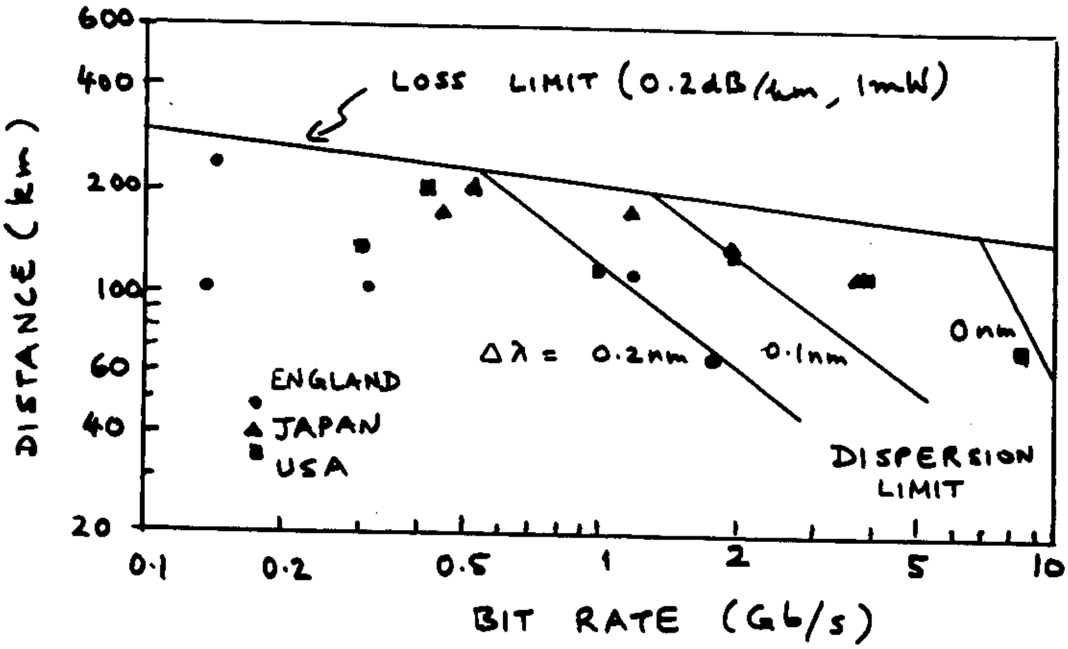
═ } DISPERSION FLATTENED





Ref: Miya et al. , Electron. Letts., 15 (1979) 106

Ref: Kimura, in *Optical Fiber Transmission* (Ed. K. Noda) North Holland, Amsterdam, 1986

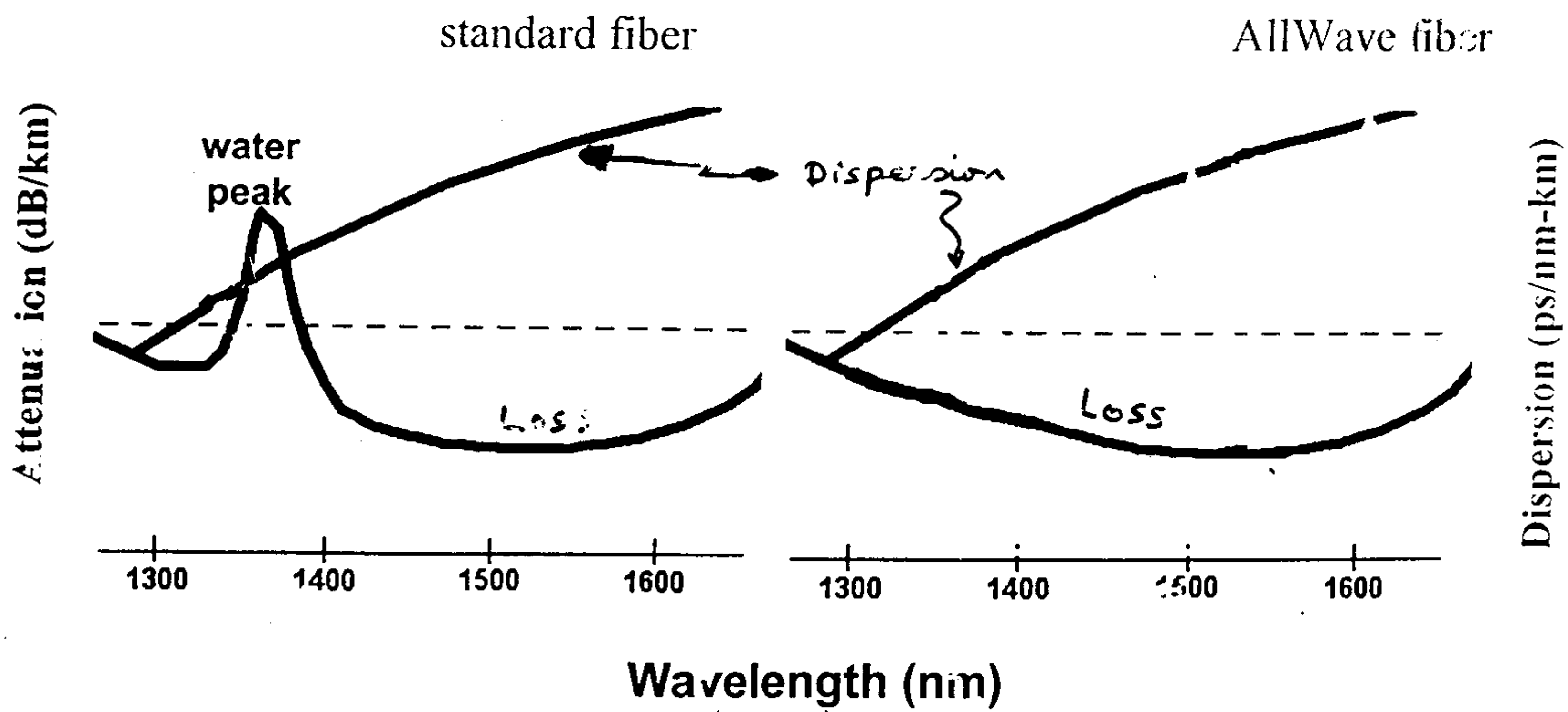


Long distance (> 100 km) transmission at ultra high (> 10 Gb/s) data rates requires

DISPERSION SHIFTED FIBERS

AllWave™ Fiber

Eliminates Water Peak to Open the 5th Operating Window



Propagation of a pulse

We first consider superposition of plane waves

$$\Psi(z,t) = \int A(\omega)\, e^{i[\omega t - k(\omega) z]}\, d\omega \quad ; k(\omega) = \frac{\omega}{c} n(\omega)$$

$$\Psi(z=0,t) = \int A(\omega)\, e^{i\omega t}\, d\omega$$

$$A(\omega) = \frac{1}{2\pi} \int \Psi(z=0,t)\, e^{-i\omega t}\, dt$$

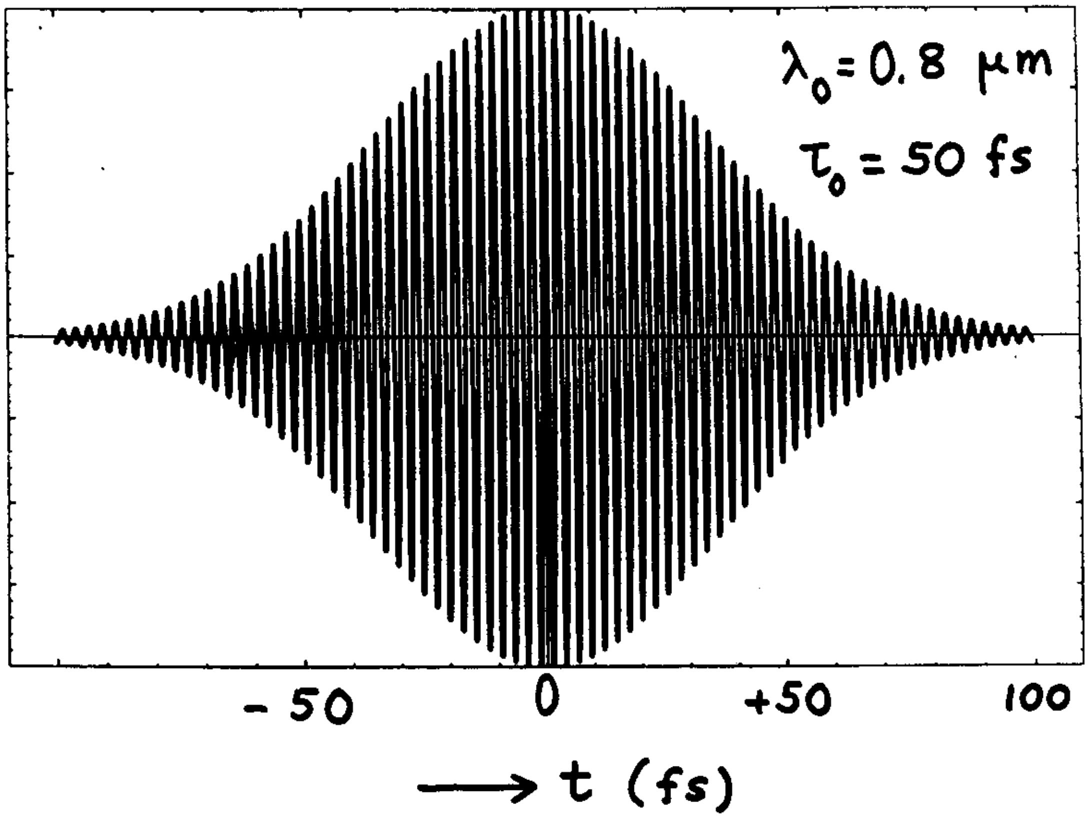
(Frequency spectrum)

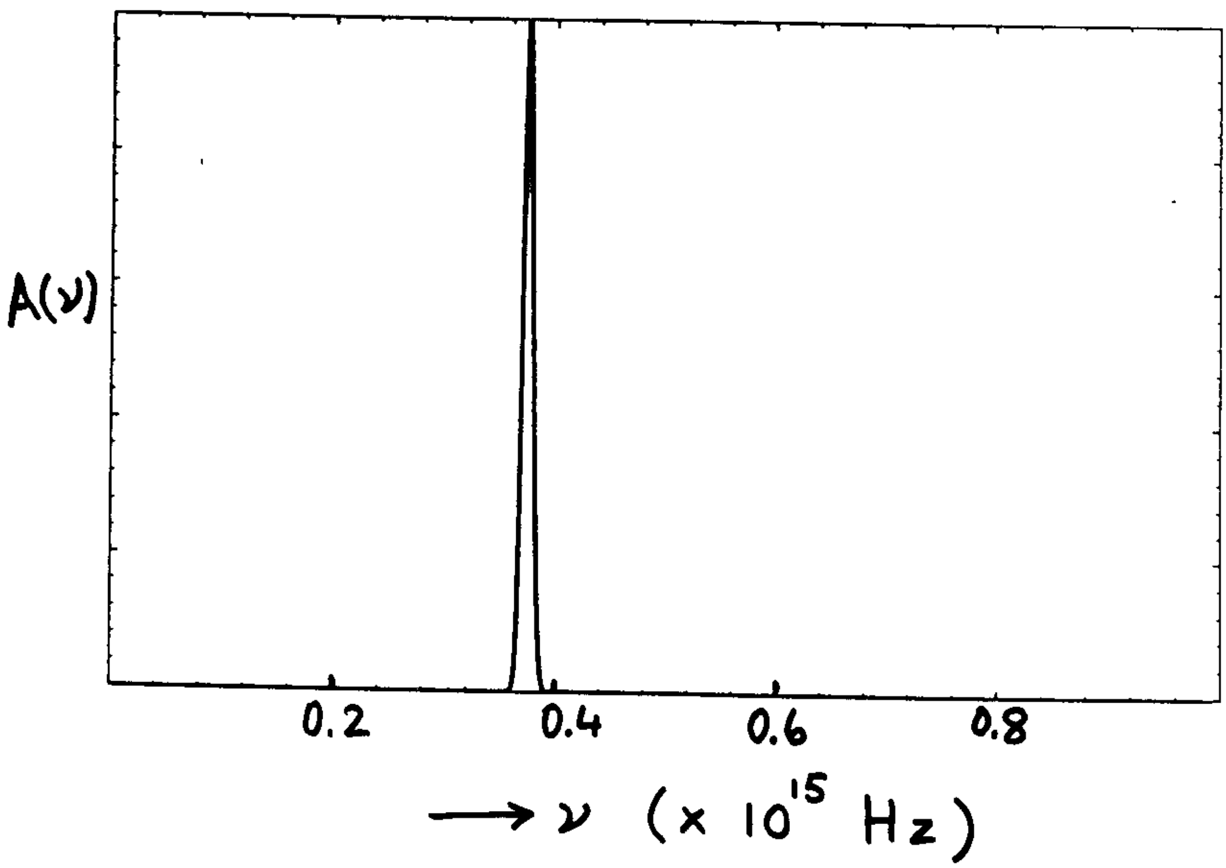
Example: Gaussian Pulse

$$\Psi(z=0,t) = C\, e^{-t^2/\tau_0^2}\, e^{i\omega_0 t}$$

$$A(\omega) = \frac{C\tau_0}{2\sqrt{\pi}} \exp\left[-\frac{(\omega-\omega_0)^2\, \tau_0^2}{4}\right]$$

Gaussian Pulse





$$\Psi(z,t) \approx \int_{\omega_0-\frac{1}{2}\Delta\omega}^{\omega_0+\frac{1}{2}\Delta\omega} A(\omega) e^{i[\omega t - k(\omega) z]} \, d\omega$$

$$k(\omega) \approx k(\omega_0) + \left.\frac{dk}{d\omega}\right|_{\omega_0} (\omega-\omega_0) + \frac{1}{2}\left.\frac{d^2k}{d\omega^2}\right|_{\omega_0} (\omega-\omega_0)^2$$

$$\approx k(\omega_0) + \frac{1}{v_g}\Omega + \frac{1}{2}\alpha\Omega^2$$

where $\Omega \equiv \omega - \omega_0$

$$\frac{1}{v_g} \equiv \left.\frac{dk}{d\omega}\right|_{\omega=\omega_0} \qquad \& \qquad \alpha \equiv \left.\frac{d^2k}{d\omega^2}\right|_{\omega=\omega_0} = \frac{\lambda_0^3}{2\pi c^2}\frac{d^2n}{d\lambda_0^2}$$

$$\omega \mathrm{t} = (\omega_0 + \Omega)\mathrm{t} = \omega_0 \mathrm{t} + \Omega \mathrm{t}$$

Thus

$$\Psi(z,t) \approx e^{i[\omega_0 t - k(\omega_0) z]} \int d\Omega \, A(\Omega) \, e^{i[\Omega(t-\frac{z}{v_g}) + \frac{1}{2}\alpha z \Omega^2]}$$

Phase Factor Envelope Function

Gaussian Pulse : $A(\Omega) = \dfrac{c\tau_0}{2\sqrt{\pi}} \exp\left[-\frac{1}{4}\tau_0^2\Omega^2\right]$

$$\Psi(z,t) = \frac{C}{[\tau(z)/\tau_0]^{1/2}} \exp\left[-\frac{(t-\frac{z}{v_g})^2}{\tau^2(z)}\right] e^{i\Phi(z,t)}$$

$$\Phi(z,t) = \omega_0 t + \kappa\left(t-\frac{z}{v_g}\right)^2 - \frac{1}{2}\tan^{-1}\left(\frac{2\alpha z}{\tau_0^2}\right) - k_0 z$$

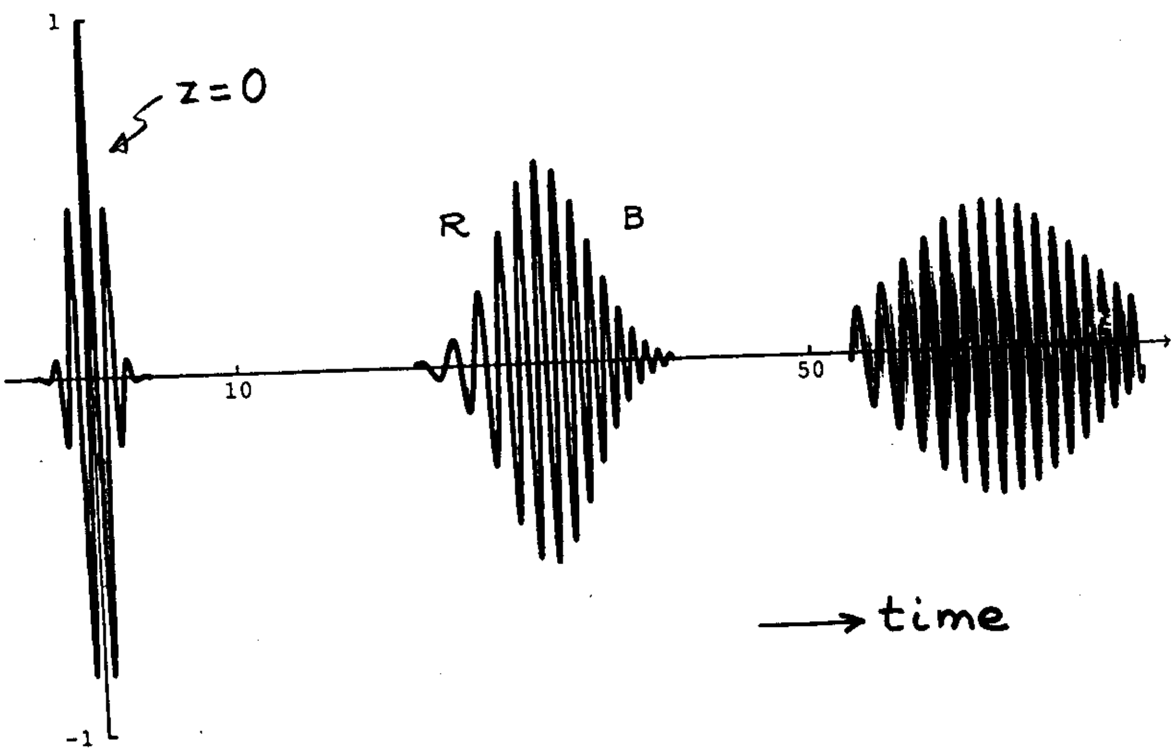
$$\omega(t) = \frac{\partial\Phi}{\partial t} = \omega_0 + 2\kappa(t-\frac{z}{v_g}) \quad ; \quad \kappa = \frac{2\alpha z}{\tau^2(z)}$$

$$\tau(z) = \tau_0\left[1+\frac{4\alpha^2 z^2}{\tau_0^4}\right]^{1/2}$$

If $d^2n/d\lambda_0^2 > 0 \Rightarrow \kappa > 0$ (Positive Chirp)

For $t < \frac{z}{v_g}$ (Leading edge), $\omega(t) < \omega_0$ (red shifted)

For $t > \frac{z}{v_g}$ (Trailing edge), $\omega(t) > \omega_0$ (blue shifted)



Dispersion Compensation

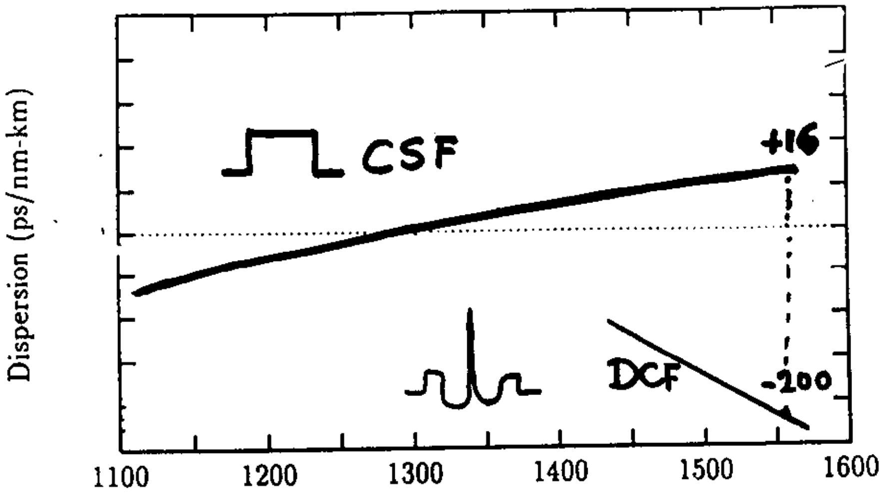
- More than 70 million km of CSF (with $\lambda_z \sim 1310$ nm) already laid (currently operating at $\lambda_0 \sim 1310$ nm)

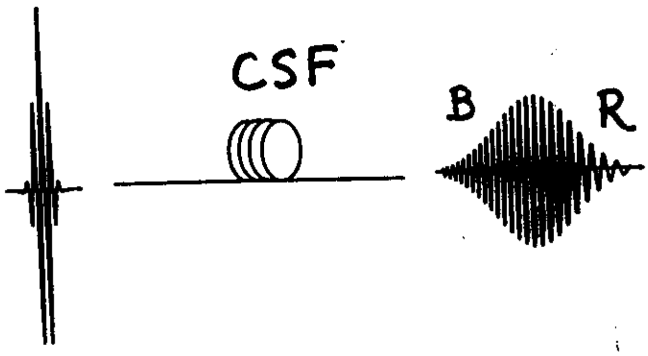
- However, the fiber has lowest loss at 1550 nm; also efficient amplifiers operate around 1550 nm

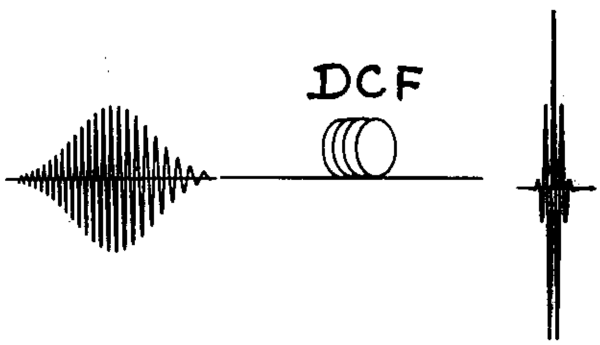
- The CSF's have D ~ 16 ps/km-nm at $\lambda_0 \sim 1550$ nm

- How to use existing CSF's at 1550 nm?

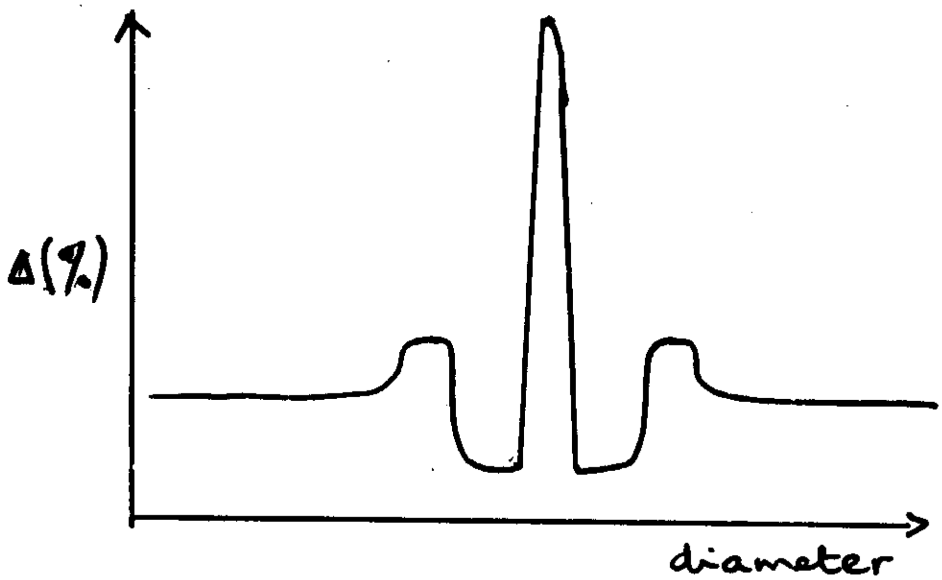
  - Through Dispersion Compensation

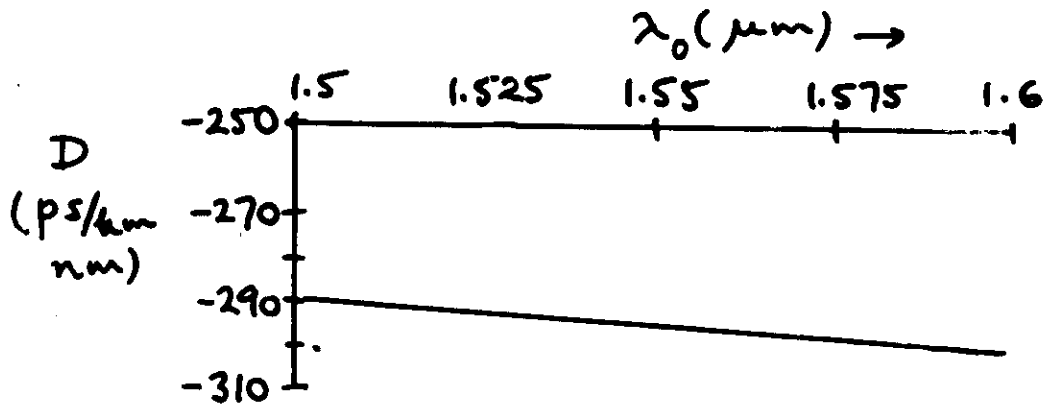

Dispersion (ps/nm-km)
CSF
+16
DCF
-200
1100
1200
1300
1400
1500
1600


CSF
B
R


DCF

Dispersion Compensating Fiber

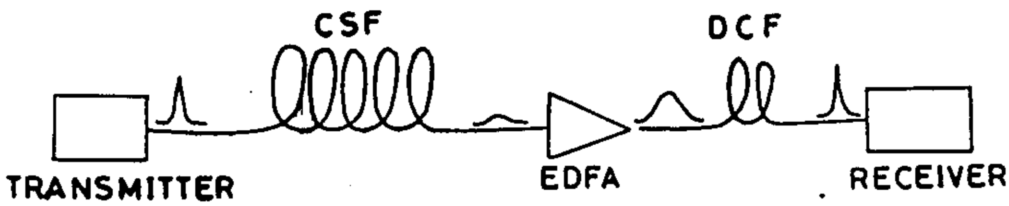




Attenuation ~ 0.7 dB/km

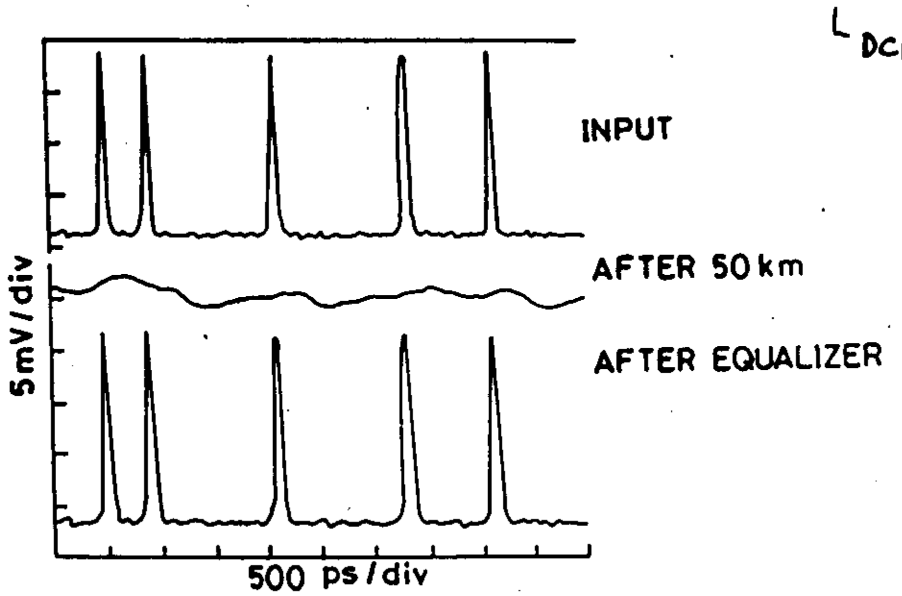
Dispersion ~ -293 ps/km.nm
(1550 nm)

Ref: Hawtof et al. OFC 1996, Post Deadline paper PD6



(a)

$D_{DCF} \simeq -548$ ps/km.nm
$L_{DCF} \simeq 1.44$ km



(a) A Schematic of dispersion compensation scheme in a conventional single mode fiber (CSF) system operating at 1550 nm using a dispersion compensatory fiber (DCF). EDFA is an erbium doped fiber amplifier. (b) A typical result showing the performance of a dispersion compensator for 2.5 Gb/s bit pattern [Poole etal, JLT, **12**, 1746 (1994)].

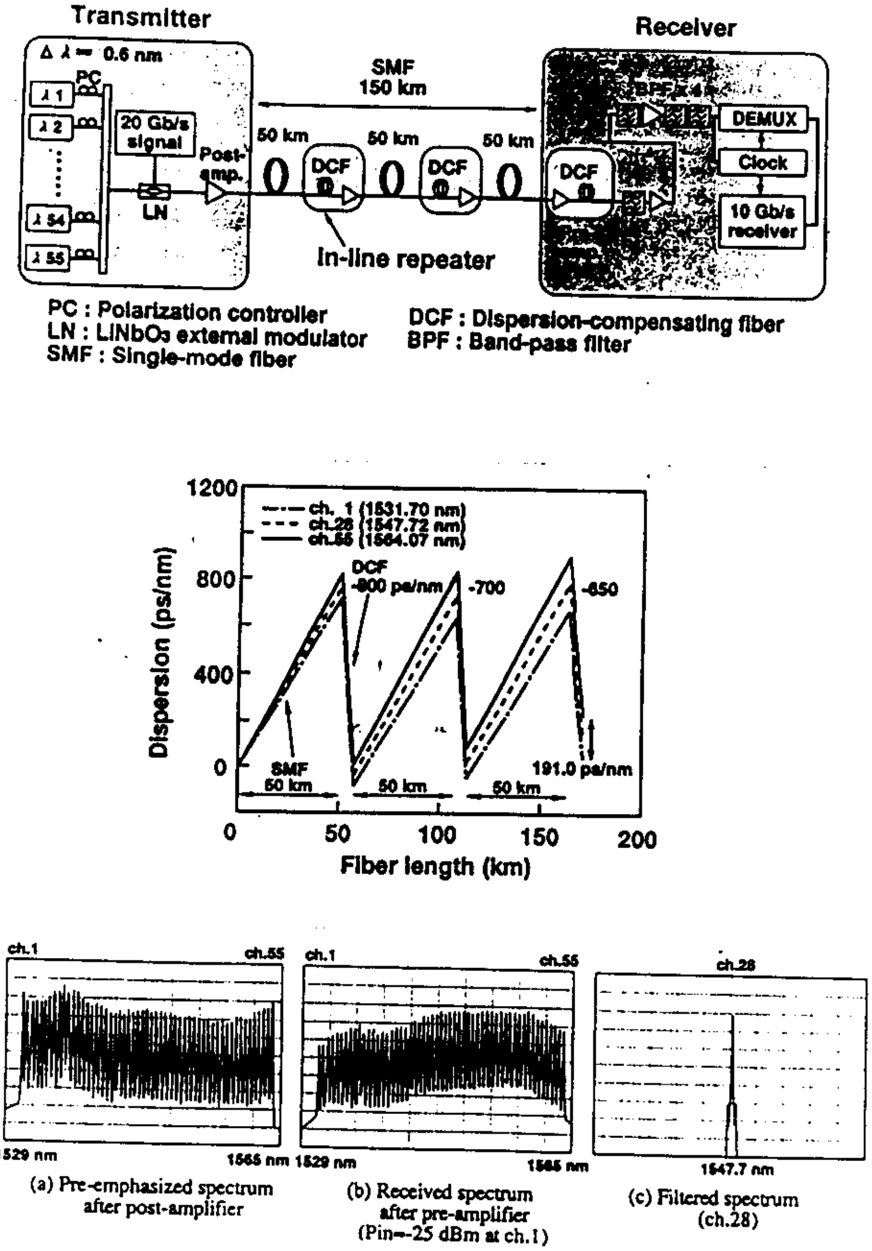
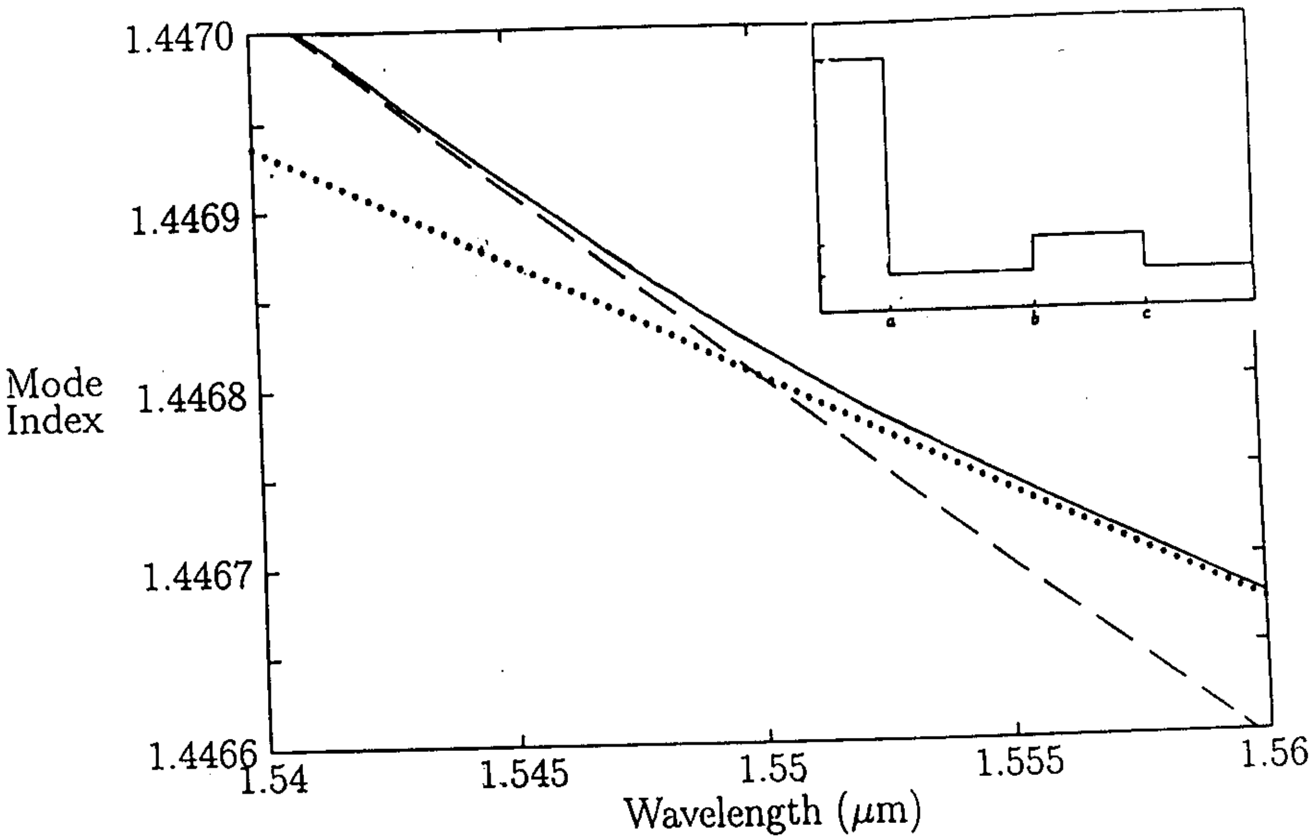
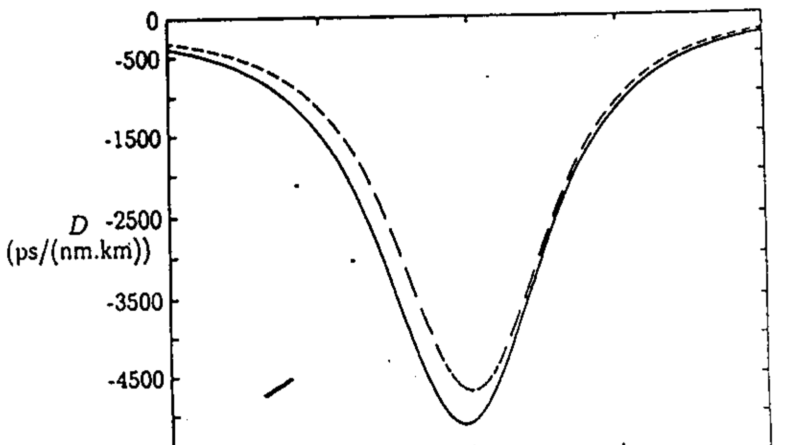


Figure 8: a) Experimental setup for 55 wavelength WDM transmission. b) The corresponding dispersion map. c) 55 wavelength spectra (H:3.6 nm/div, V: 5dB/div, Res: 0.1 nm) [adapted from Ref. 9].

Capacity : 55 x 20 Gb/s = 1.1 Terabits/s over 150 km

1 Tbit/s = sending contents of 1000 copies of a 30 volume encyclopaedia in 1 s





Variation of the mode index and D with wavelength for the refractive index profile of the dual-core DCF shown in the inset [Thyagarajan, Varshney, Palai, Ghatak and Goyal, " A novel design of a dispersion compensating fiber", IEEE Photonics Tech. Letts. **8**, November 1996].

10 mW laser beam

$A_{eff} \approx 50\ (\mu m)^2$

$\Rightarrow \quad I \approx 20{,}000\ W/cm^2$

With very low input optical powers (~ 10 mW) one can generate very high intensity levels (~ 20 kW/cm²) over very long interaction lengths (~ 100 km)

Non linear effects are relatively easy to observe using guided wave optics.

Self Phase Modulation (SPM)

$$\Psi = e^{i[\omega_0 t - kz]} \quad ; \; k(\omega_0) = k_0\, n(\omega_0) \qquad [k_0 = \frac{\omega_0}{c}]$$

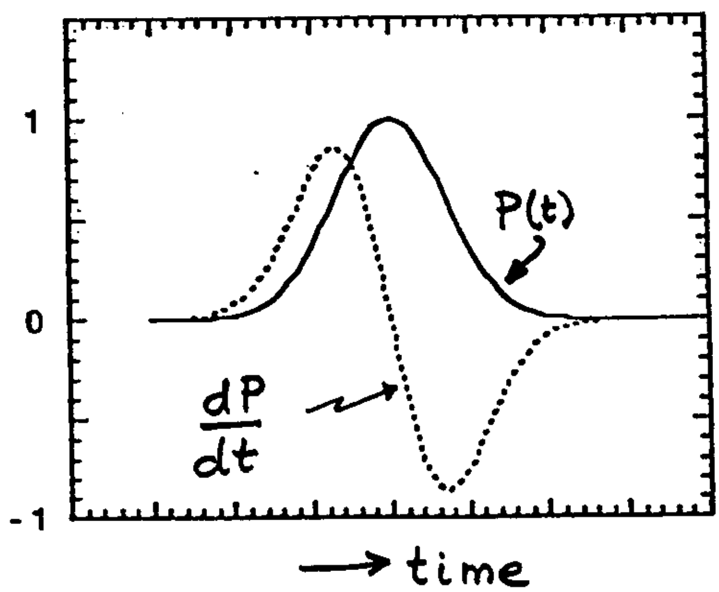
$$n = n_0 + n_2 I = n_0 + n_2 \frac{P}{A_{\text{eff}}}$$

$$\Psi = \psi(r)\; e^{i(\omega_0 t - \beta z)} = \psi(r)\, e^{i\phi}$$

$$\phi = \omega_0 t - \beta z \;\; ; \;\; \beta / k_0 = n_{\text{eff}} = (n_{\text{eff}})_0 + n_2 \frac{P}{A_{\text{eff}}}$$

$$\phi = \omega_0 t - \beta_0 z - k_0 n_2 z \frac{P(t)}{A_{\text{eff}}}$$

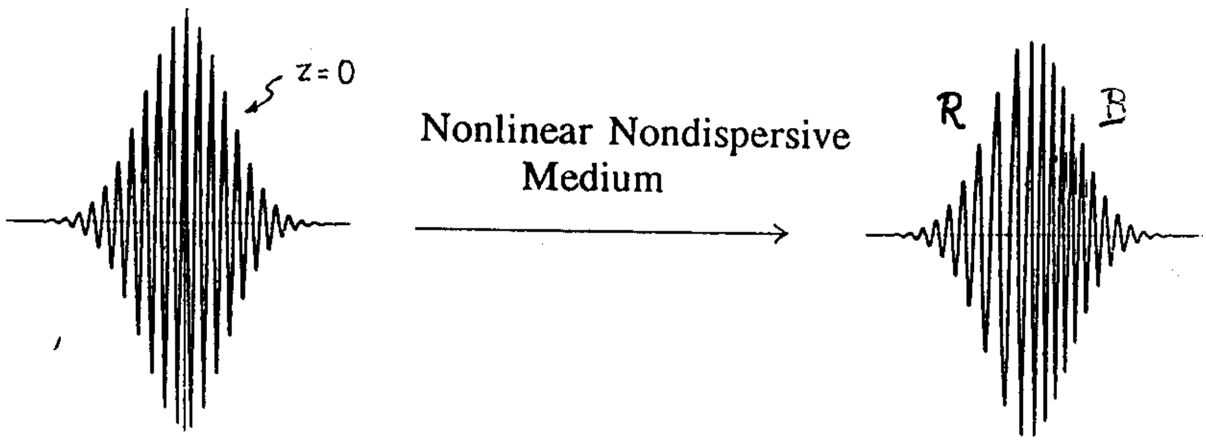
$$\omega(t) = \frac{d\phi}{dt} = \omega_0 - k_0 n_2 z \frac{1}{A_{\text{eff}}} \frac{dP}{dt}$$



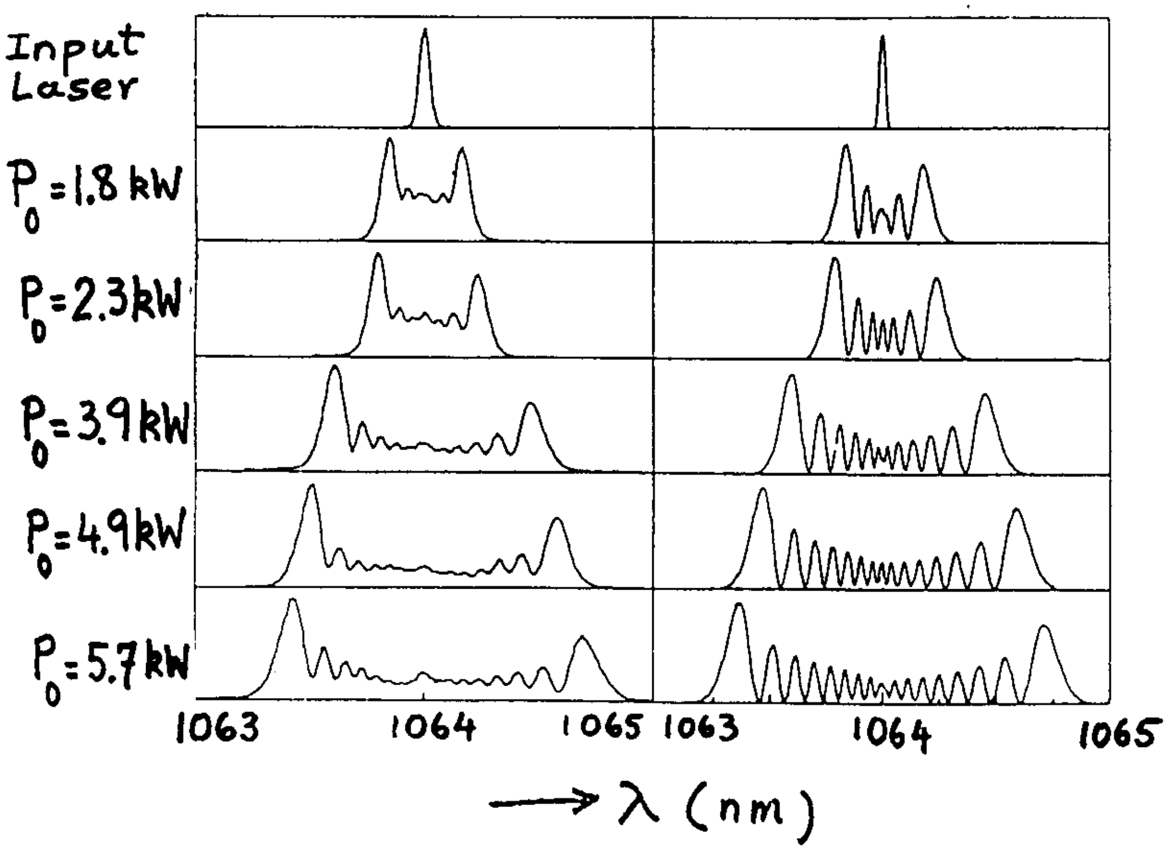
Self Phase Modulation (SPM)

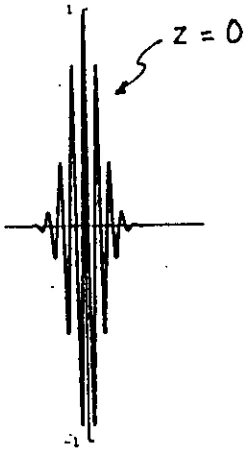
$$P(z,t) = P_0\, e^{-\frac{2\left(t-\frac{z}{v_g}\right)^2}{\tau_0^2}}$$

$$\omega(t) = \omega_0 + \frac{4k_0 n_2 z P_0}{A_{\text{eff}}\,\tau_0^2}\left(t-\frac{z}{v_g}\right) e^{-\frac{2\left(t-\frac{z}{v_g}\right)^2}{\tau_0^2}}$$

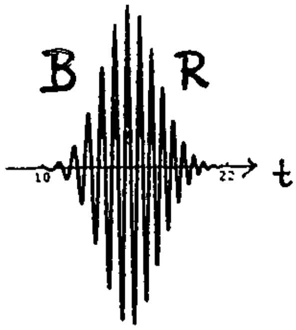


Chirping but no temporal broadening. New frequencie are generated.

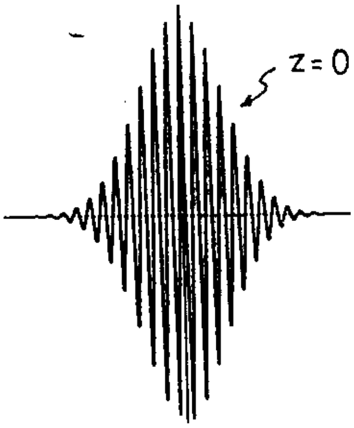




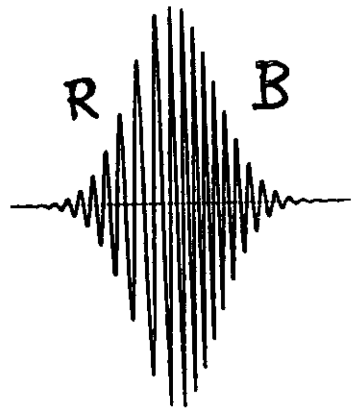
Linear Dispersive Medium →



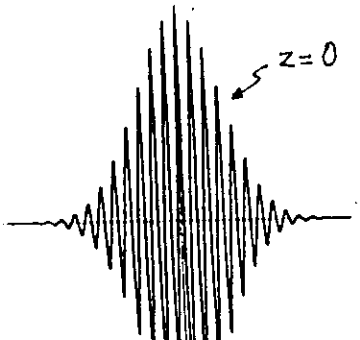
Temporal Broadening
&
Chirping



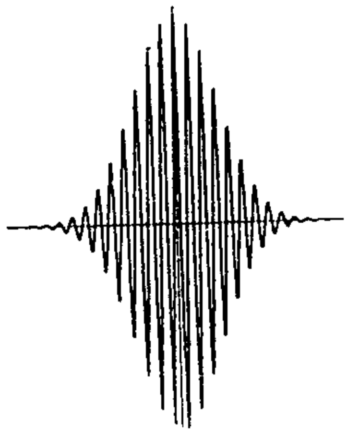
Nonlinear Nondispersive
Medium →

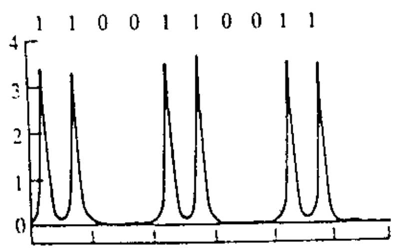


Chirping but no temporal broadening. New frequencie are generated.



Nonlinear Dispersive
Medium →





SOLITON

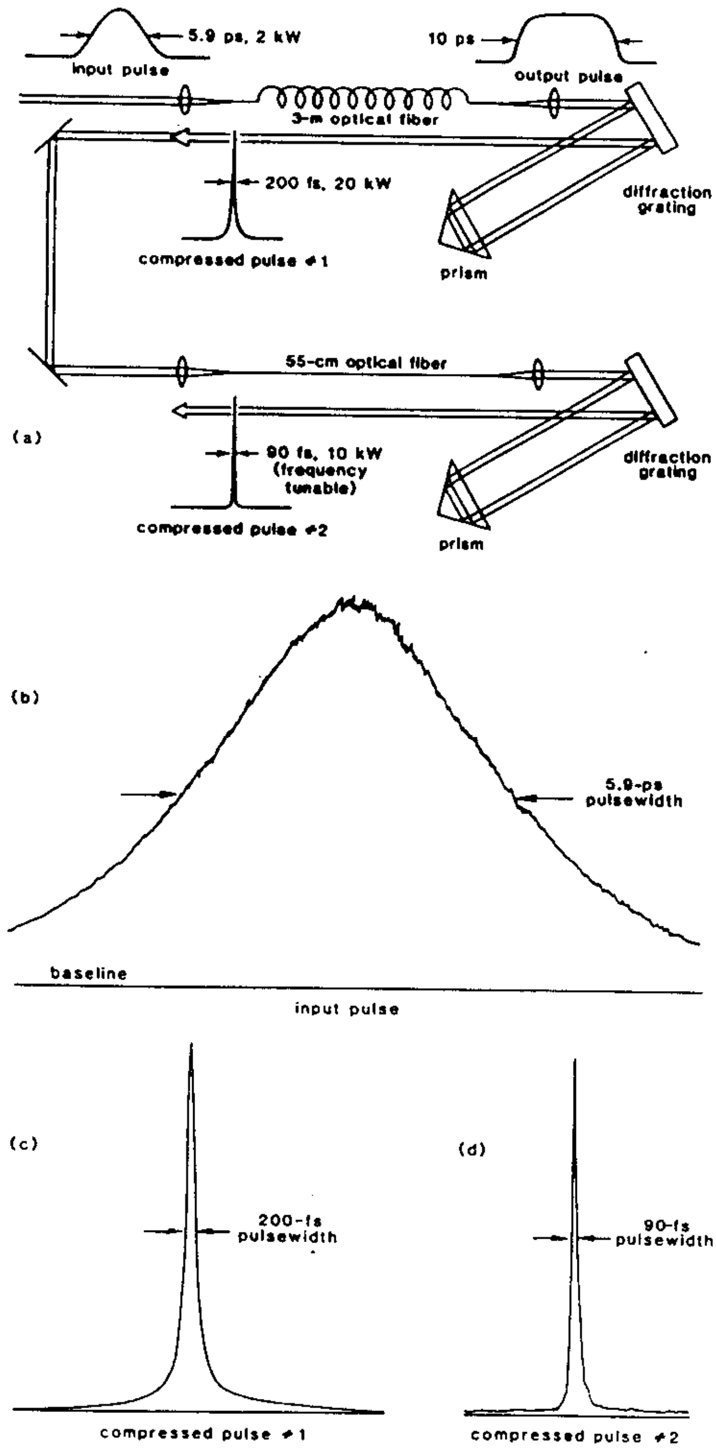


Fig. 16.8: Experimental arrangement for achieving pulse compression. With this arrangement an input pulse of 5.9 ps was compressed to 90 fs using spectral broadening through SPM in the optical fiber and pulse compression using a grating-prism arrangement. [After Nikolaus and Grischowsky (1983).]

$$\omega_{nl}(t) = \omega_0 + \frac{4k_0 n_2 z}{\tau_0^2}\left(t - \frac{z}{v_g}\right)\frac{P}{A_{eff}}$$

$$\omega_d(t) = \omega_0 + \frac{2\sigma}{(1+\sigma^2)\tau_0^2}\left(t - \frac{z}{v_g}\right)$$

$$\sigma = \frac{2z}{\tau_0^2}\alpha \quad ; \quad \alpha = \frac{\lambda_0^3}{2\pi c^2}\frac{d^2 n}{d\lambda_0^2}$$

$$\frac{4k_0 n_2 z}{\tau_0^2}\cdot\frac{P}{A_{eff}} = -\frac{2\sigma}{\tau_0^2} \qquad \sigma \ll 1$$

$$\Rightarrow \quad P = \frac{\lambda_0^3 A_{eff}}{4\pi^2 c\, n_2 \tau_0^2} D$$

$$D = -\frac{\lambda_0}{c}\frac{d^2 n}{d\lambda_0^2}$$

Nonlinear Schrödinger Equation

$$E(z,t) = \underbrace{e^{i[\omega_0 t - k(\omega_0)\, z]}}_{\text{Phase term}} \quad \underbrace{f(z,t)}_{\text{Envelope term}}$$

$$-i\left(\frac{\partial f}{\partial z} + \frac{1}{v_g}\frac{\partial f}{\partial t}\right) - \frac{1}{2}\alpha\frac{\partial^2 f}{\partial t^2} + \Gamma|f|^2 f = 0$$

$$\frac{1}{v_g} = k' = \left.\frac{dk}{d\omega}\right|_{\omega=\omega_0}$$

$$\alpha = k'' = \left.\frac{d^2k}{d\omega^2}\right|_{\omega=\omega_0}$$

$$\Gamma = \frac{1}{2}\,\omega_0\epsilon_0 n_0 n_2$$

Moving Frame

$$T = t - \frac{z}{v_g}\ ; \ z = z$$

In the moving frame

$$-i\frac{\partial f}{\partial z} - \frac{1}{2}\alpha\frac{\partial^2 f}{\partial T^2} + \Gamma|f|^2 f = 0$$

$$-i\frac{\partial f}{\partial z} - \frac{1}{2}\alpha\frac{\partial^2 f}{\partial T^2} + \Gamma|f|^2 f = 0 \qquad T = t - \frac{z}{v_g}$$

Propagation in absence of dispersion and non-linearity ($\alpha = 0$, $\Gamma = 0$)

$$\frac{\partial f(z,T)}{\partial z} = 0$$

$$\Rightarrow f = f_0(T) = f_0\left(t - \frac{z}{v_g}\right)$$

Propagation in presence of dispersion only ($\Gamma = 0$) 0)

$$-i\frac{\partial f(z,T)}{\partial z} - \frac{1}{2}\alpha\frac{\partial^2 f(z,T)}{\partial T^2} = 0$$

$$f(z,T) = \int A(\Omega)\, e^{i(\Omega T - \frac{1}{2}\alpha\Omega^2 z)}\, d$$

Propagation in presence of nonlinearity

$$-i\frac{\partial f(z,T)}{\partial z} + \Gamma |f|^2 f(z,T) = 0$$

$$\frac{\partial |f|^2}{\partial z} = 0$$

$$|f|^2 = F(T) = F\left(t - \frac{z}{v_g}\right)$$

$$f(z,T) = f_0(T)\, e^{-i\phi(z,T)}$$

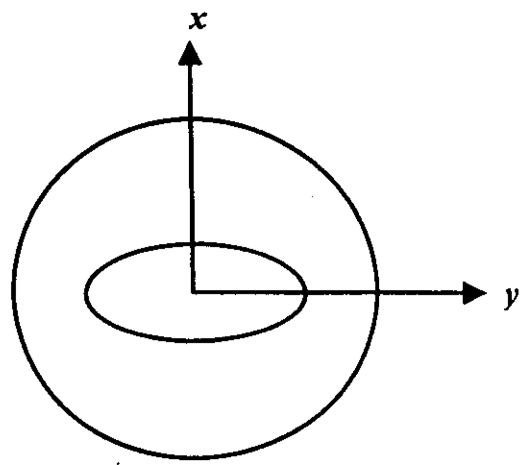
$$E(z,T) = f_0\left(t - \frac{z}{v_g}\right) e^{\left[i\left\{\omega_0 t - \Gamma \left|f_0\left(t-\frac{z}{v_g}\right)\right|^2 z - k(\omega_0) z\right\}\right]}$$

In presence of dispersion and nonlinearity we get the soliton solution

$$f(z,T) = E_0 \,\mathrm{sech}\left[\gamma\left(t - \frac{z}{v_g}\right)\right] e^{-igz}$$

$$g = -\frac{1}{2}\alpha\gamma^2 = \frac{1}{2}\Gamma E_0^2$$

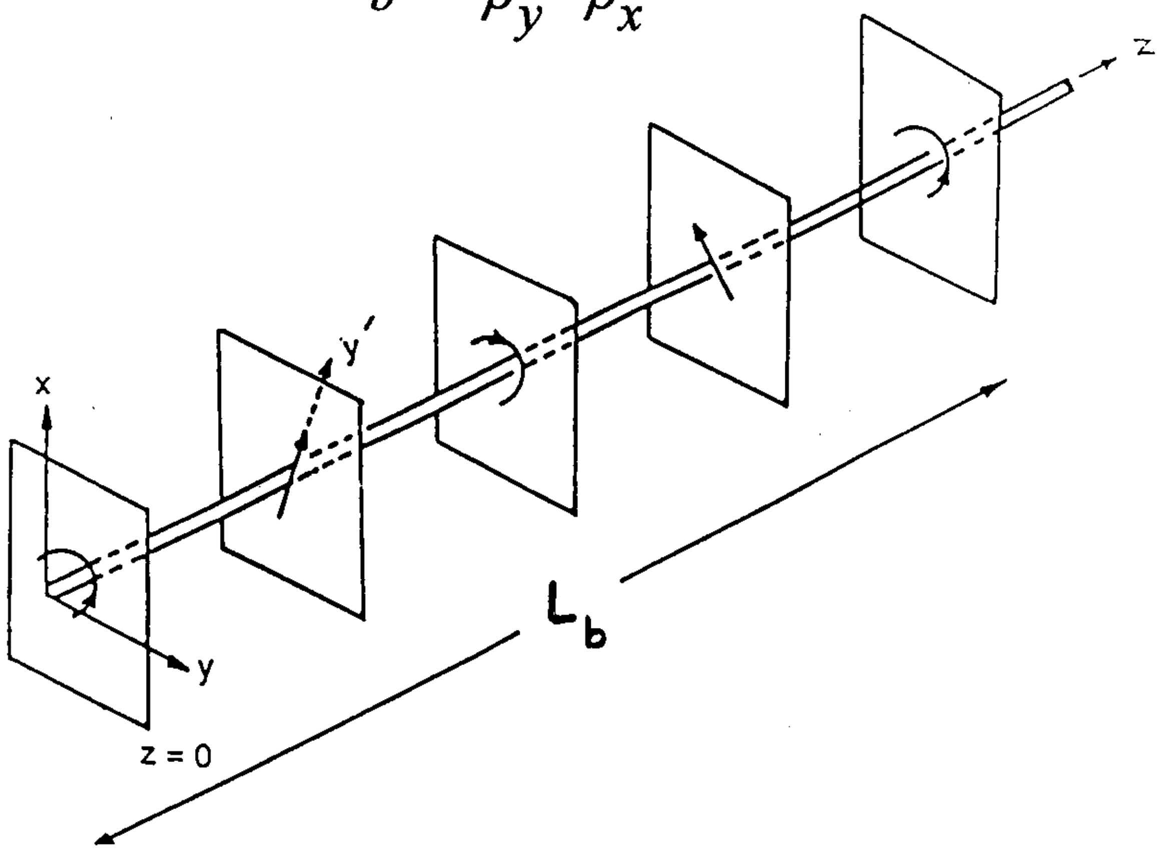
Elliptic core fiber

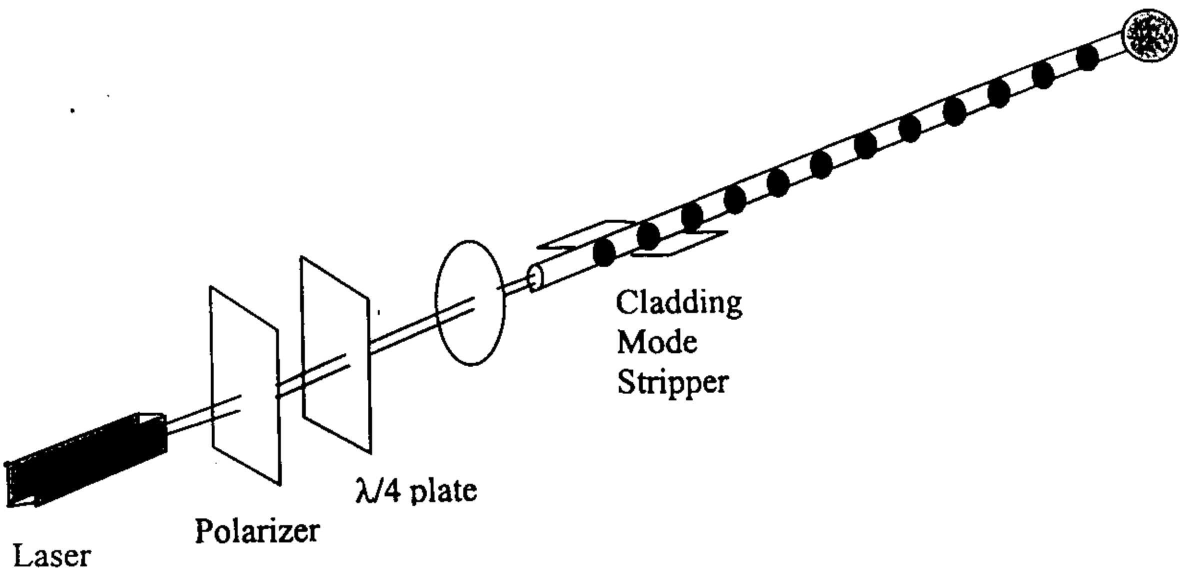


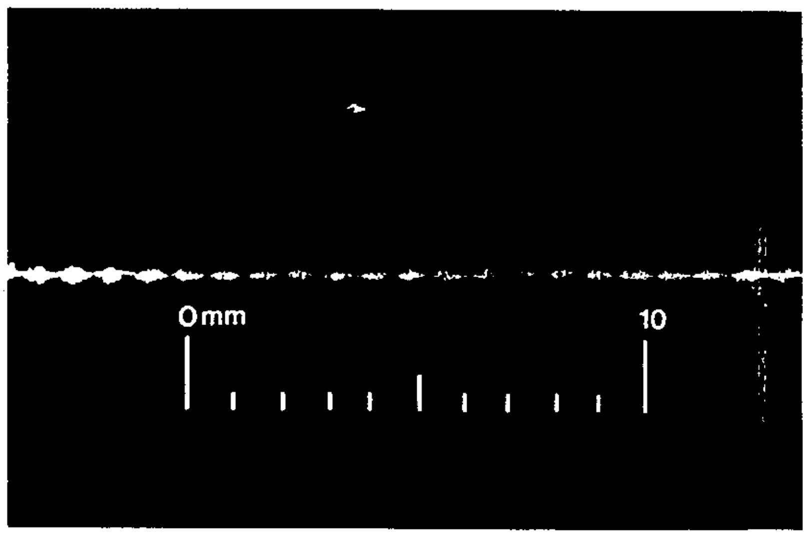
$$\mathbf{E} = \hat{\mathbf{x}} \; \psi(x,y) \cos(\omega t - \beta_x z)$$

$$\mathbf{E} = \hat{\mathbf{y}} \; \psi(x,y) \cos(\omega t - \beta_y z)$$

Beat Length $L_b = \dfrac{2\pi}{\beta_y - \beta_x}$ $\approx$ **few mm**




Cladding
Mode
Stripper
λ/4 plate
Polarizer
Laser


0mm
10

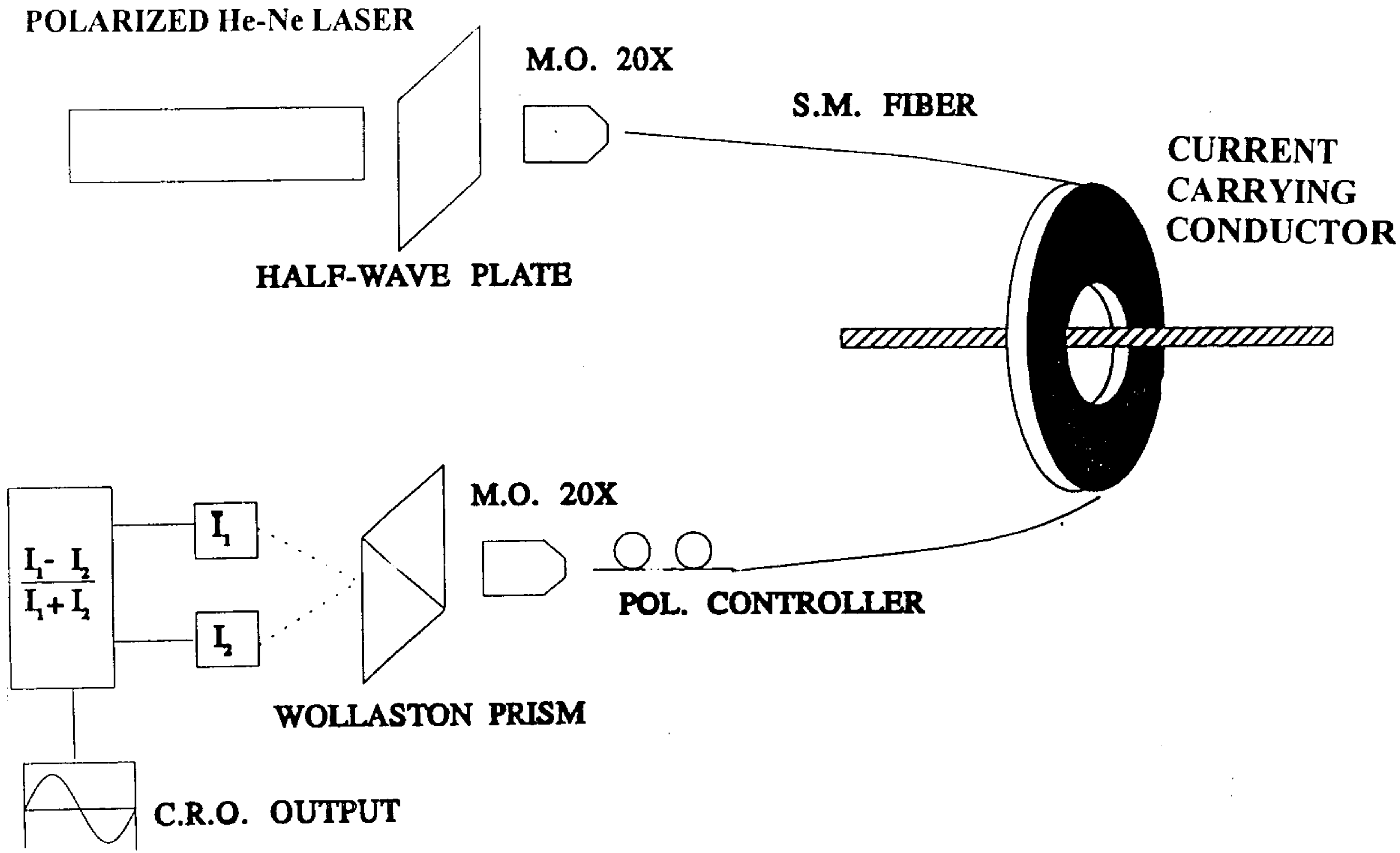
Pure silica

$$\varepsilon = \begin{pmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_1 \end{pmatrix} \quad ; \quad \varepsilon_1 \approx 2.25$$

When a polarized beam propagates through silica along $\vec{B}$, then

$$\varepsilon = \begin{pmatrix} \varepsilon_1 & \varepsilon' & 0 \\ -\varepsilon' & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_1 \end{pmatrix} \quad ; \quad \varepsilon' \approx 10^{-7} i$$

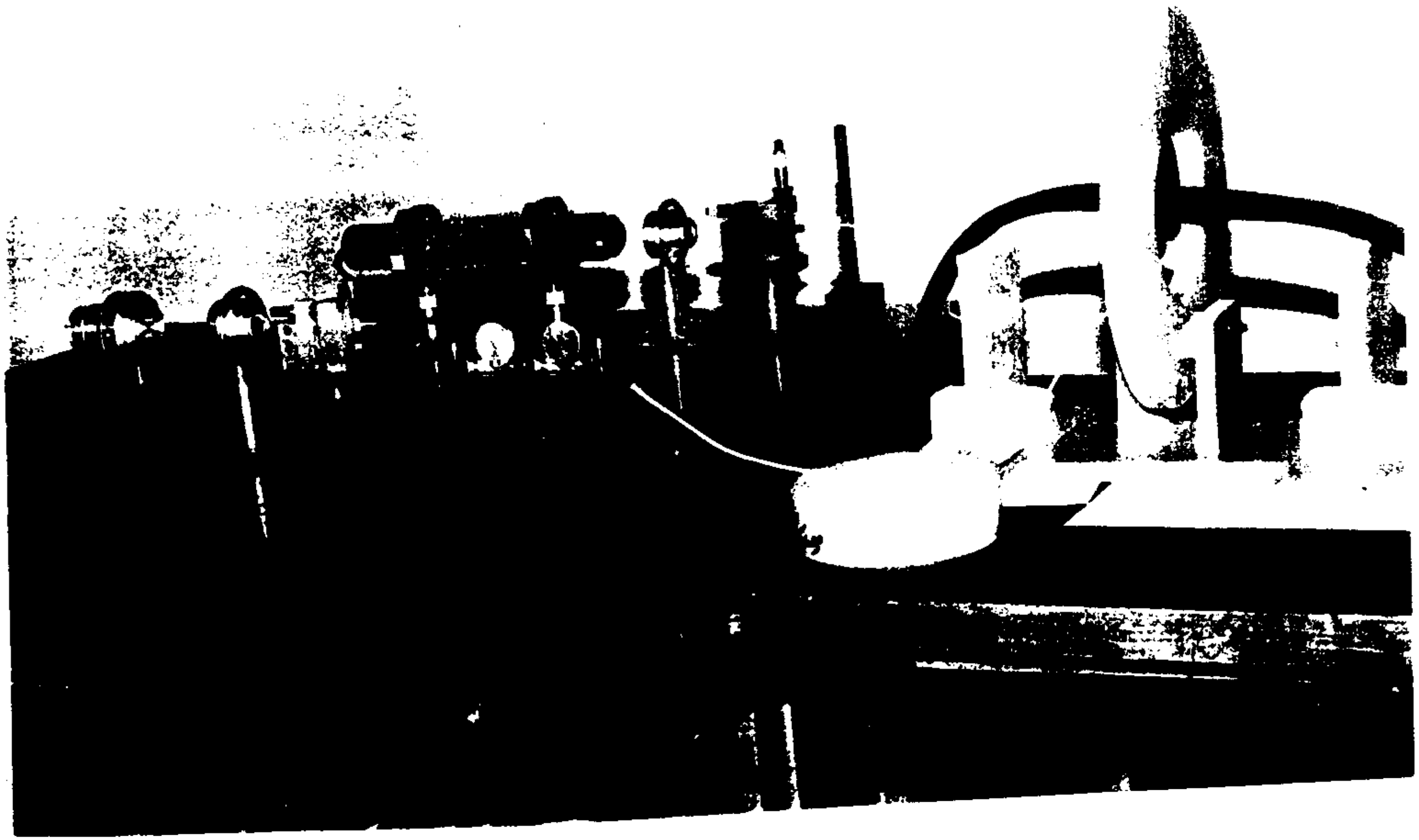
per kG of applied magnetic field.



FIBER OPTIC CURRENT SENSOR

5-4

FIBER – OPTIC CURRENT SENSOR



POLARIZATION MAINTAINING FIBERS

Most fiber optic systems rely upon detection of optical pulses in a photodetector that is independent of optical polarization or phase. However, applications in

Polarimetric & Interferometric sensors, coherent optical communication systems etc.

require that the

SOP (state of polarization) be maintained for distances ranging from ~ 100 meters (for sensor applications) to ~ 100 km (for coherent communication systems).

High Birefringent Fibers

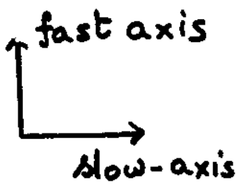
β_x very different from β_y

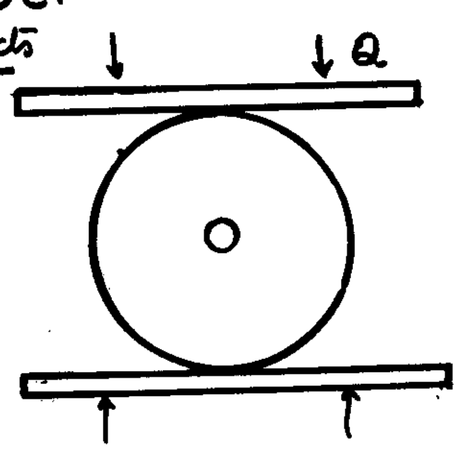
⇒ coupling between x and y polarized modes due to perturbations is almost negligible

⇒ SOP is (almost) maintained in the fiber

External Birefringence effects

1.





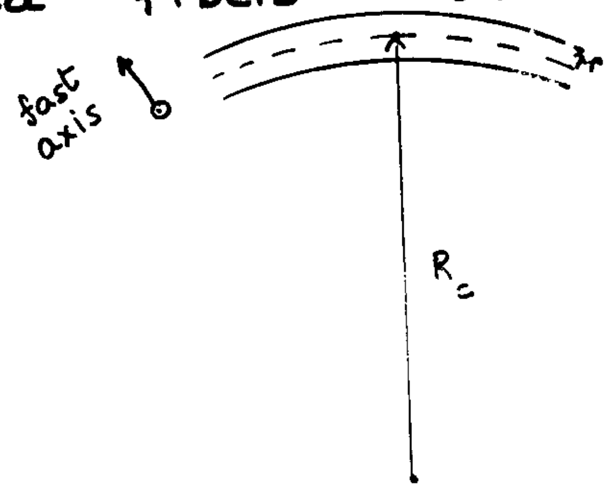
Force Q acting between parallel jaws.

$$\beta_{slow} - \beta_{fast} \approx \text{const.} \ \frac{Q}{\ell}$$

const. ≈ 1 rad/N

All numerical values correspond to silica fibers at 6328 Å

2.

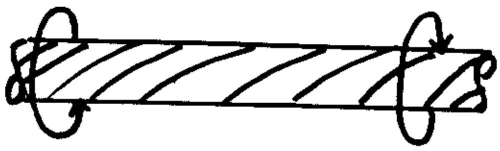


$$\beta_{slow} - \beta_{fast} \approx \text{const.} \left(\frac{1}{1}\right.$$

const. ≈ 4.9×10^{6} rad/

3. Circular Birefringence due to Elastic Twist.

⇒ Modes are circularly polarized (≡ Optical Activity)



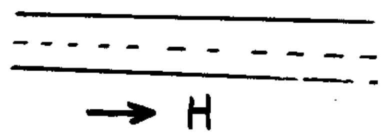
$$\beta_{slow} - \beta_{fast} \approx \text{const} \cdot \tau$$

τ: twist in rad/m

const. ≈ 0.13 – 0.16

4. Circular Birefringence due to axial magnetic field (FARADAY EFFECT)

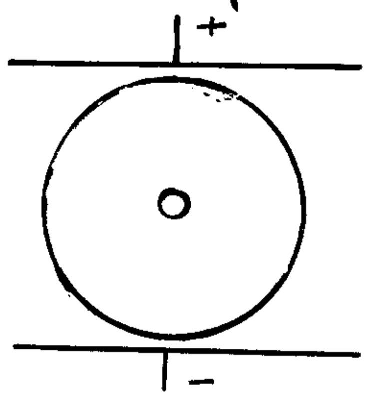
$$\beta_{slow} - \beta_{fast} \approx \text{const.}\ H$$



5. Linear Birefringence by application of a transverse electric field (Electro-optic Kerr Effect)

$$\beta_{slow} - \beta_{fast} \approx \text{const} \cdot E^2$$

$\text{const} \approx 6 \times 10^{-16}\ m/V^2$



Ref: R. Ulrich in Fiber Optic Rotation Sensors (Eds: Ezekiel & Arditty) Springer-Verlag (1982) & references therein

40 lecture course on FIBER OPTICS

Basic characteristics of the optical fiber

Numerical Aperture and attenuation; Pulse dispersion in step index and graded index optical fibers: ray analysis

Material dispersion

Modes of optical waveguides

Single mode fibers

The Gaussian approximation for the fundamental mode & loss calculations at fiber joints; far field pattern

Interplay of waveguide & material dispersion

Conventional single mode fibers, Dispersion shifted fibers & Dispersion compensating fibers, Non-zero dispersion shifted fibers, Dispersion management

Design of a fiber optic communication system

Special Topics

Nonlinear effects in Fibers

Self Phase Modulation, Soliton Propagation

Erbium doped fiber amplifiers

Fiber optic devices

directional couplers, fiber polarizers

Fiber gratings

Fiber optic sensors