The Abdus Salam
International Centre
for Theoretical Physics

2443-3

Winter College on Optics: Trends in Laser Development and Multidisciplinary Applications to Science and Industry

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SOA and Superluminescent LED

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SOA and Superluminescent LED (SLED)

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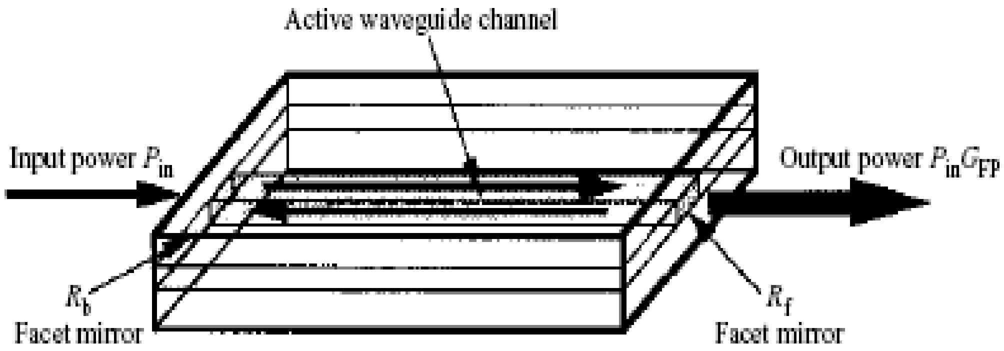
Outline

- The SOA & SLED structure and features
- SOA static and dynamic models
- SOA applications

- SOA & SLED spontaneous emission noise

- The SLED realizations
- SLED application to OCT

SOA&SLED vs Laser diodes structures



The structure is very similar to the laser diode structure
just that the feedback should be eliminated in order to have:
-Flat gain amplification
-High gain

The SOA gain can be computed from the T_{11} element of the transmission matrix of the Fabry Perot cavity

$$|T_{11}|^2 = G_{FP}(\omega) = \frac{(1-R_f)(1-R_b)G_s}{1+R_f R_b G_s^2 - 2(R_f R_b)^{1/2} G_s \cos(2\beta L)}$$

The gain is not constant with wavelength!!

$$G_s = G_s(\omega) = \exp\{[\Gamma g(\omega) - \alpha_{int}]L\}$$

G_s single pass gain

Gain and spectral ripple

Devices with not ideal ARC present an undulation in the gain and spectral emission that for the SOA is characterized by the Gain Ripple (G_r) as the ratio between maximum and minimum gain

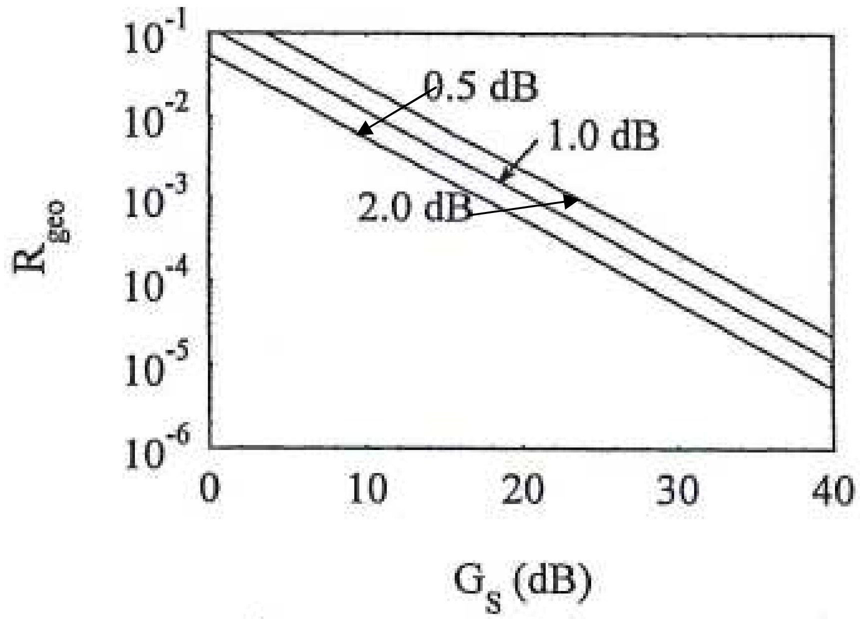
$$G_{ripple} = \left(\frac{1 + \sqrt{R_1 R_2} G_s}{1 - \sqrt{R_1 R_2} G_s} \right)^2$$

defining $R_{geo} = \sqrt{R_1 R_2}$

we can define a relation between the residual unwanted reflectivity R_{geo} and the gain ripple G_r

In order to have a good SOA gain (30dB)is necessary to have a very low residual reflectivity (10^{-4}) for a 1dB ripple!!!

Similarly for the SLED spectrum.



How to reduce the modal reflectivity

What count in the previous relation is the "modal" reflectivity ;

the part of the reflected power at the air interface that is coupled back into the backward propagating waveguide mode.

$$R = \frac{\left|\int_{-\infty}^{\infty} E_{inc}(x) E_{ref}(x) dx\right|^2}{\left|\int_{-\infty}^{\infty} E_{inc}(x)^2 dx\right|^2}$$

The most traditional method is to deposit on the cleaved facet an **antireflection coating (ARC)**

In practice a good ARC is very difficult to realize on the laser facet and usually only one or two dielectric layers can be deposited with good reliability.

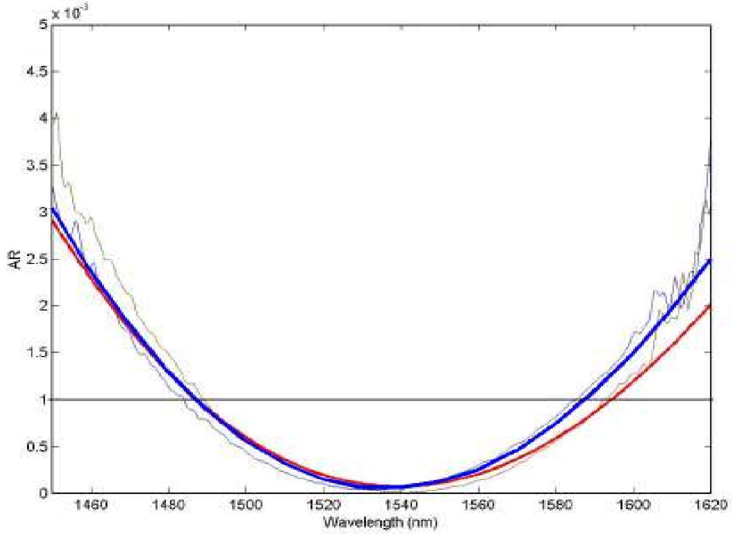
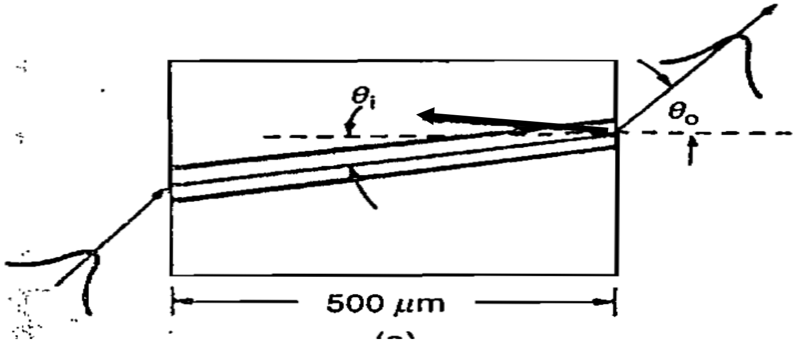
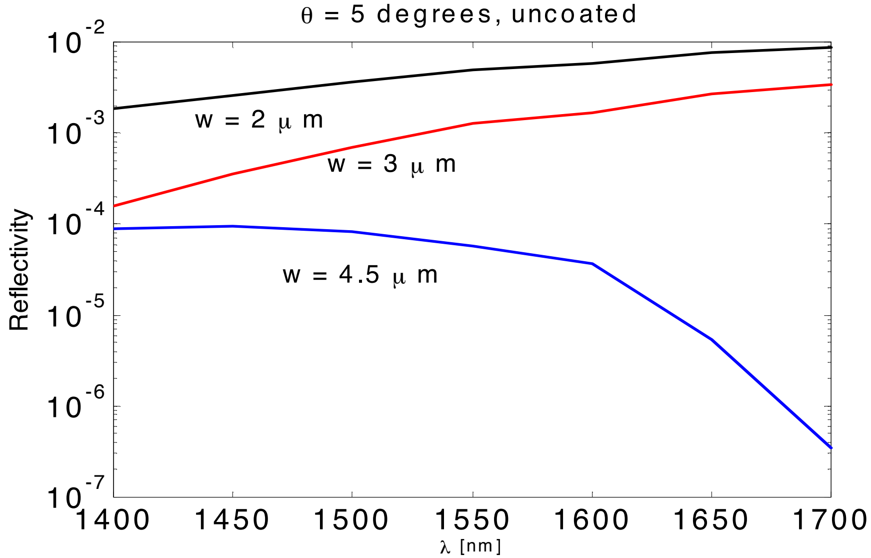


Figure 4.13. Power reflectivity for the untilted 6 μm QD structure with double AR coating ($n_1 = 1.98$ and $n_2 = 1.58$, $d_1 = 0.1185$ μm, $d_2 = 0.144$ μm; our 2D simulation results (blue curve), NetTest 1D results (red curve), NetTest experimental results (grey curve)

Waveguide tilt

The other possibility is the **waveguide tilt**





Simple and broad band

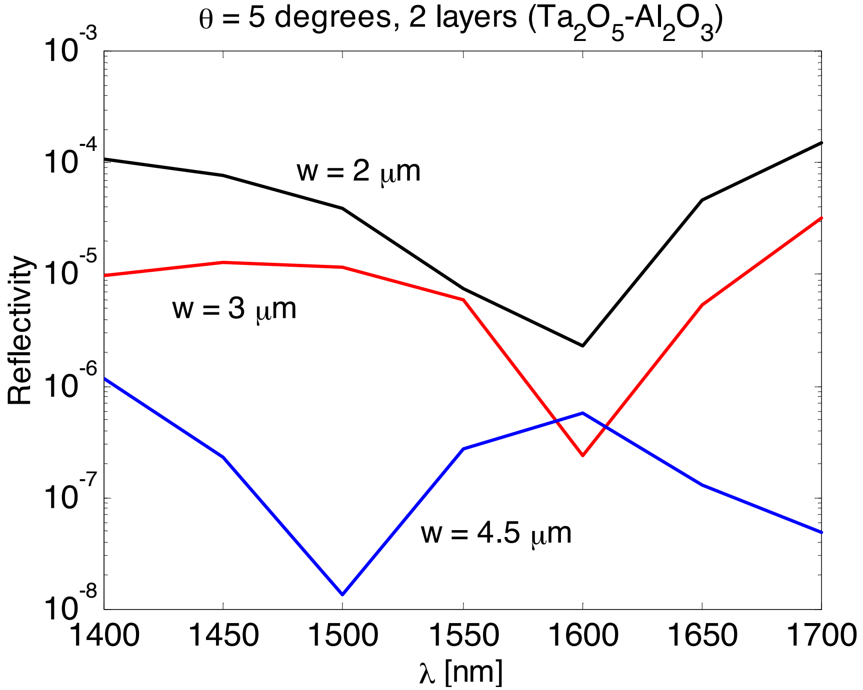
Difficult output coupling because

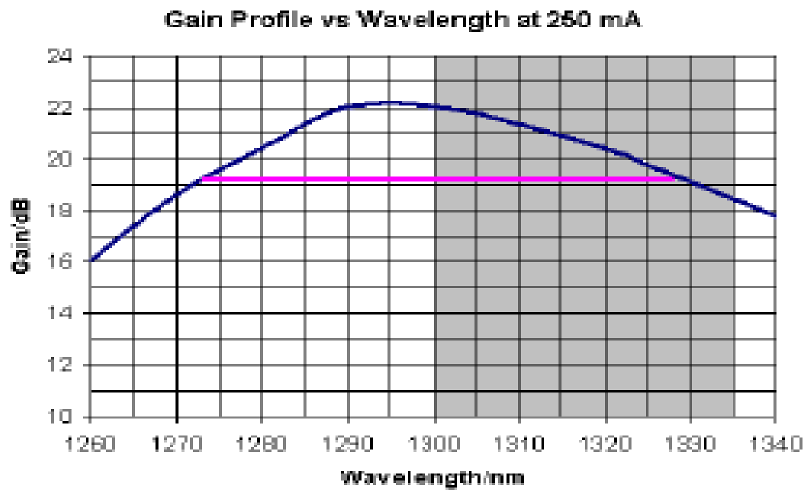
5 °tilt ->17 °air ;max 10°->35°air

Waveguide tilt + ARC

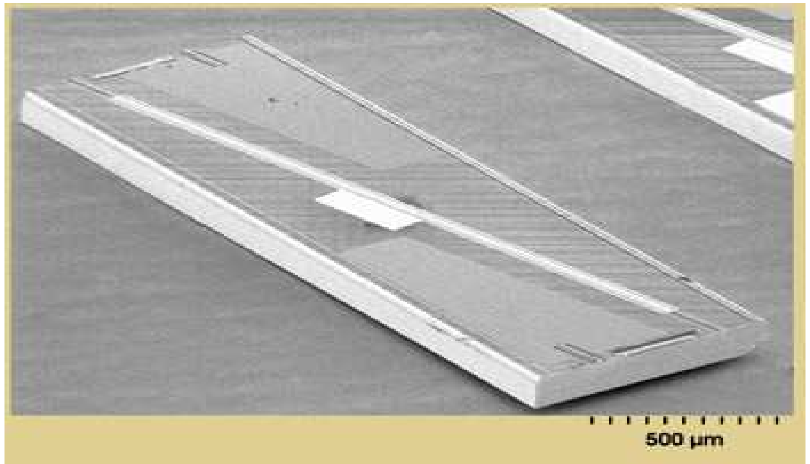
Increasing the angle the transmitted power is reduced than to improve transmission and reduce modal reflection an ARC is added

Commercial SOA fiber to fiber gain





60nm FWHM gain bandwidth



with 10^{-5} a 40dB gain is possible
with 1 dB ripple

Polarization insensitivity

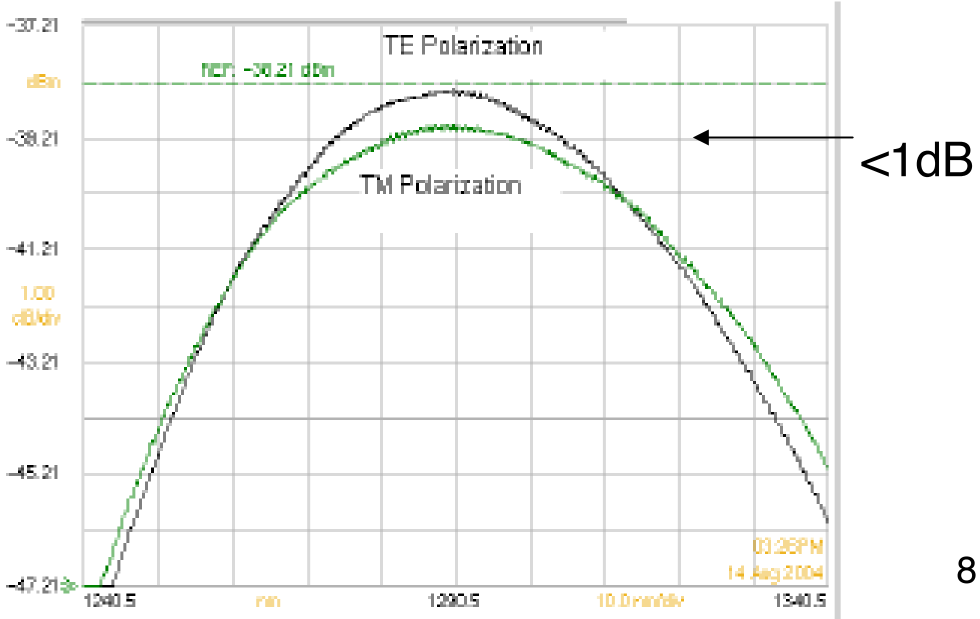
In many telecom applications is requested an SOA insensitive to the input field polarization. This dependence can be due to:

- the waveguide $\Gamma_{TE>} \Gamma_{TM}$
- the semiconductor material gain in QW with tensile (TE) or compressive TM) strain

For the wg. effect a proper design helps

For the QW a proper combination of tensile and compressive strain

Commercial device->



SOA static saturation model

$$\frac{dP}{dz} = (\Gamma g - \alpha_i)\, P$$ Longitudinal power evolution

$$P_s(z) = P_s(0)\exp\left(\int_0^z (\Gamma g_s(z') - \alpha_i)\, dz'\right)$$ $P_s(0)$ input power

where taking into account the carriers RE one obtain

$$g_s = \frac{g_0}{1 + P_s(z)/P_{sat}}$$ and $$P_{sat} = \hbar\omega_0 A_{ph}\tau_s / a;$$ $A_{ph}=A/\Gamma_{xy}$ photon area

Neglecting internal losses $\alpha_i \ll \Gamma g$ we obtain

$$P_s(L) = P_s(0)\, G_0 \exp\left(-\frac{P_s(L) - P_s(0)}{P_{sat}}\right)$$

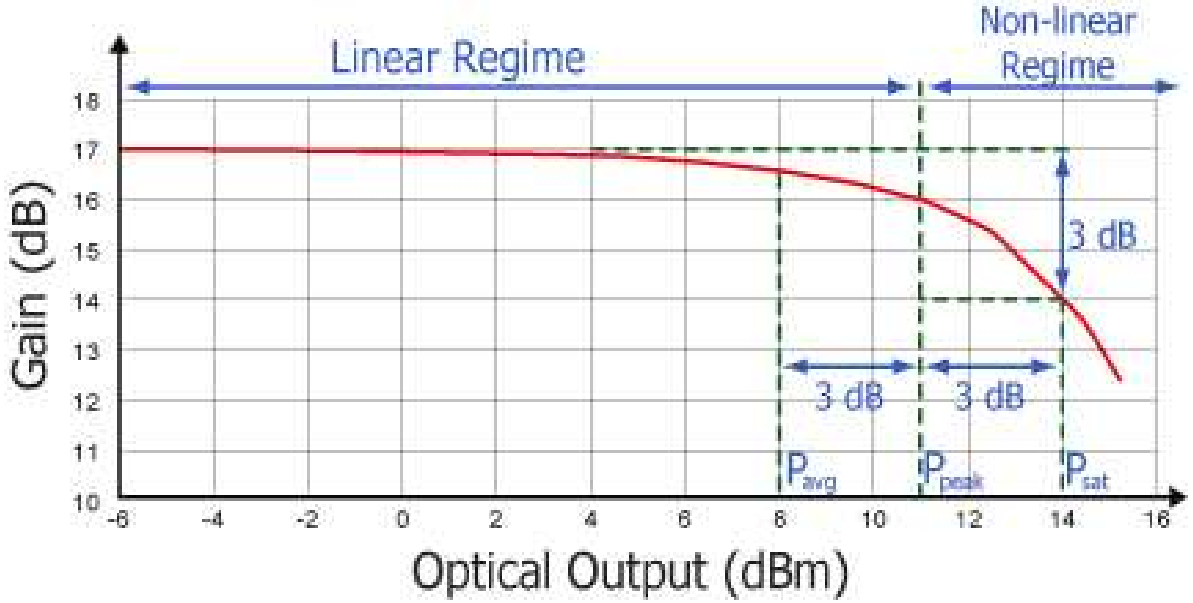
$$G = \frac{P_s(L)}{P_s(0)} = G_0 \exp\left(-\frac{P_s(L)}{P_{sat}}\frac{G-1}{G}\right)$$

where $G_0 = e^{\Gamma g_0 L}$ and if G>>1

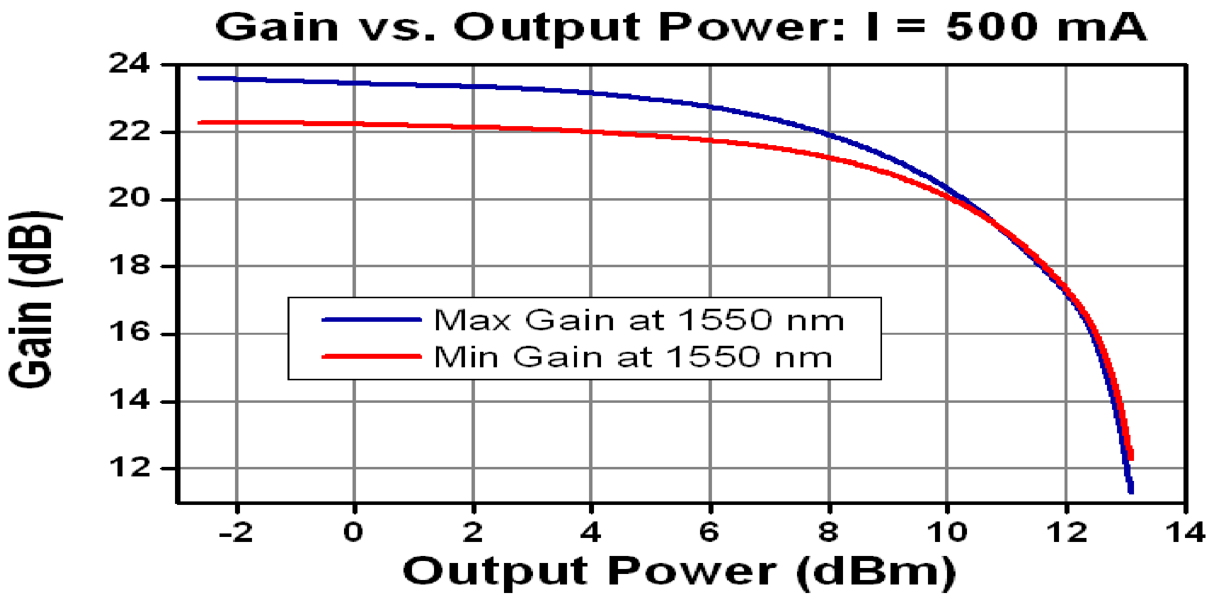
$$G \cong G_0 \exp\left(-\frac{P_s(L)}{P_{sat}}\right)$$

G_0 unsaturated gain

SOA Static model results



Theory R_{geo}=0

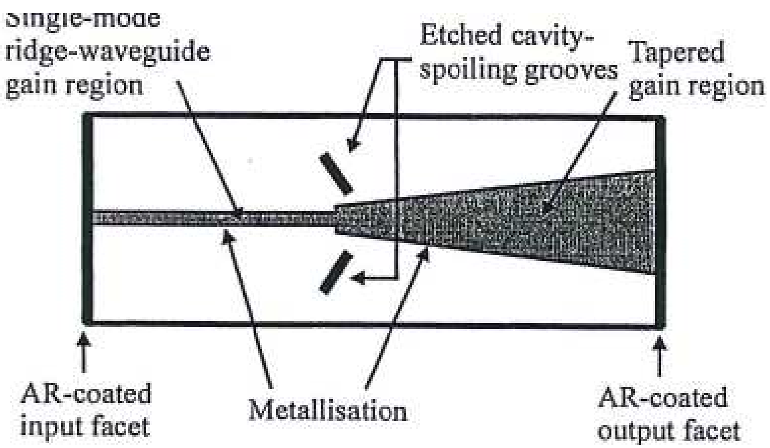


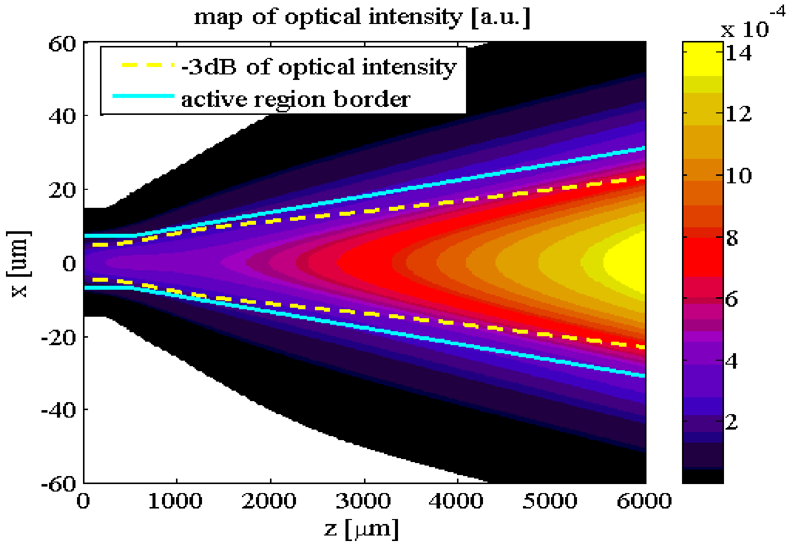
Experimental: $R_{geo} \neq 0$

Increase the saturation power

Been $P_{sat} = \hbar \omega_0 A_{ph} \tau_s / a;$ and $A_{ph}=A/\Gamma_{xy}$ photon area

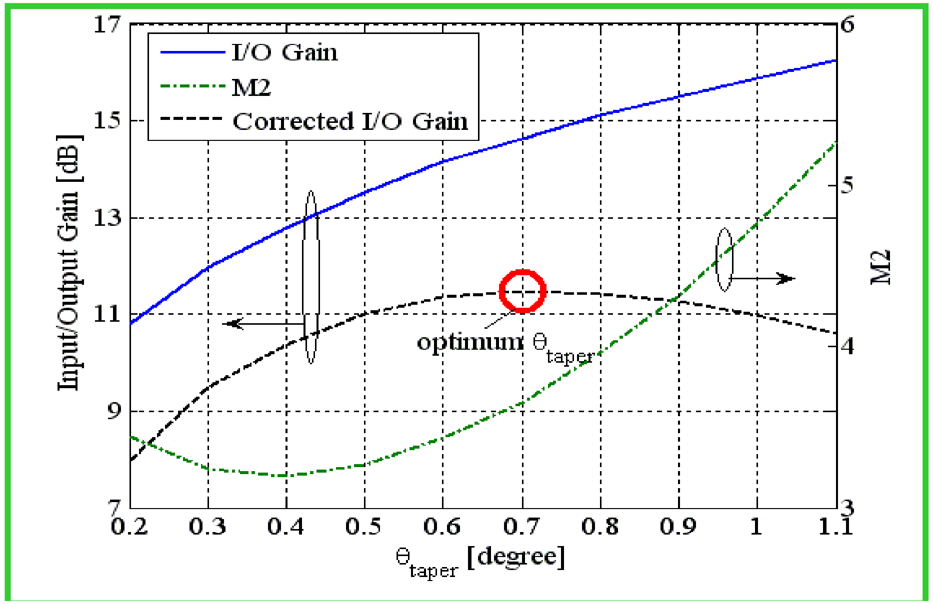
The photon area can be easily increased widening the waveguide width



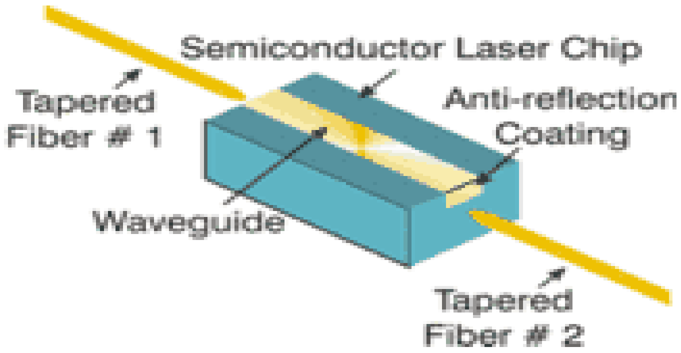


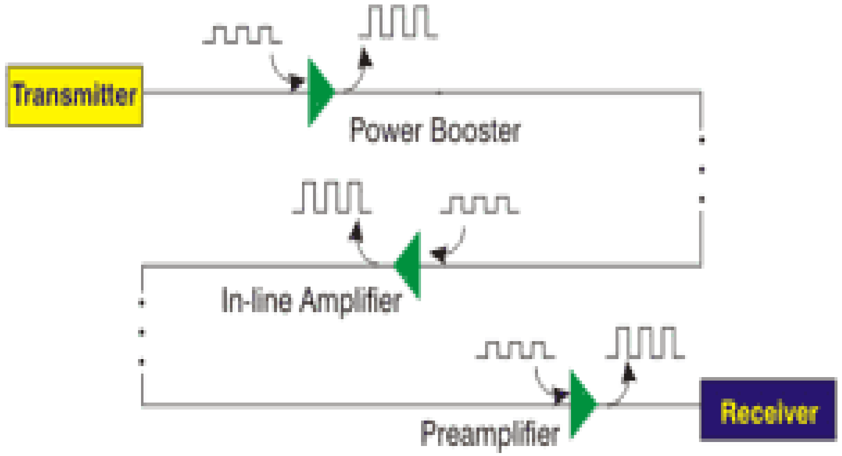
In the analysis of this kind of structures the diffraction effects should be properly considered with the possibility to excite high order mode in the tapered section. The analysis can be done using the Beam Propagation Method (BPM).

M^2 has influence on the fiber coupling

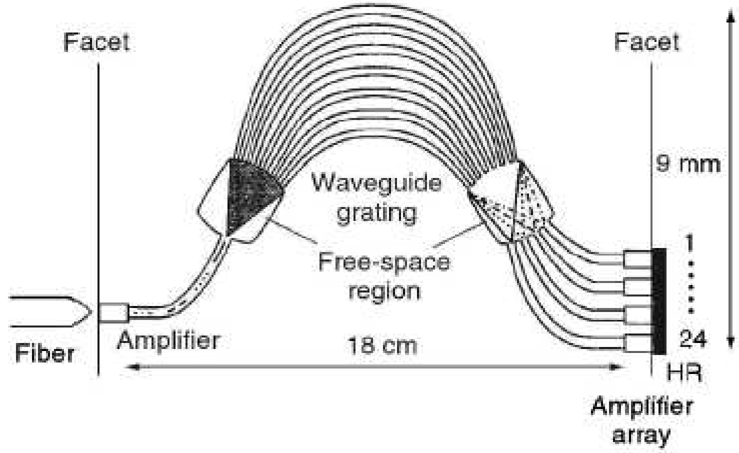


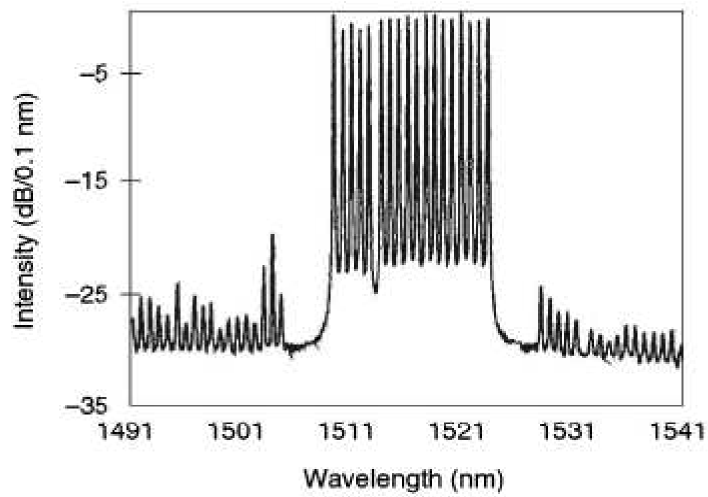
SOA applications in the linear regime

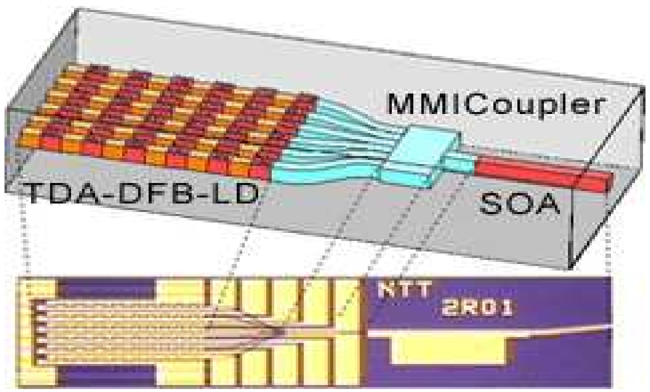




Multi wavelength laser





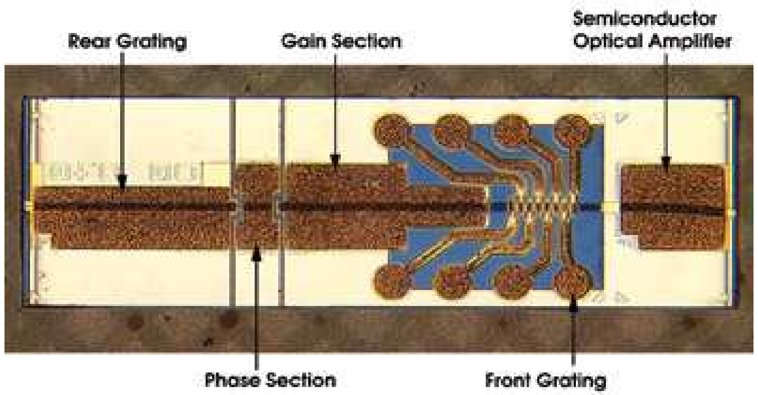


Booster amplifier

1/N losses compensated by the SOA

Other SOA applications - 1

SG-DBR + SOA



MOPA

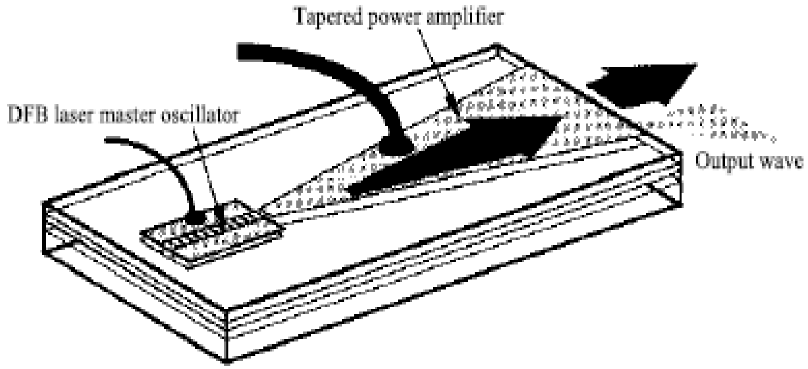
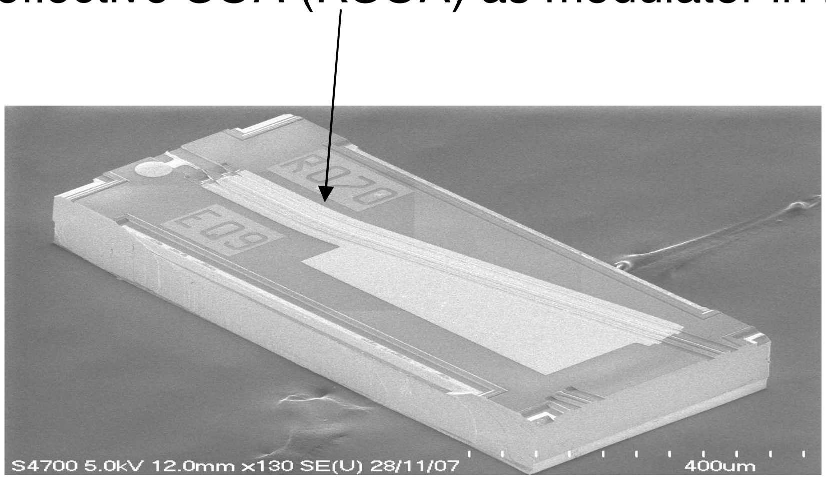
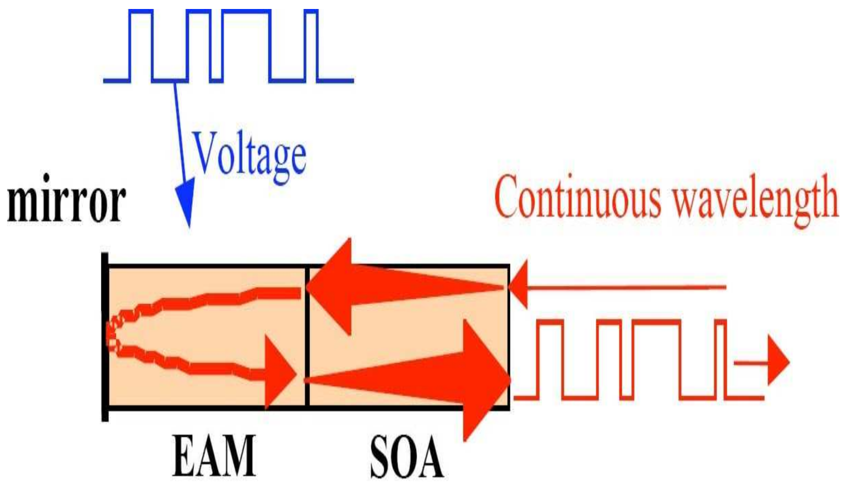


Figure 8.8 Monolithic MOPA.

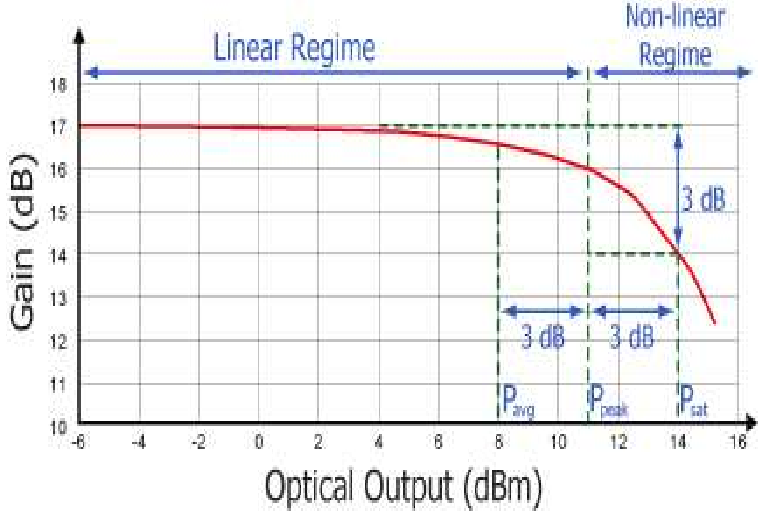
Reflective SOA (RSOA) as modulator in PON

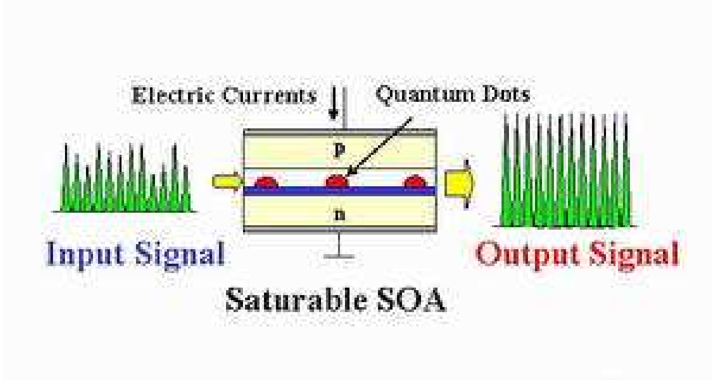


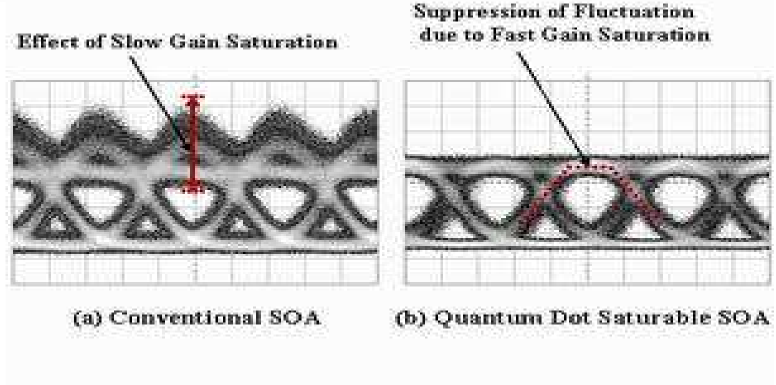
As an amplifier in a REAM



Other SOA applications – XGM







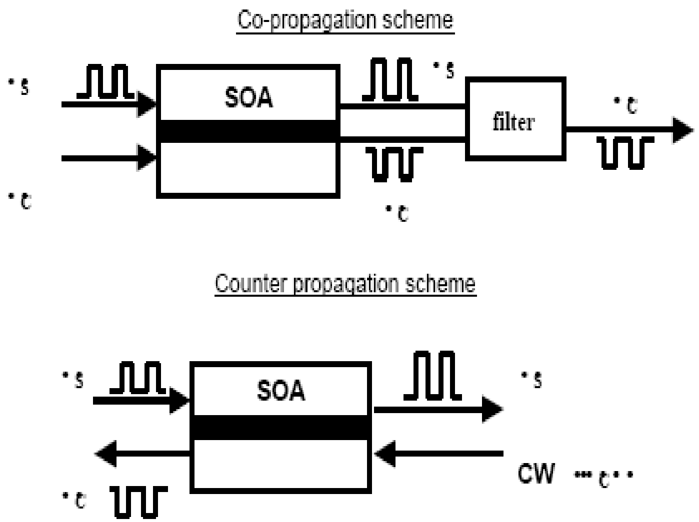
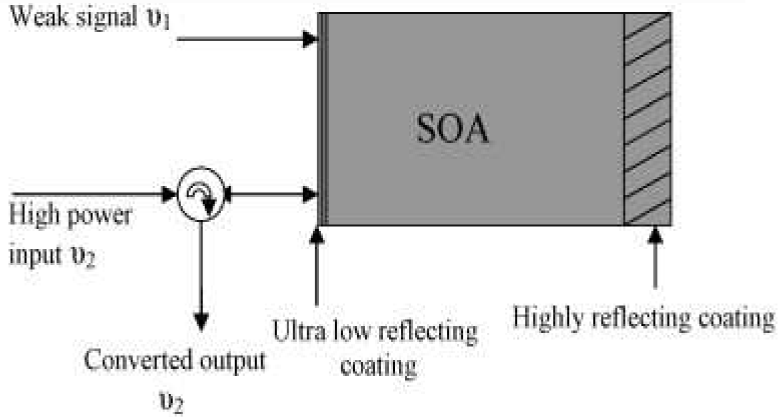
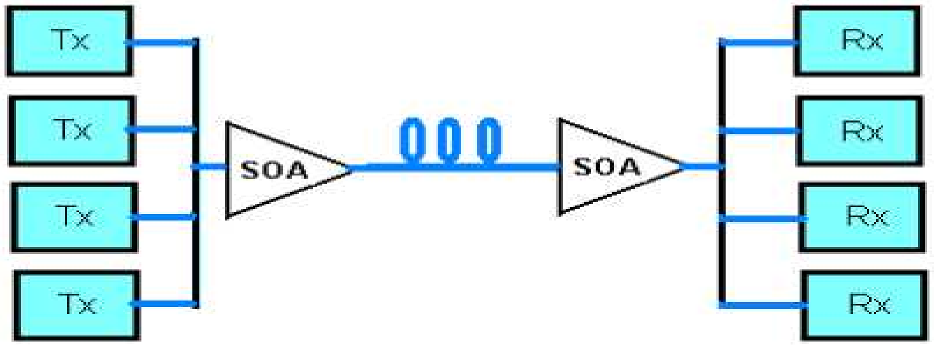
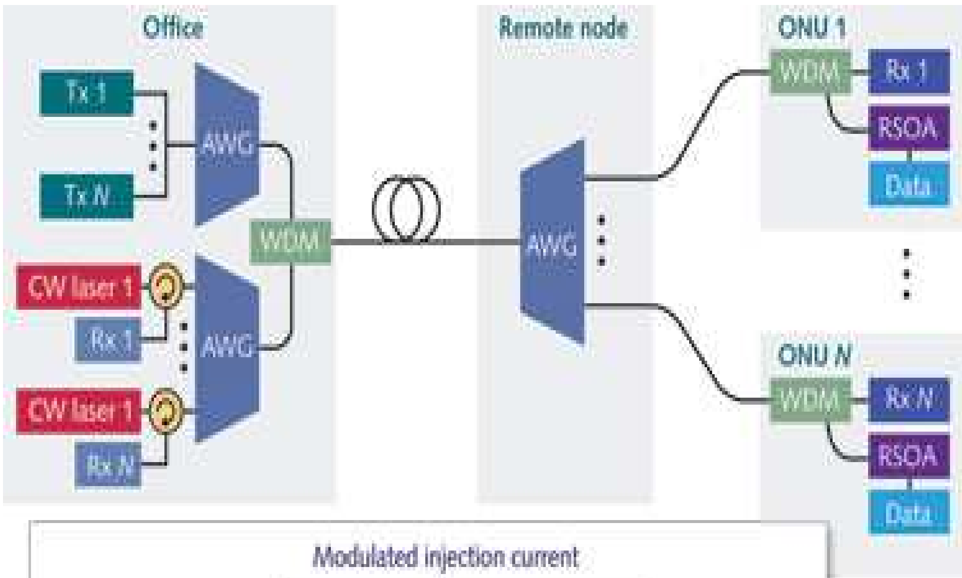


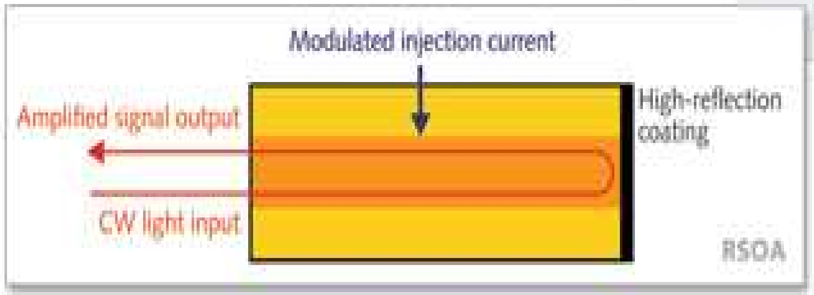
Fig. 6 Schematic of the co- and counter-propagation XGM wavelength conversion principle. by cross gain modulation

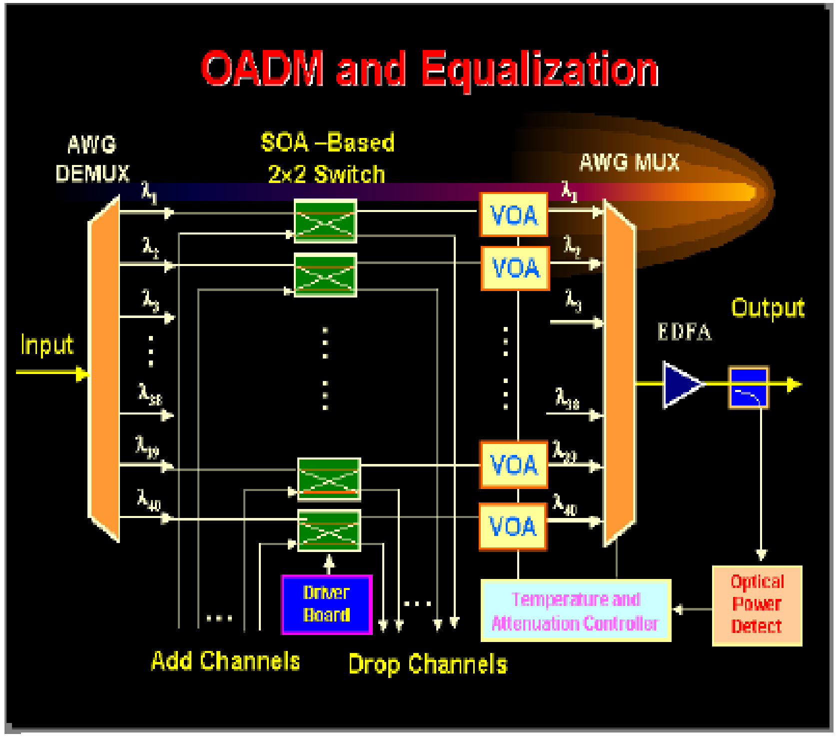


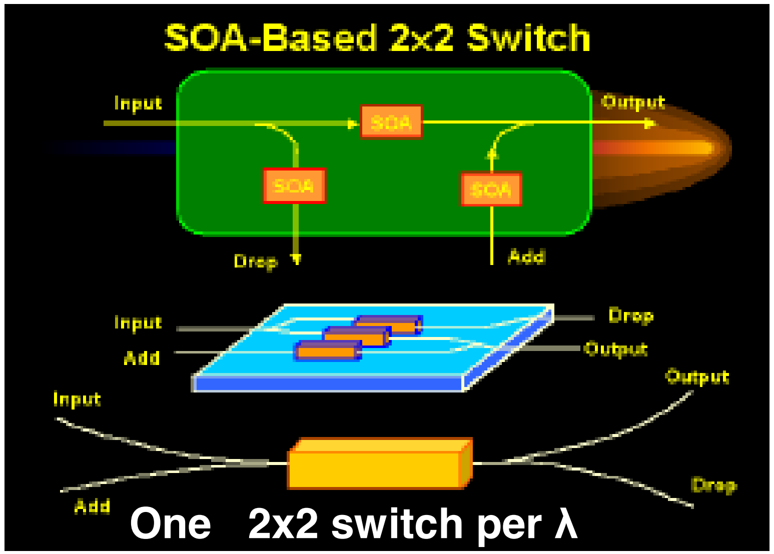
Other SOA system applications











SOA non linear dynamics

The most general formulation used to analyze the laser dynamic can be used for the study of the SOA dynamic; only one equation can be used

$$\left(\frac{1}{v_g}\frac{\partial}{\partial t}+\frac{\partial}{\partial z}\right)E(z,t)=\tfrac{1}{2}\left((1+j\alpha)\Gamma g-\alpha_i\right)E(z,t)+f_E(z,t)$$

$$\frac{dN}{dt}=J-\frac{N}{\tau_s}-\frac{g\left|E\right|^2}{\hbar\omega_0 A_{ph}}$$

Assuming $g=a(N-N_{tr})$

$$\frac{dg}{dt}=\frac{g_0-g}{\tau_s}-\frac{g\left|E\right|^2}{\tau_s P_{sat}}$$

and using for pulse propagation a local reference system

$$z'=z$$

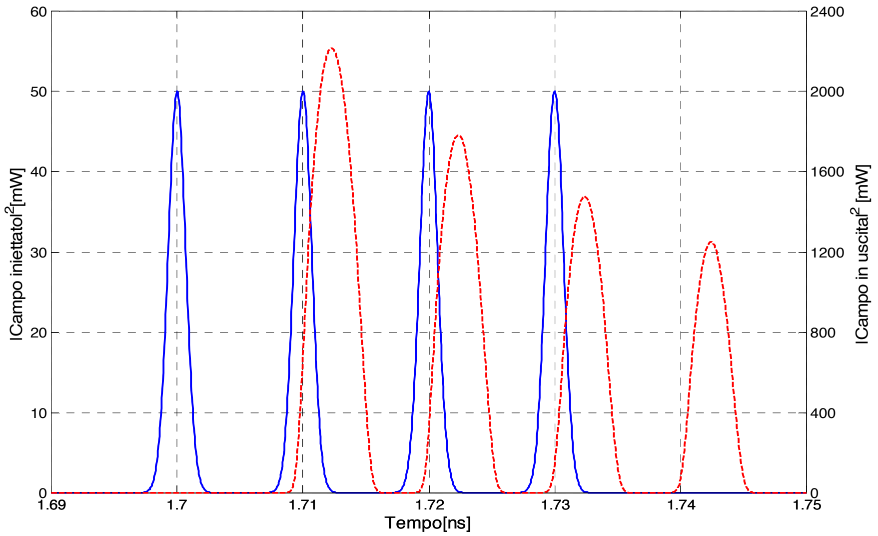
$$t'=t-\frac{z}{v_g}$$

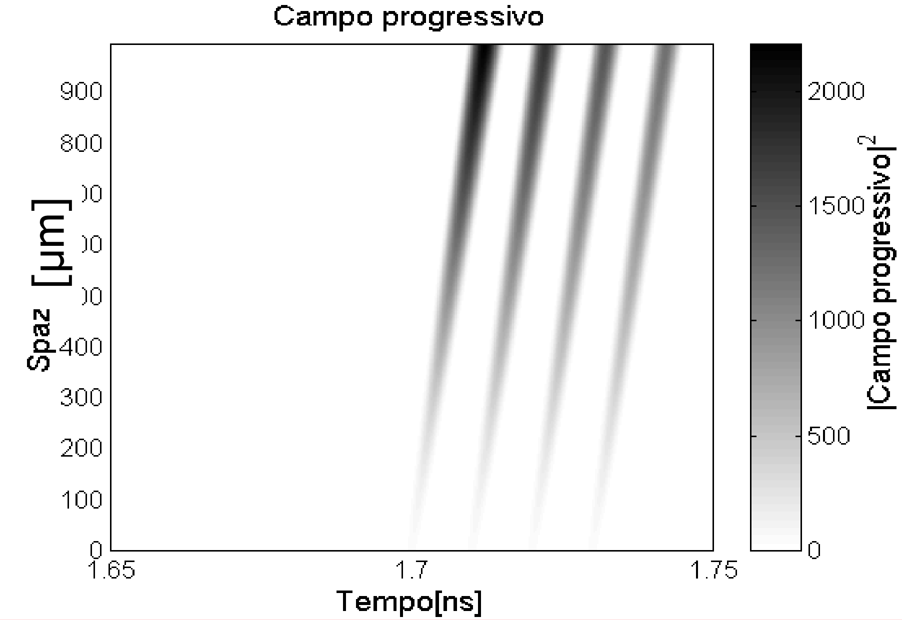
$$\frac{\partial}{\partial z'}E(z',t')=\tfrac{1}{2}((1+j\alpha)\Gamma g-\alpha_i)E(z',t')+f_E(z',t')$$

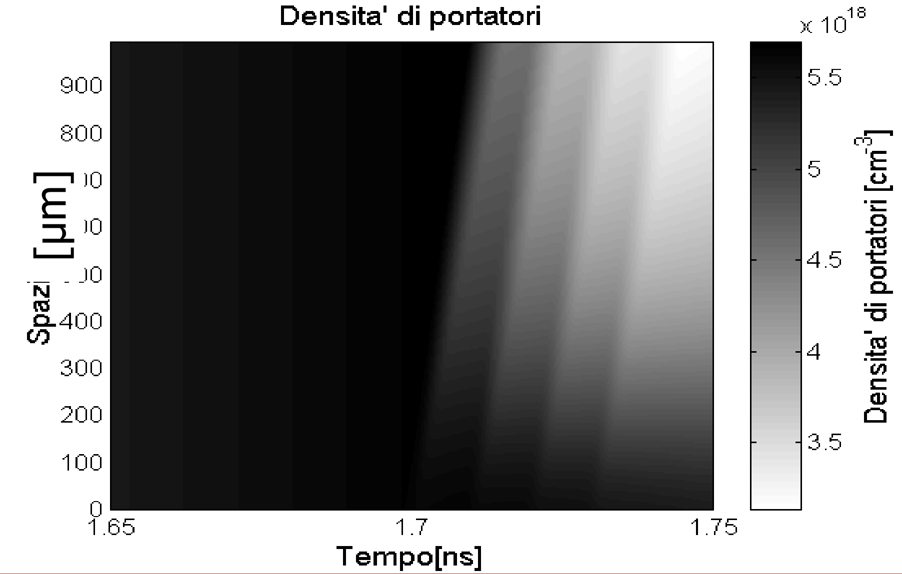
$$\frac{dg(z',t')}{dt'}=\frac{g_0-g(z',t')}{\tau_s}-\frac{g(z',t')\left|E(z',t')\right|^2}{\tau_s P_{sat}}$$

Pulse train propagation

10ps repetition rate 1ps duration







The carrier changes are producing a gain (XGM: Cross Gain Modulation) and a refractive index (XPM Cross Phase Modulation) variation.

The peak power decrease is due to the incomplete carrier recovery at high repetition rate

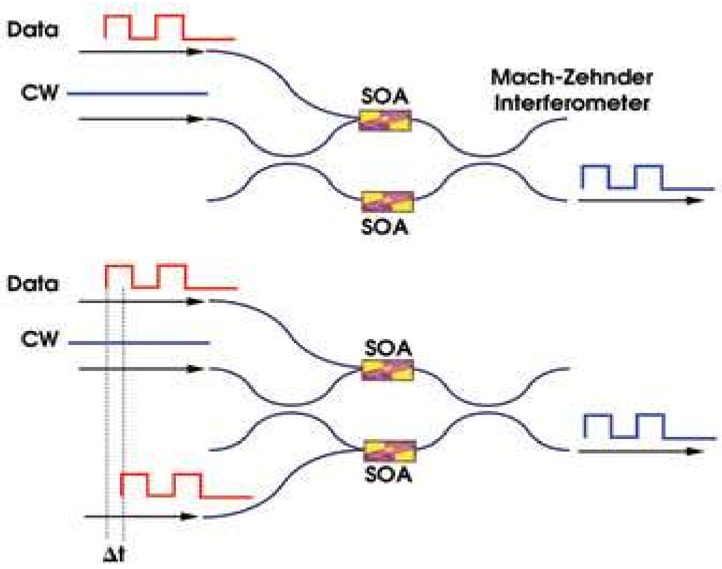
SOA applications: XPM

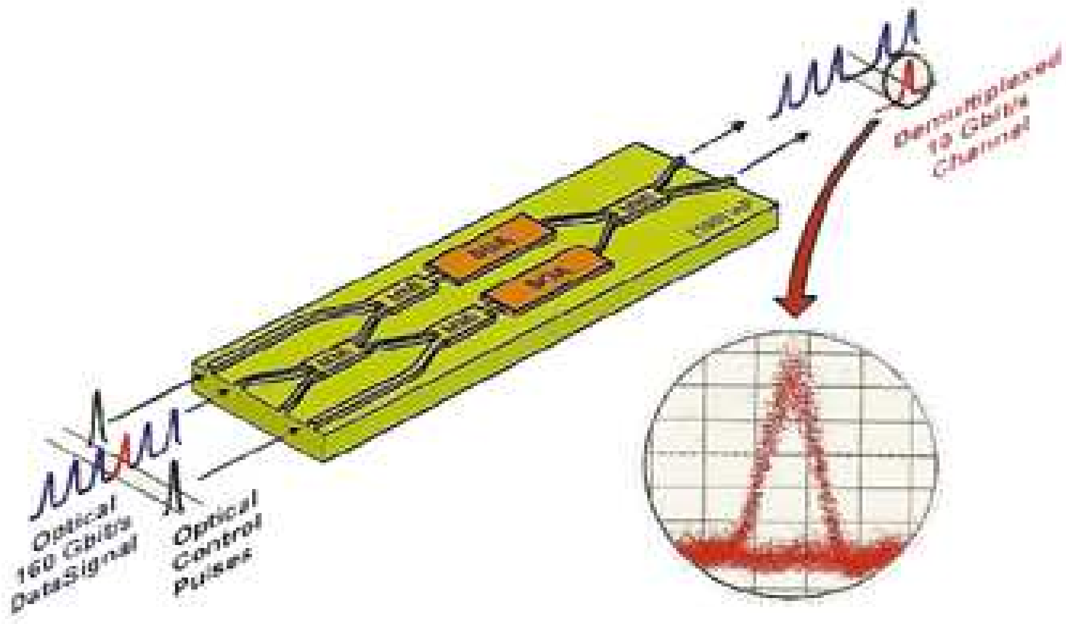
λ- converter using XPM

The IM modulation is transferred to CW by XPM at the output interferometer. Better Extinction Ratio than XGM device

Demultiplexing of a 160Gb/s data stream.

The first pulse saturate the upper SOA, the unbalanced MZI let the pulse to be switched at the other port, second pulse needed to balance the MZI due to the slow carrier recovery





SOA applications: FWM

λ- converter using FWM

The carrier pulsation due to the beating between pump and probe generate a conjugate signal at a frequency opposite respect to the pump

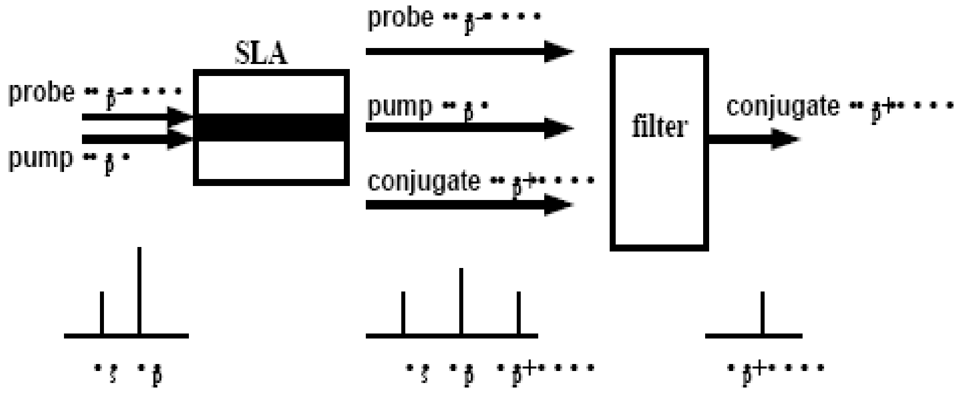
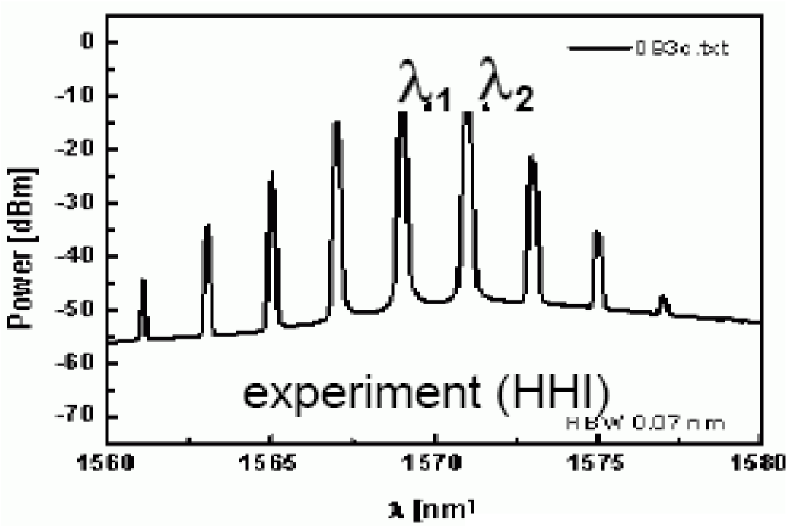
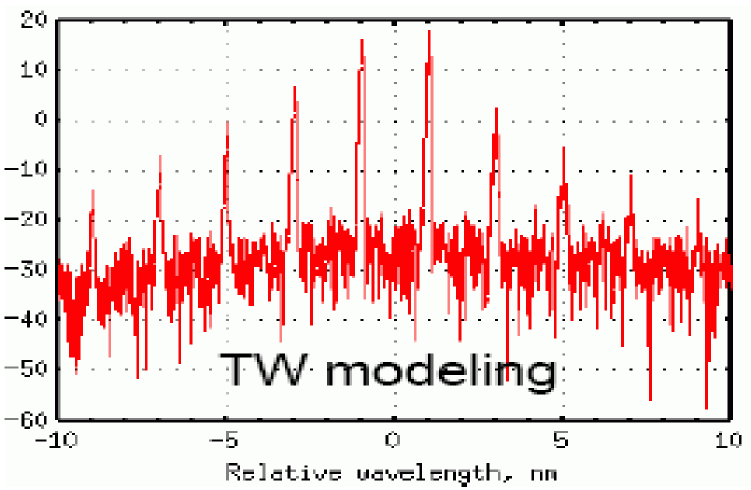


Fig.8 FWM phenomenon in an SOA



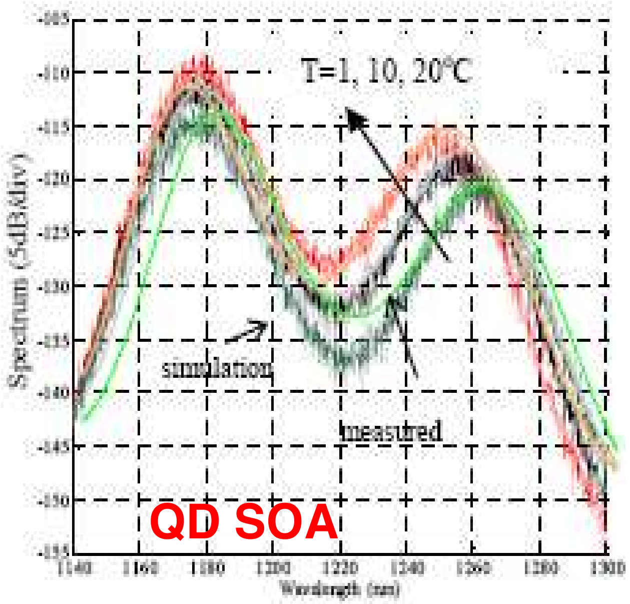


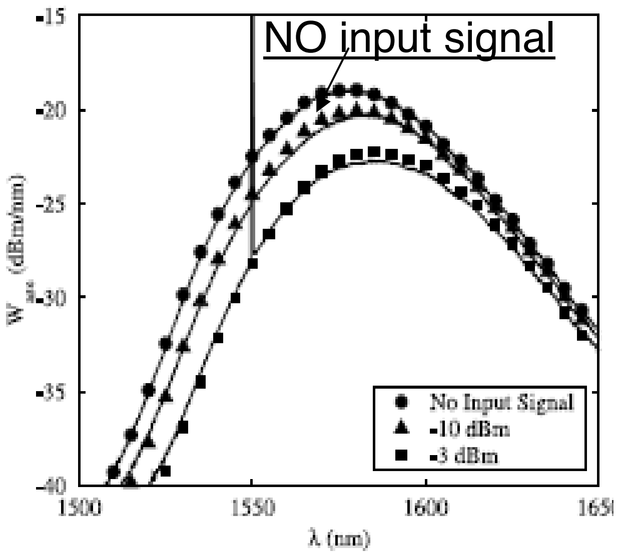
TW model inherently contains the generation of satellite waves by four wave mixing

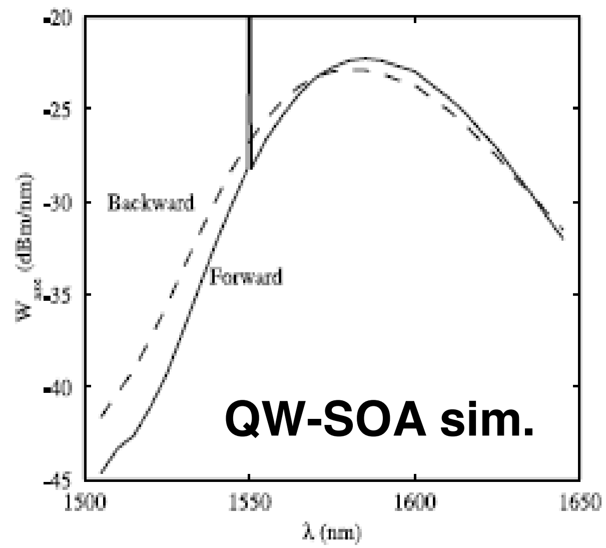
SOA noise - ASE

Is due to the spontaneous emission generated in each longitudinal section, propagating in both directions and amplified by the SOA:
Amplified Spontaneous Emission (ASE)

How can be computed:
- The FTTW method can include the noise and is well adapted to compute the ASE. It is important to well represent the gain function spectrum using proper numerical filters
- Other existing techniques are based on the spectral “slicing” and consist in integrating the longitudinal evolution of each component of the SE in both direction and also of the input field







SLED structure

The structure is very similar to the SOA with NO input signal and as a output the Amplified Spontaneous Emission (ASE)
All the described solution to reduce the mirror reflectivity in SOA are used and furthermore one can use an <u>absorbing section</u>

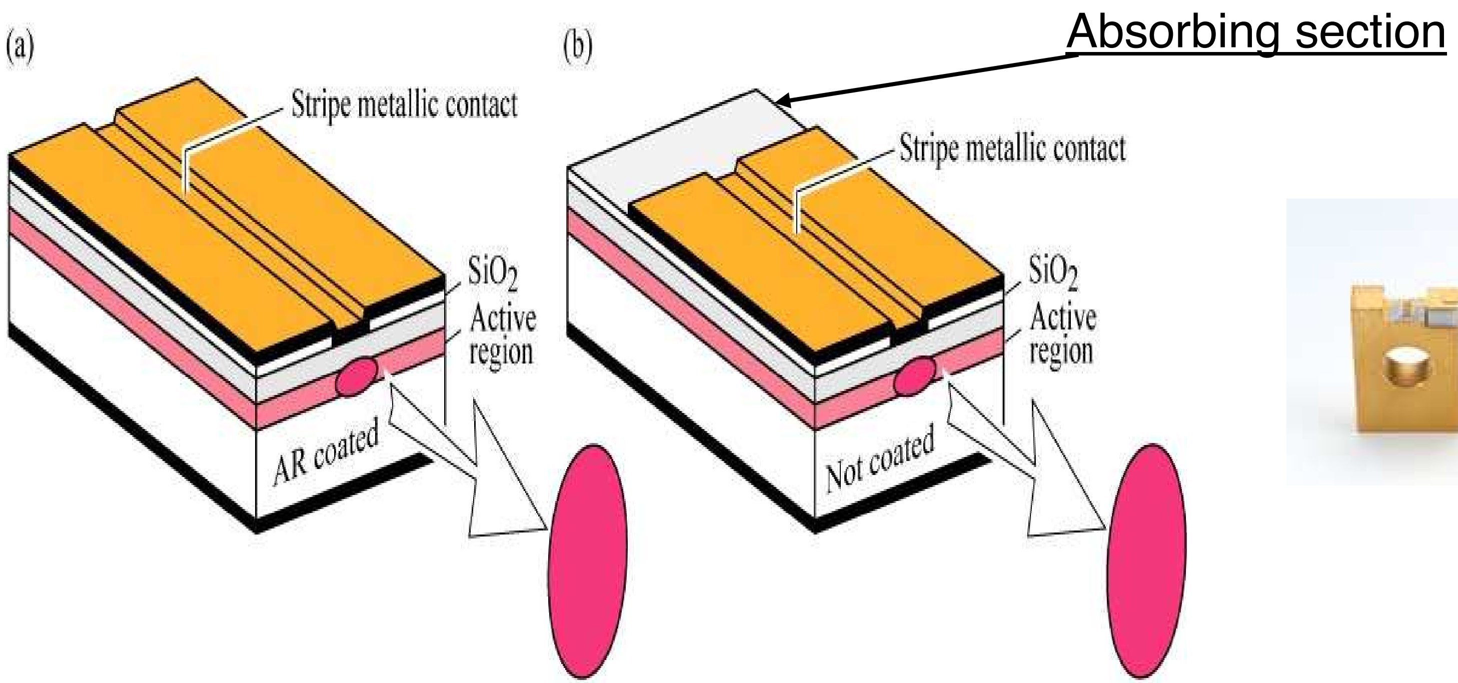
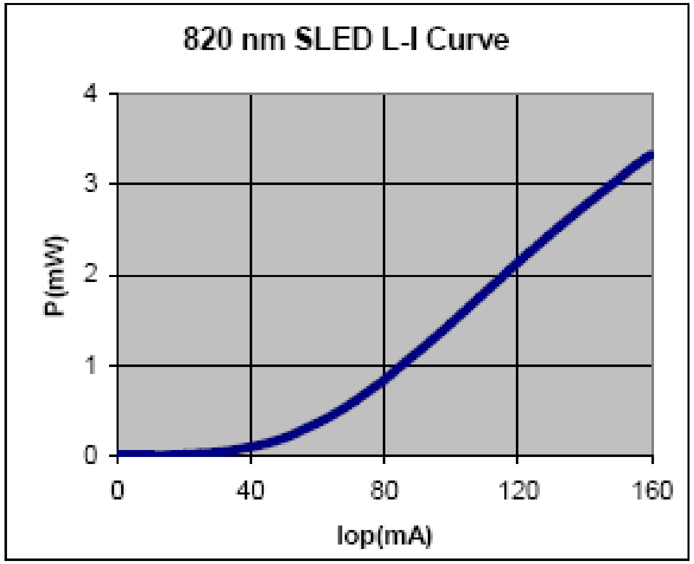


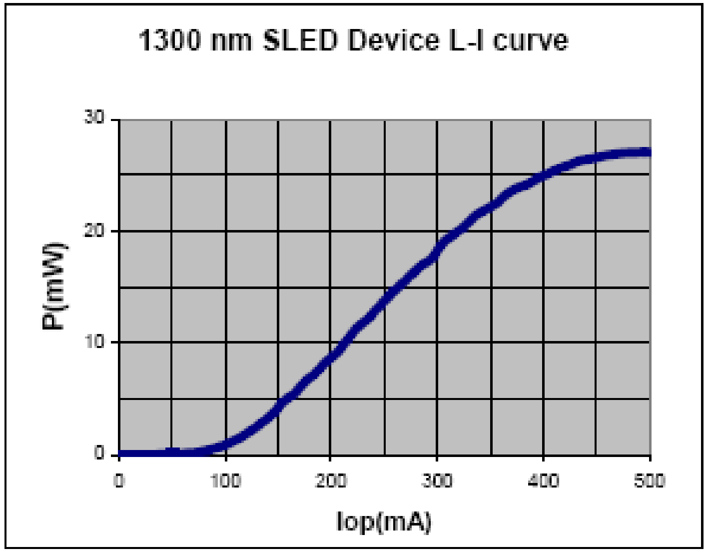
Fig. 23.9. Common structures of superluminescent diodes (SLDs). (a) SLD with cleaved facets coated with anti-reflection (AR) coatings. (b) SLD with cleaved, reflecting facets and stripe contact injecting current over the partial length of the device.

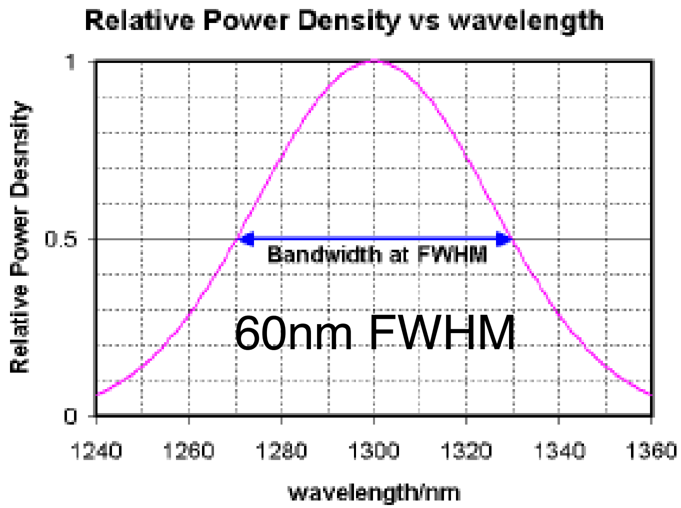
E. F. Schubert

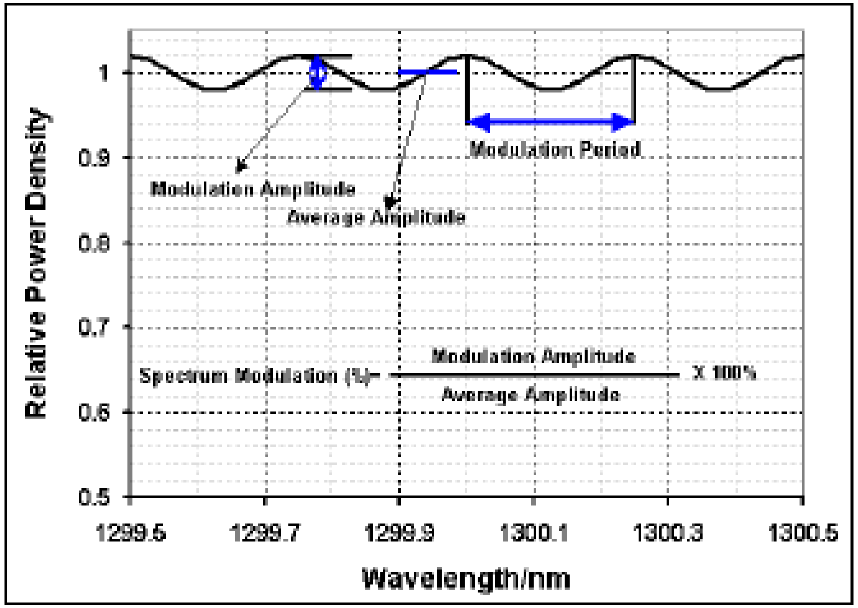
Examples of SLED characteristics - 1



(a)







Examples of SLED characteristics - 2

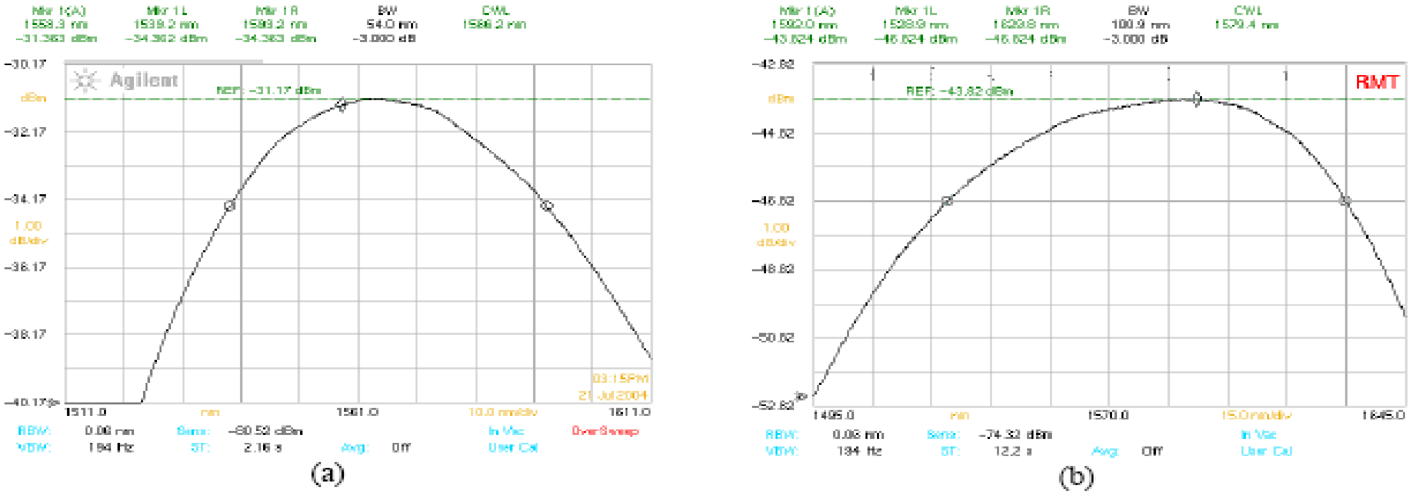
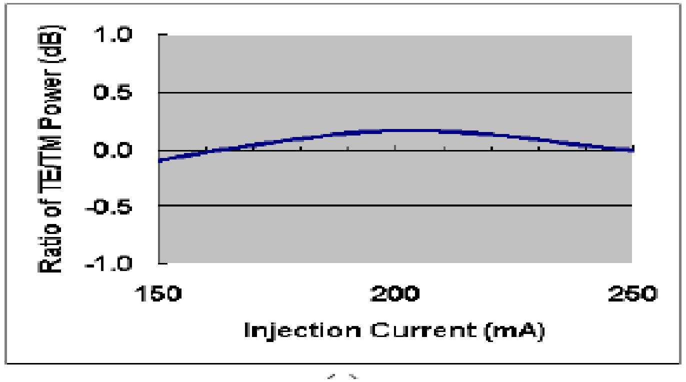
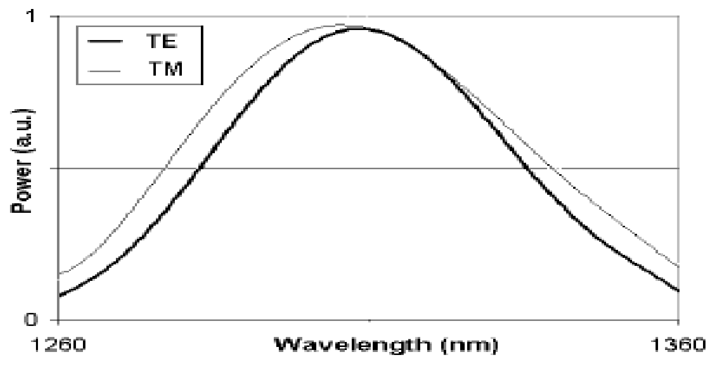


Fig. 4 1550 nm SLED bandwidth at 250 mA (Inphenix's IPSDD1502 and IPSDD1503 Products) is about 50 nm for bulk structure (a), and 100 nm for MQW structure (b).



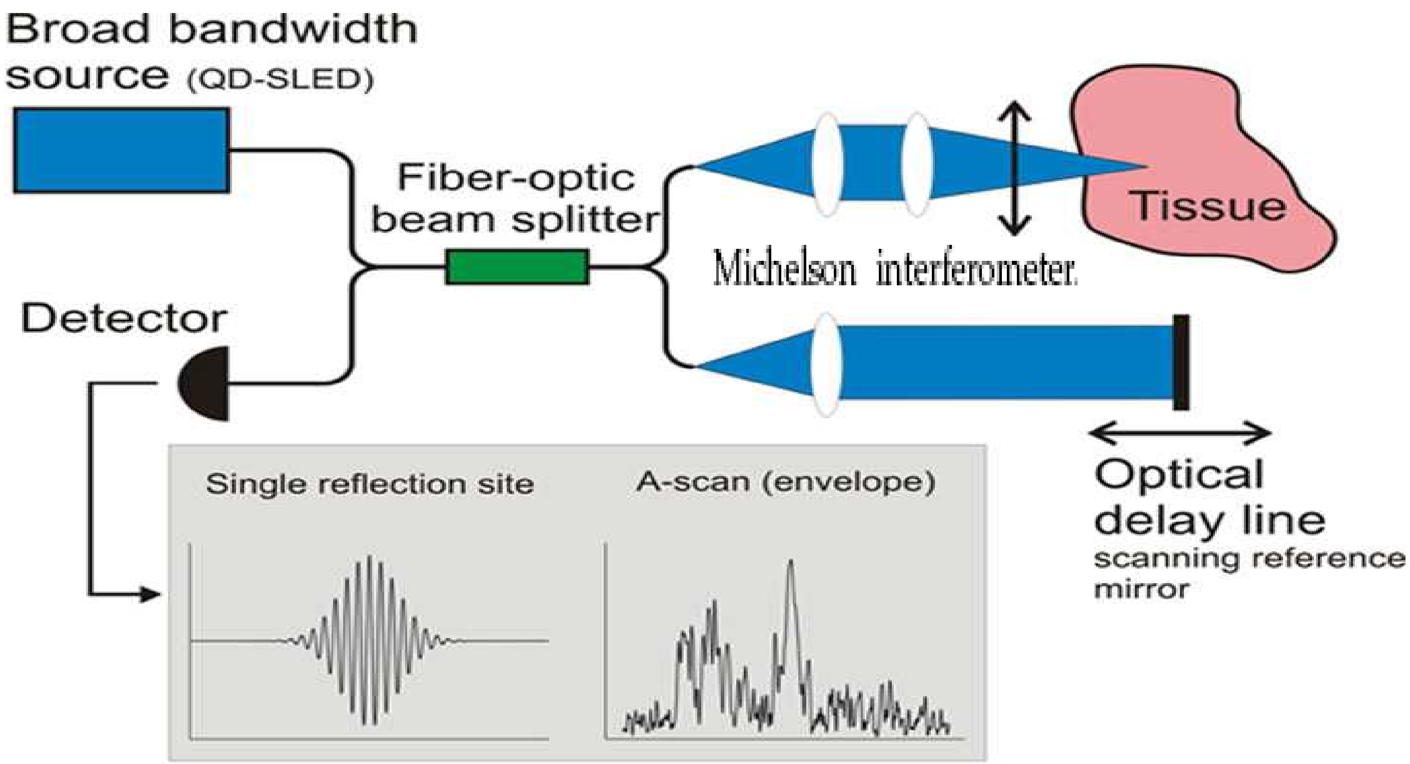


SLED application to OCT

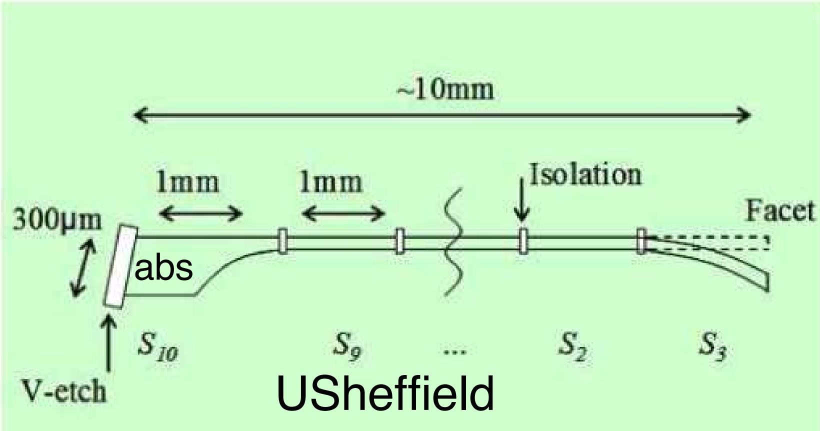
Optical coherence tomography (OCT) can perform micron scale, noninvasive imaging of biological tissue morphology and is successfully applied in the clinic.

OCT is based on low-coherence interferometry: **the axial image resolution is determined by the bandwidth and center wavelength of the light source.**

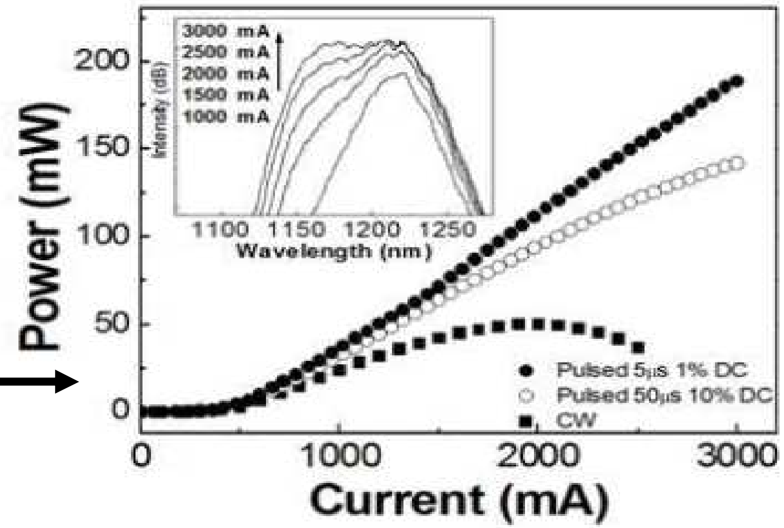
Assuming a Gaussian like light source spectrum shape, **the axial resolution is** $\mathbf{\Delta z = 0.44\ \lambda_c^2/\ \Delta\lambda_{FWH}}$; axial resolution less than 5 μm in tissue at 1300 nm.



SLED for OCT: the structure



A schematic of a multi-contact QD-SLED



High power and broadband intermixed QD-SLED

2 sections device to reduce longitudinal saturation

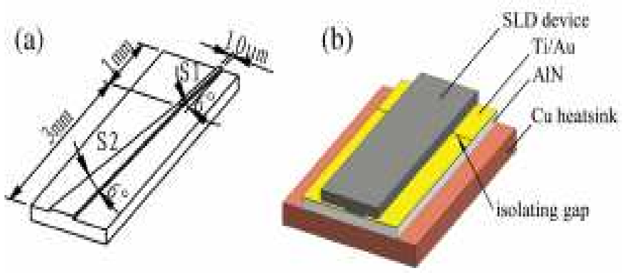
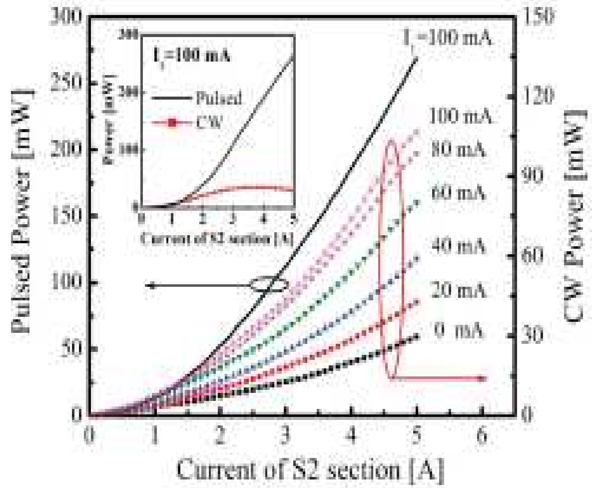
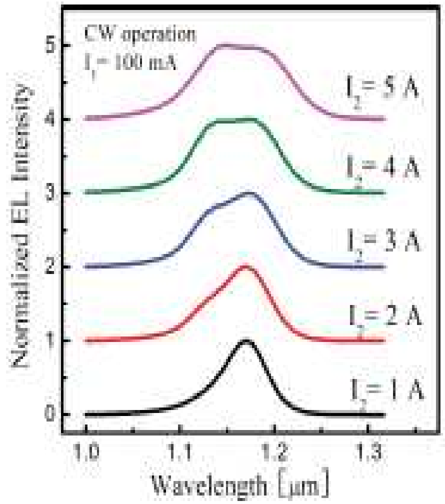


Fig. 1. Schematic design of the two-section QD-SLD device. (a) SLD device with two-section structure. (b) Epi-down mounting structure for the two-section SLD device.





SLED: spectral characteristic

A part the spectral width also its Fourier Transform, the SLED Point Spread Function, is important because high levels of the side lobes may generate ghost images

Change in the QD material (USheffield)

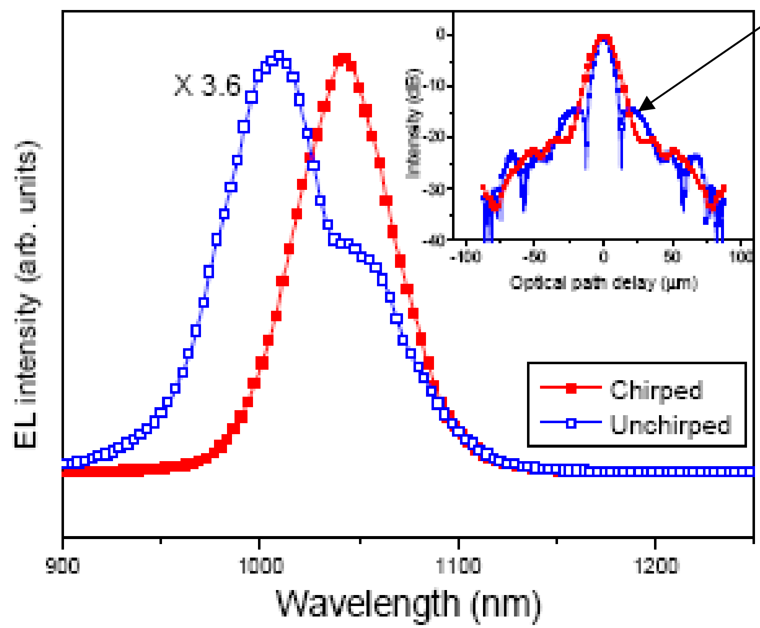


Figure 4. (a) Normalised CW EL spectra for unchirped and multi-contact chirped devices at current densities described in the text. (b) Calculated PSF of the best EL emission spectra recorded for unchirped and multi-contact chirped

Combination of SLED

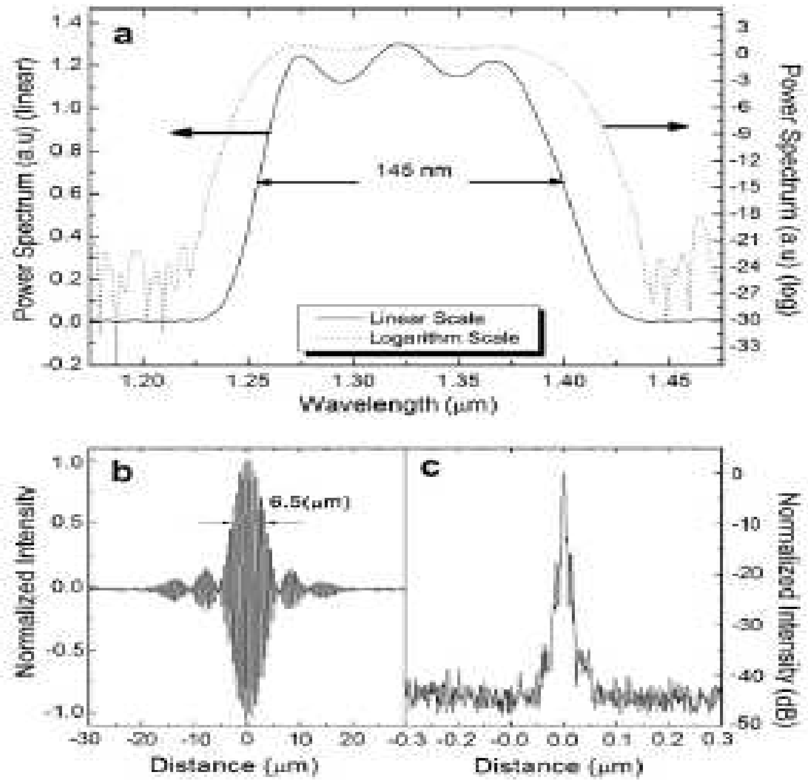
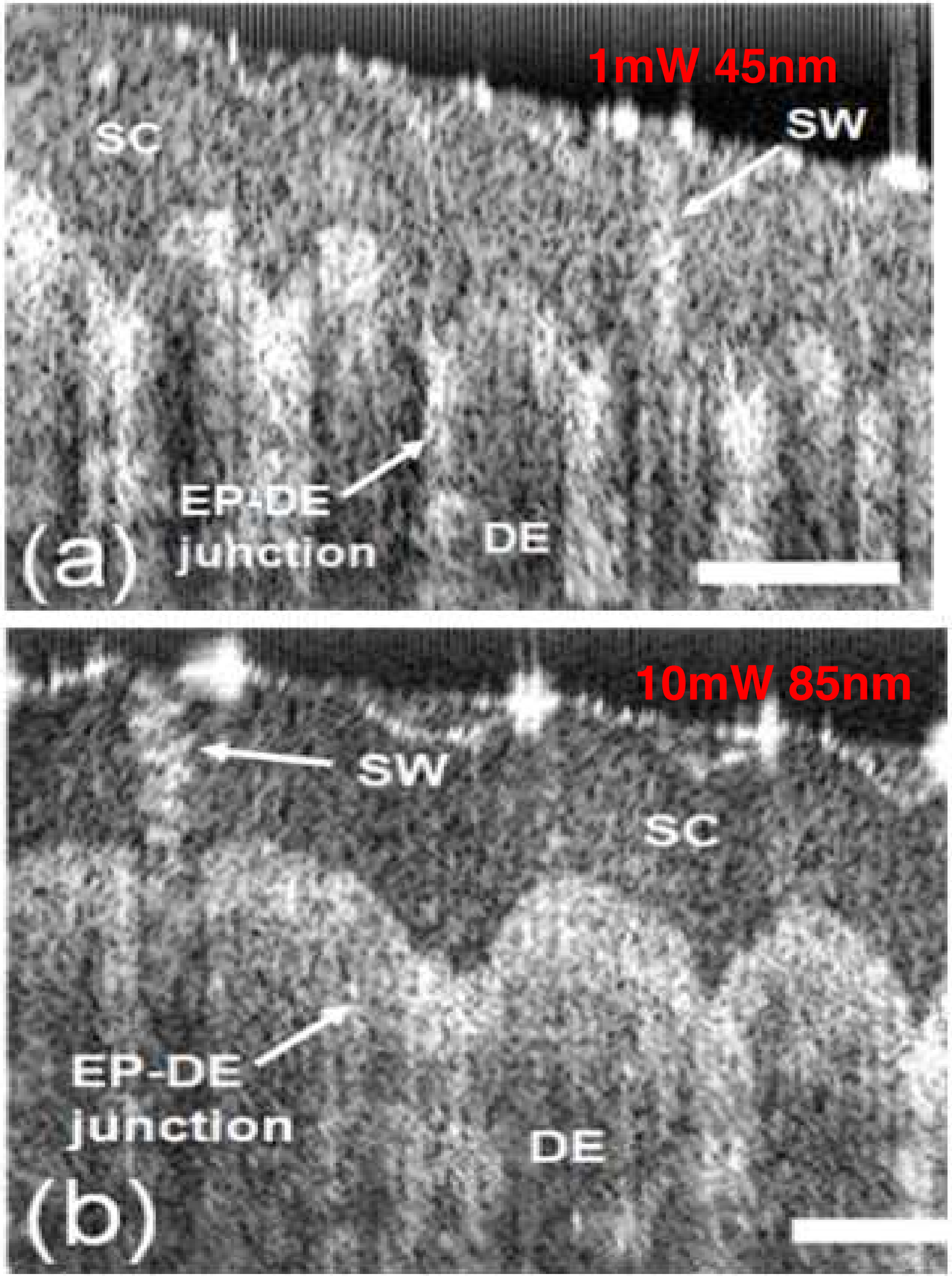


Fig. 3. Combined SLEDs: (a) combined spectrum of SLEDs shown in Fig. 1(a), (b) measured point spread function of combined spectrum and (c) measured demodulated point spread function in logarithmic scale.

Examples of OCT images



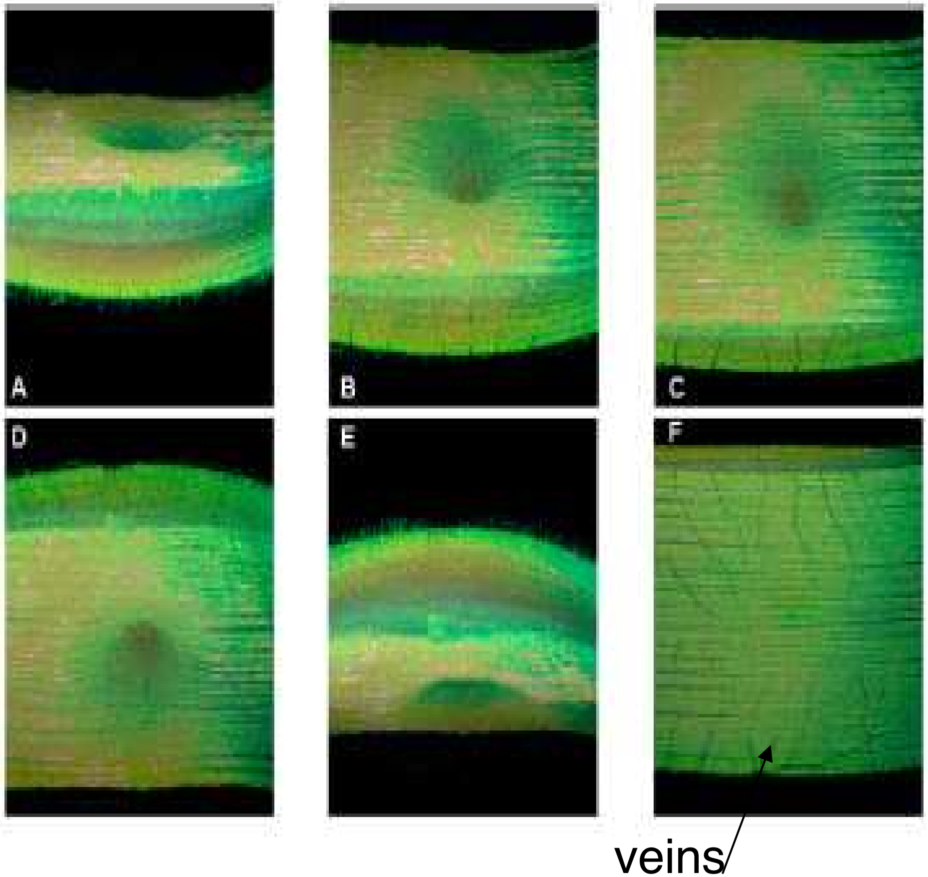


Figure 2. Three-dimensional images of part of a normal human eye obtained using OCT. The images (a)–(e) show both the topography and morphology of the entire foveal depression, and (f) shows the pattern of the retinal vascular net. (Figure courtesy of W. Drexler, Medical University, Vienna, Austria, 2005).