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Conference on
Ultrafast Transmission Systems in Optical Fibres

13 - 17 February 1995

Erbium-Doped Fiber Amplifiers: Key Features and Applications

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Erbium-Doped Fiber Amplifiers: Key features and applications

by

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Outline

1- Impact of EDFAs

2- Key features

- silica-based EDFAs
- fluoride-based EDFAs

3- Device and system applications

1- The impact of EDFAs

- Can be measured by the overall progress in optical communications performance:

		Before (1988)	Now (1994)
- Record (direct) photodetection sensitivity		646 photon/bit	102 photon/bit
- Maximum distance × bit rate *		0.9 Tbit/s.km	90 Tbit/s.km
- Maximum distance * *			
	NRZ	200 km	21,000 km
	Soliton	6,000 km	$> 10^6$ km

* straight-line transmission
* * 1-10 Gbit/s, 10^{-9} BER, loop transmission

- Can be appreciated by the progress in the soliton field, both conceptually and experimentally:

For fiber lengths greater than $1/\alpha \approx 22$km, solitons should be viewed (realistically) as being based not on two, but <u>three</u> fundamental effects:

1- self-phase modulation
2- anomalous dispersion
3- in-line, periodic loss compensation:

- fundamental N=1 soliton --> distributed loss compensation
- guiding-center soliton --> lumped loss compensation

<u>Two types of 1.5µm fiber amplifiers:</u>

Raman amplifiers (RFAs):	EDFAs:
200-300mW pump	10-50mW pump
quasi-distributed gain	lumped or distributed gain
30nm bandwidth, tunable	bandwidth 20nm (silica) or 30nm (fluoride)

- **Can be appreciated by new functions and devices:**

EDFAs made possible to realize practical LD-controlled devices based on fiber nonlinearities (Kerr, FWM), which offer a variety of ultrafast all-optical signal generation/processing functions:

- Fiber lasers
  - ultrashort pulse generation (DDF and F8L)
  - clock recovery
- Nonlinear optical loop mirrors (NALM, NOLM)
  - switching, demultiplexing, RZ ↔ NRZ format conversion
  - wavelength conversion
  - pulse shaping
  - saturable absorption
  - timing jitter suppression (regeneration)
- Spectral inversion by four-wave mixing
  - dispersion compensation
  - demultiplexing
- Repeaterless transmission (power boosters and remote-pumping)

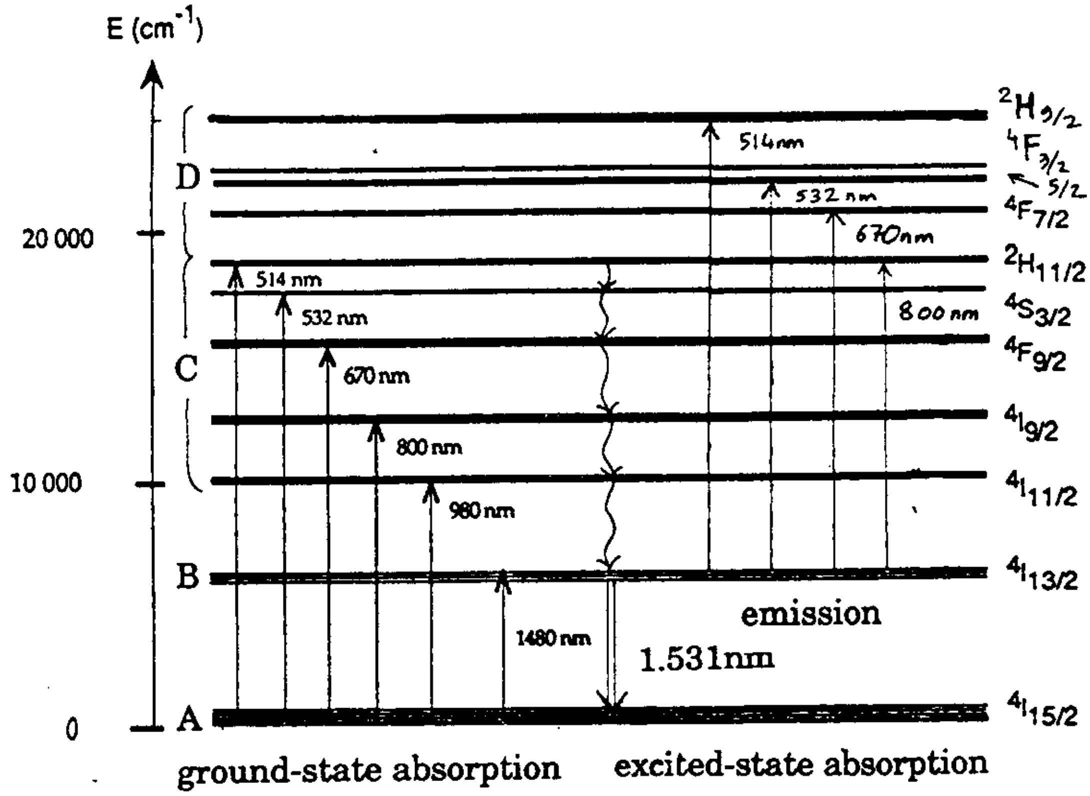
2- Key features of EDFAs

- A list of advantages with respect to electronics amplifier counterparts:

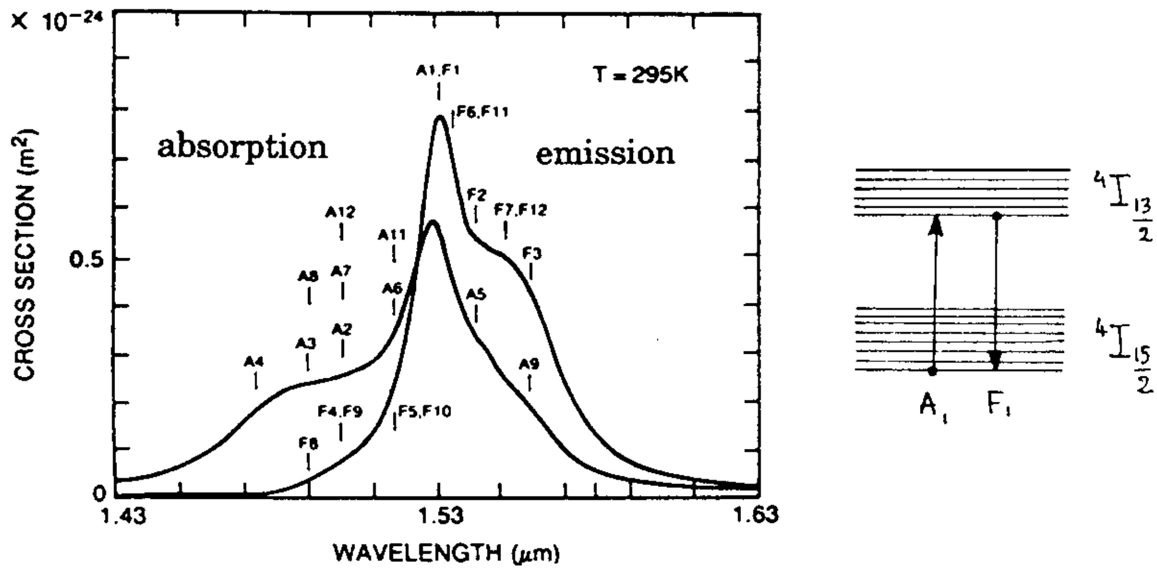
Optical amplifiers	Fiber amplifiers	Raman	EDFAs
DC-THz operating bandwidth	index-matching with fibers	×	×
bit-rate and modulation format transparency	low/negligible coupling loss (NF)	×	×
Boost laser transmitter power (system power margin)	power-scalable (glass breakdown intensity: $10GW/cm^2$)	×	×
	temperature-insensitive gain	×	×
multiple-channel amplification FM/SCM→ FDM/WDM	polarization-insensitive gain	eff.	×
low noise figure	lowest noise figure (NF=3dB)	×	×
increase direct-detection receiver sensitivity	high F/F gain (>20dB) with LD-pumping	-	×
	efficient LD-pumping	-	×
	high power conversion efficiency	-	×
linear under saturation !	slow gain dynamics (crosstalk-free)	-	×

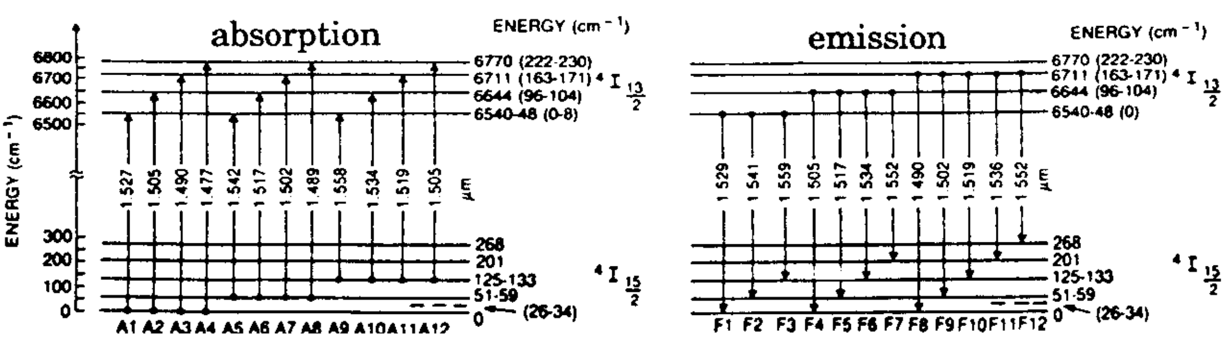
- Spectrocopy of Er-doped fibers

Energy levels of the 4-f shell in Er: glass [1]

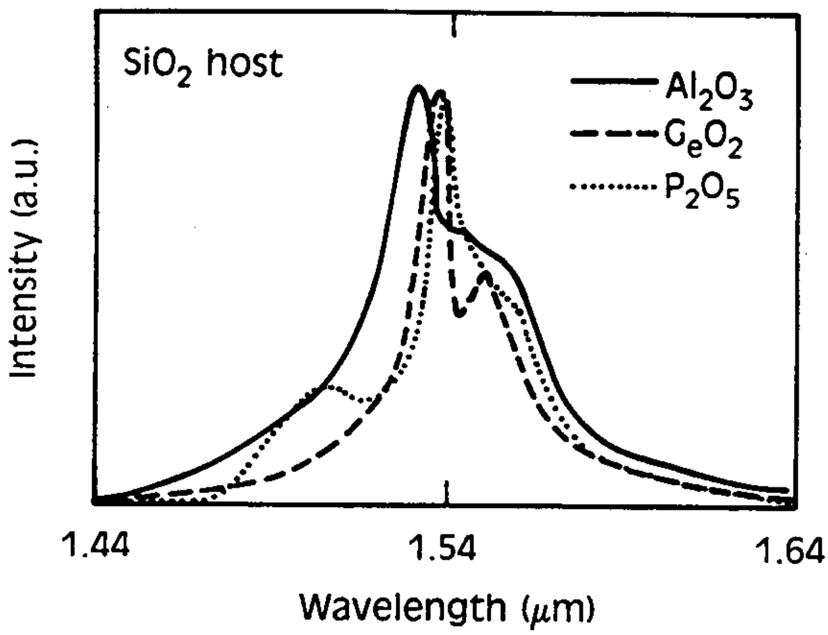


- Er:glass Stark sublevels





- Fluorescence spectrum vs. glass host type



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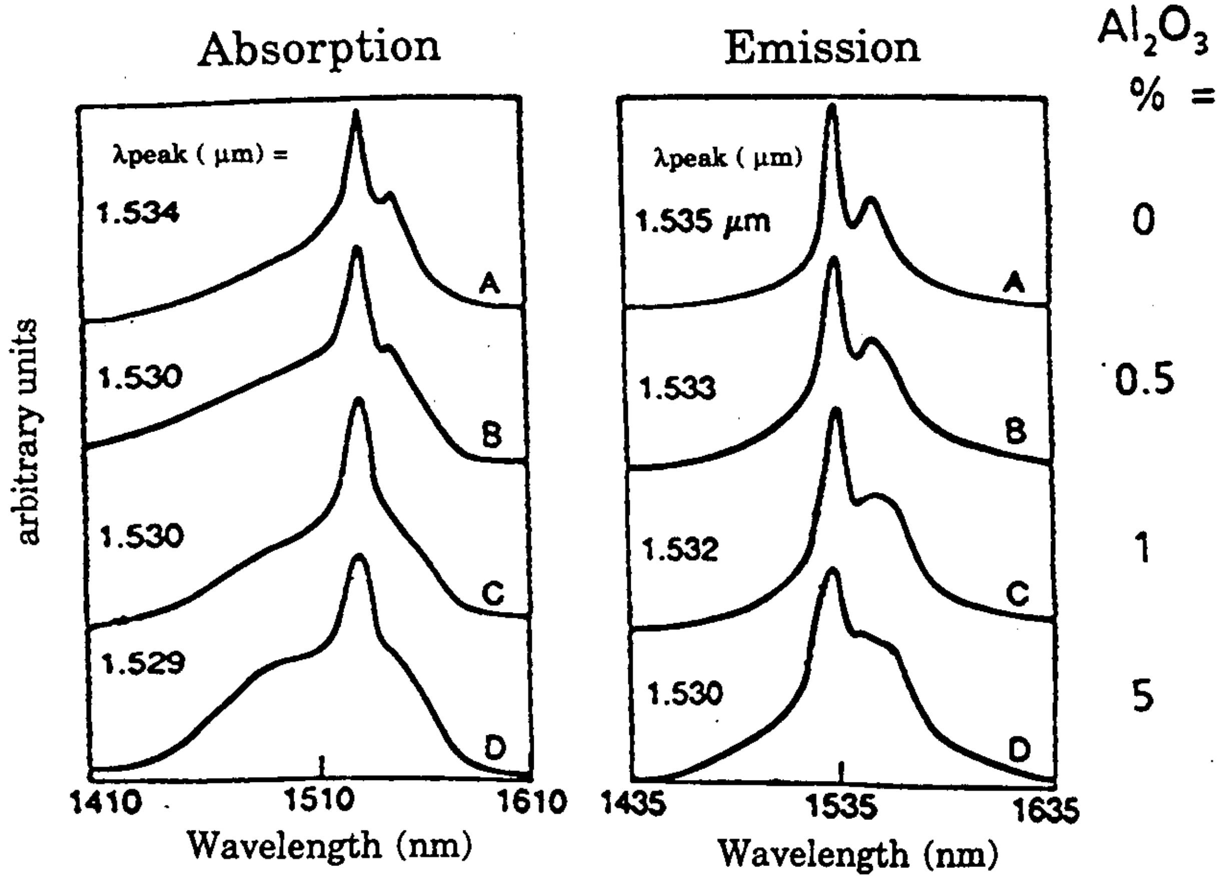
- Effect of alumina co-doping



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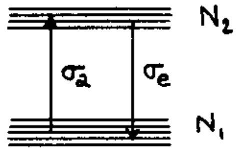
EDFA spectral gain coefficient

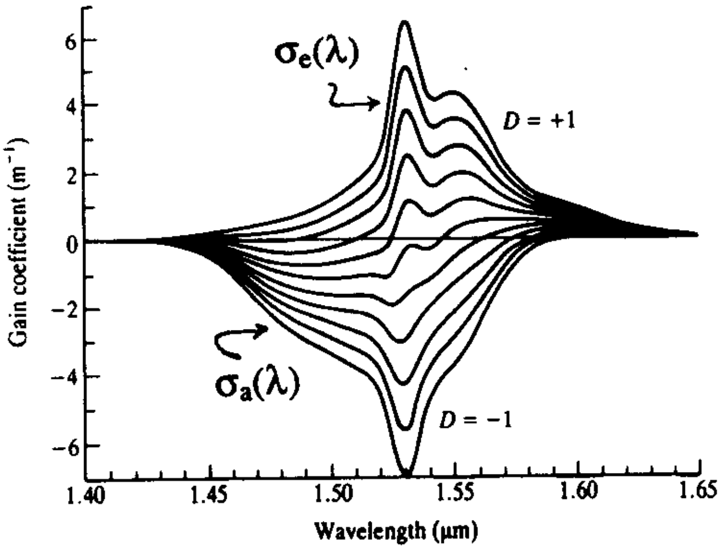
- Gain $G = \exp \int_0^L \left\{ \iint \underbrace{(\sigma_e N_2 - \sigma_a N_1)\, \rho(r)}_{g} \psi_s(r)\, ds \right\} dz$



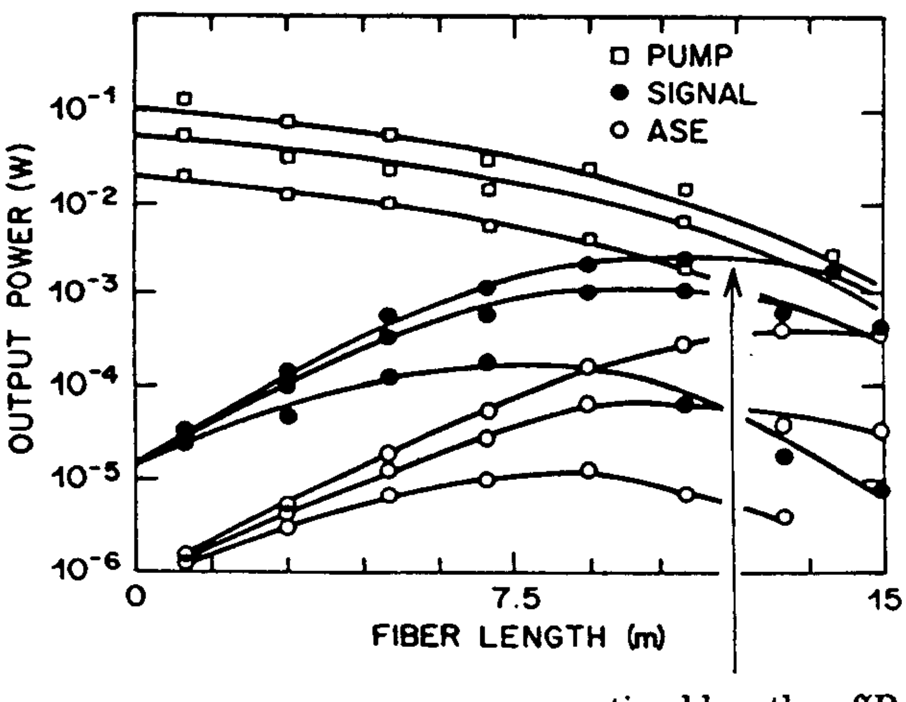
$$D = \frac{N_2 - N_1}{\rho}$$

spectral gain coefficient:

$g = \rho\, [\sigma_e(1+D) - \sigma_a(1-D)]$



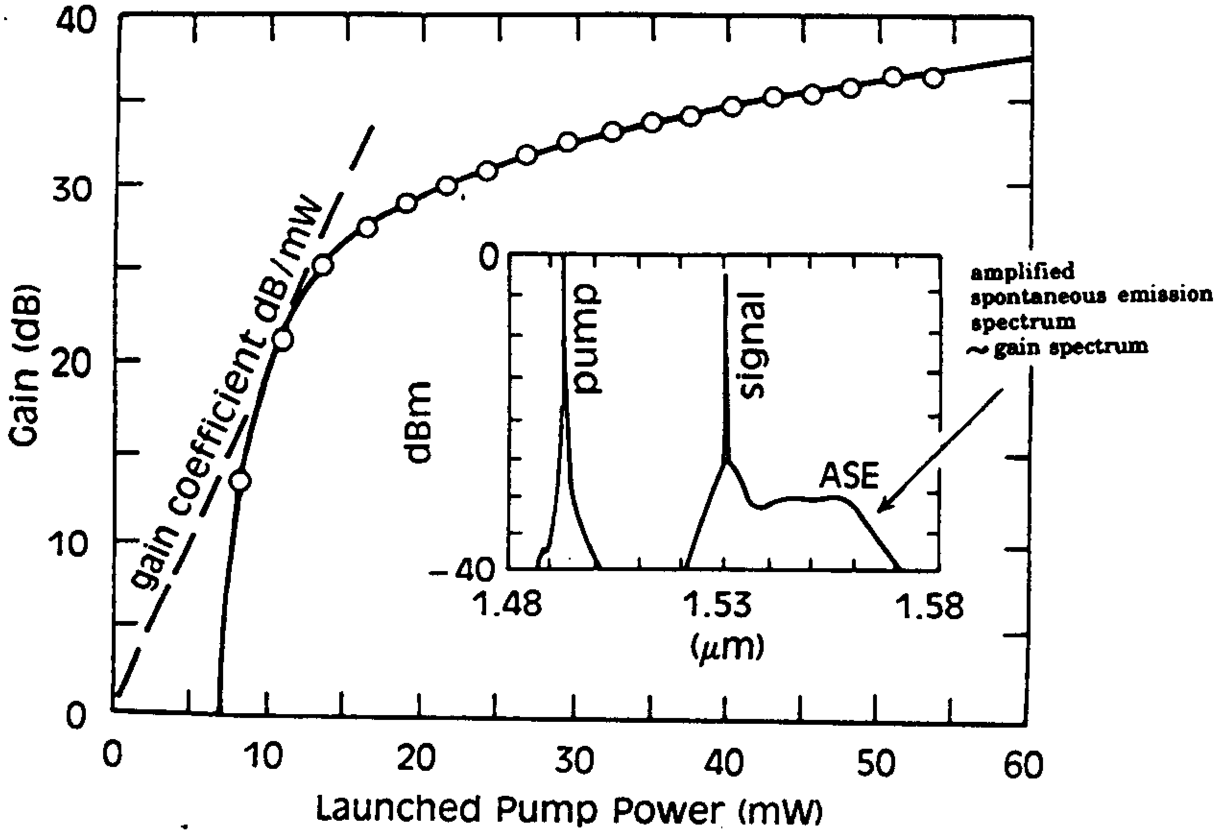
Gain vs. fiber length



optimal length = f(Pp)

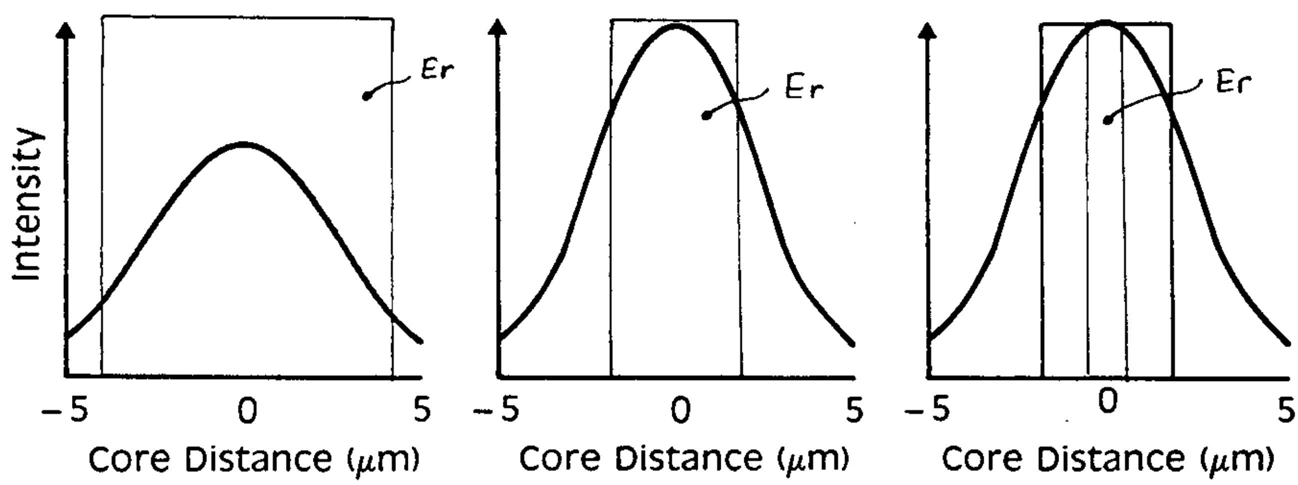
Desurvire *et al.*, 1987 [10]

Gain vs. pump power



Desurvire *et al.* [11]

- Optimization of fiber design



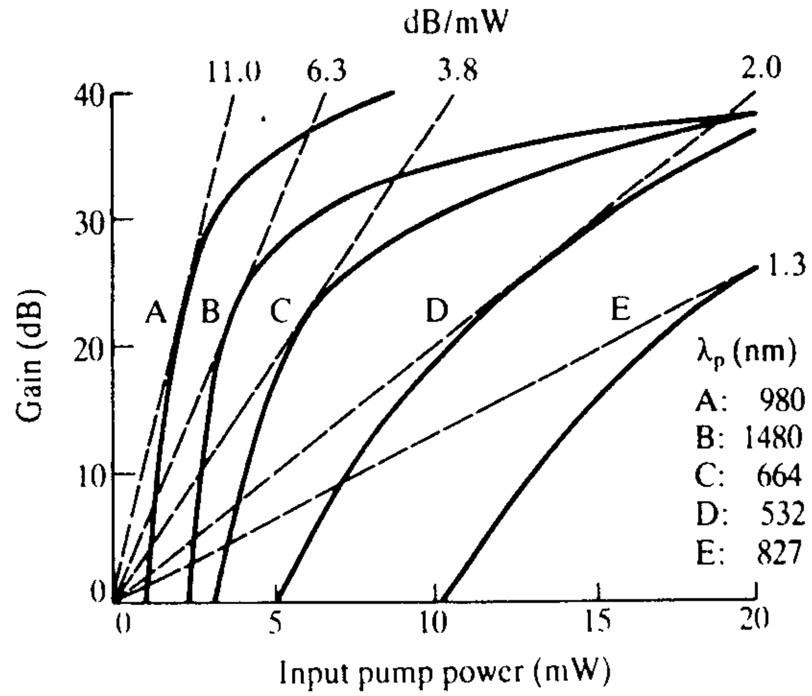
Standard fiber
SMF

confinement of
pump mode

confinement
of Er-doping

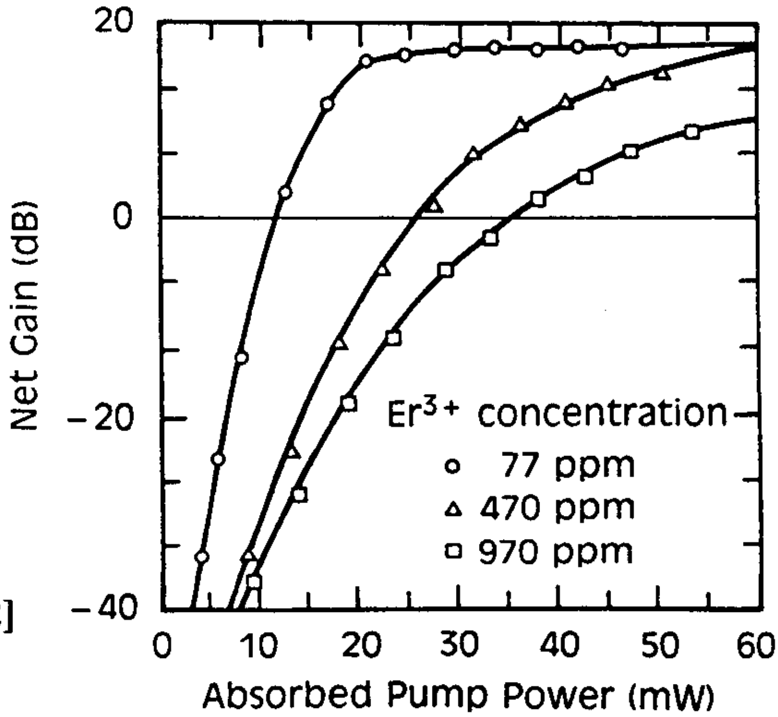
⇨ optimal cutoff wavelength

- pump wavelength and dB/mW coefficient



(best achieved to date, optimized fiber designs)

Effect of Er^{3+} concentration

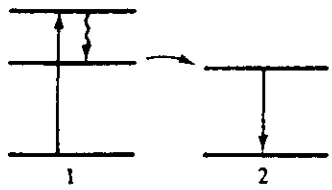


Shimizu *et al.* [12]

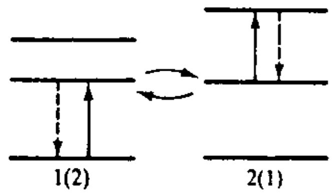
⇨ gain reduction due to cooperative Er-Er energy transfer (quenching)

Cooperative energy transfer: basic processes [1]

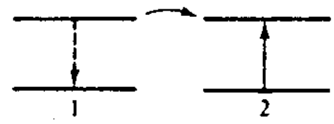
donor acceptor



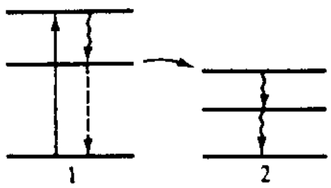
- sensitized fluorescence (e.g. $Yb^{3+} \rightarrow Er^{3+}$)



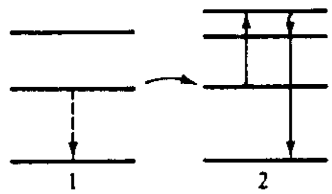
- cross-relaxation (e.g. $Er^{3+} \rightarrow Er^{3+}$)



- resonant energy migration

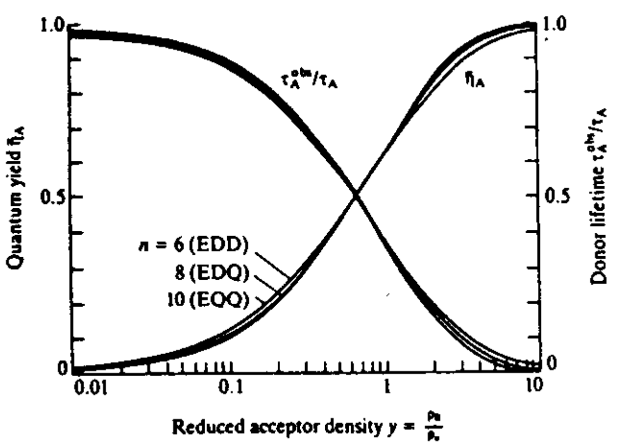


- fluorescence quenching (e.g. $Er^{3+} \rightarrow Nd^{3+}$)



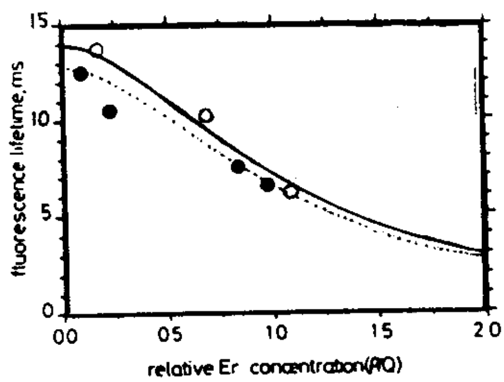
- frequency upconversion (e.g. $Yb^{3+} \rightarrow Pr^{3+}$)

Cooperative energy transfer: Dexter theory



[1]

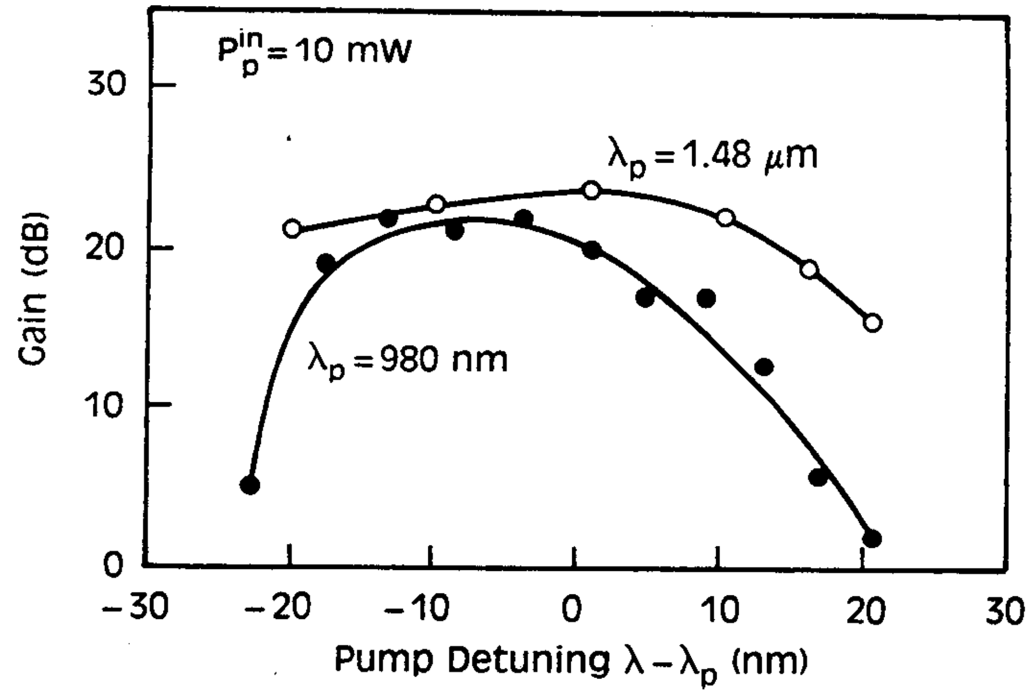
- experimental measurement of τ_A^{obs} with $Er:P_2O_5$, $Er:SiO_2$



$$Q = \rho_0(\tau_A^{obs} = \tau_A/2)$$

[after Lumholt et al., Electron. Lett., 29, 5, 495 (1993)]

Gain vs. pump wavelength detuning



Becker *et al.* [13], Zyskind *et al.* [14]

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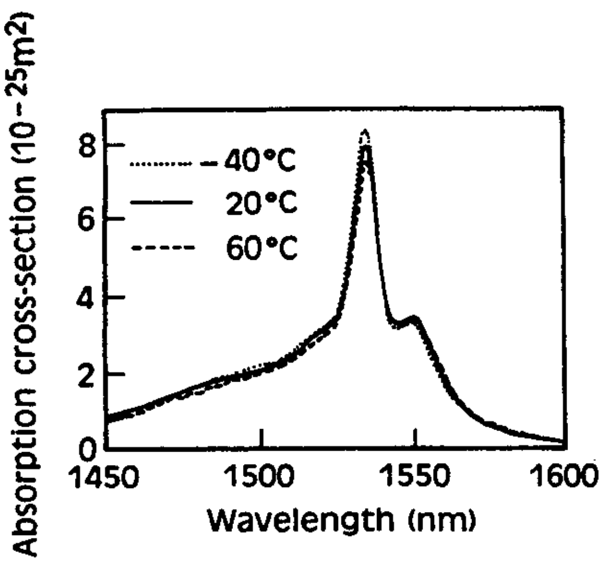
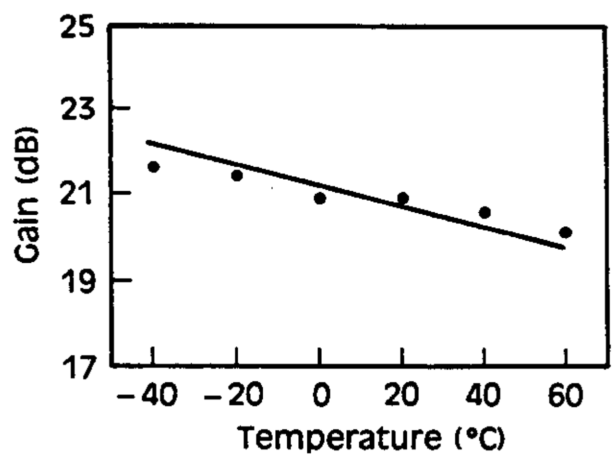
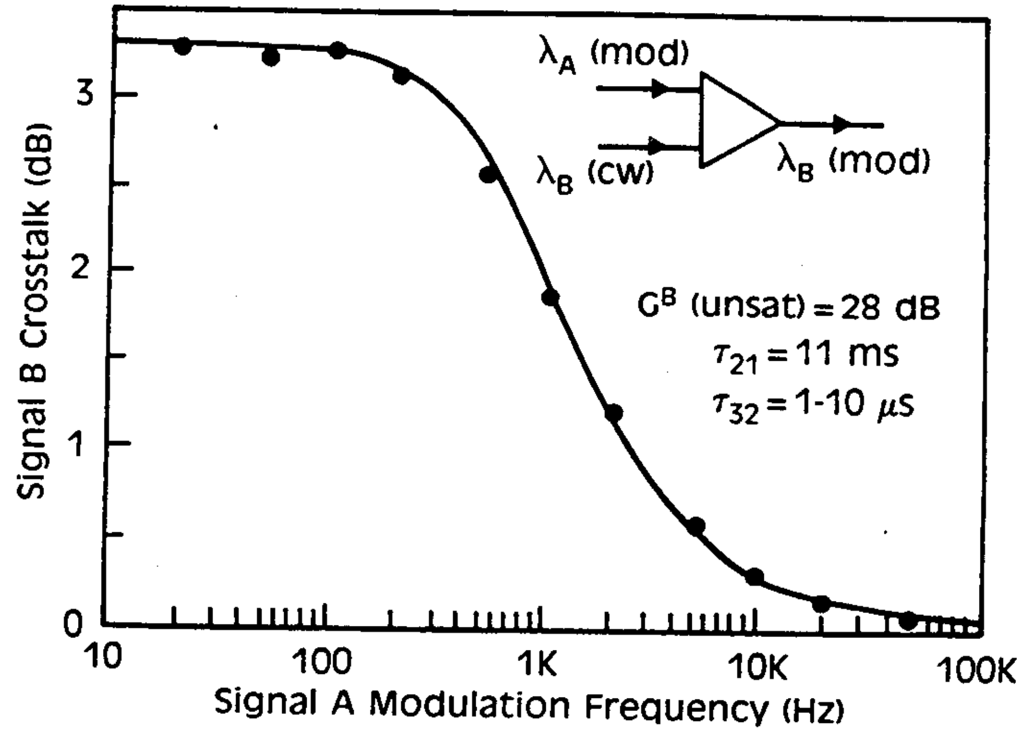
Gain dependence with temperature





**M. Suyama et al., OAA'90, paper WD3*

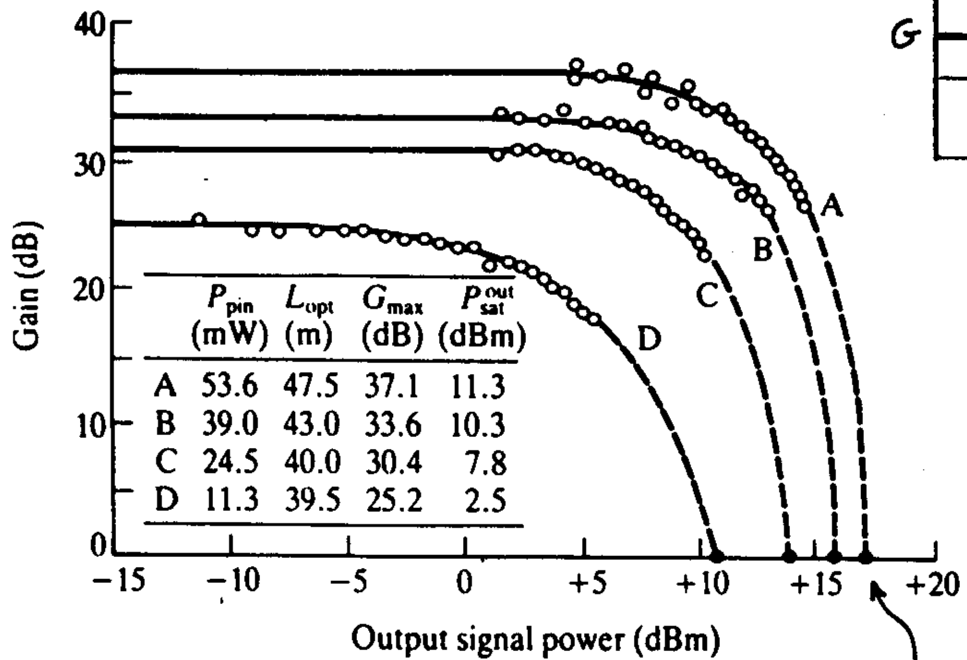
Frequency response of gain saturation



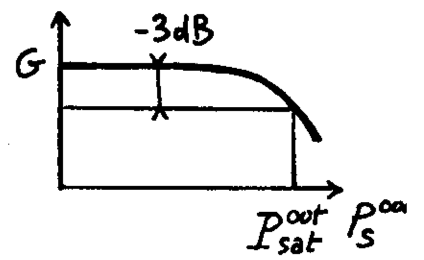
Giles *et al.* [15], Laming *et al.* [16]

Gain vs. output signal power

1480nm pump



	P_{pin} (mW)	L_{opt} (m)	G_{max} (dB)	P_{sat}^{out} (dBm)
A	53.6	47.5	37.1	11.3
B	39.0	43.0	33.6	10.3
C	24.5	40.0	30.4	7.8
D	11.3	39.5	25.2	2.5



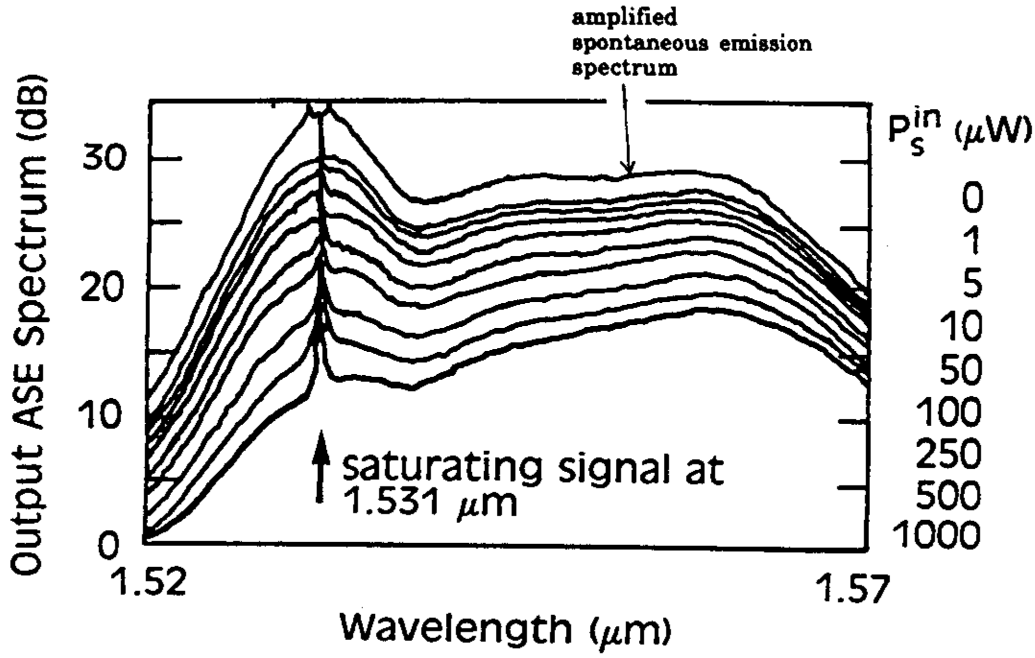
3dB saturation output power $\neq P_{sat}(\lambda)$!

PCE quantum limit

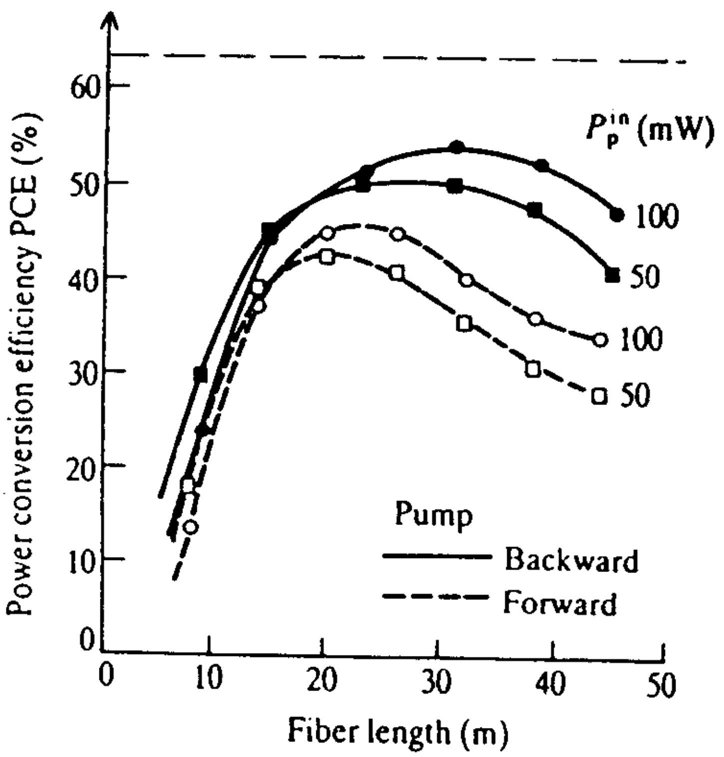
Desurvire *et al.* [11]

$$P_s^{out}(\max) = \frac{\lambda_p}{\lambda_s} P_p^{in}$$

- Homogeneity of gain saturation [1]



Power conversion efficiency



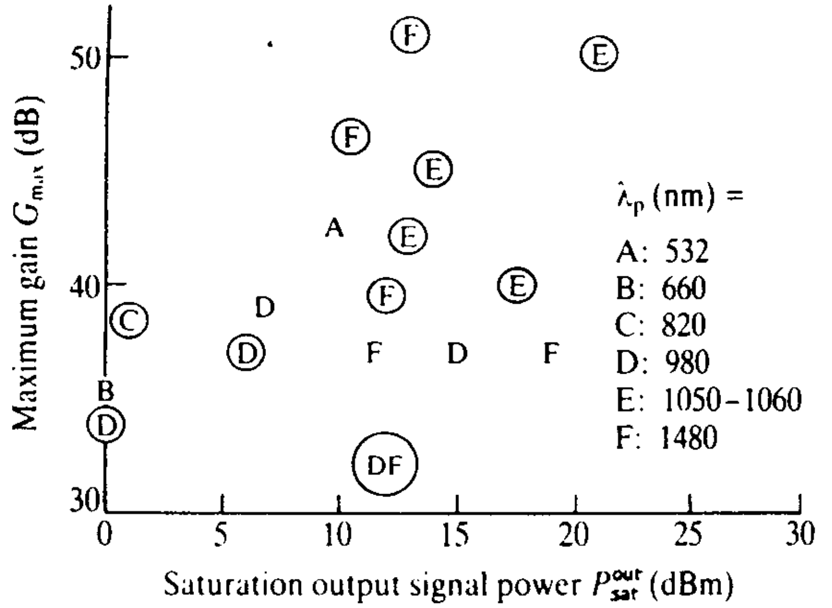
$$\frac{\lambda_p}{\lambda_s} = \frac{980\text{nm}}{1550\text{nm}} = 63\%$$

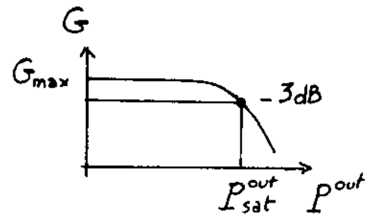
Laming *et al.* [17]

⇨ PCE highest with backward pumping: explained by ASE self-saturation
Desurvire [18]

- Power (booster) amplifiers - best results (1993)

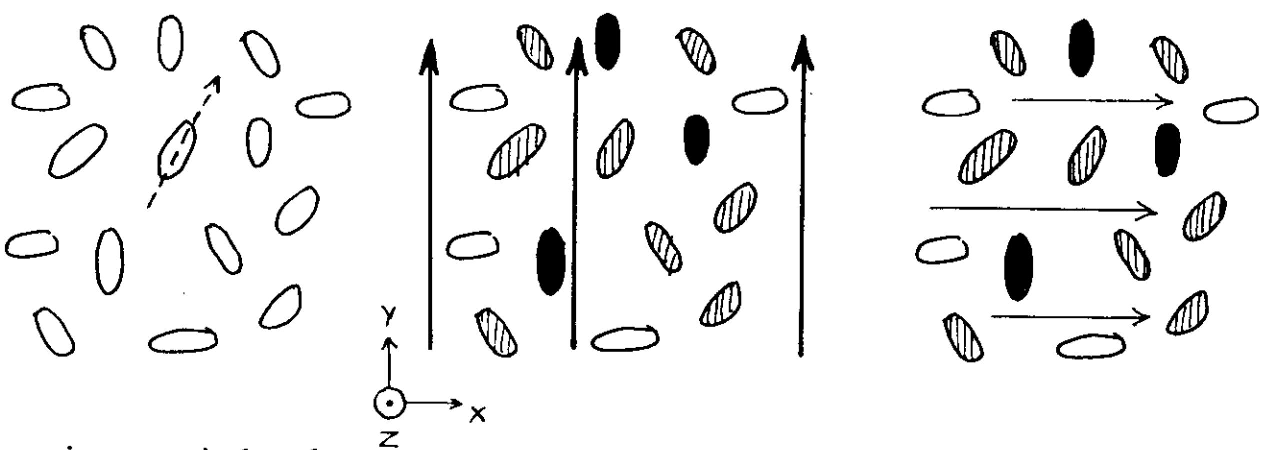
→ Maximum gain vs. saturation output power (3dB compression)





Polarization hole-burning

- EDFA gain is intrinsically polarization independent
  (random Er-dipole orientations averaged at macroscopic level)



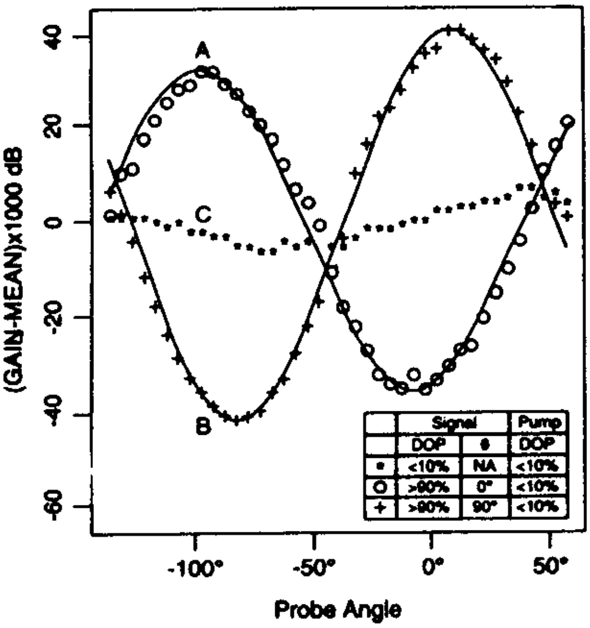
microscopic level

strong saturating linearly polarized signal

weak probe in orthogonal polarization experiences higher gain

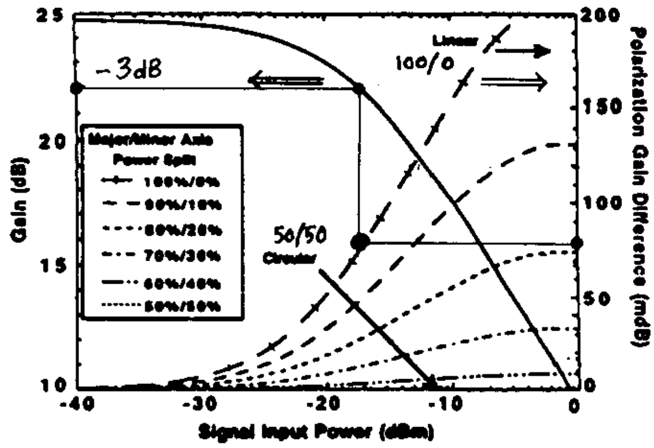
Polarisation-dependent gain (PDG)

Experimental (compression 3dB)



Mazurczyk *et al.* [19]

Theoretical



PDG=80-200mdB at 3-6dB compression, as measured in experiments

Wysocki *et al.* [20]

EDFA noise figure

- Noise figure in linear regime: $F = \frac{1}{\eta_{in}} \frac{1+2n_{sp}(G-1)}{G} \longrightarrow 2n_{sp}$ as $G \gg 1$

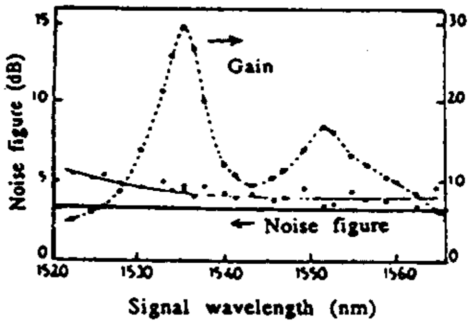
η_{in} = input coupling loss
n_{sp} = spontaneous emission factor

- Minimum noise figure: $F_{min} = 2n_{sp}^{min} = \frac{2}{1-\eta_p/\eta_s}$; $\eta_i = \frac{\sigma_e(\lambda_i)}{\sigma_a(\lambda_i)}$

pump λ_p = 980nm → $\eta_p=0$ → $F_{min}=2\equiv3$dB (quantum limit)
(3-level system)

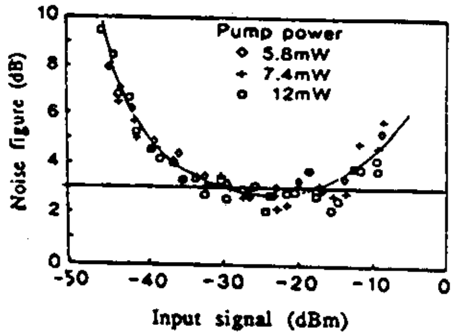
pump λ_p = 1480nm → $\eta_p=0.25$, $\eta_s=1\text{-}1.2$ → $F_{min}=2.5\equiv4$dB
(2-level system)

Noise figure vs. pump band



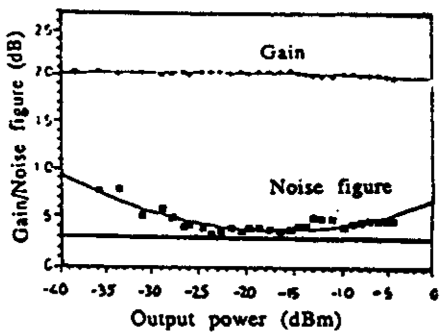
810nm band

F=3.9-4.7dB



980nm band

F=3.0dB



1480nm band

F=4.5-6dB

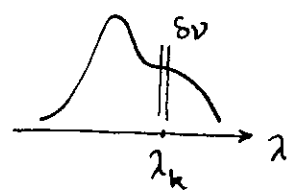
Kimura *et al.* [21]

Laming *et al.* [22]

Blair *et al.* [23]

EDFA modelling: general rate equations [1,2]

- Most general case : spectral components at λ_k (width $\delta\nu$)
  bidirectional ($\pm$) pump(s) and signal(s)



$$\frac{dp_k^{\pm}}{dz} = \pm\, \rho_o \sigma_a(\lambda_k) \frac{2}{\omega_k^2} \int_S r\,dr\, \frac{\rho(r)}{\rho_o}\, \psi_{sk}(r) \times$$

$$\left\{ \frac{\eta_k \left[\sum_j \frac{(p_j^+ + p_j^-)}{1+\eta_j} \psi_{sj}(r) \right] [p_k + 2p_{ok}] - \left[1 + \sum_j \frac{\eta_j (p_j^+ + p_j^-)}{1+\eta_j} \psi_{sj}(r) \right] p_k}{1 + \sum_j (p_j^+ + p_j^-) \psi_{sj}(r)} \right\}$$

$$p_k \equiv \frac{P(\lambda_k)}{P_{sat}(\lambda_k)}$$

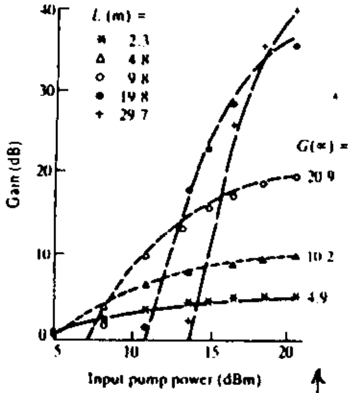
$$\eta_k \equiv \frac{\sigma_e(\lambda_k)}{\sigma_a(\lambda_k)}$$

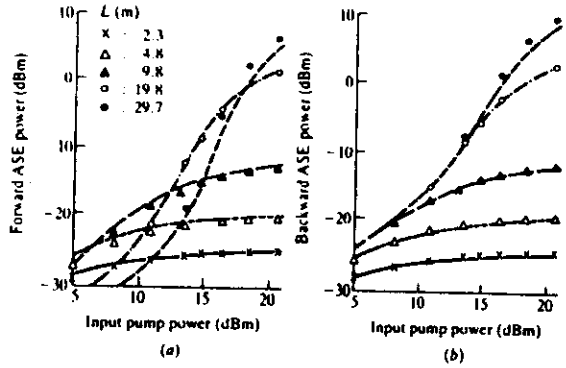
⟶ 2-level system (1480nm pumping) : $\eta_p \neq 0$

⟶ 3-level system (980nm pumping) : $\boxed{\eta_p = 0}$

⇒ integration heavy in ASE self-saturation regime !..

- Comparison theory/experiment with general EDFA model





gain at infinite pump : $G(\infty) = \left\{ \frac{\eta_s-\eta_p}{1+\eta_p} \alpha_s L \right\}$ Pedersen *et al.* [24]

Analytical models

- rapid evaluation of EDFA performance and parametric optimization
- trial ASE boundary values for general EDFA model
- to include in NLSE simulators for finer WDM soliton system predictions

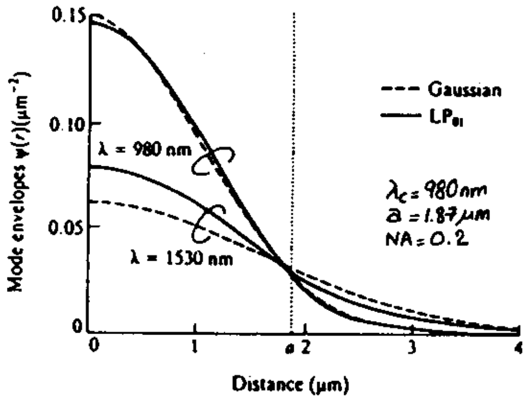
predicts:	saturation by signal(s)	ASE spectra	ASE self-saturation	REF
Transcendental equation	yes	no	no	[1,4]
Saleh	yes	no	no	[5]
Desurvire	no	yes	no	[1,6-7]
Georges	yes	yes	yes	[8]
Hodgkinson	yes	yes	yes	[9]
Saleh+Desurvire	yes	yes	yes	[1]

Semi-analytical models: <u>power-dependent overlap integrals</u> analytically solved using "good" Gaussian approximation

Giles [2], Desurvire [1]

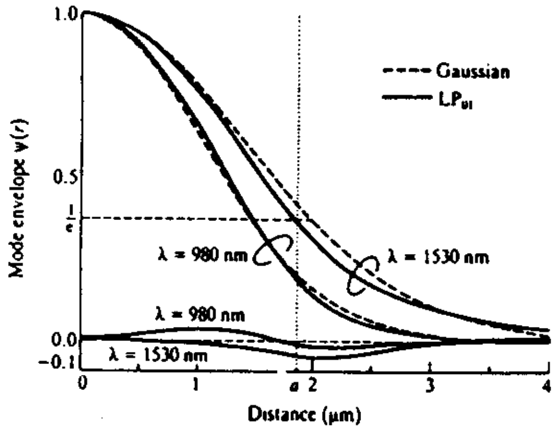
A new gaussian mode approximation for RE-doped fibers [1]

- Gaussian approximation (Marcuse)



$$\omega_s = \frac{a}{\sqrt{2}}\left(0.65 + \frac{1.619}{1.5} + \frac{2.879}{V^6}\right)$$

- Gaussian approximation (new)



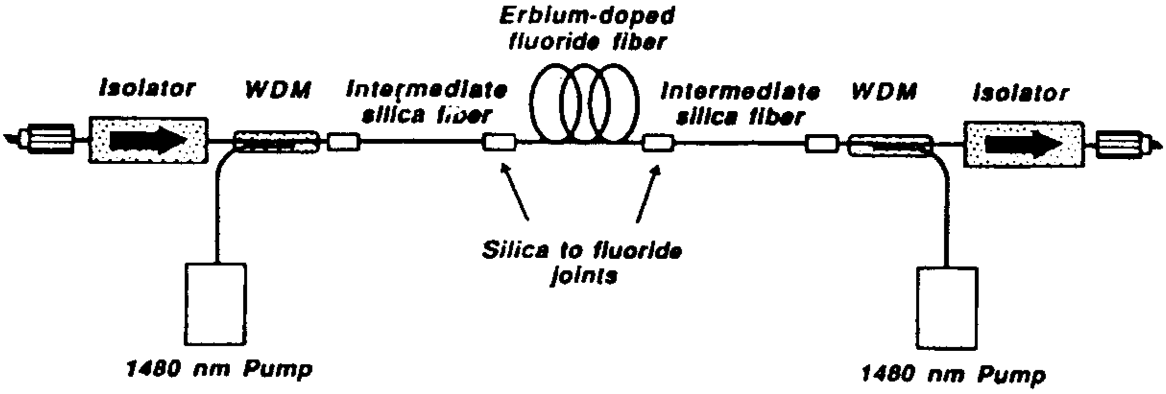
$$\omega_s = \left(2\int_0^{\infty} \psi_{LP_{01}}(r)\, r\,dr\right)^{\frac{1}{2}} = a\,\frac{VK_1(W)}{UK_0(W)}\,J_0(U)$$

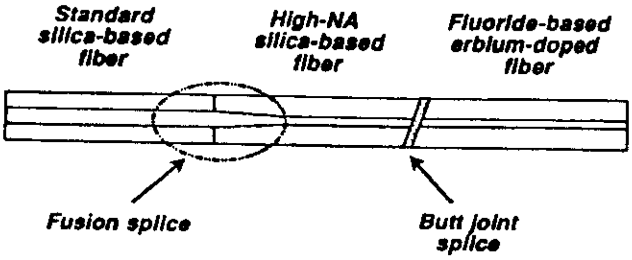
Fluoride-based EDFAs

- Matrix host: ZrF_4-BaF_2-LaF_3-AlF_3-NaF (ZBLAN)
- Mostly radiative de-excitation ⟶ 1.48μm pumping for Er^{3+}
- (Suitable glass host for other rare-earths: Pr^{3+}, Tm^{3+})
- Fabrication by casting/centrifugating under controlled atmosphere; high-purity and uniformity required for low backround loss
- Splicing to silica fibers: tapers and butt-joint splices
- Major advantage: intrinsic flat-gain characteristics:

The *ideal* EDFA for WDM systems?

Bidirectionally-pumped fluoride-EDFA

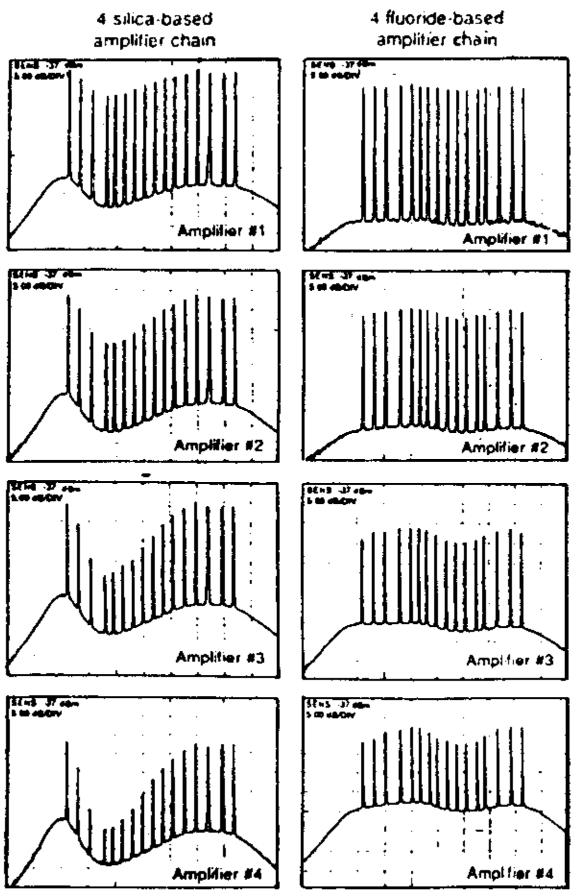




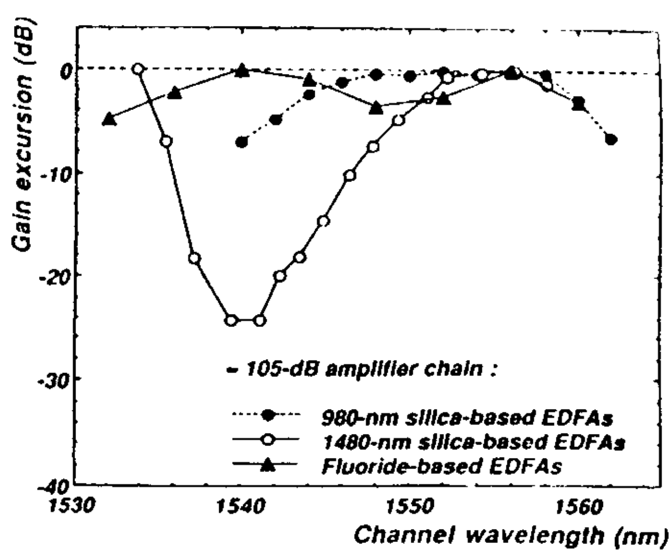
Input coupling loss	0.5 dB
Total pump power	100 mW
F/F flat gain	25 dB
Overall noise figure	7 dB
Max. output power	+16 dBm

Courtesy J.L.Beylat, Alcatel-Alsthom Recherche

Silica- and fluoride-EDFA chains: gain excursion characteristics



Amplifier spacing 120km (25dB gain/OA)



B.Clesca et al.,Optical FiberTechnol., Vol.1, N°2, 1995

Fluoride-EDFAs: where applicable?

- Terrestrial systems (SMF): - high dispersion (17ps/nm.km)
  - but no FWM phase-matching

⟶ fluoride-EDFAs amenable to dense WDM, low bit rates (1.25-2.5Gbit/s)

- Undersea systems (DSF): - near-zero dispersion
  - but FWM phase-matching

⟶ fluoride-EDFAs amenable to WDM, large channel spacing (1-5nm), higher bit-rates (5-10Gbit/s)

- WDM soliton systems: - automatic power control through bandwidth-limited amplification
  - but EDFA saturation causes large gain excursion between channels

⟶ fluoride-EDFAs flat gain could enhance transmission performance

The EDFA: do we now understand it all?

No!... Several issues still remain at the frontiers of knowledge [1]:

- the actual coordination of the Er^{3+} site in glass hosts
- inhomogeneous broadening and theoretical modeling (room-temperature weak "hole-burning" under saturation)
- theoretical prediction of cross-sections
- a full theory of pump and signal-induced PDG
- quenching mechanisms at high Er^{3+} concentrations and identification of EDD, EDQ, EQQ interaction types
- nonlinear photon statistics and impact on saturated noise figure

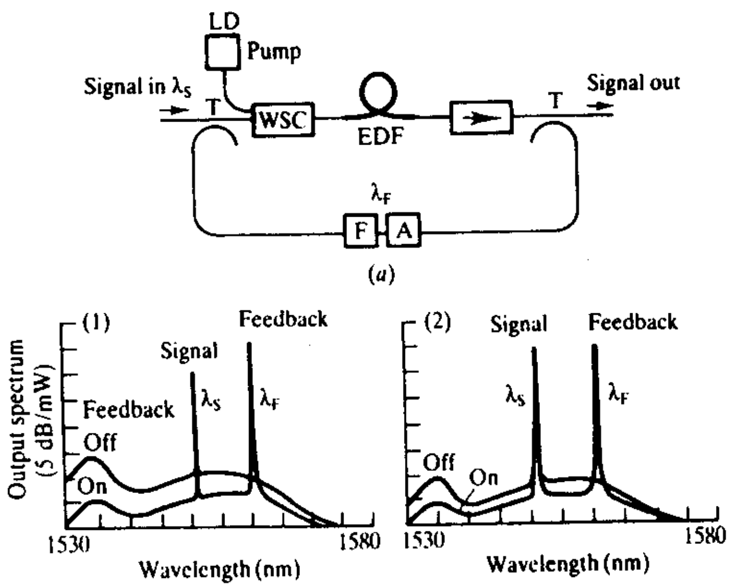
3- Device and system applications of EDFAs

(this is just a selection!..)

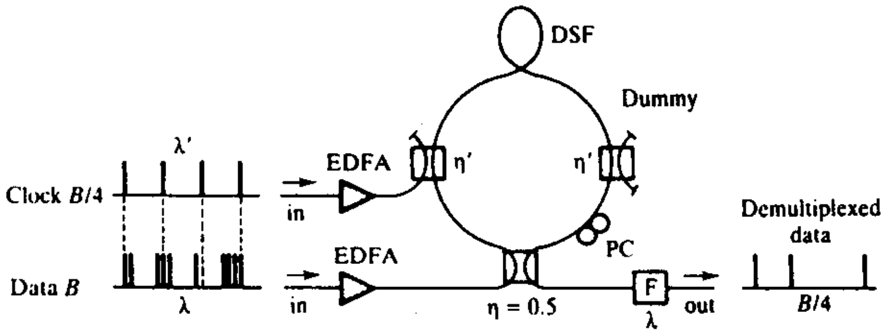
- All-optical automatic gain control
- All-optical demultiplexing
- All-optical regeneration
- All-optical clock recovery
- All-optical NRZ <-> RZ format conversion

- Dispersion compensation by FWM
- Dispersion compensation by DC fiber
- 16x2.5Gbit/s WDM transmission over 440km SMF with fluoride EDFAs
- Video broadcast networks
- Lossless local area networks

- All-optical automatic gain control (Zirngibl [25])

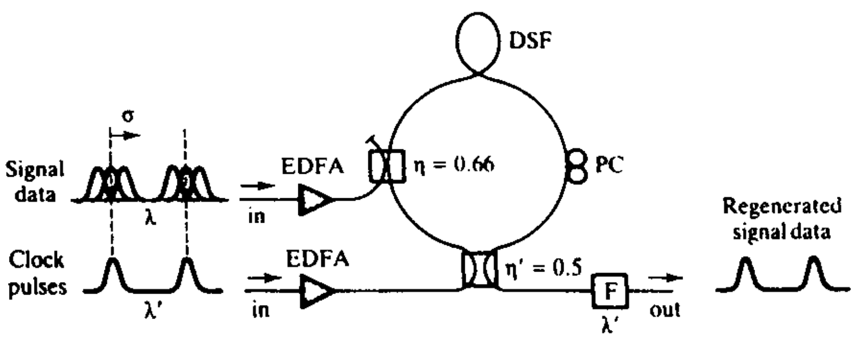


- All-optical demultiplexing (Jinno [26], Blow [27])



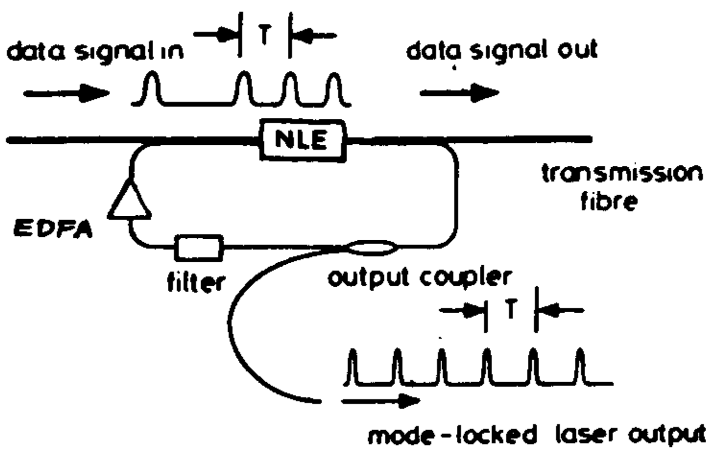
→ demonstrated up to B=100Gbit/s in polarization-independent configuration (Uchiyama [37])

- All-optical regeneration (Jinno [28])



signal/clock walkoff determines NOLM switching window
data is transferred to switched clock pulses without jitter

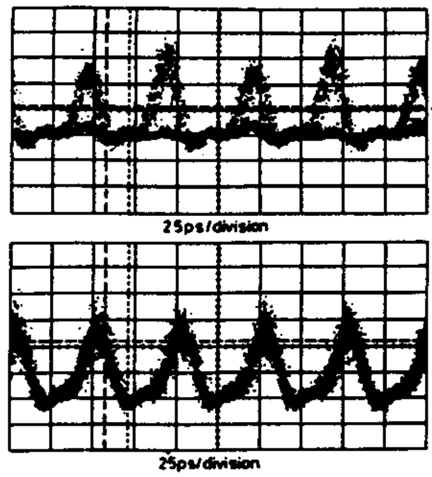
- All-optical clock recovery



NLE= nonlinear element (FM modulator)

(Smith [29])

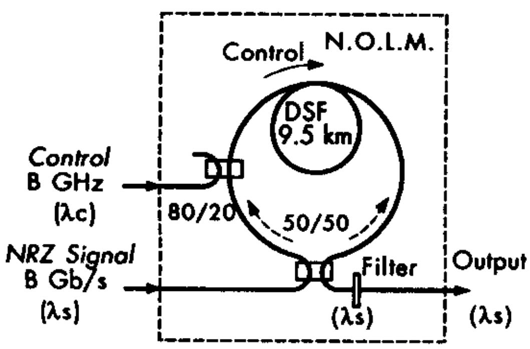
20Gbit/s PRBS signal in



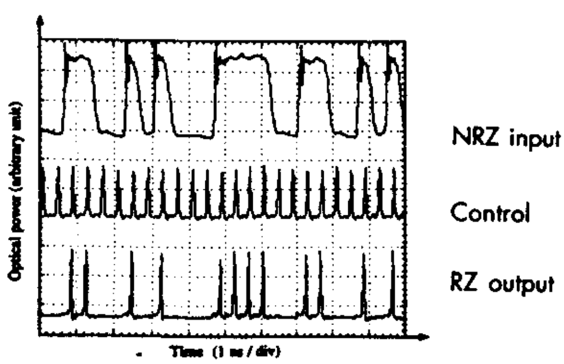
20GHz recovered clock

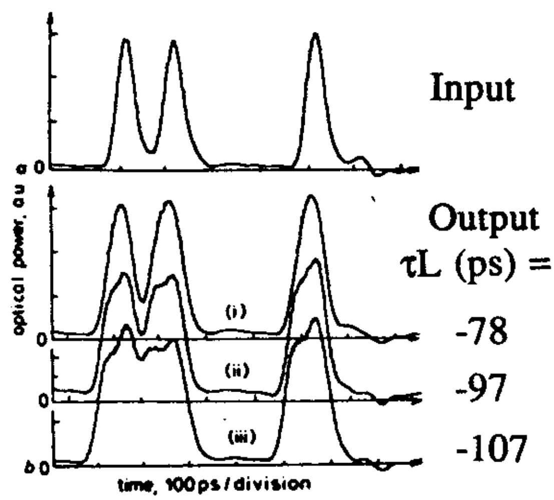
(Patrick [30])

- All-optical NRZ <——> RZ format conversion (Bigo [31-32])



NRZ —> RZ conversion



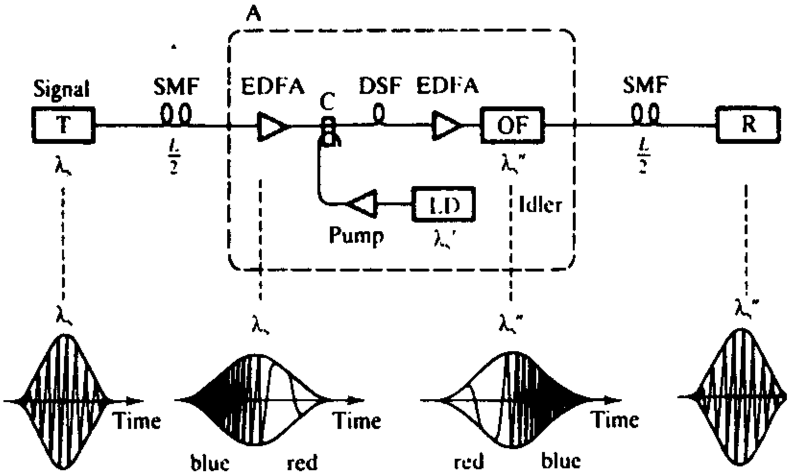


RZ —> NRZ conversion

→ NRZ time-division MUX and soliton conversion

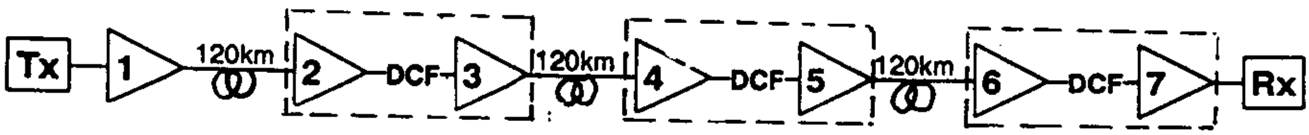
→ Soliton receiver eye opening

- Dispersion compensation by FWM (Jopson [33])



→ 10Gbit/s transmission over 360km standard fiber

- Dispersion compensation by dispersion-compensating fiber (Chen [34])

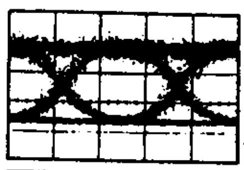


Dispersion (ps)	+2120	-2168	+2116	-1770	+2105	-1770

→ Effect of SPM makes undercompensation necessary

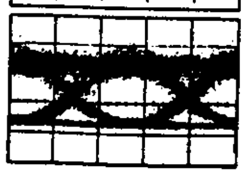
10 Gb/s Transmitter Output
λ = 1552nm
$\bar{P}_{out}$ = -4dBm

120km Transmission Without DCF



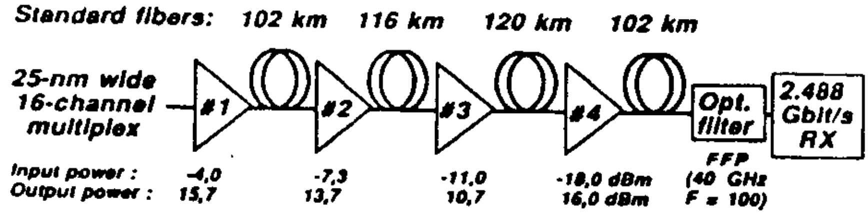
120km with DCF
SNR = 30.5dB

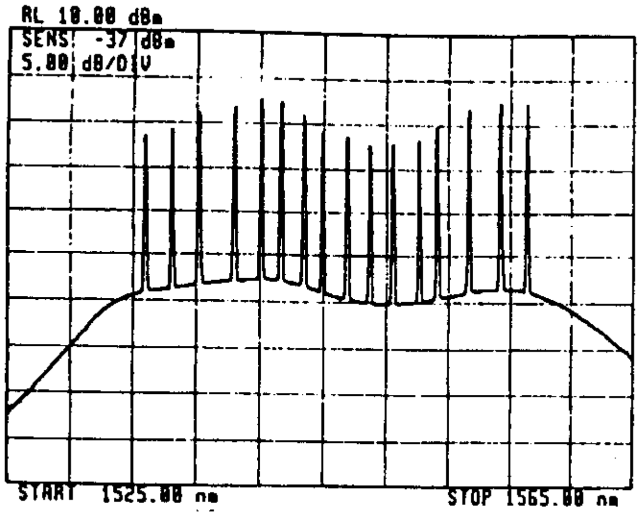
240km with DCFs
SNR = 28dB

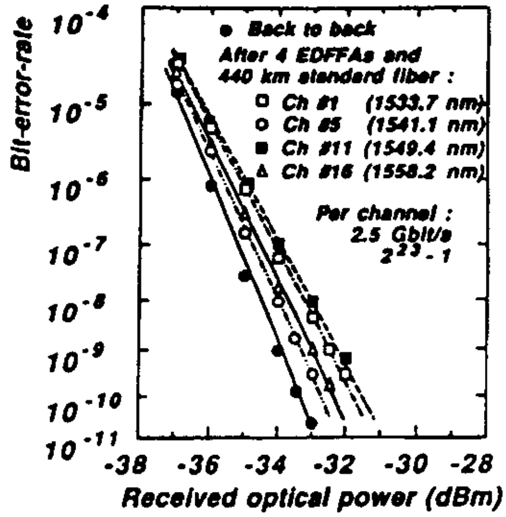


360km with DCFs
SNR = 26.5dB

- 16 x 2.5Gbit/s WDM transmission over 440km SMF with fluoride-EDFAs

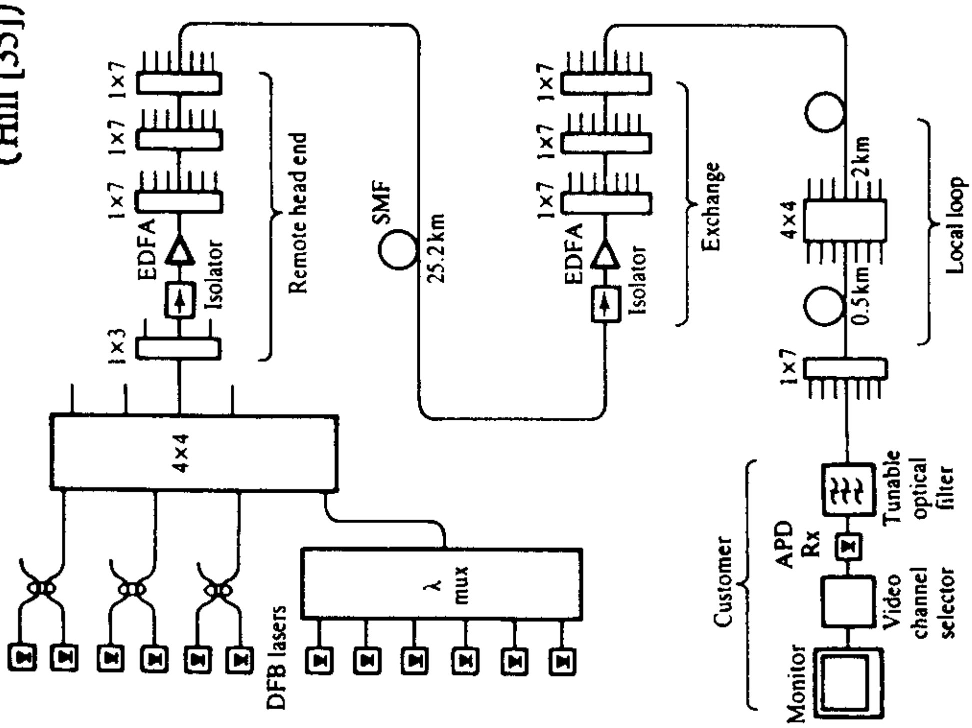






B.Clesca et al., Alcatel-Alsthom Recherche, OFC'94

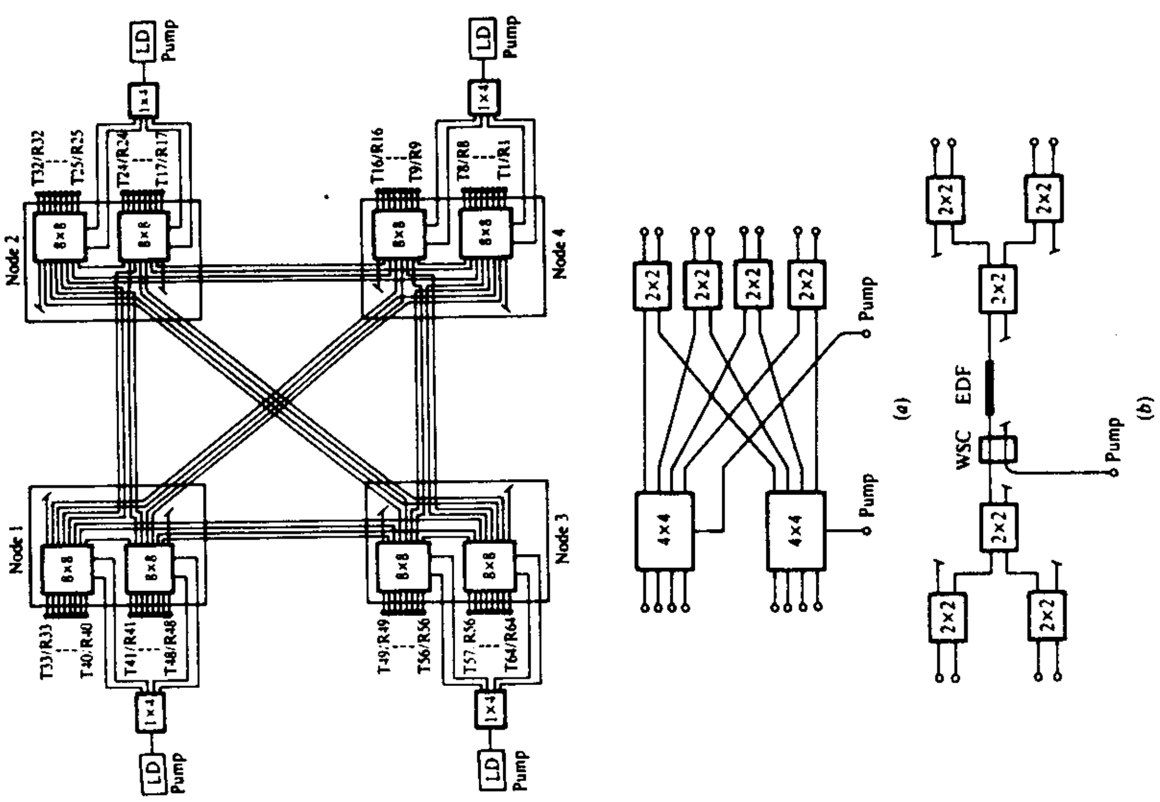
- Video broadcast networks (Hill [35])



→ feasability demonstration of 12-channel WDM CATV distribution of 384 video chanels to 39,530,064 users

(4116 EDFAs, one EDFA per 9604 users)

• Lossless local area networks (Chen [36])



CONCLUSION

Erbium-doped fibers
combine all the advantages
of near-ideal optical amplification

Diode-pumped EDFAs
have become ubiquitous components
in a new generation of lightwave systems

Future world communications,
heretofore limited by electronics bottleneck,
will now rely upon unregenerated fiber links

All this success comes from a very basic idea:
stimulate signal light emission *within* the guiding fiber

EDFAs: Key features and applications

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* * *

Fiber amplifiers vs. semiconductor amplifiers

EDFA	Raman FA	Brillouin FA	Semiconductor
wide operating bandwidth (20-30nm)	yes	no (15MHz)	yes
low insertion loss (< 0.2dB)	yes	yes	no (1-3dB)
temperature-insensitive gain (-40/+60°C)	yes	yes	no
efficient pumping (LD or RF)	no	yes	yes
high saturation output power (> 20 dBm)	yes	no	yes (theo.)
polarization-insensitive gain	effectively		no (>0.5dB)
slow gain dynamics (none at f>10kHz)	no	no	no
best intrinsic noise figure of 3dB	yes	no (NF=500)	no (>4dB)
packaging: min. 1 LD/fiber coupling	yes	yes	no (two)

1.55 μm Polarisation Independent Semiconductor Optical Amplifier with 25 dB Fiber to Fiber Gain

P. Doussiere, P. Garabedian, C. Graver, D. Bonnevie, T. Fillion, E. Derouin, M. Monnot, J. G. Provost, D. Leclerc, *Associate, IEEE,* and M. Klenk

{Alcatel Alsthom Recherche
Alcatel-SEL}

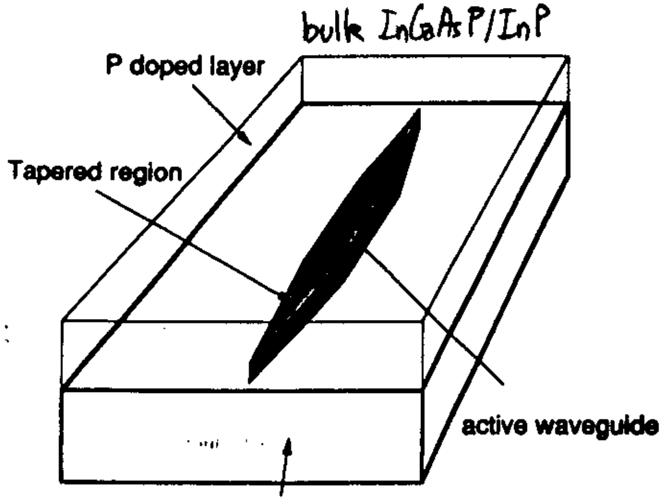

Fig. 1. Schematic view of polarisation independent amplifier with tapered width active stripe and buried facets.

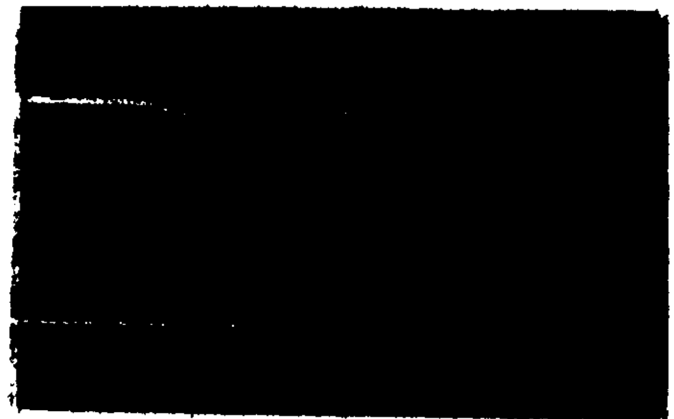

Fig. 2. SEM photograph of the cross-sectional view of polarisation independent amplifier with buried square active stripe.

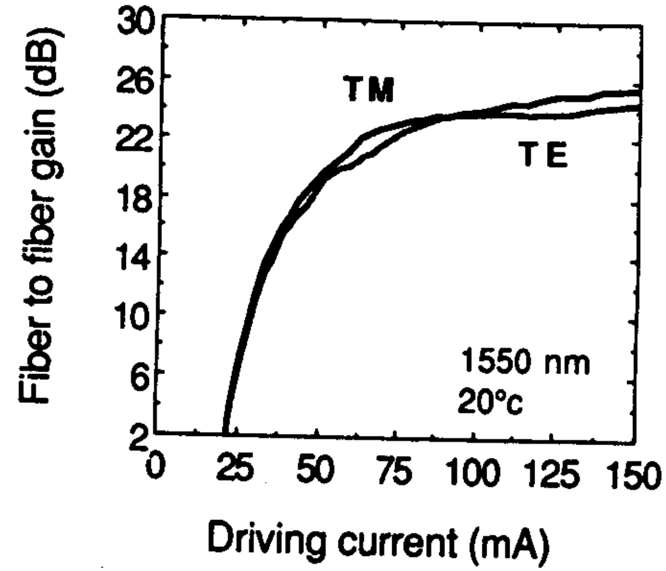

Fig. 4. Fiber to fiber gain for TE anTM signal polarisation versus current of tapered amplifier for 1550 nm wavelength.

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Polarization-Insensitive Semiconductor Optical Amplifier Array Grown by Selective MOVPE

S. Kitamura, K. Komatsu and M. Kitamura

(NEC Corporation)

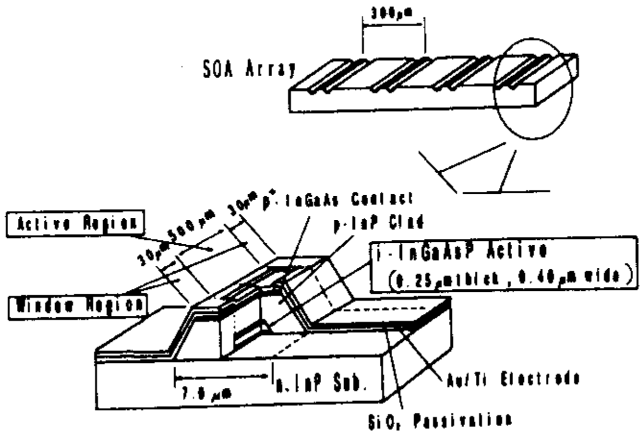


Fig. 1. SOA array structure.

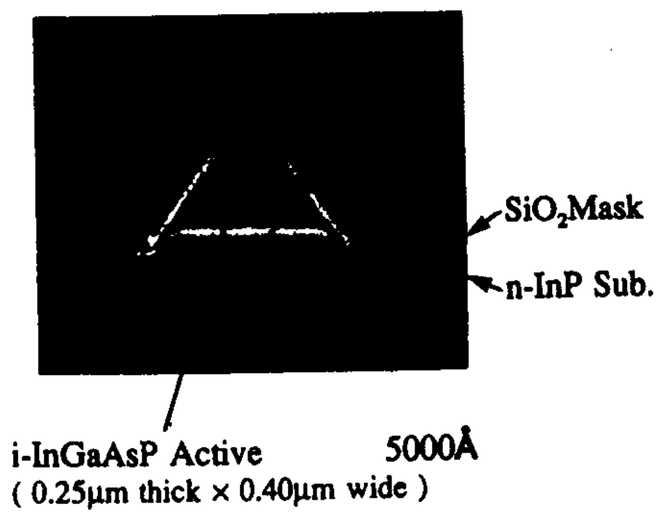


Fig. 2. SEM cross sectional view of grown semiconductor stripe.

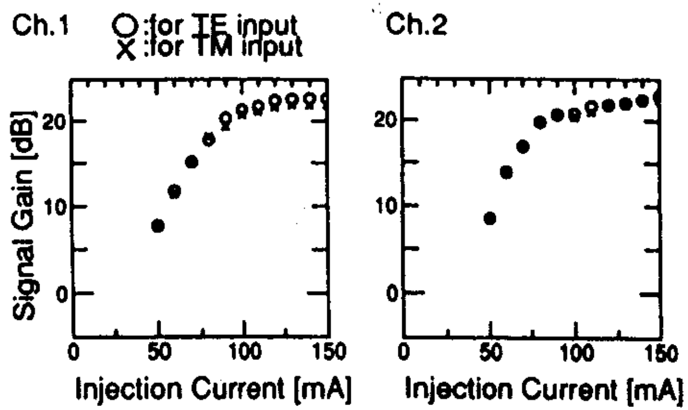


Fig. 3. Signal gain characteristics of a four-channel SOA array.

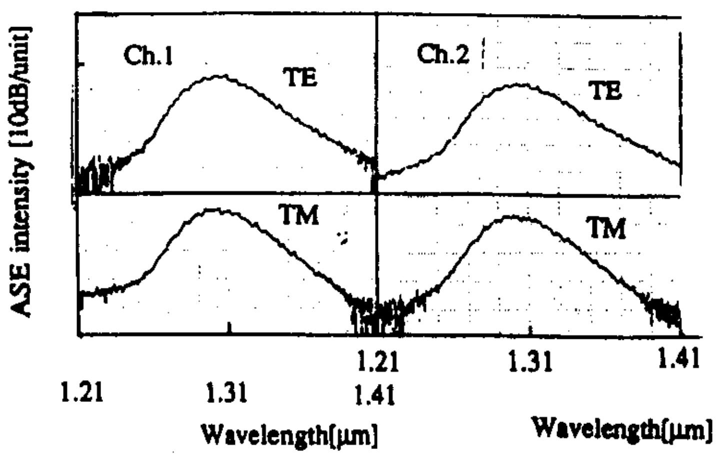


Fig. 4. ASE spectra of a four-channel SOA array.

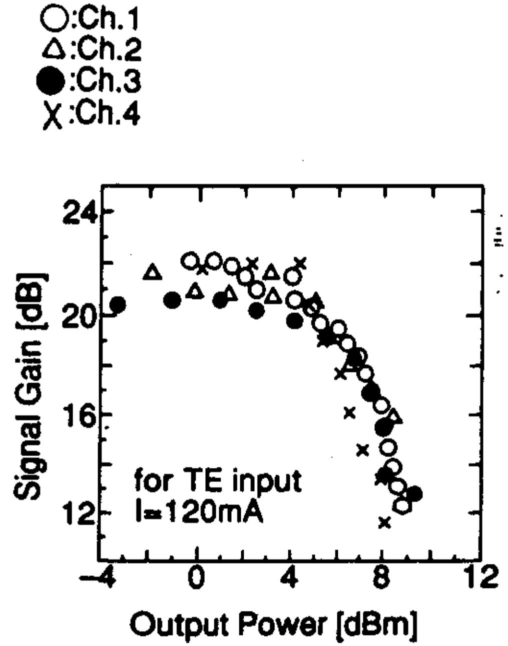


Fig. 5. Gain saturation characteristics of a four-channel SOA array.

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 6, NO. 2, FEBRUARY 1994 , 176

Gain Saturation Properties of a Polarization Insensitive Semiconductor Amplifier Implemented with Tensile and Compressive Strain Quantum Wells

(USC Los Angeles)

Serge Dubovitsky, Atul Mathur, William H. Steier, *Fellow, IEEE,* and P. Daniel Dapkus, *Fellow, IEEE*

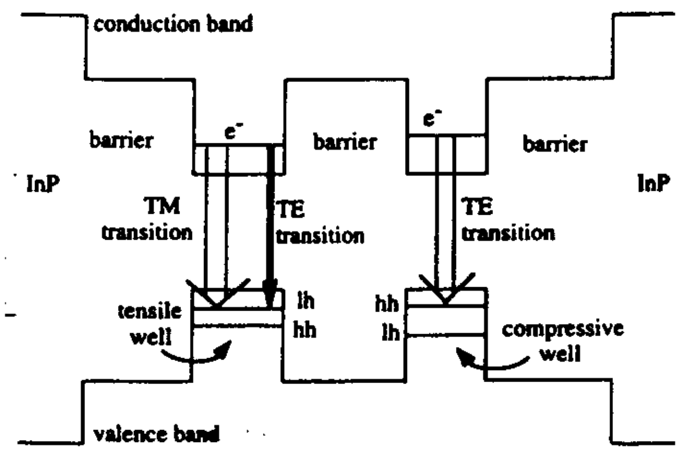


Fig. 1. Simplified band diagram of the amplifier gain region. The active region actually consists of six quantum wells: three compressively strained wells alternating with three tensile strain quantum wells.

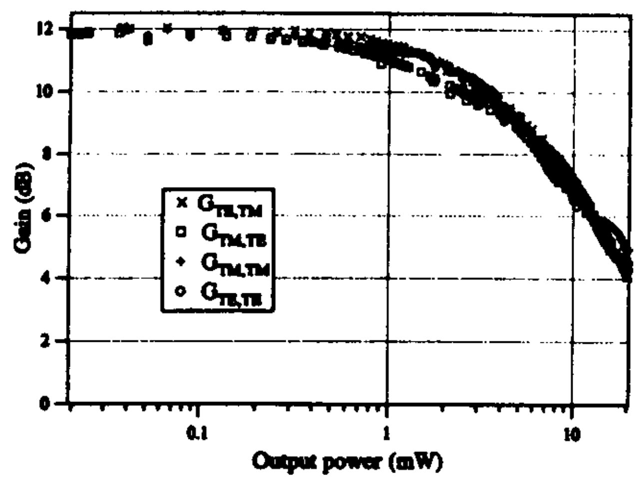


Fig. 3. TE and TM gain saturation versus TE or TM output pump power at an injection current of 90 mA: $G_{TE,TE}$—TE gain saturation by TE pump; $G_{TM,TM}$—TM gain saturation by TM pump; $G_{TE,TM}$—TE gain saturation by TM pump; $G_{TM,TE}$—TM gain saturation by TE pump.

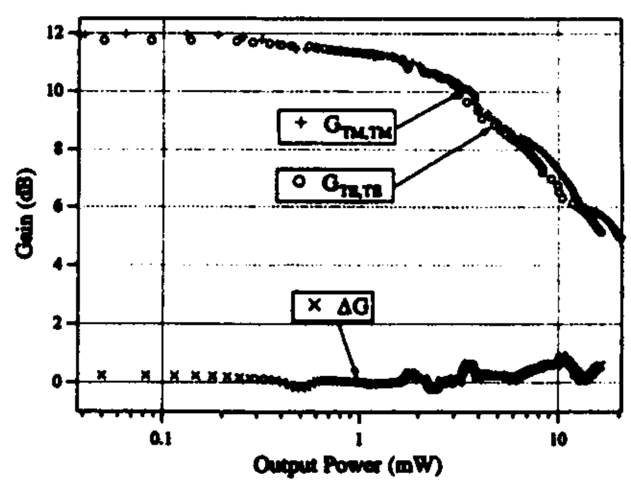


Fig. 4. Self-saturation curves, $G_{TE,TE}$ and $G_{TM,TM}$, and the gain saturation induced dichroism, ΔG.

IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-23, NO. 6, JUNE 1987 , 1010

1.5 μm GaInAsP Traveling-Wave Semiconductor Laser Amplifier

TADASHI SAITOH AND TAKAAKI MUKAI, MEMBER, IEEE

(NTT)

TABLE I
THEORETICAL NOISE PARAMETERS FOR TWA AND FPA AT A 20 dB SIGNAL GAIN

Amplifier	TWA		FPA
(R_1, R_2) [%]	(0.013, 0.123)	(0.123, 0.013)	(31.6, 31.6)
n_{sp} [dB]	2.14	2.14	5.80
χ [dB]	0.05	0.47	2.53
$2n_{sp}\chi$ = F [dB]	5.20	5.63	11.34
F* [dB]	——	5.2	——

*Experimental

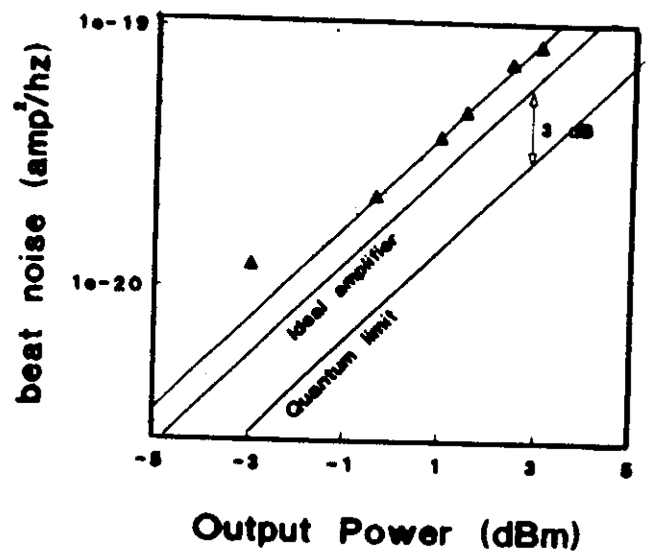
4:45pm OFC '92

TuM2 Low-noise figure 1.5 μm MQW optical amplifier

D. Tauber, R. Nagar, A. Livne, G. Eisenstein, U. Koren,* G. Raybon*

Technion, Department of Electrical Engineering, Haifa 32000, Israel, * AT&T Bell Laboratories, Holmdel NJ

Efficient inversion possible in a MQW medium results in a low spontaneous emission factor, N_{sp}, (Saitoh) and hence a low noise figure. This has been recently demonstrated in an AlGaAs/GaAs MQW optical amplifier for which a 4.6-dB noise figure was reported.[5] This paper reports noise figure studies of InGaAs/InGaAsP MQW optical amplifiers operating near 1.5 μm. We demonstrate an amplifier with a 4.4 dB noise figure at a gain of 19 dB. To our knowledge, this is the lowest noise figure reported to date for any semiconductor optical amplifier.



TuM2 Fig. 2. Beat noise measurements at a gain of 19 dB.