DESIGN TEMPLATE

- ISSUES
  - performance, yield, reliability
- ANALYSIS FOR ROBUST DESIGN
  - properties, figure-of-merit
  - thermodynamics, kinetics, process margins
  - process control
- OUTPUT
  - models, options

Optical Amplification

- WDM
  - Data Rate: B_0>10 Gb/s
  - problem: wide (25THz) channel range
    - $1.45<\lambda<1.65$ μm
    - dispersion (17 ps/km-nm)
    - loss (0.16 dB/km)
  - solution
    - dispersion compensation
    - **optical amplifier**

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(Optoelectronics, Electronic Materials and Devices)

Fiber Amplifiers

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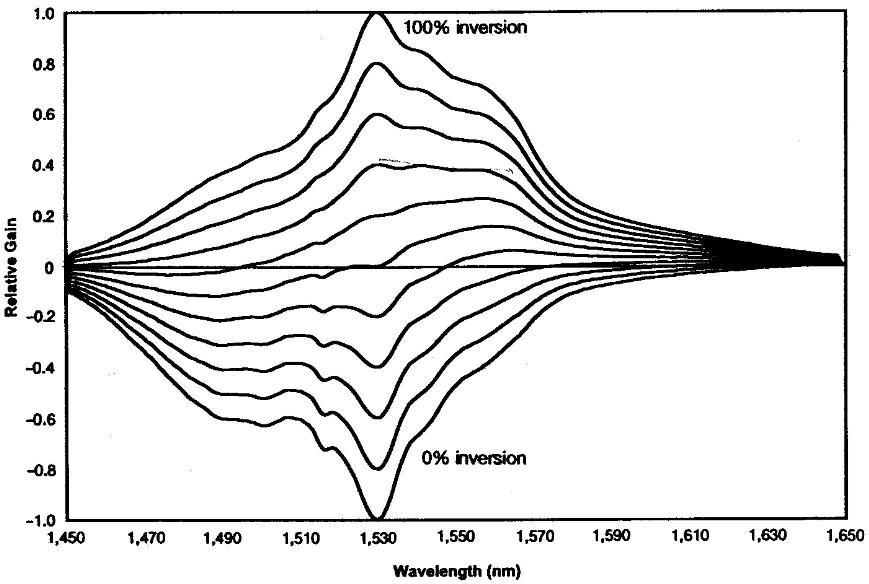
Graph of wavelength spectrum and windows addressed by different device families.

Optical Amplification Options

- **Optical Pumping of Er**
  - EDFA, insulator host for Er atom (ceramic)
- Optical Pumping with Sensitizer
  - Lowers pump power requirement for Population Inversion (Yb^{+3})
- **Electrical Pumping**
  - Semiconductor Optical Amplifier (SOA)
    - high noise figure

Er vs SOA

- EDFA
  - atomic transition (Er)
  - 200 nm bandwidth
  - 25 dB gain ↔ 20 m
  - τ~ms ↔ 4 dB noise



Source: Figure 3 in Dejneka, M. and B. Samson. "Rare Earth-Doped Fibers for Telecom Applications." Source MRS Bulletin, v24 (9) 1999, pp 39-45.

- SOA
  - electronic (InGaAsP)
  - ~30 nm bandwidth
  - 36 dB gain ↔ 350 μm
  - τ~ns ↔ 12 dB noise

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(Fundamentals of Photonics, Saleh & Teich)

Er Gain-Limiting Effects

- Increase N $\Rightarrow$ high [Er] $\Rightarrow$ gain-limiting effects
  - excitation migration and non-rad. quenching
  - cooperative upconversion (10^{19}-10^{20} Er/cm^3)
  - excited-state absorption

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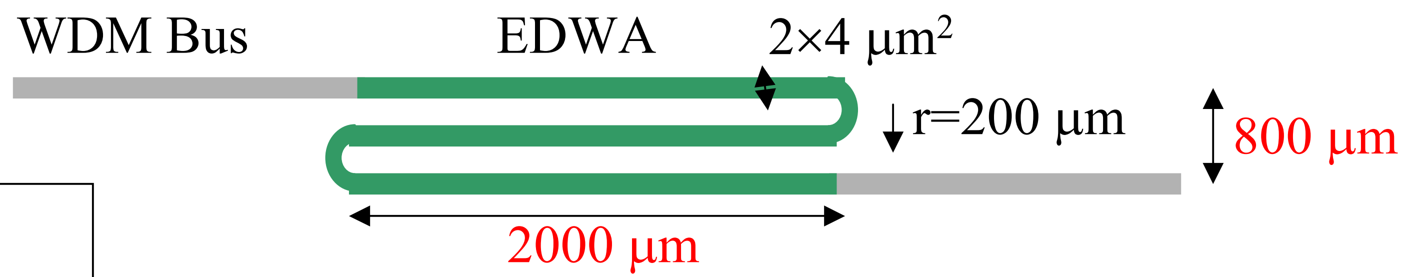
Optical Pumping: SiON:Er

- High index contrast (Δn=0.1-0.5)
  - Gain length 3 dB amplifier



Δn=0.1

(SiON core)

(SiO_2 cladding)

[Er]=2×10^{20} cm^{-3}

3 dB gain/ring, NF=1.5 dB

EDWA length: 6 mm

EDWA: ERBIUM DOPED WAVEGUIDE AMPLIFIER

History

- RE ions
  - Long τ: low crosstalk, noise
  - Broadband
  - Symmetric mode
  - $T(\lambda)$, mech. Stability
- History
  - 1964: first RE fiber ampl/laser
  - 1987: first EDFA (Mears, Payne-Univ. of Southampton
    [28 dB, Ar ion pump]
  - 1992: first commercial EDFA

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Nonradiative lifetime

- In silica: $\tau_{rad} \approx 5.48 \times 10^3 (g_2/g_1)(\lambda_o{}^2/f)$
  - $f \approx 10^{-5}$-$10^{-7} \Rightarrow \tau_{rad} \approx 0.1\ \mu s$-$10 ms$
  - Far IR trans more likely to have faster non-rad. rate than visible transition
  - Want host with low phonon energy

High Concentration

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Graph of absorption cross-section vs. wavelength.

- ESA=0.1GSA considered "okay"
  - 980 nm, 1480 nm are free of ESA
- High Rare Earth Clustering
  - Sub-μs cross-relax. vs. >50 μs rad. Decay
- Al co-doping: improve RE solubility
  - Clustering onset: 50 ppm $Er_2O_3 \leftrightarrow 10^{18}\ cm^{-3}$
  - 300-500 ppm: gain drop 10% ($10^{18}\ cm^{-3}$)
  - Al alternative: Fluorozirconate (ZBLAN), phosphate fibers

ASE

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Two graphs.

- ASE influences gain profile

Optimizing gain (Pump Mode)

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Graph of single pass gain vs. core radius.

- Mode order, confinement (single mode~ $\lambda/2n_{core}$!!!)
  - Lesson: trade-off in optimizing gain overlap between signal and pump
  - higher confinement: $\gamma\uparrow$, $P_{sat}\downarrow$

Amplifier Length

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Graph of fiber length vs. gain.

- Non-uniform gain profile: $\gamma \rightarrow \alpha$ at $x=l$: $f(ASE)=f(l,P_{pump})$
  - Get higher gain at 1530 than 1550 nm!
- Record single-pass efficiency:“gain coefficient”=11 dB/mW

Gain Flattening

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Graph of gain vs. signal wavelength: filter, unfiltered gain, filtered gain.

- Why is gain flattening important?
  - After (~200 km) $\Delta P > 5\text{-}10$ dB and BER degraded

Gain Flattening

- Filter after amplifier: Pump efficiency ↓, NF ~same
- Filter before amplifier: Pump eff ~same, NF ↑
- Narrowband gain clamping:
  - lasing λ locally flattens γ
- Broadband (1530-1610 nm) gain in tellurite fiber

Challenges/Issues for WDM Components

- Wavelength selectable sources
- Optical amplifier gain equalization
- Optical mux/demux
- Flatband, “square” filter response for concatenation
- Reconfigurable wavelength add/drop multiplexers
- Optical cross-connect
- Wavelength alignment of sources, routers, X-connects, receivers
- High integration levels for scalable cross-connects
- Low cost manufacturing and packaging
- Polarization

Images removed due to copyright considerations.

1) Er-doped Fiber Amplifier: schematic, energy level diagram, gain performance

2) Optical Circuit Configurations: bulk-type + fiber-type evolving to planar-type

3) Gain equalization: EDFA + equalizer curves = combined (flatter) curve

4) Wavelength Grating Router/DWDM schematic (WGR)

5) DWDM: Gratings in MZIs