



High Gain Fiber Amplifiers for DWDM and Metro Networks

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Report Documentation Page

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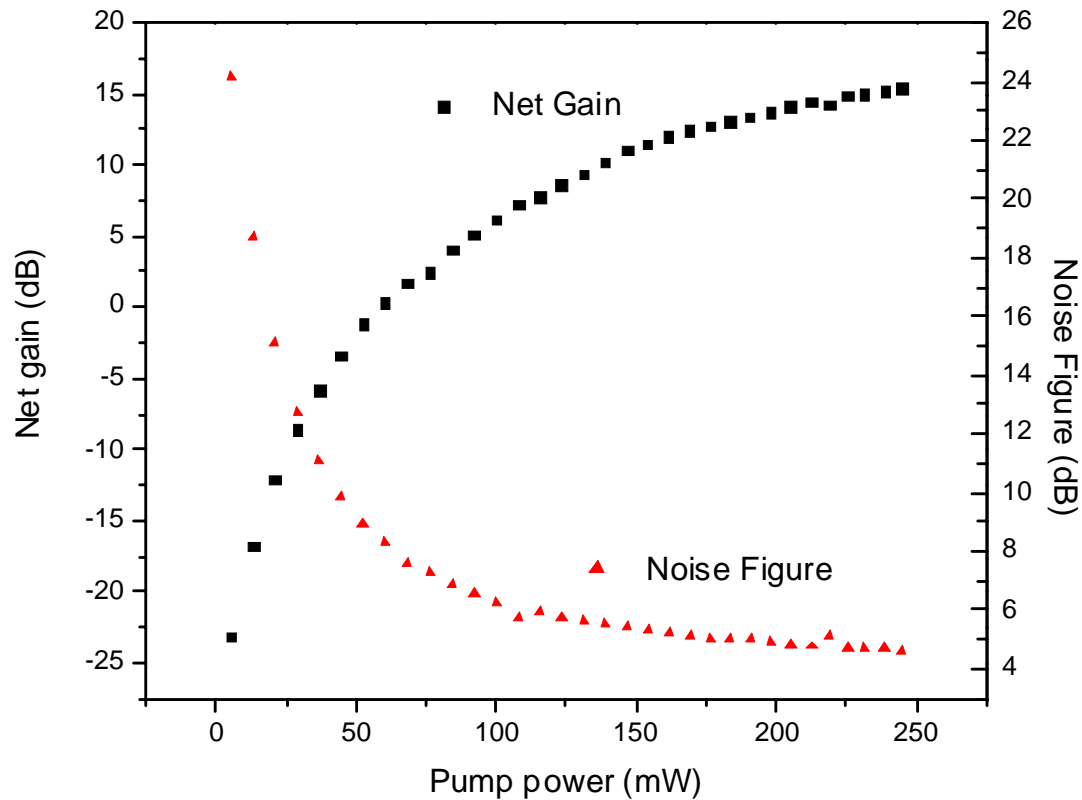
OUTLINE



- Motivation
- Glass and Fiber Fabrication
- Spectroscopic Characterization
- Gain Performance
- Conclusion

Amplifier Performance

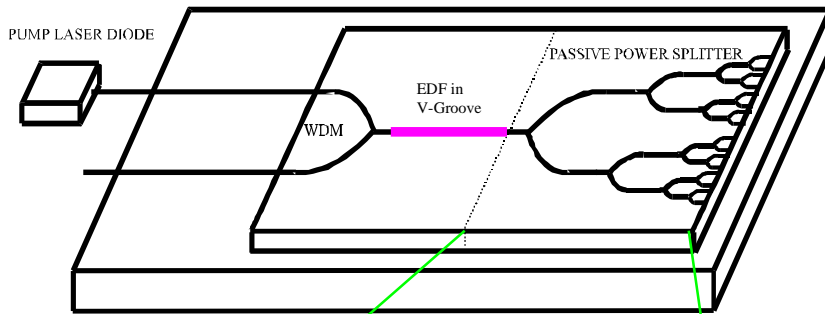
Signal: 1534.9 nm at -31 dBm



15.5 dB net gain for 5.1 cm fiber

Motivation

Lossless Splitter



1x16 splitter: 15dB loss

Commercial EDFA
gain : 0.02dB/cm

Ultra Compact 1.54 μm Fiber Amplifier

High Er^{3+} Doping Concentration

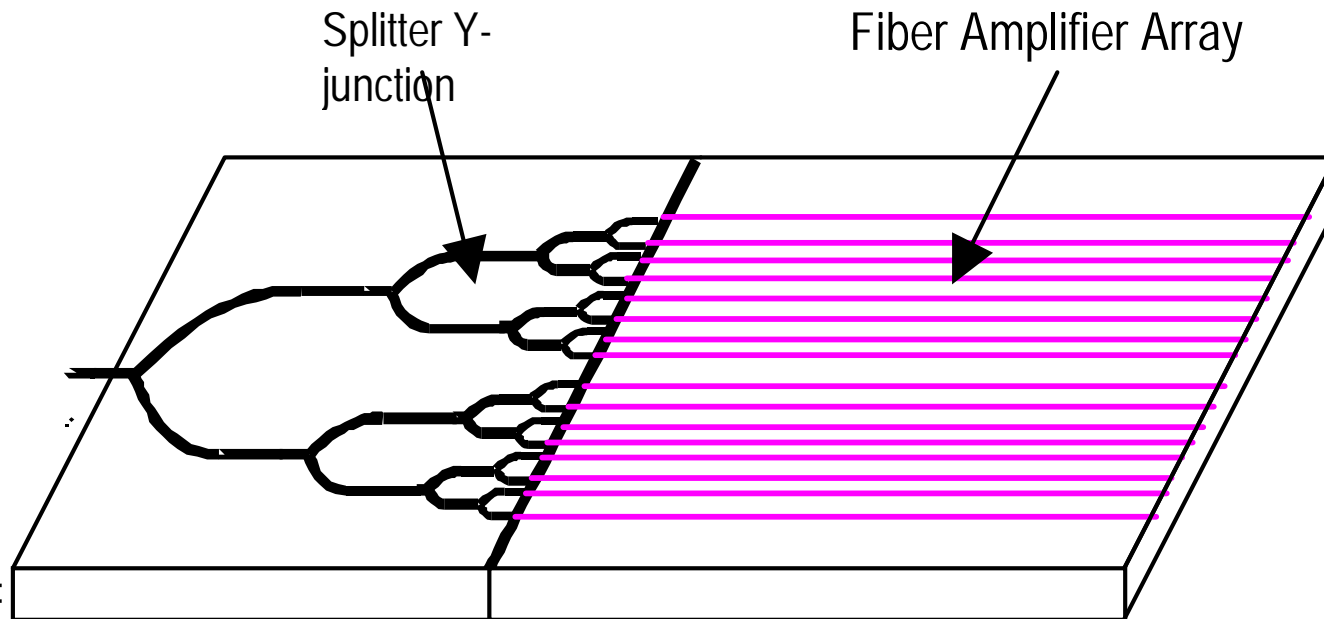
Low Cooperative Upconversion Co.

Phosphate Glasses

Phosphate Glass Fiber Amplifier

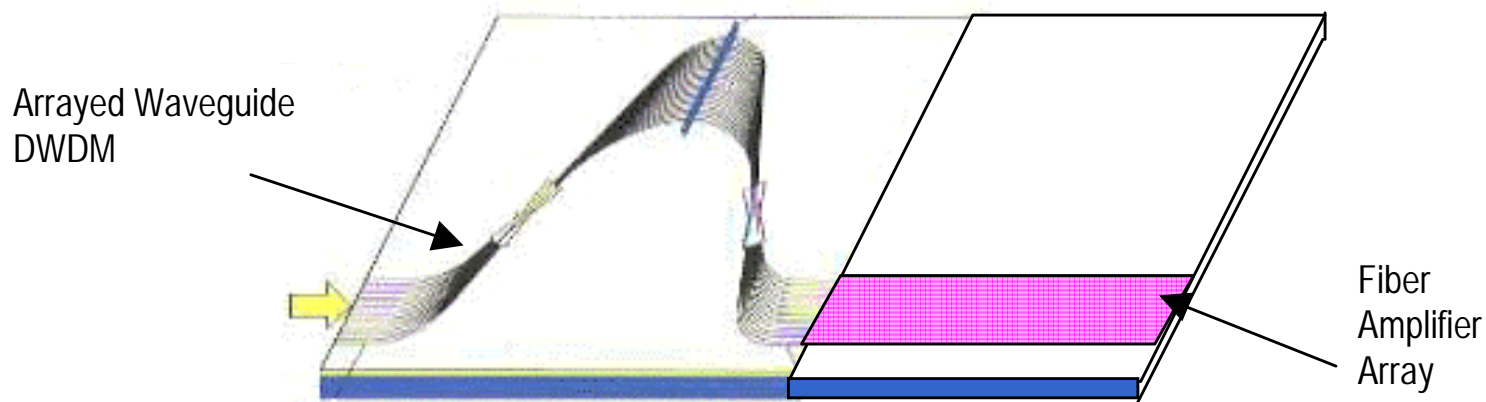
Amplifying Splitter

NP Integrated Power Splitter Concept

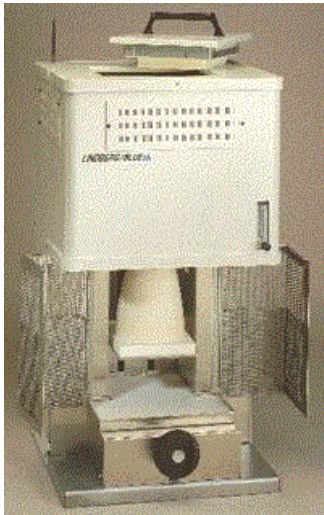


NP Amplifying Arrayed Waveguide Multiplexer

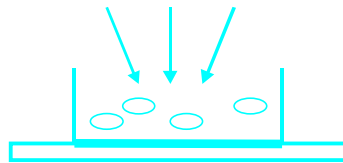
NP Arrayed Waveguide Multiplexer



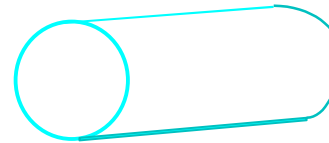
Glass Fabrication



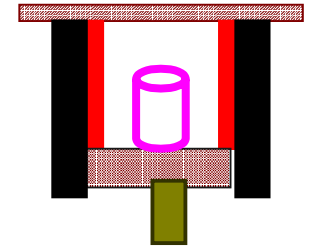
P_2O_5 Al_2O_3 R_2O , et al



Batch



Mixing



Melt

Cast

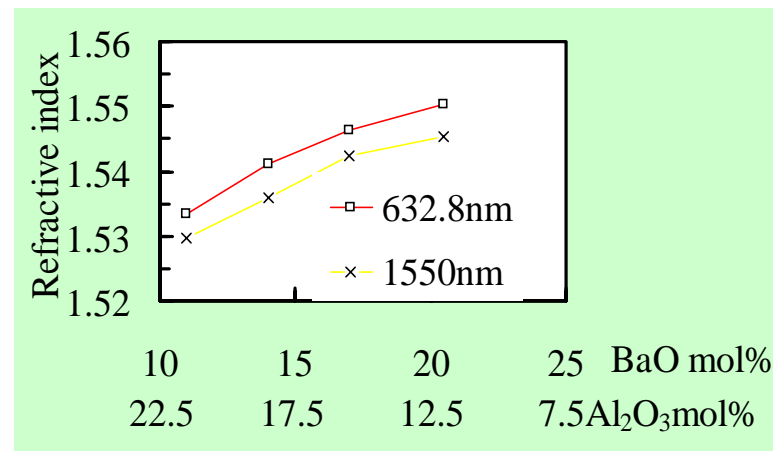
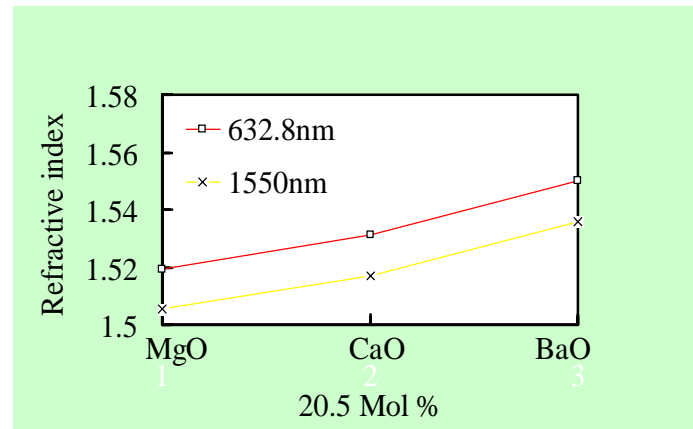
Annealing

Inspection

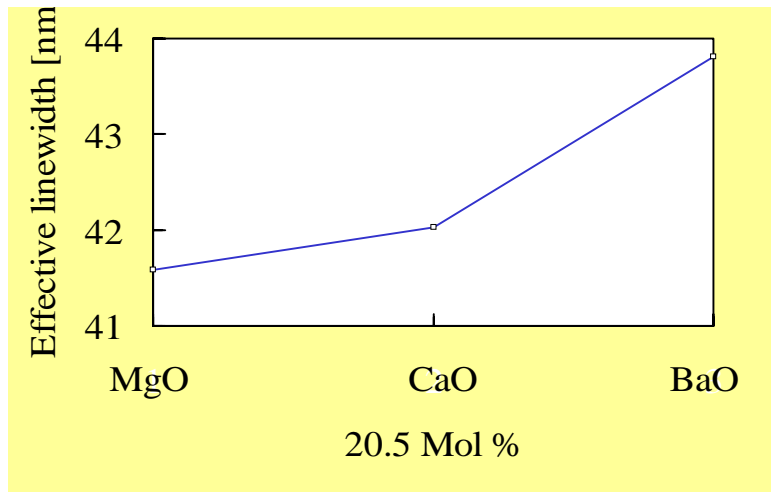
Fabrication

Influence of Glass Composition on Refractive Index

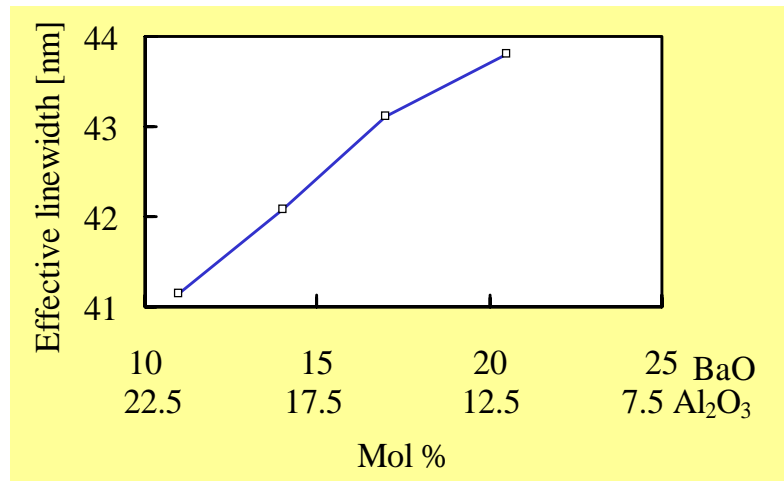
Glass type	Glass composition (Mole %)					
	P ₂ O ₅	Al ₂ O ₃	La ₂ O ₃	MgO	CaO	BaO
P1	64	12	3.5	20.5		
P2	64	12	3.5		20.5	
P3	64	12	3.5			20.5
P4	64	15.5	3.5			17
P5	64	18.5	3.5			14
P6	64	21.5	3.5			11



Influence of Glass Composition on Effective Linewidth of $\text{Er}^{3+} \ ^4\text{I}_{13/2} - \ ^4\text{I}_{15/2}$ Transition



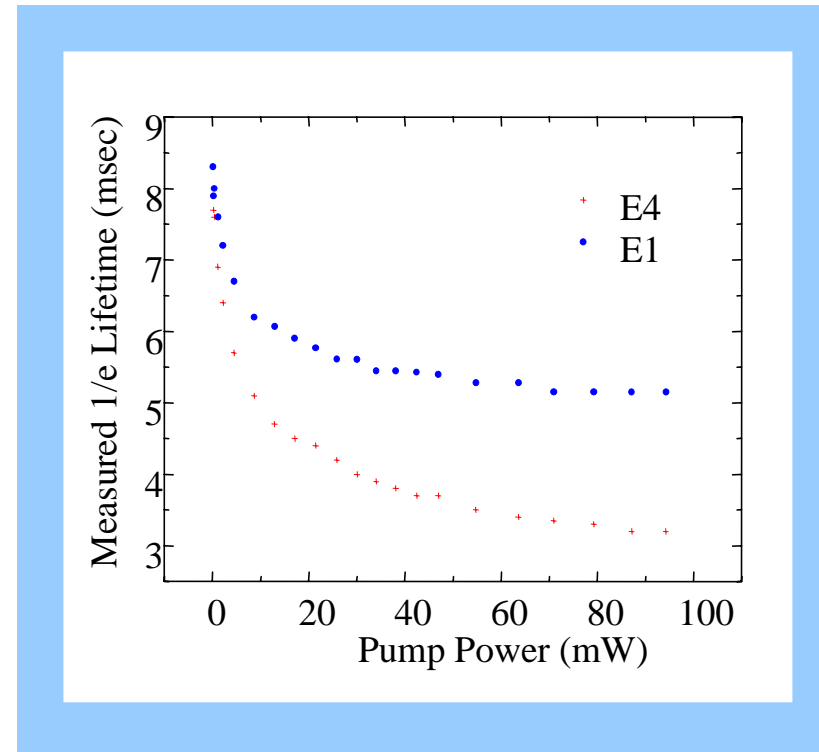
Effective Line width of the 1.54 μm transition



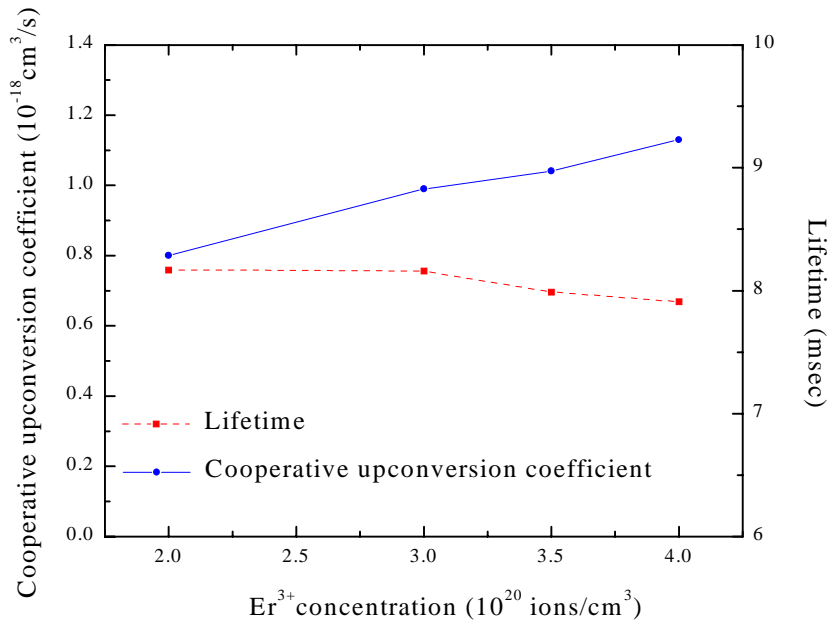
$$\Delta\lambda_{eff} = \frac{\int \alpha(\gamma) d\gamma}{\alpha_{peak}}$$

Measured 1/e Lifetime of Er³⁺ Ions

Samples	Er ³⁺ concentration (ions/cm ³)	Yb ³⁺ concentration (ions/cm ³)
E1	2.0×10^{20}	0
E2	3.0×10^{20}	0
E3	3.5×10^{20}	0
E4	4.0×10^{20}	0
YE1	2.0×10^{20}	2.0×10^{20}
YE2	2.0×10^{20}	4.0×10^{20}
YE3	2.0×10^{20}	6.0×10^{20}



Cooperative Upconversion Coefficient and Spontaneous Lifetime

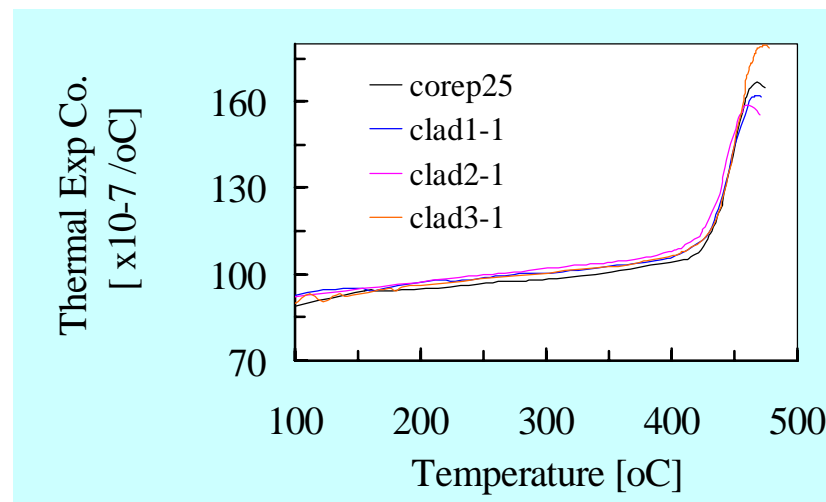


$$N_{E2}(t) = \frac{1}{\tau_E^0} \left[\left(\frac{1}{\tau_E^0 N_{E2}(0)} + C \right) \exp\left(\frac{t}{\tau_E^0}\right) - C \right]^{-1}$$

$$N_{E2}(0) = \frac{R_{E13} \tau_E^0 + 1}{2C \tau_E^0} \left(\sqrt{1 + \frac{4CN_E R_{E13} \tau_E^0}{R_{E13} \tau_E^0 + \tau_E^0}} - 1 \right)$$

Cladding Glasses

Glass type	Refractive index			
	632.8 nm	830 nm	1300 nm	1550 nm
Core P25	1.5431	1.5389	1.5318	1.5290
Cladding1-1	1.5365	1.5309	1.5249	1.5217
Cladding2-1	1.5298	1.5250	1.5187	1.5158
Cladding3-1	1.5257	1.5206	1.5150	1.5116



$$\Delta n/n_1 = 0.48\% \sim 1.14\%,$$

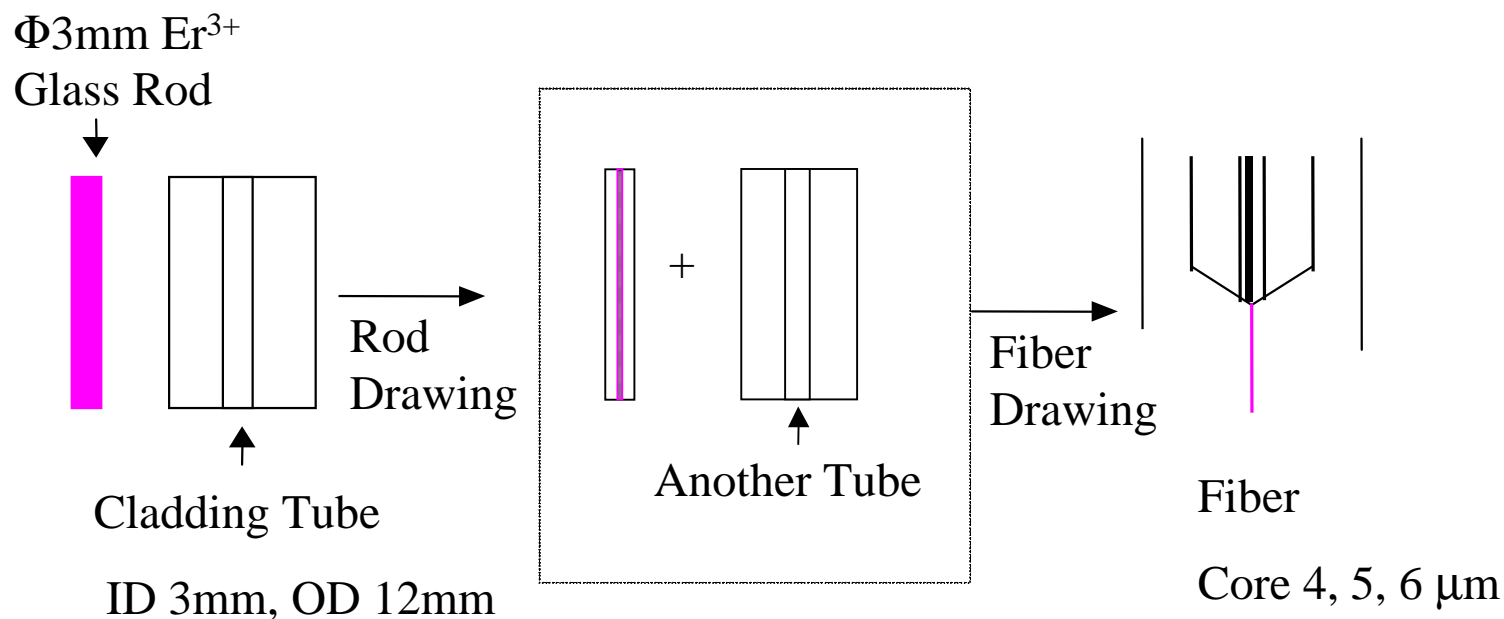
$$NA = 0.149 \sim 0.230$$

$$\Delta \alpha/\alpha_1 < 3\%$$

$$\Delta T_g/T_{g1} < 1\%$$

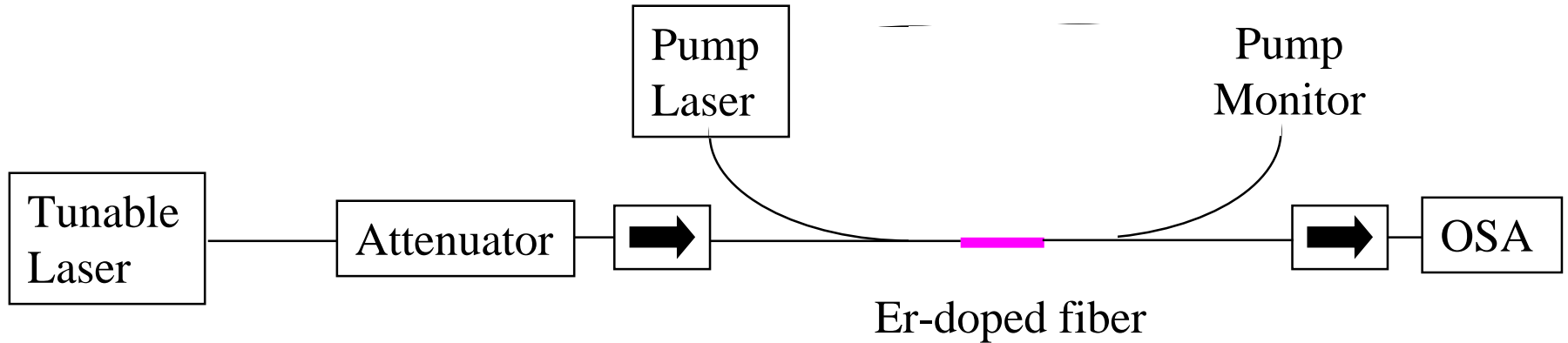
$$\Delta T_f/T_{f1} < 3\%$$

Rod-in-tube technique

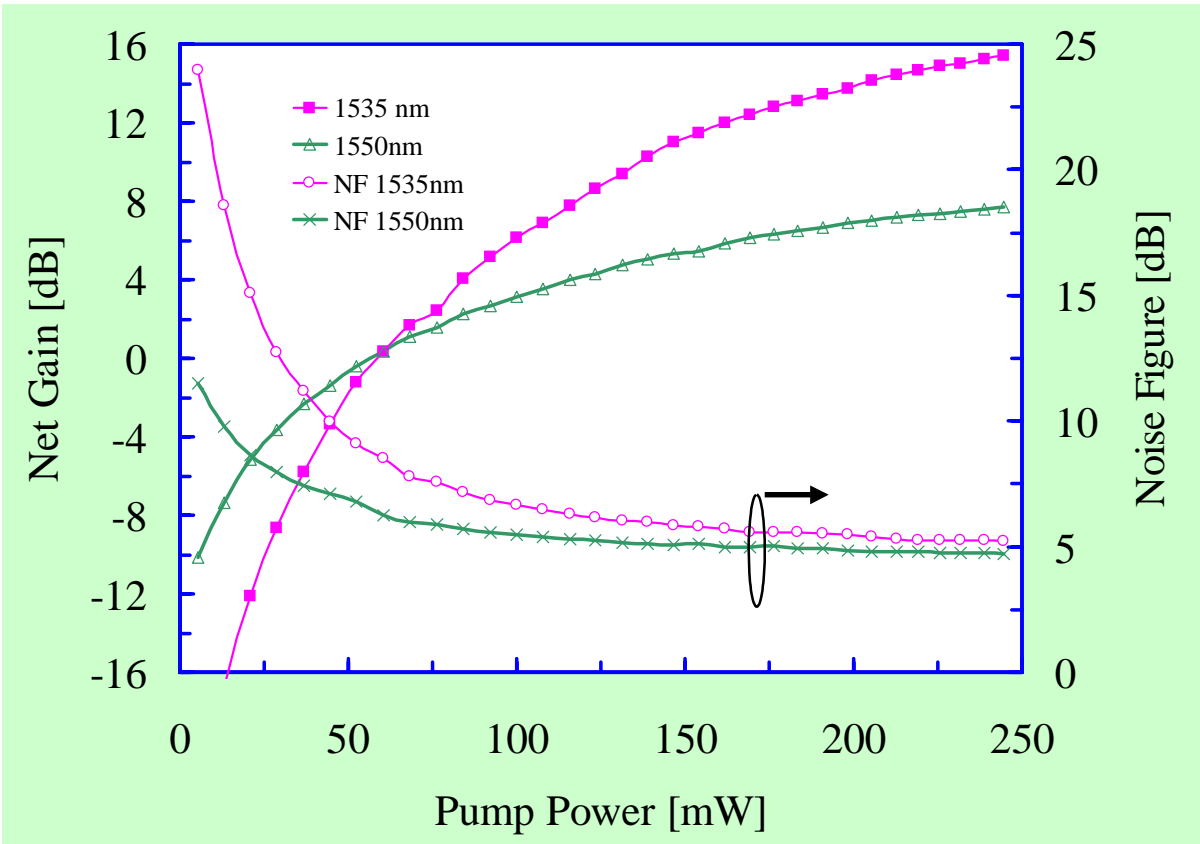


Core Diameter: 4-6 μm

Experimental Setup for Gain Measurement

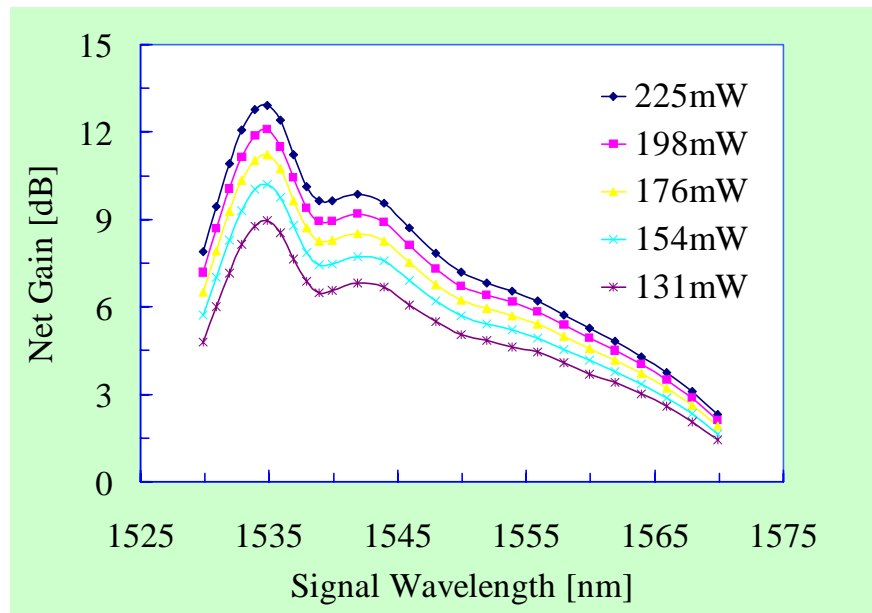
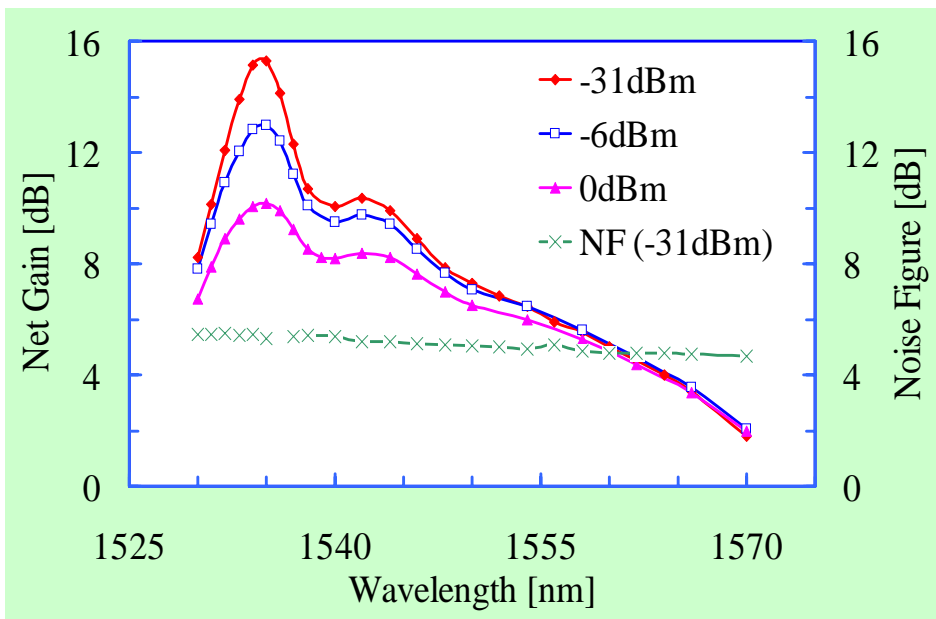


Gain Characteristics

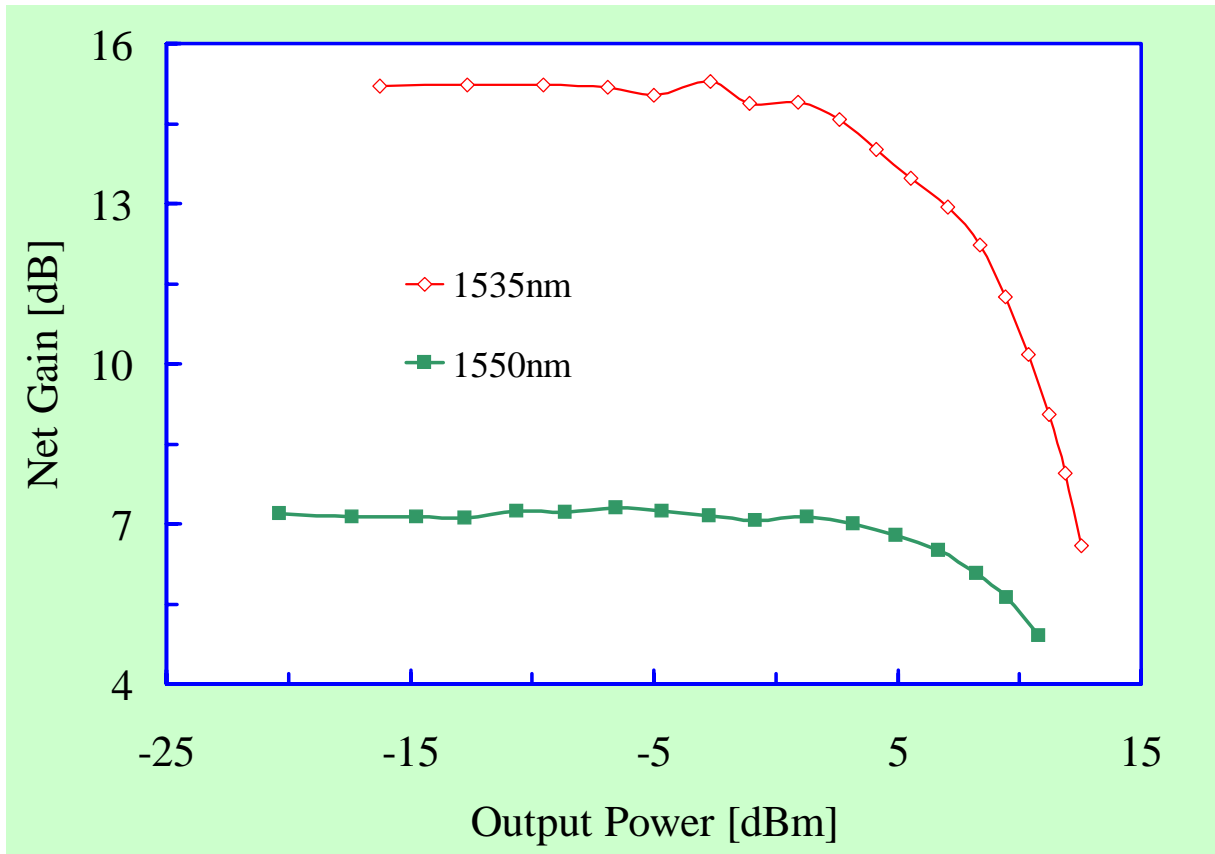


Fiber Length:
5.1cm

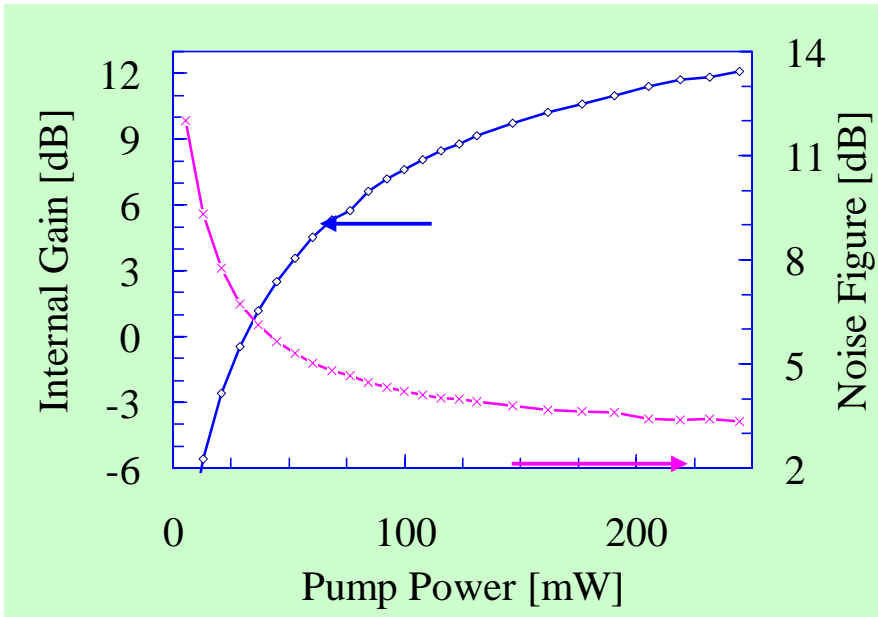
Gain Spectrum



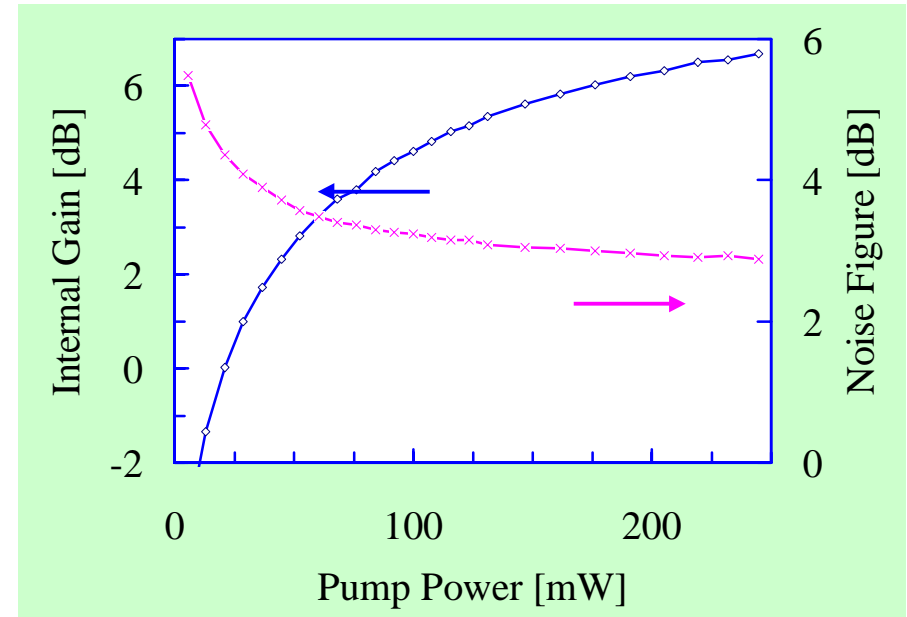
Gain Saturation



Gain Performance

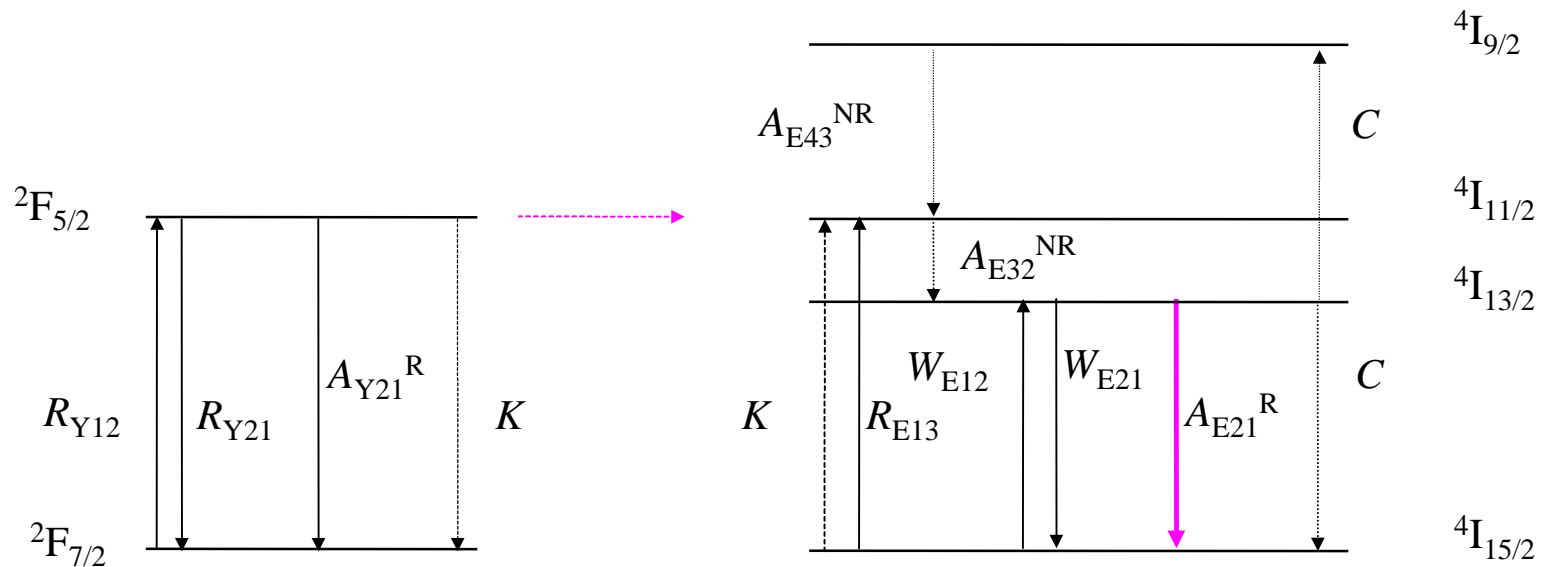


1535nm, -31.6dBm
3.2cm-long fiber



1550nm, -31.6dBm
3.2cm-long fiber

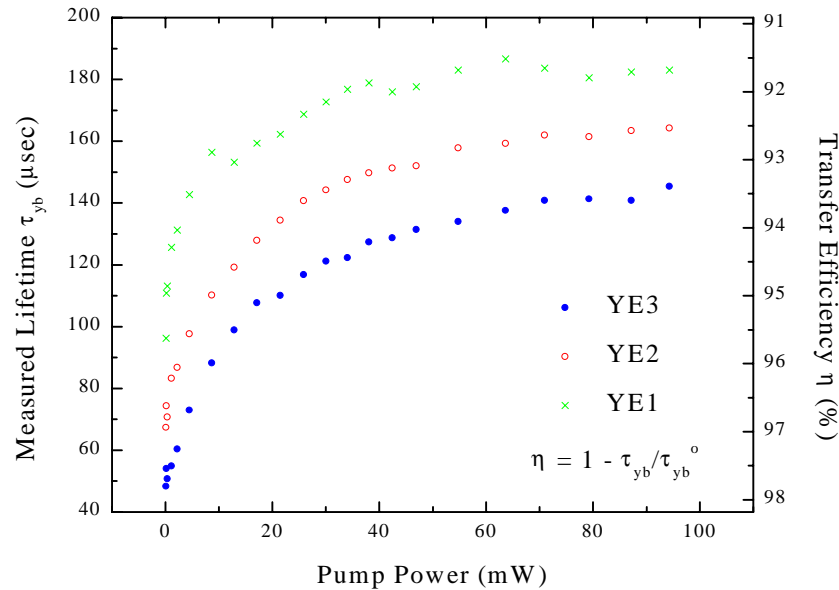
Spectral Properties



Yb^{3+} ions

Er^{3+} ions

Energy Levels of Er^{3+} and Yb^{3+} Ions



Efficiency

$$\eta = 1 - \frac{\tau_{Yb}}{\tau_{Yb}^0}$$

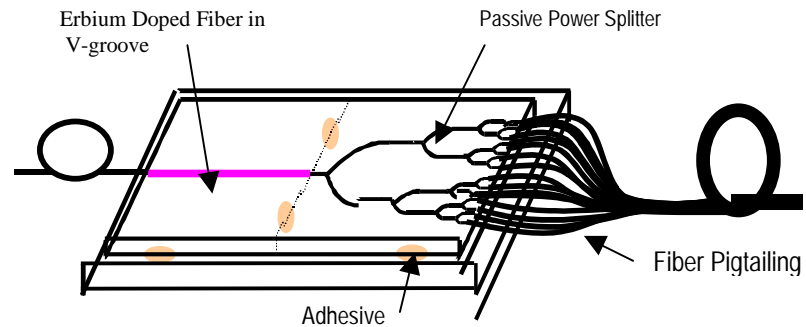
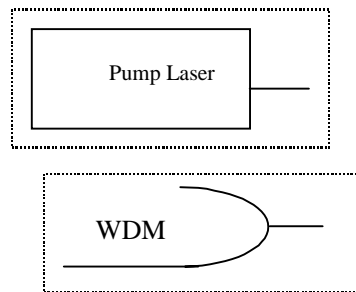
τ_{Yb}^0 Lifetime without Er^{3+} ions

τ_{Yb} Measured lifetime

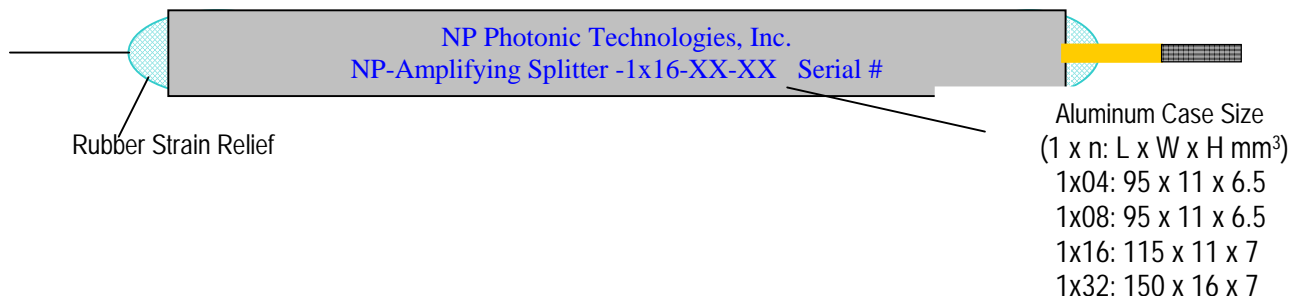
Amplifying Splitter (and Combiner)

One Input Port and Multiple Ourput Ports (n) for
 Amplifying and Dividing Optical Signals Near 1.54 μm

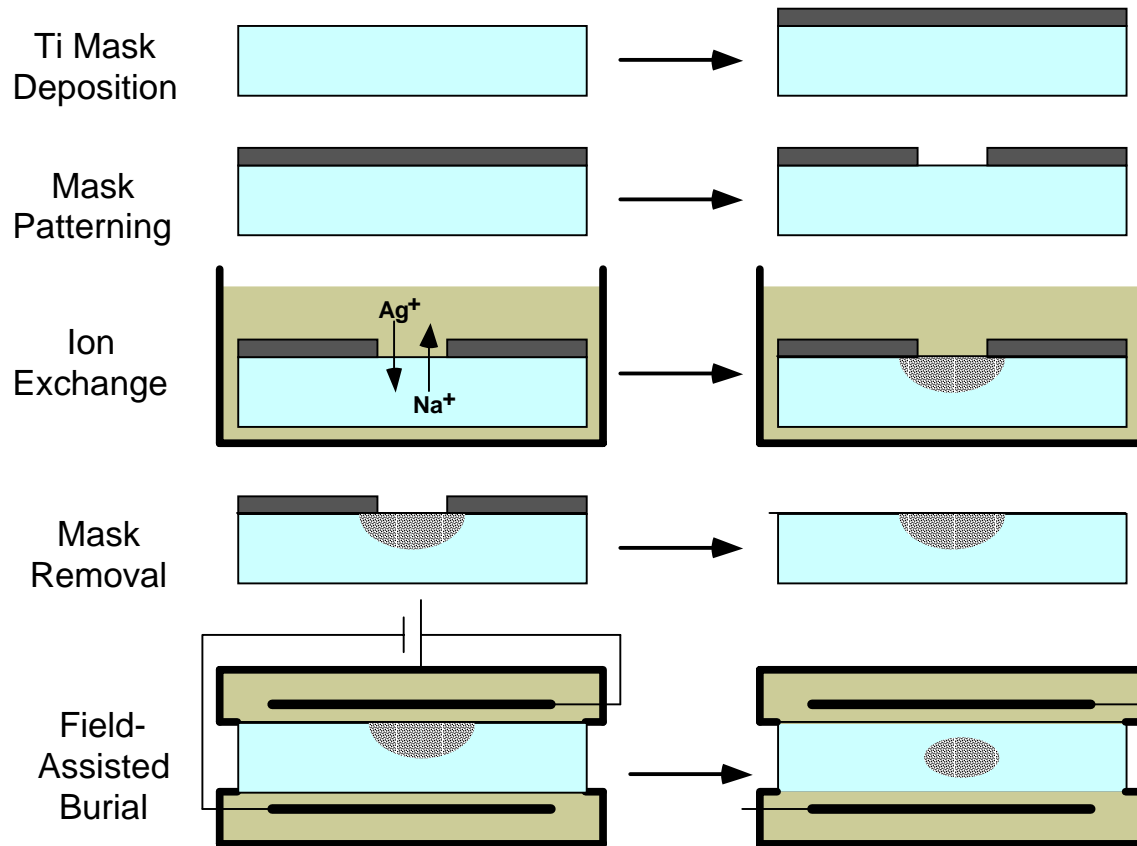
Technical Drawing



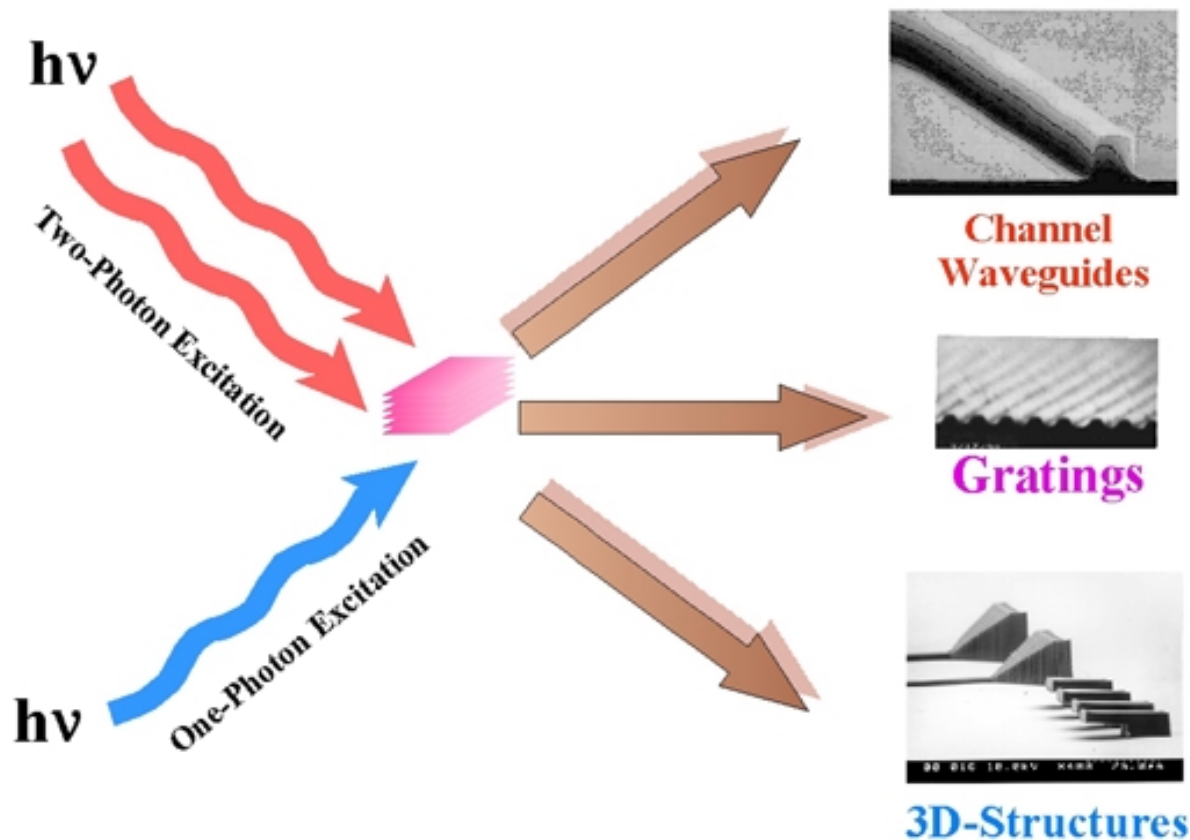
Packaged Product:



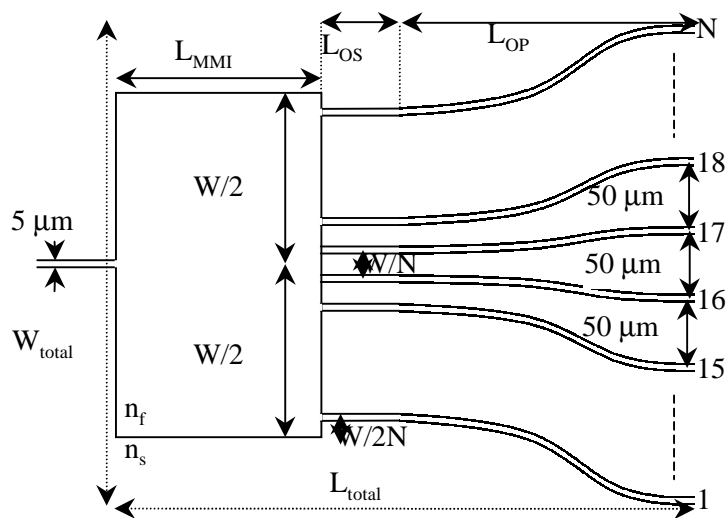
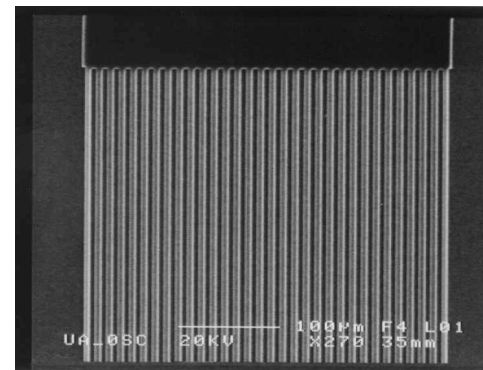
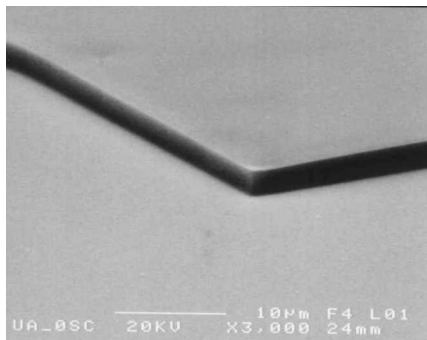
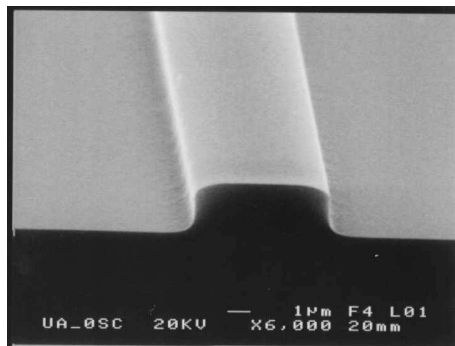
Ion-Exchanged Waveguide Fabrication



Photoimagable Hybrid Materials

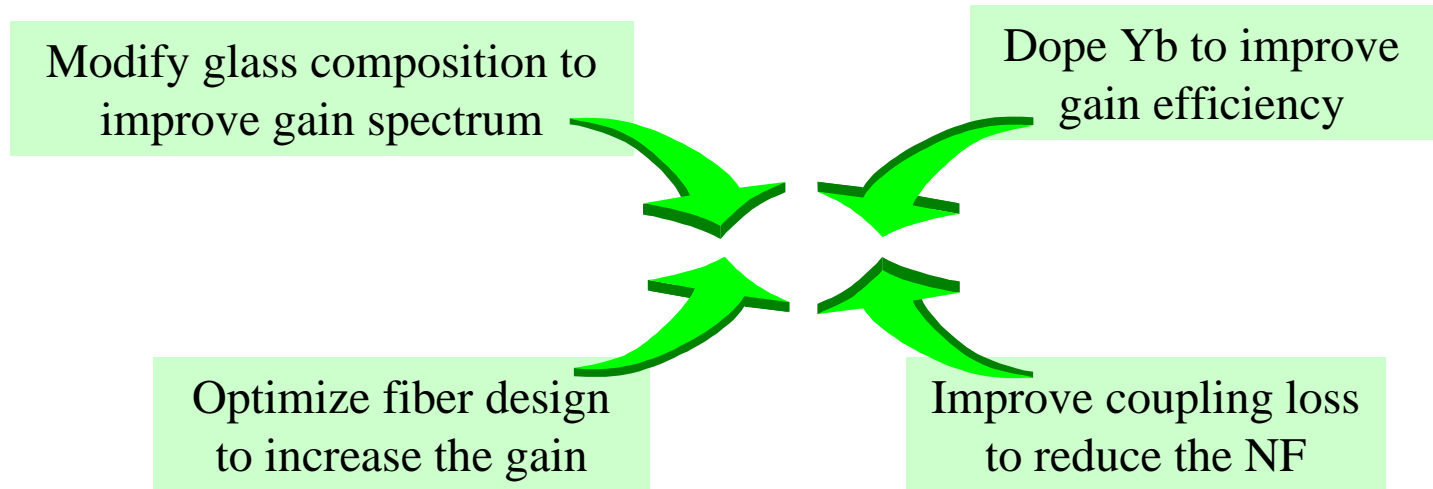


1-N Sol-Gel MMI Splitter



1x32 MMI output

- Er³⁺-doped phosphate glasses
- Single mode phosphate glass fiber
- Phosphate glass fiber amplifier
- 15.5dB net gain from a 5.1cm fiber



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Prof. Jacques Lucas (Universite de Rennes 1)

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NP Photonic Technologies, LLC

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Arizona 85747

Parameters of Single Mode Fiber

Core diameter	5 μm
Refractive index of cladding glass at 1.535 μm	1.5170
Refractive index of core glass at 1.535 μm	1.5327
Numerical aperture	0.219
Cut-off wavelength	1.43 μm
Attenuation	<0.3dB/cm
Er ³⁺ concentration	35000ppm