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WINTER COLLEGE
on
QUANTUM AND CLASSICAL ASPECTS
of
INFORMATION OPTICS

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Optical Communication Channels

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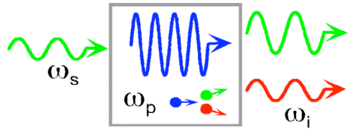
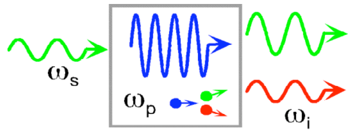


Optical Communication Channels

Prem Kumar
Northwestern University

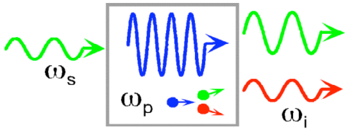
Winter College on
Quantum and Classical Aspects of Information Optics
ICTP, Trieste, Italy
February 8, 2006

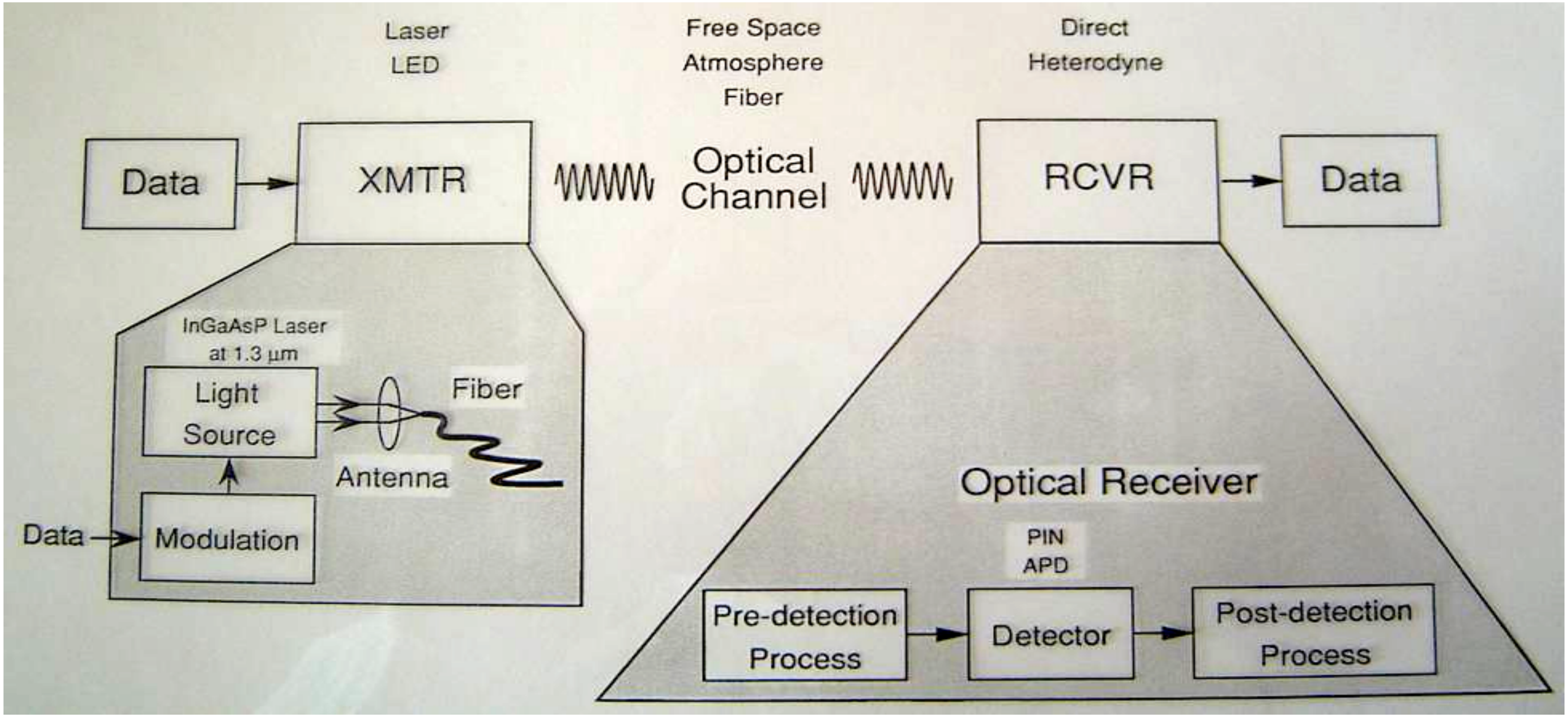


Topics for Lecture 2

- Free-space channel for optical communications
- Optical fiber channel for optical communications
- Wavelength/frequency division multiplexing
- Optical amplifiers, EDFA, Raman, Parametric etc.
- Channel impairments due to ASE and Nonlinearity
- Role of quantum noise in optical Communications
- Signal regeneration and some advanced concepts

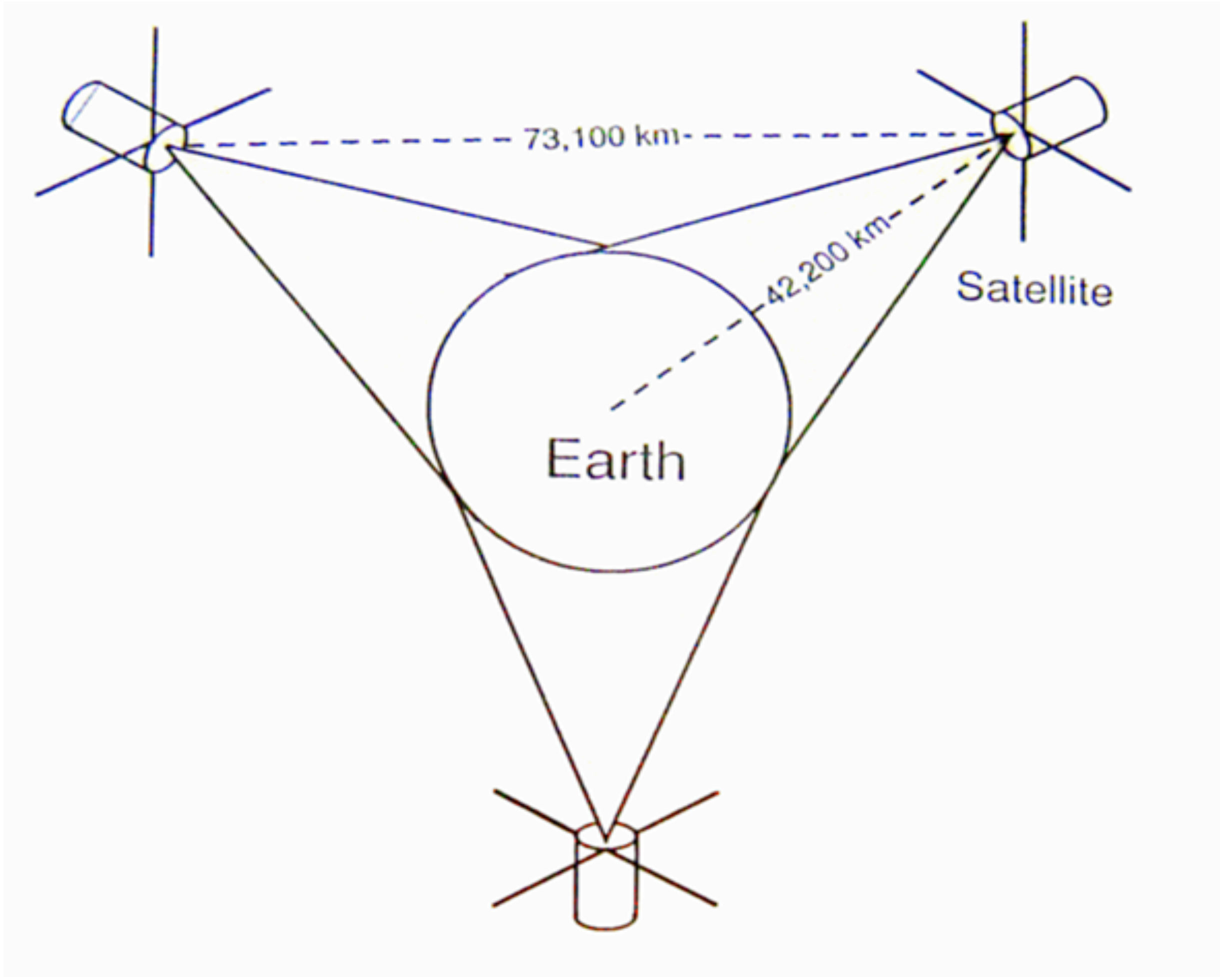
A Generic Optical Communication System



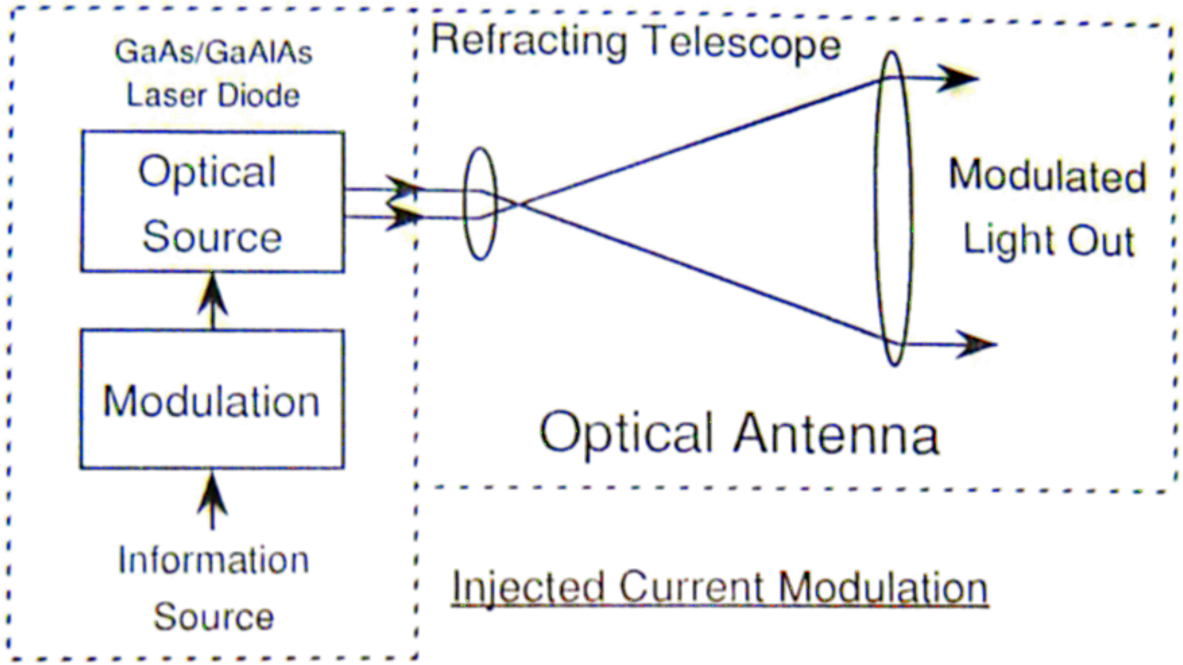


This is an old schematic, but now a days in most high-end fiber-optic systems the lasers are at 1.5 mm wavelength.

Free-Space Optical Channel

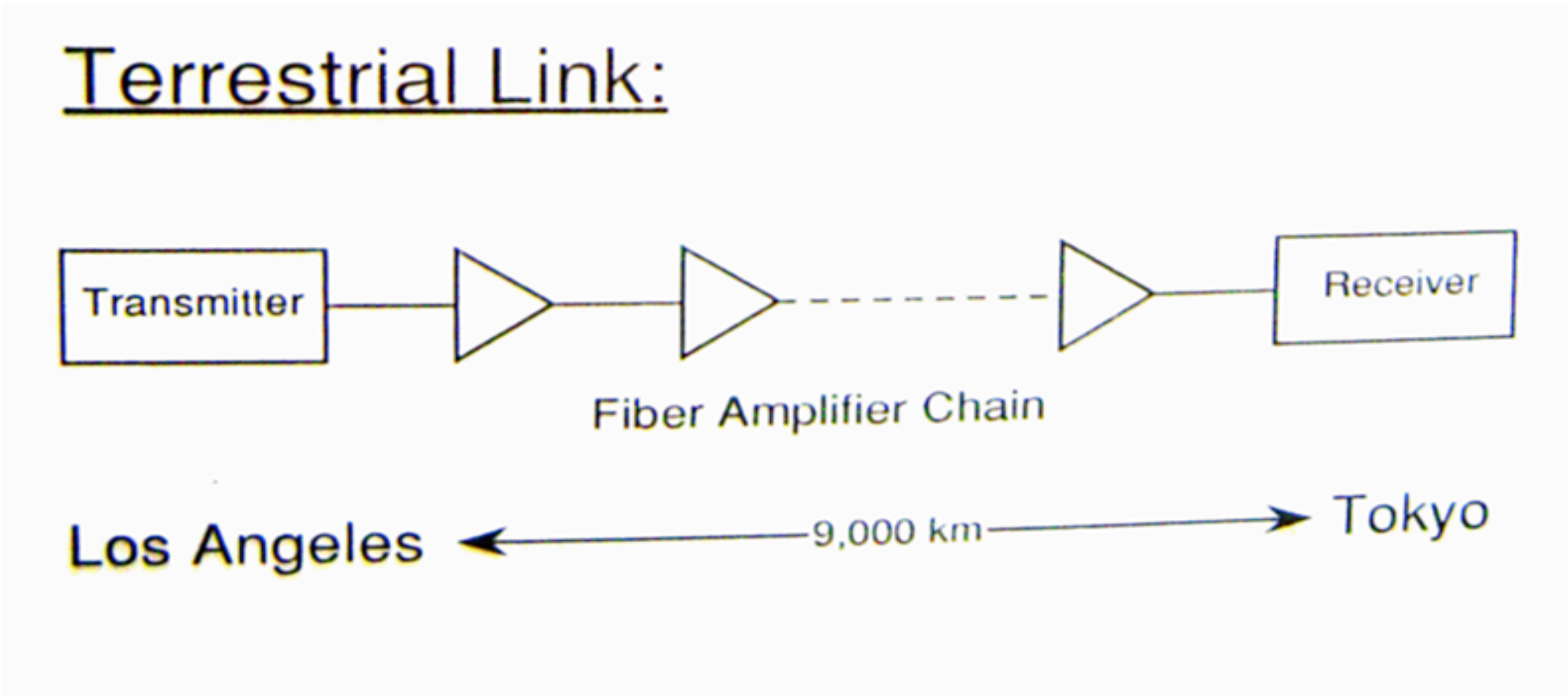


Transmitter for Free Space Channel

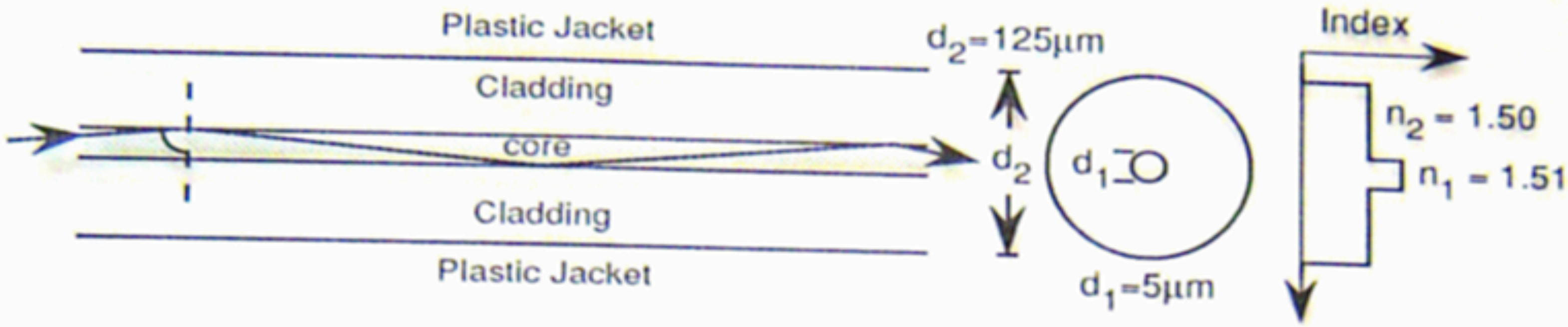


Injected Current Modulation

Optical Fiber Channel

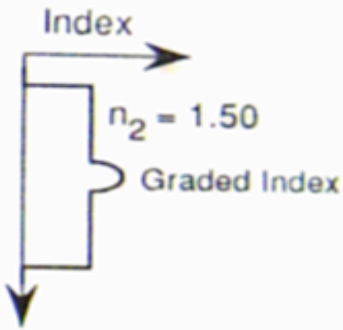


Structure of Optical Fiber

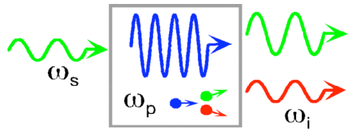


Schematic of a Step Index Single Mode Fiber

Fiber Types: Single Mode (d_1 = 5 µm), Multimode (d_1 = 50 µm) — Step Index or Graded Index



Fiber Material: Fused Silica, Plastic



Key Properties of Optical Fiber

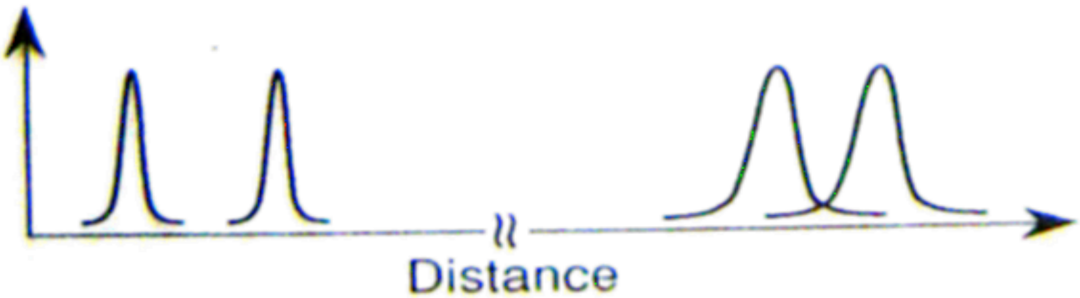
- Loss (less than 0.2 dB/km at 1.55 μm)

  The emergence of the erbium-doped fiber amplifier has revolutionized fiber-optic communications

- Dispersion (group velocity is a function of λ)

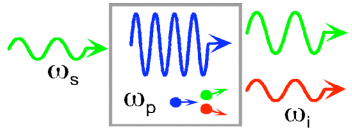
- Nonlinearity (intensity dependent refractive index)

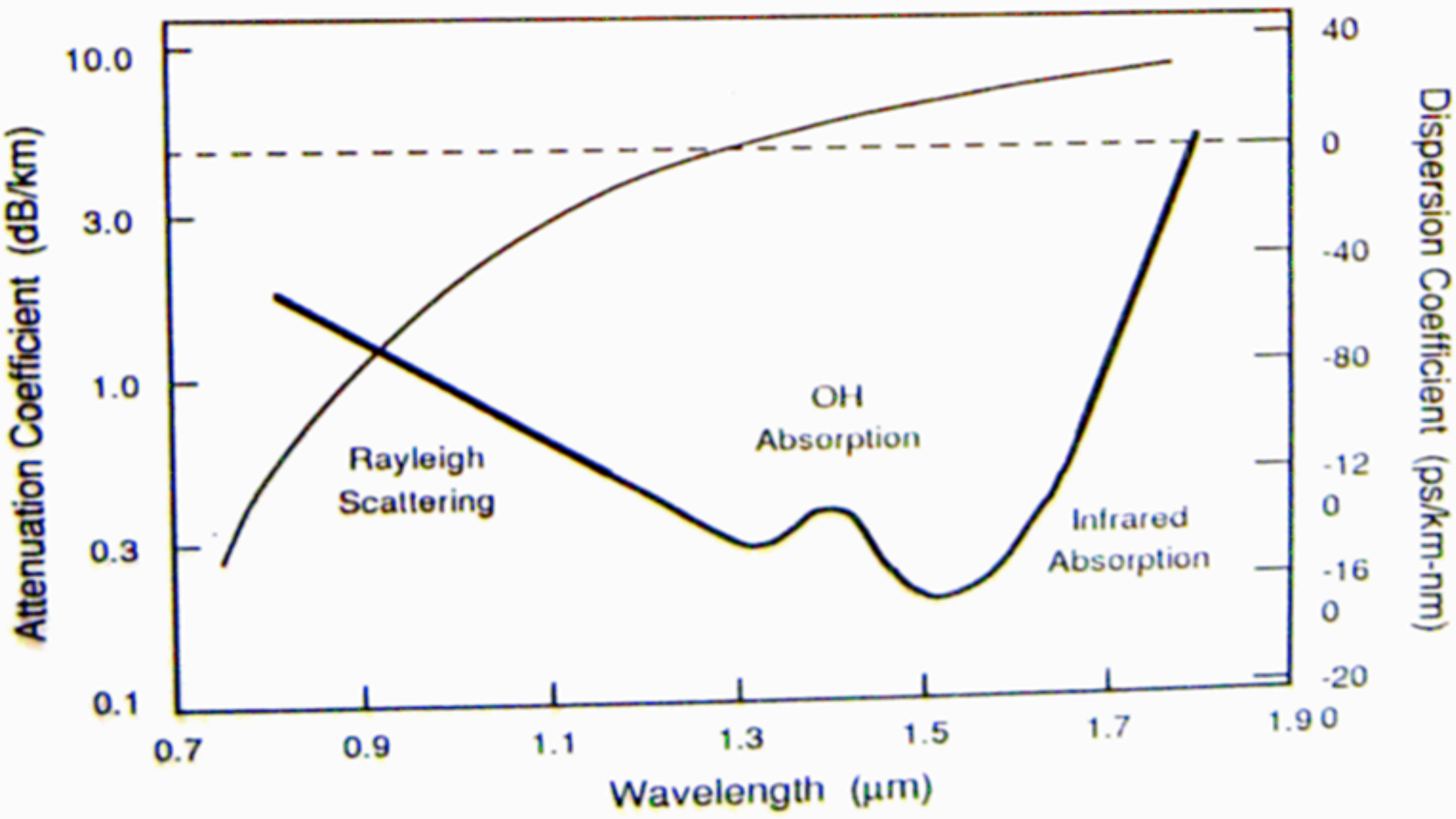
  Dispersion and nonlinearity can compensate each other to form *optical solitons*
  -- pulses of light that travel without spreading



Effect of Dispersion

Attenuation Spectra of Fused Silica Fibers





* R. J. Hoss, *Fiber-Optic Communications: Design Handbook*, (Prentice-Hall, New Jersey, 1990).

Optical Power Transfer

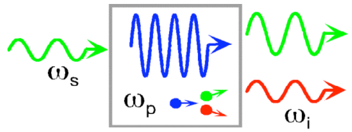
- **Free-Space Channel:**

  The received optical power is given by

$$P_r = P_t \left(\frac{A_t A_r}{\lambda L} \right)^2, \qquad (1)$$

whenever $\sqrt{A_t A_r} \ll \lambda L$, i.e., the receiver is in the far-field region. Here

P_r = optical power at the receiver,
P_t = optical power transmitted,
A_r = area of the receiving aperture,
A_t = area of the transmitting aperture,
λ = wavelength of light, and
L = transmitter-receiver distance.



Optical Power Transfer

- **<u>Fiber-Optic Channel:</u>**

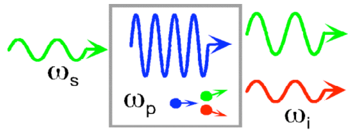
$$P_r = P_c\, e^{-\log(10)\alpha L/10}\,, \qquad (2)$$

where

P_r = optical power received,
P_c = optical power coupled into the fiber,
α = fiber loss coefficient in dB/km.

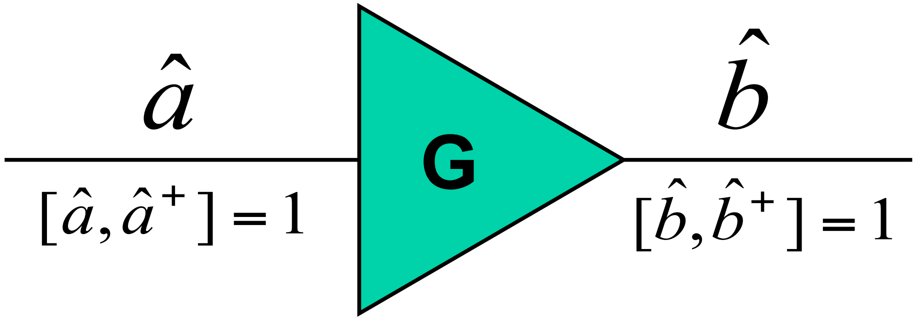
<u>Note:</u> One should take into account the various coupling losses.

Fundamental Noise Limits of Linear Optical Amplifiers



Lumped Amplifier Model:

Haus & Mullen, 1962; Caves, 1982; Yuen, 1992



- Phase Insensitive Amplifiers (PIA)
  - Erbium-doped fiber amplifier
  - Semiconductor optical amplifier
  - Fiber Raman Amplifier
  - Optical parametric amplifier
- Phase Sensitive Amplifiers (PSA)
  - Optical parametric amplifier

- For PSA:

$$\hat{b} = \sqrt{G}\,\hat{a} + \sqrt{G-1}\,\hat{a}^{+}$$

- Or in terms of quadratures

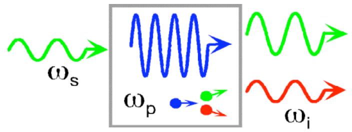
$$\hat{b} = \sqrt{g}\,\hat{a}_1 + i\frac{1}{\sqrt{g}}\,\hat{a}_2$$

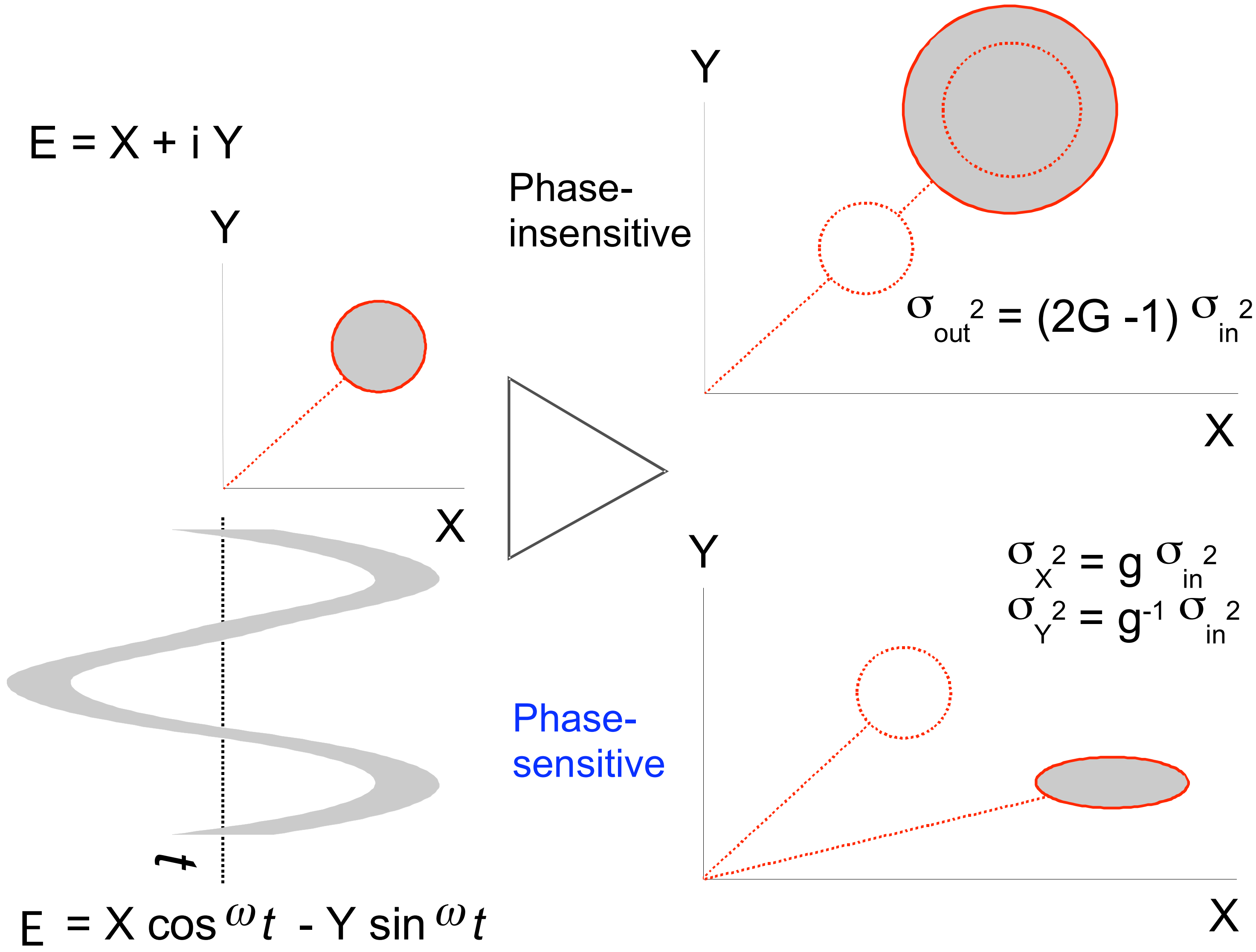
- No need for an extra noise source

- For homodyne detection and for direct detection with $\langle N_a \rangle \gg 1$

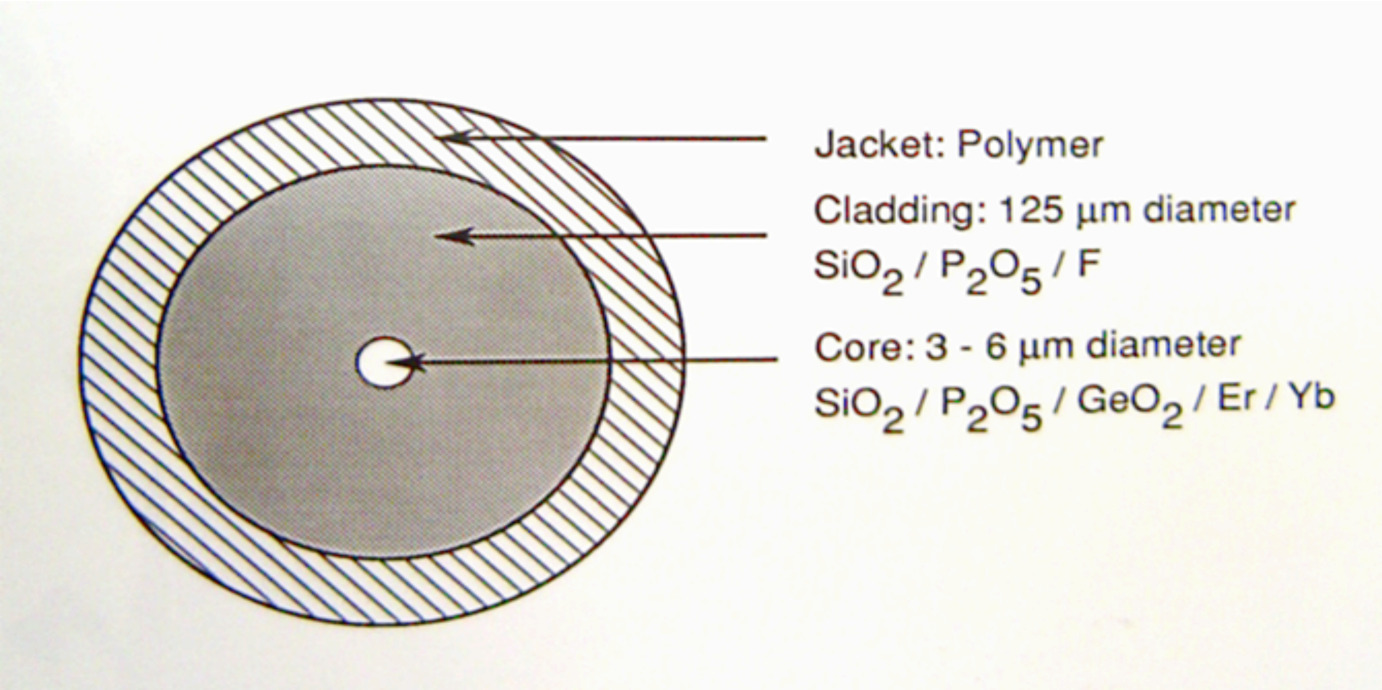
$$NF_{PSA} = 1 \;\; (0\,dB)$$

Pictorial View of Amplification of Coherent Input Light

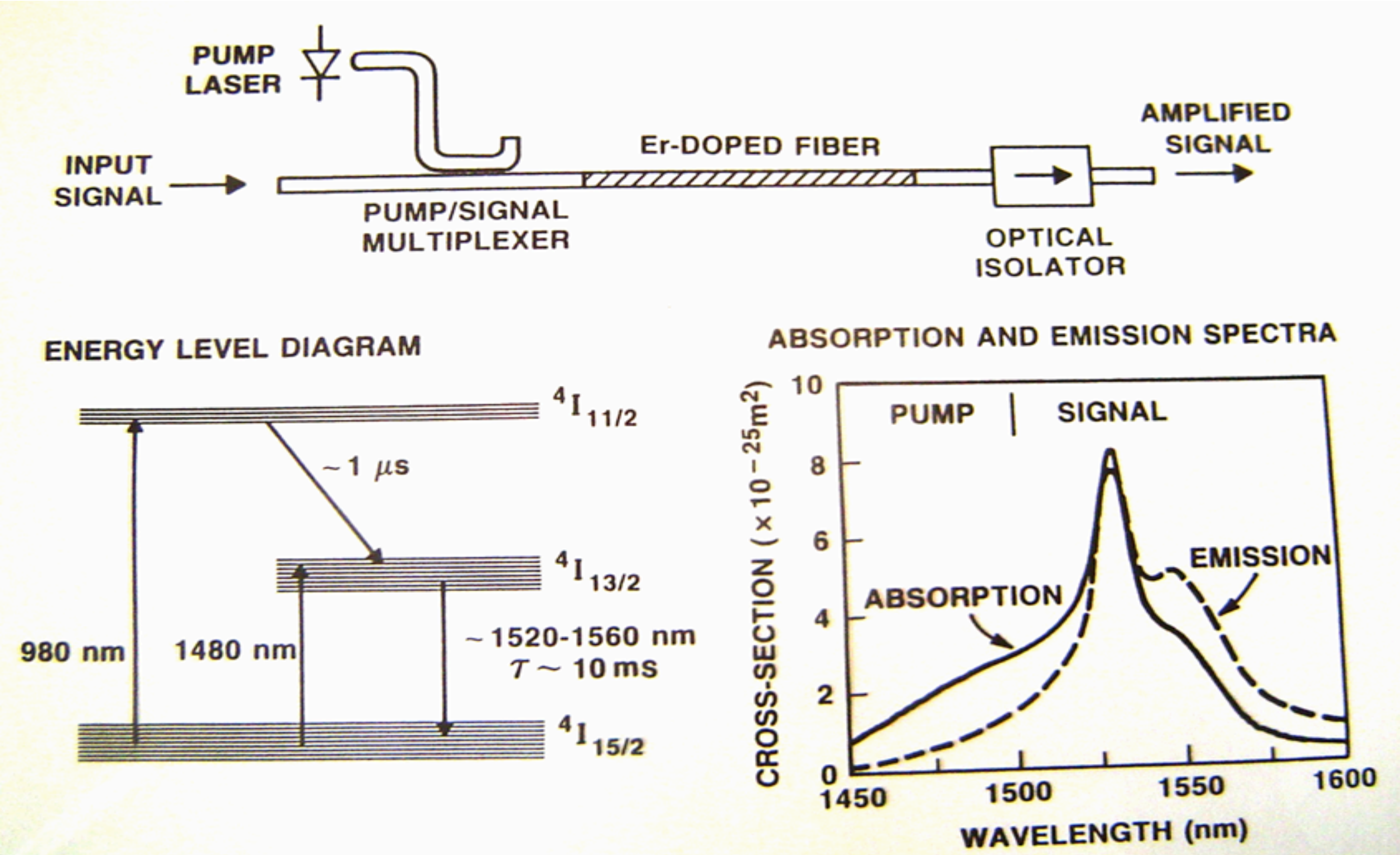




Erbium-Doped Fiber

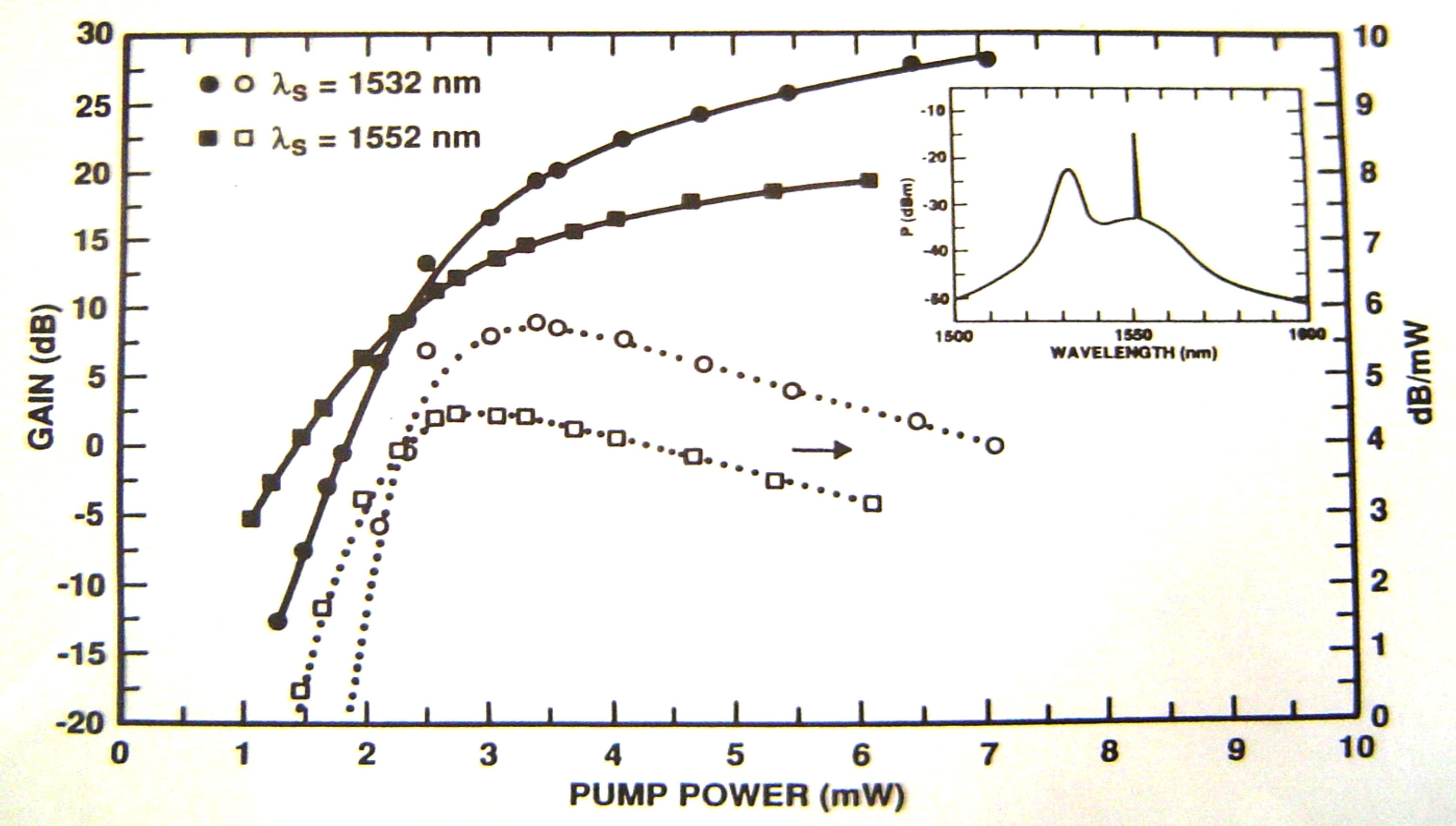


Erbium-Doped Fiber Amplifier

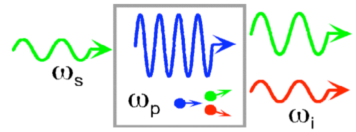


Gain Properties of an EDFA

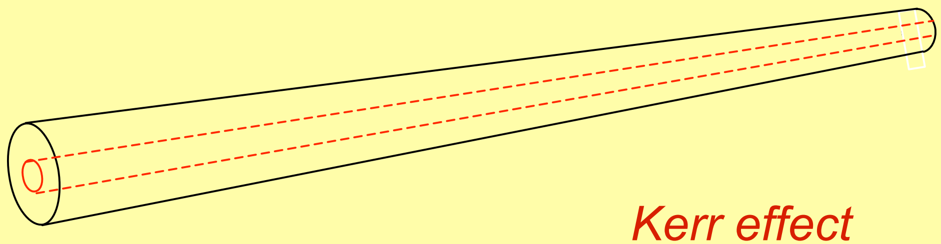
Pump Wavelength = 980 nm



Nonlinear Optics in Fiber



Glass as a c$^{(3)}$ Medium



Kerr effect

- <u>Small core → high intensity</u>
- Large interaction length
- Excellent mode matching
- Low loss for some λ's
- Doping is possible
- Dispersion
- Relatively small $\chi^{(3)}$

Pump SPM

$$\frac{\partial A_p}{\partial z} + \frac{\alpha}{2} A_p + i\frac{\beta_2}{2}\frac{\partial^2 A_p}{\partial T^2} = i\gamma(|A_p|^2 A_p)$$

XPM

Four-Wave Mixing

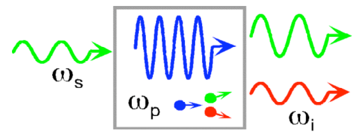
$$\frac{\partial A_{s(i)}}{\partial z} + \frac{\alpha}{2} A_{s(i)} + d\frac{\partial A_{s(i)}}{\partial T} + i\frac{\beta_2}{2}\frac{\partial^2 A_{s(i)}}{\partial T^2} = i\gamma\left[|A_p|^2 A_{s(i)} + A_p^2 A_{i(s)} * \exp(i\Delta k z)\right]$$

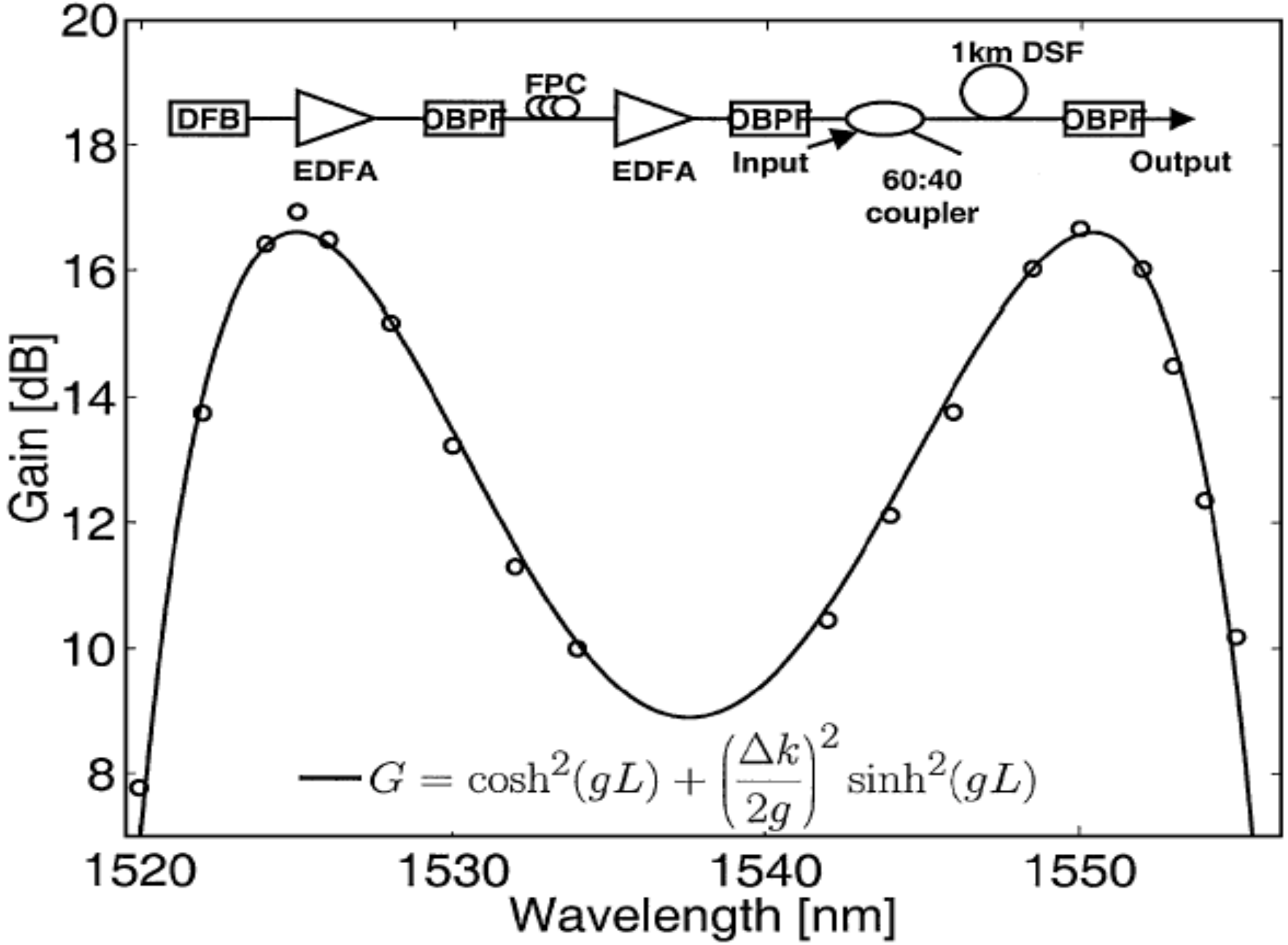
$$2\omega_p = \omega_s + \omega_i \qquad \Delta k = 2k_p - k_s - k_i \qquad \gamma = \frac{n_2 \omega_p}{A_{eff} c}$$

Phase Matching

Nonlinear Coefficient

Fiber Optical Parametric Amplifier (FOPA): An Example of a PIA



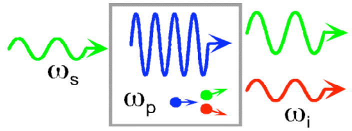


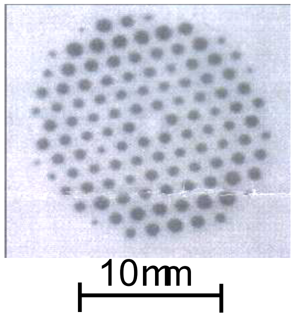
$$g = \sqrt{\left[(\gamma P_p)^2 - \left(\frac{\delta k}{2}\right)^2\right]}$$

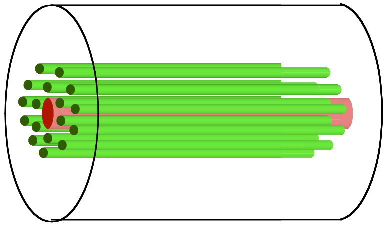
$$\delta k = 2\gamma P_p + (k_s + k_i - 2k_p) \approx 2\gamma P_p + \beta_2(\omega_s - \omega_p)^2$$

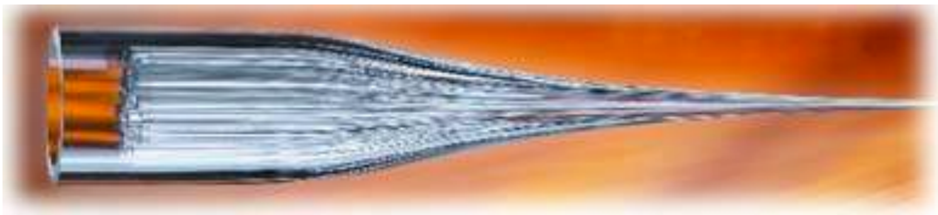
- 1 km linear FOPA configuration
- Gain as high as 20 dB
- 1537.5 nm pump
- 1.3 W pump peak power
- 700 ns pump pulses
- 8 kHz pump pulse rate
- CW signal

Crystal Fibre™ Microstructure Fiber









Fiber Parameters

- $n_2 = 2.8 * 10^{-20}\ m^2/W$
- Core diameter = 2.4 +/- 0.2mm, surrounded by a hexagonal array of ~0.8mm diameter air voids.
- Effective mode area of 7mm^2 at 1550nm
- a = 0.1dB/m @ 1550 nm
- g » 24 W^{-1} Km $^{-1}$ at 1550nm
- Asymmetry in the core results in polarization-maintaining fiber

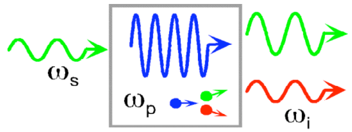
Pros/Cons

+ Smaller core Þ higher nonlinear coefficient
+ Shorter interaction length
+ Less optical power required
+ Doping is possible
– Larger dispersion slope
– Higher loss for some l 's

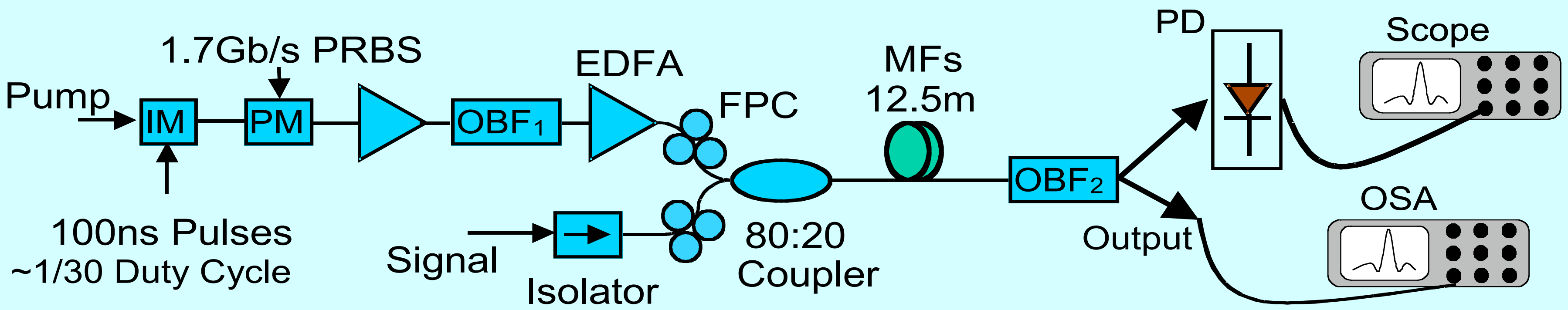
	MF1	MF2
l_0	1544 +/- 5nm	1558 +/- 5nm
Length	12.5m	11m

Telecom-Band High-Gain MFOPA

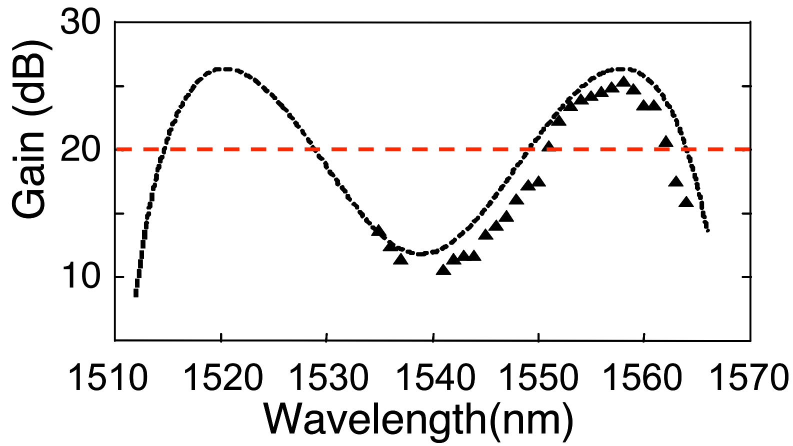
(Gain Slope ~200 dB/W/km)

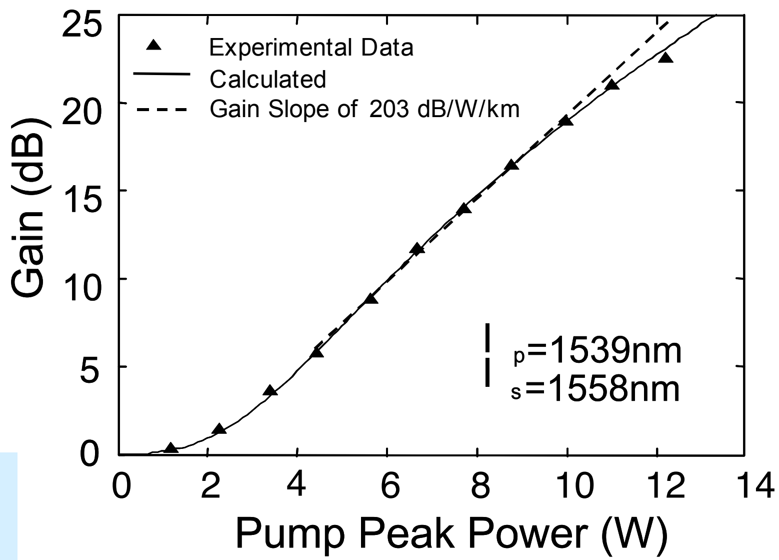


Experimental Setup Tang *et al.*, *Electron. Lett.* **39** (2) 195 (2003).



- l $_p$ = 1539nm, peak pump power ~12W, l $_s$ from 1535nm to 1565nm, l $_0$ ~1544 (+/- 3) nm





- Gains >20dB over ~30nm using only 12.5m-long MF
- A record gain slope of ~203dB/W/Km (~8.7g)