Nonlinear Fibre Optics

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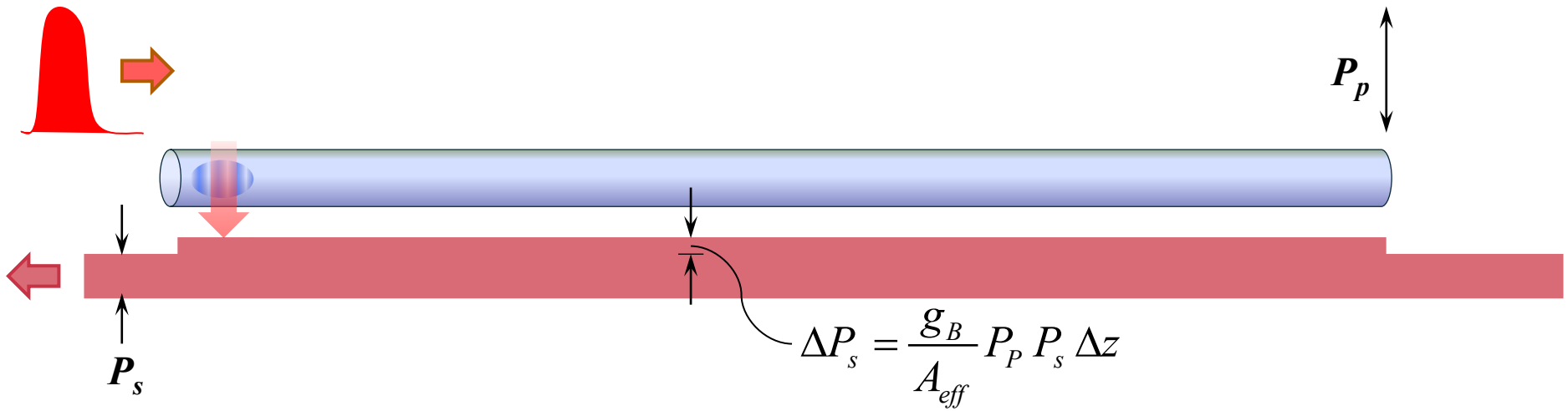
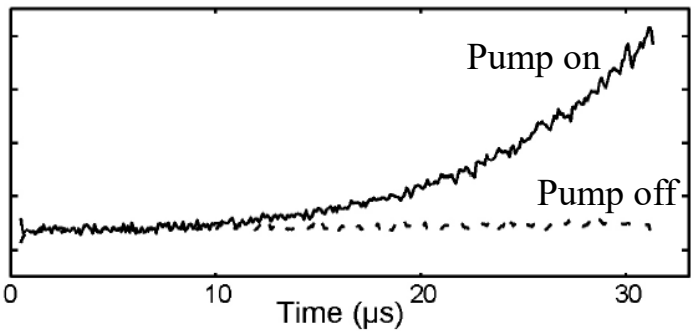
Access to the local power of a lightwave

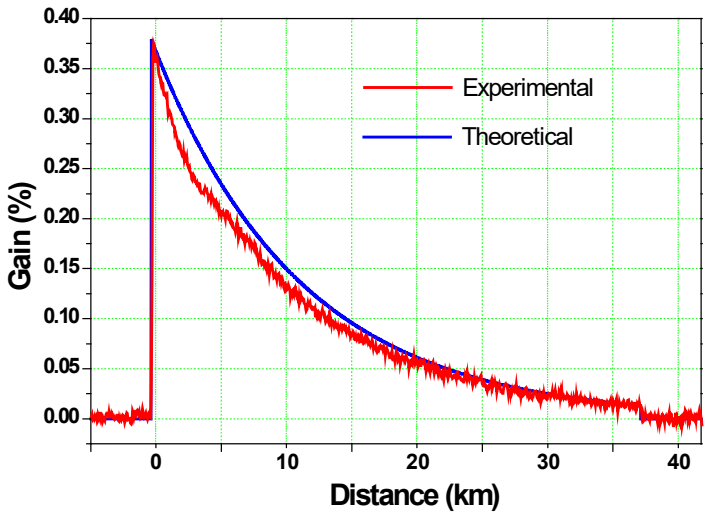


Recording in time-domain the continuous lightwave a map of the power distribution along the fibre can be obtained for:

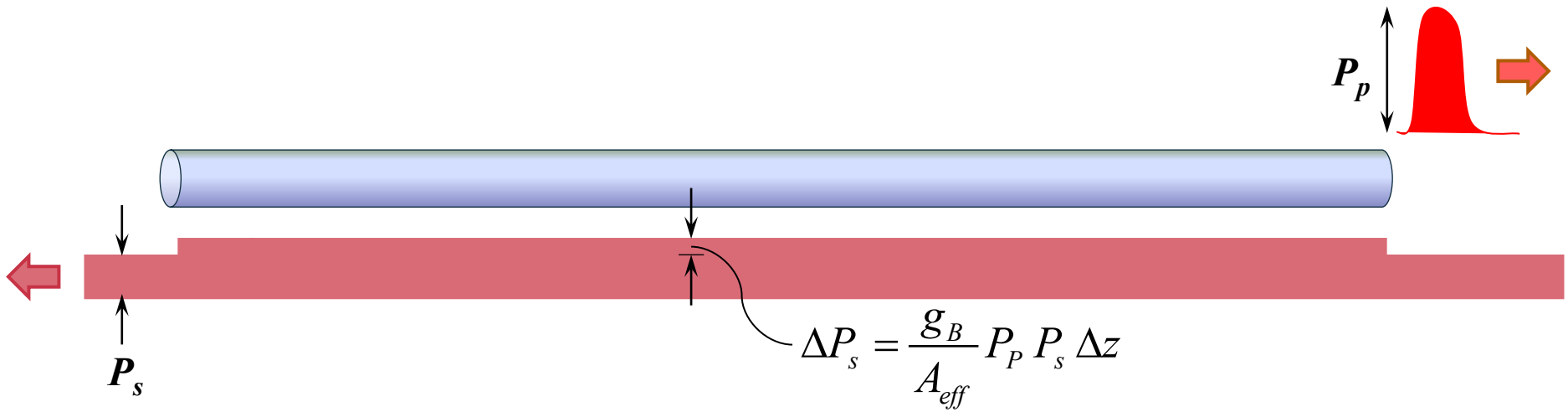
1. either the pulse signal $P_p(z)$

Amplification along a parametric amplifier



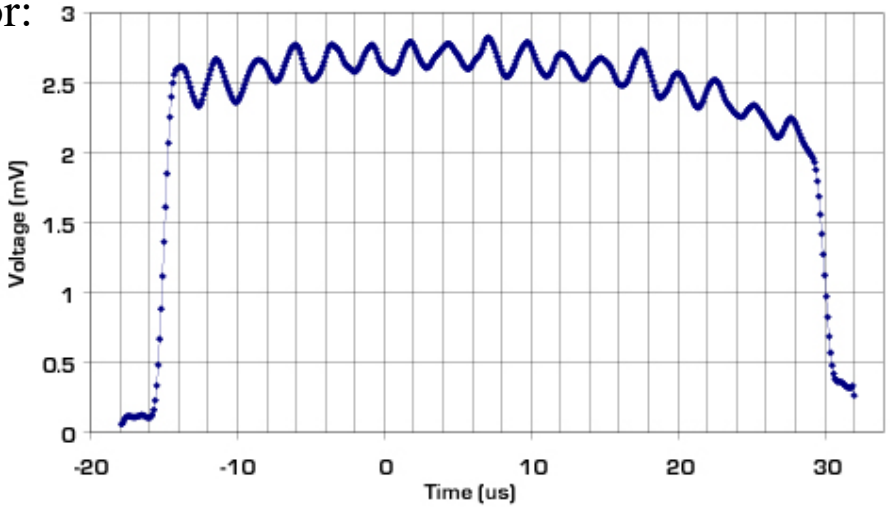


Access to the local power of a lightwave



Recording in time-domain the continuous lightwave a map of the power distribution along the fibre can be obtained for:

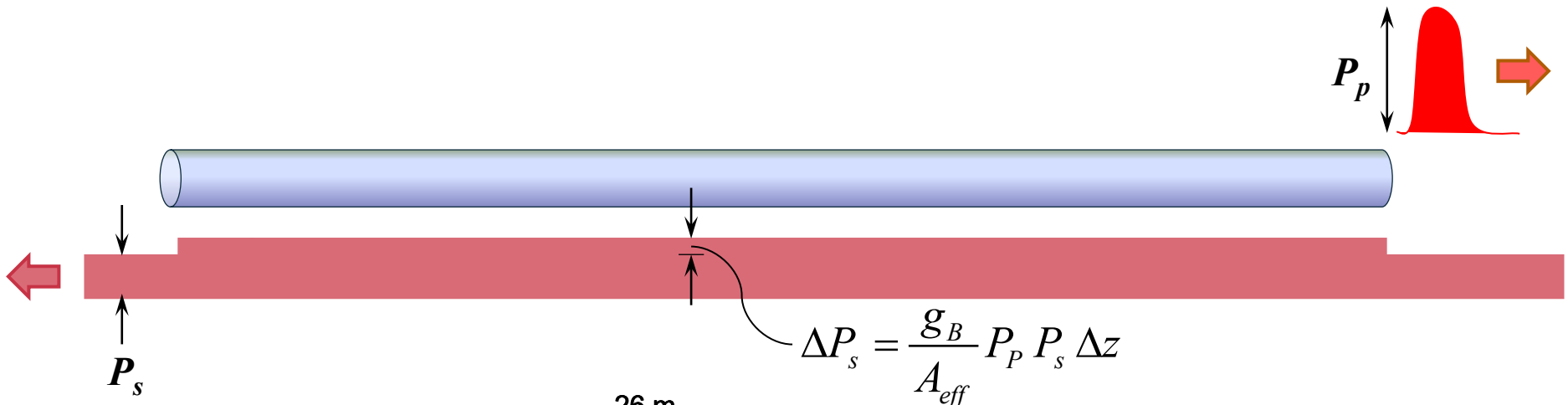
1. either the pulse signal $P_p(z)$
2. or the continuous lightwave $P_s(z)$

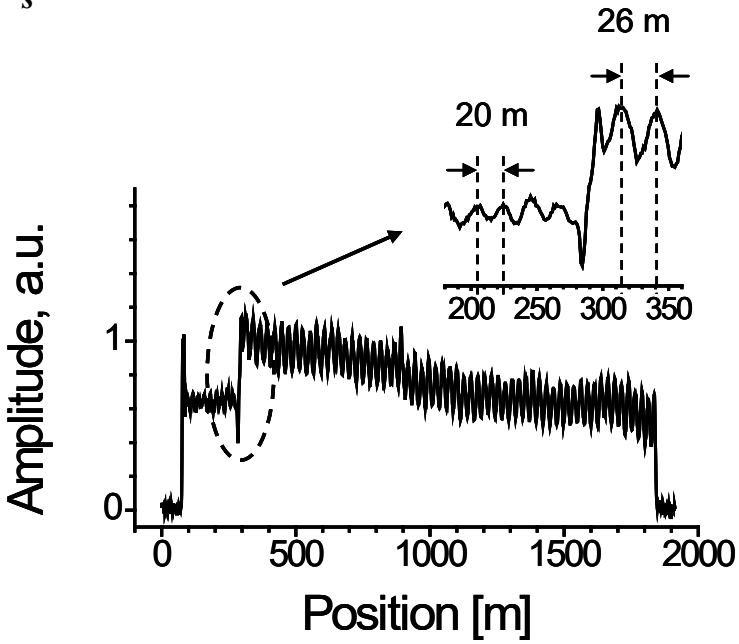


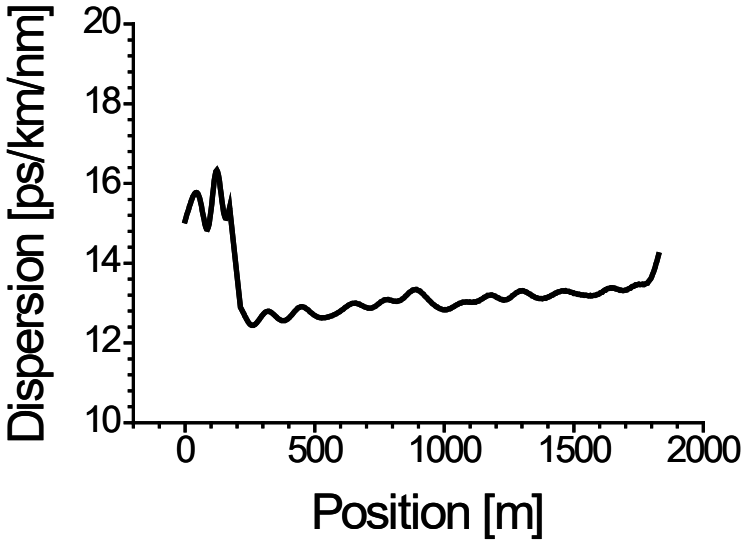
Non-phase-matched 4-wave mixing

$$P_C(L) \sim \frac{\alpha^2}{\alpha^2 + \Delta\beta^2}\left[1 + \frac{4\,e^{-\alpha L}\sin^2(\Delta\beta L/2)}{1 - e^{-\alpha L}}\right]$$

Access to the local power of a lightwave





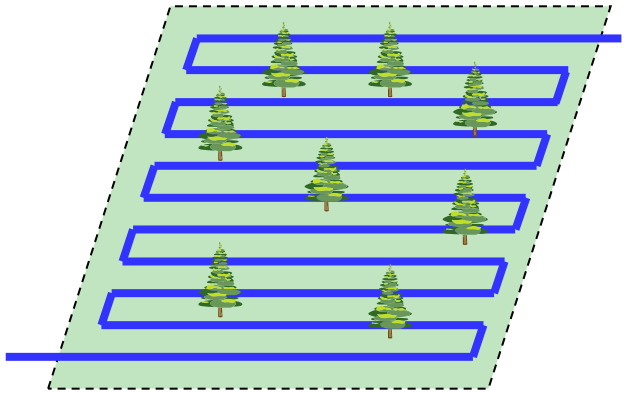


Concept of distributed sensing

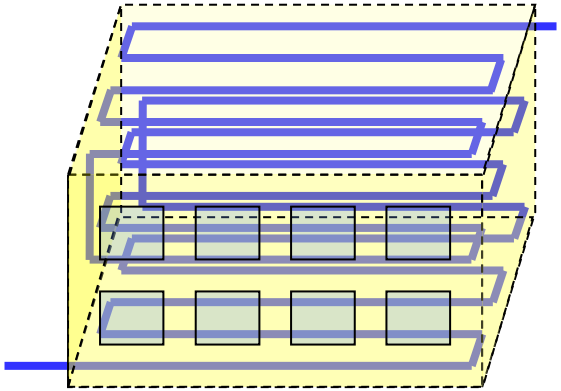
The fiber combines 2 functions: **sensing element** + **signal propagation**

The sensor continuously informs about a large structure, that can be…

1D



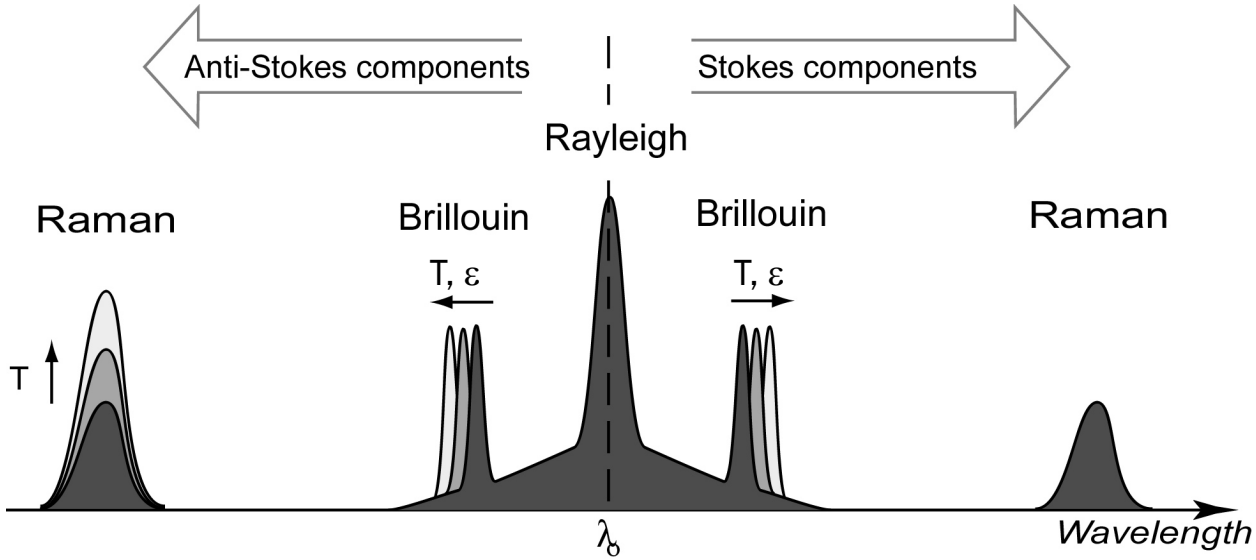
2D



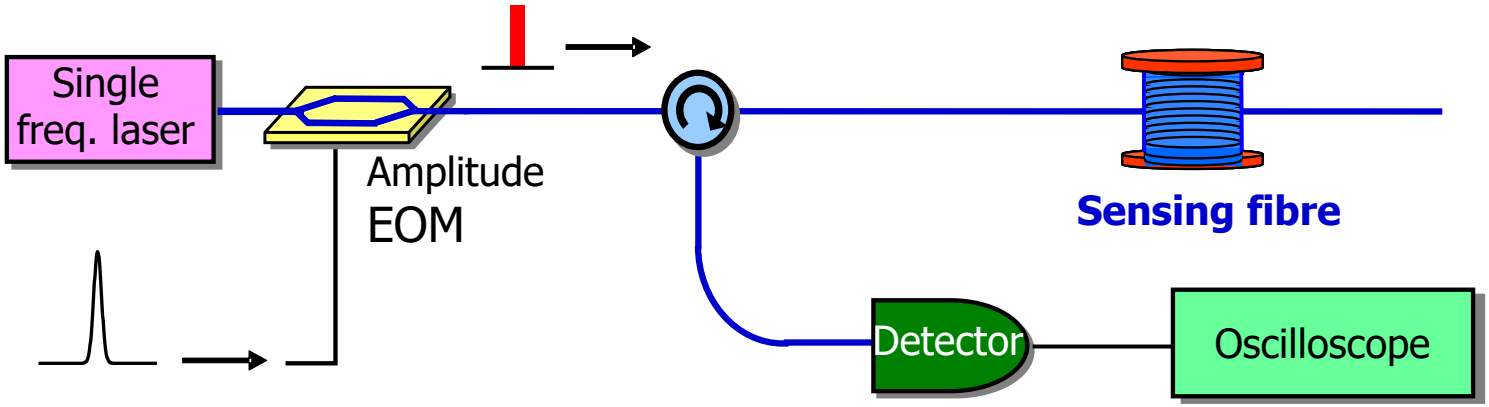
3D

Sensing using Scatterings in Optical Fibres

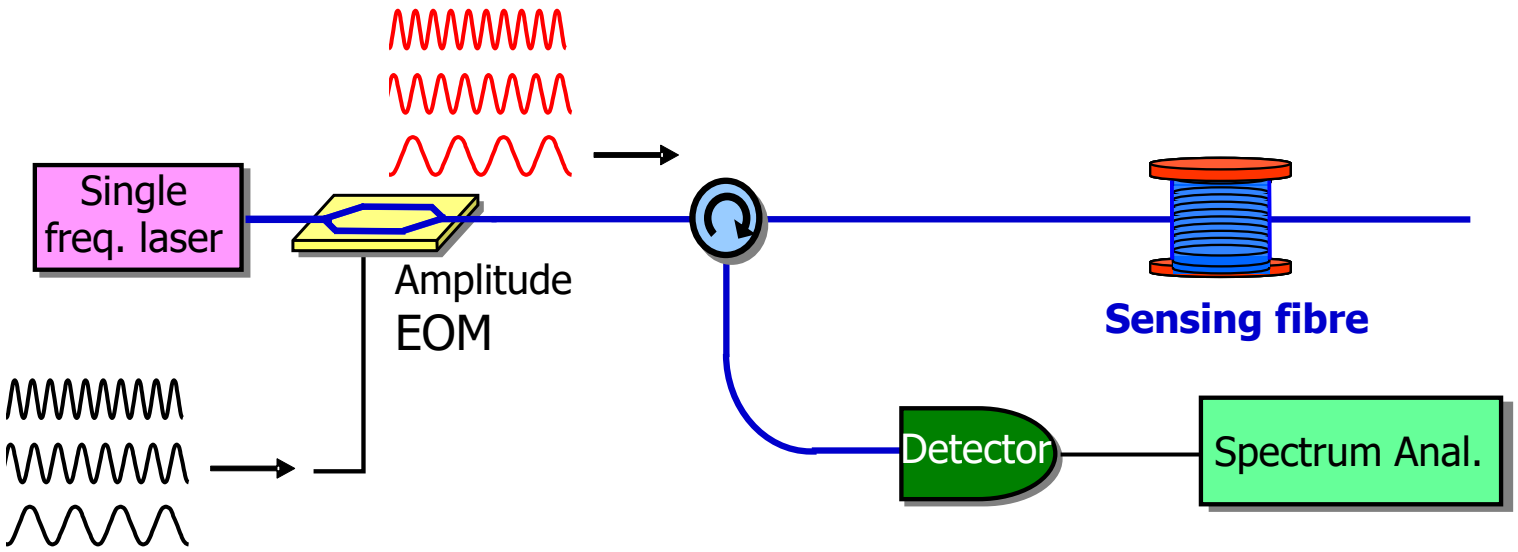
- Scattering processes used for sensing applications
  - **Rayleigh** is a pure *distributed reflection* with a random amplitude.
  - **Raman** scattered magnitude is *temperature* dependent
  - **Brillouin** lines are spectrally *temperature* and *strain* sensitive



Optical Time-Domain Analyzer

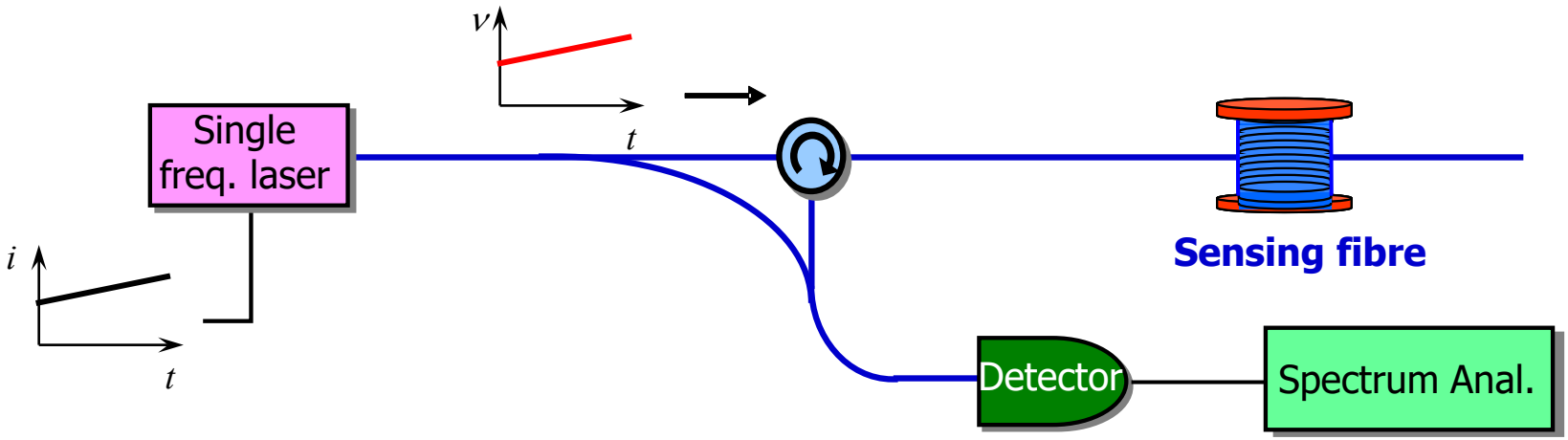


Optical Frequency-Domain Analyzer



1:1 equivalent to Time-Domain analysis!

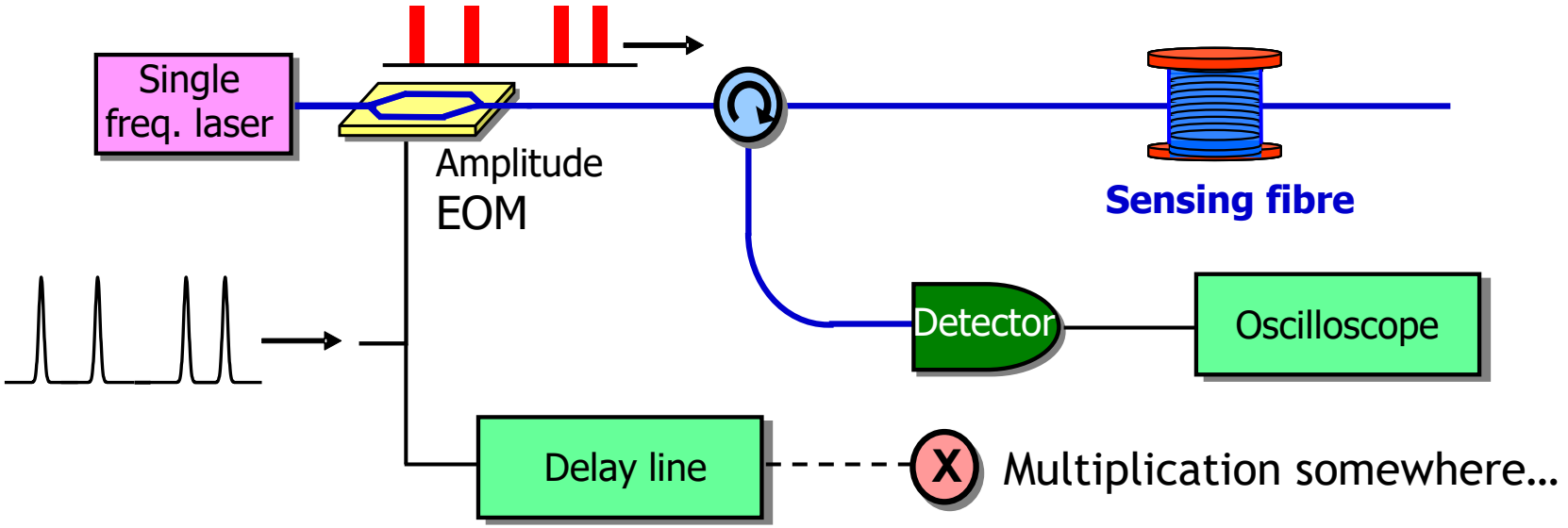
Coherent Optical Frequency-Domain Analyzer



Signal from different positions gives different beat notes

Laser coherence length must be larger than distance range!

Optical Correlation-Domain Analyzer



Each point can be addressed randomly and statically

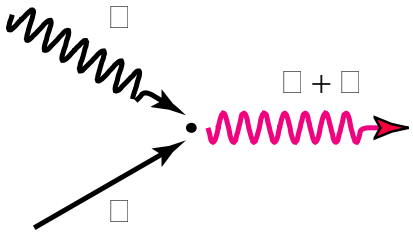
Low frequency detection possible ➔ weak signals!

Principle of Raman distributed sensing

Based on the **temperature dependence** of **Raman spontaneous** scattering cross section, that is by essence **thermally activated.**

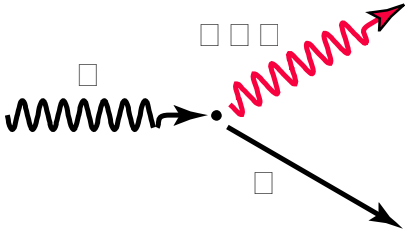
- **Anti-Stokes** scattering annihilates a phonon
  - ➔ Scattering coefficient is proportional to $\bar{n}$

$$C_{AS} \sim \bar{n} = \frac{1}{e^{\frac{h\Omega}{kT}} - 1}$$



- **Stokes** scattering creates a phonon
  - ➔ Scattering coefficient proportional to $\bar{n}+1$

$$C_S \sim \bar{n} + 1 = \frac{e^{\frac{h\Omega}{kT}}}{e^{\frac{h\Omega}{kT}} - 1}$$



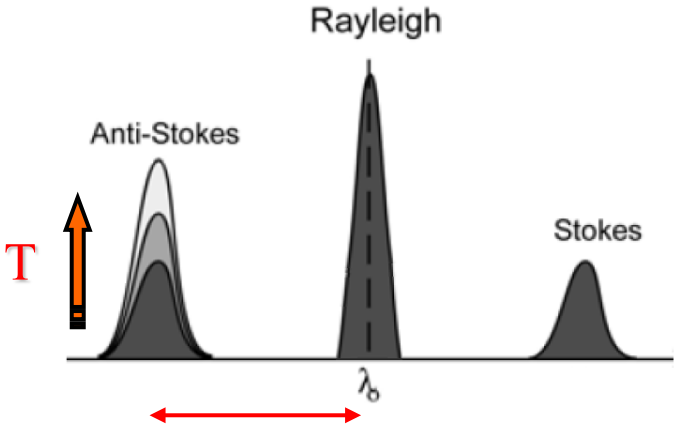
Temperature is evaluated by measuring the **ratio between Anti-Stokes and Stokes intensities** :

$$\frac{I_{AS}}{I_S} = \frac{C_{AS} I_{inc}}{C_S I_{inc}} = e^{-\frac{h\Omega}{kT}}$$

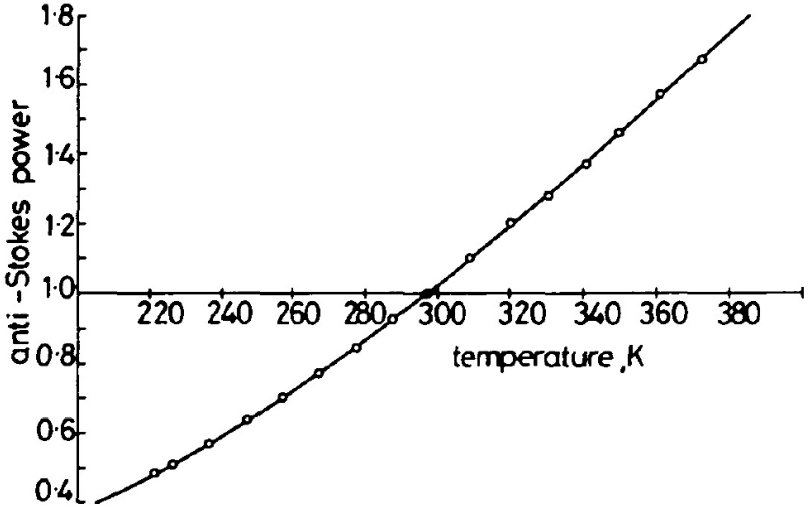
Raman distributed temperature sensors

Spontaneous Raman scattering

- Interaction between incident light and vibrational modes of the molecules of the fiber
- Thermally activated process
- Anti-Stokes power depends on temperature

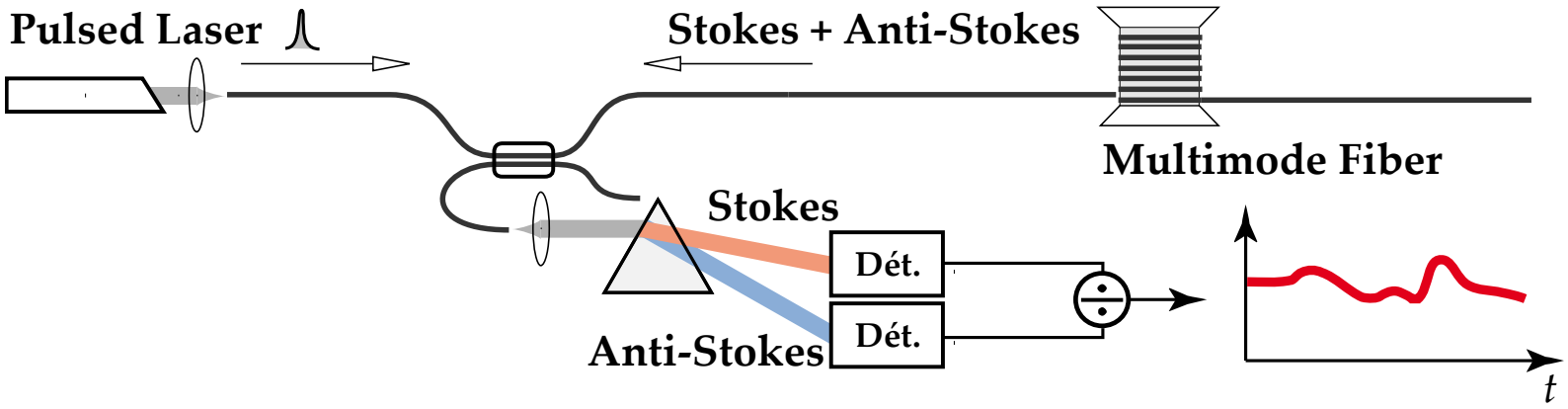


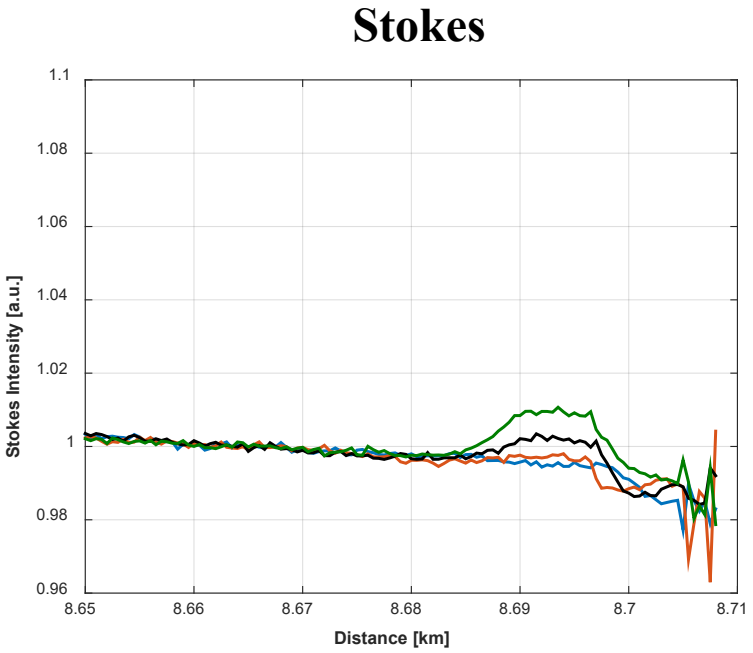
12.5 THz
(100 nm @1550 nm)

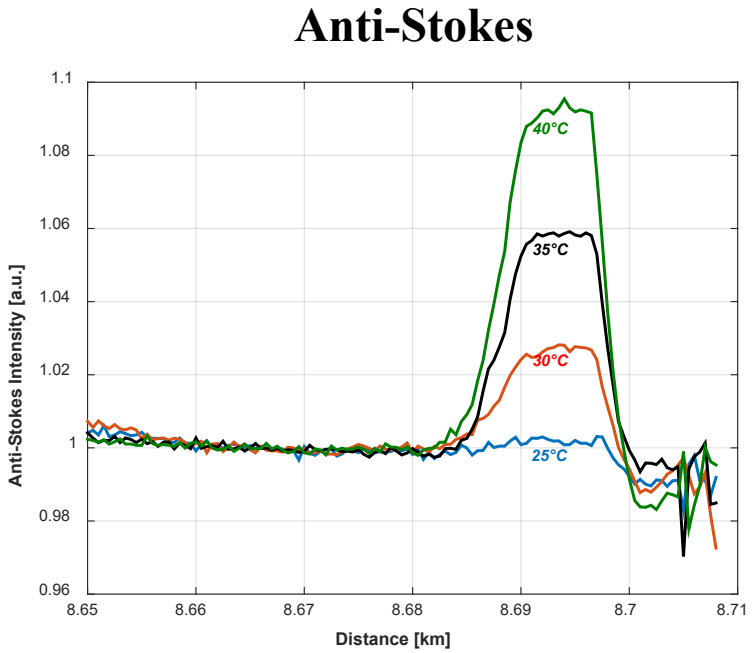


Sensitivity (@ 300K) : 0.8 % /K^{-1}

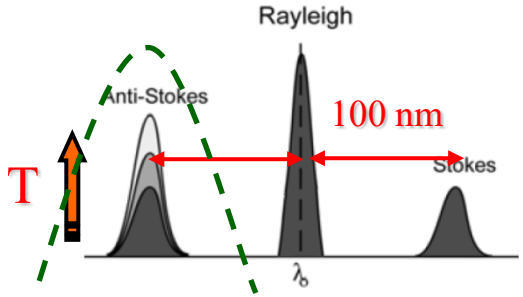
Raman distributed sensing



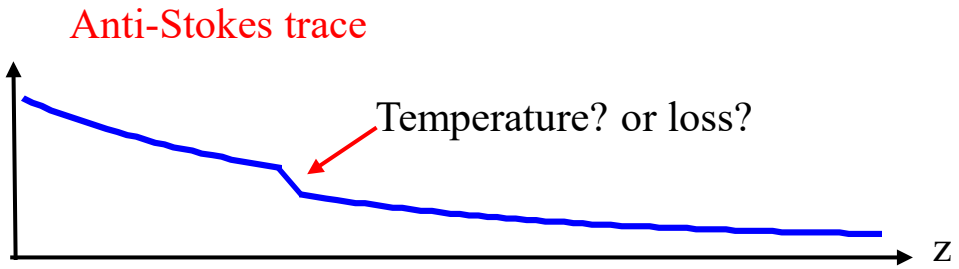




Sensor response



Broadband Optical filter

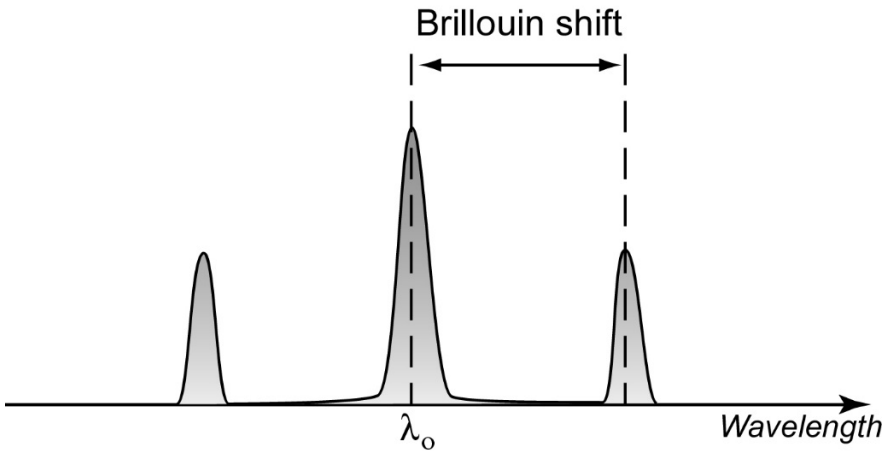


Usually the ratio $R(T)$ between $P_{AS}/P_{Rayleigh}$ or P_{AS}/P_S is used to get rid of losses

- Fast & cost-effective solution for range up to 10km (Intermodal dispersion ~1 ns/km)
- < 1K temperature & 1m spatial resolutions.
- Very sensitive to wavelength-dependent losses! ➔ Biased temperature measurement.

Brillouin sensing

- Brillouin scattering is characterized by the Brillouin shift
- The Brillouin shift depends on the *acoustic velocity* of the medium, which is *temperature* and *density* dependent



$$V_a = \sqrt{\frac{E}{\rho}\frac{(1-\kappa)}{(1+\kappa)(1-2\kappa)}}$$

E: Young's modulus
κ: Poisson's ratio

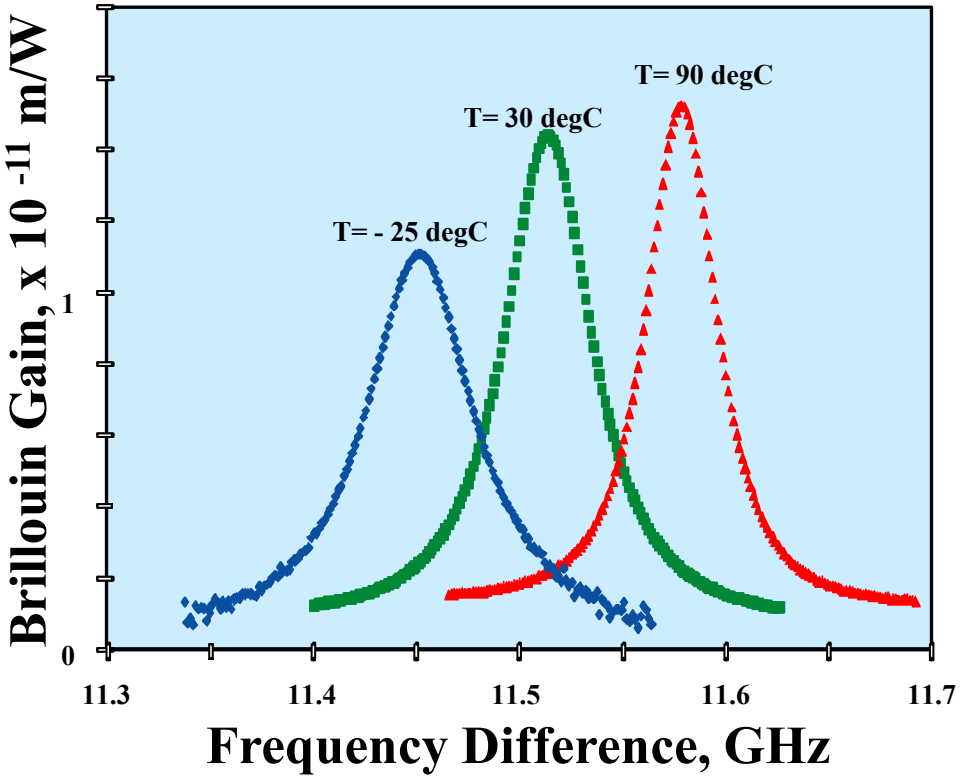
Brillouin Frequency Shift:

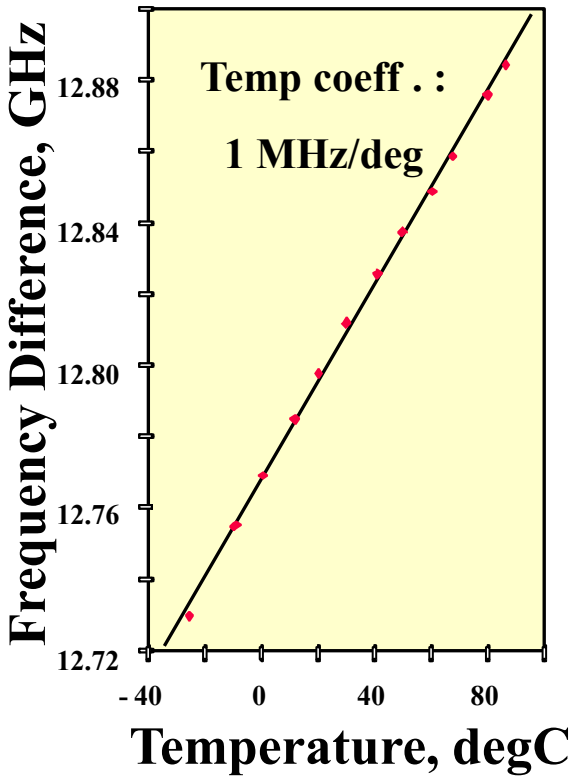
$$\nu_B = 2nV_A / \lambda$$

$\nu_B(T,\varepsilon)$ depends on *temperature* and *density*

Brillouin sensing

- Temperature effects on the Brillouin scattering spectrum

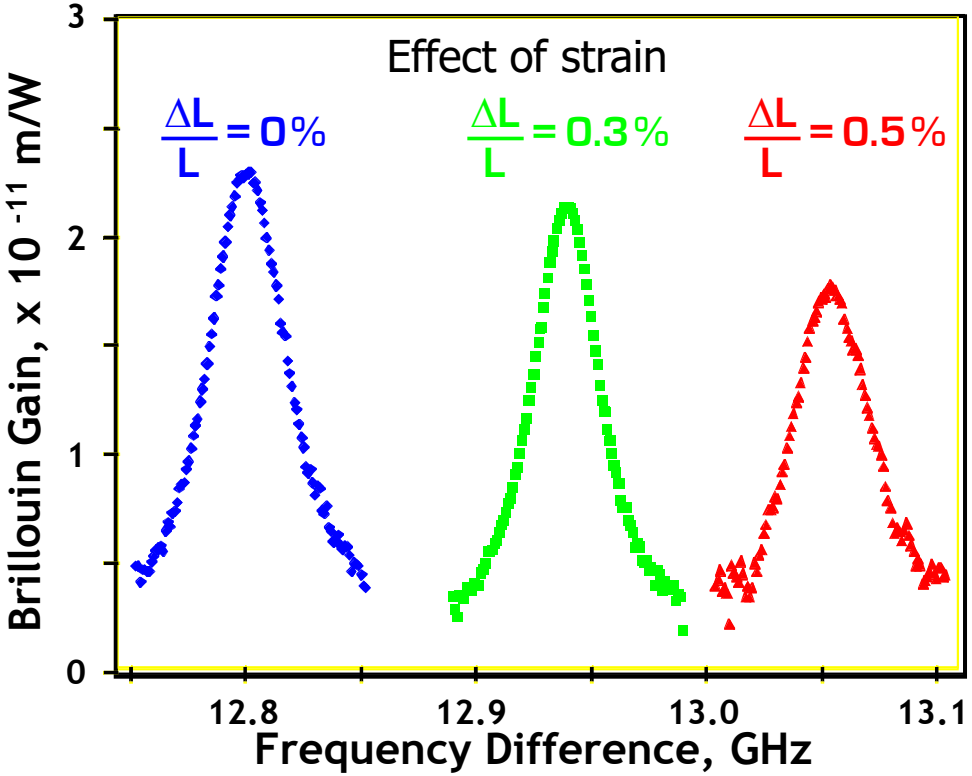


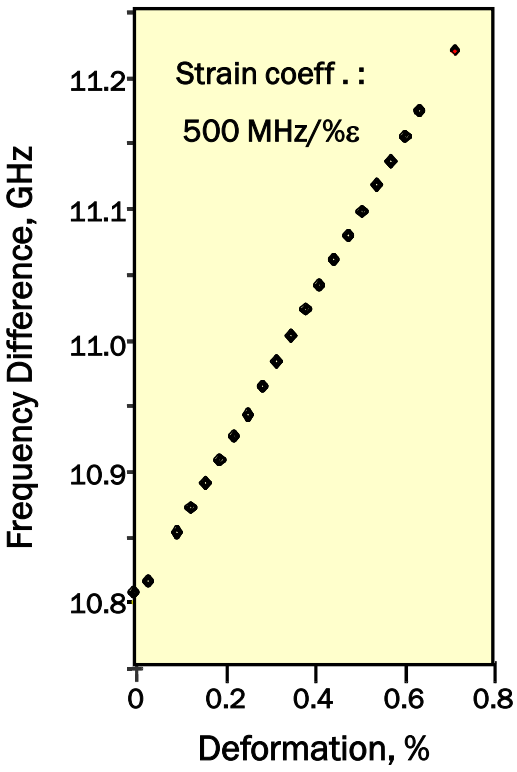


Brillouin sensing

- Strain effects on the Brillouin scattering spectrum

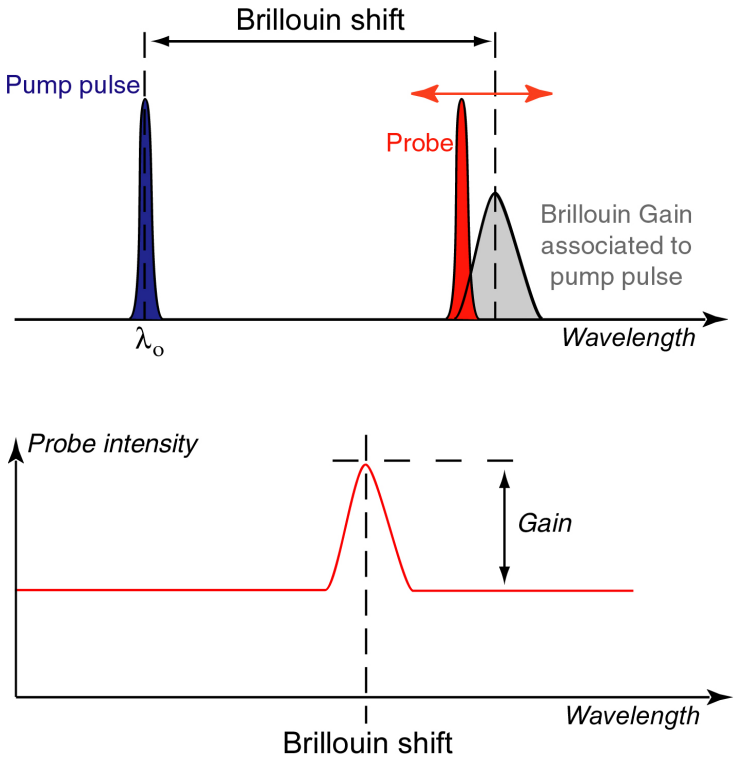
  Deformation $\varepsilon = \Delta L/L$ ➔ Density change $\Delta\rho$





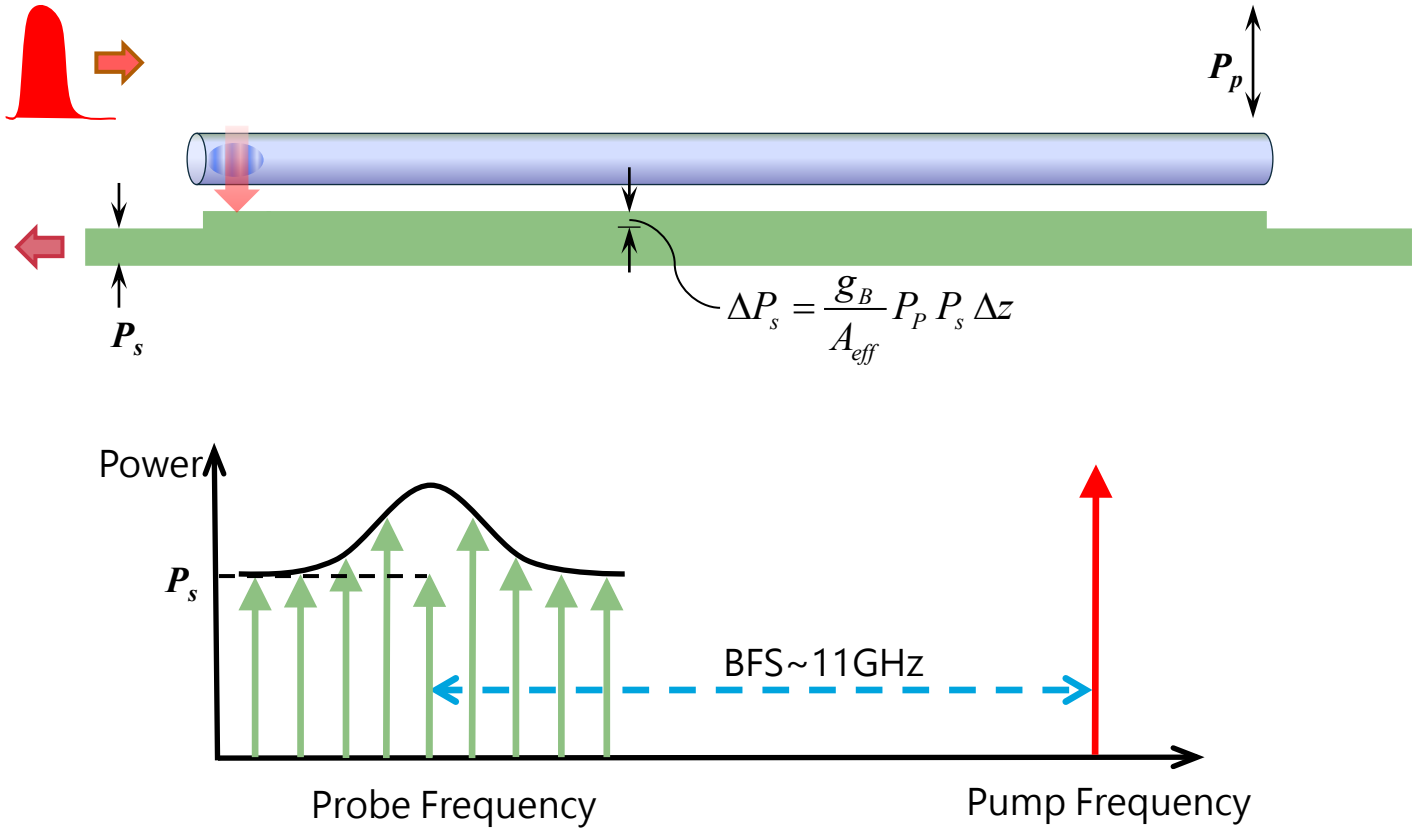
Brillouin Optical Time-Domain Analysis

- Based on the use of a *probe signal* which wavelength is precisely controlled and scanned

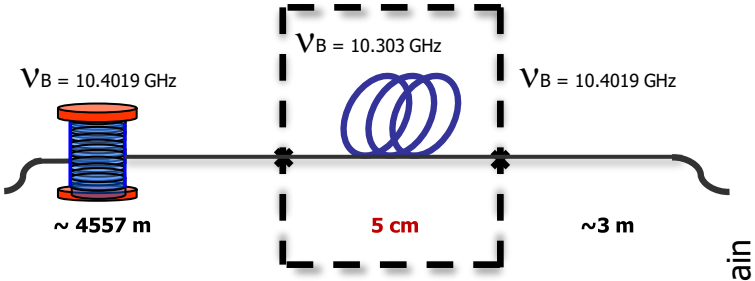


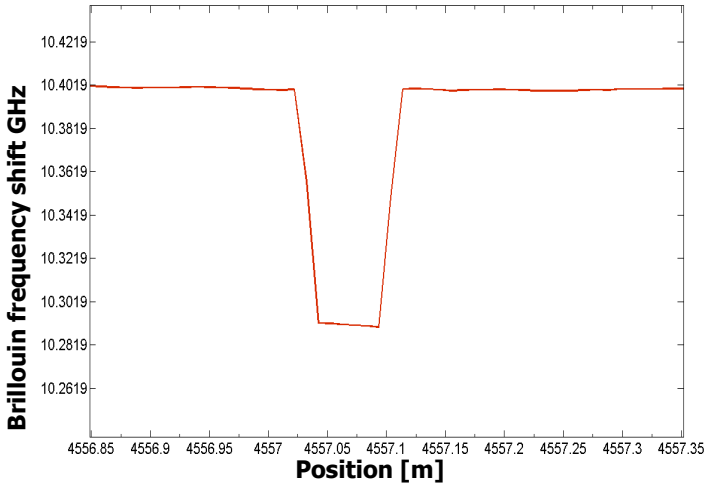
Record probe intensity while its wavelength is scanned

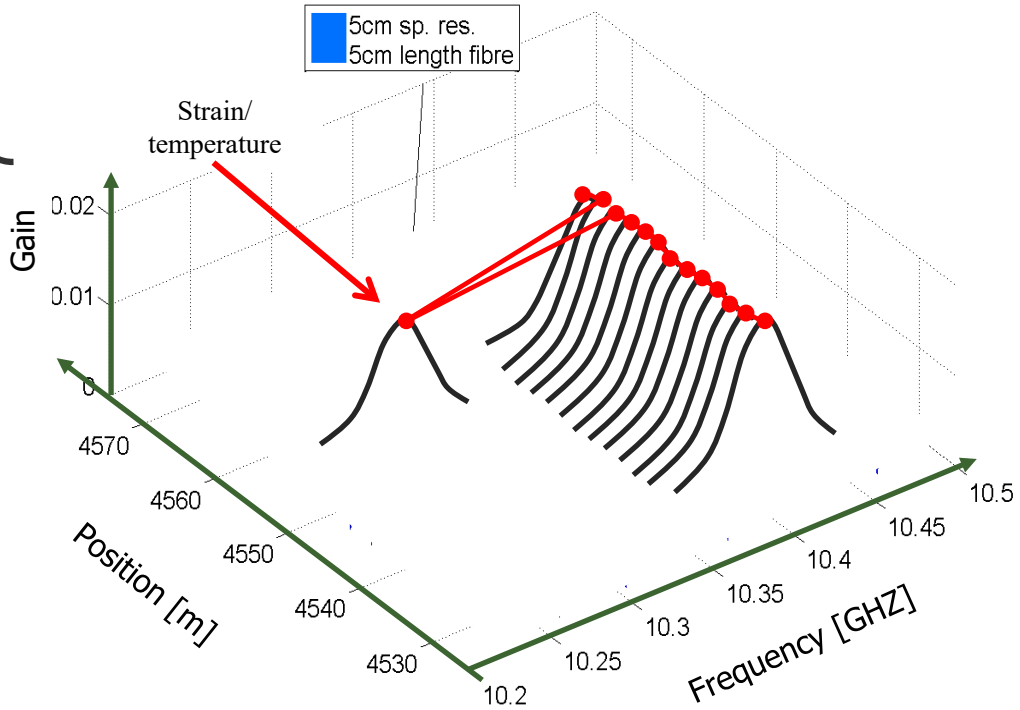
Brillouin Optical Time-Domain Analysis



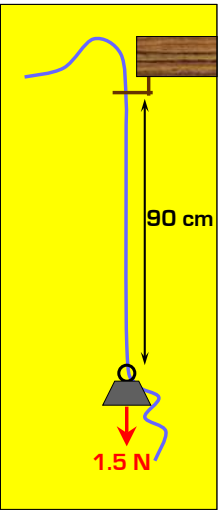
Brillouin Optical Time-Domain Analysis

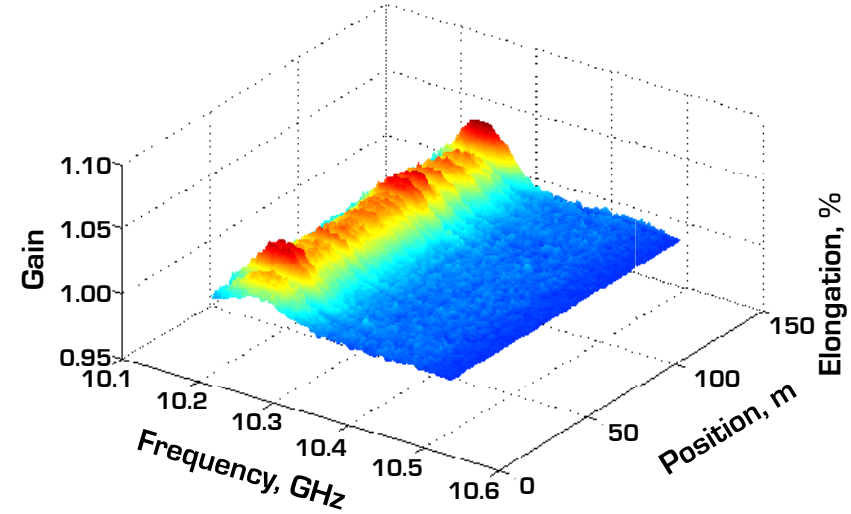


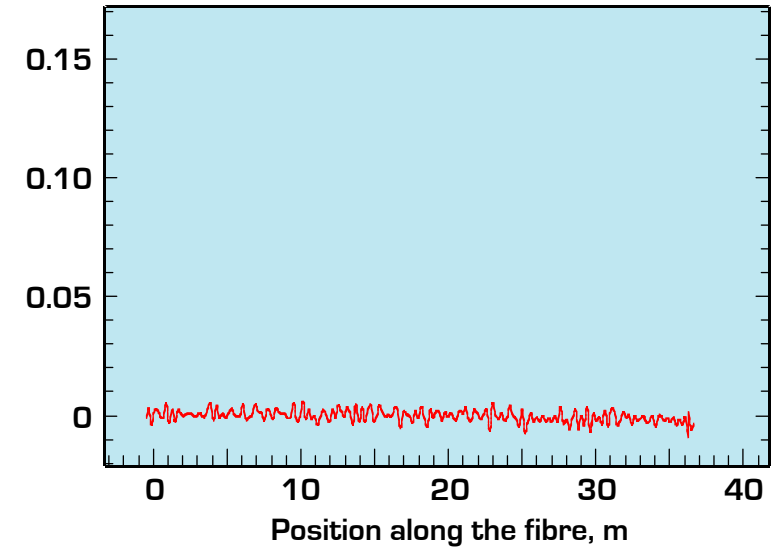


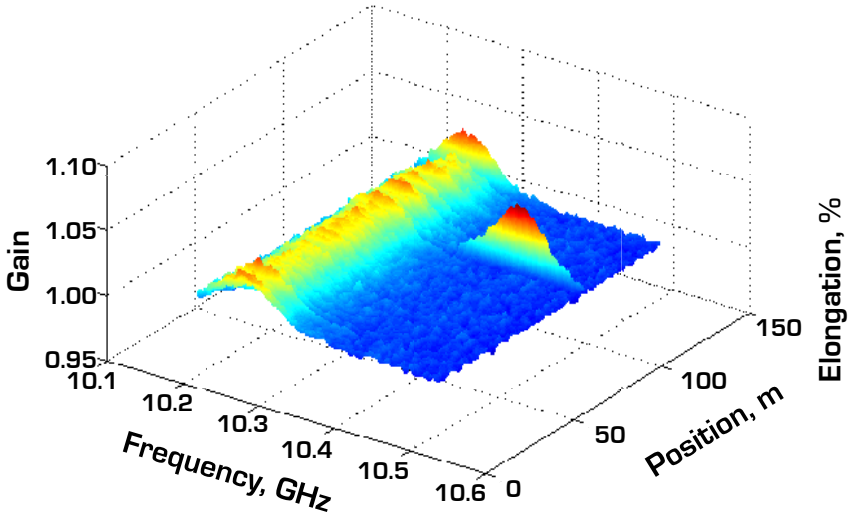


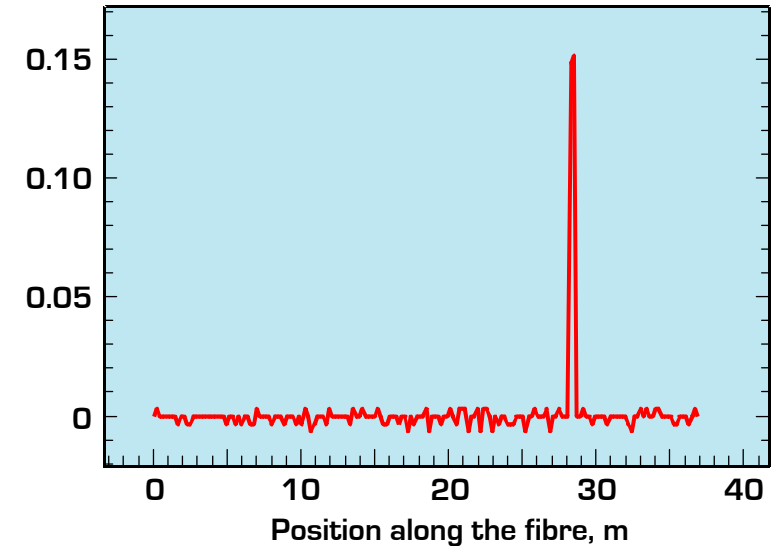
Strain distributed sensing





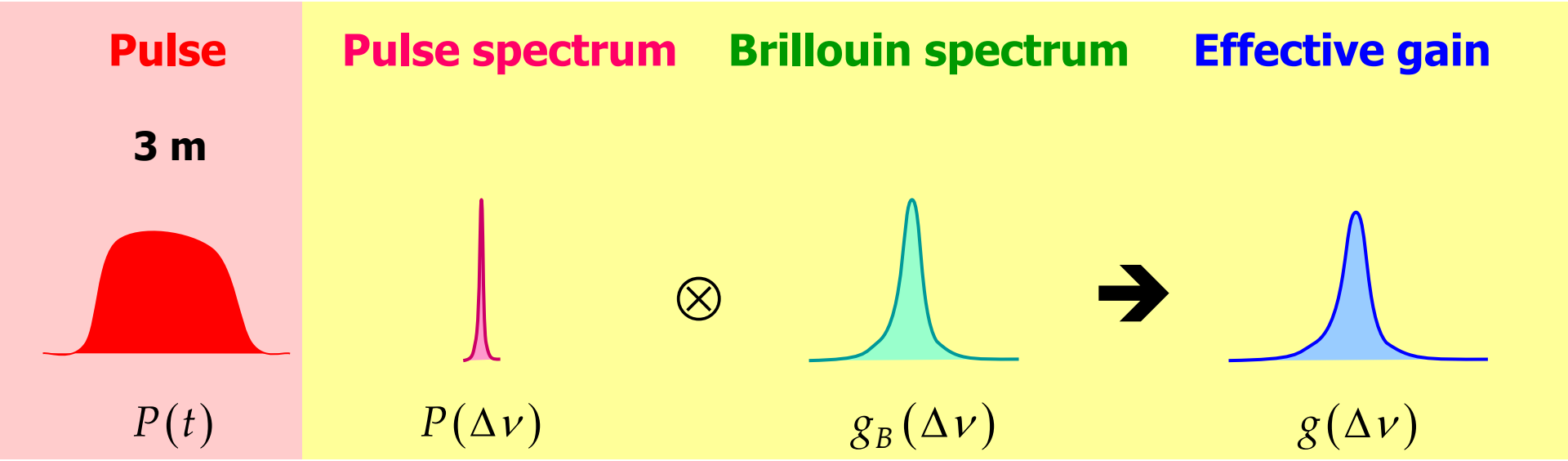






Limit to spatial resolution

The natural pulse **spectral broadening** further decreases the interaction strength and makes the strain resolution worse.

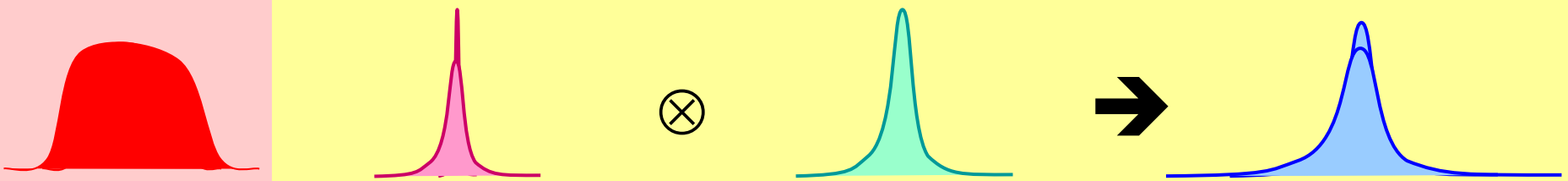


Limit to spatial resolution

The natural pulse **spectral broadening** further decreases the interaction strength and makes the strain resolution worse.

Pulse **Pulse spectrum** **Brillouin spectrum** **Effective gain**

1 m



$P(t)$ $P(\Delta\nu)$ $g_B(\Delta\nu)$ $g(\Delta\nu)$

Limit to spatial resolution

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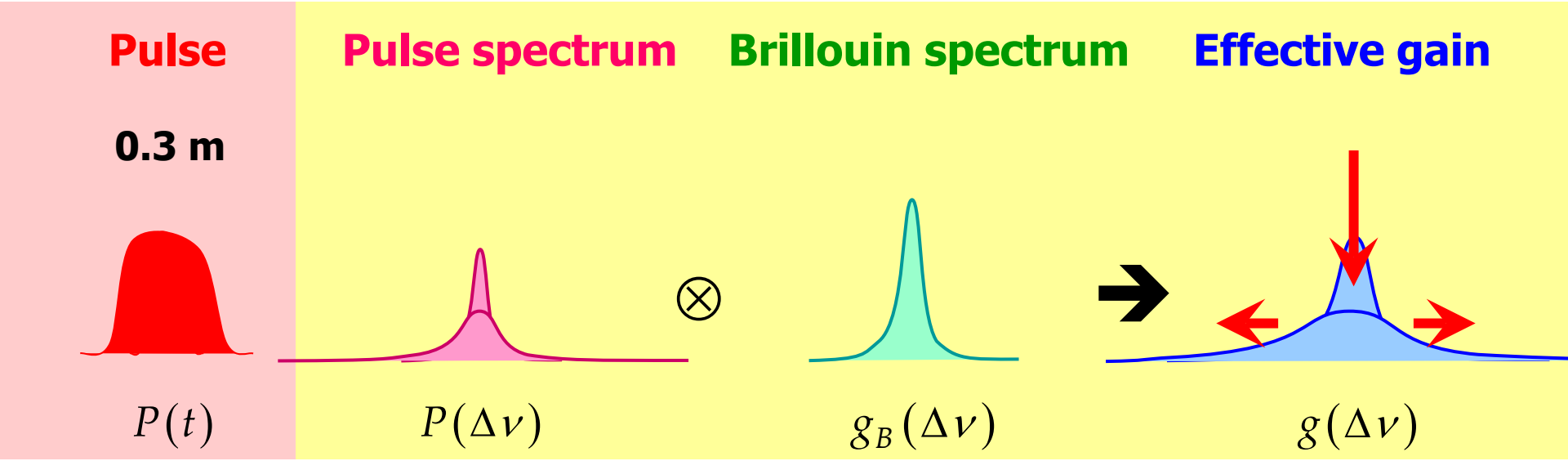
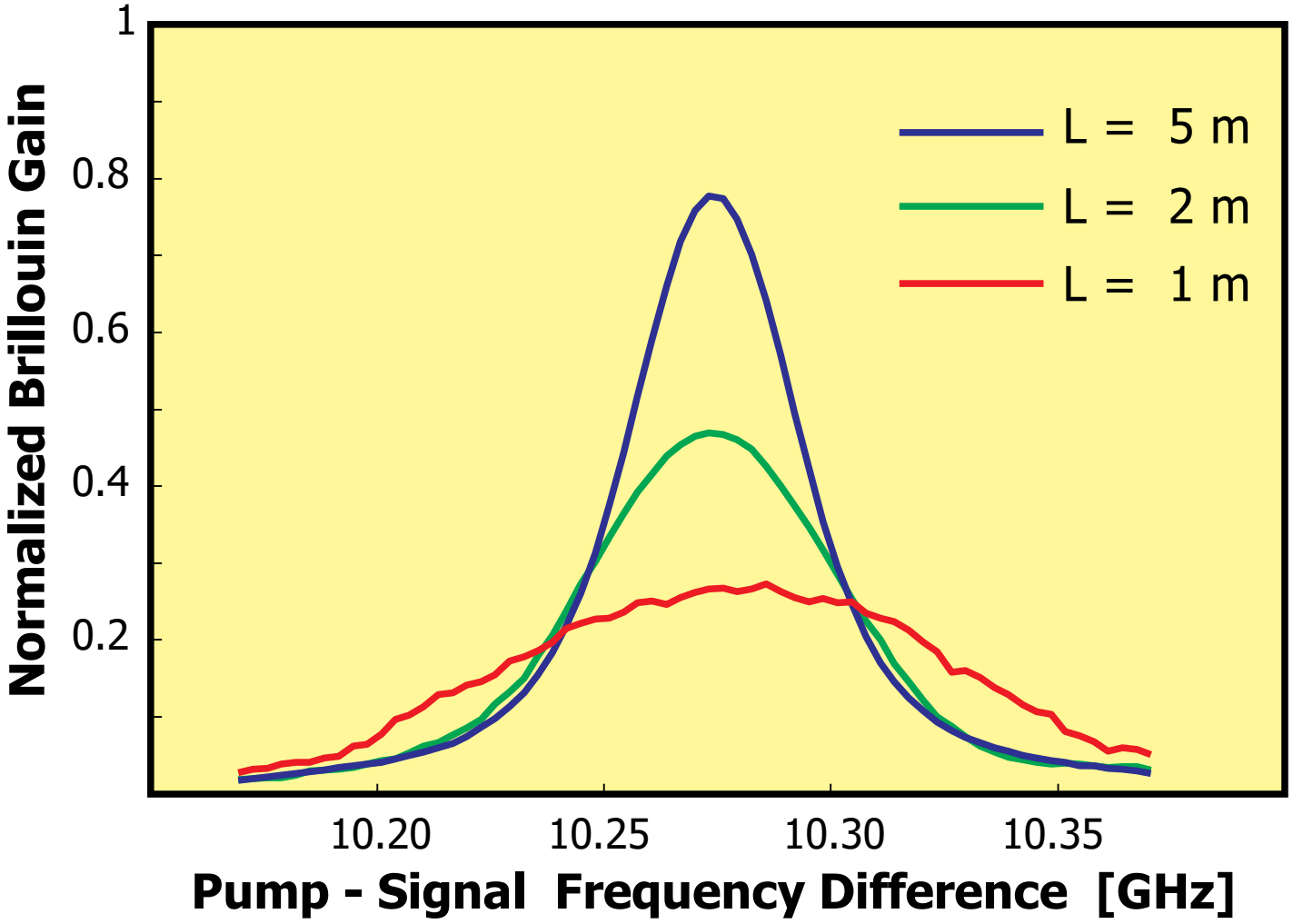


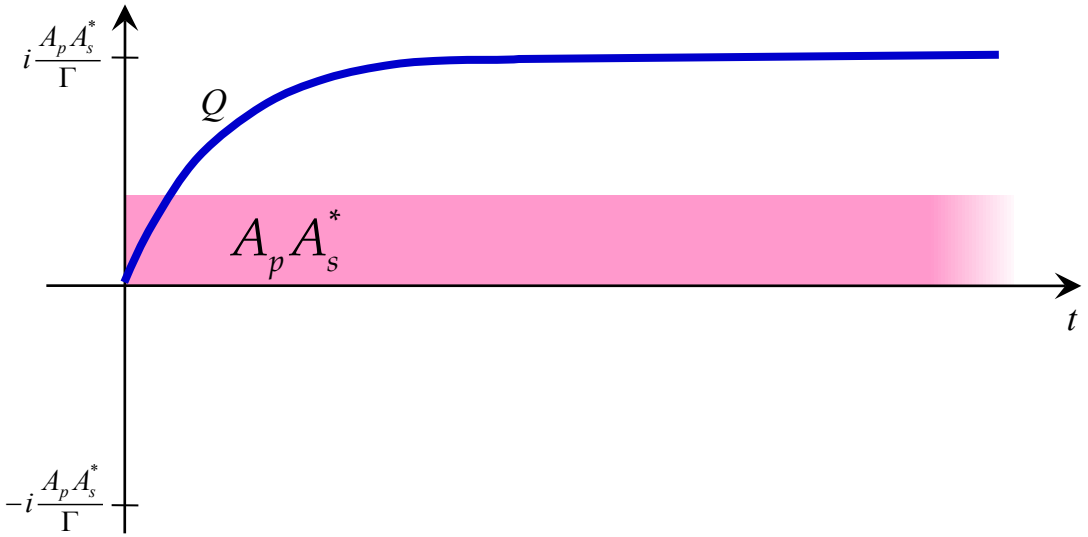
The **contrast** of the measurement is **severely decreased** by the summed effect of shorter interaction length and spectral broadening.

Observation of spectral broadening



Inertial behaviour of the acoustic wave

$$Q(t) = i\frac{A_p A_s^*}{\Gamma}\left[1 - \mathrm{e}^{-\Gamma t}\right]$$



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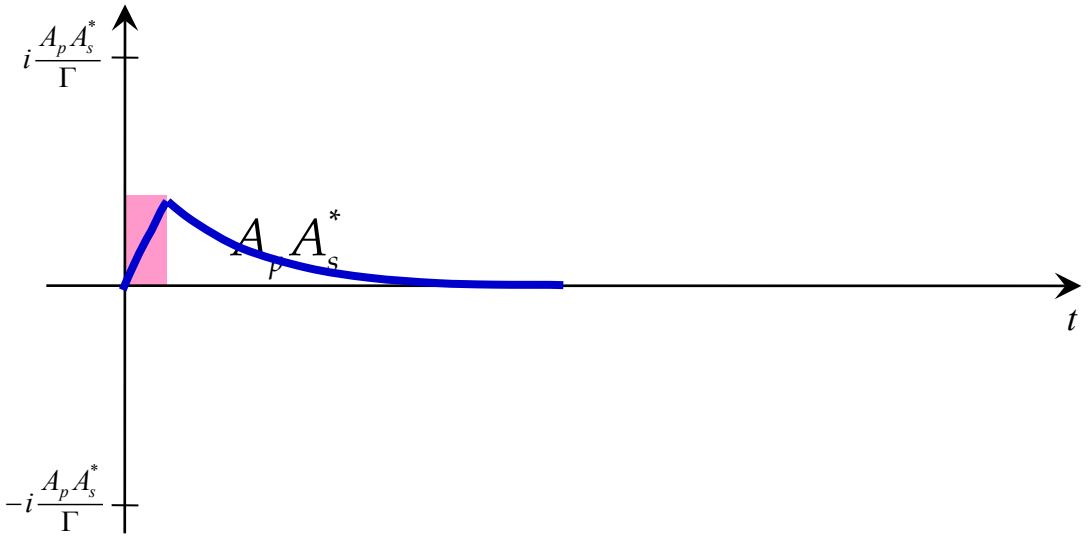
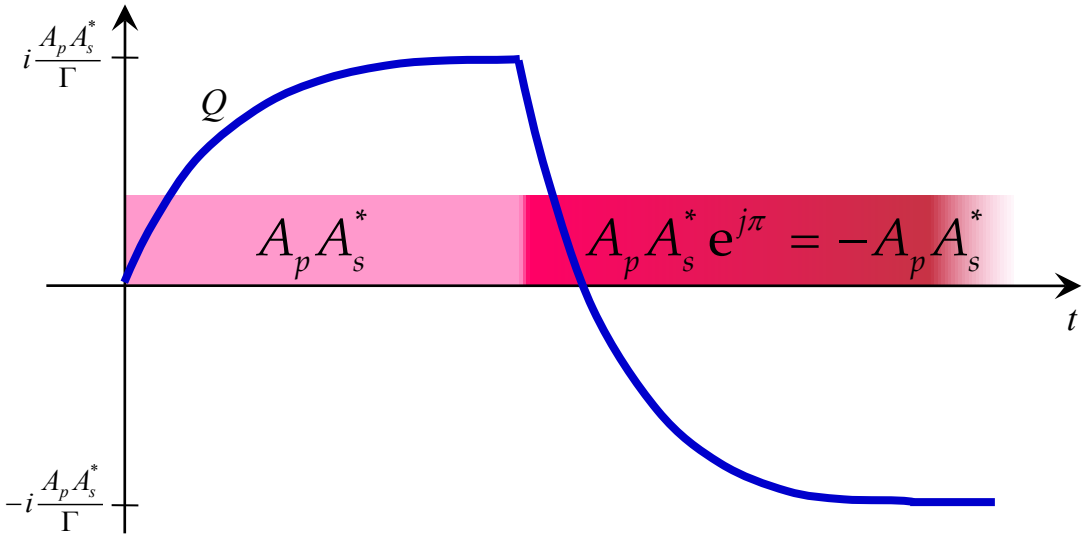


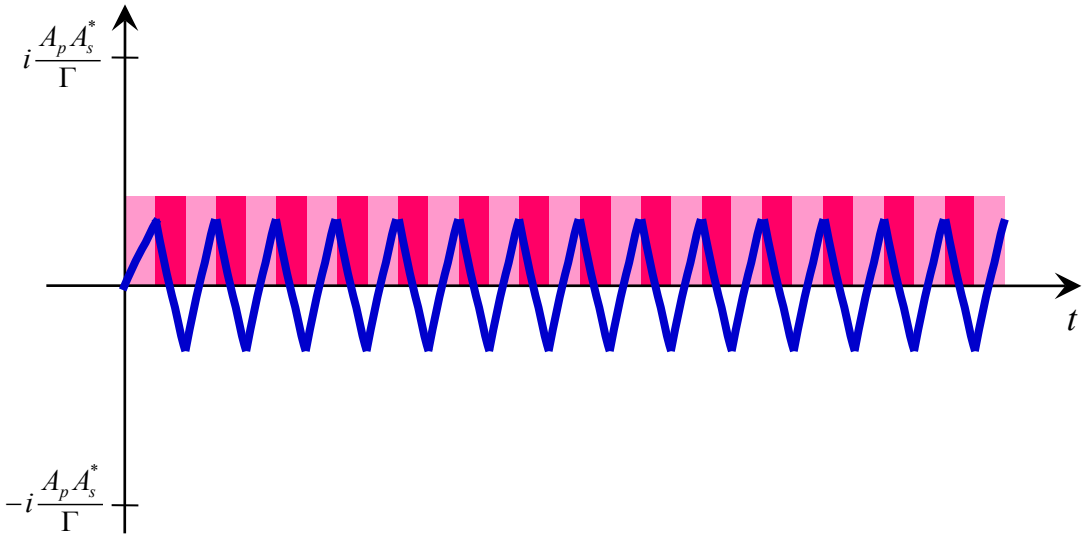
Effect of π-phase modulation

$$Q(t) = i\frac{A_p A_s^*}{\Gamma}\left[1 - \mathrm{e}^{-\Gamma t}\right]$$

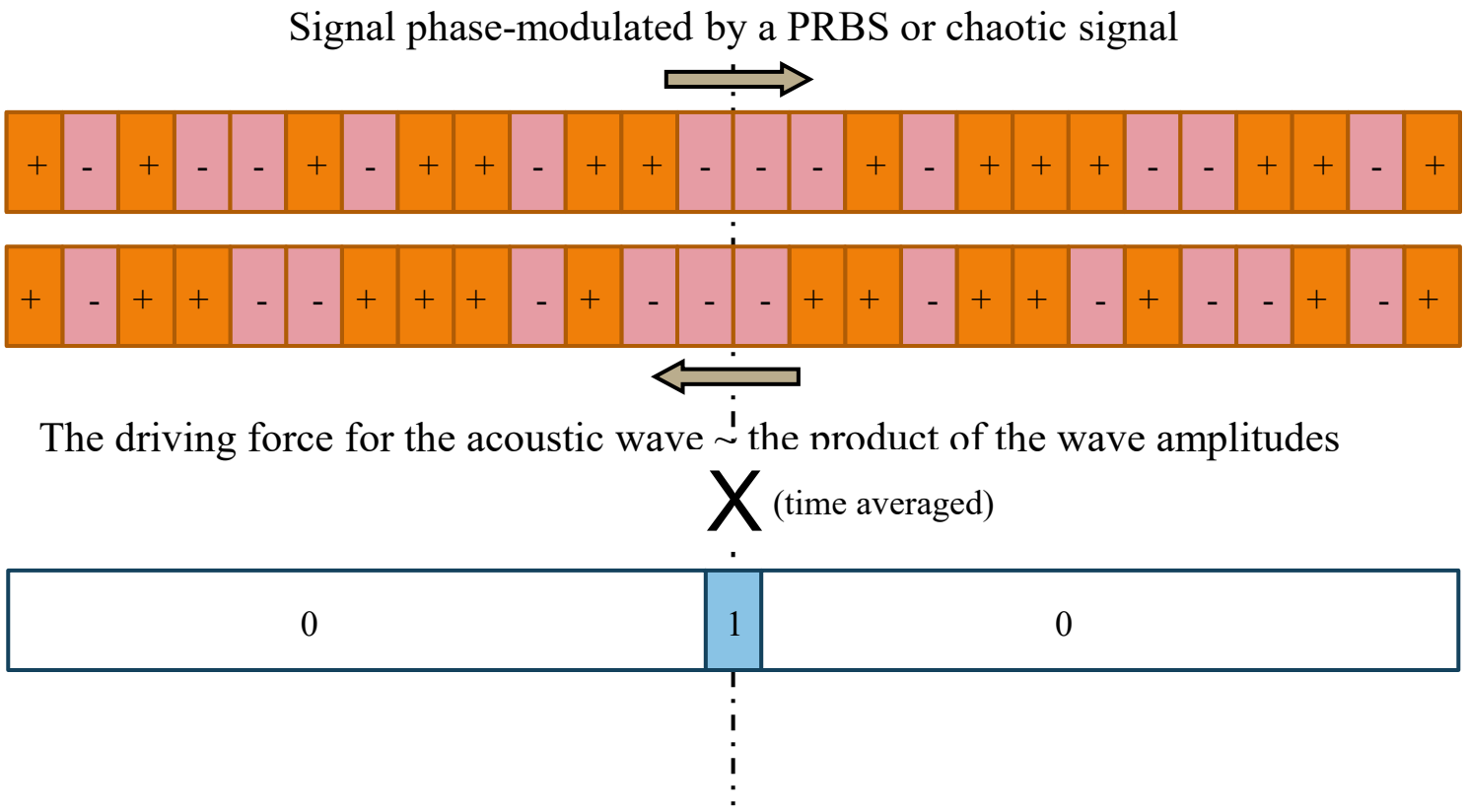


Damping the acoustic wave using phase modulation

$$Q(t) = i\frac{A_p A_s^*}{\Gamma}\left[1 - \mathrm{e}^{-\Gamma t}\right]$$



Generation of local stationary gratings



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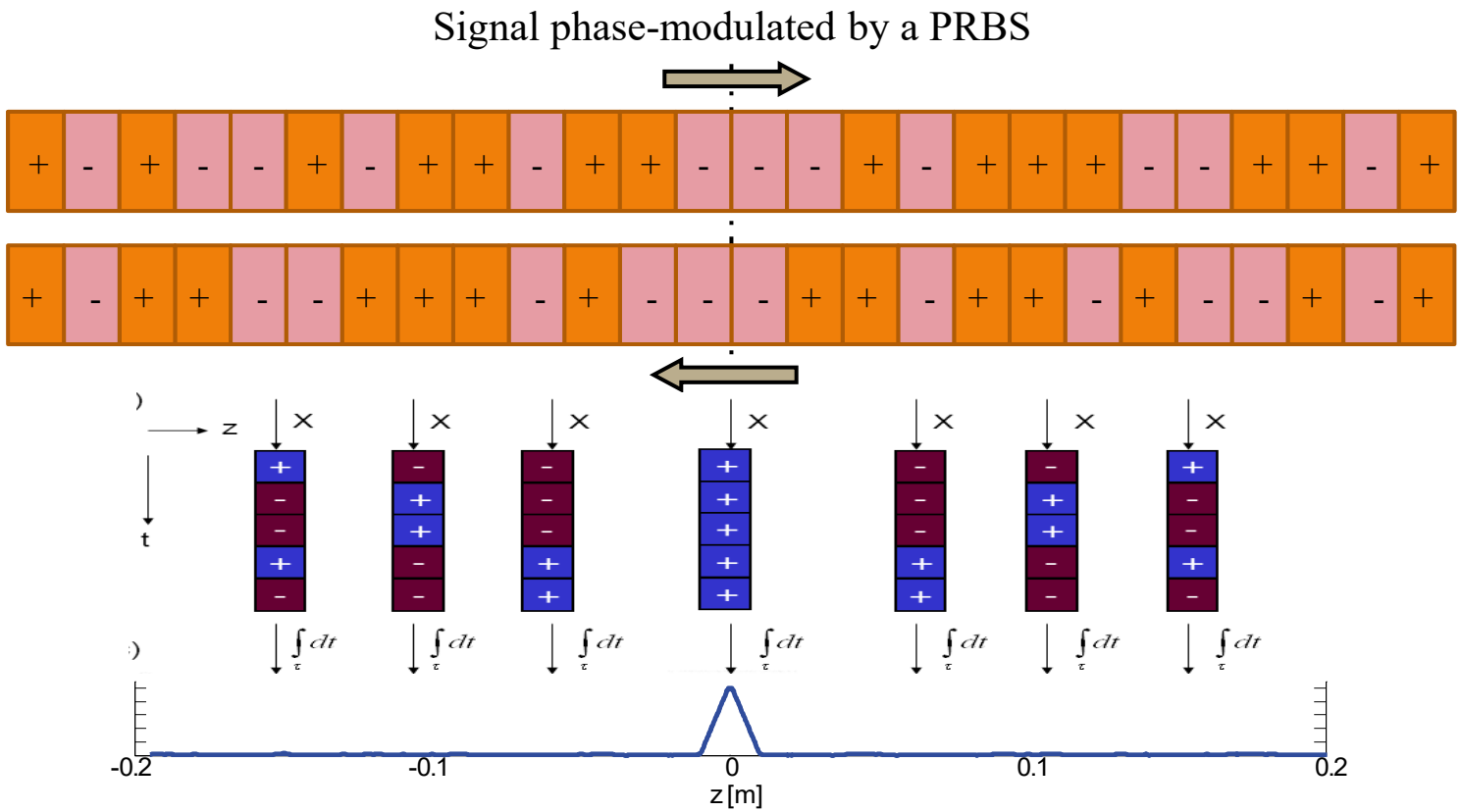
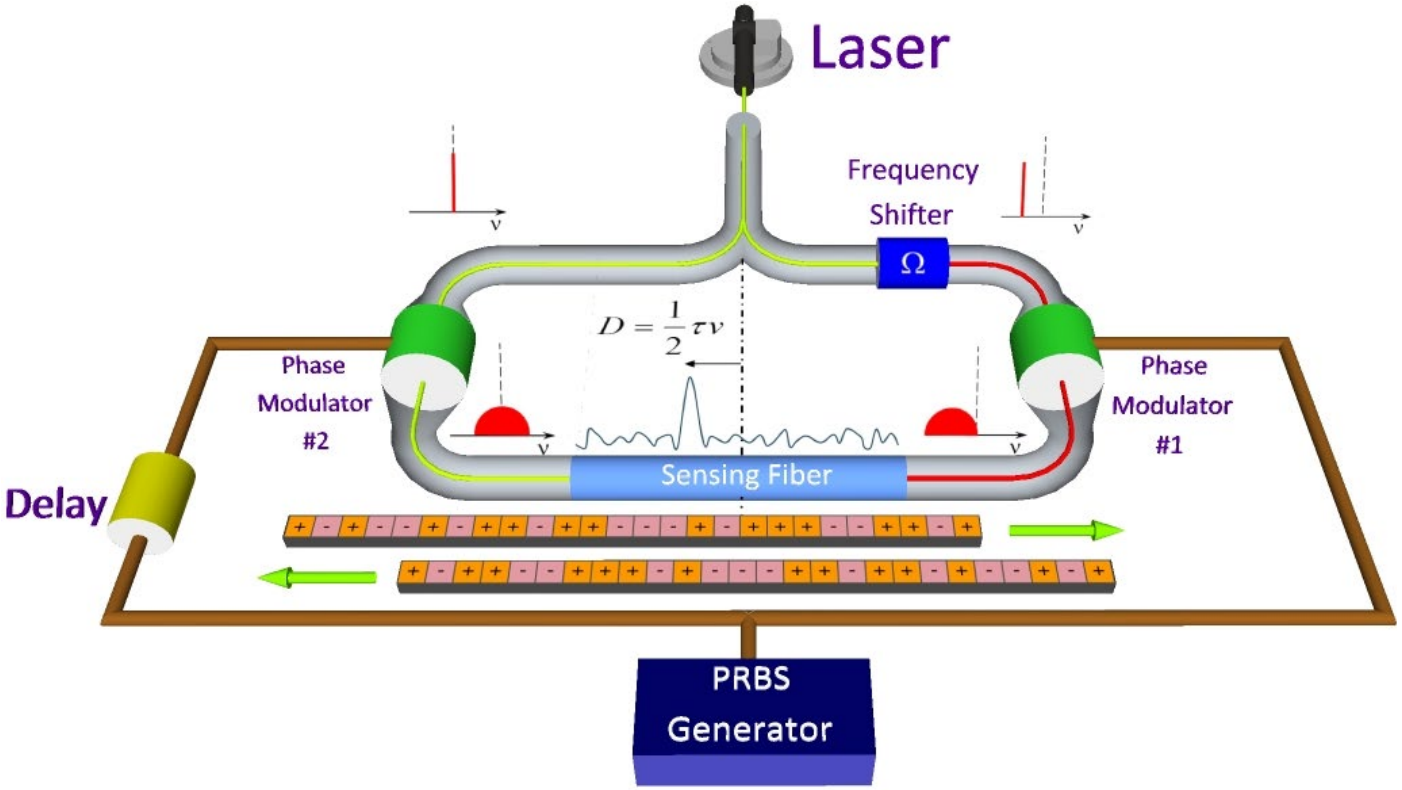
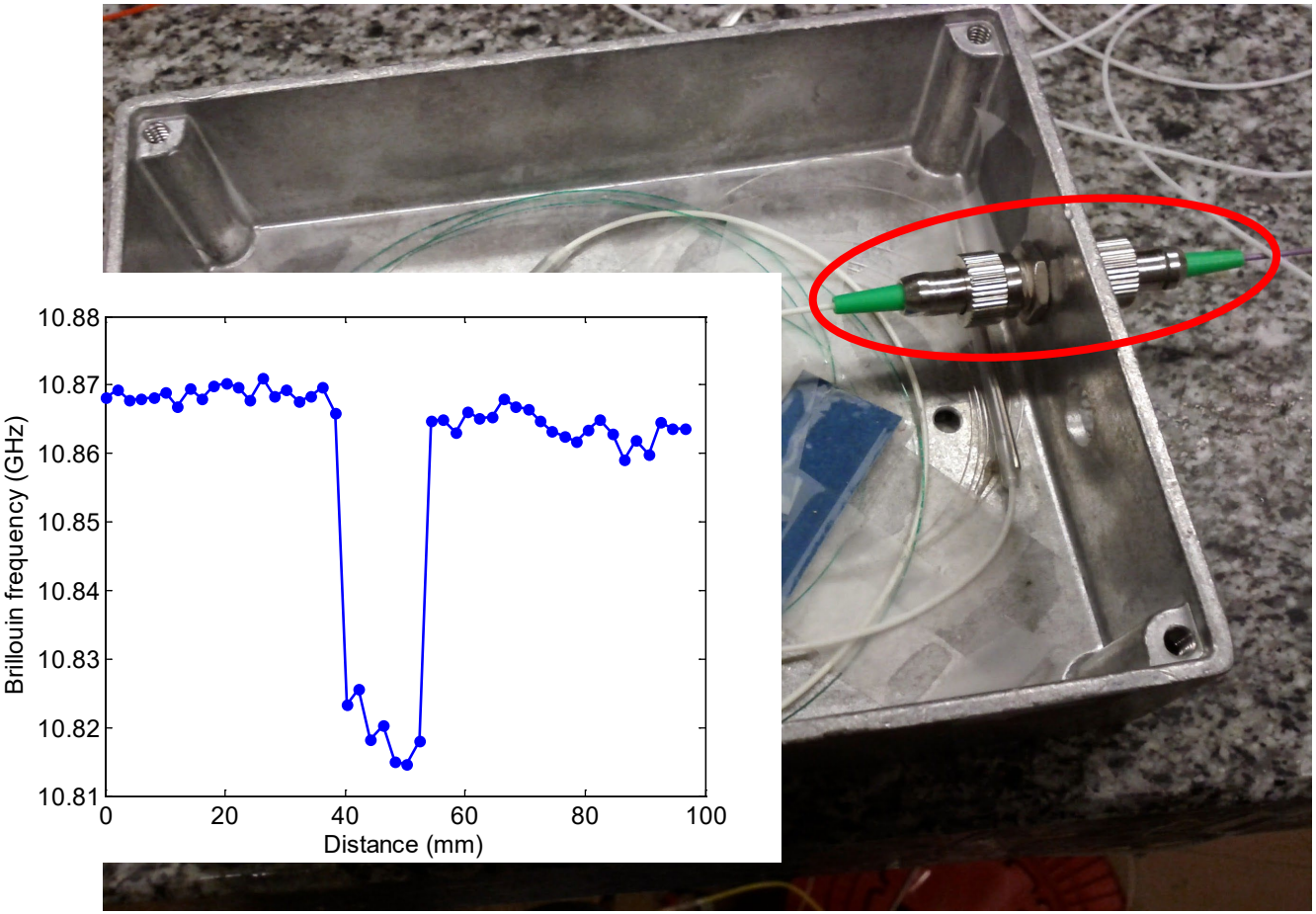


Generation of local stationary gratings



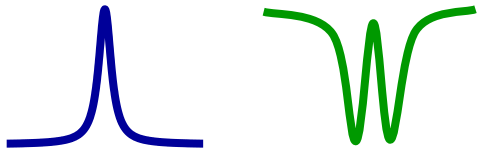
A. Zadok, Y. Antman, N. Primerov, A. Denisov, J. Sancho, and L. Thévenaz, "Random-access distributed fiber sensing," Laser & Photonics Reviews 6, L1–L5 (2012).

Example of fibre components inspection



What is slow & fast light?

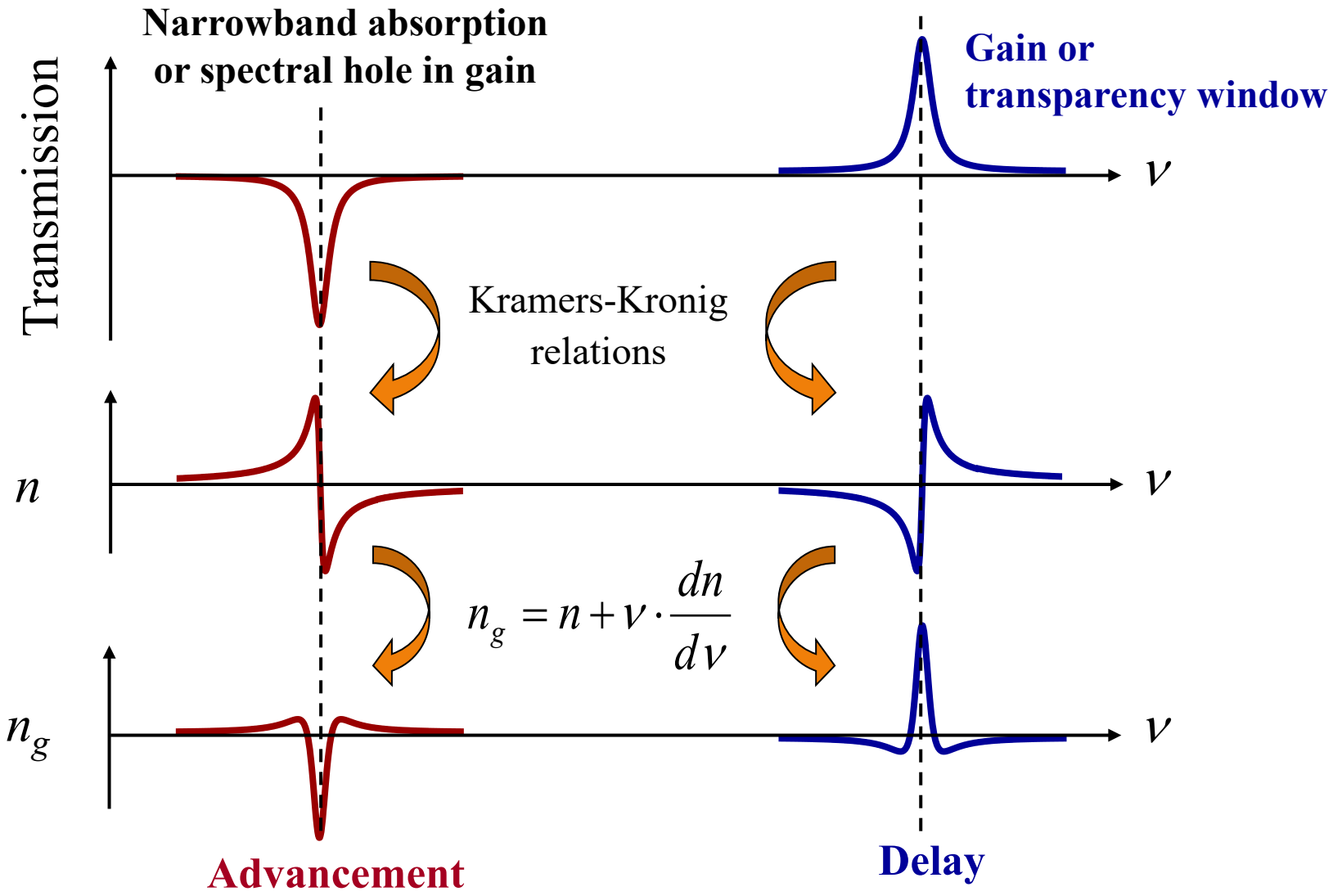
- **Slow & fast light** designates the possibility to modify the light **group velocity** by propagating the light in a medium showing **abrupt changes** in its **spectral transmission** (narrowband gain or loss)



- Even though **negative group velocities** were reported using **fast light**, this is a phenomenon entirely distinct from *negative refraction* since changes in phase velocity are normally very **minor** in slow & fast light.

- Slow & fast light offers the possibility to **delay** or **accelerate** optical *signals* and, if the narrowband spectral feature is generated by **optical pumping**, to control the **timing of an optical signal by light**.

How can we modify the group velocity?



Commonly shared vision on slow & fast light

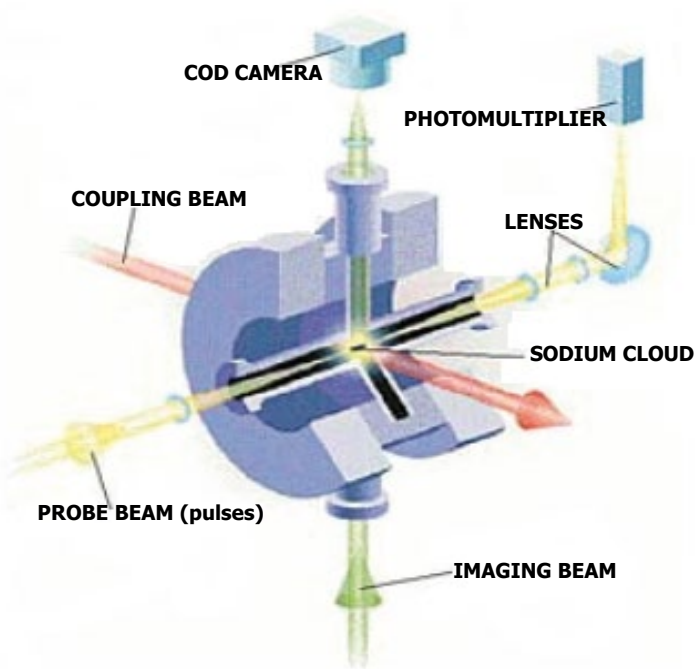
"The possibility of slowing or advancing light is very interesting since it can be potentially used for the development of fast-access memories and ***optically-controlled delay lines****. They are believed necessary for the development of the* ***future all-optical packet routers****."*

"Slow light has attracted significant interest recently as a potential solution for optical delay lines and time-domain optical signal processing. Perhaps even more significant is the possibility of dramatically ***enhancing nonlinear optical effects*** *due to the spatial compression of optical energy."*

Demonstration of slow light by Electromagnetically Induced Transparency

Light speed reduction to 17 metres per second in an ultracold atomic gas

Lene Vestergaard Hau*†, S. E. Harris‡, Zachary Dutton*† & Cyrus H. Behroozi*§



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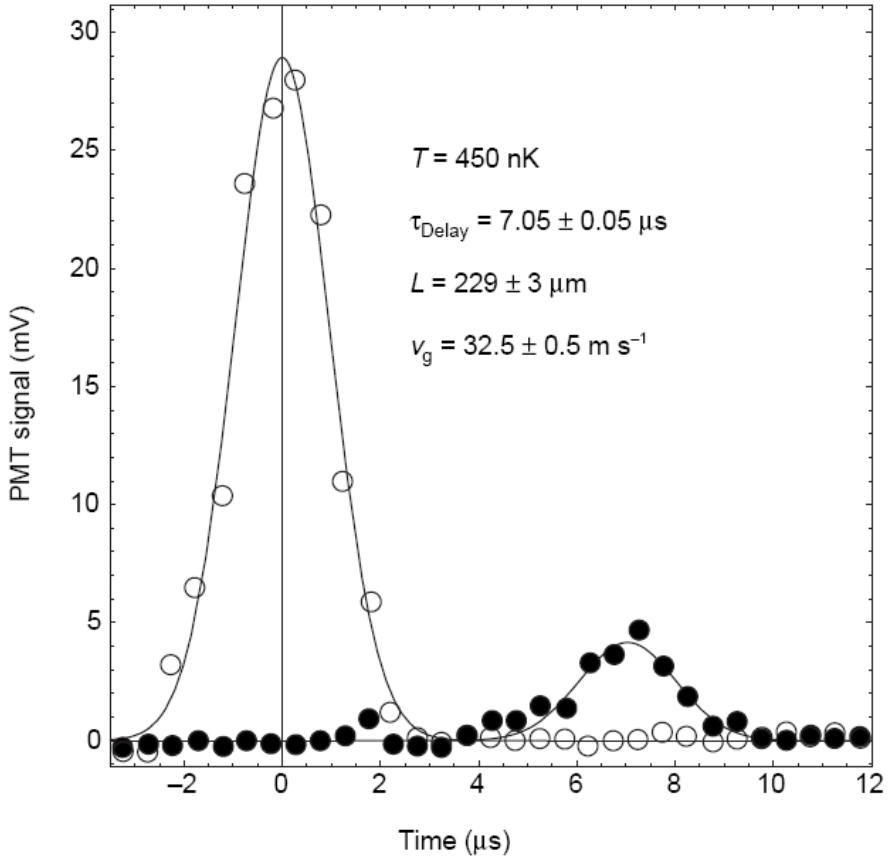
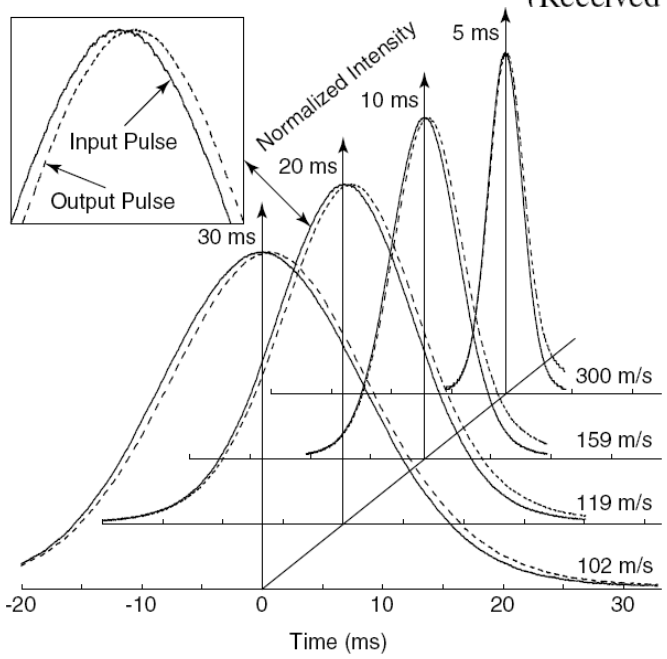


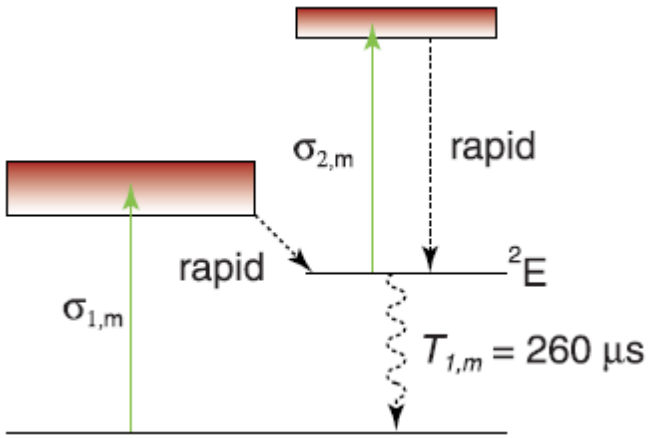
Demonstration of slow light by Coherent Population Oscillation

VOLUME 90, NUMBER 11 PHYSICAL REVIEW LETTERS week ending 21 MARCH 2003

Observation of Ultraslow Light Propagation in a Ruby Crystal at Room Temperature

Matthew S. Bigelow, Nick N. Lepeshkin, and Robert W. Boyd
The Institute of Optics, University of Rochester, Rochester, New York 14627
(Received 31 October 2002; published 21 March 2003)





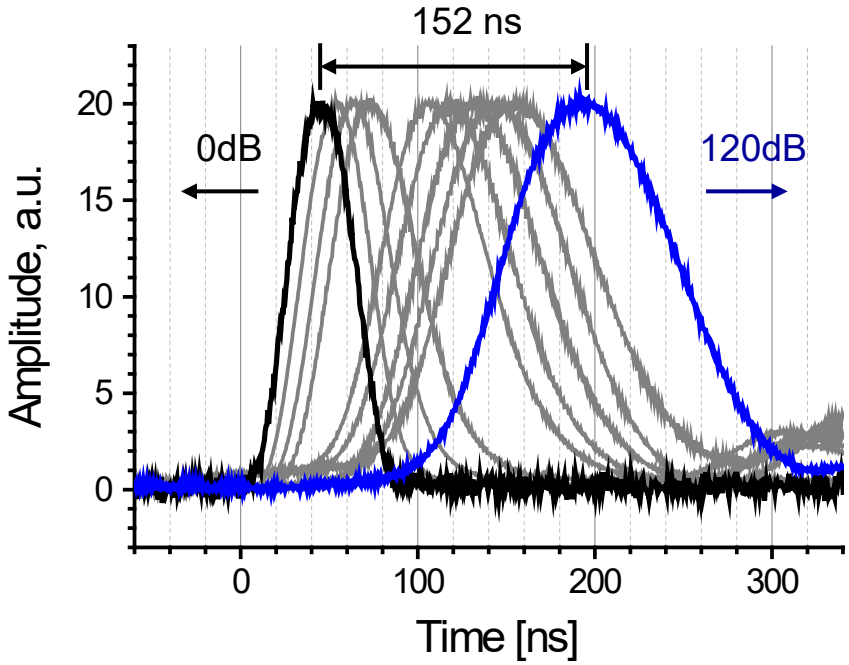
Demonstration of slow light in optical fibres

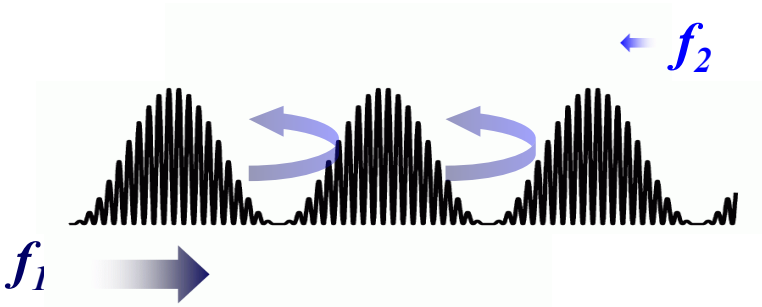
APPLIED PHYSICS LETTERS 87, 081113 (2005)

Optically controlled slow and fast light in optical fibers using stimulated Brillouin scattering

Miguel González-Herráez,[a] Kwang-Yong Song,[b] and Luc Thévenaz
Nanophotonics and Metrology Laboratory, Ecole Polytechnique Federale de Lausanne, STI-NAM Section 11, Lausanne CH-1015, Switzerland.

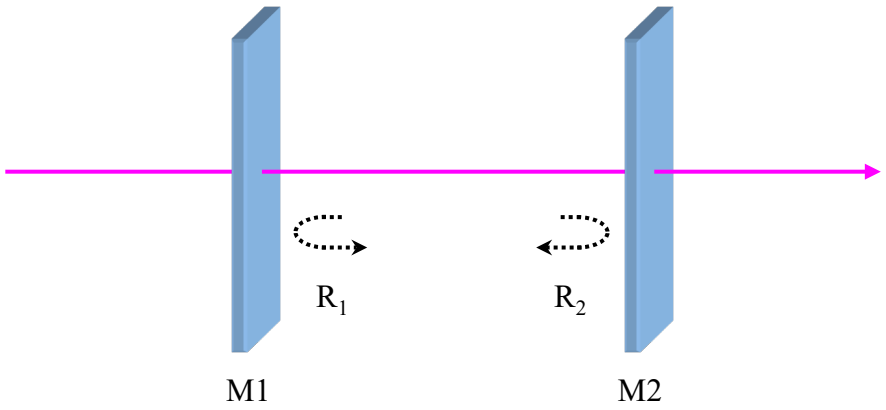
(Received 18 January 2005; accepted 6 July 2005; published online 18 August 2005)





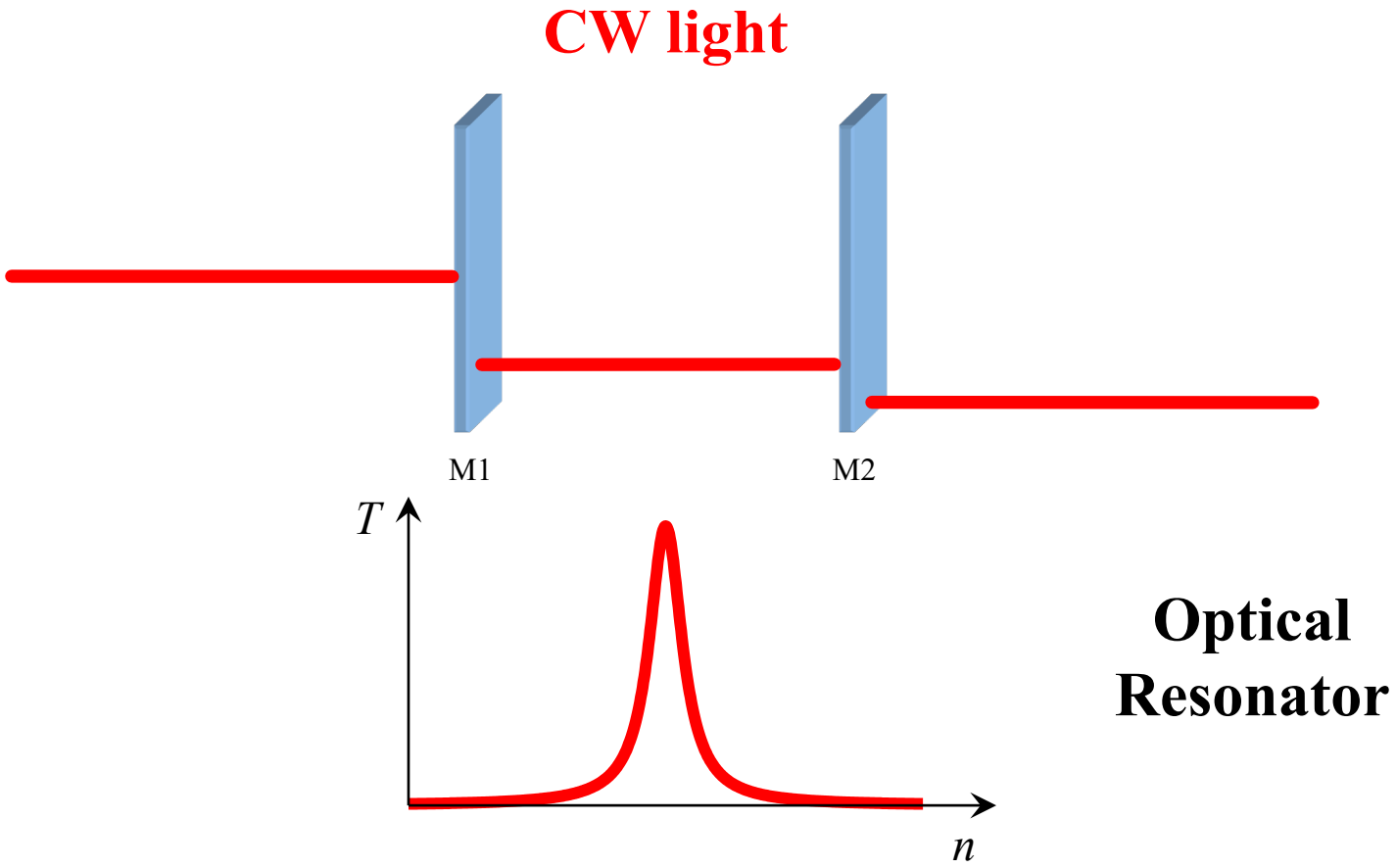
Slow light present in any causal resonant systems

Light propagation through an optical cavity

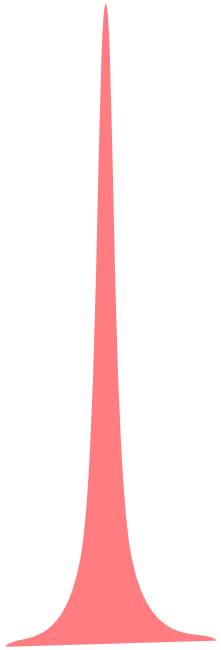


Slow light present in any causal resonant systems

Light propagation through an optical cavity

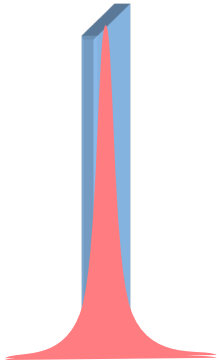


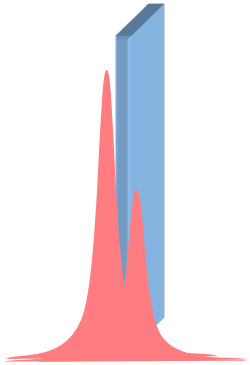
Slow light present in any causal resonant systems

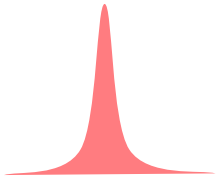


Light propagation through an optical cavity

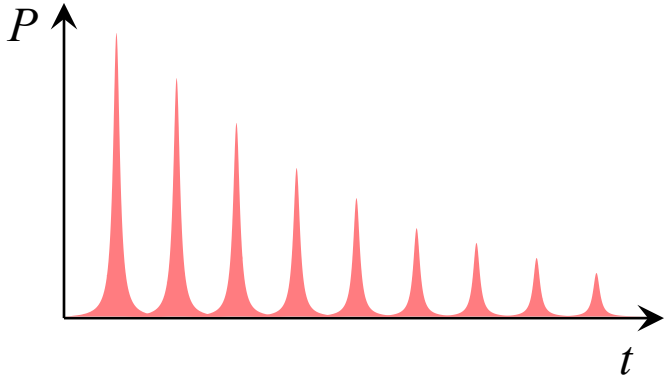
Short light pulses







M1 M2

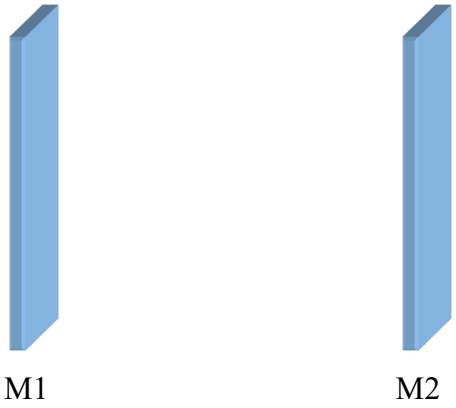


Cavity Ringdown

Slow light present in any causal resonant systems

Light propagation through an optical cavity

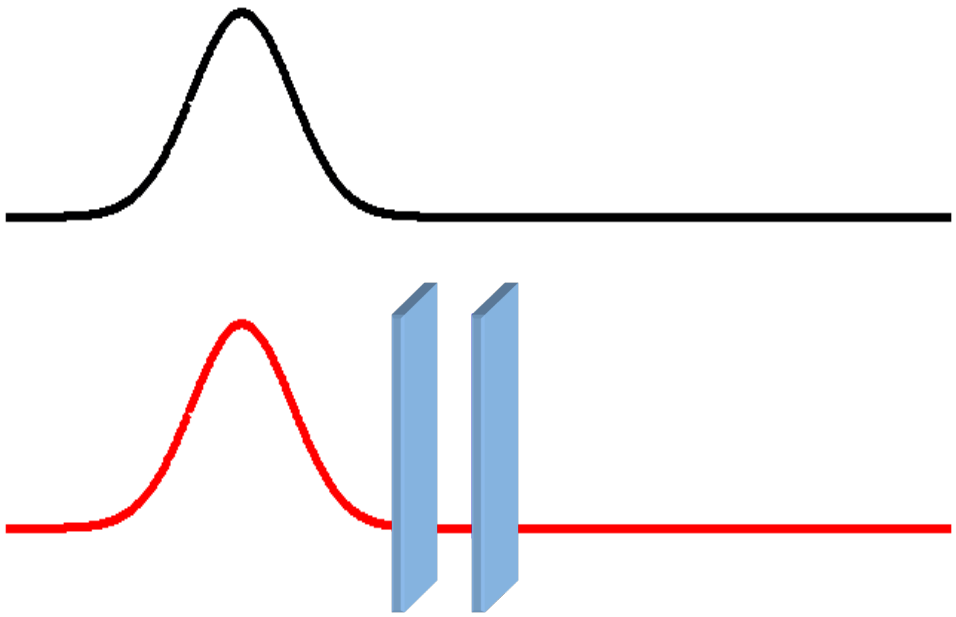
Long resonant pulses



Slow light present in any causal resonant systems

Light propagation through an optical cavity

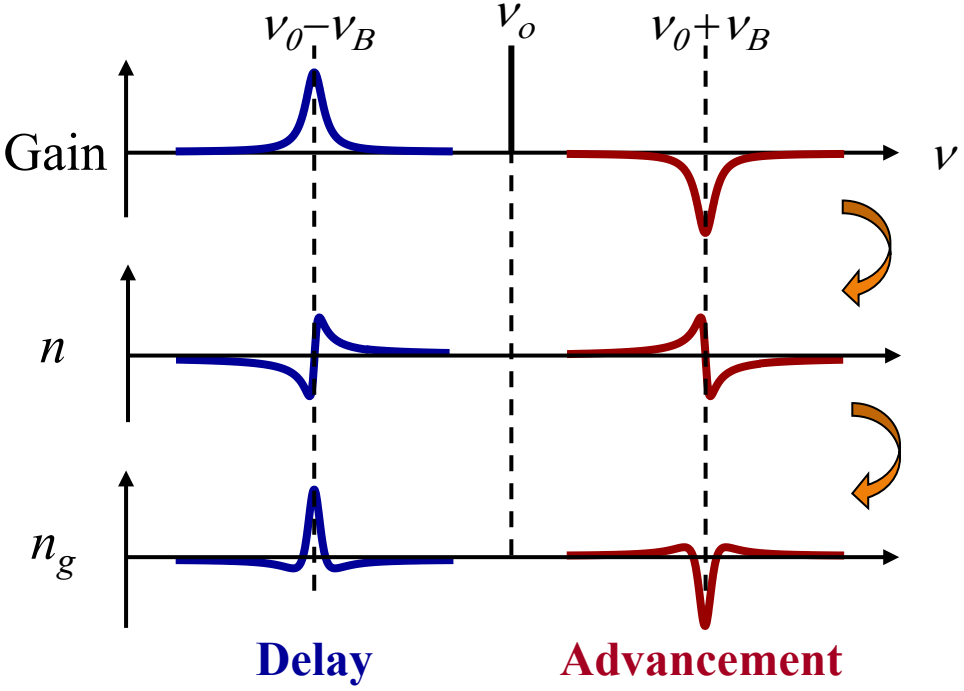
Long resonant pulses

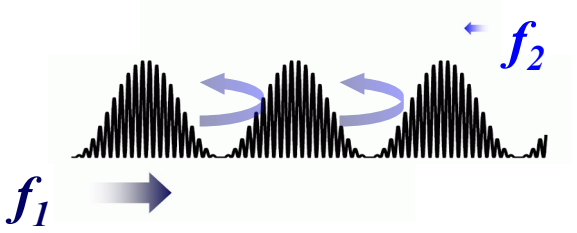


Delaying ➔ **Slow light!**

Slow & Fast Light in Optical Fibres

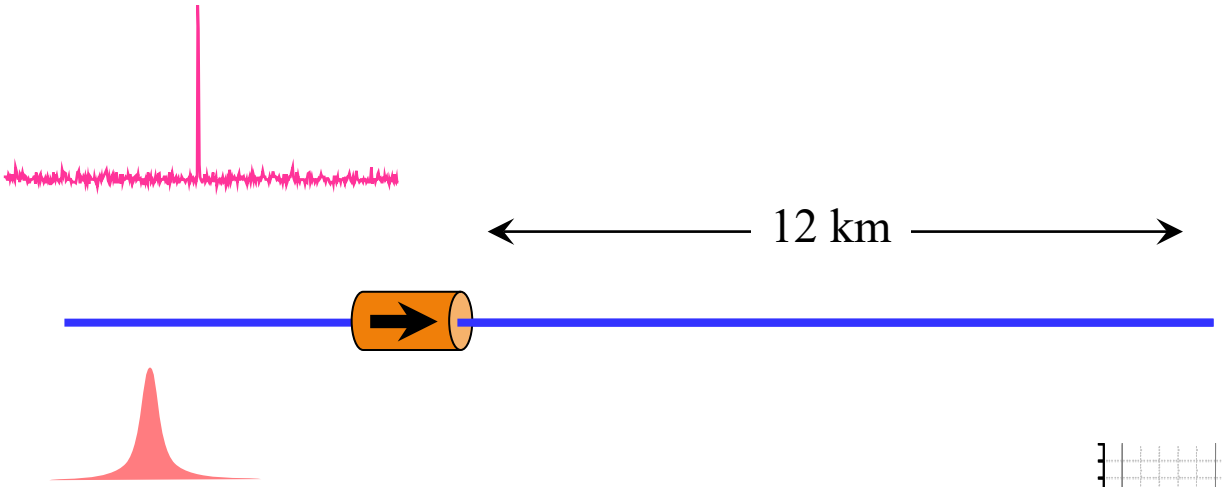
- How can this be achieved in optical fibres?
  - ➔ The challenge was to find a narrow-band interaction in such a highly disordered medium.
- The solution is given by **Stimulated Brillouin Scattering** that can be viewed as a **narrowband gain** (for f_2) or **loss** (for f_1) process





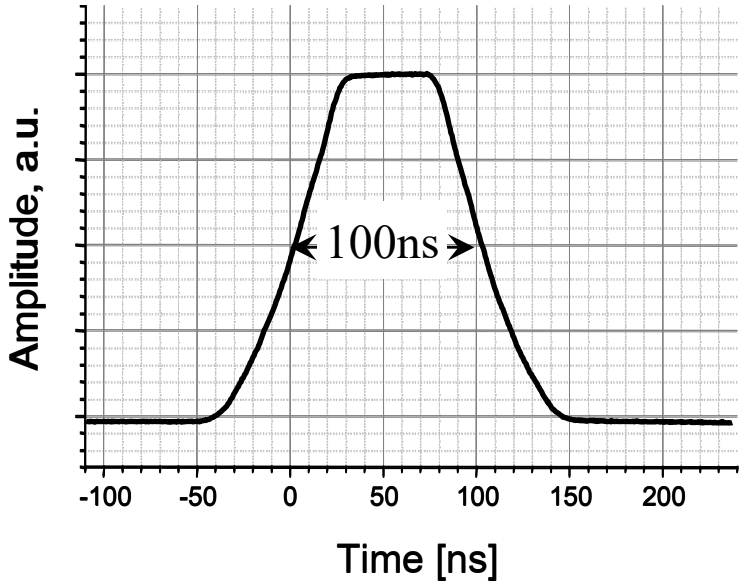
- A pulse propagating along a fibre while undergoing significant **Brillouin gain** or **loss** during the propagation can be **delayed** or **advanced**.

Slow light fibre delay line

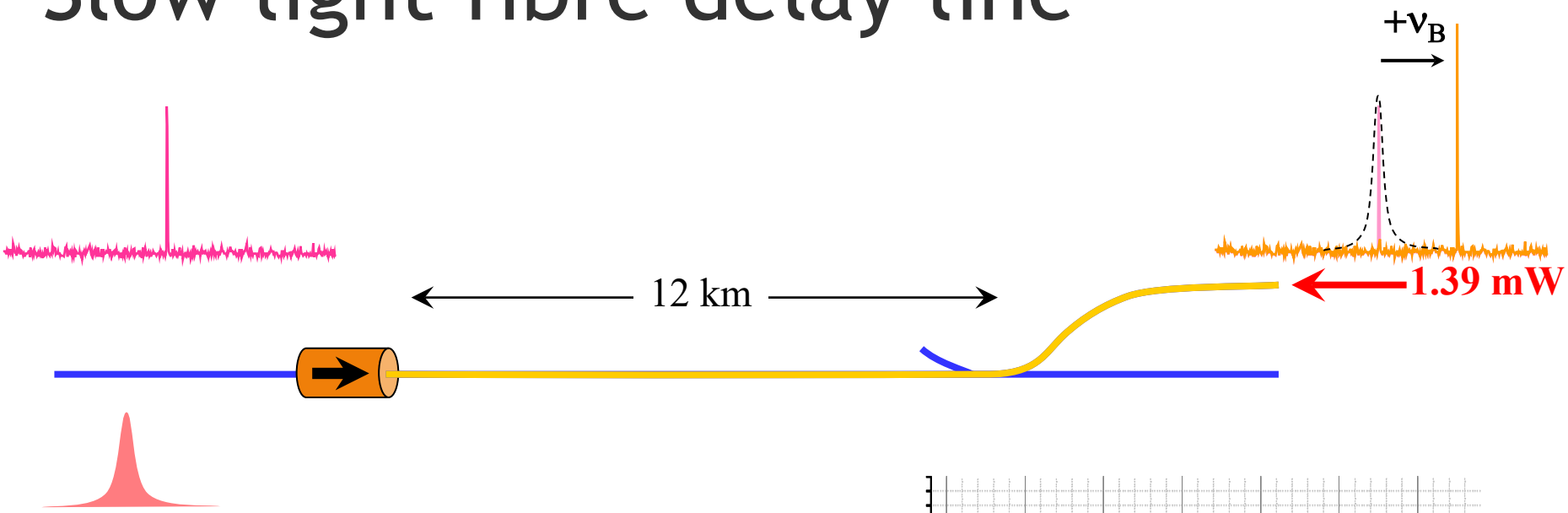


Gain: **0 dB**

Delay: **0 ns**

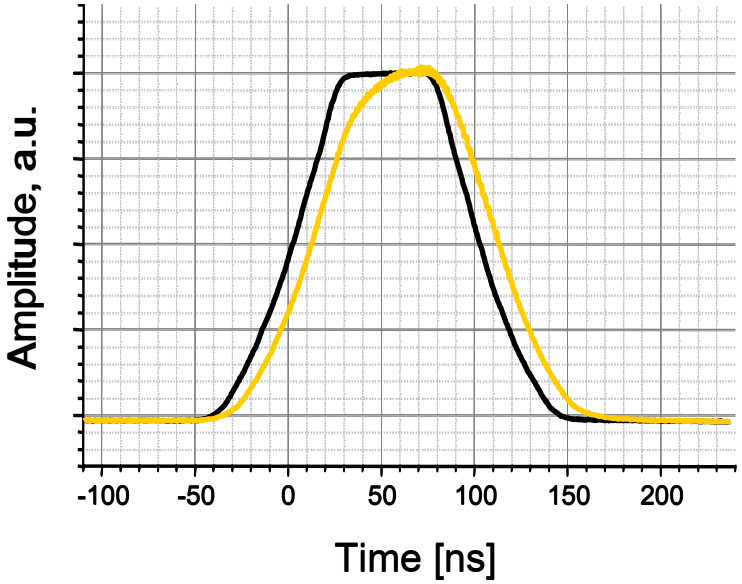


Slow light fibre delay line

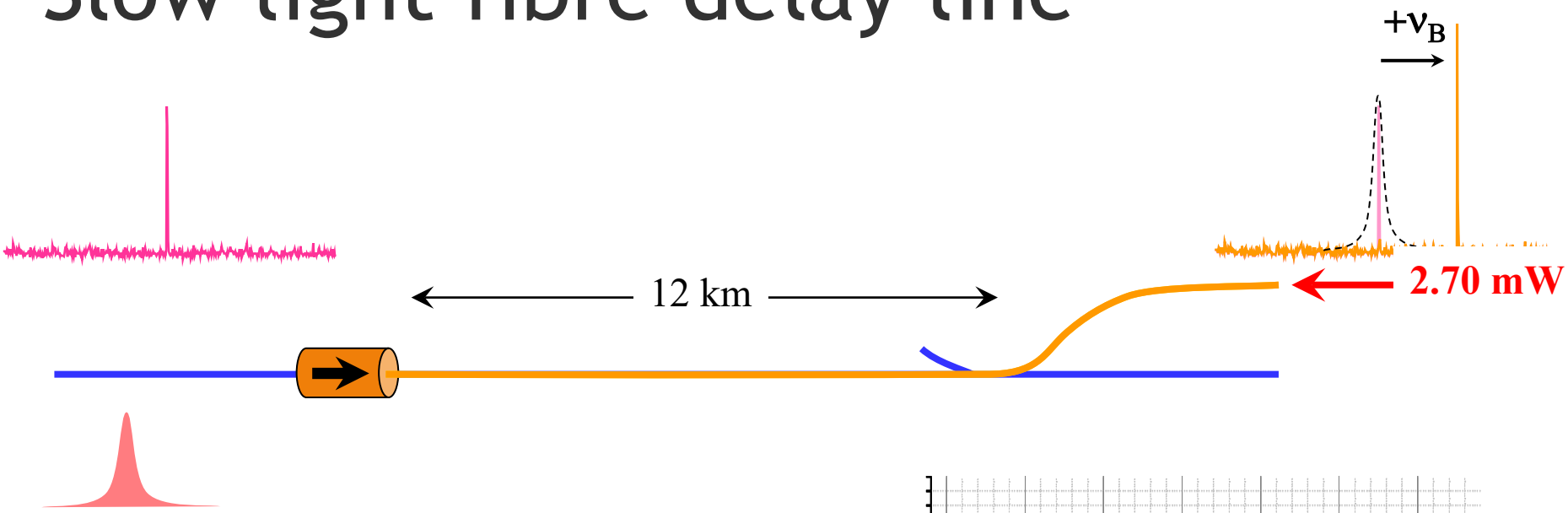


Gain: **10 dB**

Delay: **10.03 ns**

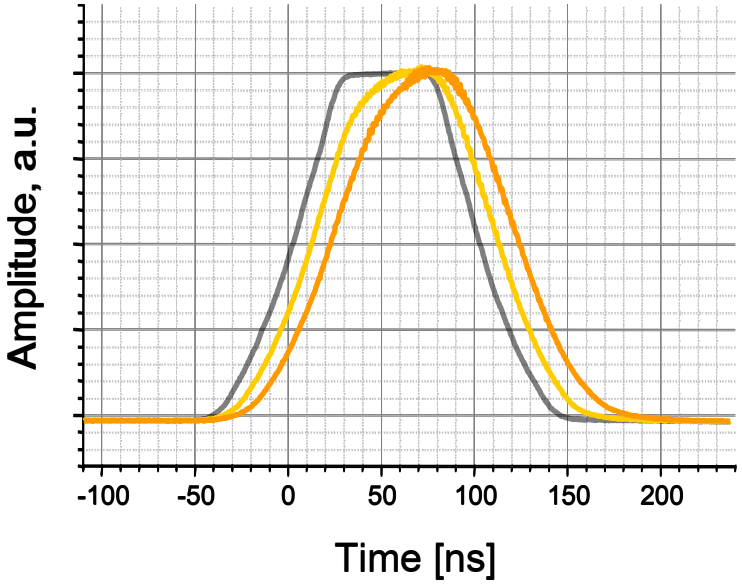


Slow light fibre delay line

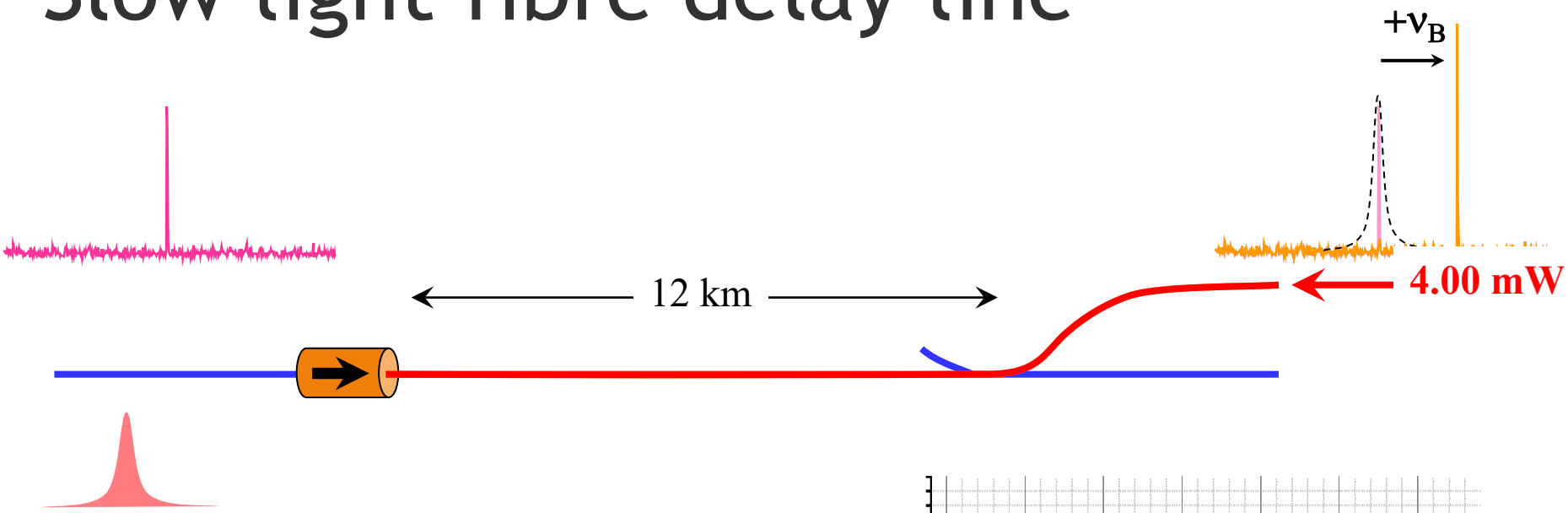


Gain: **20 dB**

Delay: **20.43 ns**

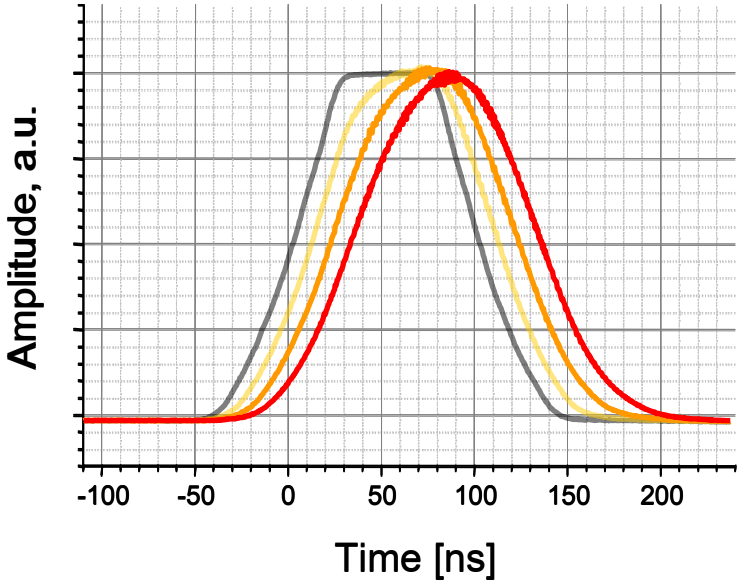


Slow light fibre delay line

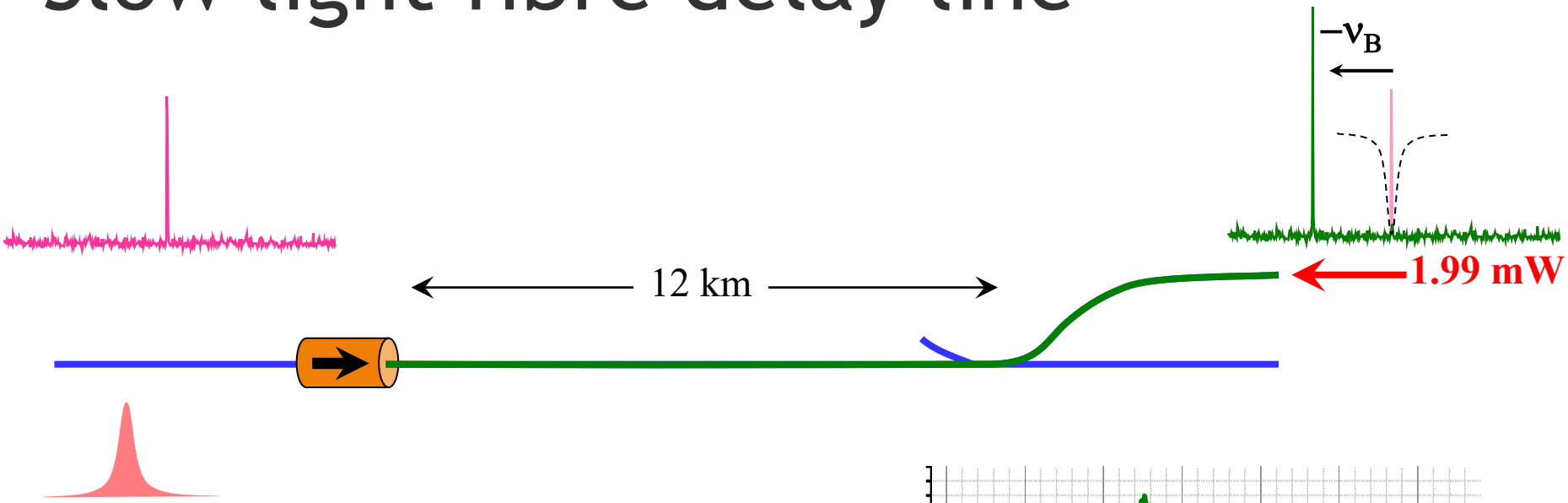


Gain: **30 dB**

Delay: **31.67 ns**

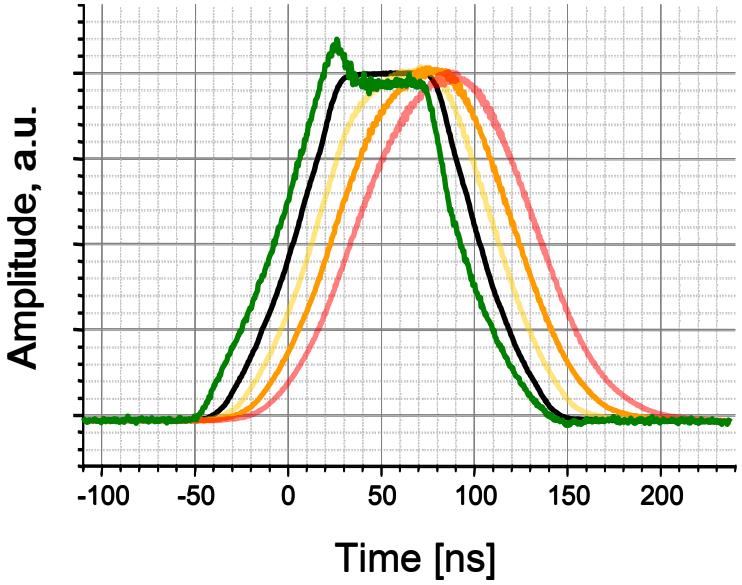


Slow light fibre delay line



Loss: **-12 dB**

Delay: **-8.35 ns**



Theoretical estimation

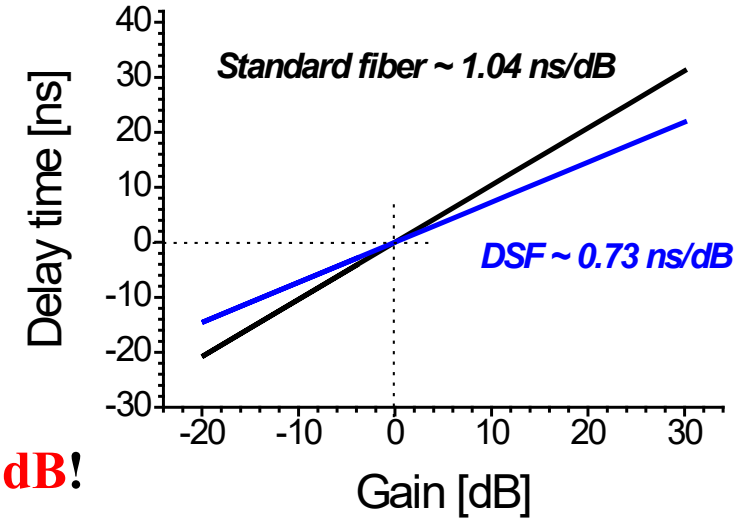
- Signal envelope in a gain medium is expressed as: $A_s(z) = A_s(0)\,\mathrm{e}^{\frac{G(z)}{2} - j\Phi(z)}\,\mathrm{e}^{-\frac{\alpha}{2}z}$
- For a Lorentzian spectral line, **gain** and **phase shift** read:

$$G(z,\nu) = g_B \frac{1}{1+\left(\frac{\nu-\nu_B}{\Delta\nu_B/2}\right)^2} I_o\,\mathrm{e}^{-\alpha L}\frac{\mathrm{e}^{\alpha z}-1}{\alpha} \quad ; \quad \Phi(z,\nu) = \frac{1}{2} g_B \frac{\frac{\nu-\nu_B}{\Delta\nu_B/2}}{1+\left(\frac{\nu-\nu_B}{\Delta\nu_B/2}\right)^2} I_o\,\mathrm{e}^{-\alpha L}\frac{\mathrm{e}^{\alpha z}-1}{\alpha}$$

- At the output $z=L$ and with the signal spectrum at the centre of the line $\nu=\nu_B$:

$$G = g_B\, I_o\, L_{eff} \qquad \text{with} \quad L_{eff} = \frac{1-\mathrm{e}^{-\alpha L}}{\alpha}$$

$$\Delta T = \Delta n_g \frac{L}{c} = g_B\, I_o\, L_{eff} \frac{1}{2\pi\,\Delta\nu_B} = G\frac{1}{2\pi\,\Delta\nu_B}$$



➡ Delay is larger for **narrow** lines and only depends linearly on the amount of **gain in dB**!

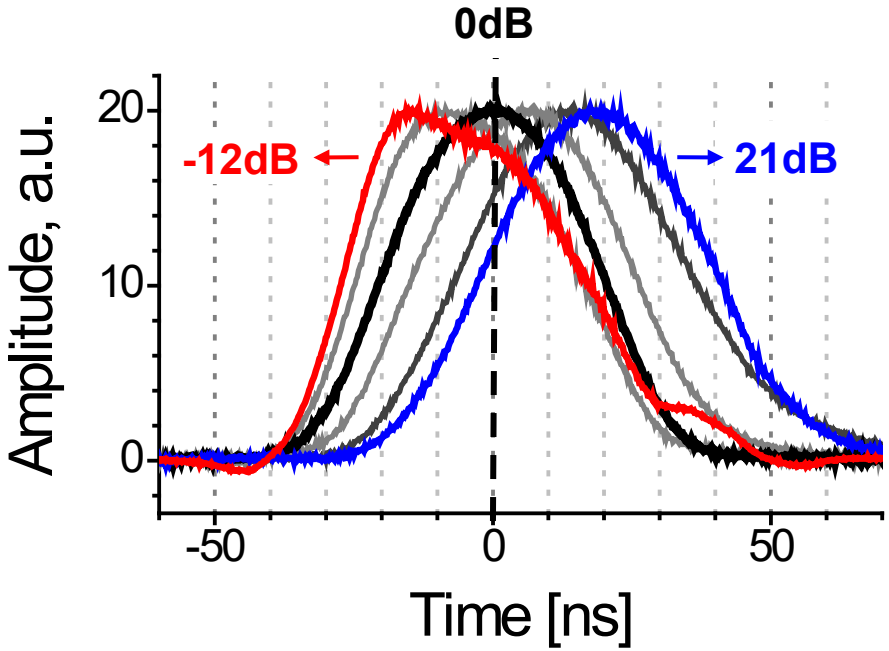
Realization of large group index change

Delay: $\Delta T = \Delta n_g \frac{L}{c} = G \frac{1}{2\pi \Delta \nu_B}$

$$\Delta n_g = \Delta T \frac{c}{L} = \frac{G}{L} \frac{c}{2\pi \Delta \nu_B}$$

- Unity change of group index is possible a in meter-long fibre.
- The challenge is to achieve a high gain on a short distance.
- This is possible using pump power in the 10W range.

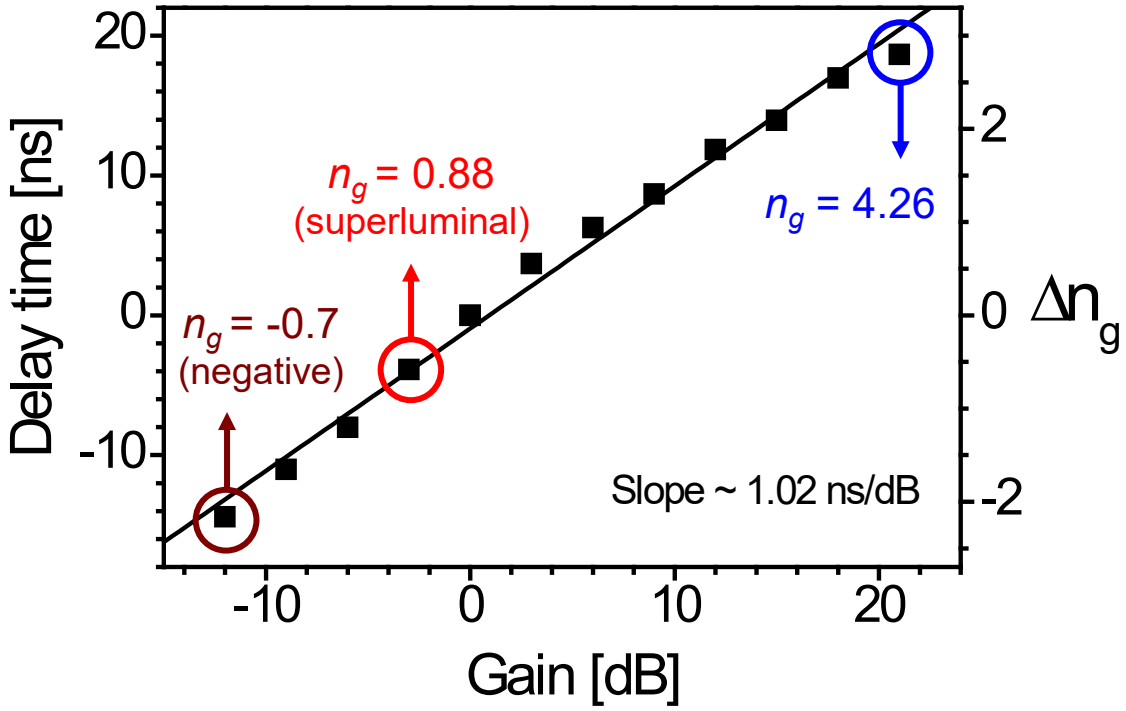
Delaying & Advancement in a short fibre



- Pulse delaying from **-14.4 ns to +18.6 ns** is realized in a **2-m** standard fibre, which corresponds to a change of the propagation length from -3 m to +3.8 m
- Strong distortion of steeper leading edge and longer trailing edge is observed in the case of large advancement.

M. Gonzalez-Herraez, K.Y. Song, L.Thévenaz, Applied Physics Letters **87** 081113 (2005)

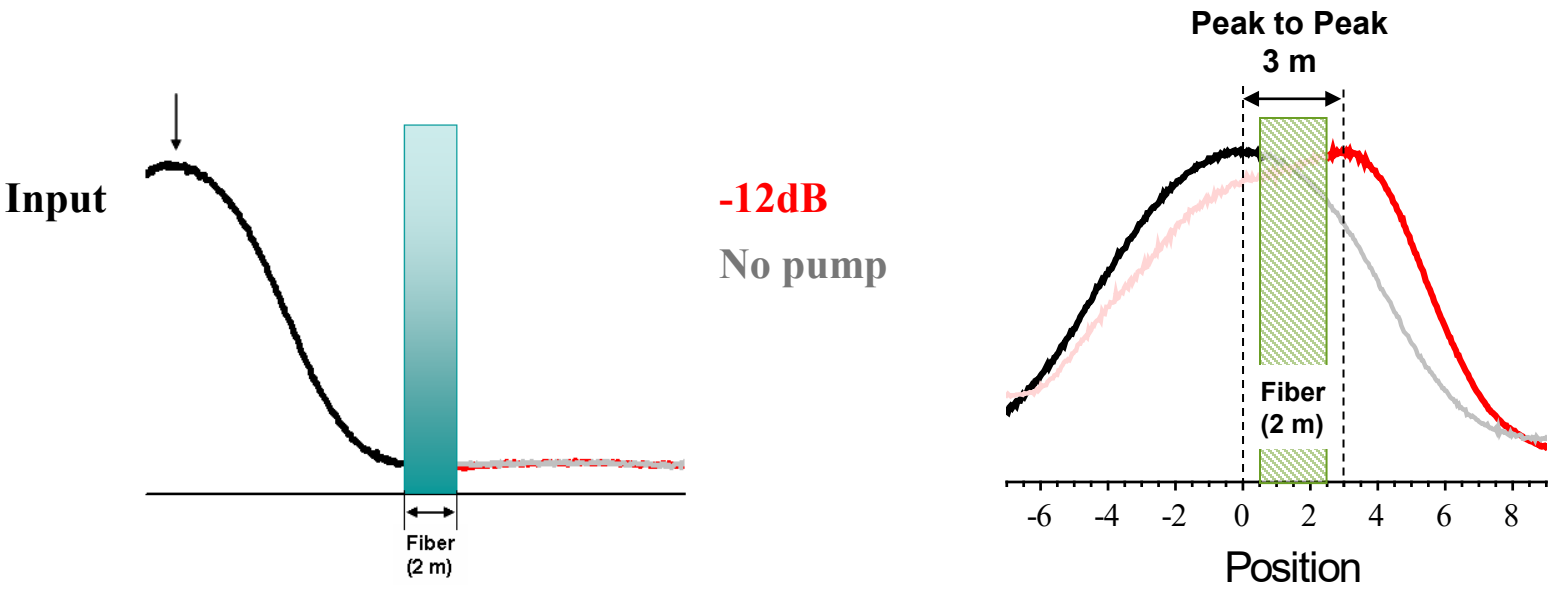
Delaying & Advancement in a short fibre



- Δn_g is continuously varied from -2.16 to +2.8, which corresponds to n_g from **-0.7** to **+4.26**.

M. Gonzalez-Herraez, K.Y. Song, L.Thévenaz, Applied Physics Letters **87** 081113 (2005)

Pulse propagation in negative group index



➡ **The peak of the pulse exits before it enters the fiber !**

M. Gonzalez-Herraez, K.Y. Song, L.Thévenaz, Applied Physics Letters **87** 081113 (2005)

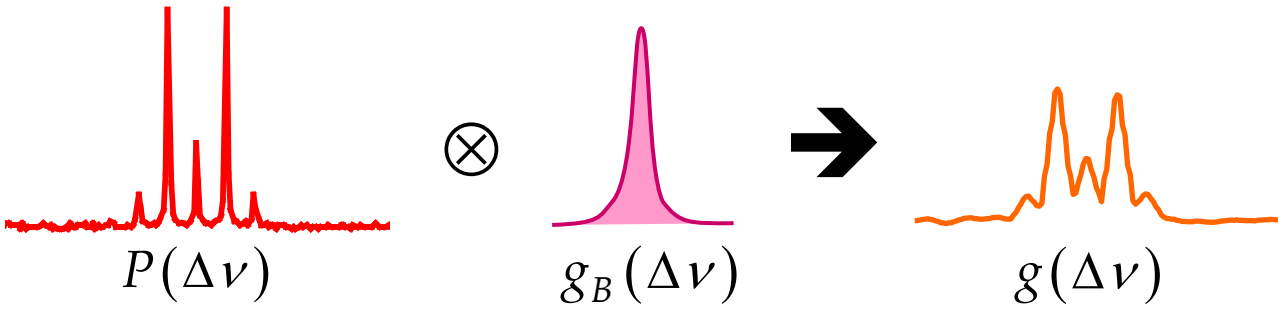
Principle of spectral tailoring using SBS

- Amplification through SBS is a **linear** transformation:

$$dE_s = \frac{1}{2} g(\nu) E_p^* E_p E_s \; dz = \frac{1}{2} g(\nu) I_p E_s \; dz$$

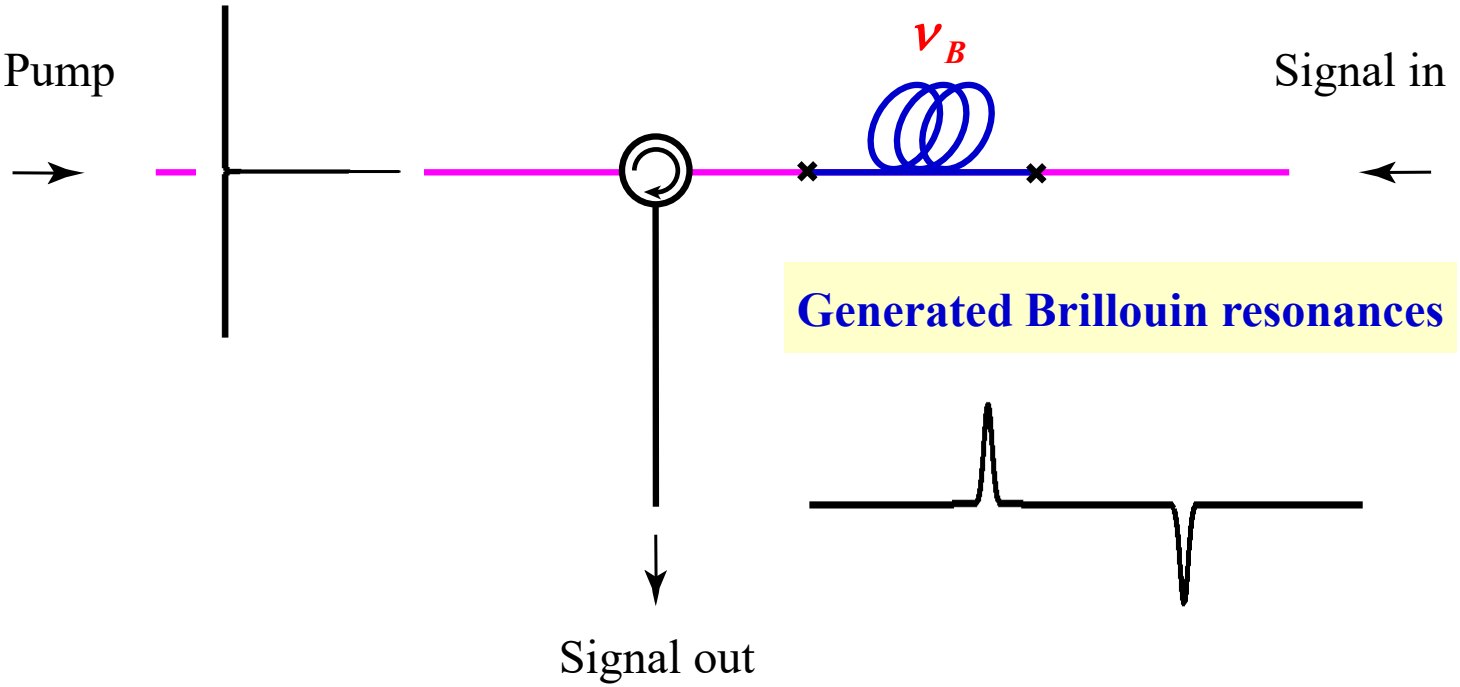
- Effective Brillouin gain spectrum $g(\Delta\nu)$ is given by the **convolution** of the natural Brillouin gain spectrum $g_B(\Delta\nu)$ with the pump source spectrum $P(\Delta\nu)$:

$$g(\Delta\nu) = P(\Delta\nu) \otimes g_B(\Delta\nu)$$

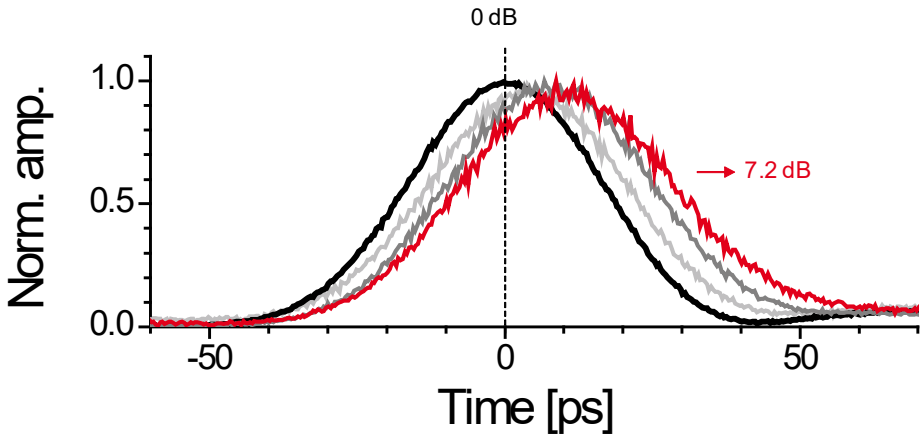


- For a pump source spectrum much broader than the natural Brillouin linewidth, the **effective gain spectrum maps closely the pump spectrum**.
- This gives the possibility to **synthesize** a wide range of original and optimized gain or loss spectral distribution.

Broadband slow & fast light using SBS



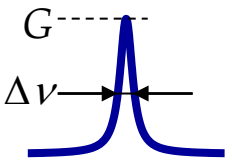
- Maximal bandwidth limited by the overlapping of the gain and loss spectra ➔ ~ 11 GHz



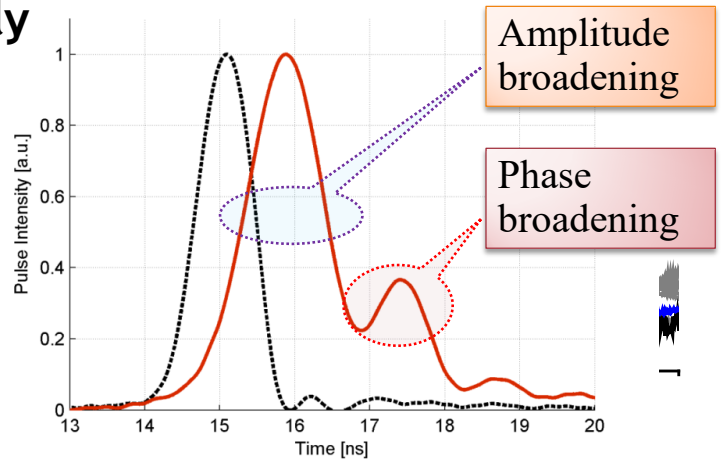
Fundamental limitations to timing power

- **Signal delay or advancement are directly function of the resonance properties:**

$$\Delta T = \Delta n_g \frac{L}{c} = G \frac{1}{2\pi \Delta \nu}$$



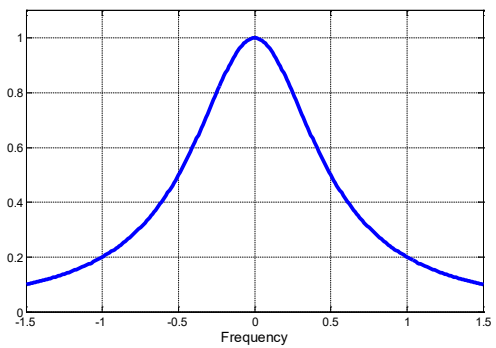
- **Delaying turns out to be intrinsically accompanied by distortion:**

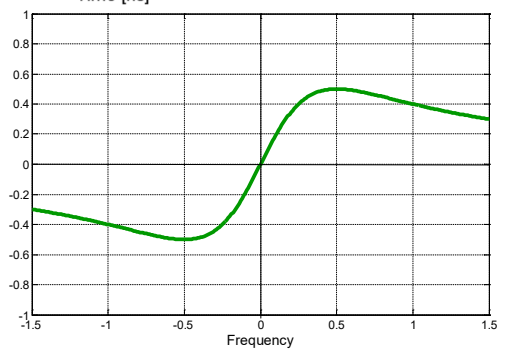


- **Distortion results from 2 causes:**
  - **Amplitude low-pass filtering**
  - **Nonlinear phase response**

- **Practically:**

Delay × *Bandwidth* ≃ 1





Amplitude and phase responses

In a medium showing a **microscopic** response, real and imaginary parts of the transfer function can be associated to amplitude and phase responses:

$$dA(\omega,z) = T(\omega)\,A(\omega,z)\,dz = [G(\omega) + i\,\Phi(\omega)]A(\omega,z)\,dz$$

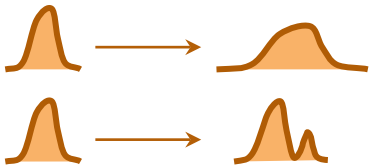
$$\rightarrow \quad A(\omega,z) = A(\omega,0)\,e^{[G(\omega)+i\Phi(\omega)]z} = A(\omega,0)\,e^{G(\omega)z}\,e^{i\Phi(\omega)z}$$

Real part: $G(\omega) = G_o + G_2(\omega-\omega_o)^2 + G_4(\omega-\omega_o)^4 + \ldots$ Even terms

Imaginary part: $\Phi(\omega) = \Phi_1(\omega-\omega_o) + \Phi_3(\omega-\omega_o)^3 + \ldots$ Odd terms

$G_2(w)$ is responsible for amplitude distortion (gain broadening).

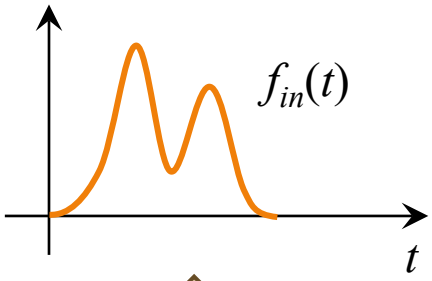
$\Phi_3(w)$ is responsible for phase distortion (dispersion broadening).

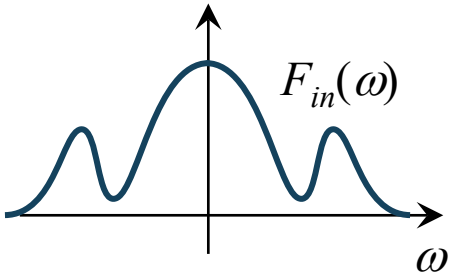


In a **macroscopic** medium (structural slow light), real and imaginary parts of the transfer function can no longer be strictly identified to amplitude and phase responses, but the following theory can be easily extended to that case.

Basics in linear time-invariant systems

$f_{in}(t) \rightarrow f_{out}(t)$ $\quad$ $c_1 f_{in}(t_1)+c_2 f_{in}(t_2) \rightarrow c_1 f_{out}(t_1)+c_2 f_{out}(t_2)$ $\quad$ $f_{in}(t-T) \rightarrow f_{out}(t-T)$





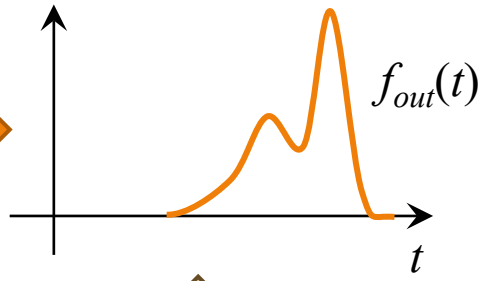
$$f_{out}(t)=\int_{-\infty}^{+\infty} f_{in}(t-t')\,h(t')\,dt'$$

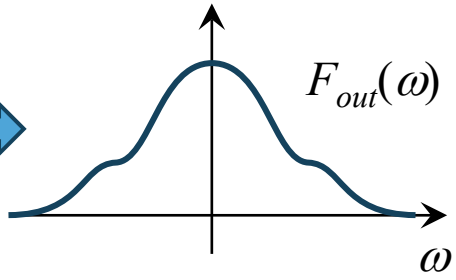
$h(t)$: **Impulse response**

Linear system

$$F_{out}(\omega)=T(\omega)F_{in}(\omega)$$

$T(\omega)$: **Transfer function**

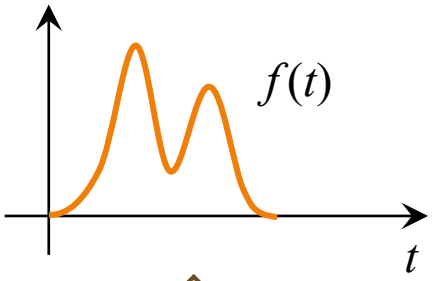


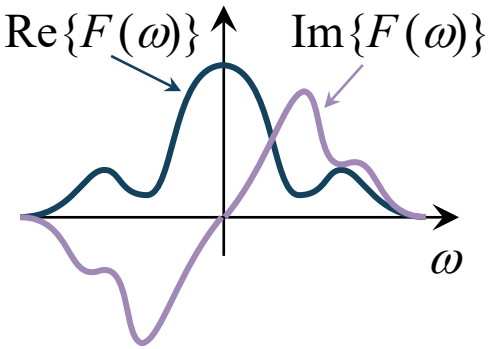


$$T(\omega)=FT\{h(t)\}$$

Strong analytic signal

- Real signal

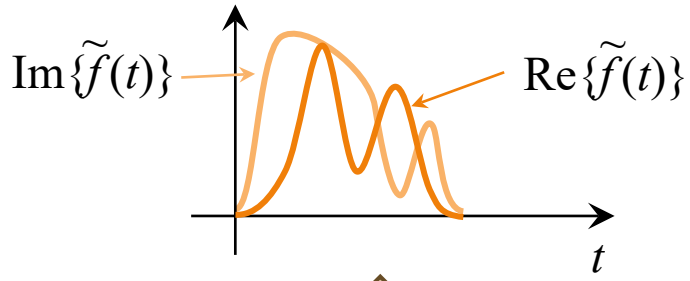


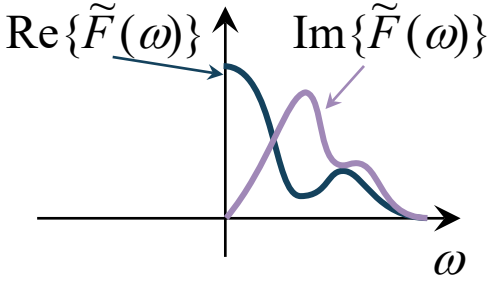


Spectral distribution is **Hermitian**

$f(t)=\mathrm{Re}\{\tilde{f}(t)\}$

- Analytic signal





Positive only spectrum

Strong analytic signal

$$f(t)=a\cos\omega t \quad \rightarrow \quad \tilde{f}(t)=a\,e^{j\omega t}$$

Let $\tilde{f}(t)=f(t)+j\,\hat{f}(t)$

with $$\hat{f}(t)=\frac{1}{\pi}\mathrm{P}\int_{-\infty}^{+\infty}\frac{f(t')}{t-t'}dt'$$

$$=\lim_{\varepsilon\to 0^+}\left(\frac{1}{\pi}\int_{-\infty}^{\varepsilon}\frac{f(t')}{t-t'}dt'+\int_{-\varepsilon}^{+\infty}\frac{f(t')}{t-t'}\right)$$

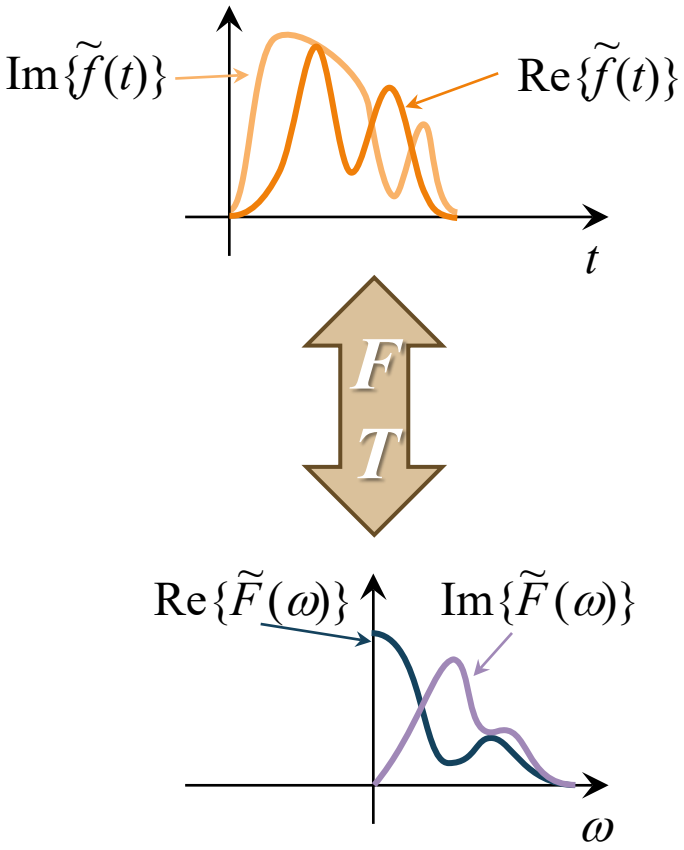
$$=H\{f(t)\}$$

Hilbert transform of $f(t)$

equivalent to apply a π/2 phase shift on all frequency components of the signal.

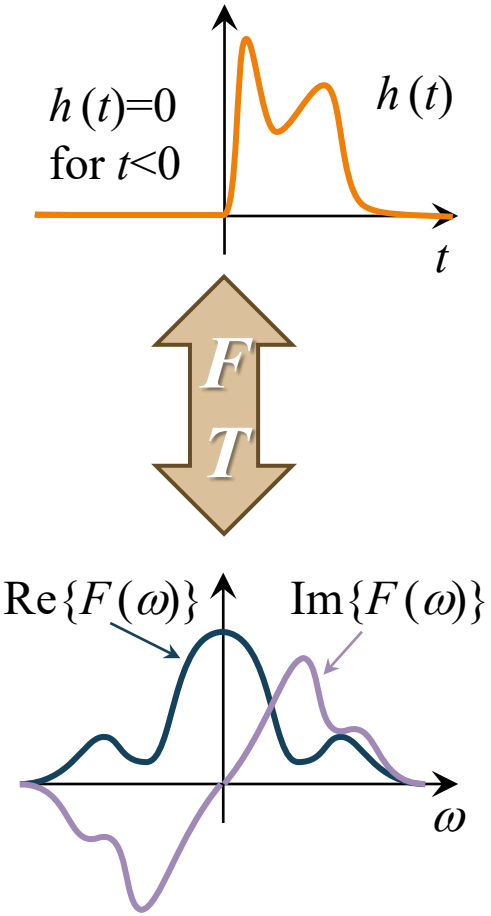
Tool to suppress the negative part of the transformed function in the conjugate space.

- Analytic signal



Positive only spectrum

Causal linear real system



The causality requires no negative part on the impulse response.

➔ Real and imaginary parts of the transfer function are related by a **Hilbert transform**:

$$\mathrm{Im}\{F(\omega)\}=\mathrm{H}\{\mathrm{Re}\{F(\omega)\}\}$$

➔ In any causal real system real and imaginary parts of the transfer function are fully **interdependent**.

➔ In an optical medium this property is the background for the **Kramers-Kronig relations**.

Kramers-Kronig relations

In a medium showing a **microscopic** response, the real and imaginary parts of the transfer function can be associated to the amplitude and phase response:

$$A(\omega, z+dz) = A(\omega, z) + [\frac{g(w)}{2} + i\phi(w)]A(\omega, z)dz = \left\{1 + [\frac{g(w)}{2} + i\phi(w)]dz\right\} A(\omega, z)$$

$g(\omega)$: linear gain (loss if <0) $\qquad \phi(\omega) = k_o n(\omega) = \frac{\omega}{c_o} n(\omega)$: linear phase

For g and ϕ independent of z: $\quad A(\omega, L) = \mathrm{e}^{\frac{1}{2}gL}\, \mathrm{e}^{jk_o nL}\, A(\omega, 0)$

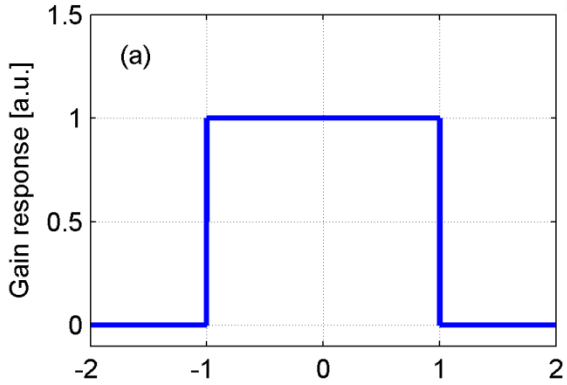
As a result of causality, amplitude and phase responses are related by Hilbert transforms:

$$\frac{g(\omega)}{2} = -\frac{1}{\pi c_o} \int_{-\infty}^{\infty} \frac{\omega' n(\omega')}{\omega - \omega'} d\omega'$$

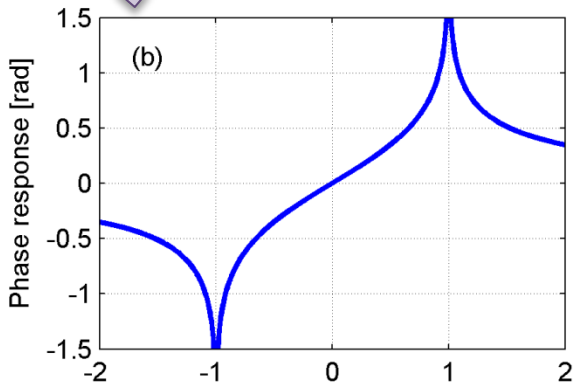
$$\frac{\omega n(\omega)}{c_o} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{g(\omega')}{\omega - \omega'} d\omega'$$

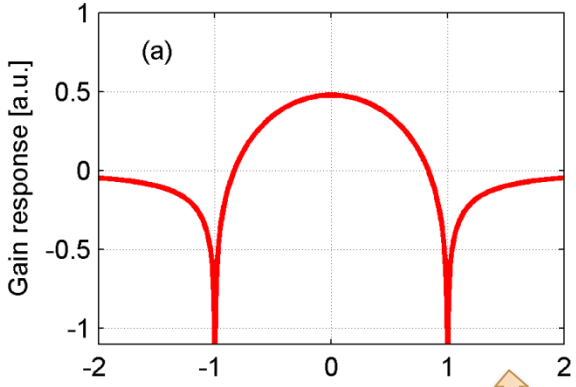
Delaying with no distortion?

Free of amplitude distortion

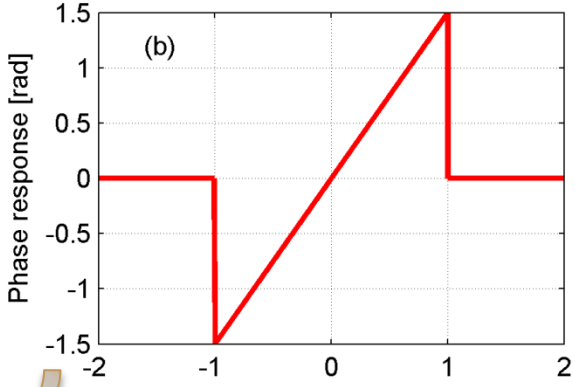


Hilbert Transform





Inverse Hilbert Transform



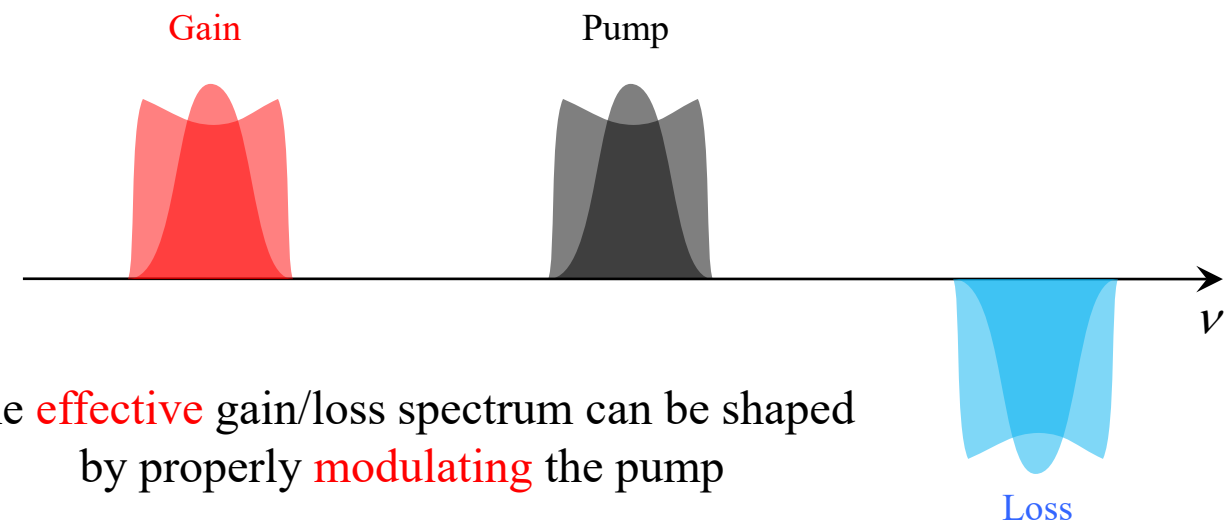
Free of phase distortion

Amplitude and phase distortions can never mutually compensate in linear slow light systems ! !

Brillouin slow & fast light: a linear system

The signal spectrum $S_{in}(\omega)$ is transformed by the Brillouin gain:

$$S_{out}(\omega) = \underbrace{e^{g_B(\omega) I_{Pump} L}}_{\text{Transfer function}} S_{in}(\omega) = A(\omega) e^{j\Phi(\omega)} S_{in}(\omega) = e^{G(\omega)+j\Phi(\omega)} S_{in}(\omega)$$



The effective gain/loss spectrum can be shaped by properly modulating the pump

Generic simplified gain spectral profile

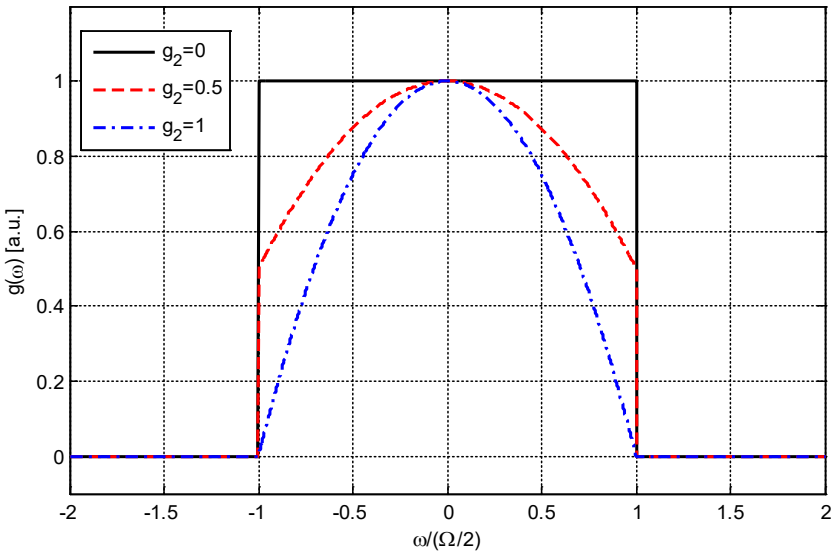
Gain profile can be generically described by the simplified distribution for **a gain window** of strictly limited bandwidth Ω.

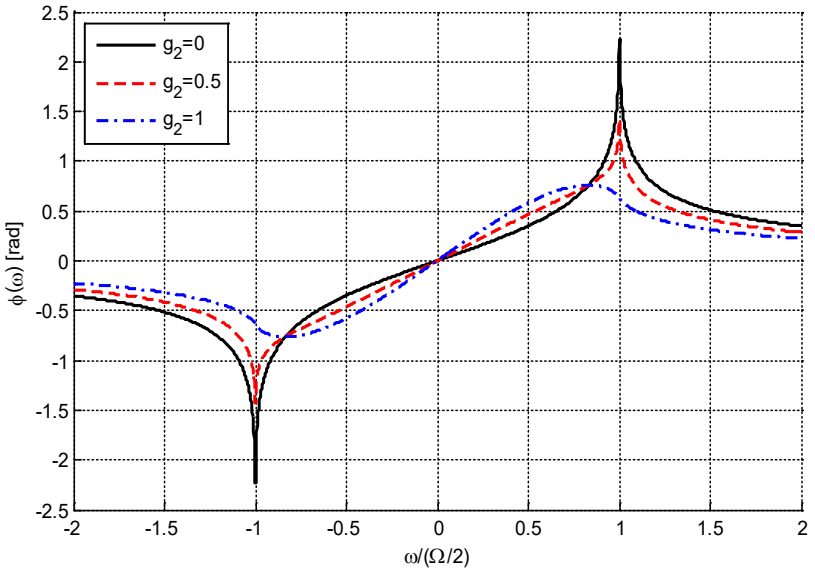
- g_0 is the peak gain
- g_2 is **the *gain profile index*** defining the spectral curvature

$$g(\omega)=\left[g_0-g_2\left(\frac{\omega}{\Omega/2}\right)^2+O(\omega^4)\right]\cdot\Pi\left(\frac{\omega}{\Omega/2}\right)$$

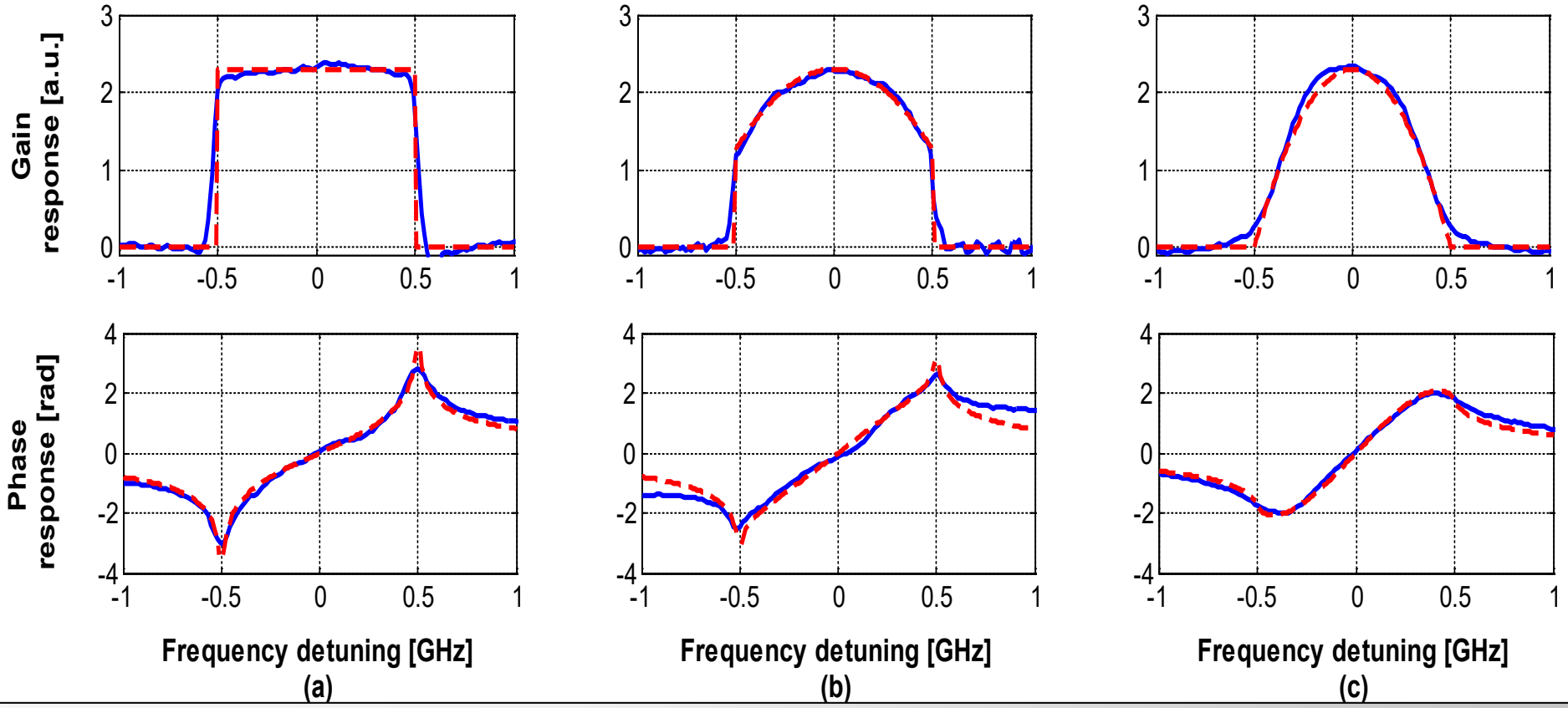
Hilbert Transform

$$\varphi(\omega)=\frac{g_0}{\pi}\left\{\left[1+g_2\left(\frac{\omega}{\Omega/2}\right)^2\right]\cdot\left[\ln\left(1+\frac{\omega}{\Omega/2}\right)-\ln\left(1-\frac{\omega}{\Omega/2}\right)\right]-2g_2\cdot\frac{\omega}{\Omega/2}\right\}$$





Experimental validation



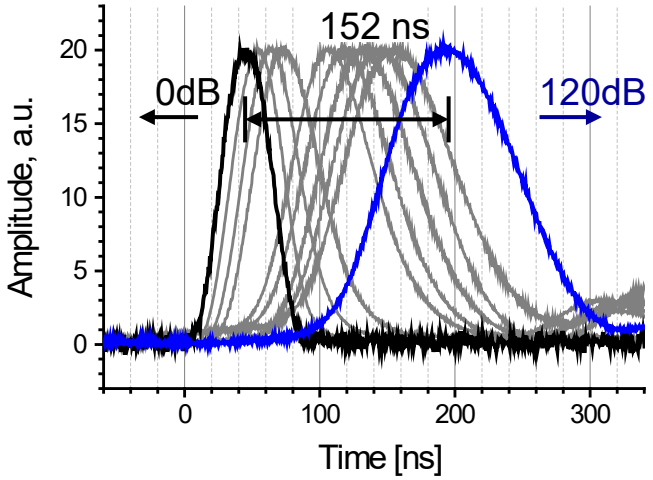
(a) $g_2 = 0$;	(b) $g_2 = 0.5$;	(c) $g_2 = 1$.
• Free from amplitude distortion • A strong phase distortion	• A limited low-pass effect on the amplitude. • A nearly perfect linear phase response	• High amplitude distortion • Moderate phase-distortion

General comments on slow light linear systems

- The ideal profile for **amplitude** distortion presents a *phase distortion*, though smaller than the Lorentzian profile.
- The ideal profile for **phase** distortion presents an *amplitude distortion*, comparable to the Lorentzian profile.
  - The Lorentzian gain is a bad choice in all situations
- A **positive** delaying (slow light) always results in **low frequency** accentuation (low pass filtering) ➔Pulse broadening and signal smoothing.
- A **negative** delaying (fast light) always results in **high frequency** accentuation (high pass filtering)
- There is **no possibility** to realize **a zero distortion linear slow light system** and amplitude and dispersive terms cannot mutually cancel their specific distortion effects.
- This limits the maximum distortion-free delaying to **one** pulse width.
- The only way to reduce or even cancel broadening is to use a **nonlinear** system (nonlinear transfer function).

Slow light and light-matter interactions

- It is now commonly accepted that slow light is an imperfect solution to realize all-optical buffering and delay lines
  Good for retiming of a single bit
  Good for microwave photonics applications



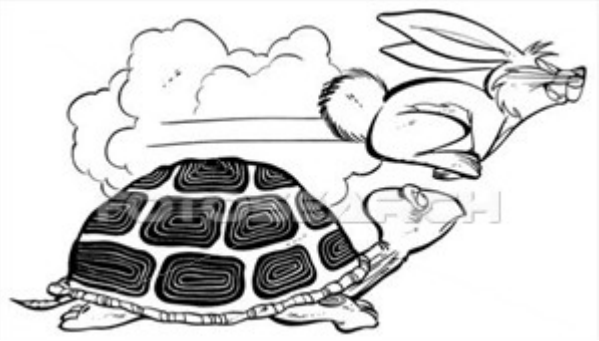
- A foreseen application of slow light has been the possibility to enhance the light-matter interactions through the following effects:
  - ~~Longer transit time of light pulses in the medium~~
  - Higher energy density due to spatial compression: $u \sim \frac{1}{4}(\varepsilon + \omega\frac{d\varepsilon}{d\omega})E^2$
- These features may lead to:
  - Enhanced interactions and improved sensitivity
  - Smaller photonic devices

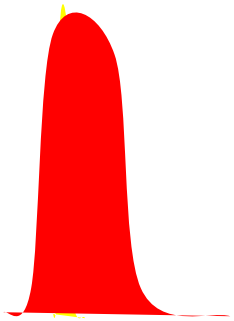
Slowing: no change in the interaction time

"Let the good times roll"

"No need to rush"

"Slow is beautiful"





Intuition suggests that light-matter interaction can be enhanced by slowing the light, since it would let **more time** to the photon to spend with each atom.

This picture turns out to be entirely wrong!

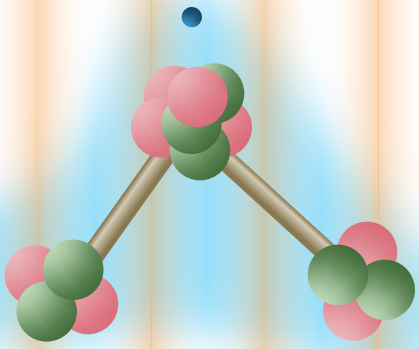
A 1 ns pulse remains a 1 ns pulse, whatever its speed

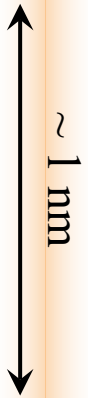
The interaction time is unchanged!

Basics of light absorption by molecules

Optical wave:

$$\vec{E} = \vec{E}_o e^{i(\omega t - \vec{k}\vec{r})}$$

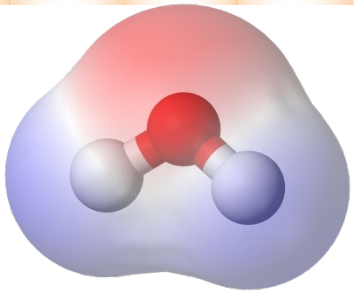




Lightwave: ~ λ
~ 1000 nm

Molecule is electrically neutral, but charge distribution is non-uniform:

➔ Representation using multipolar moment for the atom ➔



Dominant term is the dipole moment $\vec{d} = \sum q_i \vec{r_i}$

➔ Absorption rate is proportional to:

$$R \sim \left| \left\langle f \left| \vec{E} \cdot \vec{d} \right| i \right\rangle \right|^2 \sim B \left| \vec{E}_o \right|^2$$

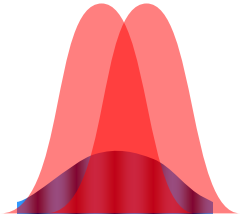
The absorption rate scales with the **electric field intensity** $\left| \vec{E}_o \right|^2$

➔ **Enhancing the electric field is crucial**

Material and Structural Slow Light

Material slow light

Microscopic response of the medium (polarization) is modified by a light-matter interaction and can be controlled by optical pumping.



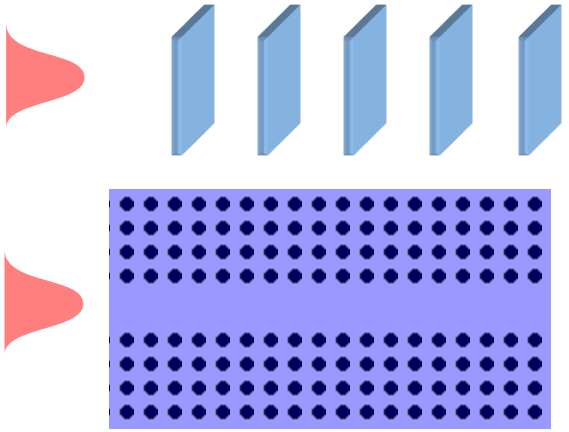
Continuously tunable delays

The extra energy density is stored in the material

Minor change of the electric field intensity

Structural slow light

Macroscopic optical structures generate a group delaying through multiple interferences.



Limited tunability

The extra energy density is created by waves superposition

Major change of the electric field intensity

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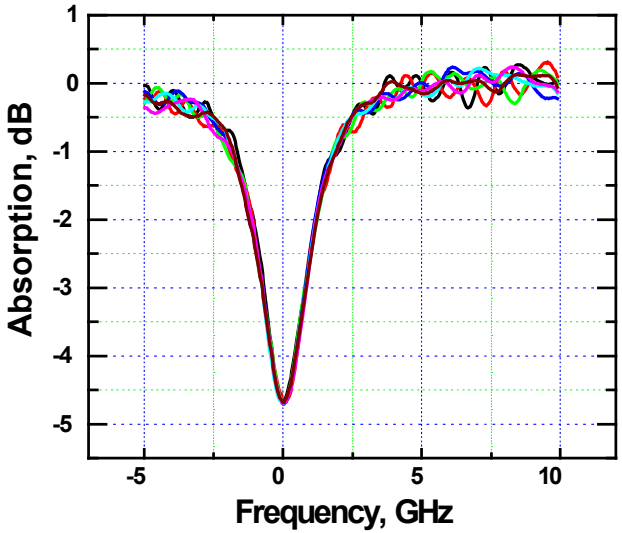

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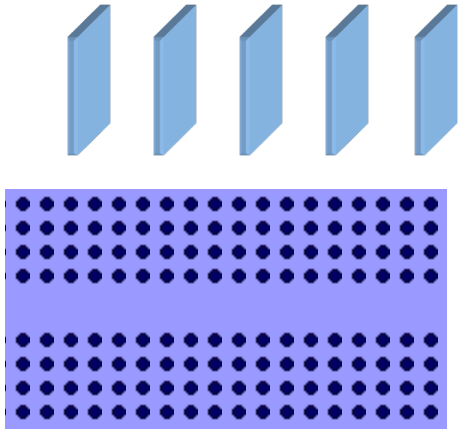

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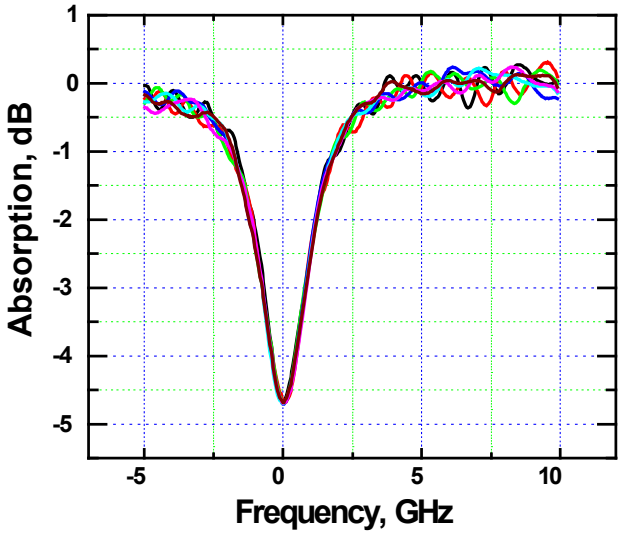

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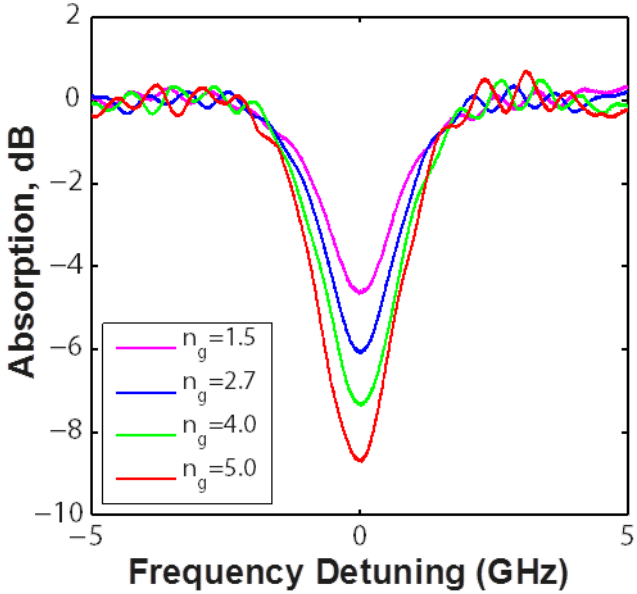
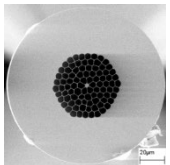


Experimental tests realized on the **same fibre** and on the **same absorption line** of acetylene at 1535.4 nm (P17)



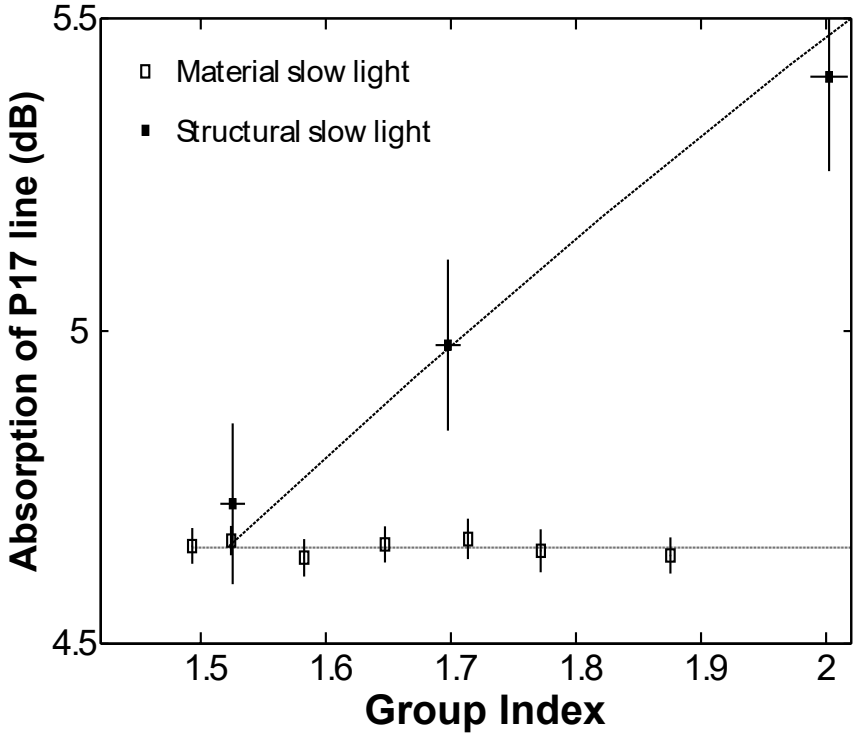
Material and Structural Slow Light

Material slow light

Microscopic response of the medium (polarization)

Structural slow light

Macroscopic optical structures generate a group delaying



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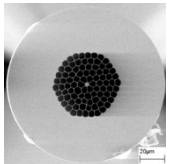
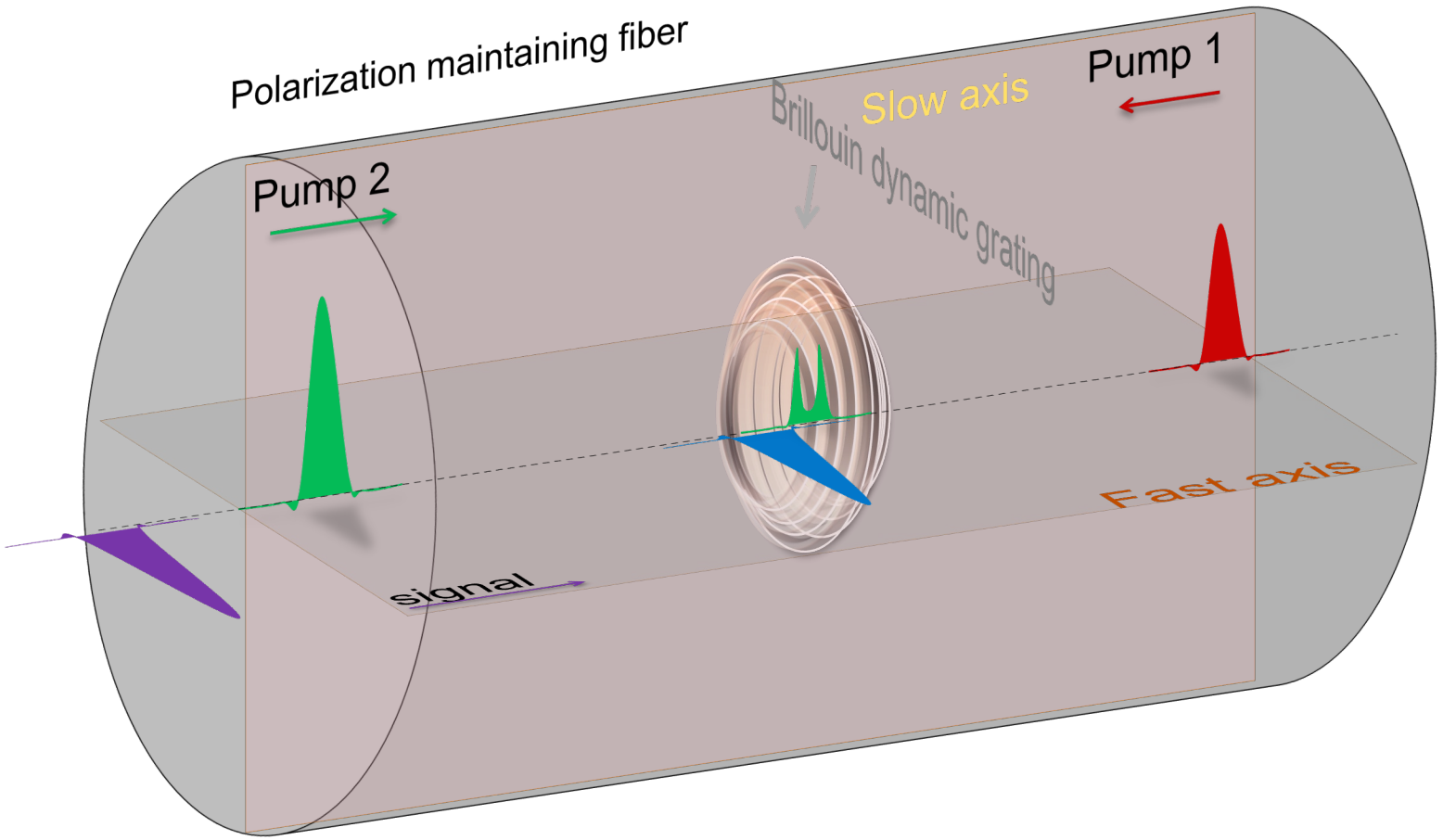
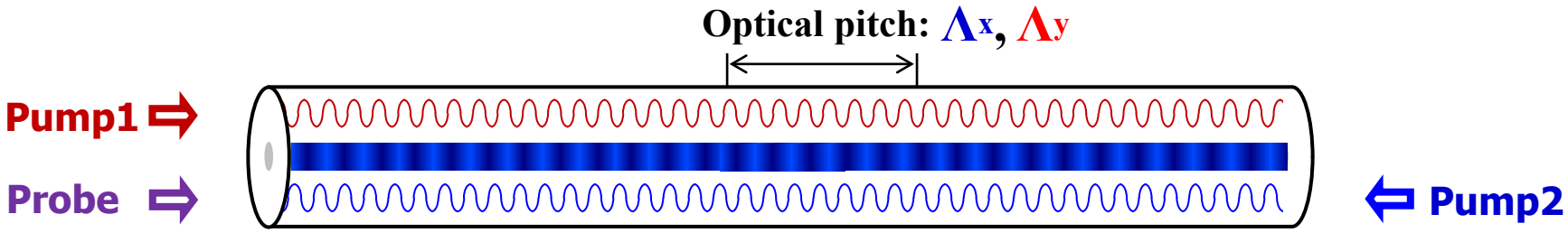


Dynamic Brillouin gratings

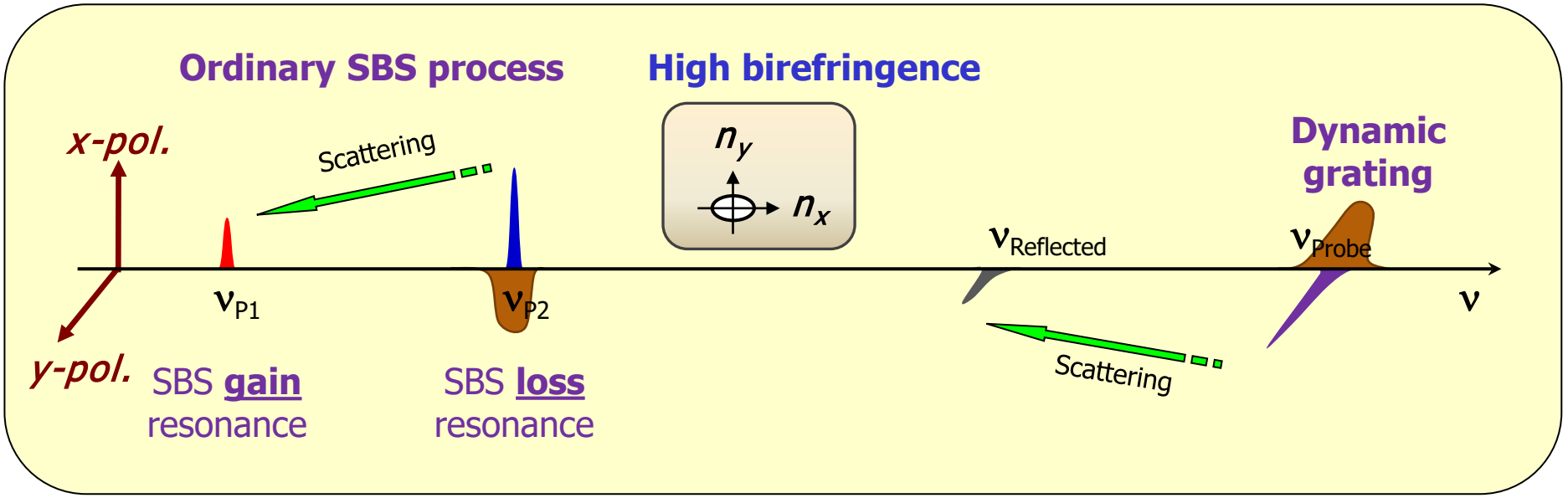


Dynamic Brillouin grating in Hi-Bi fibres

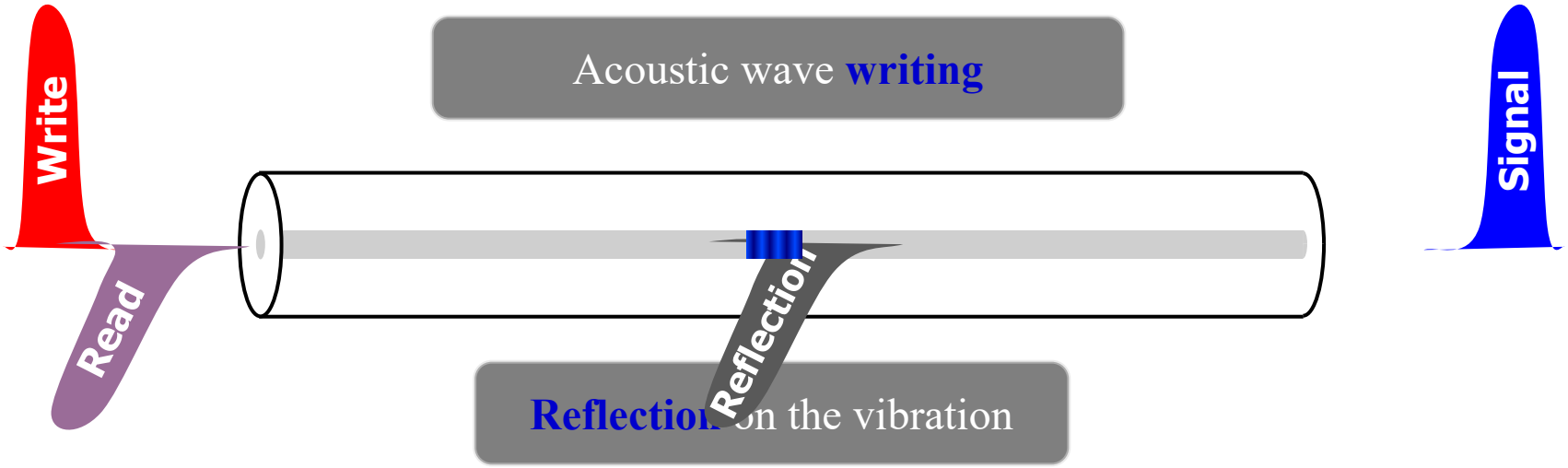


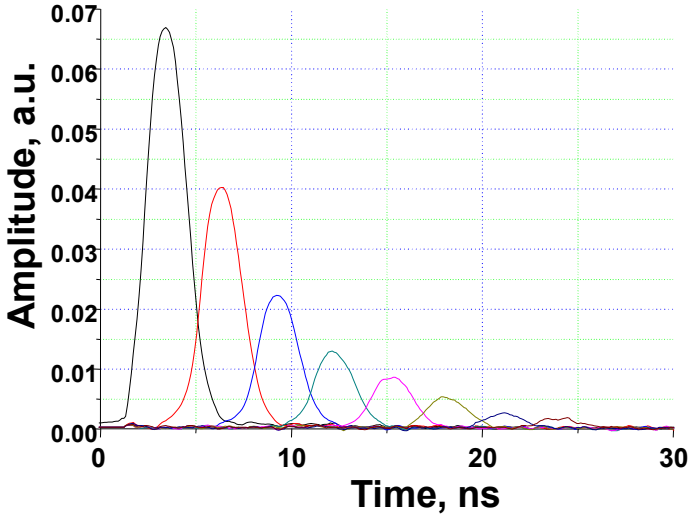
- Under **phase-matching conditions** ($\nu_{P1}=\nu_{P2}+\nu_B$), where $\nu_B = \frac{2nV_a}{\lambda} \approx 11\,GHz$,

  a **Bragg-type moving grating** is generated along the fiber core by **electrostriction**.

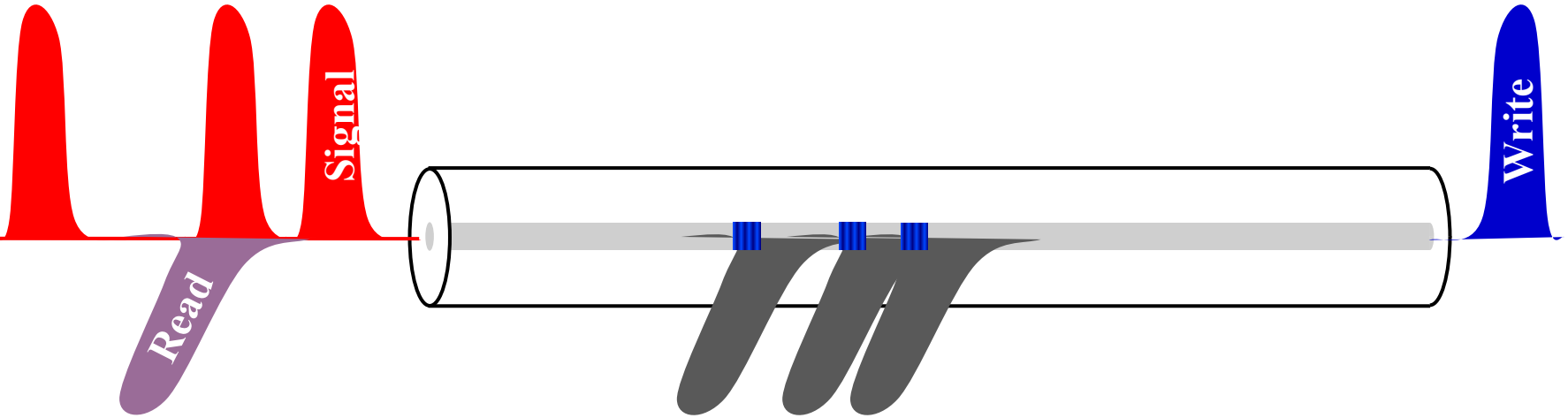


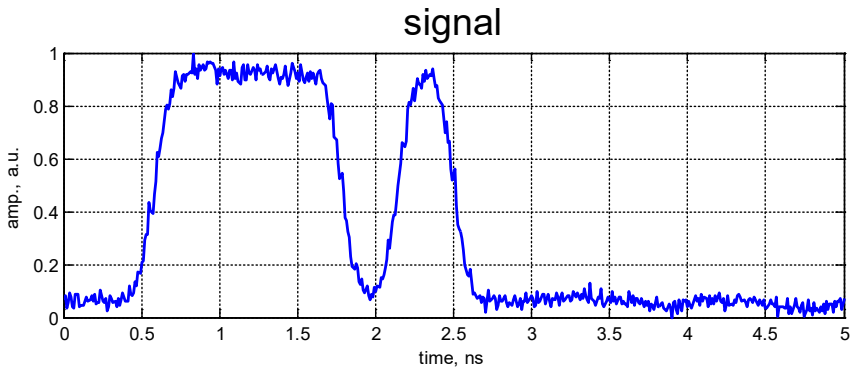
Temporary Optical Storage mediated by SBS

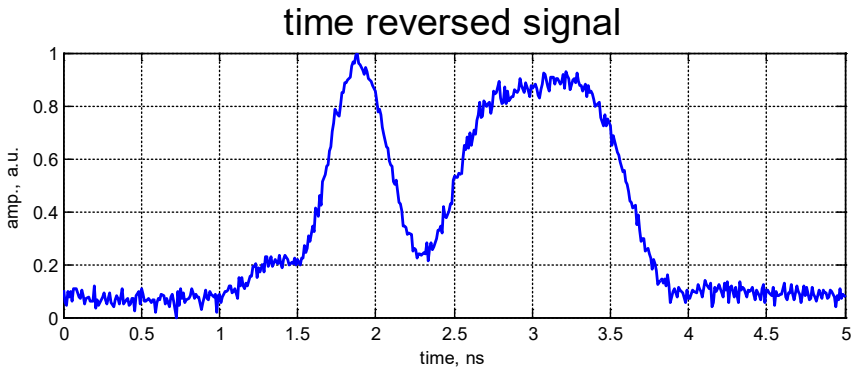




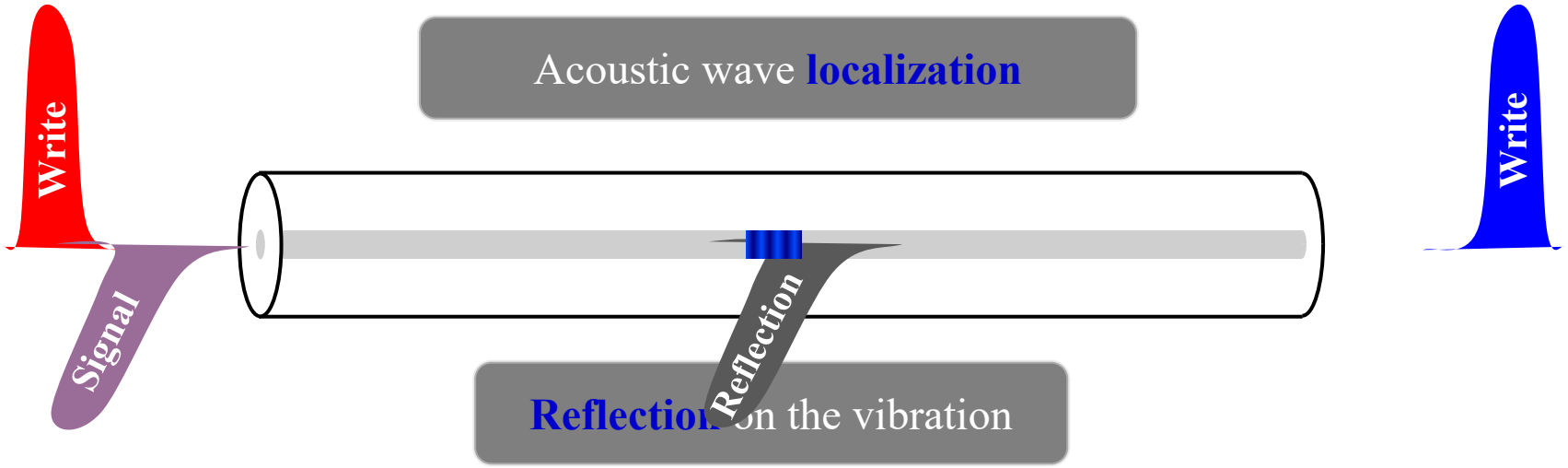
Time reversal of a data sequence



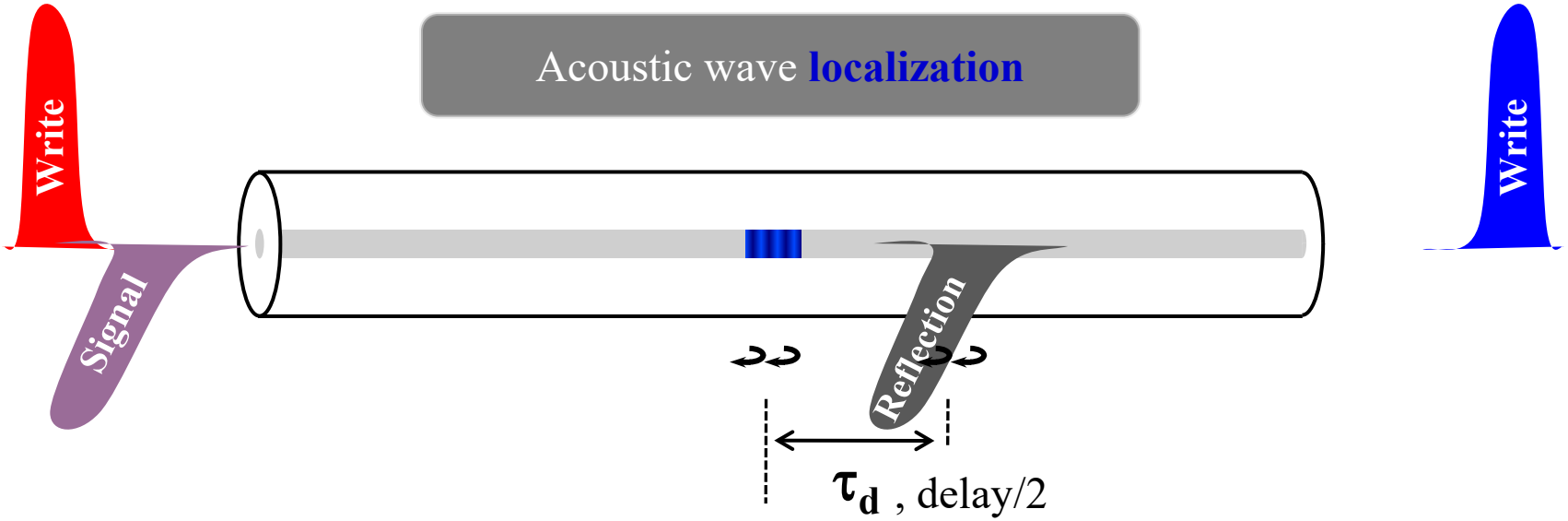




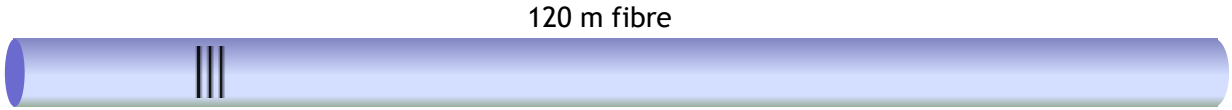
Tuneable delay line
based on Brillouin grating reflection

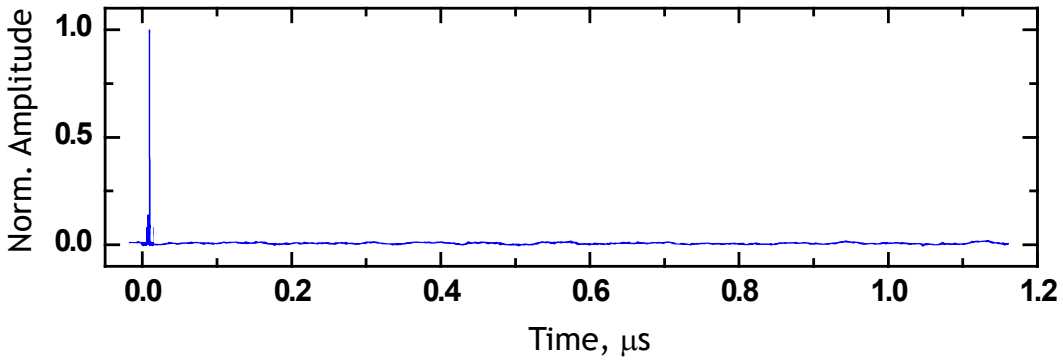


Tuneable delay line
based on Brillouin grating reflection

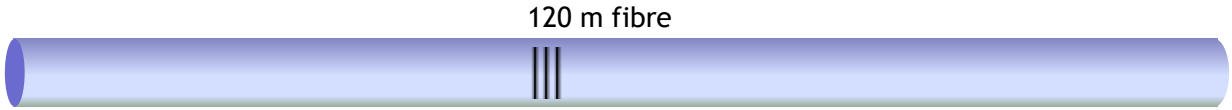


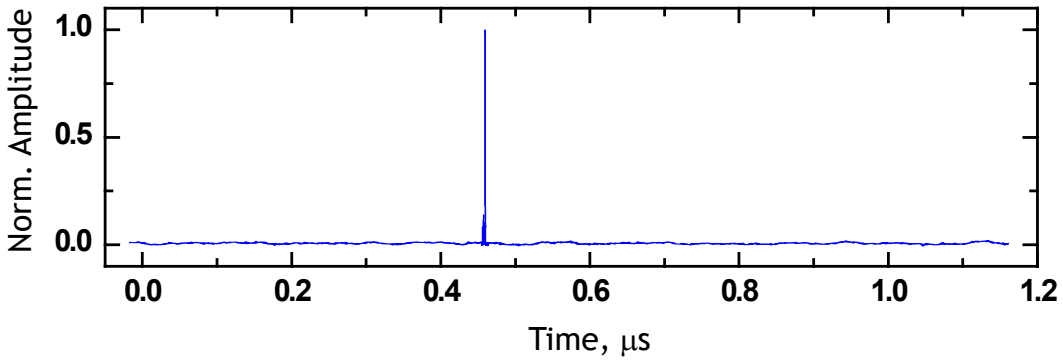
Tunable true time delays



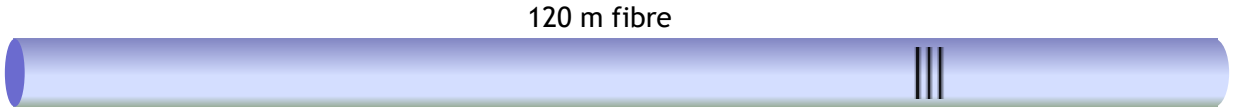


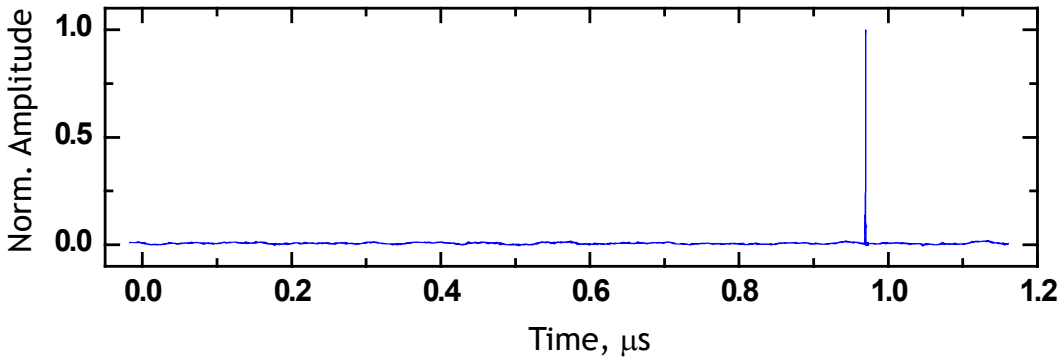
Tunable true time delays



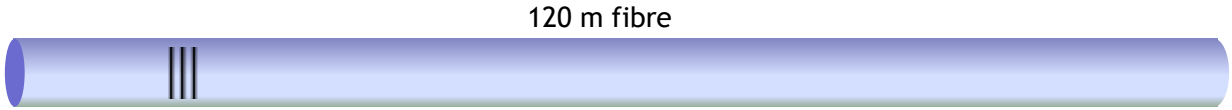


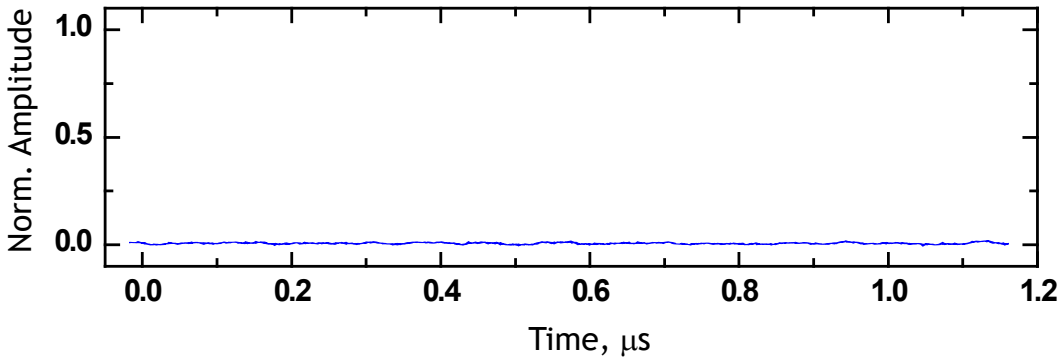
Tunable true time delays



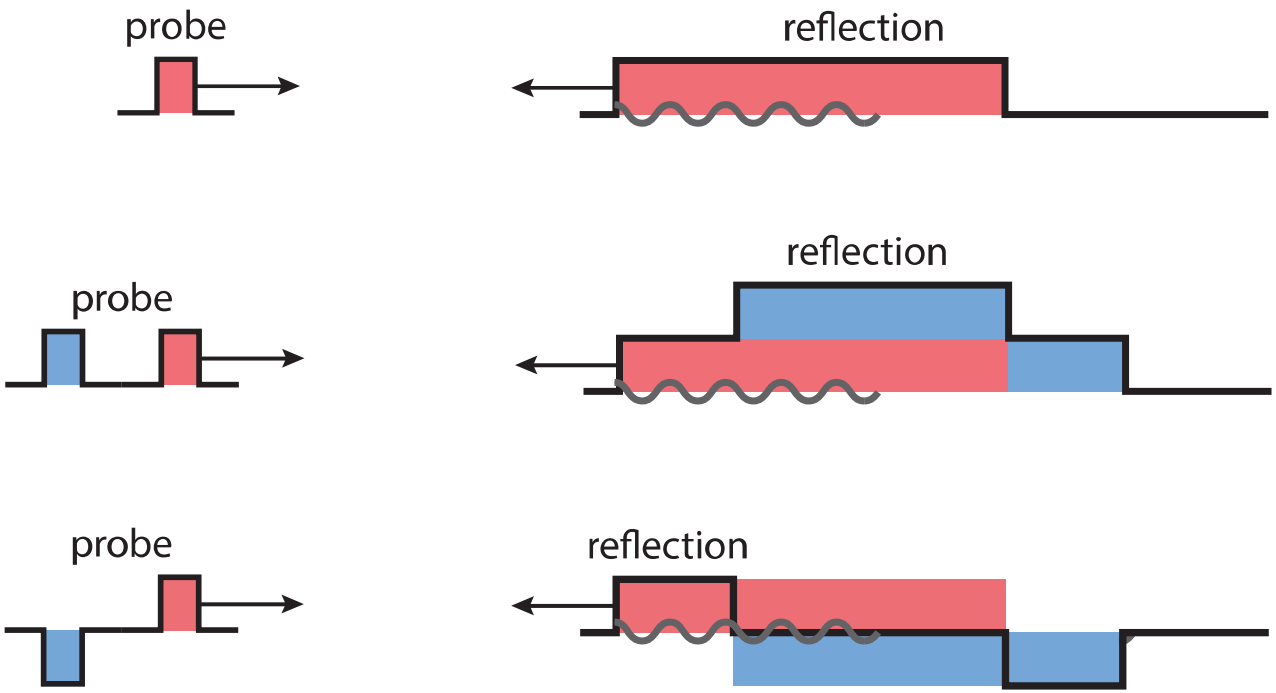


Tunable true time delays



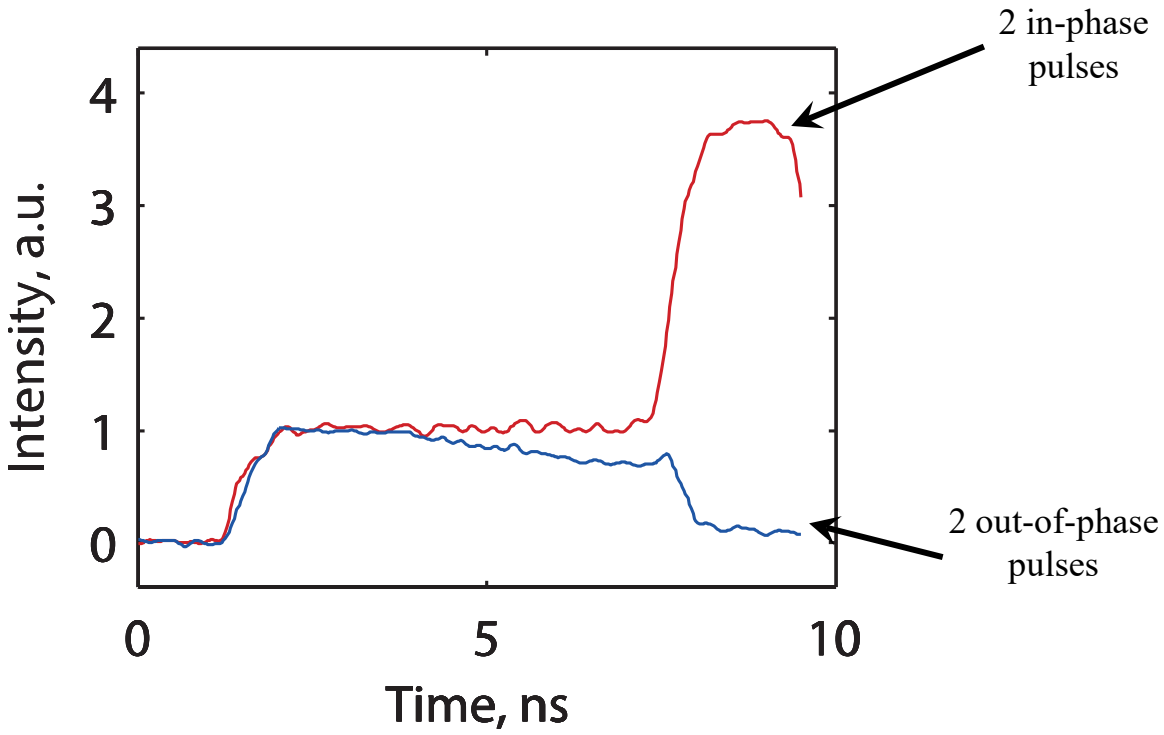


All-optical flip-flop



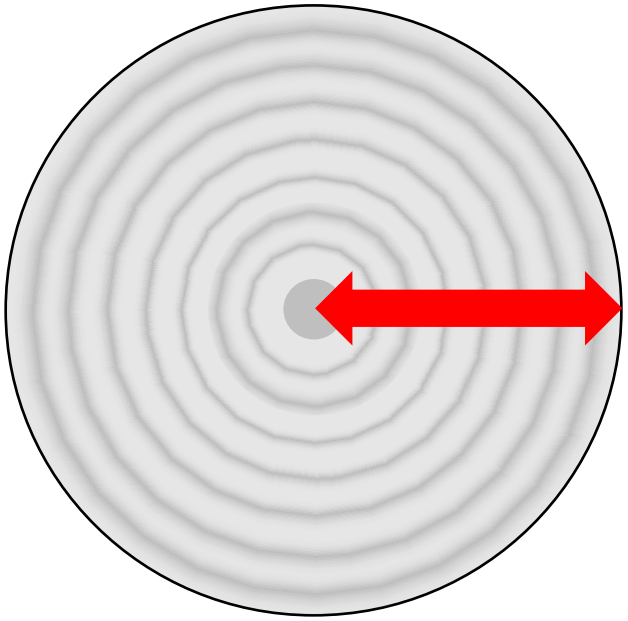
M. A. Soto, A. Denisov, X. Angulo-Vinuesa, S. Martin-Lopez, L. Thévenaz, and M. Gonzalez-Herraez, *All-optical flip-flops based on dynamic Brillouin gratings in fibers*, Optics Letters **42**, 2539 (2017).

All-optical flip-flop

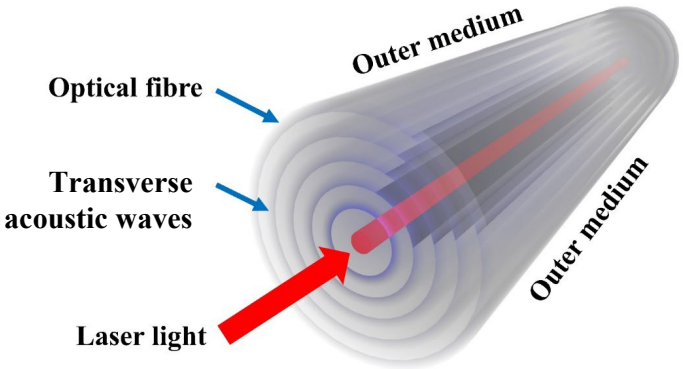


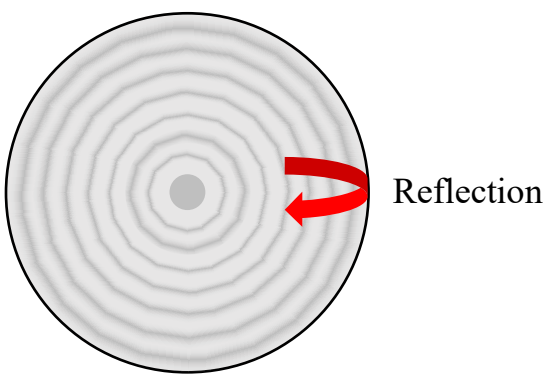
M. A. Soto, A. Denisov, X. Angulo-Vinuesa, S. Martin-Lopez, L. Thévenaz, and M. Gonzalez-Herraez, *All-optical flip-flops based on dynamic Brillouin gratings in fibers*, Optics Letters **42**, 2539 (2017).

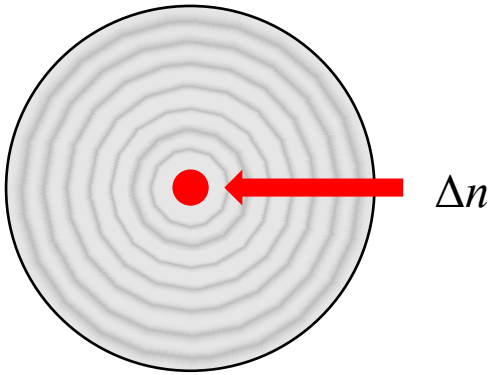
Transverse acoustic wave



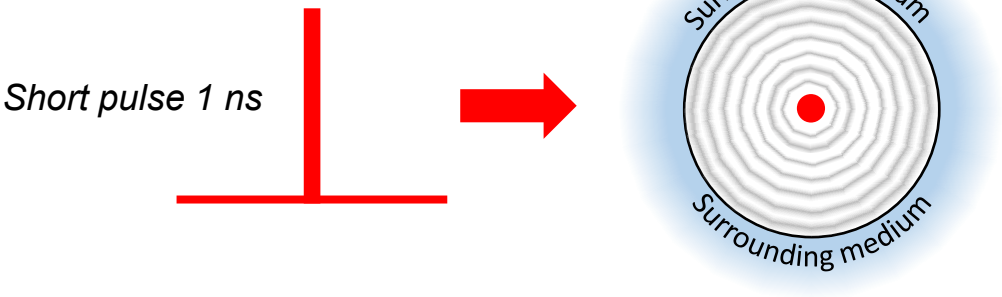
Forward Stimulated Brillouin Scattering (FSBS)

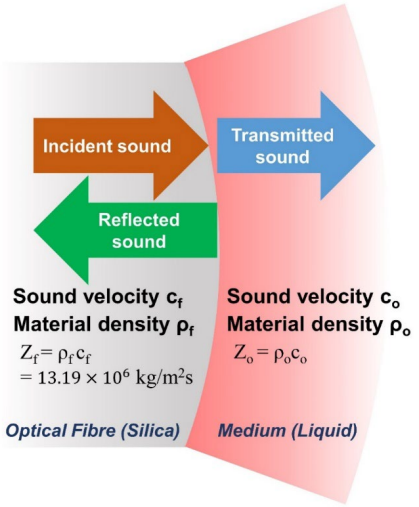


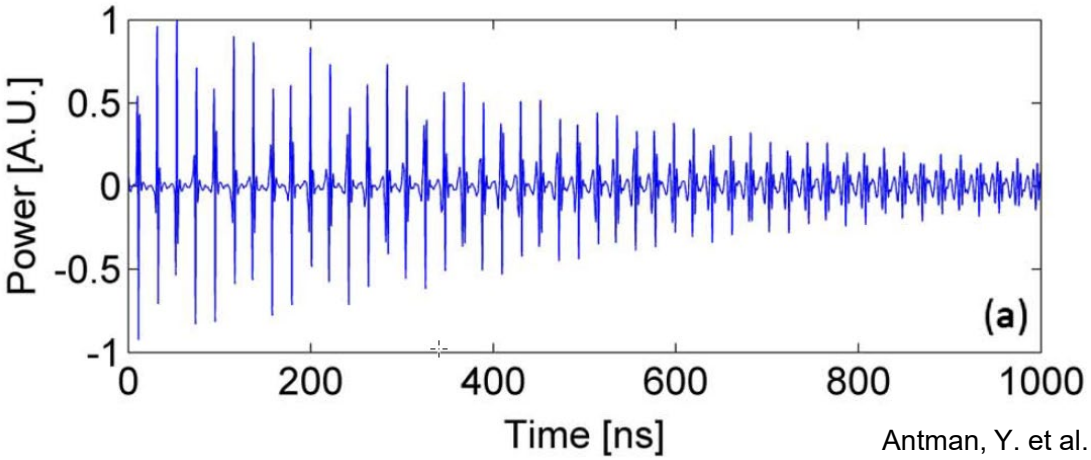


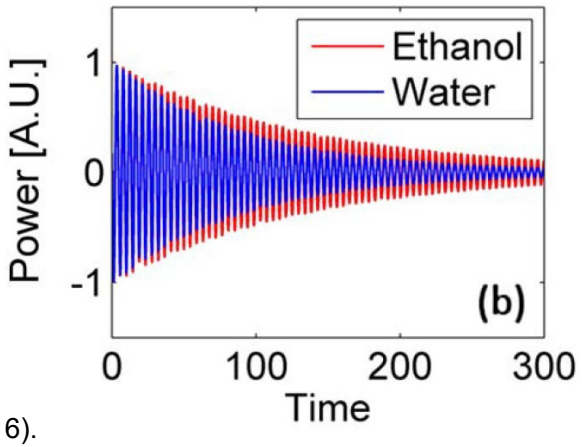


Acoustic impedance sensing using FSBS





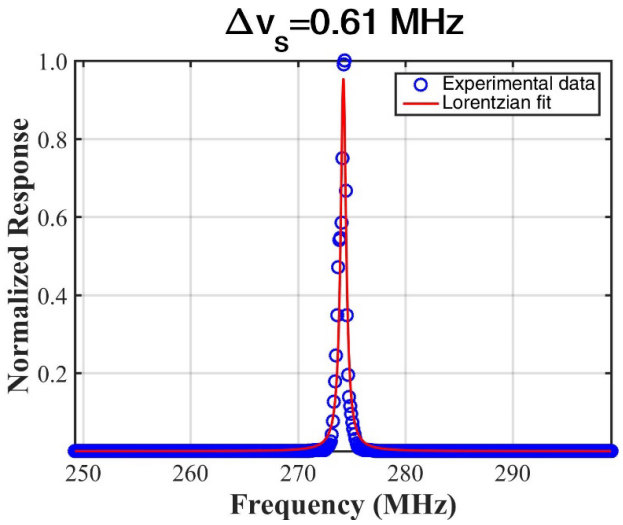




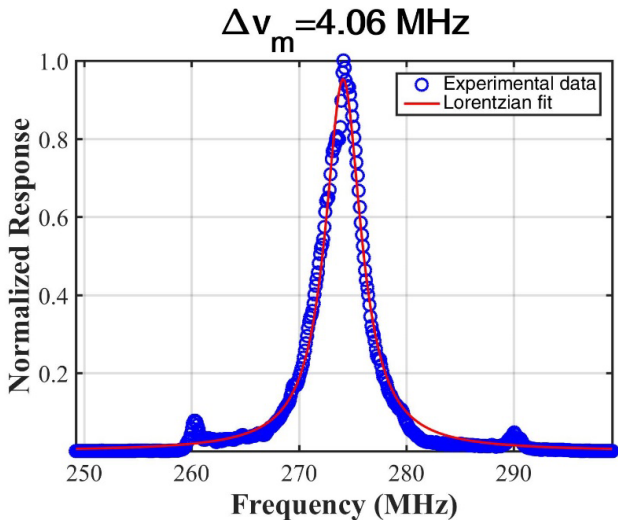
Antman, Y. et al. (2016). *Optica*.

Measured FSBS resonance for different surrounding fluids

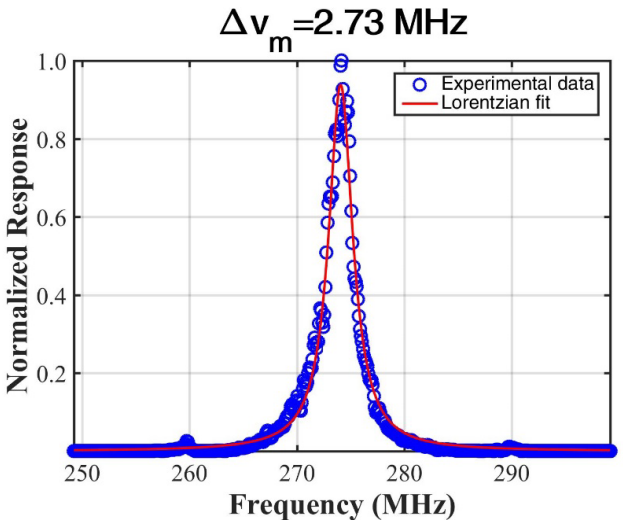
Air



Water

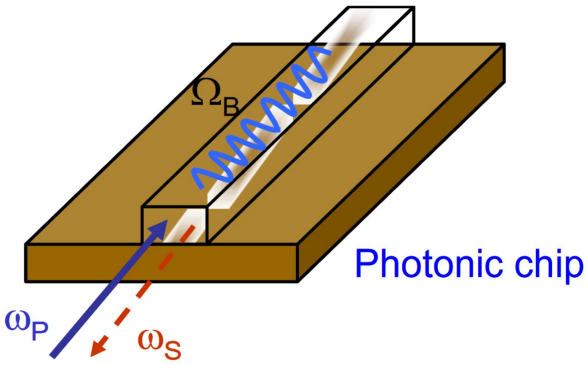


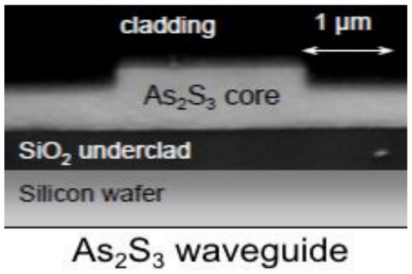
Ethanol



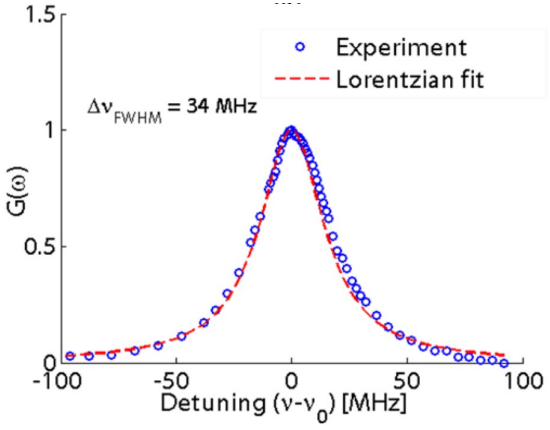
Stimulated Brillouin scattering in other materials

Chalcogenide (SBS material gain 200xSiO_2)





As_2S_3 waveguide



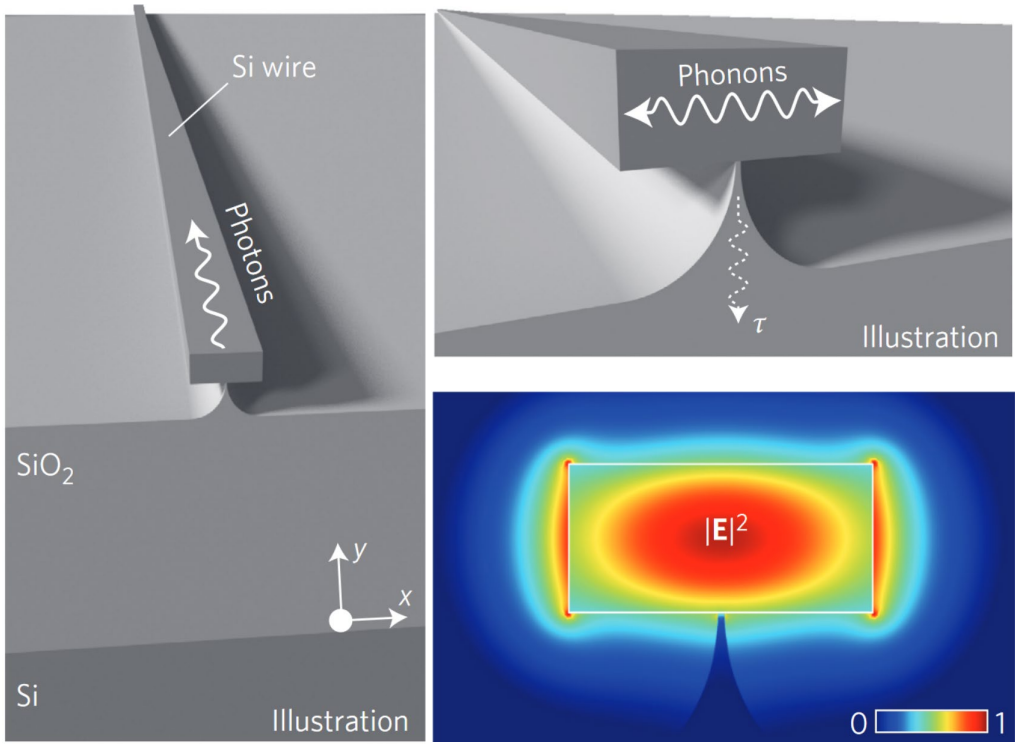
Effective gain is 40x larger than in silica

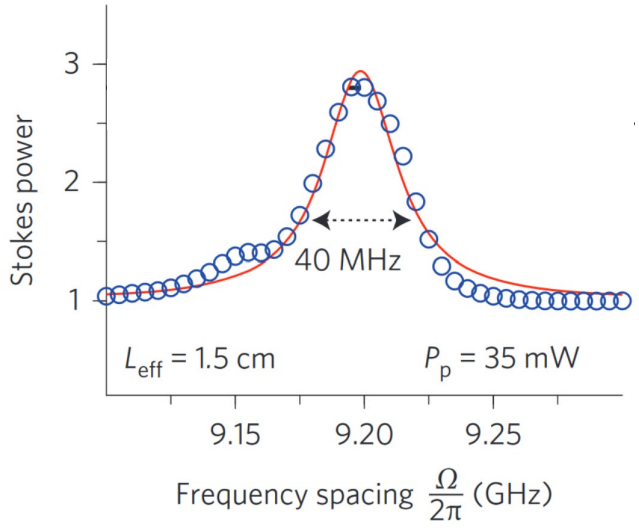
Offers an attractive planar platform to realize all functions demonstrated in fibres

K. S. Abedin, Opt. Express **13**, 10266–10271 (2005)
R. Pant *et al*, Opt. Express **19**, 8285–8290 (2011)

Stimulated Brillouin scattering in other materials

Silicon (SBS material gain (1/200)xSiO_2)

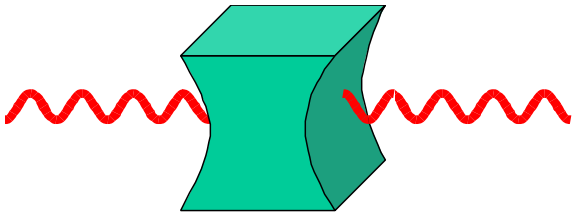




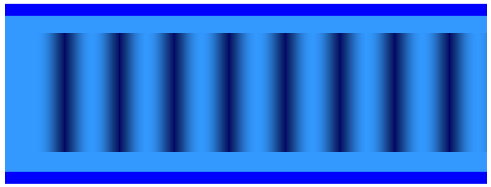
Effective gain hardly compensates loss

H. Shin *et al*, Nat Commun **4**, (2013).
R. Van Laer *et al*, Nat Photon **9**, 199–203 (2015)

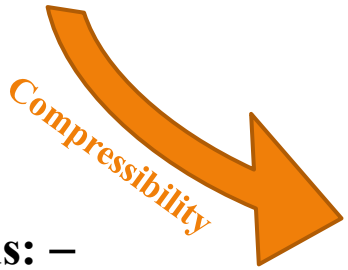
Stimulated Brillouin scattering in other materials



Electrostrictive force

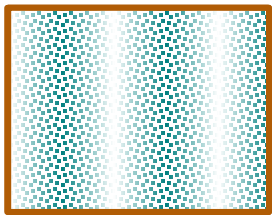


Refractive index change

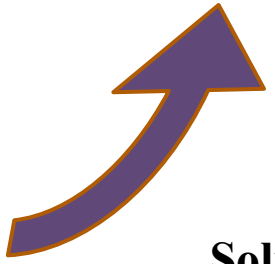


Solids: –

Gases: +



Medium densification

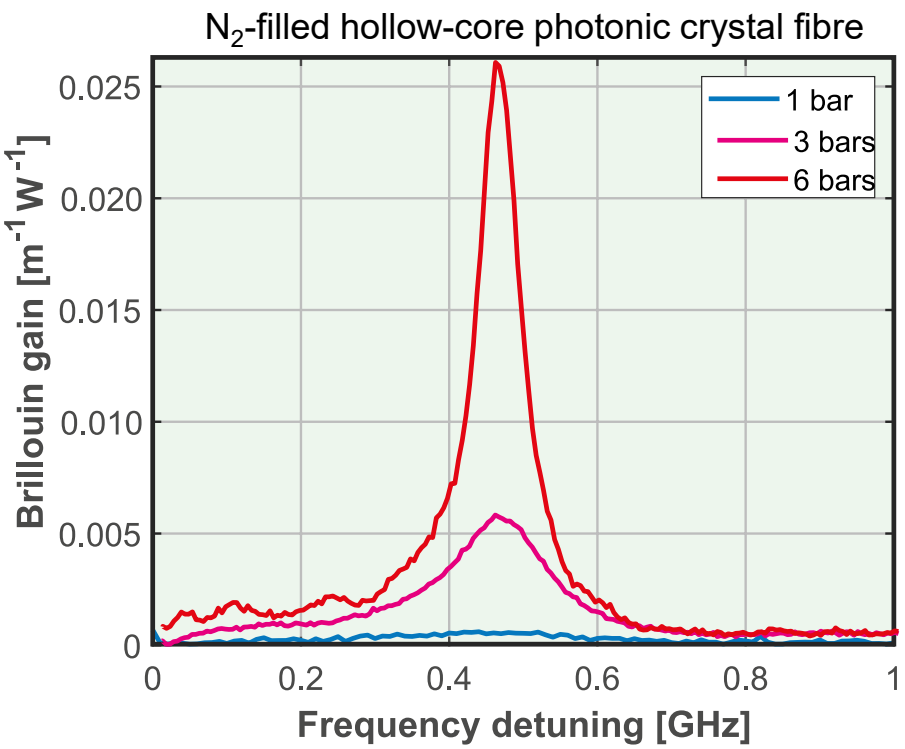


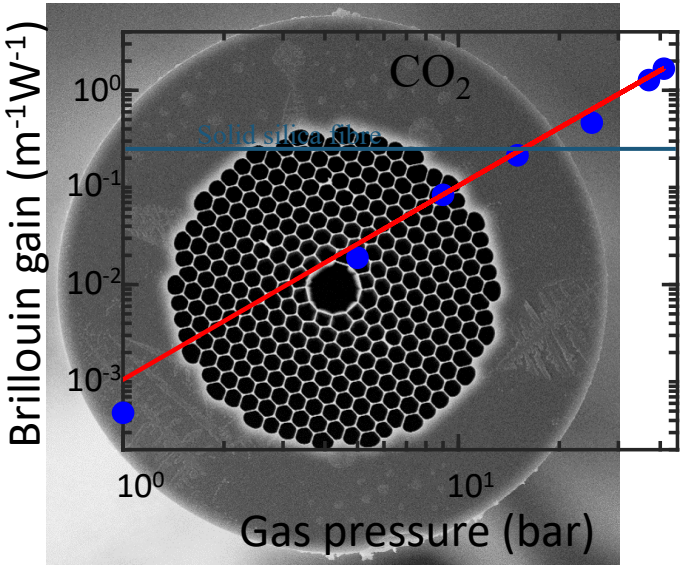
Solids: +

Gases: –

Stimulated Brillouin scattering in other materials

Gas





Brillouin linear gain in silica fibres is 100X larger!

F. Yang, F. Gyger, and L. Thévenaz, "Intense Brillouin amplification in gas using hollow-core waveguides," Nat. Photonics **14**, 700–708 (2020).

Influence of the gas species

The Brillouin gain depends on several material parameters:

- Molecular mass ↗
- Molecular size ↗
- Viscosity ↘
- Polarisability ↗

Gas	Name	V_a[m/s]	m[g/mol]	d[pm]	$\eta_s[10^{-5}\mathrm{Pa}\cdot\mathrm{s}]$
CH_4	Methane	466	16	400	1.88
N_2	Nitrogen	354	28	370	2.86
CO_2	Carbon dioxide	280	44	232	2.71

Measured Brillouin gains at 24°C and 10 bar:

Gas	Name	ν_B[MHz]	$\Delta\nu_B$[MHz]	G[$\mathrm{m^{-1}W^{-1}}$]
N_2	Nitrogen	451	41	0.025
CH_4	Methane	580	40	0.034
CO_2	Carbon dioxide	351	21	0.105

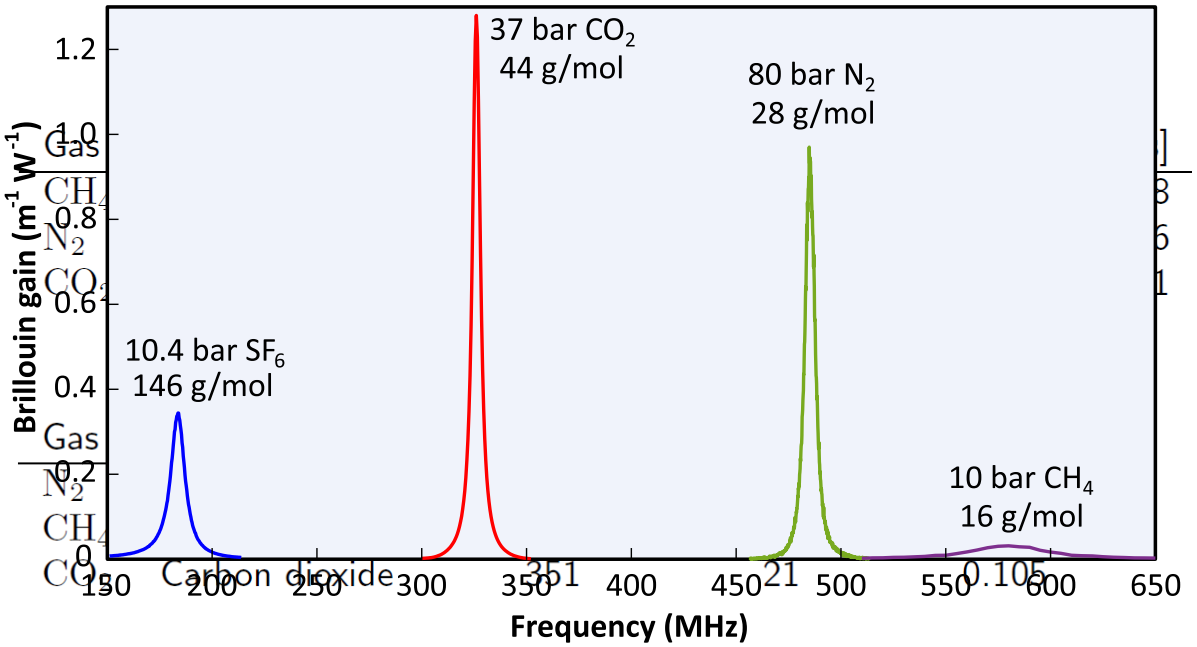
At first glance, gases with complex and heavy molecules should deliver more gain.

Influence of the gas species

The Brillouin gain depends on several material parameters:

- Molecular mass ↗
- Molecular size ↗
- Viscosity ↘
- Polarisability ↗

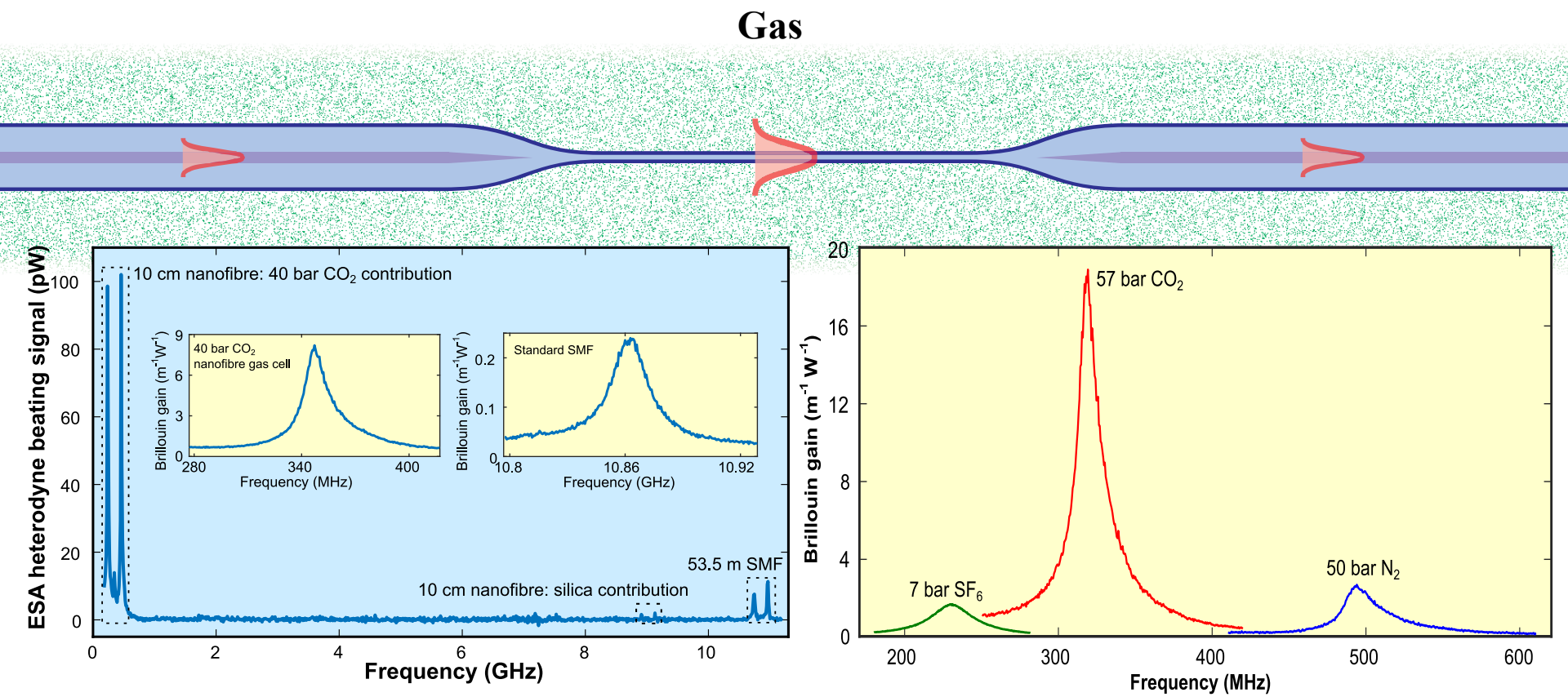
Measured Brillouin gains at 24°C and 10 bar:



At first glance, gases with complex and heavy molecules should deliver more gain.

But:
- May quickly turn into **liquid phase** at higher pressure.
- May show **spectral absorption lines**, moreover significantly broadened at high pressure

Stimulated Brillouin scattering in other materials



F. Yang *et al*, "Large evanescently-induced Brillouin scattering at the surrounding of a nanofibre," Nat Commun **13**, 1432 (2022).

End of the 6th lesson