



Óptica no lineal aplicada en guías de onda

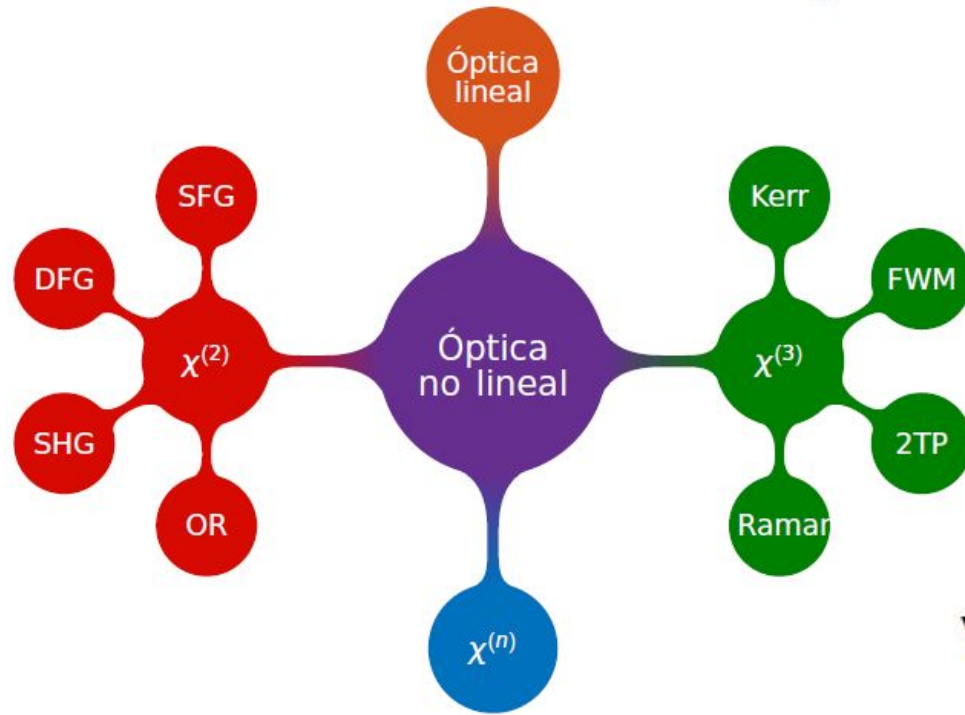
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Óptica no lineal. Susceptibilidad, polarización



$$\tilde{P}(t) = \epsilon_0 [\chi^{(1)} \tilde{E}(t) + \chi^{(2)} \tilde{E}^2(t) + \chi^{(3)} \tilde{E}^3(t) + \dots]$$

ecuación de ondas

$$\nabla^2 \tilde{E} - \frac{n^2}{c^2} \frac{\partial^2 \tilde{E}}{\partial t^2} = \frac{1}{\epsilon_0 c^2} \frac{\partial^2 \tilde{P}^{\text{NL}}}{\partial t^2}$$

Óptica no lineal. Procesos $\chi^{(2)}$

Difference Frequency Generation (DFG): amplificación paramétrica

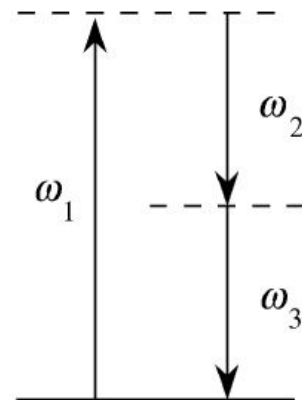
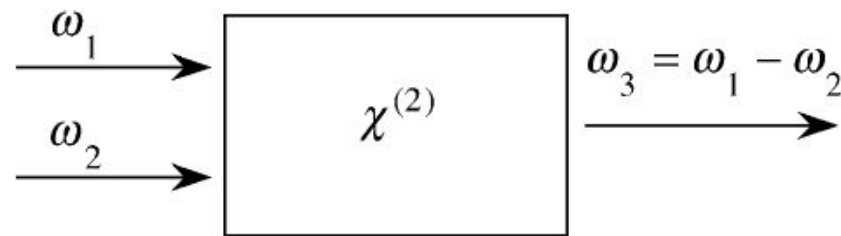

$$P(2\omega_1) = \epsilon_0 \chi^{(2)} E_1^2 \quad (\text{SHG}),$$

$$P(2\omega_2) = \epsilon_0 \chi^{(2)} E_2^2 \quad (\text{SHG}),$$

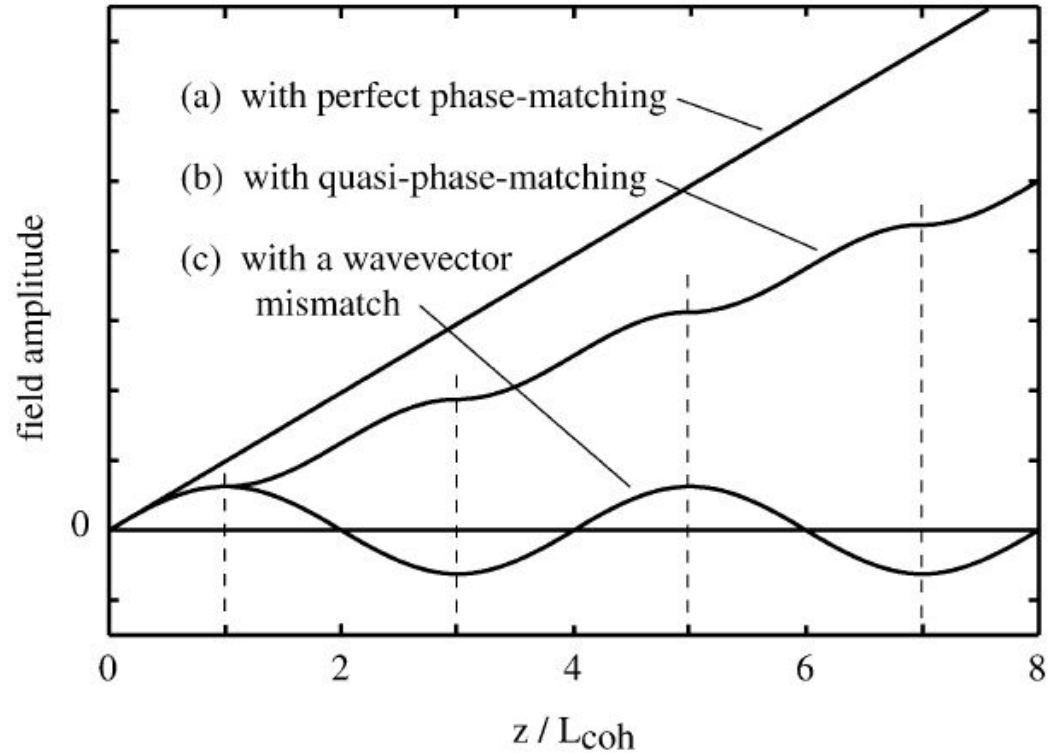
$$P(\omega_1 + \omega_2) = 2\epsilon_0 \chi^{(2)} E_1 E_2 \quad (\text{SFG}),$$

$$P(\omega_1 - \omega_2) = 2\epsilon_0 \chi^{(2)} E_1 E_2^* \quad (\text{DFG}),$$

$$P(0) = 2\epsilon_0 \chi^{(2)} (E_1 E_1^* + E_2 E_2^*) \quad (\text{OR}).$$



Eficiencia del proceso paramétrico: *phase matching*



Óptica no lineal. Procesos $\chi^{(3)}$

$$P(\omega_1) = \epsilon_0 \chi^{(3)} (3E_1 E_1^* + 6E_2 E_2^* + 6E_3 E_3^*) E_1,$$

$$P(\omega_2) = \epsilon_0 \chi^{(3)} (6E_1 E_1^* + 3E_2 E_2^* + 6E_3 E_3^*) E_2,$$

$$P(\omega_3) = \epsilon_0 \chi^{(3)} (6E_1 E_1^* + 6E_2 E_2^* + 3E_3 E_3^*) E_3,$$

$$P(3\omega_1) = \epsilon_0 \chi^{(3)} E_1^3, \quad P(3\omega_2) = \epsilon_0 \chi^{(3)} E_2^3, \quad P(3\omega_3) = \epsilon_0 \chi^{(3)} E_3^3,$$

$$P(\omega_1 + \omega_2 + \omega_3) = 6\epsilon_0 \chi^{(3)} E_1 E_2 E_3,$$

$$P(\omega_1 + \omega_2 - \omega_3) = 6\epsilon_0 \chi^{(3)} E_1 E_2 E_3^*,$$

$$P(\omega_1 + \omega_3 - \omega_2) = 6\epsilon_0 \chi^{(3)} E_1 E_3 E_2^*,$$

$$P(\omega_2 + \omega_3 - \omega_1) = 6\epsilon_0 \chi^{(3)} E_2 E_3 E_1^*,$$

$$P(2\omega_1 + \omega_2) = 3\epsilon_0 \chi^{(3)} E_1^2 E_2,$$

$$P(2\omega_2 + \omega_1) = 3\epsilon_0 \chi^{(3)} E_2^2 E_1,$$

$$P(2\omega_3 + \omega_1) = 3\epsilon_0 \chi^{(3)} E_3^2 E_1,$$

$$P(2\omega_1 - \omega_2) = 3\epsilon_0 \chi^{(3)} E_1^2 E_2^*,$$

$$P(2\omega_2 - \omega_1) = 3\epsilon_0 \chi^{(3)} E_2^2 E_1^*,$$

$$P(2\omega_3 - \omega_1) = 3\epsilon_0 \chi^{(3)} E_3^2 E_1^*,$$

$$P(2\omega_1 + \omega_3) = 3\epsilon_0 \chi^{(3)} E_1^2 E_3,$$

$$P(2\omega_2 + \omega_3) = 3\epsilon_0 \chi^{(3)} E_2^2 E_3,$$

$$P(2\omega_3 + \omega_2) = 3\epsilon_0 \chi^{(3)} E_3^2 E_2,$$

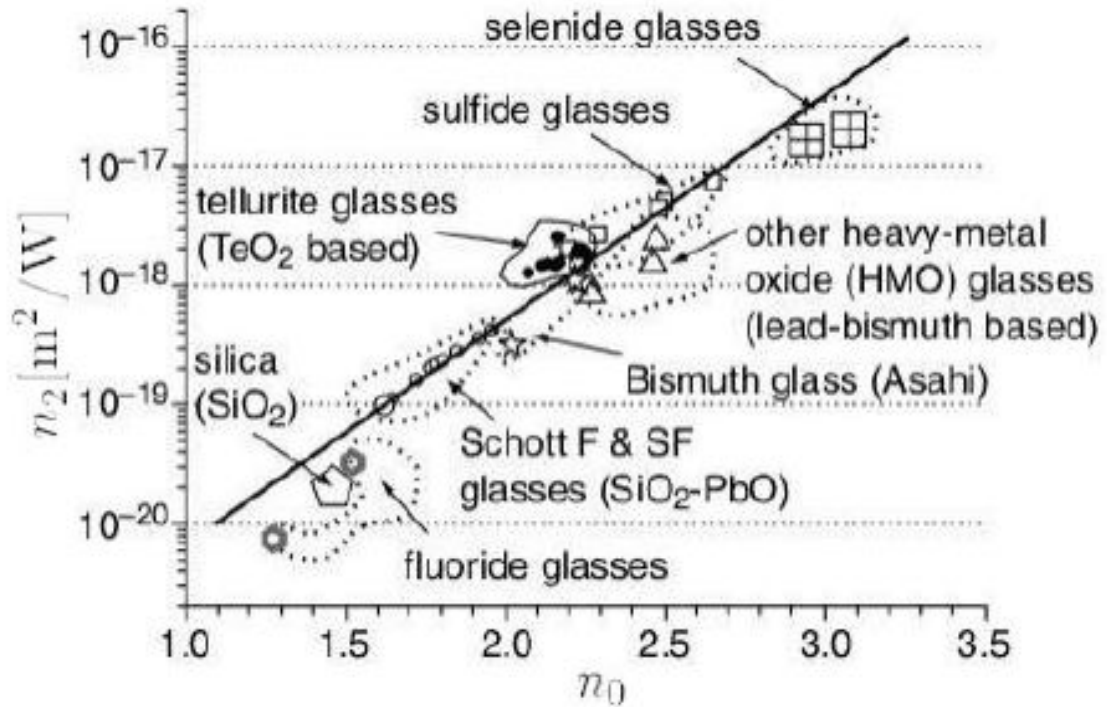
$$P(2\omega_1 - \omega_3) = 3\epsilon_0 \chi^{(3)} E_1^2 E_3^*,$$

$$P(2\omega_2 - \omega_3) = 3\epsilon_0 \chi^{(3)} E_2^2 E_3^*,$$

$$P(2\omega_3 - \omega_2) = 3\epsilon_0 \chi^{(3)} E_3^2 E_2^*$$

Entrada: E_1, E_2, E_3
¡44 términos!

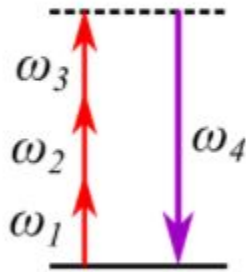
Índice de refracción no lineal (n_2)



Procesos paramétricos $\chi^{(3)}$: THG, Four-wave mixing

$$\omega_4 = \omega_1 + \omega_2 + \omega_3$$

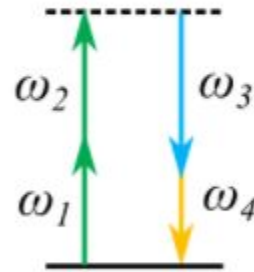
$$\omega_1 = \omega_2 = \omega_3$$



Generación de tercer armónico

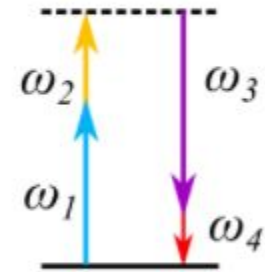
$$\omega_3 + \omega_4 = \omega_1 + \omega_2$$

$$\omega_1 = \omega_2$$



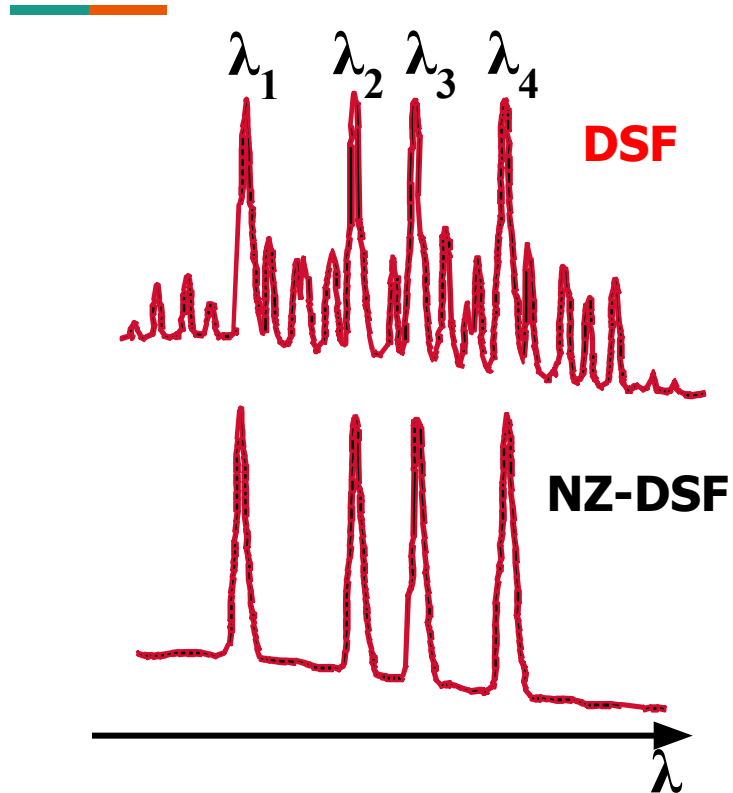
FWM Degenerado

$$\omega_1 \neq \omega_2$$



FWM No-Degenerado

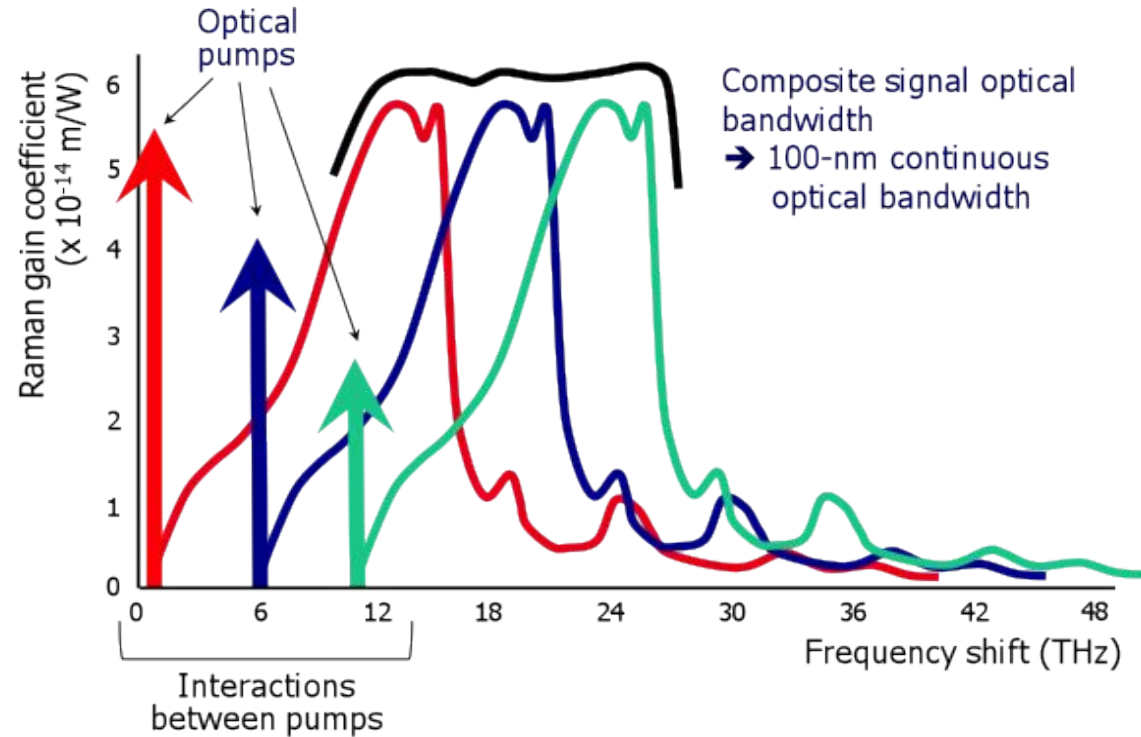
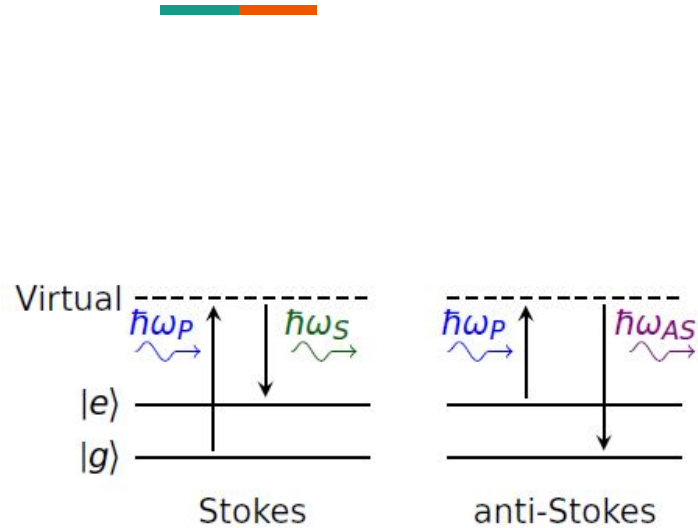
Four-wave mixing en fibras ópticas



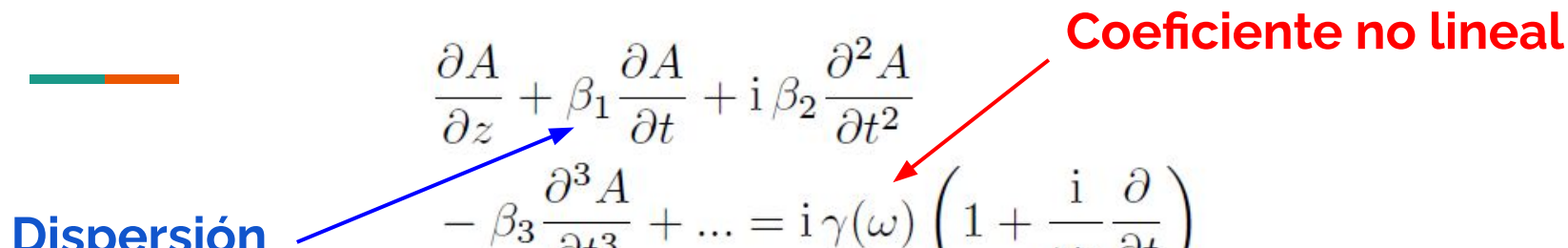
Dispersion-Shifted Fiber: dispersión "nula"
Fibra Nonzero-DSF: baja dispersión

La dispersión destruye
el *phase matching*

Procesos no paramétricos: scattering de Raman



Ecuación no lineal de Schrödinger generalizada



Dispersión

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + i \beta_2 \frac{\partial^2 A}{\partial t^2} - \beta_3 \frac{\partial^3 A}{\partial t^3} + \dots = i \gamma(\omega) \left(1 + \frac{i}{\omega_0} \frac{\partial}{\partial t} \right) \times \left(A(z, t) \int_{-\infty}^{\infty} R(t') |A(z, t - t')|^2 dt' \right),$$

Coeficiente no lineal

Respuesta Raman (retardada)

$$R(t) = (1 - f_R) \delta(t) + f_R h_R(t),$$

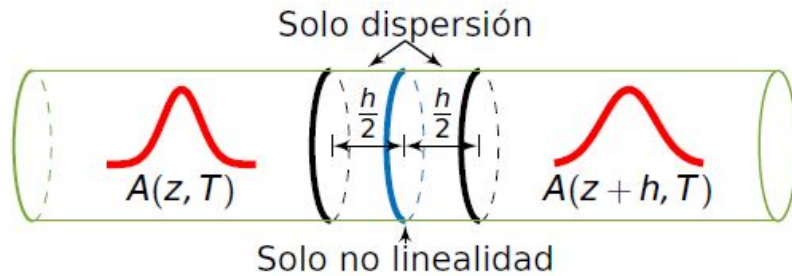
$$h_R(t) = (f_a + f_c) h_a(t) + f_b h_b(t),$$

$$h_a(t) = \tau_1 (\tau_1^{-2} + \tau_2^{-2}) e^{-t/\tau_2} \sin(t/\tau_1),$$

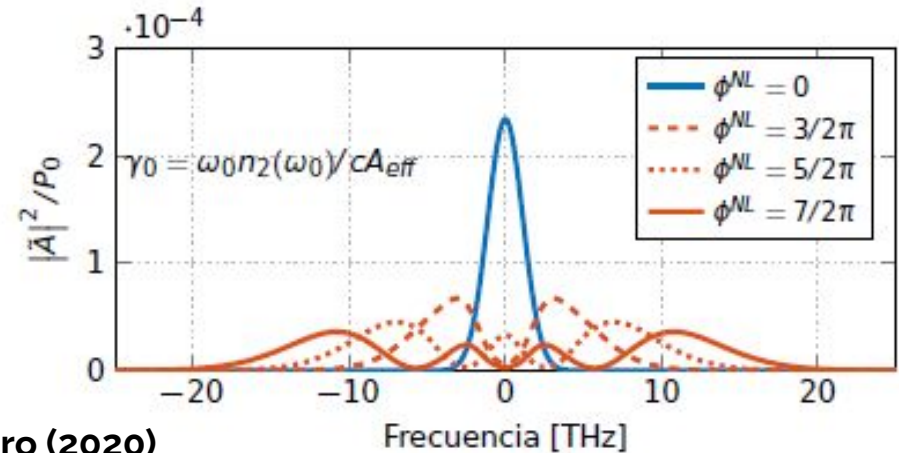
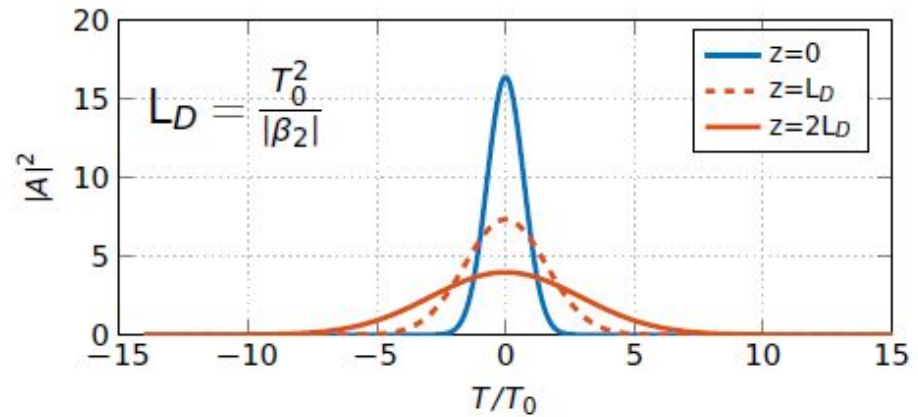
$$h_b(t) = [(2\tau_b - t) / \tau_b^2] e^{-t/\tau_b},$$

Dispersión (GVD) y automodulación de fase (SPM)

Split-step Fourier



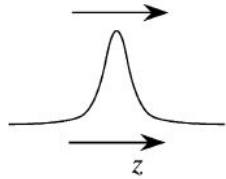
$$L_D = \frac{T_0^2}{|\beta_2|} \quad L_{NL} = \frac{1}{\gamma P_0}$$



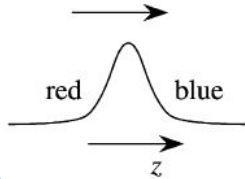
Solitón fundamental: GVD vs. SPM



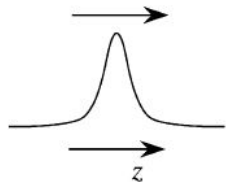
GVD



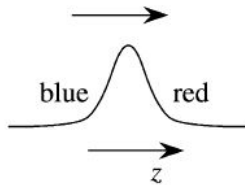
$$k_2 < 0$$



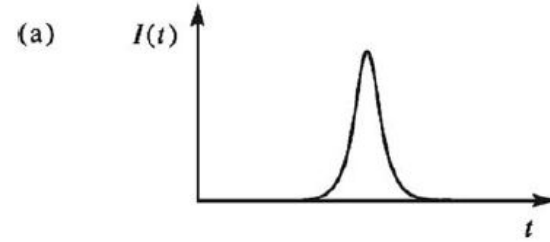
Régimen anómalo



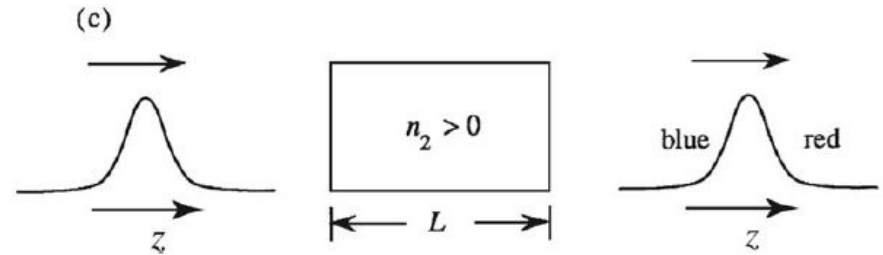
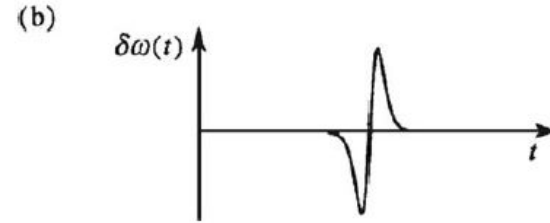
$$k_2 > 0$$



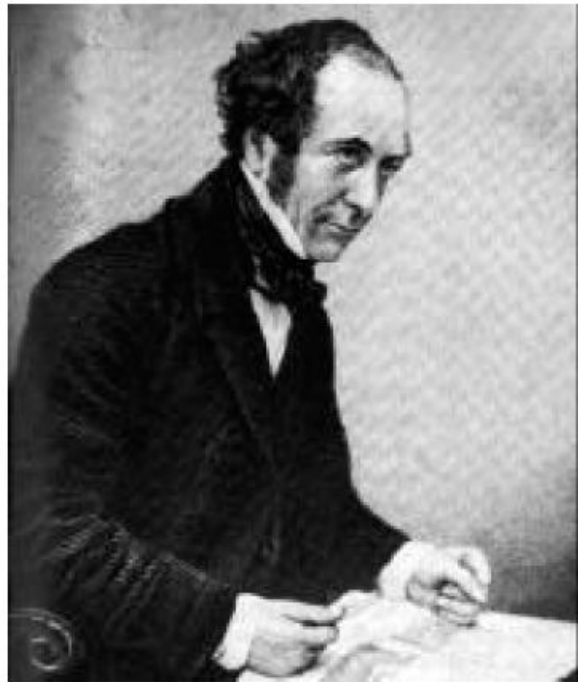
Régimen normal



SPM



Soliton: primera observación

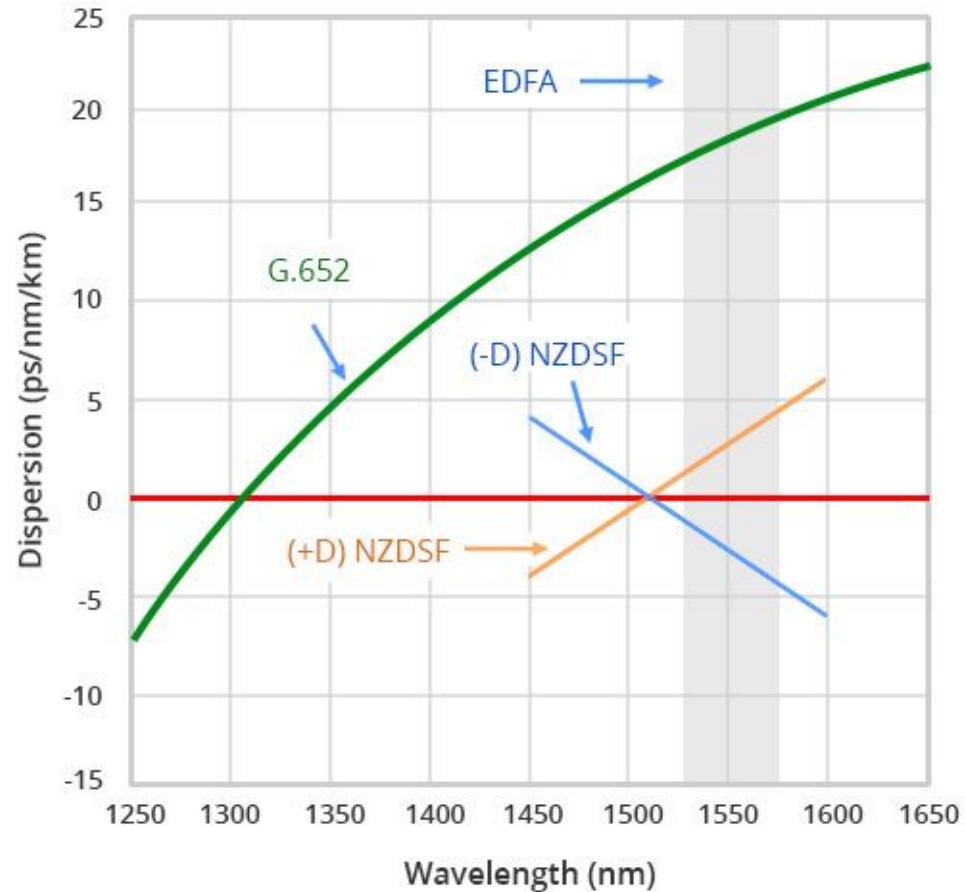


"I was observing the motion of a boat which was rapidly drawn along a narrow channel by a pair of horses, when the boat suddenly stopped - not so the mass of water in the channel which it had put in motion; it accumulated round the prow of the vessel in a state of violent agitation, then suddenly leaving it behind, rolled forward with great velocity, assuming the form of a large solitary elevation, a rounded, smooth and well-defined heap of water, which continued its course along the channel apparently without change of form or diminution of speed. I followed it on horseback, and overtook it still rolling on at a rate of some eight or nine miles an hour, preserving its original figure some thirty feet long and a foot to a foot and a half in height. Its height gradually diminished, and after a chase of one or two miles I lost it in the windings of the channel. Such, in the month of August 1834, was my first chance interview with that singular and beautiful phenomenon which I have called the Wave of Translation".

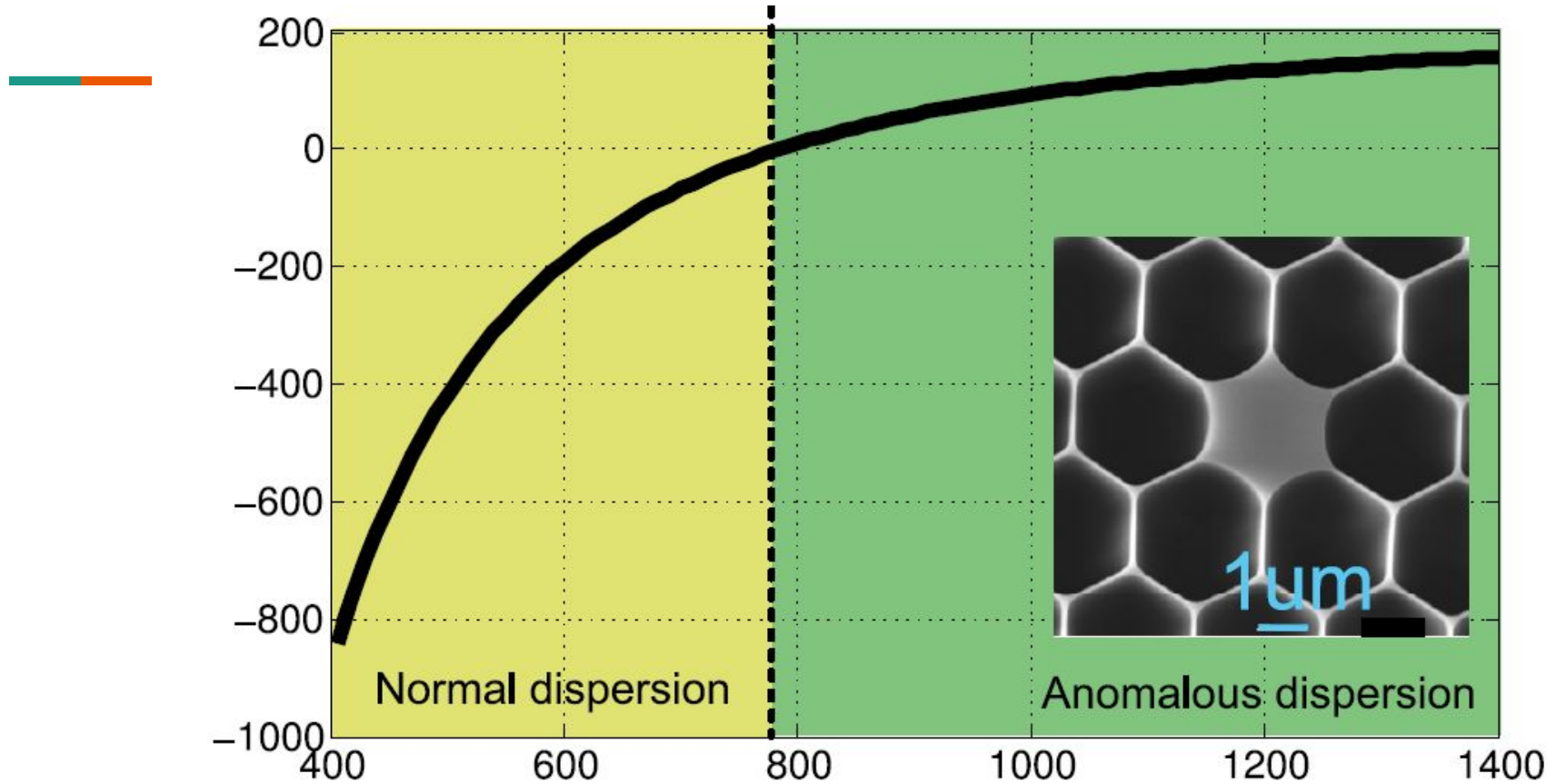
Soliton: reconstruyendo la primera observación



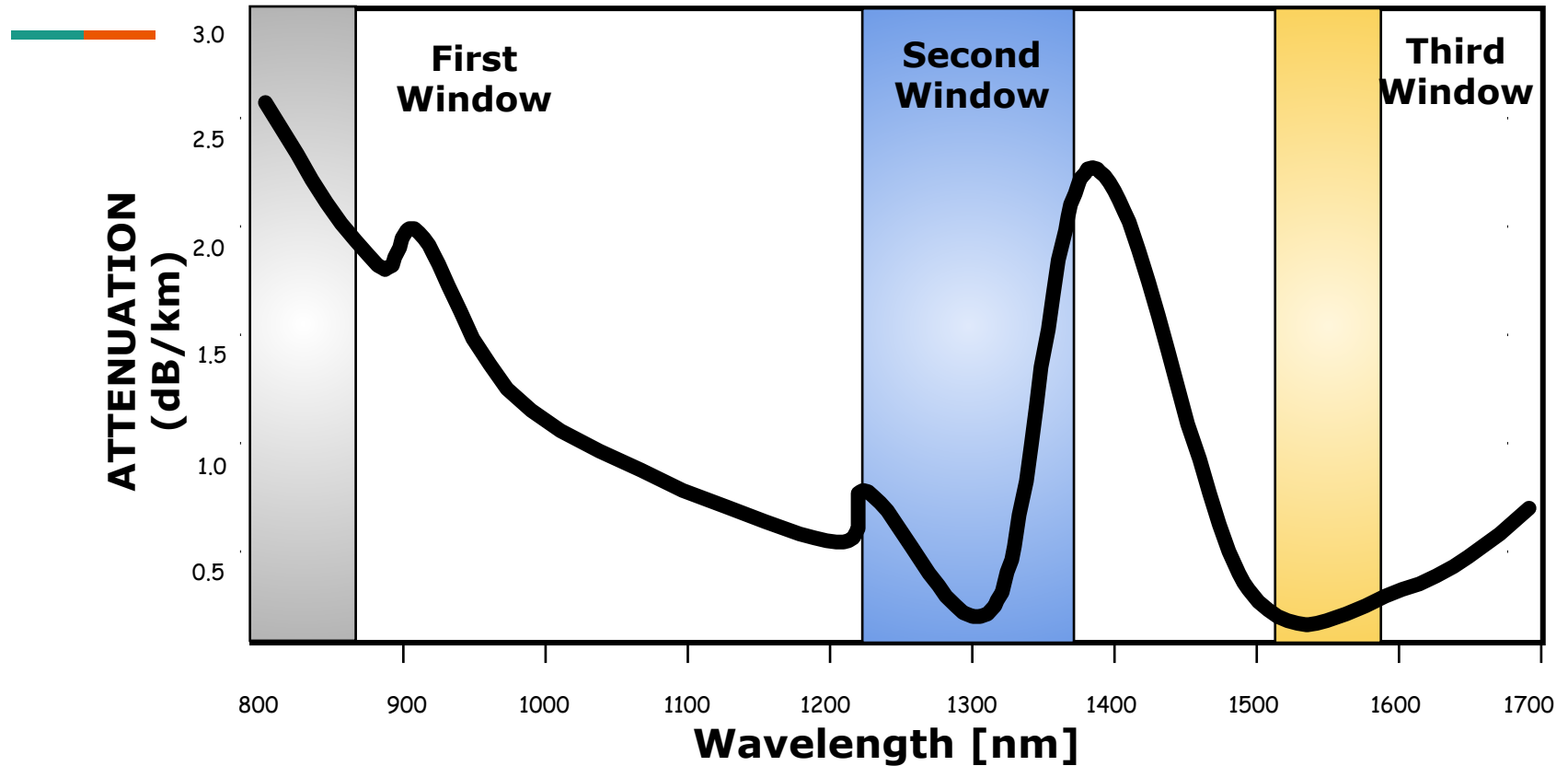
Dispersión de las fibras ópticas



Photonic-crystal fiber (PCF)

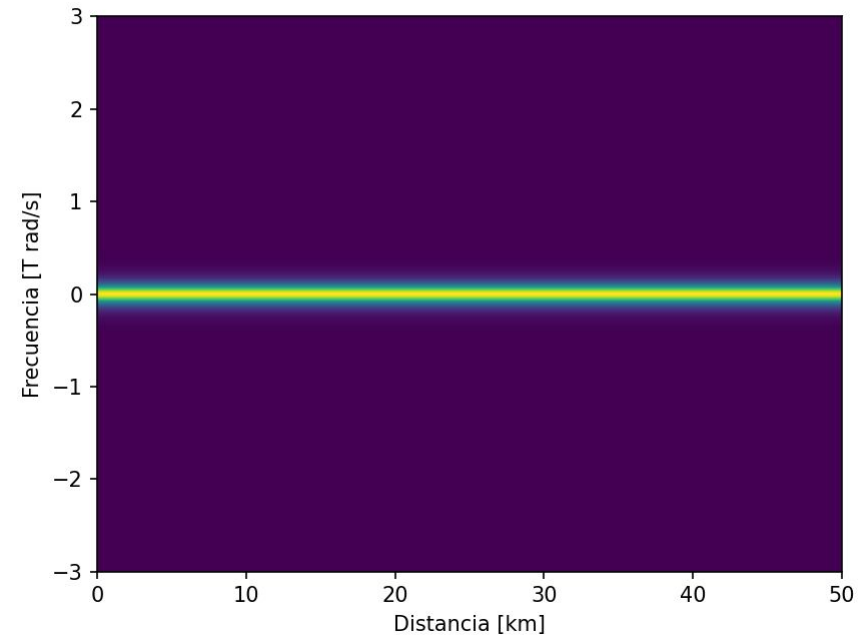
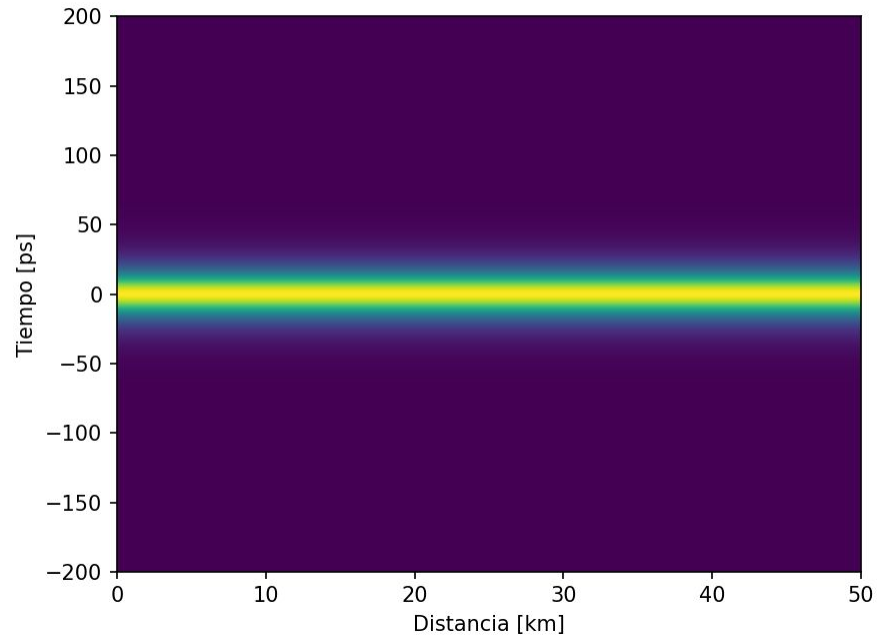


Atenuación/absorción de las fibras ópticas

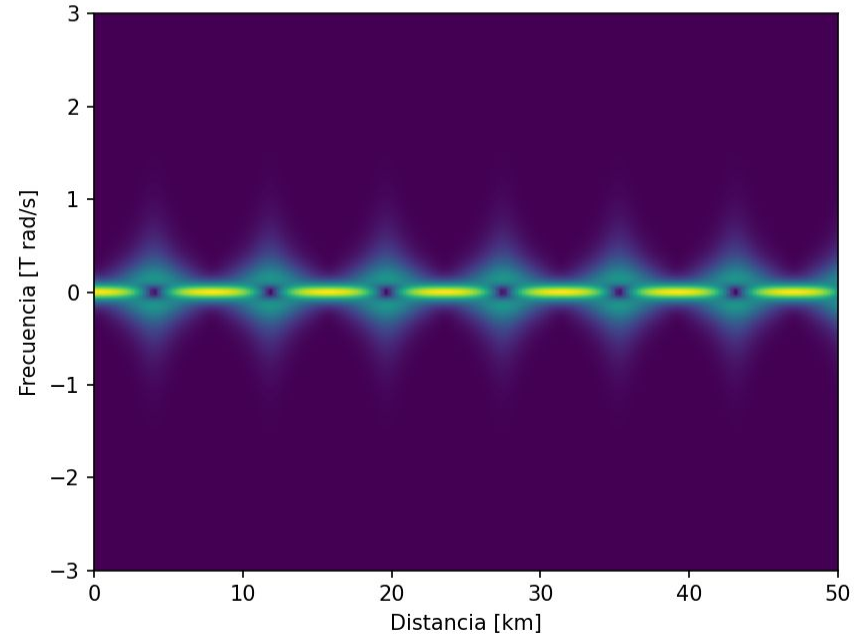
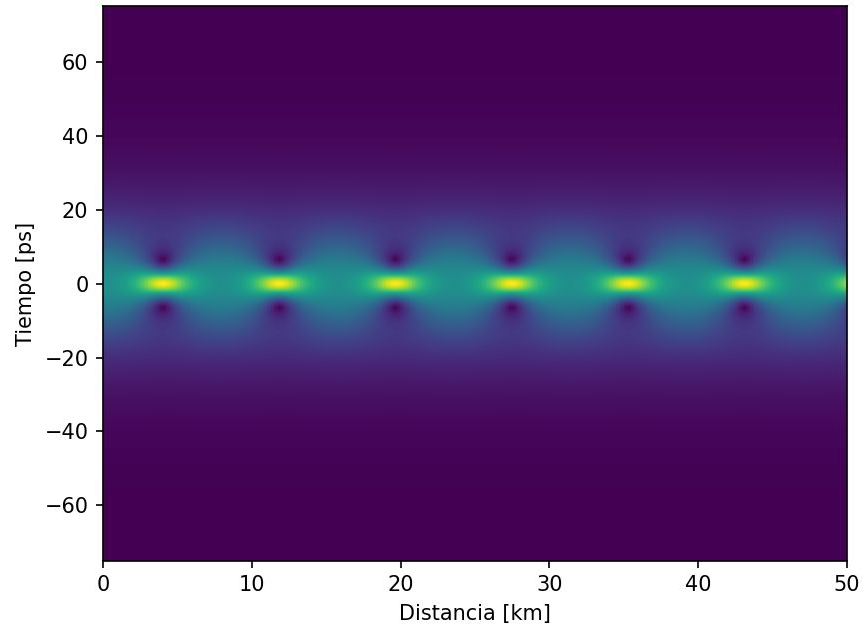


Solitón fundamental

$$L_D = L_{NL}$$

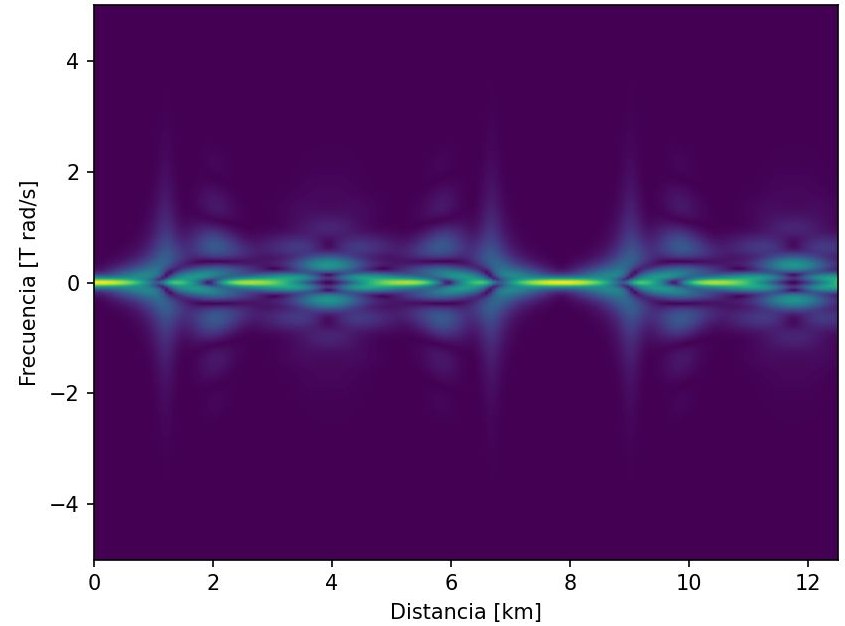
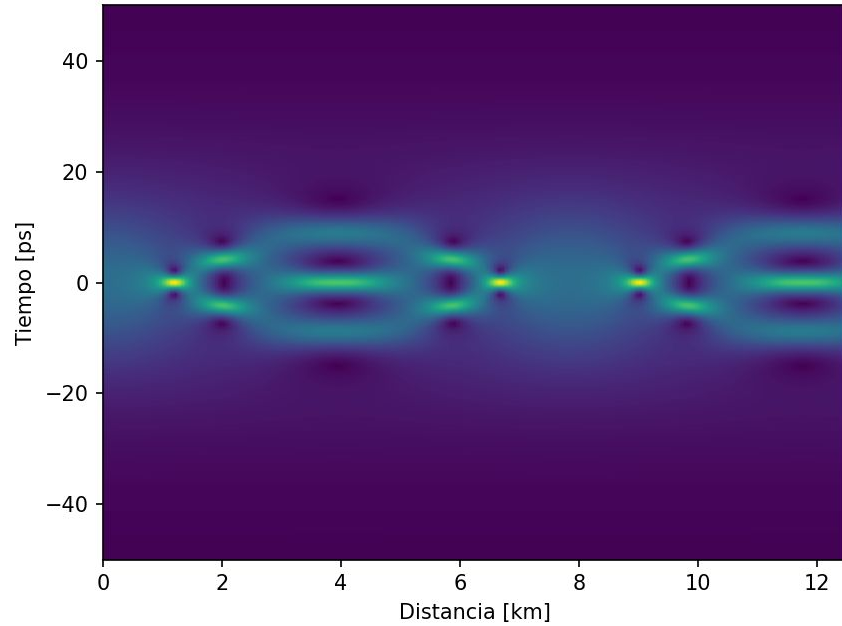


Solitón de orden superior ($N = 2$)



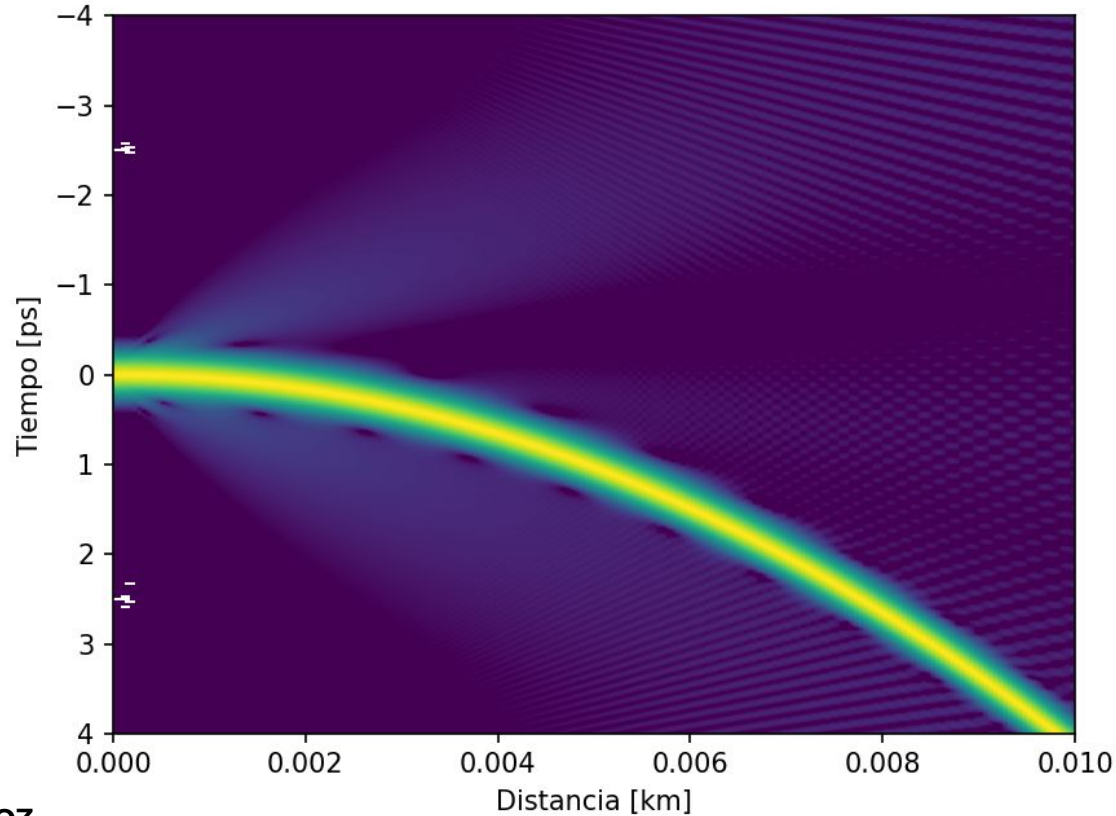
Cortesía: S. Hernandez

Solitón de orden superior ($N = 4$)



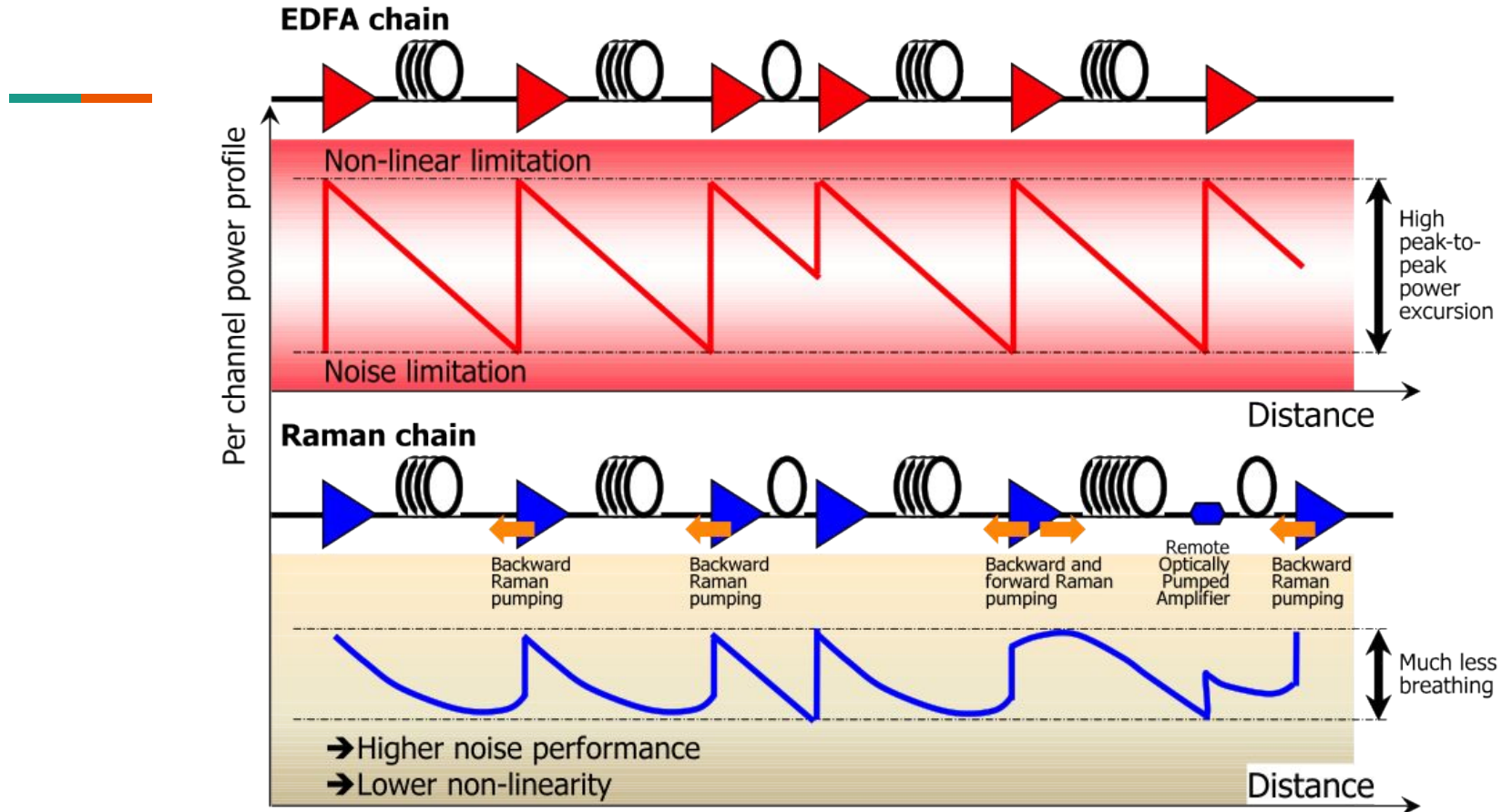
Cortesía: S. Hernandez

Soliton Raman *self-frequency shift*



Cortesía: S. Hernandez

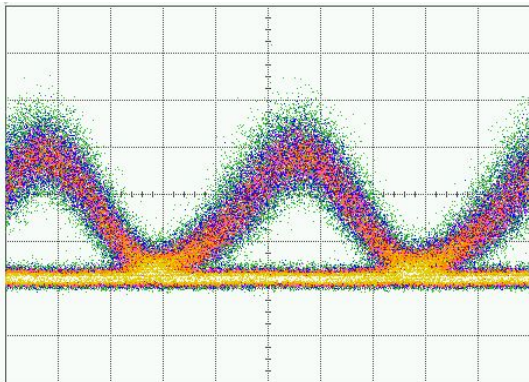
Solitones en un sistema de comunicación



Dispersion-managed solitons

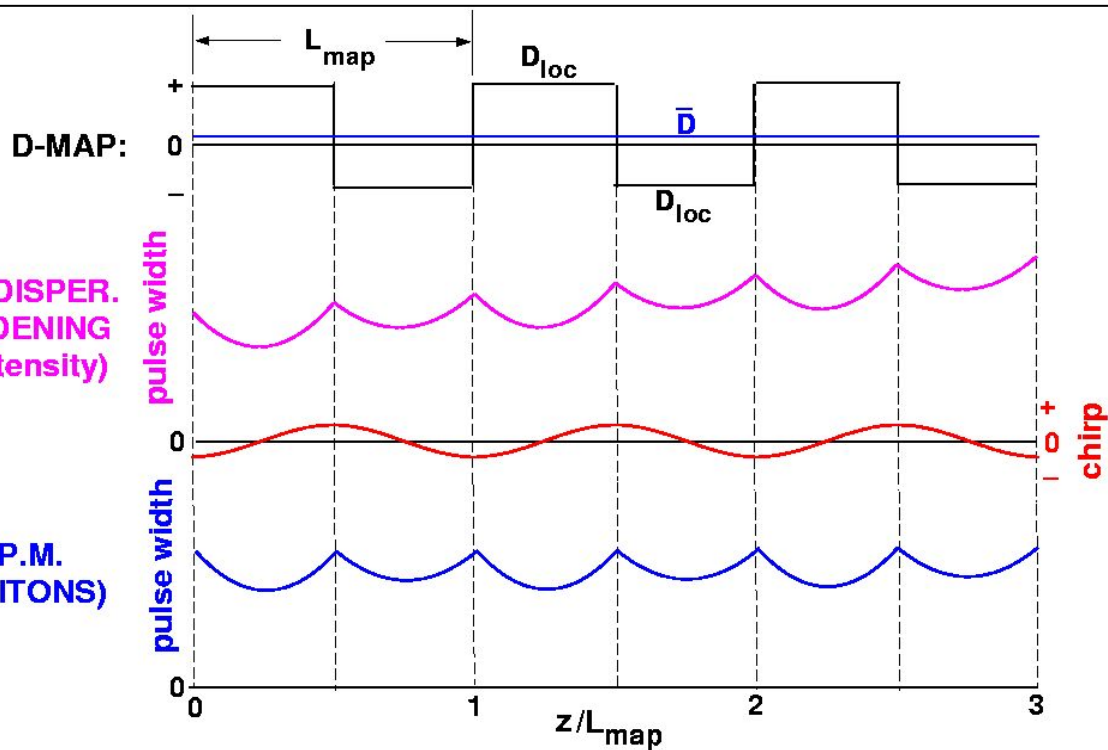


$L = 4000$ km



PURE DISPER.
BROADENING
(low intensity)

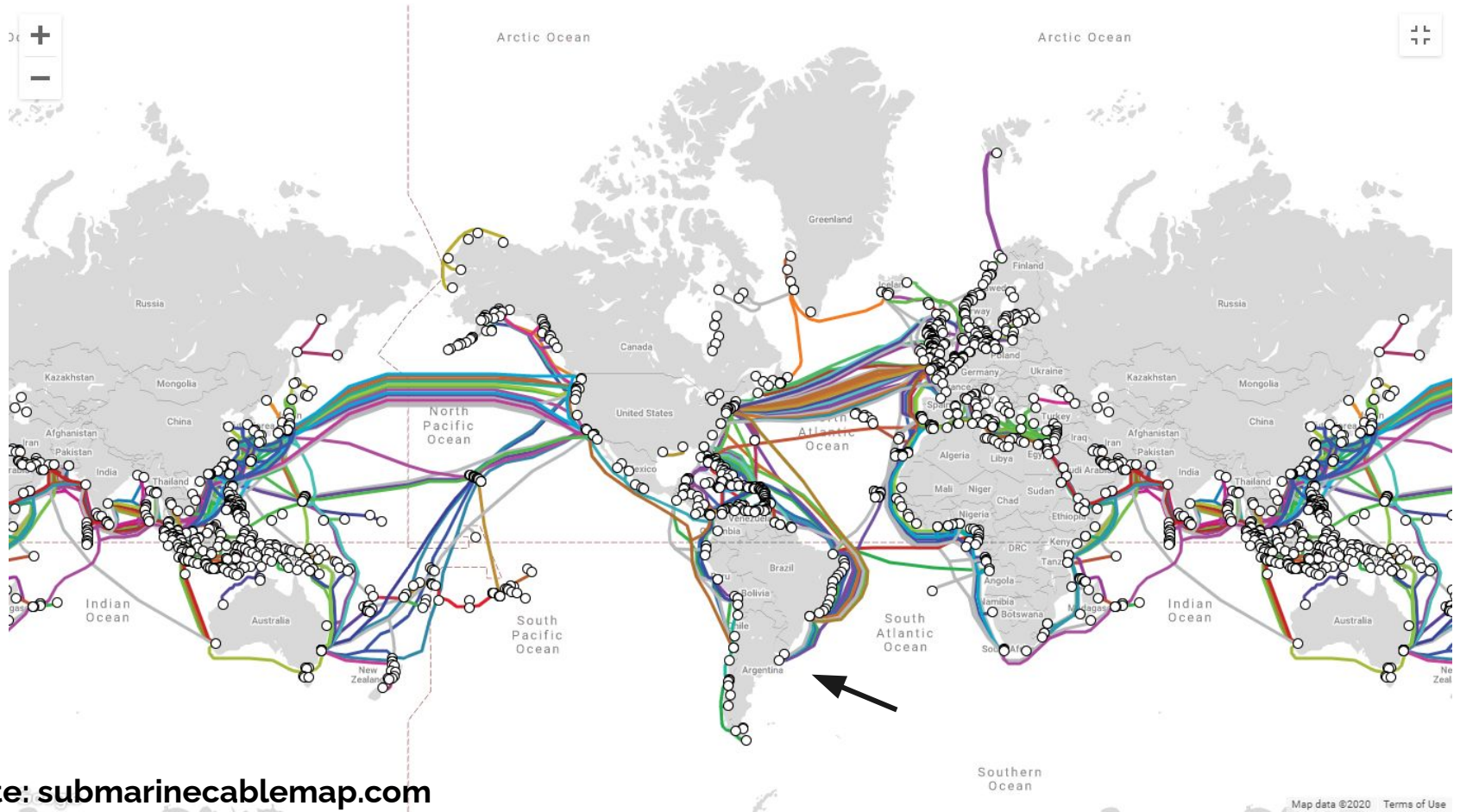
+ S.P.M.
(SOLITONS)



Path-av. SPM and $\bar{D}$ cancel each other's effects exactly over each L_{map}

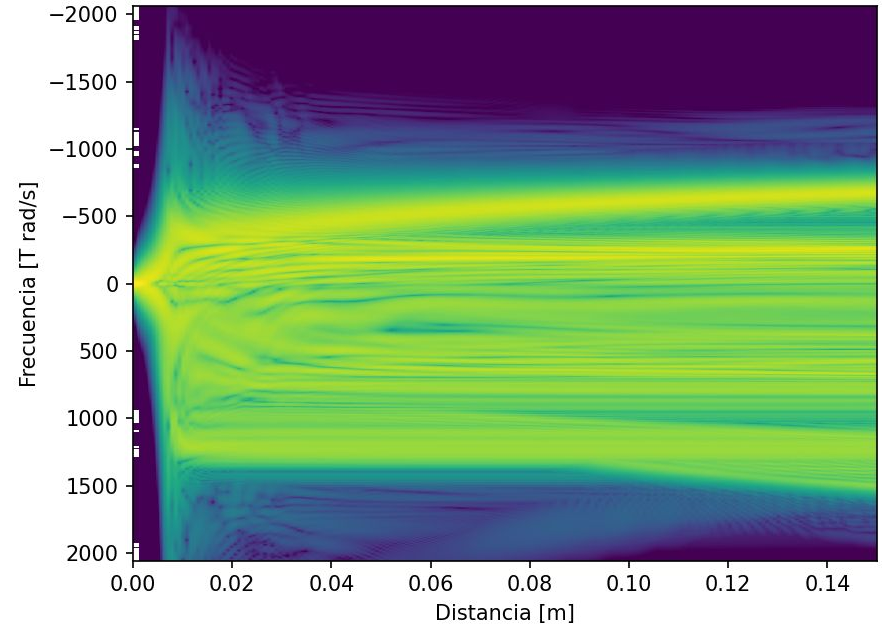
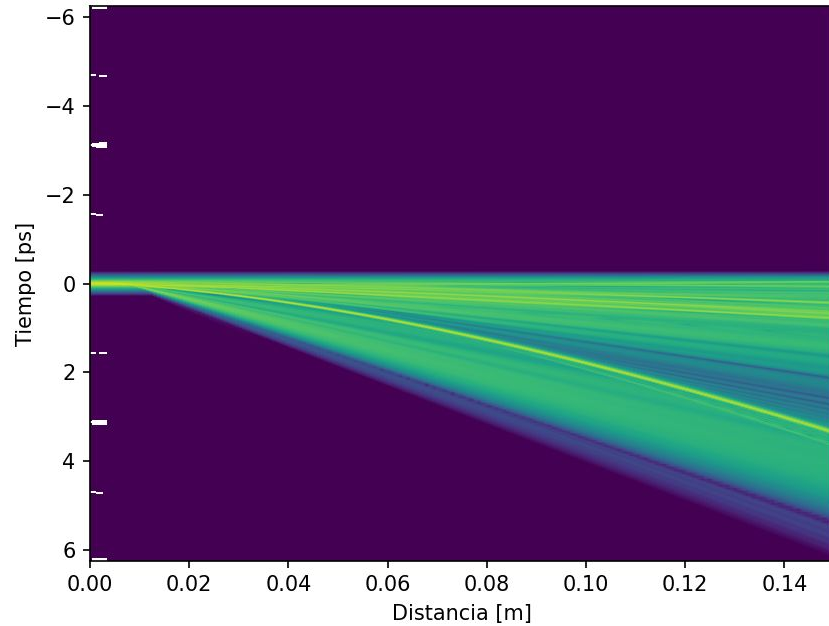
Pulse shape, however, is largely determined by D_{loc} (the dominant term).
Thus, pulse shape tends to be Gaussian.

Cables submarinos de fibra óptica



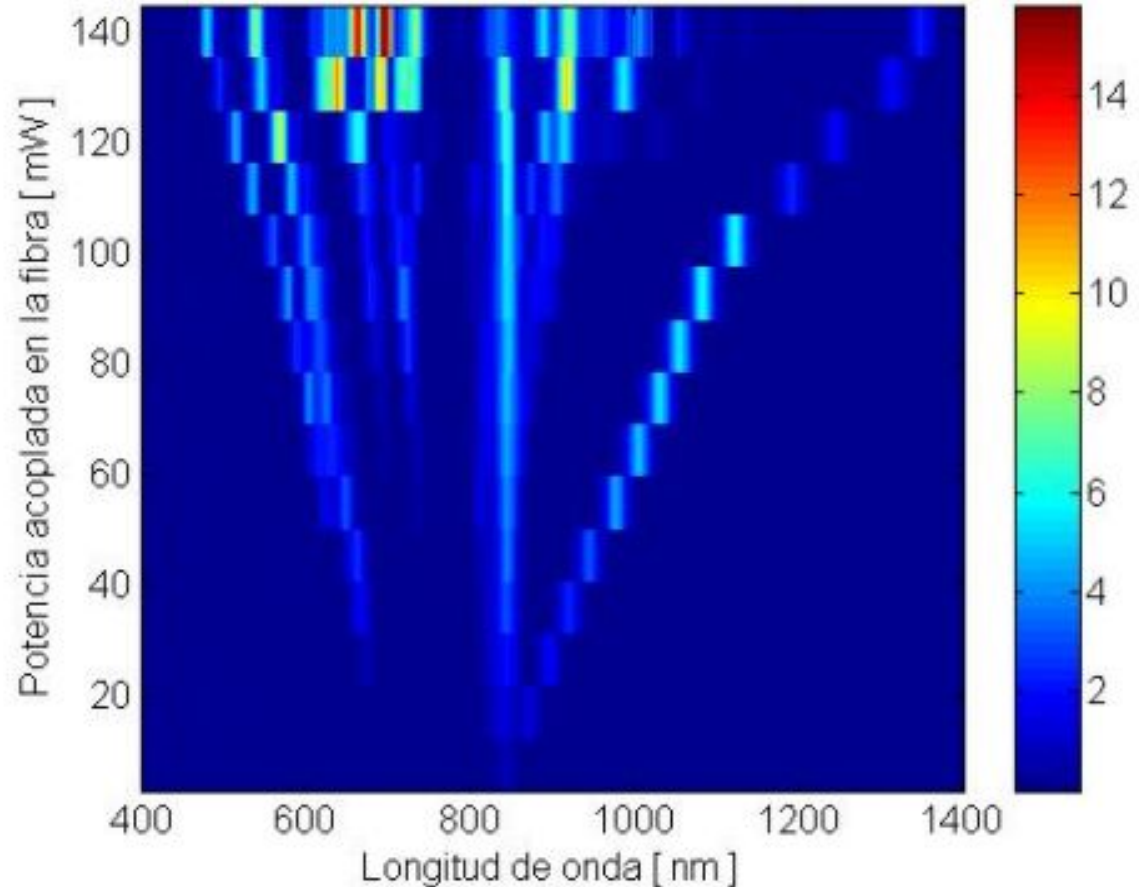
Fuente: submarinecablemap.com

Solitón y generación de supercontinuo

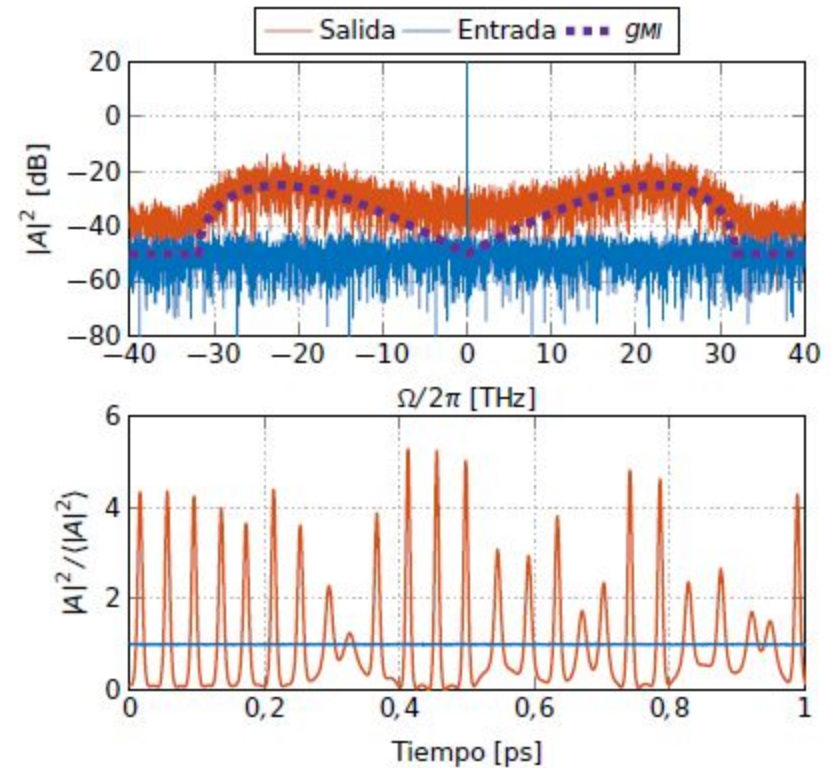
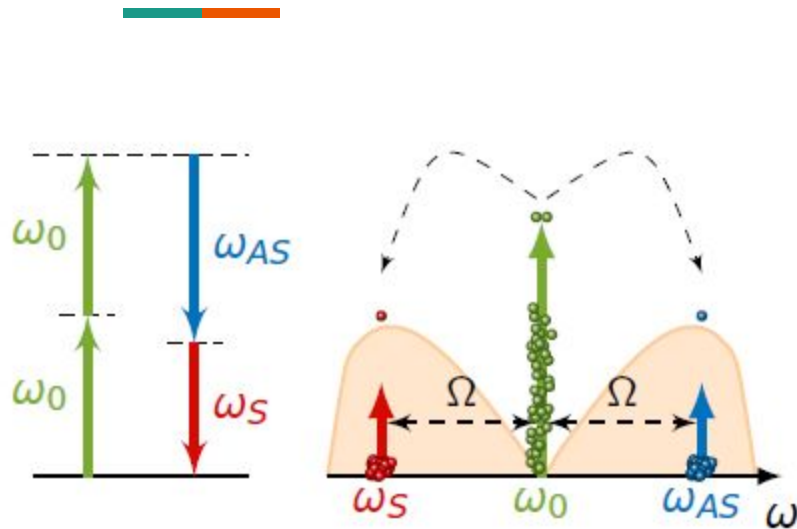


Cortesía: S. Hernandez

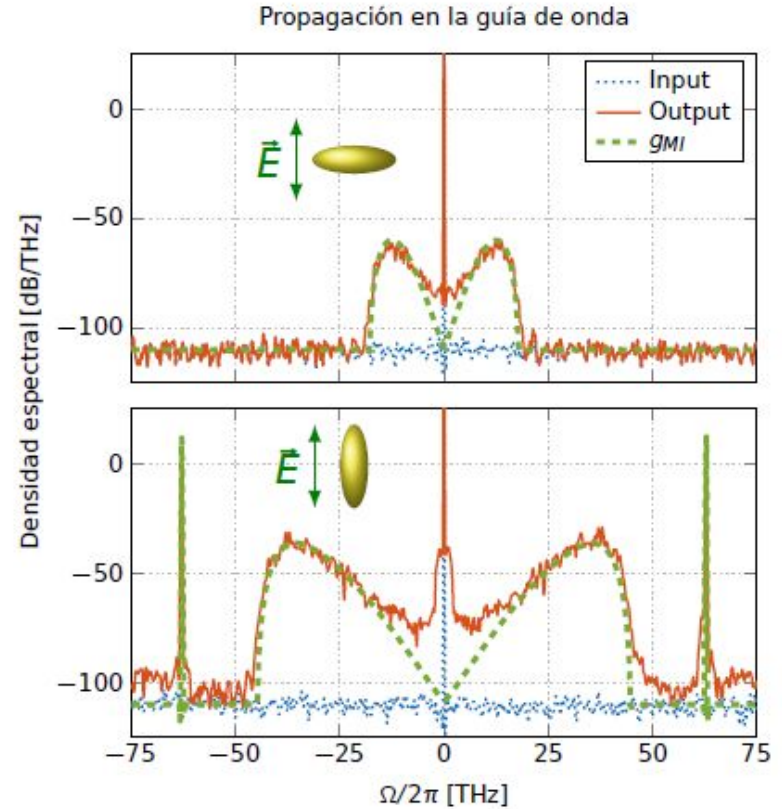
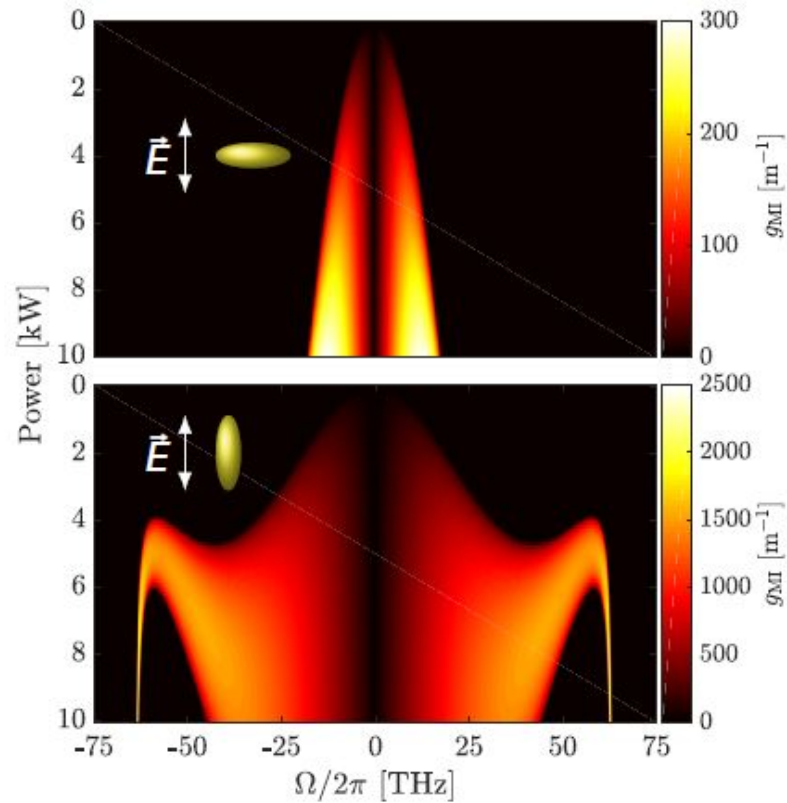
Fuente sintonizable de pulsos cortos (vía Raman)



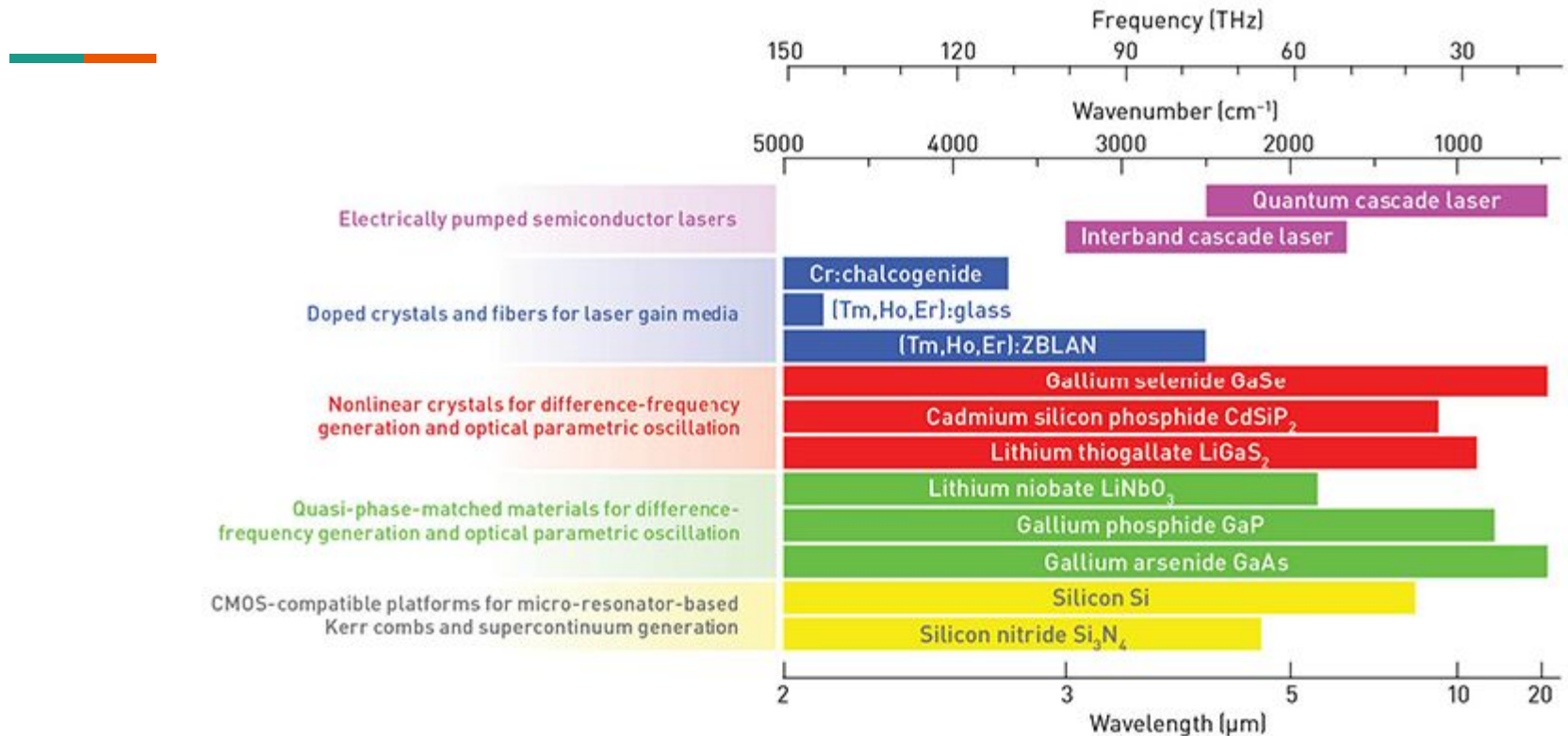
Inestabilidad modulacional (MI)



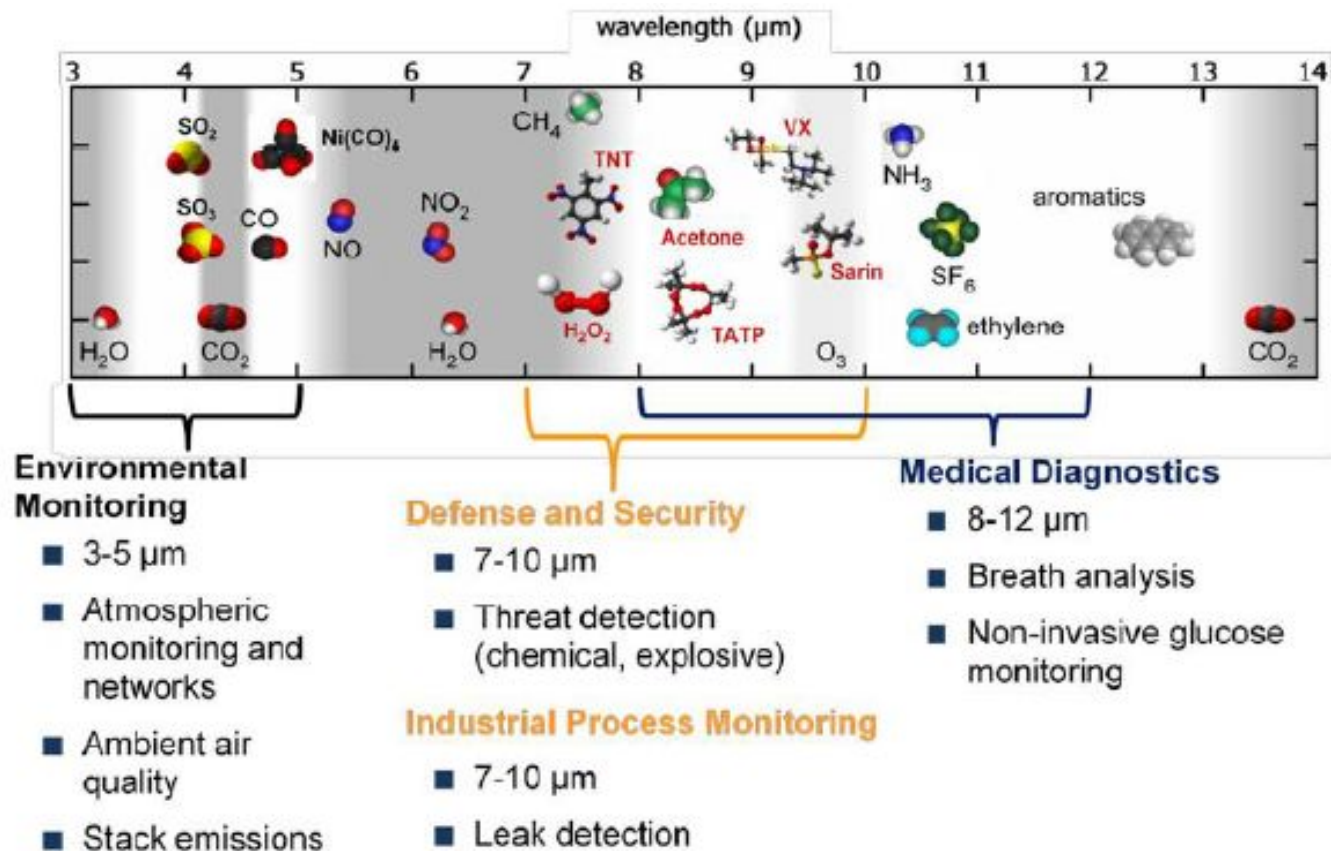
MI en fibras dopadas con *nanorods*



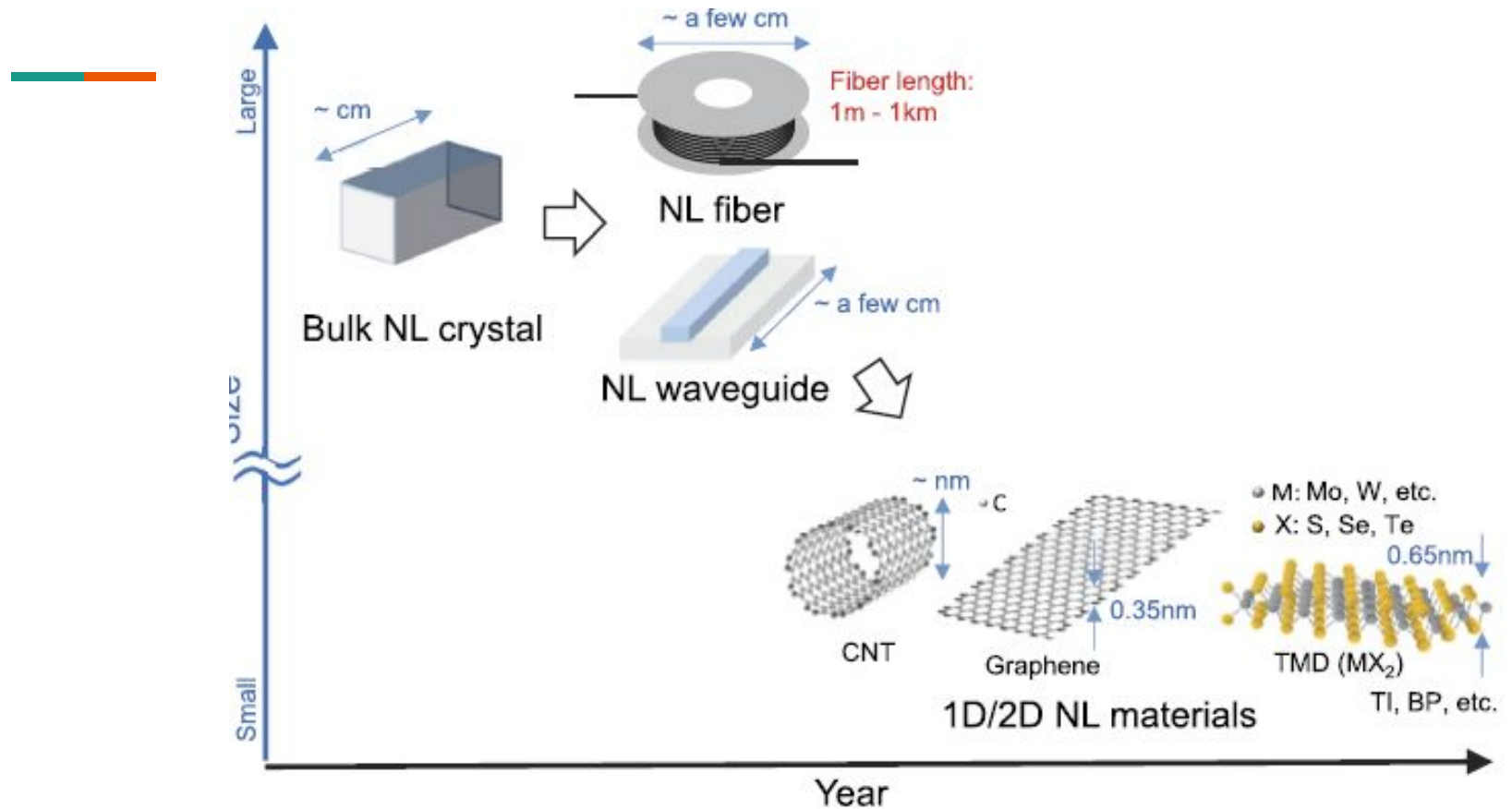
Fuentes en diferentes rangos espectrales



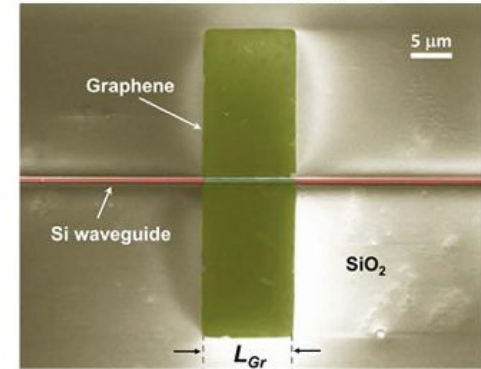
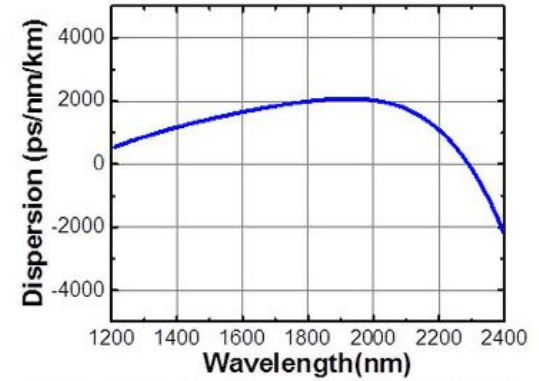
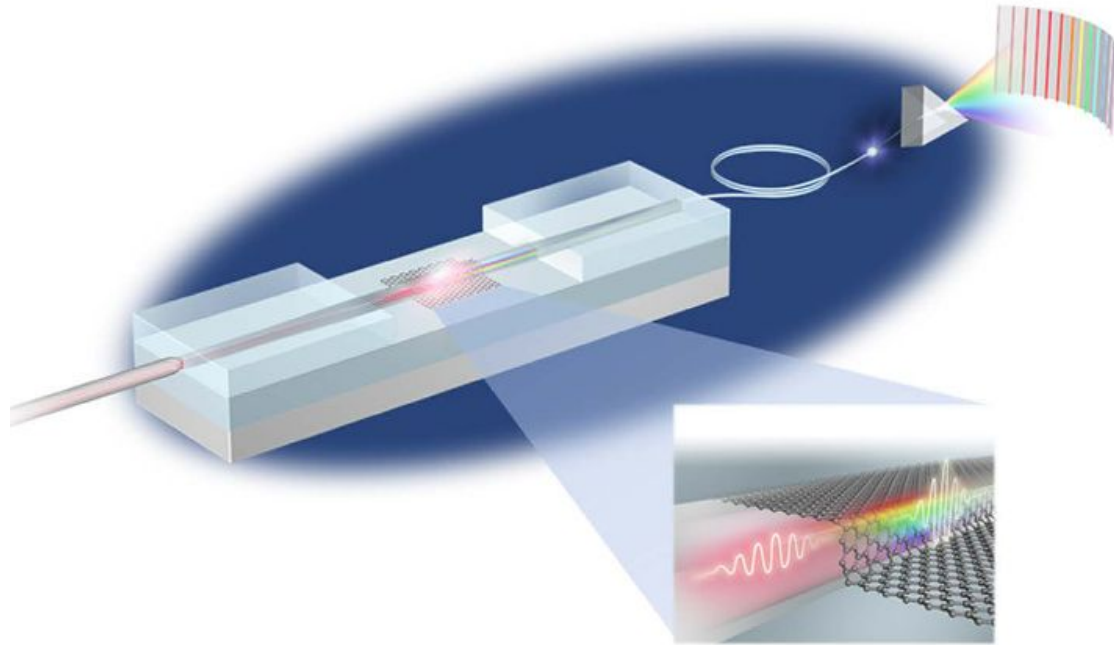
Infrarrojo medio



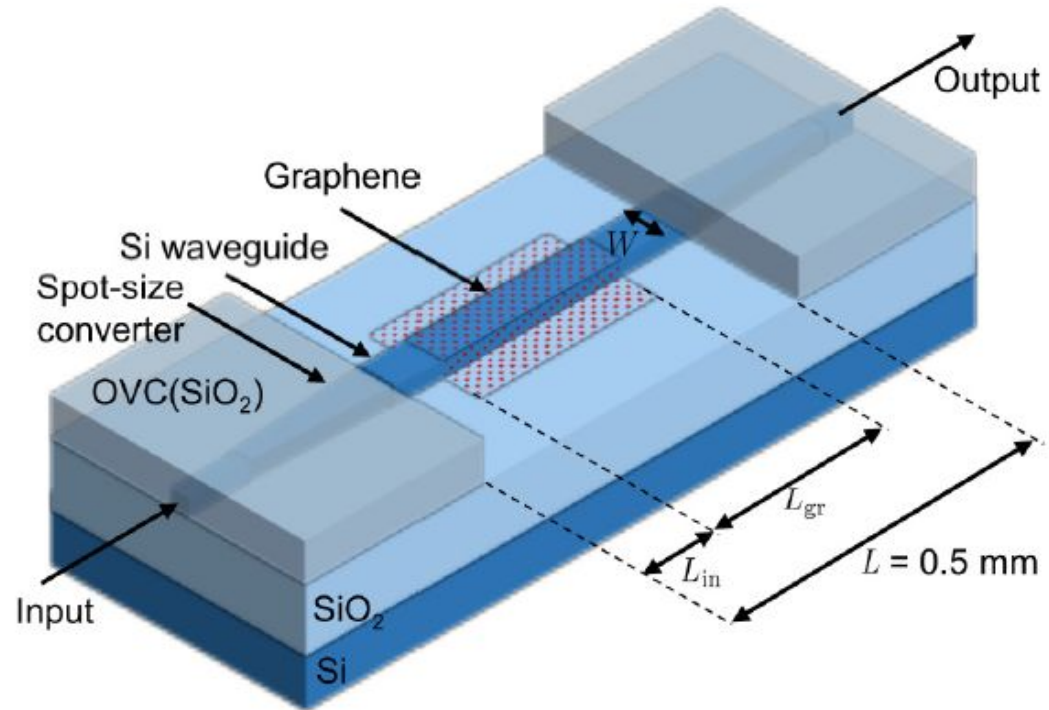
Óptica no lineal: del bulk al 2D



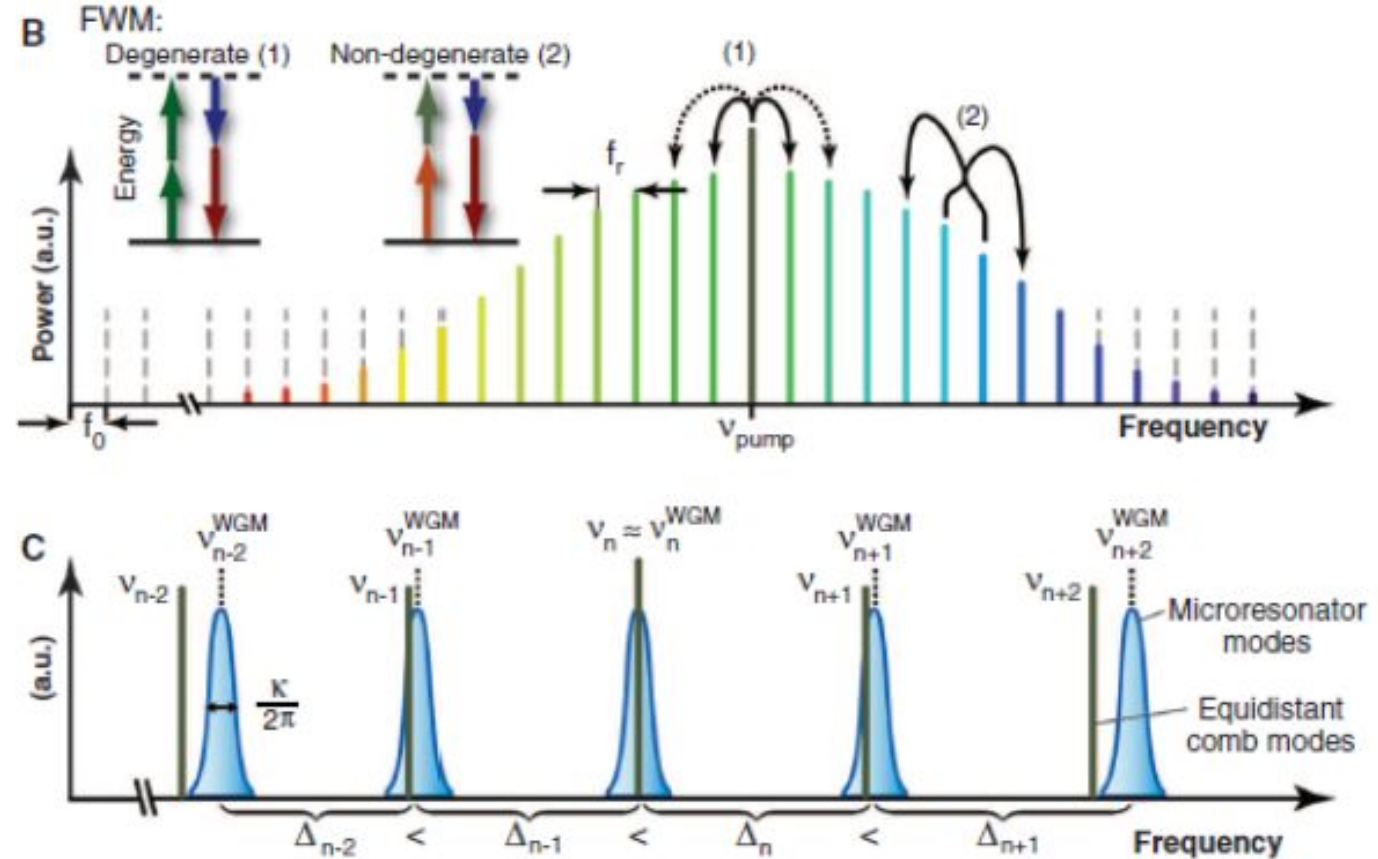
Nanowires “decorados”



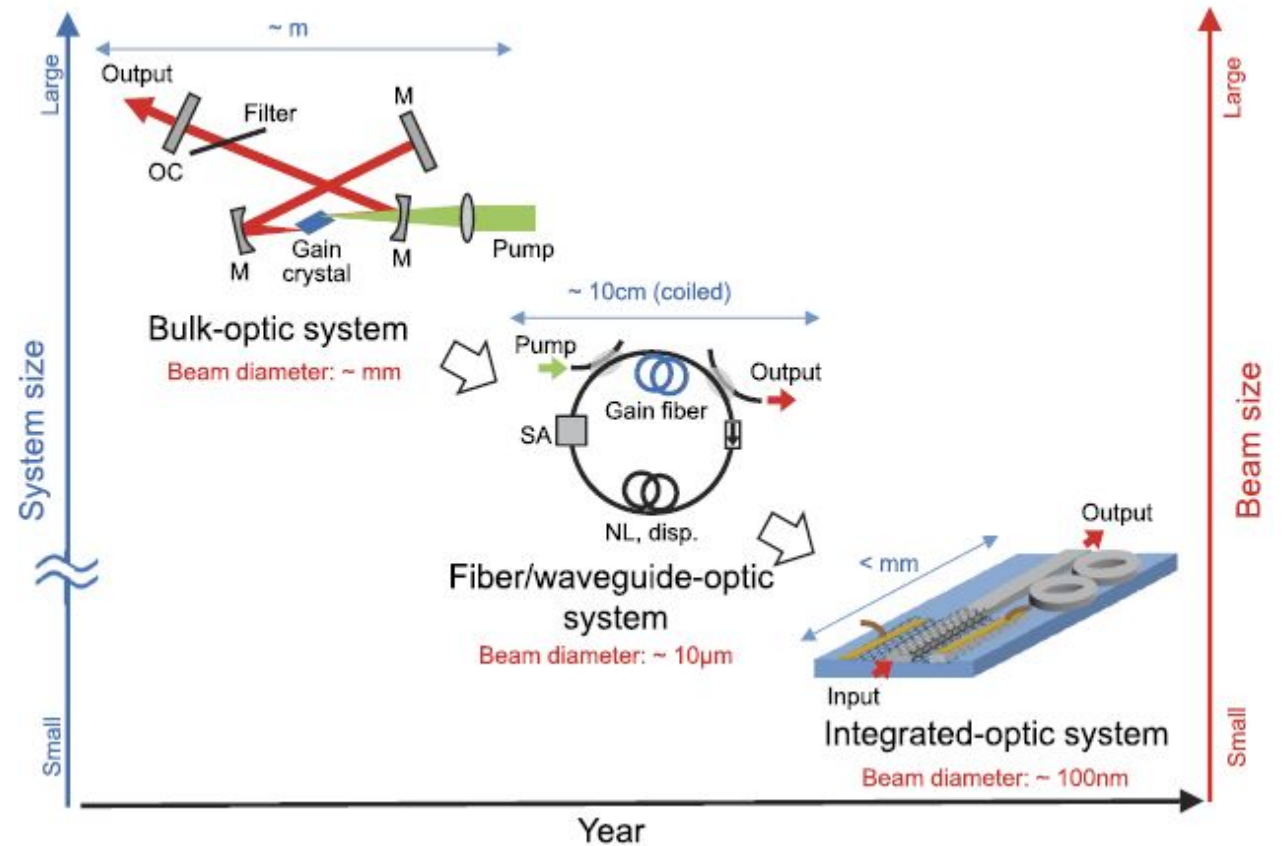
Nanowires “decorados”



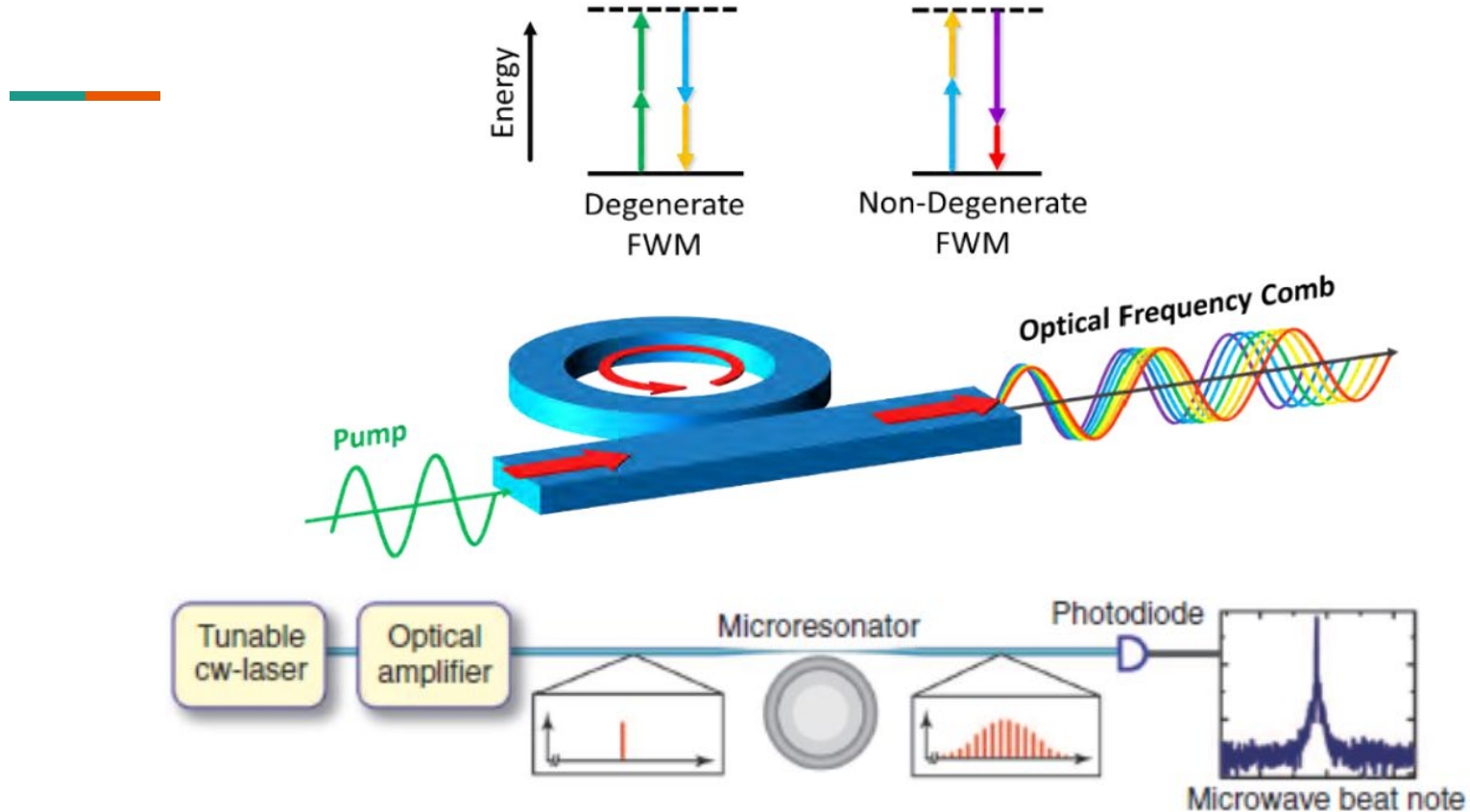
Frequency combs



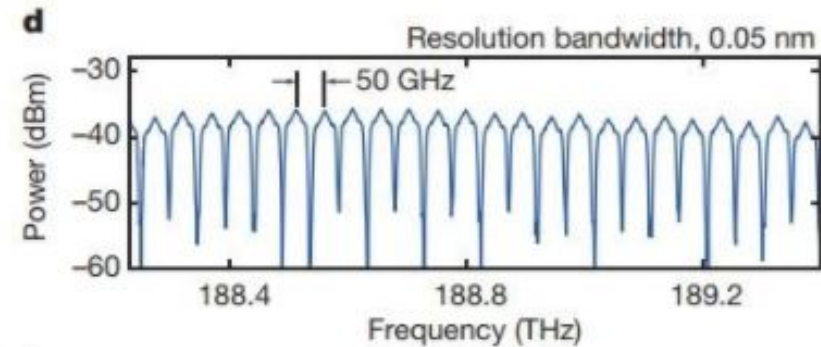
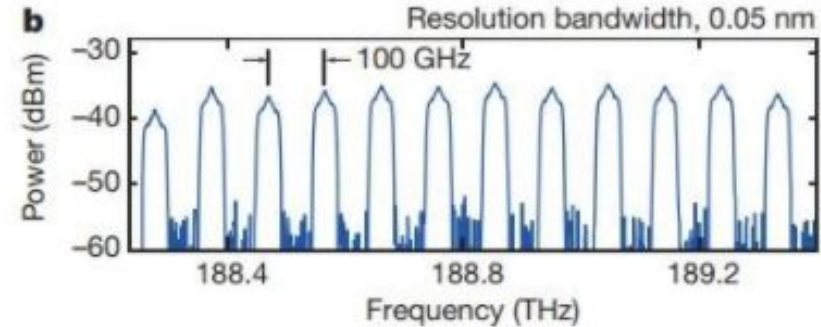
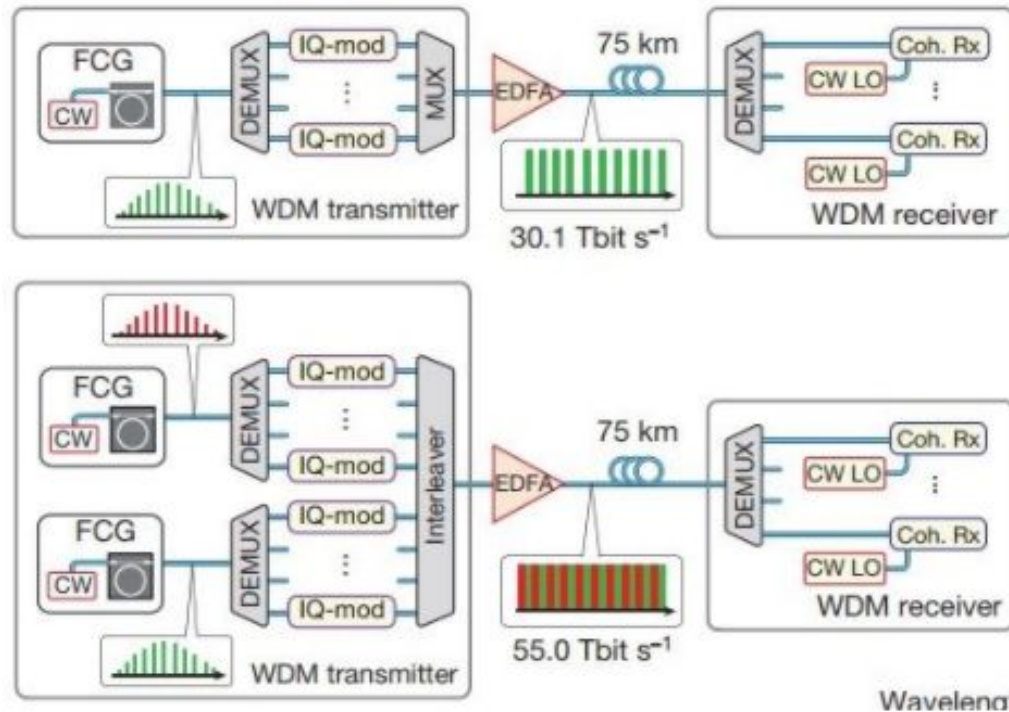
Frequency combs



Frequency combs: Kerr microresonator



Frequency combs: aplicación a sistemas ópticos



Resumiendo: ¿sobre qué estuvimos hablando?



- Óptica no lineal en fibras ópticas. Sistemas de comunicación
- Ecuación no lineal de Schrödinger: propagación no lineal
- Solitones: equilibrio entre no linealidad (SPM) y dispersión. Raman self-frequency shift
- Inestabilidad modulacional
- Generación de supercontinuo: fuentes de luz coherentes en rangos espectrales de interés (mid IR)
- No linealidad en óptica integrada: nanowires y microresonadores
- Frequency combs