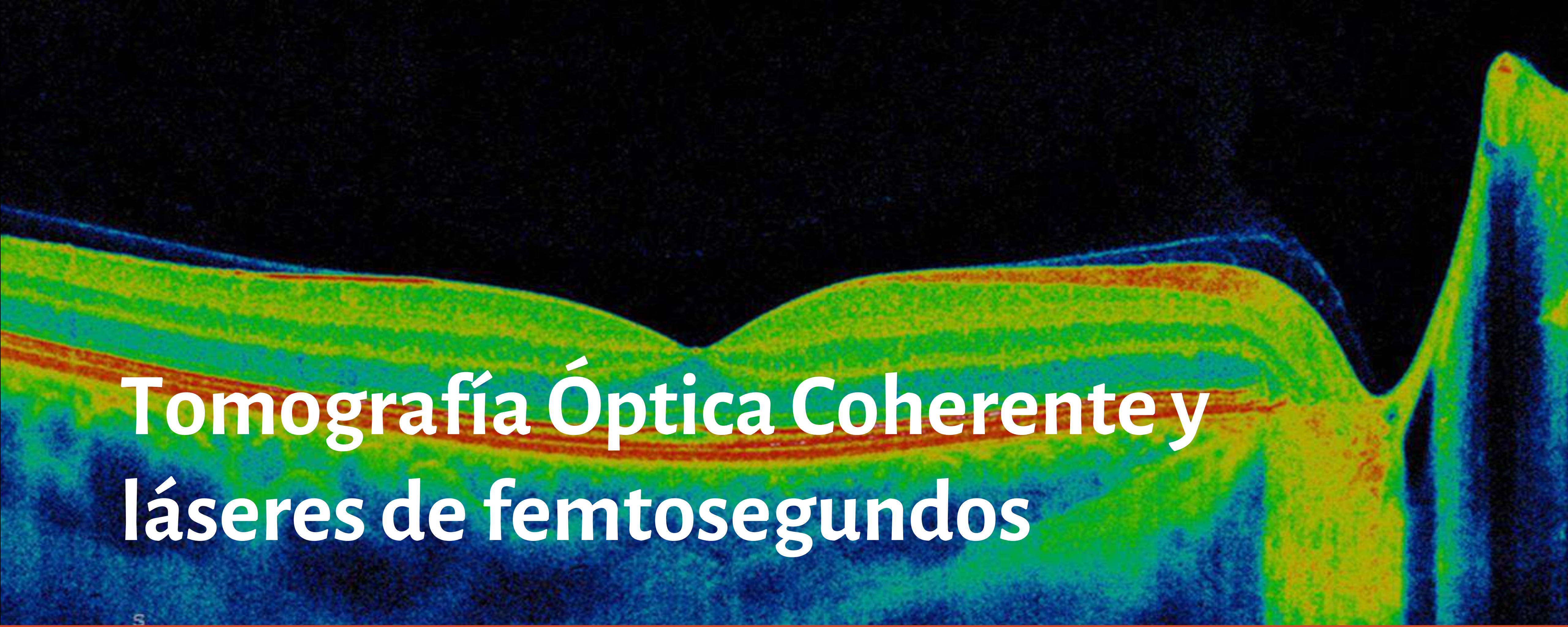


Tomografía Óptica Coherente y láseres de femtosegundos

Axel Lacapmeusre

Laboratorio de Fotónica, Facultad de Ingeniería, UBA

1. ¿Qué es OCT?

2. Láseres de fs en OCT

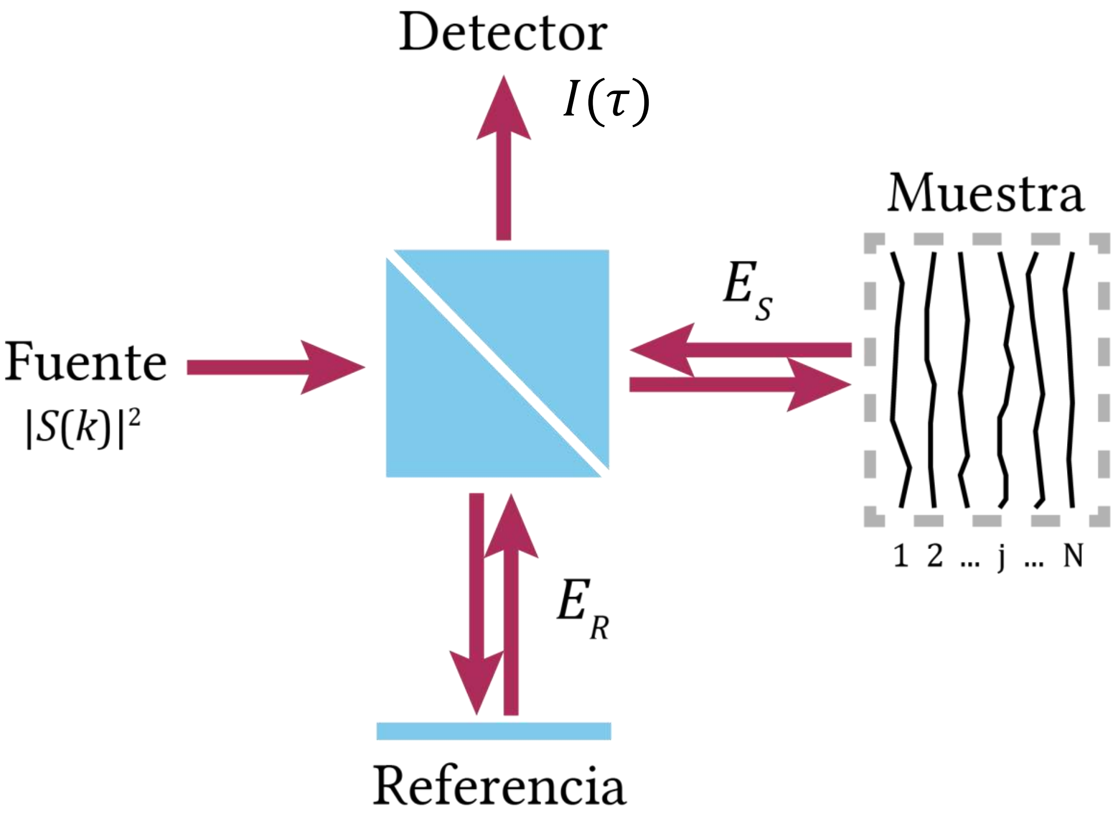
¿Qué es OCT?

$$E_R = S(\omega)\frac{1}{2}\sqrt{r_R}\exp\left(\mathrm{i}\omega_0\tau_{fR} + \mathrm{i}\omega\tau_{gR}\right)$$

$$E_S = S(\omega)\frac{1}{2}\sum_{k=1}^{N}\sqrt{r_j}\exp\left(\mathrm{i}\omega_0\tau_{fk} + \mathrm{i}\omega\tau_{gk}\right)$$

$$\tau_f = \frac{z}{v_f}$$

$$\tau_g = \frac{z}{v_g}$$



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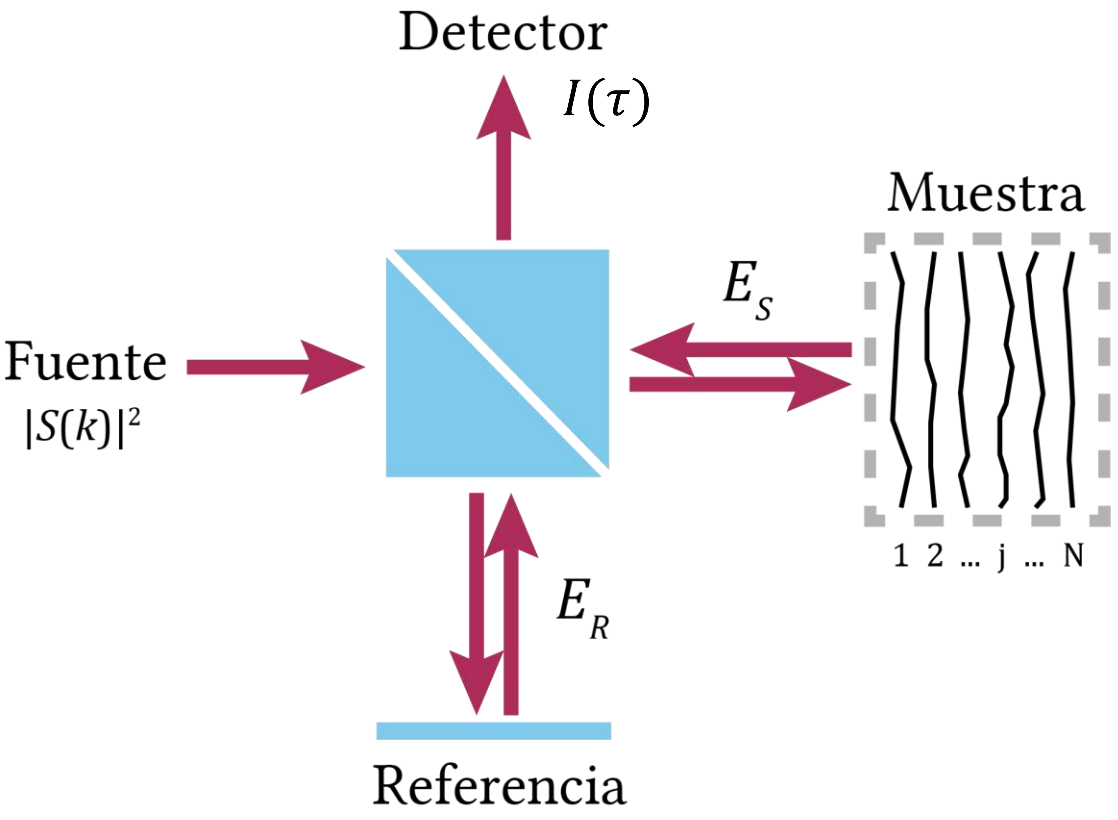
$$\tau_g = \frac{z}{v_g}$$

$$I_D\left(\Delta\tau_g\right) = \gamma(\tau) \otimes \sqrt{r_R}\;\rho(\Delta\tau_g)$$

$$+ \text{ Términos DC}$$

$$+ \text{ Términos de autocorrelación}$$



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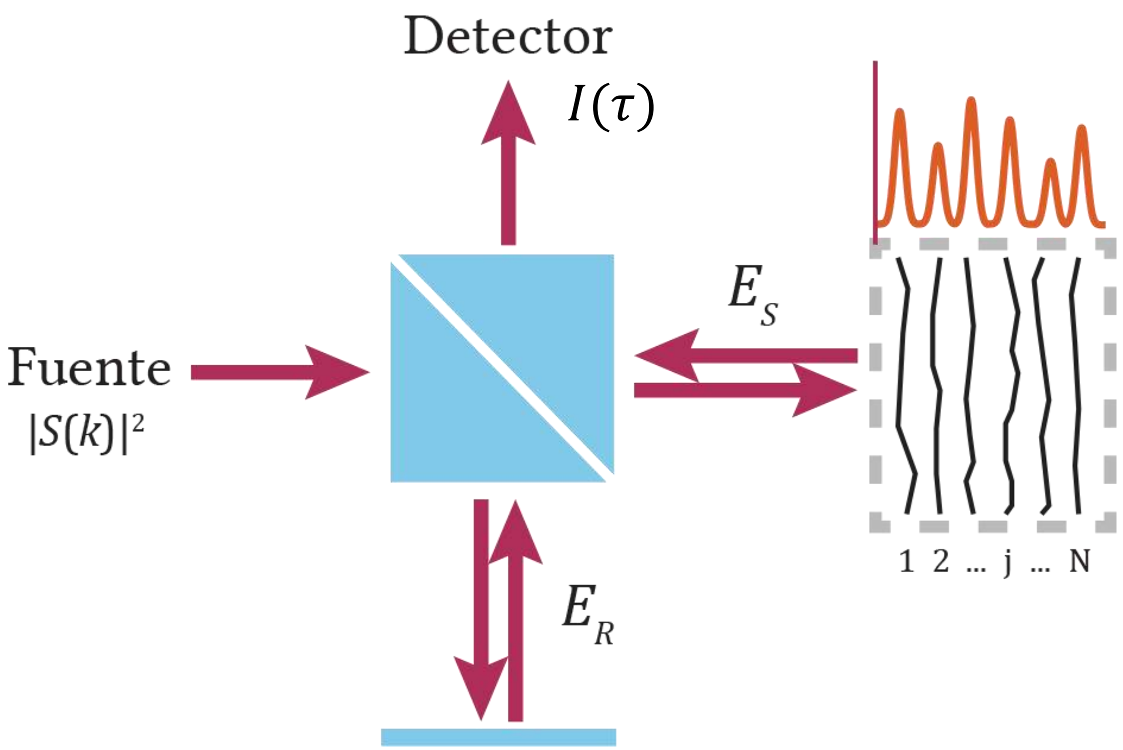

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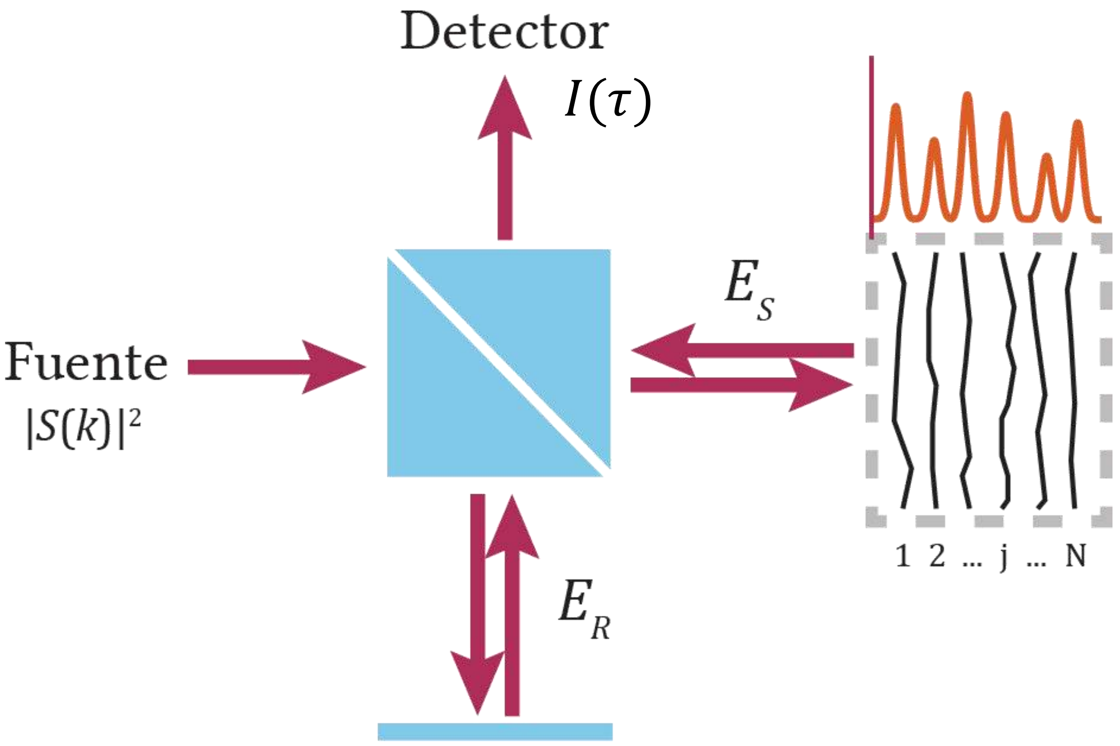
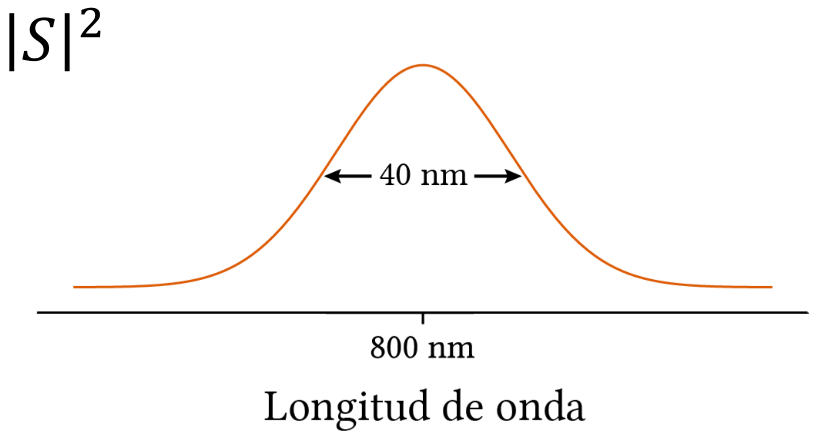


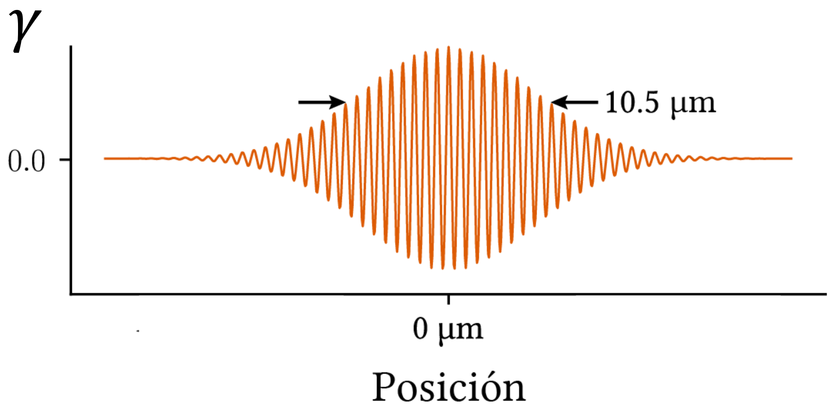
¿Qué es OCT?

Resolución axial: $\Delta\tau \sim \dfrac{1}{\Delta\nu}$ $\Delta z \sim \dfrac{\lambda_0^2}{\Delta\lambda}$



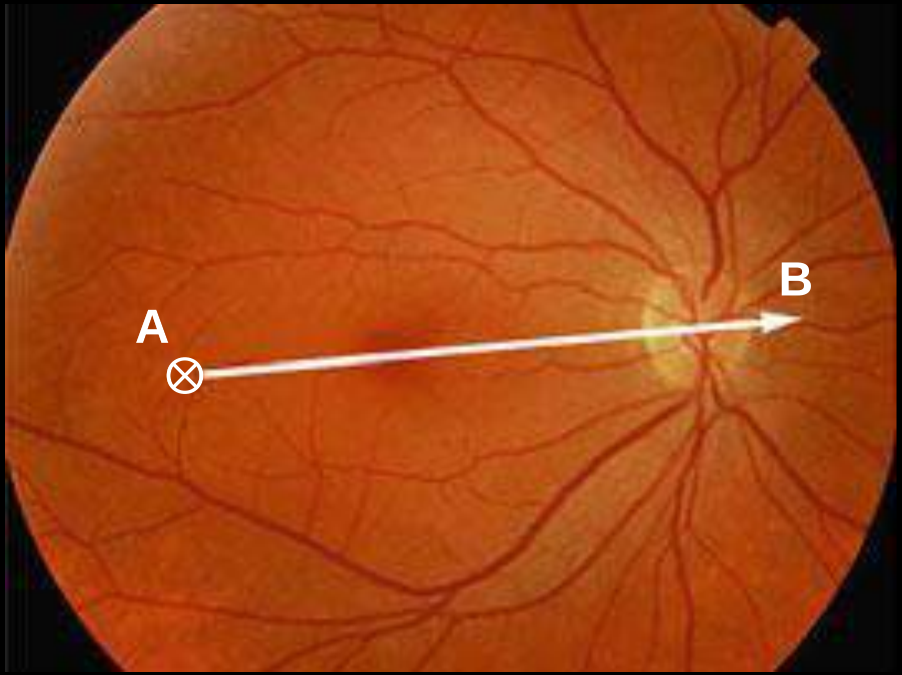
$\Delta\lambda = 40$ nm

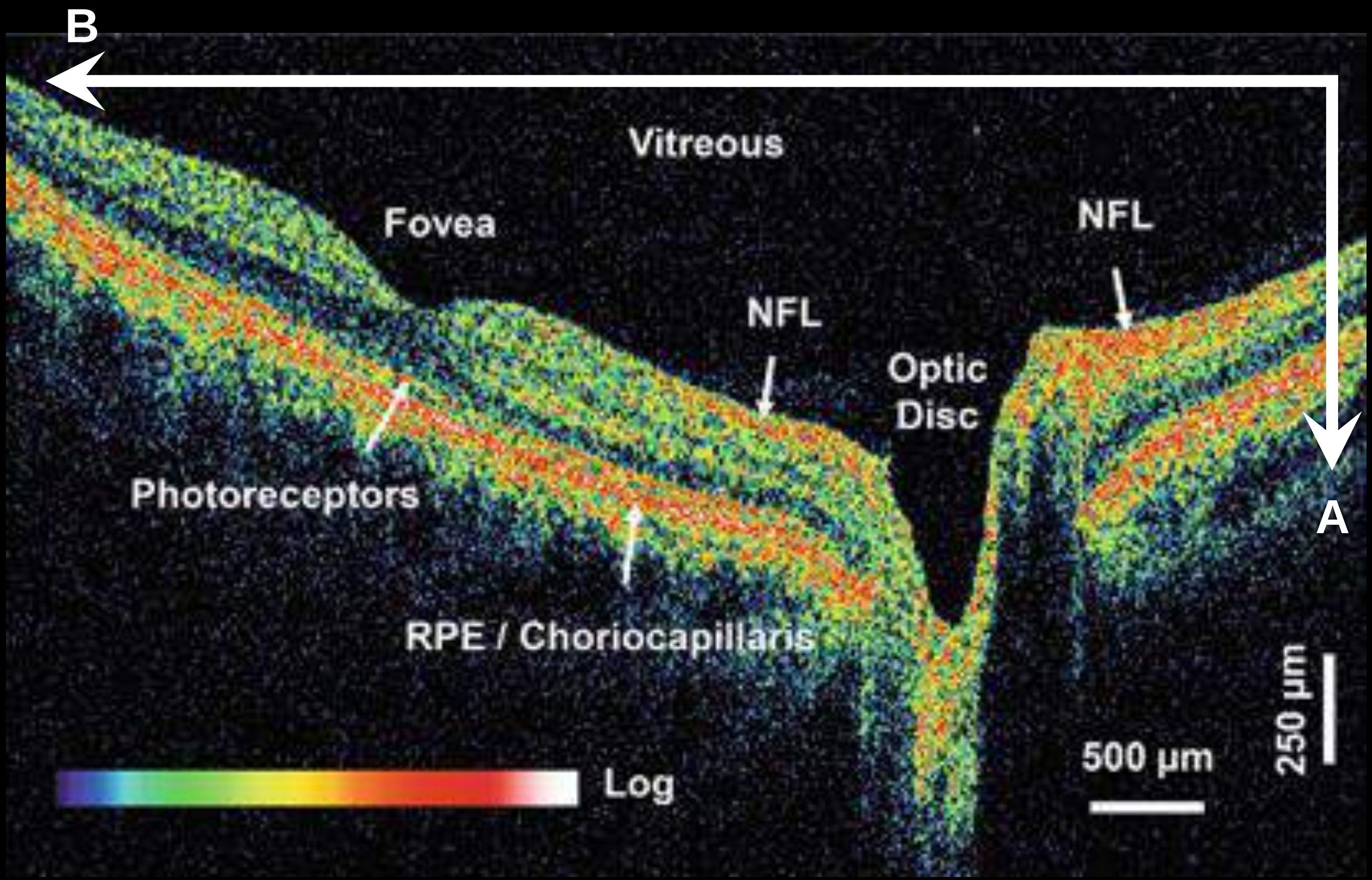
$\Delta\nu = 14$ THz



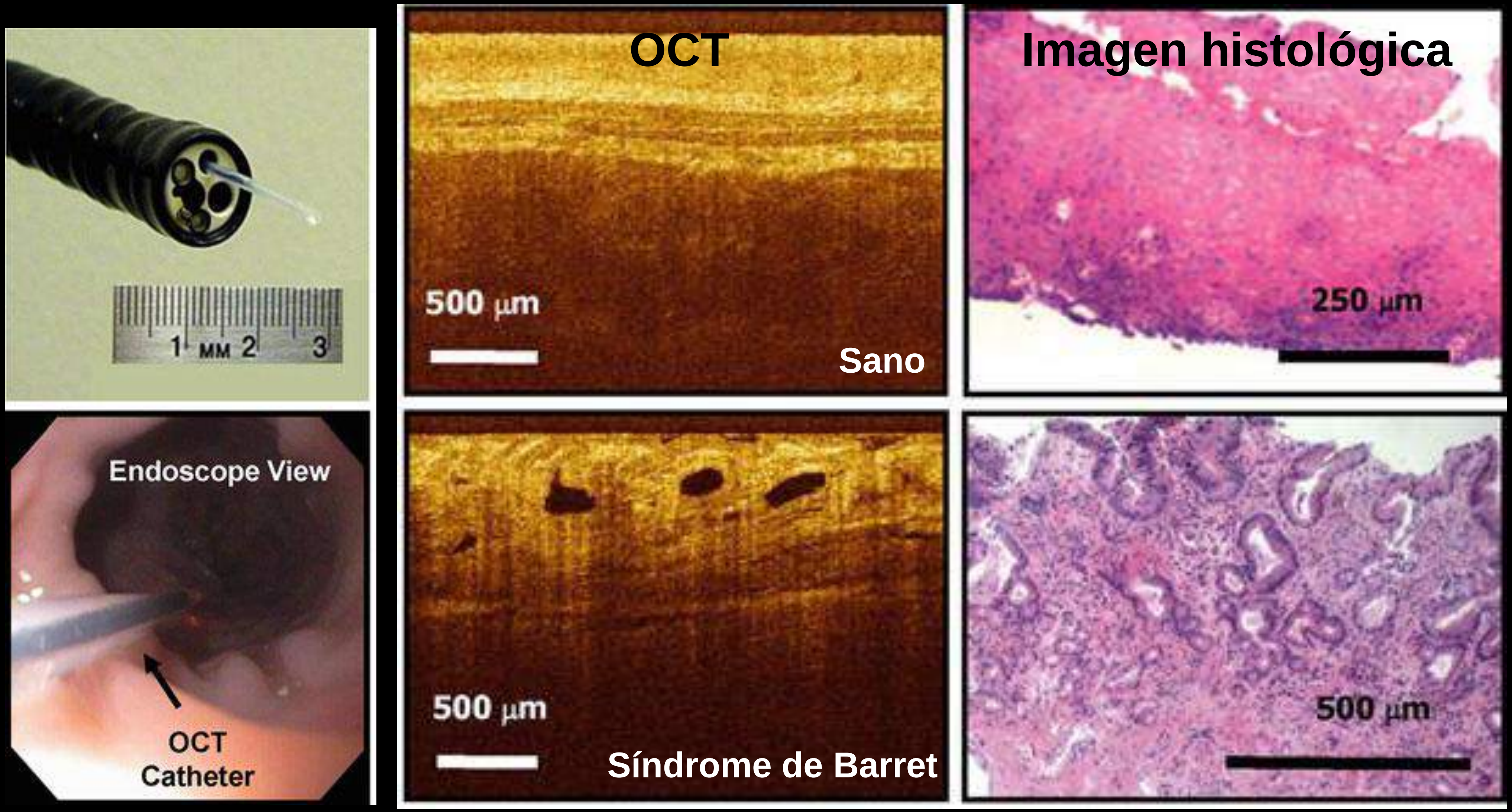
$\Delta z = 10.5$ μm

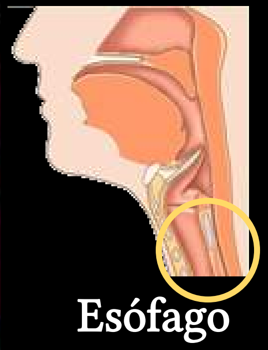
$\Delta\tau = 47$ fs





Hee et al. 1995, "*Optical coherence tomography of the human retina*". Arch. Ophthalmol. 113





Chen et al 2007, *"Ultrahigh resolution optical coherence tomography of Barrett's esophagus: preliminary descriptive clinical study correlating images with histology"*. Endoscopy 39

1. ¿Qué es OCT?

2. Láseres de fs en OCT

Láseres de femtosegundos en OCT

$$\gamma(z) = \mathrm{FT}\{|S(k)|^2\}$$

Espectro ancho: $\frac{\lambda_0^2}{\Delta\lambda}$

Penetración: λ_0

Forma del espectro: $|S(k)|^2$

Láseres de femtosegundos en OCT

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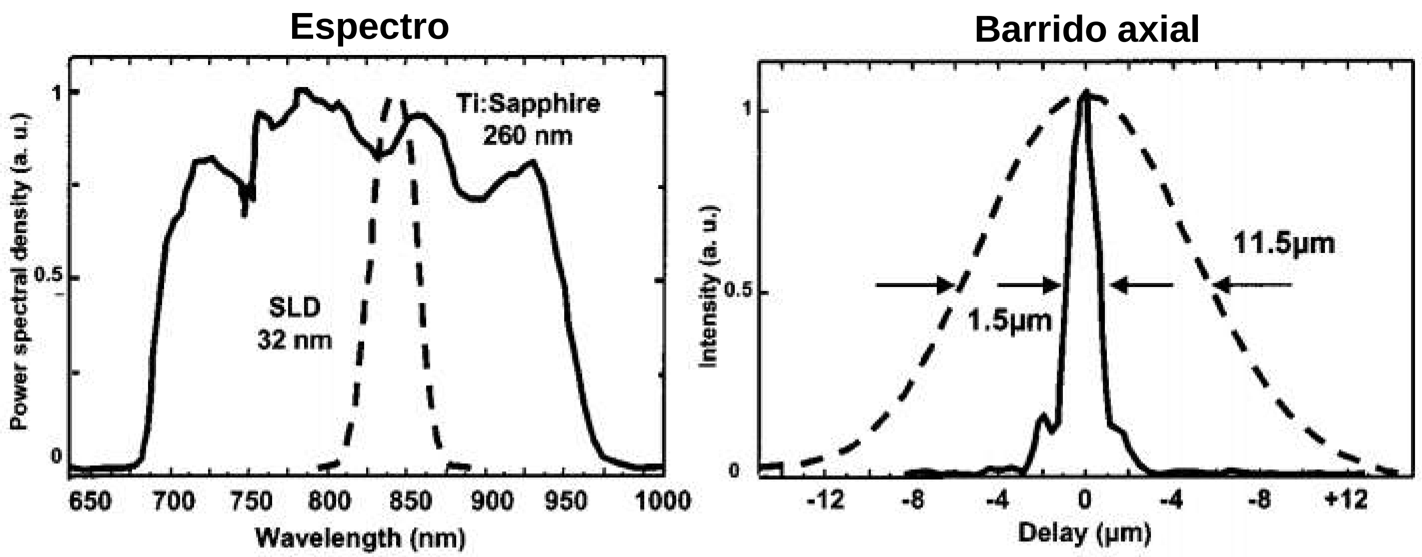
Ti:Za vs diodo superluminiscente estándar



Ancho de pulso < 5.5 fs

Drexler 2004, *"Ultrahigh-resolution optical coherence tomography"*, J. of Biomedical Optics 9

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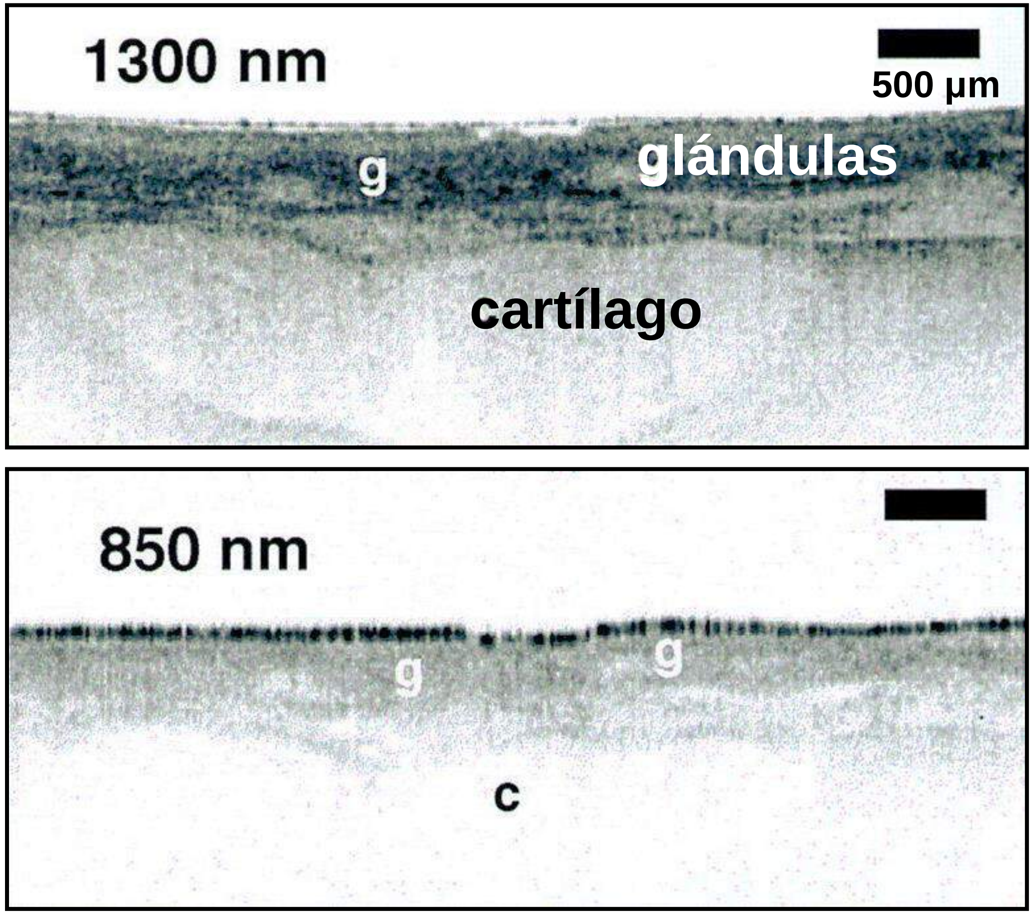
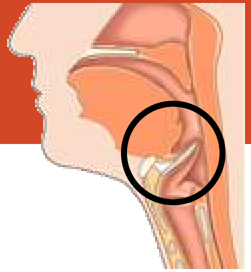


Brezinski et al 1996, *"Optical coherence tomography for optical biopsy. Properties and demonstration of vascular pathology"*, Circulation 93

Láseres de femtosegundos en OCT


Epiglotis humana

$$\gamma(z) = \mathrm{FT}\{|S(k)|^2\}$$

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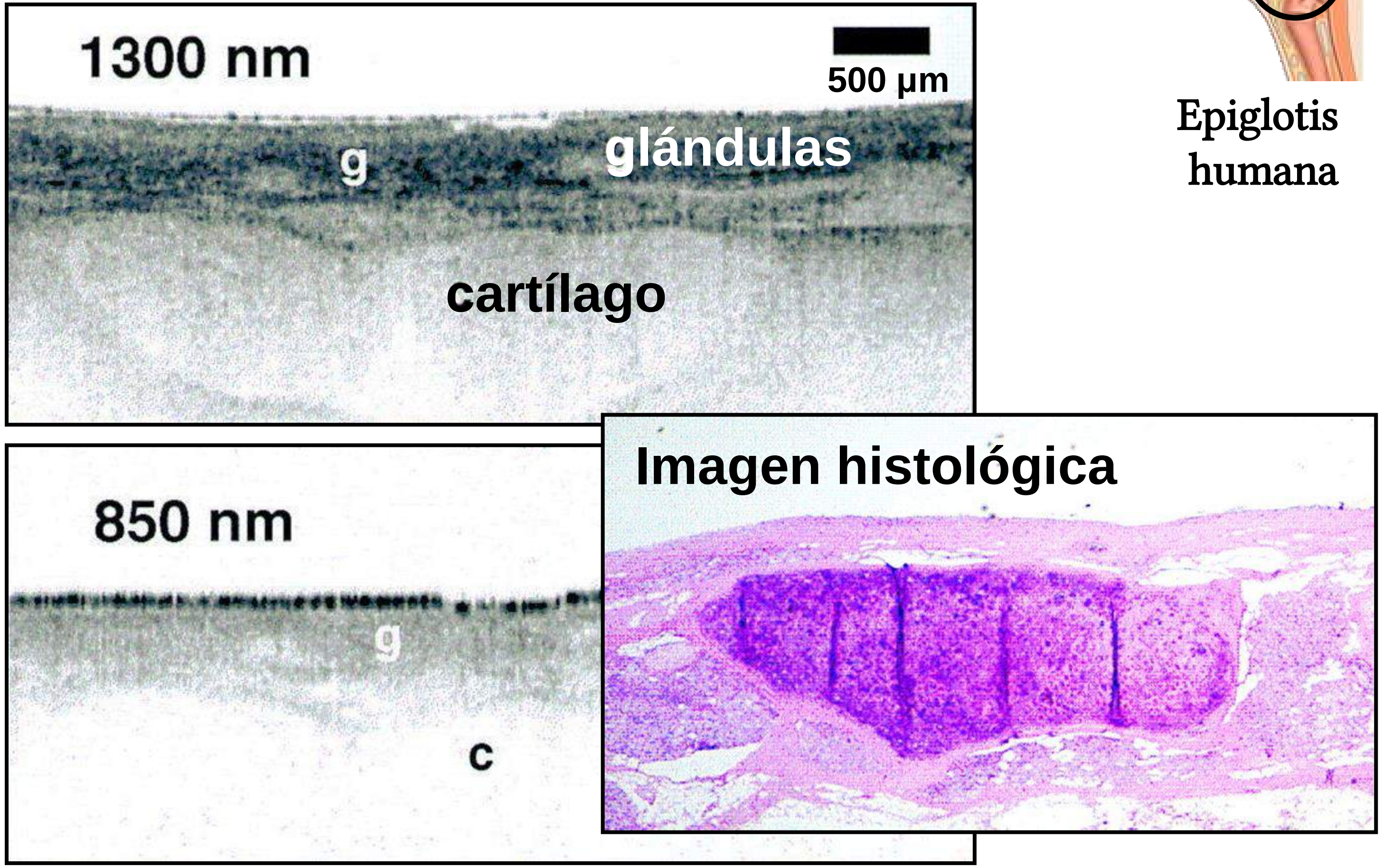

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Propagación en el medio

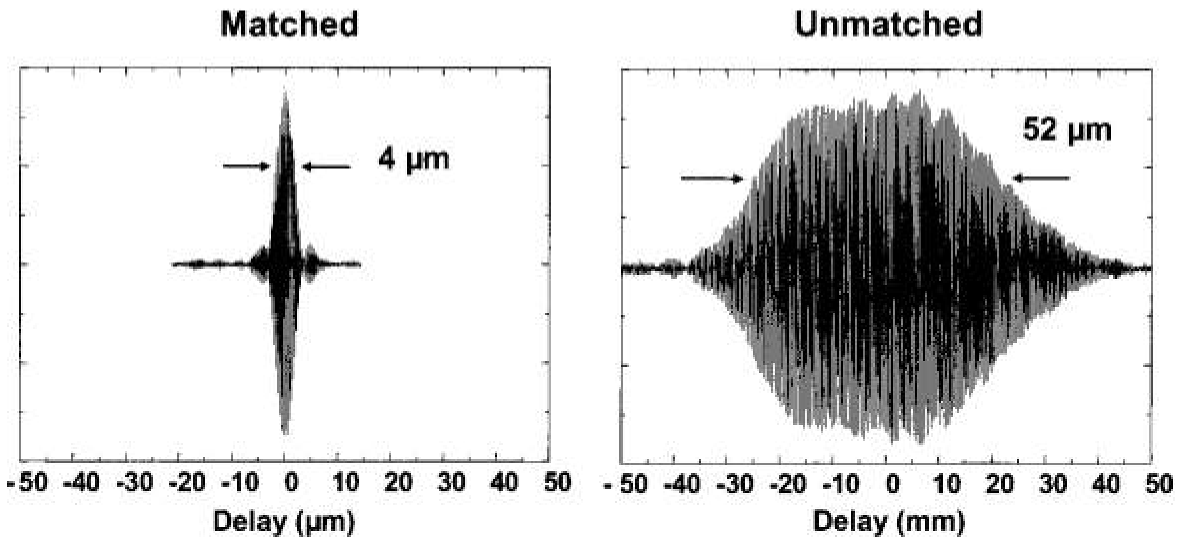
$$\gamma(\tau) = \langle E_R(t) E_S(t+\tau) \rangle$$

Dispersión en la velocidad de grupo

Pérdida de resolución

Pérdida de rango dinámico

Propagación en el medio



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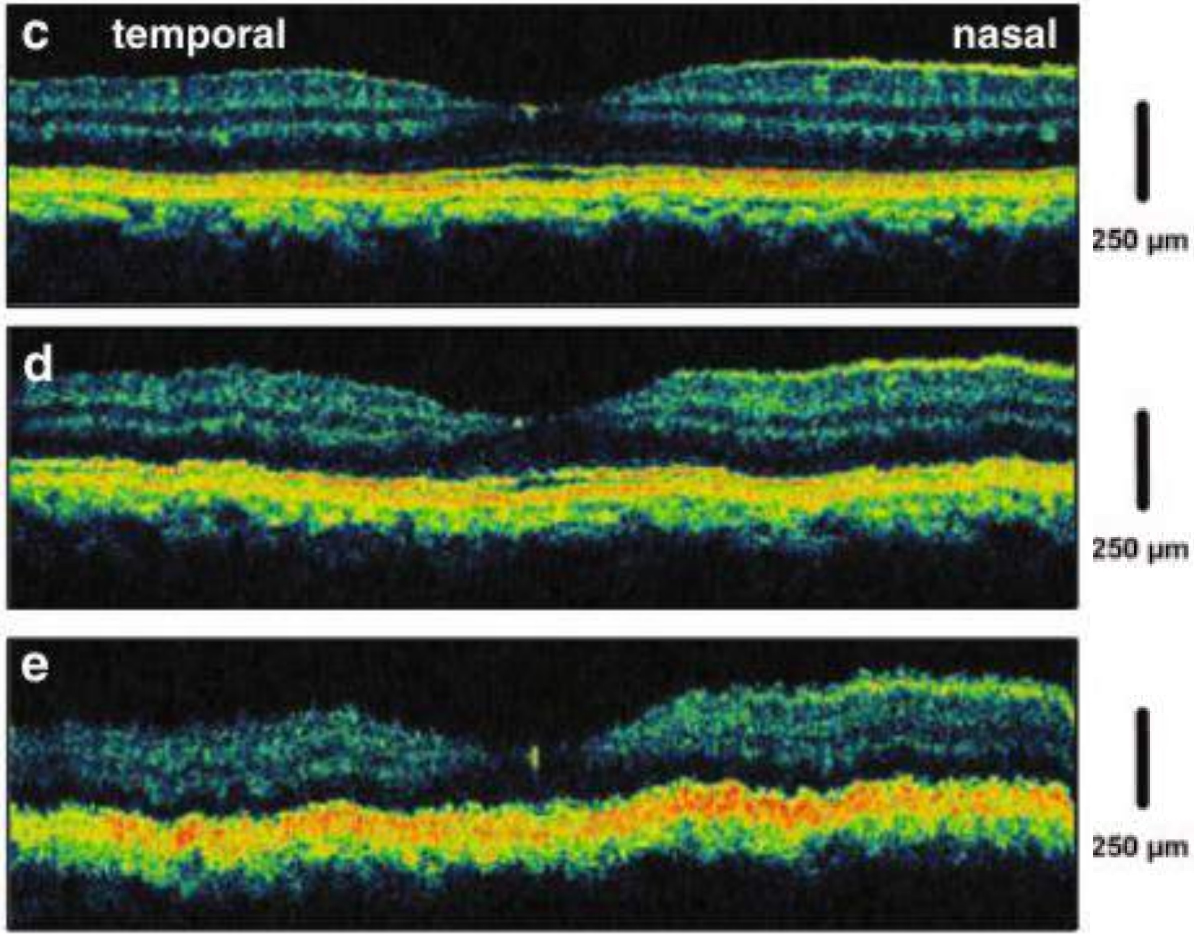

3 mm
cuarzo
-3dB

9 mm
cuarzo
-5dB

Drexler 2004, *"Ultrahigh-resolution optical coherence tomography"*, J. of Biomedical Optics 9

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Dispersión en la velocidad de grupo

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Propagación en el medio

Pérdida de resolución (calculada)

Ocular segment	Effective water length L_{eff}	Broadband SLD $\lambda_0 = 800$ nm $\Delta\lambda = 61$ nm	Ti:Al_2O_3 $\lambda_0 = 820$ nm $\Delta\lambda = 140$ nm
Air (no dispersion)	0 mm	$l_c = 4.6\ \mu m$	$l_c = 2.1\ \mu m$
		$V_{max,m} = 1$	$V_{max,m} = 1$
Cornea	2.65 mm	$l_{c,m} = 5.7\ \mu m$	$l_{c,m} = 6.9\ \mu m$
		$V_{max,m} = 0.90$	$V_{max,m} = 0.55$
Anterior segment	12.4 mm	$l_{c,m} = 16.2\ \mu m$	$l_{c,m} = 31.0\ \mu m$
		$V_{max,m} = 0.53$	$V_{max,m} = 0.26$
Axial eye length,	26.5 mm	$l_{c,m} = 33.5\ \mu m$	$l_{c,m} = 66.1\ \mu m$
posterior segment		$V_{max,m} = 0.37$	$V_{max,m} = 0.18$

Hitzenberger 1999, *"Dispersion effects in partial coherence interferometry: implications for intraocular ranging"*, J. of Biomedical Optics 4

$$\gamma(\tau) = \langle E_R(t) E_S(t+\tau) \rangle$$

Dispersión en la velocidad de grupo

Pérdida de resolución

Pérdida de rango dinámico

Conclusiones

Técnica

Ventajas

- *In vivo,* no invasivo (o casi)
- Resolución axial $\sim 1 - 10$ µm
- 1D (axial) + 2D (transversal, barrido)
- Alta velocidad
- Compacto
- Portable
- Barato
- etc
- etc

Desventajas

- Penetración limitada $1 - 3$ mm

Láseres de femtosegundos

Nos importa el espectro, no el pulso

- Resolución axial $\longrightarrow \lambda_0^2/\Delta\lambda$
- Penetración $\longrightarrow \lambda_0$
- Forma

Compensamos *diferencia* de dispersión

- Dispersión de velocidad de grupo

  Dispersión depende de la profundidad

  Compensación por *hardware* y por *software*

Gracias

¿Preguntas?

¿Qué es OCT?

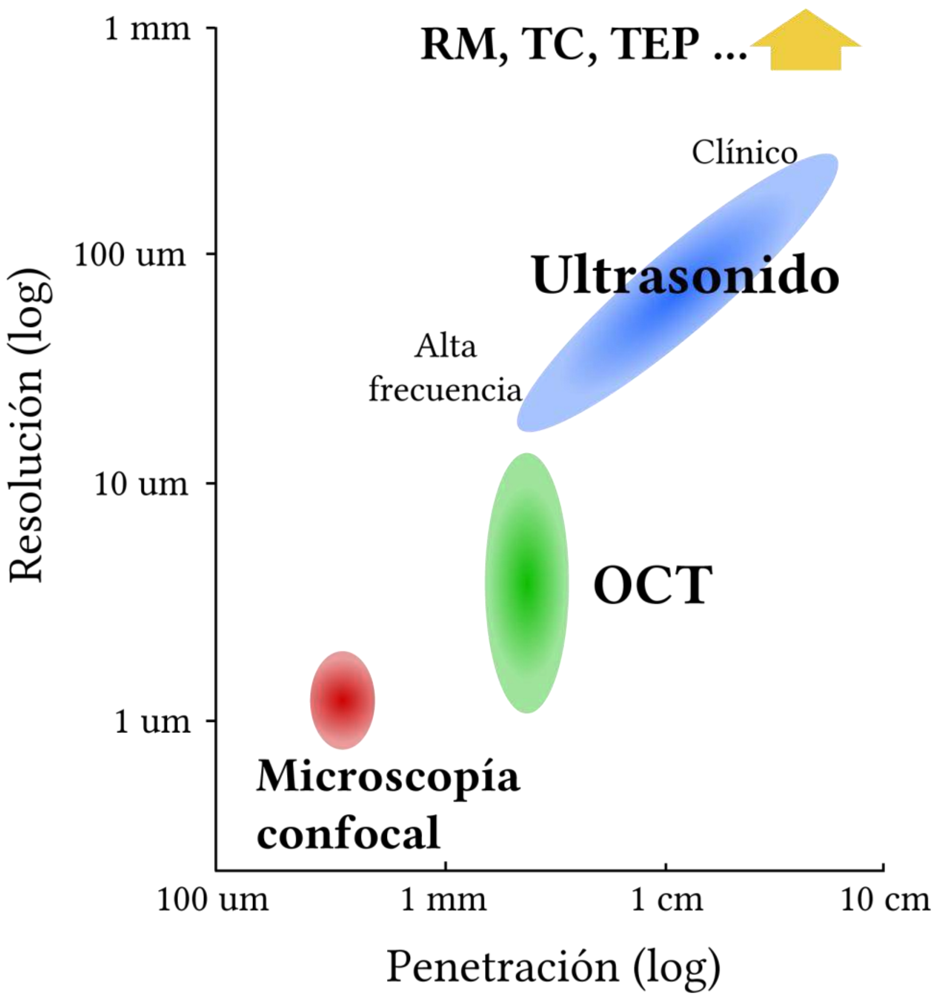
Interferometría de baja coherencia

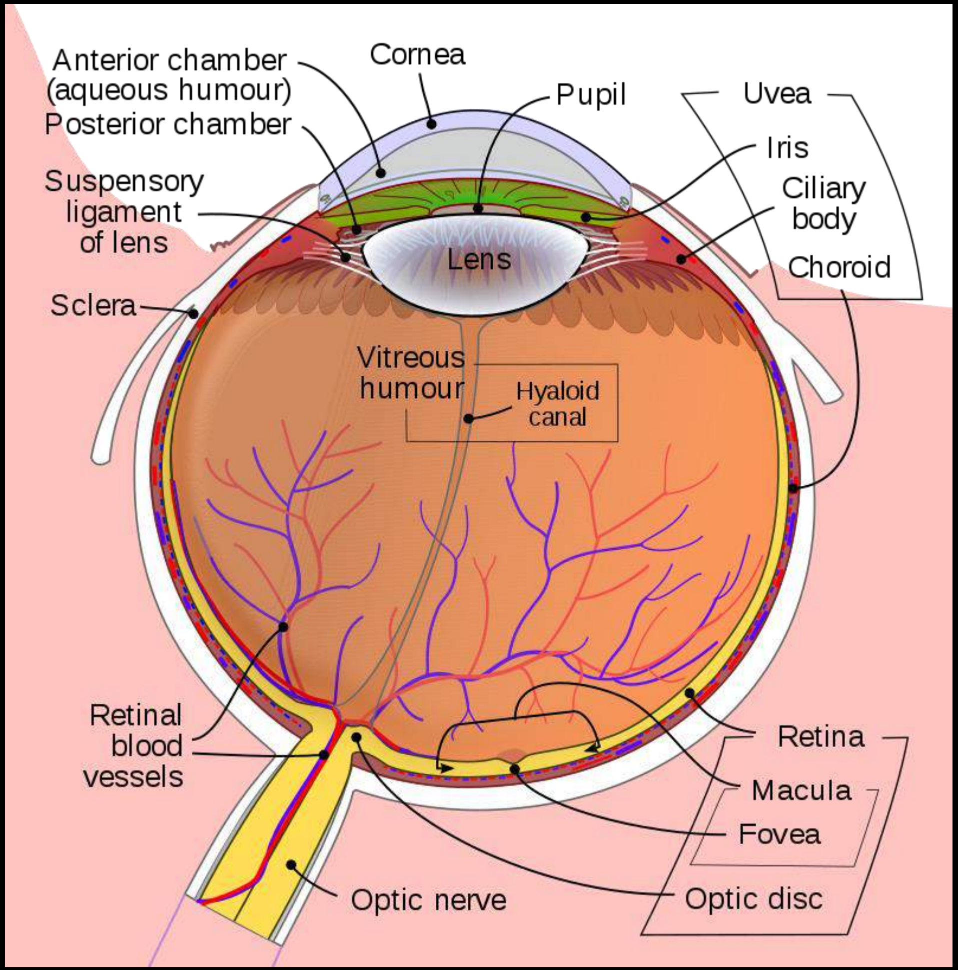
Ventajas:

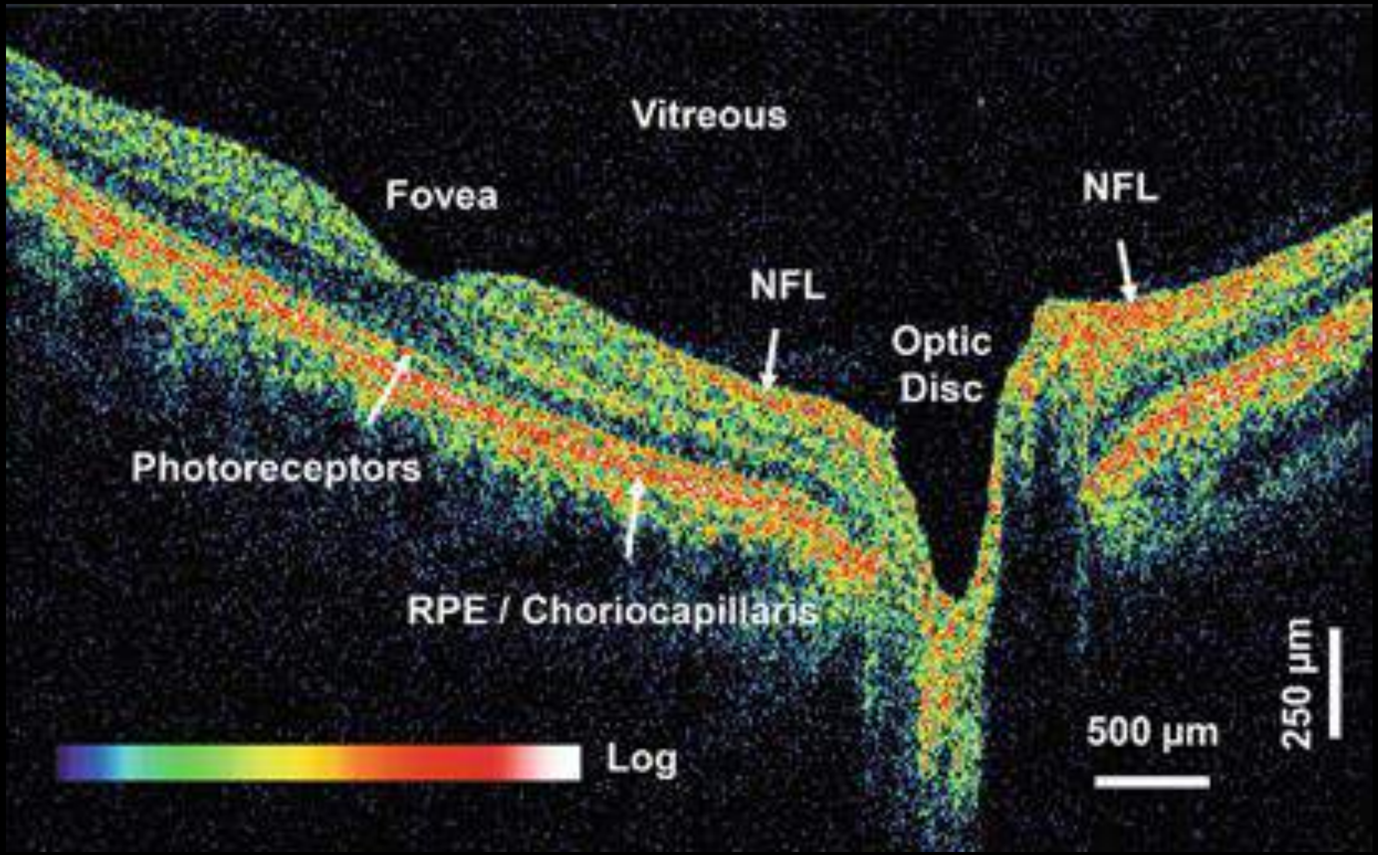
- *In vivo,* no invasivo (o casi)
- Resolución axial ~ $1 - 10$ µm
- 1D (axial) + 2D (transversal, barrido)
- Alta velocidad
- Compacto, portable, "barato“ ($10 - 100$ kUSD)

Desventajas

- Penetración limitada $1 - 3$ mm







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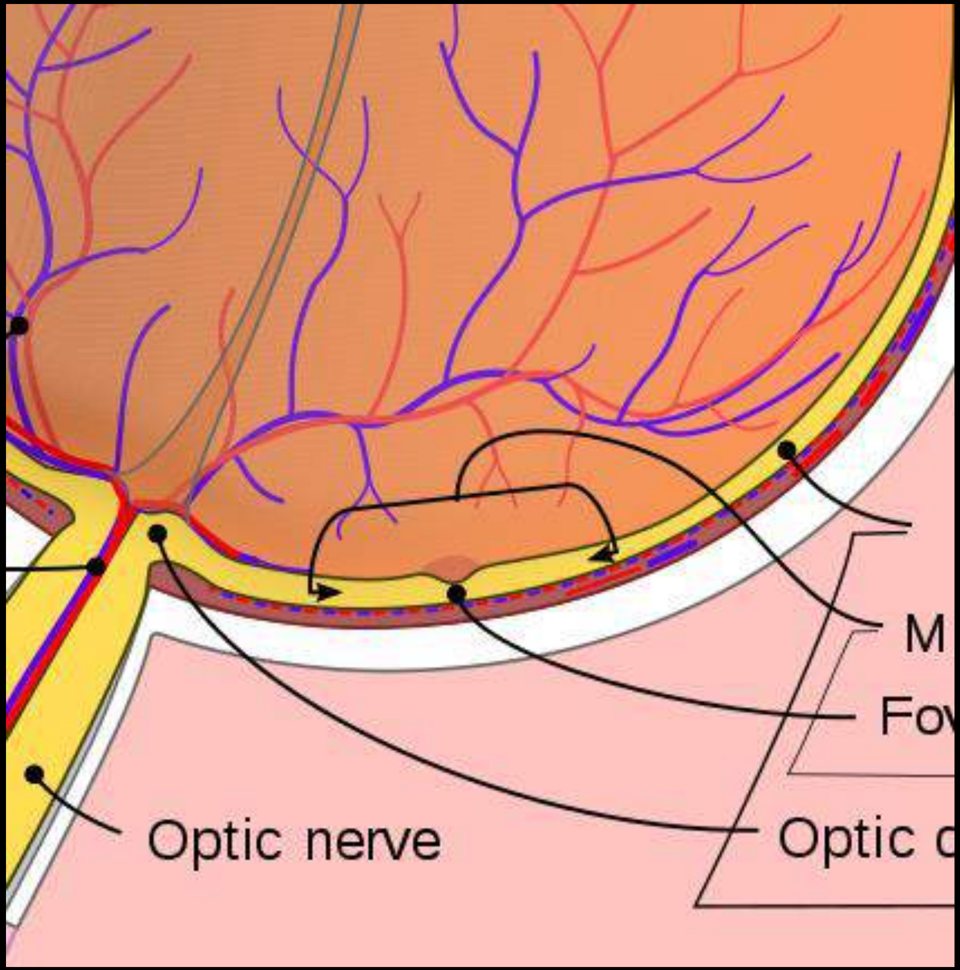

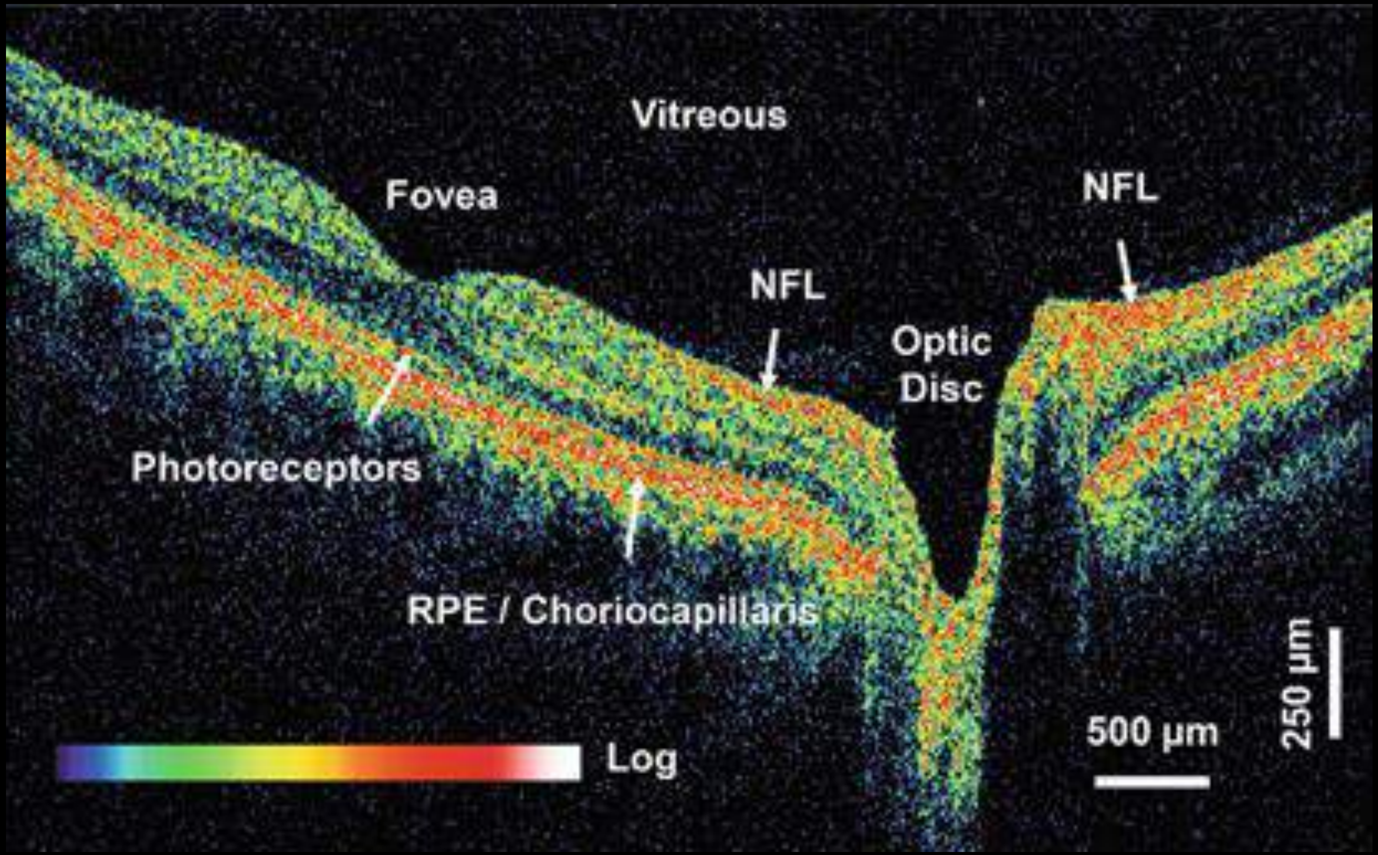

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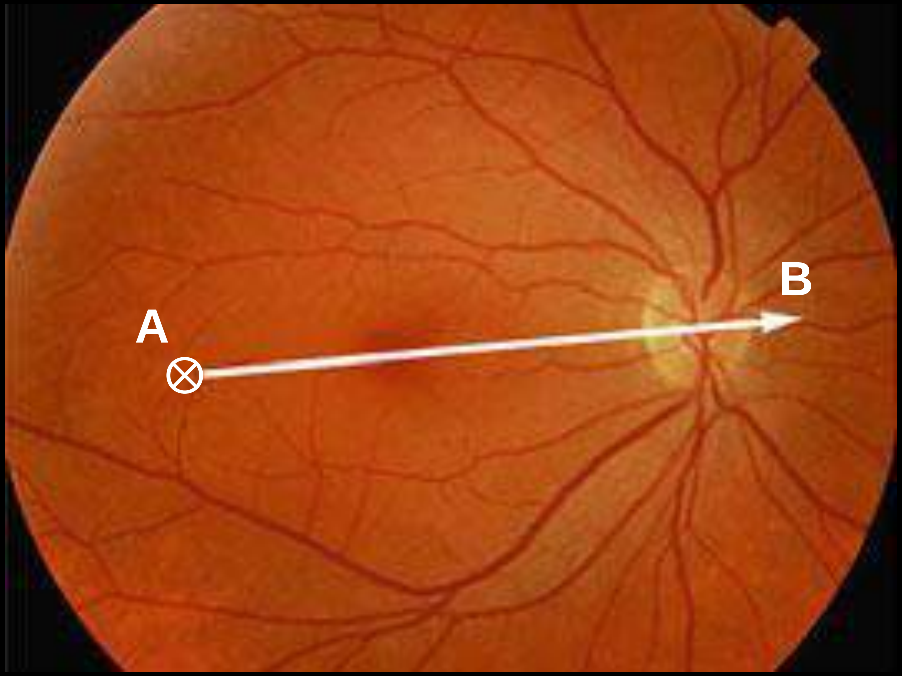

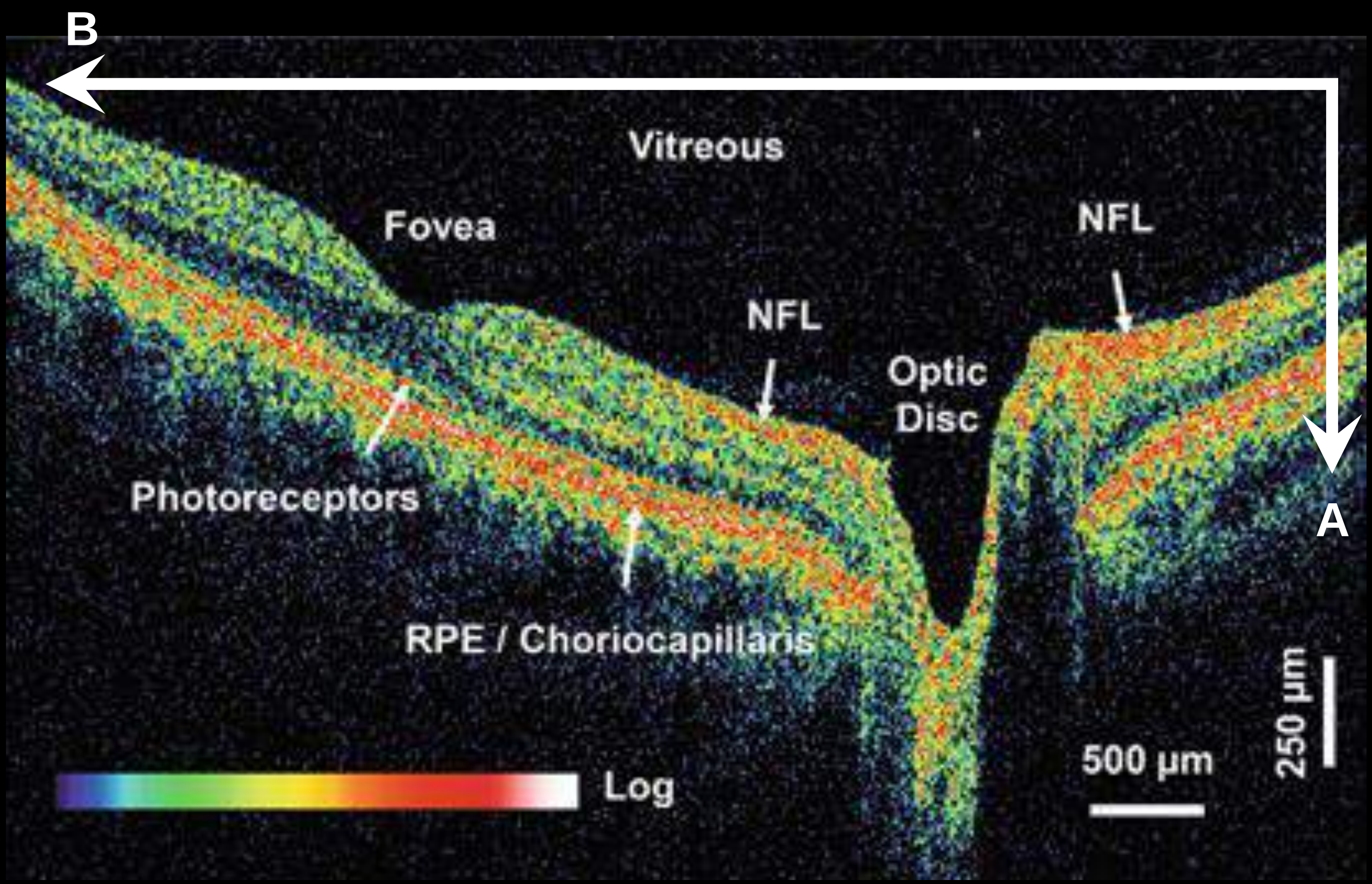

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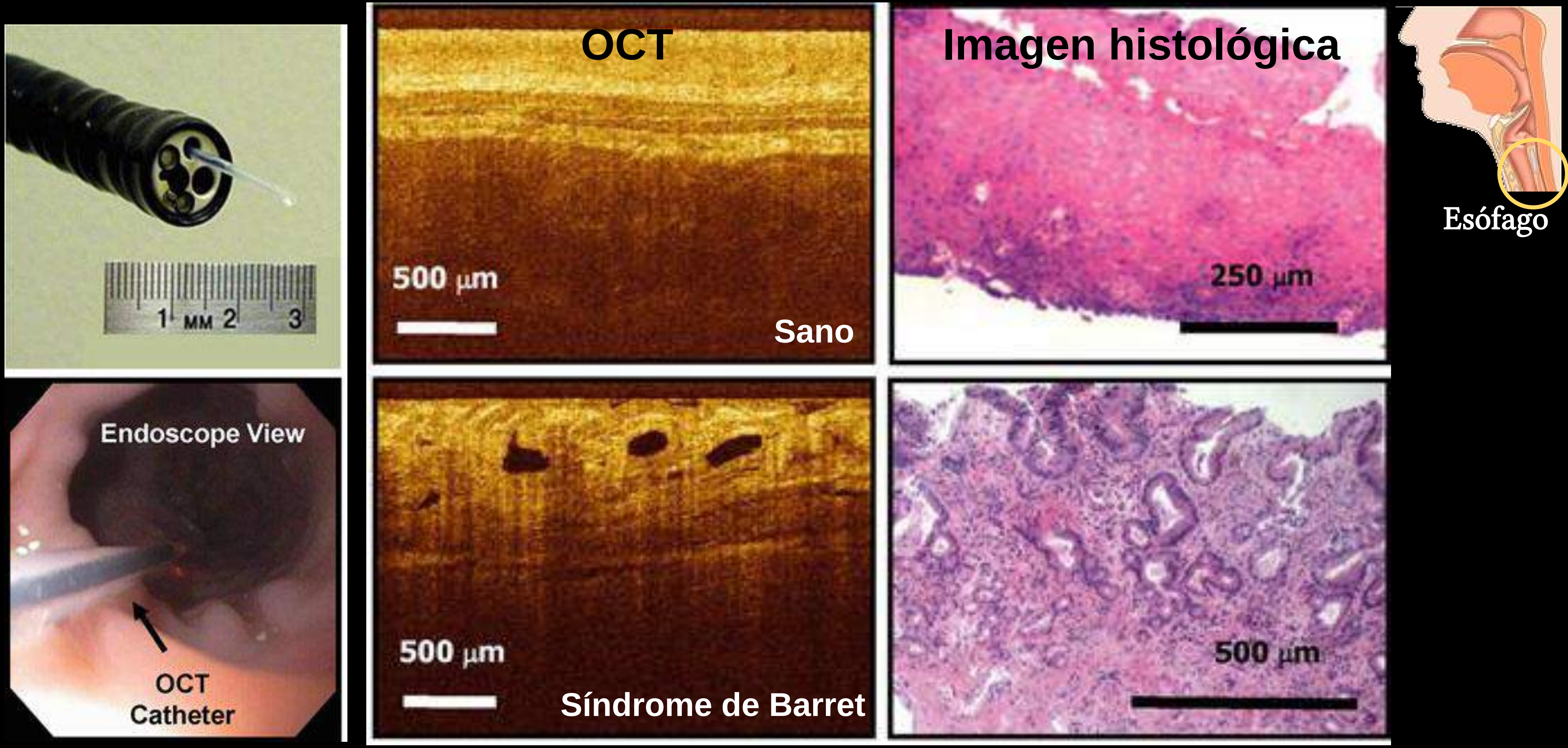

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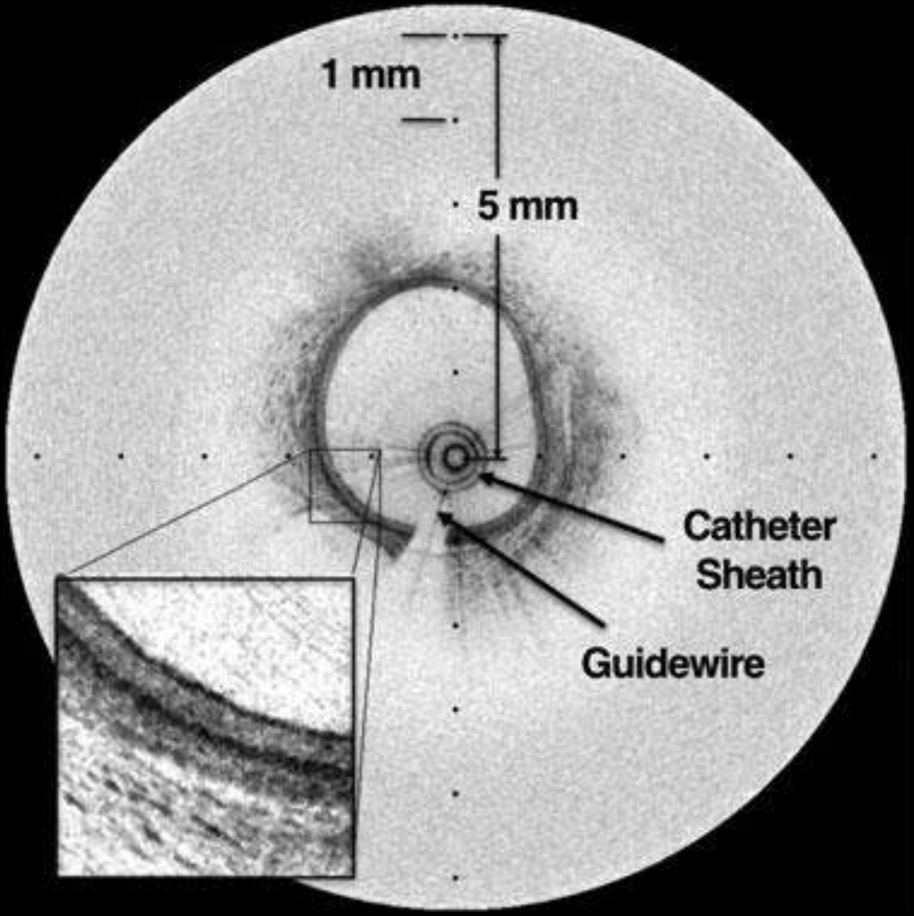

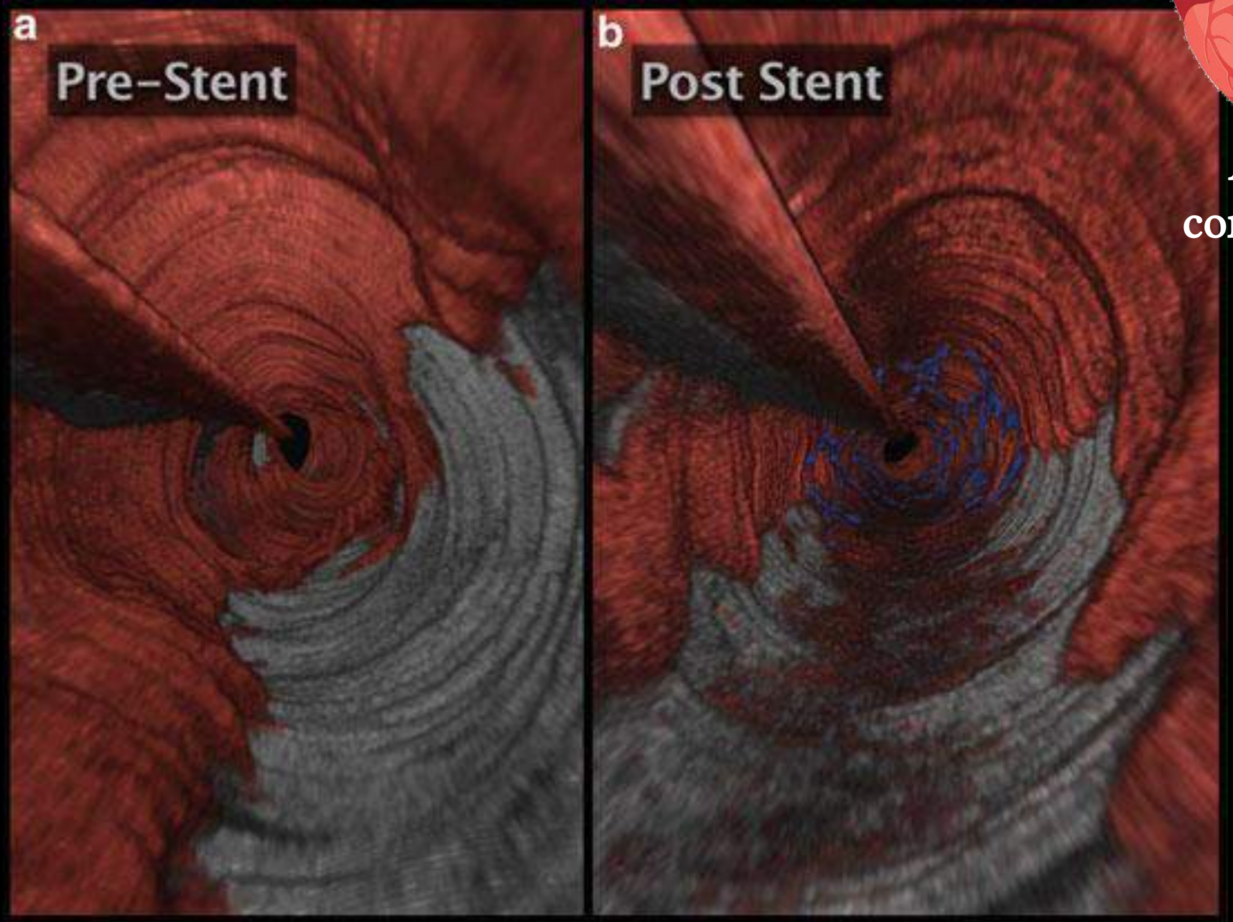

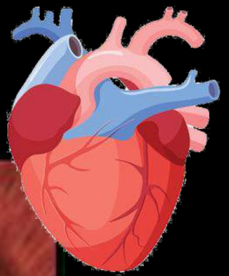

Arteria
coronaria

Tearney et al 2008, *"Three-dimensional coronary artery microscopy by intracoronary optical frequency domain imaging"*, JACC Cardiovasc. Imaging 1

W. Drexler, J. G. Fujimoto

Optical Coherence Tomography: Technology and Applications

Volume 3

¿Qué es OCT?

$$E_R = S(k)\frac{1}{2}\sqrt{\rho_R}\,\exp(i\varphi_R)$$

$$E_S = S(k)\frac{1}{2}\sum_{j=1}^{N}\sqrt{\rho_j}\,\exp(i\varphi_j)$$

$$I_D(k) = \frac{1}{4}|S(k)|^2\left[\rho_R + \textstyle\sum_j \rho_j\right]$$

$$+\frac{1}{2}|S(k)|^2\left[\textstyle\sum_j \sqrt{\rho_R\rho_j}\,\cos(\Delta\varphi_{Rj})\right]$$

$$+\frac{1}{4}|S(k)|^2\left[\textstyle\sum_{j\neq k} \sqrt{\rho_j\rho_k}\,\cos(\Delta\varphi_{jk})\right]$$

Transformo Fourier

$$\mathrm{FT}\{|S(k)|^2\} = \gamma(z)$$

$$\mathrm{FT}\{\cos x\} \propto \frac{1}{2}\big(\delta(x) + \delta(-x)\big)$$

$$\mathrm{FT}\{A\,B\} \propto \mathrm{FT}\{A\}\otimes\mathrm{FT}\{B\}$$

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Términos "DC"

$$+\frac{1}{4}\gamma(z)\otimes\left[\textstyle\sum_j \sqrt{\rho_R\rho_j}\left(\delta(z+\Delta z_{Rj}) + \delta(z-\Delta z_{Rj})\right)\right]$$

Términos de correlación cruzada

$$+\frac{1}{8}\gamma(z)\otimes\left[\textstyle\sum_{j\neq k} \sqrt{\rho_j\rho_k}\left(\delta(z+\Delta z_{jk}) + \delta(z-\Delta z_{jk})\right)\right]$$

Términos de autocorrelación

Resolución

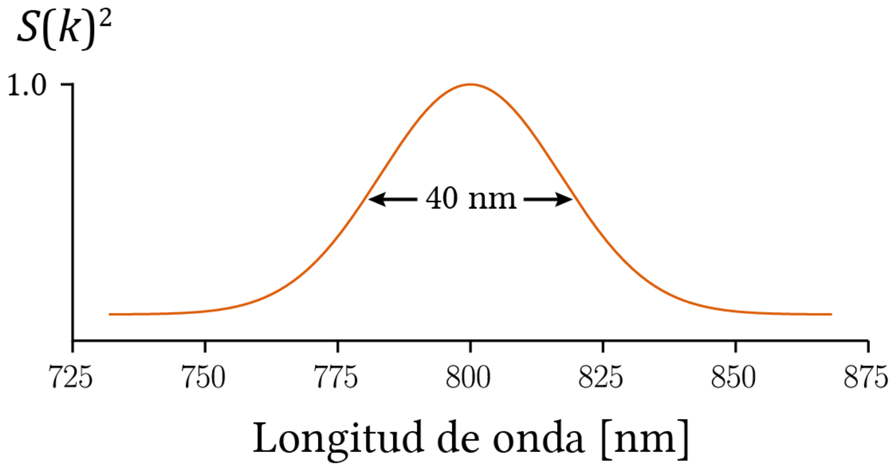
Espectro gaussiano

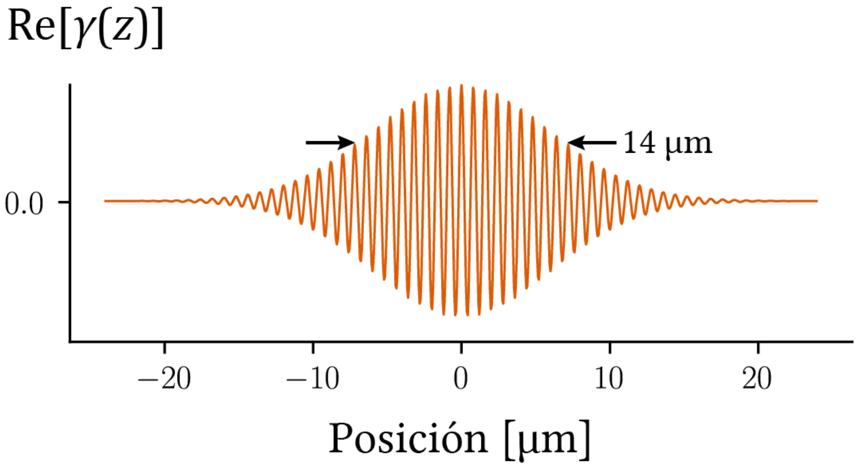
$$|S(k)|^2 = \frac{1}{\sigma_k} \exp\left(-\frac{(k-k_0)^2}{2\sigma_k^2}\right)$$

$\Updownarrow$ Fourier + Wiener Khinchin

$$\gamma(z) = \exp\left(-\sigma_k^2 \frac{z^2}{2}\right) \exp(ik_0 z)$$

Resolución axial: $$\Delta z = \frac{2 \ln 2}{\pi} \frac{\lambda_0^2}{\Delta\lambda}$$





Fuentes en OCT

Wavelength range	NIR				Visible	
Authors	Xu et al.[26]	Kolb et al.[27]	You et al.[28]	Werkmeister et al.[29]	Lichtenegger et al.[30]	Chong et al.[22]
Year	2017	2016	2015	2017	2017	2017
Axial resolution in tissue	7.5 μm	5.6 μm	1.7 μm	1.2 μm (theoretical)	0.88 μm	1.4 μm
Center wavelength	1310 nm	1000 nm	1300 nm	800 nm	555 nm	560 nm
Bandwidth	100 nm	120 nm	420 nm	170 nm	156 nm	100 nm
Sensitivity	105 dB (7 mW)	—	—	97 dB (1.5 mW)	89 dB (0.8 mW)	94 dB (0.1 mW)
Roll-off	~0 dB/mm	—	—	10 dB/mm	24 dB/mm	5 dB/mm
A-line rate	100 kHz	1670 kHz		140 kHz	30 kHz	10 kHz
Light source	Swept source	Swept source	SC	Ti:sapphire	SC	SC
Sample	Brain (*in vivo*)	Retina	Onion	Cornea	Brain (*ex vivo*)	Retina

Shu et al 2017, *"Visible-light optical coherence tomography: a review"*, J. of Biomedical Optics

Láseres de femtosegundos en OCT

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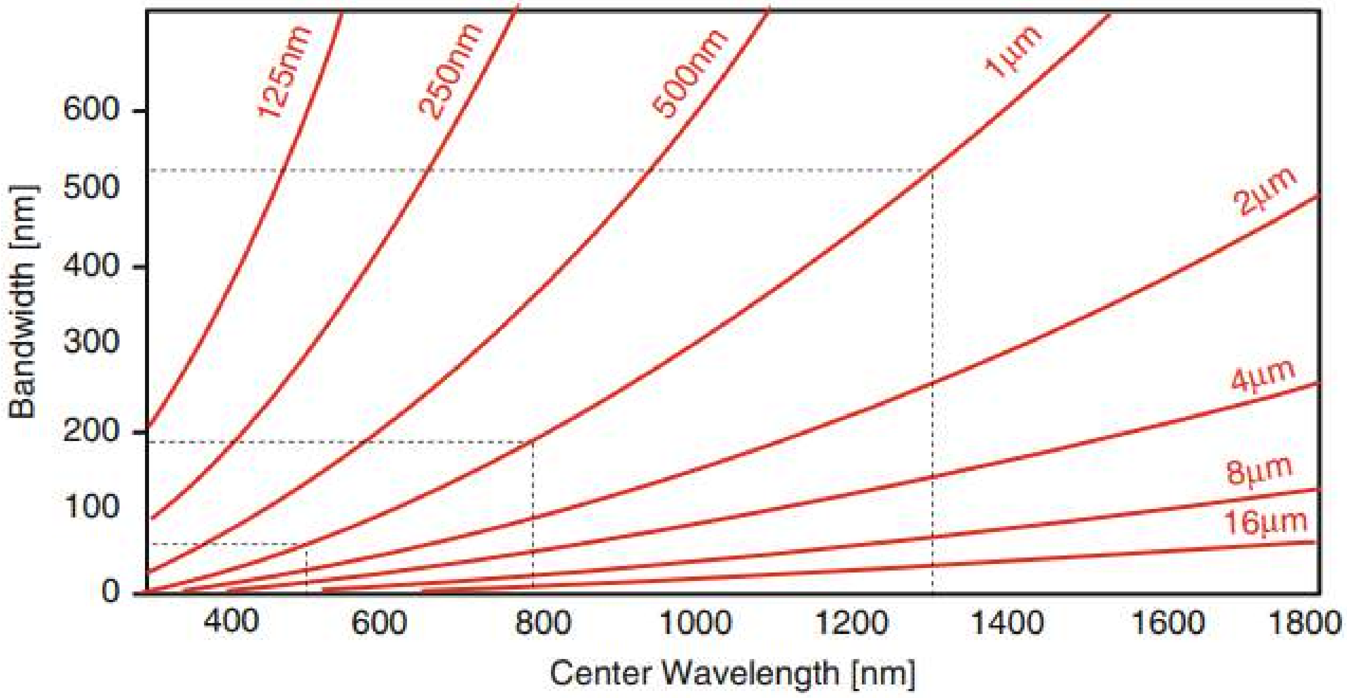
Espectro ancho: $\frac{\lambda_0^2}{\Delta\lambda}$

Penetración: λ_0

Forma del espectro: $|S(k)|^2$



Drexler et al 2015, *"Optical Coherence Tomography: technology and applications"*, cap. 9, Springer

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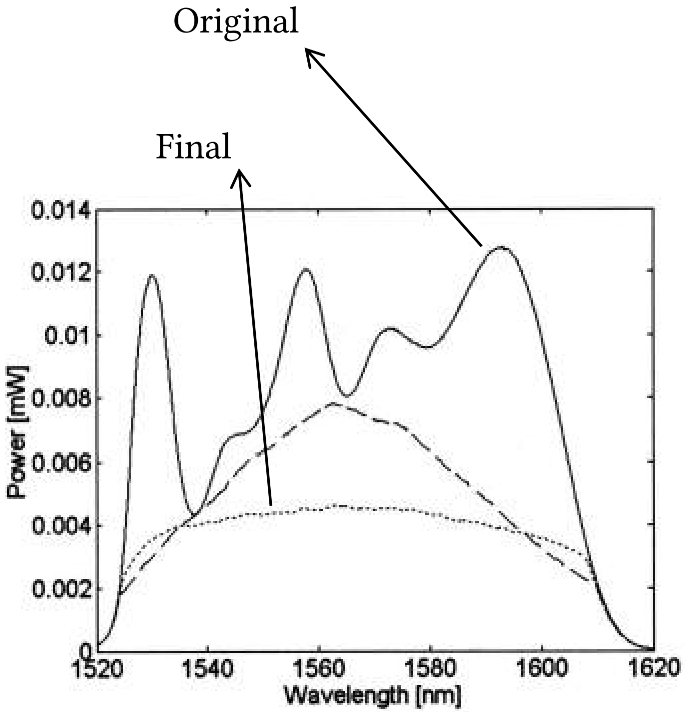

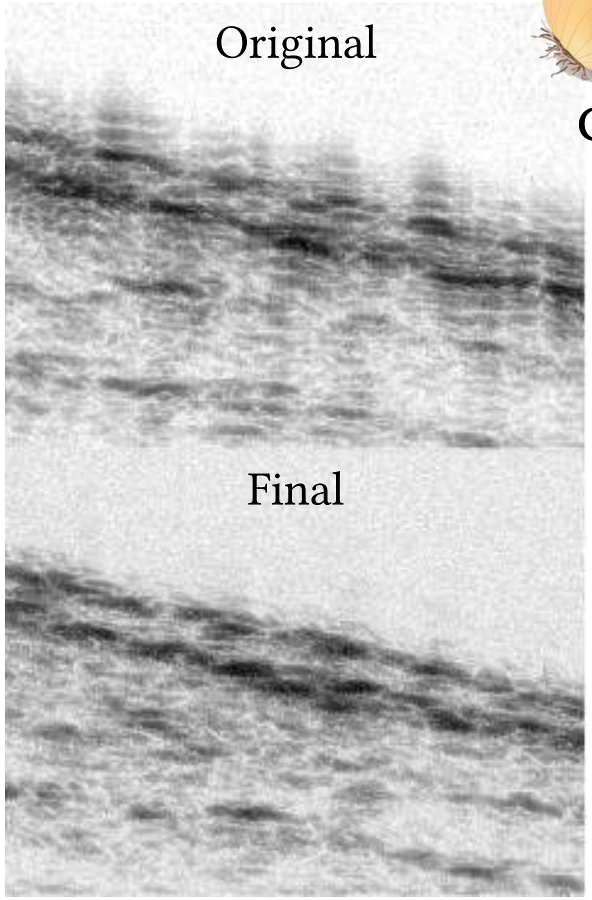

Cebolla

Ackar et al 2003, *"Spectral shaping to improve the point spread function in optical coherence tomography"*, Optic Letters 28

Propagación en el medio

$$\Delta\varphi(\omega) = k(\omega_0)(2L_R - 2L_S)$$

$$+[k_R'(\omega_0)2L_R - k_S'(\omega_0)2L_S]\ \ (\omega - \omega_0)$$

$$+\frac{1}{2}[k_R''(\omega_0)2L_R - k_S''(\omega_0)2L_S]\ \ (\omega - \omega_0)^2$$

$$+\cdots$$

$$\gamma(z) = \langle E_R(t)E_S(t+\tau)\rangle$$

Velocidad de grupo distintas

Reescaleo de distancias

Dispersión en la velocidad de grupo

Pérdida de resolución

Pérdida de rango dinámico

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$$+\cdots$$

$$z_j - z_R \quad \rightarrow \quad \frac{z_j - z_R}{n_g} \qquad \Delta z = \frac{2\ln 2}{\pi\, n_g}\frac{\lambda_0^2}{\Delta\lambda}$$

$$n_g = \frac{c}{k'(\omega_0)}$$

$$\gamma(z) = \langle E_R(t)E_S(t+\tau)\rangle$$

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Pérdida de rango dinámico

Propagación en el medio

$$\Delta\varphi(\omega) = k(\omega_0)(2L_R - 2L_S)$$

$$+[k'_R(\omega_0)2L_R - k'_S(\omega_0)2L_S] \ (\omega - \omega_0)$$

$$+\frac{1}{2}[k''_R(\omega_0) - k''_S(\omega_0)]\, 2l \ (\omega - \omega_0)^2$$

$$+\cdots$$

$$2\tilde{\sigma}_\omega = 2\sigma_\omega \sqrt{1 + \left(\frac{\Delta k''(\omega_0)\, 2l}{\sigma_\omega^2}\right)^2}$$

$$\gamma(z) = \langle E_R(t) E_S(t+\tau)\rangle$$

Velocidad de grupo distintas

Reescaleo de distancias

Dispersión en la velocidad de grupo

Pérdida de resolución

Pérdida de rango dinámico

Propagación en el medio

Tamaños característicos:

Largo del ojo	$23{,}929 \pm 2$ mm
Córnea	0,530 mm
Humor acuoso	3,689 mm
Cristalino	3,630 mm

Dispersión a 800 nm

Agua k'' (fs^2/mm)	**Humor vítreo** k'' (fs^2/mm)	**Cornea-cristalino** φ'' (fs^2/mm)	**Cuarzo** k'' (fs^2/mm)
24.76 ± 0.13	25.05 ± 0.11	$32 \pm$ ¿?	$36.163 \pm$ ¿?

Cohelo 2008, *"Group-velocity dispersion measurements of water, seawater, and ocular components using multiphoton intrapulse interference phase scan"*, Applied Optics 46

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$$\gamma(z) = \langle E_R(t) E_S(t+\tau) \rangle$$

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