IREA-CNR

Distributed fiber optic sensors based on the stimulated Brillouin scattering in the frequency domain

Macrolinea Diagnostica Elettromagnetica

- **Local sensors**

- **Distributed sensors**

Advantages of distributed sensors

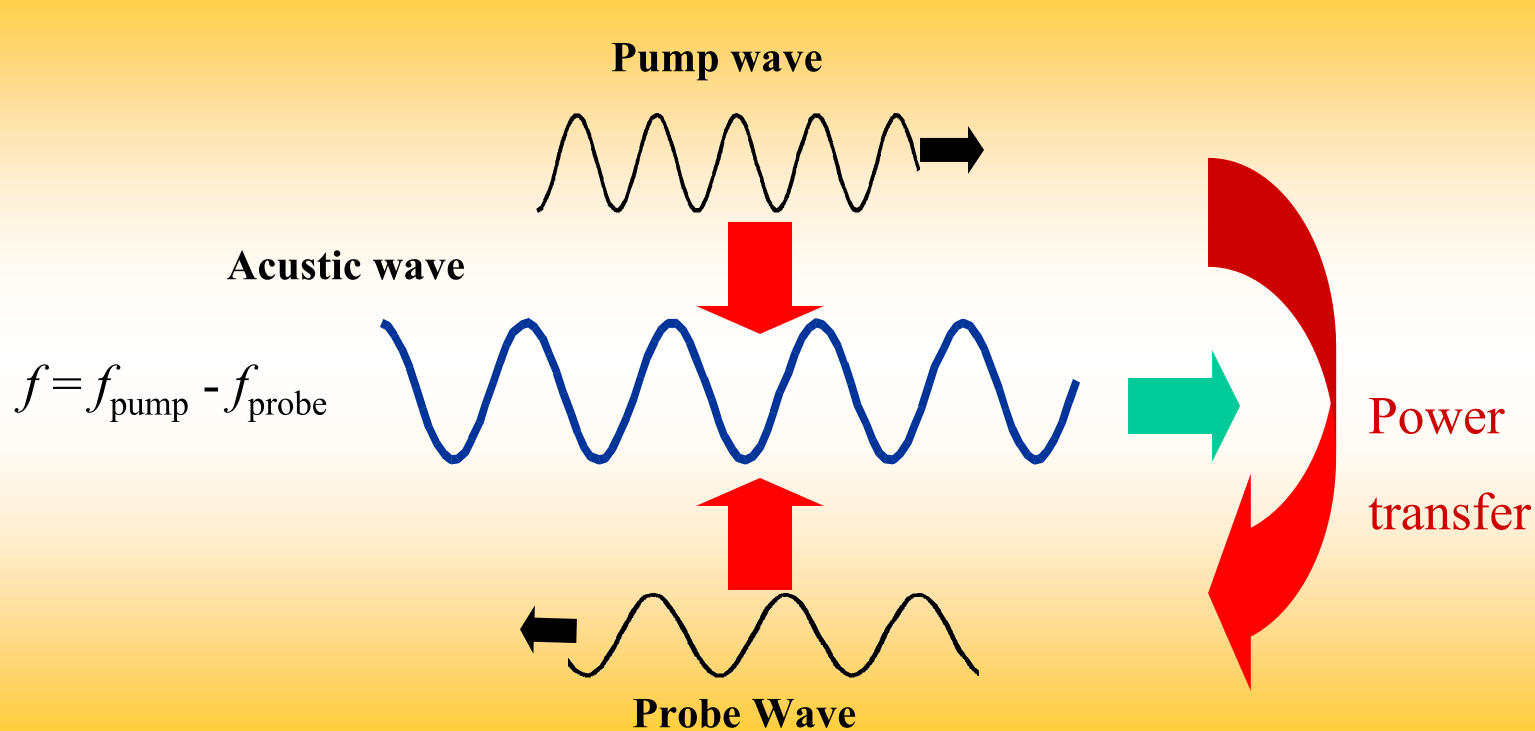
- Single optical fiber Vs. thousand local sensor
- The measurement resolution can be changed without change the sensor installation

Applications of distributed sensors

- Long term strain monitoring of large structures (bridges, dams, …)
- Electrical cable monitoring
- Pipeline monitoring
- Post-seismic damage evaluation
- Environmental monitoring (lakes temperature, …)

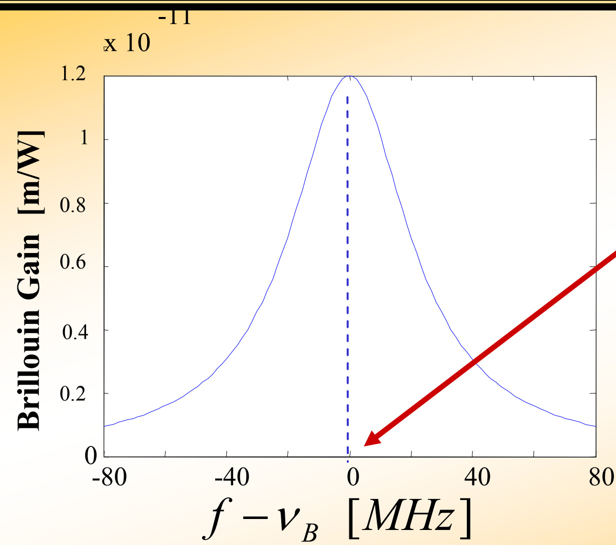
Brilluoin stimulated scattering

- Two counterpropagating lightwaves with slightly different wavelengths generate an acoustic wave by electrostriction
- The acoustic wave causes an optical power transfer from the pump lightwave to the probe one.



Measurement principle

The Brillouin gain is a function (typically a Lorentzian) of the pump-probe frequency offset



The gain peak is reached at the so-called Brillouin frequency shift ν_B

The Brillouin shift ν_B in an optical fiber depends on the local temperature T and strain ε

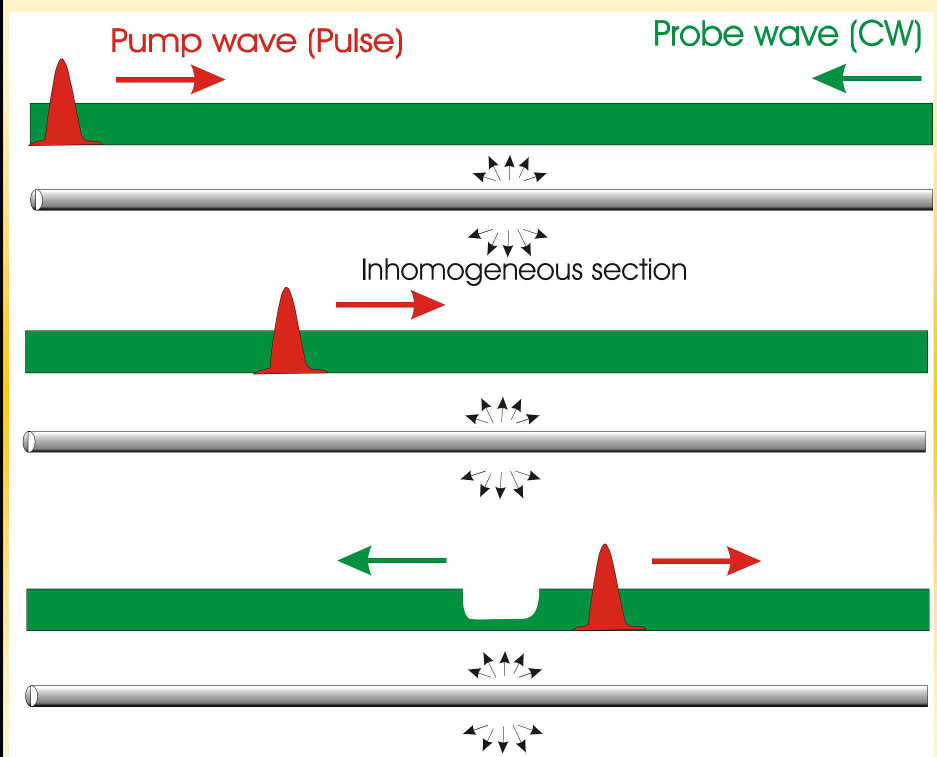
It is possible to measure temperature (ΔT) and strain (Δ ε) variations along the fiber through the measurement of ν_B

$$\nu_B = \nu_{B0} + C_T \Delta T + C_\varepsilon \Delta \varepsilon$$

Measurement principle

Time domain approach

- A pulsed beam and a CW beam having different frequencies are used
- The change in CW power received is measured as a function of the time, while scanning the pump-probe frequency offset

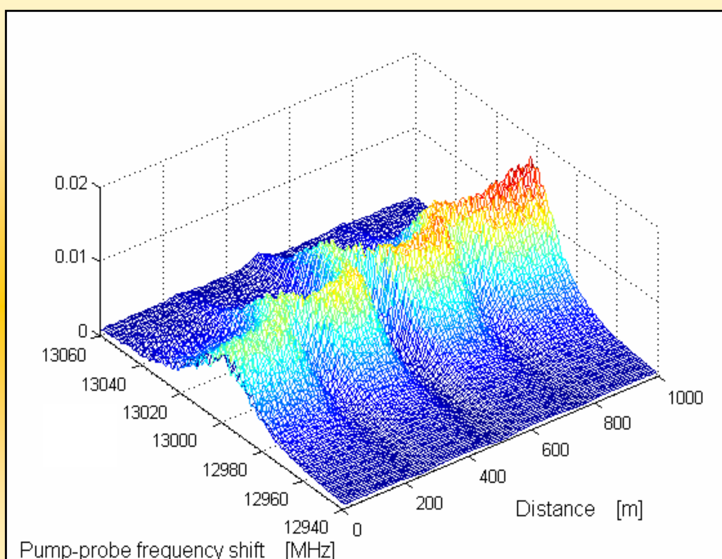


Pump-probe shift tuned at the unperturbed fiber Brillouin shift

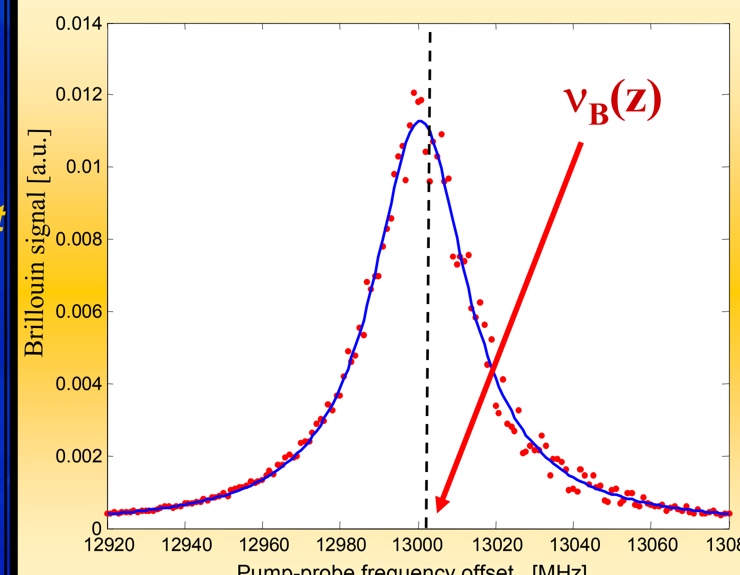
- **Spatial resolution** is related to the pulsewidth (typically 1meter with 10ns)
- **Sensing length:** tens of kilometers
- **Temperature and strain resolutions:** 1°C and 20με respectively

Reconstruction: Classical Approach

- The Brillouin signals are measured as a function of a time, while scanning the pump-probe frequency offset over a few hundreds of MHz range
- The time coordinate is converted into a spatial one through the round-trip time of the pulse
- At each section along the fiber, the Brillouin shift is calculated by fitting the measured data to a peaked shape (typically a Lorentzian)

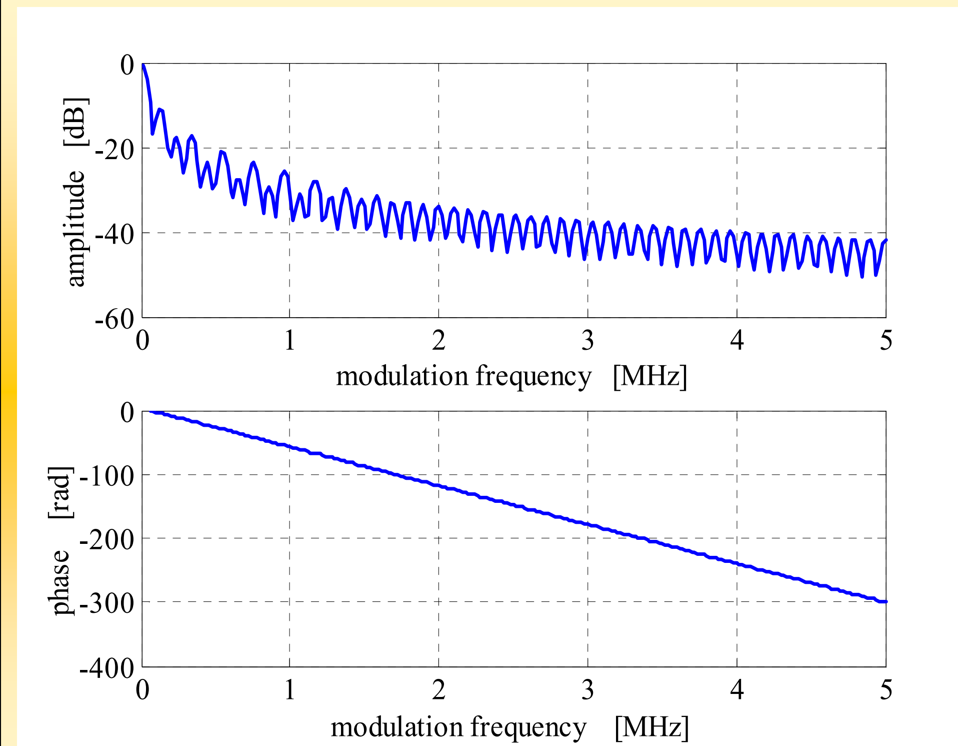


Transverse cut and fitting



Pump-probe Frequency Domain approach

• A **complex transfer function** is evaluated pointwise by using a CW beam and a counterpropagating intensity-modulated one



<u>Advantage</u>

Narrow band detection

↓

S/N improvement

SBS Equations

$$\begin{cases} \left[\frac{n}{c}\left(\frac{\partial}{\partial t}\right)-\frac{\partial}{\partial z}\right]I_{st} = \left(-\alpha + g_B I_{pu}\right)I_{st} \\ \left[\frac{n}{c}\left(\frac{\partial}{\partial t}\right)+\frac{\partial}{\partial z}\right]I_{pu} = \left(-\alpha - g_B I_{st}\right)I_{pu} \end{cases}$$

Boundary conditions

$$I_{Pu}(0,t) = I_c$$
$$I_{St}(L,t) = I_{m0} + I_{m1}\cos(\omega t)$$

SBS Equations

- small modulation depth ($I_{m0} >> I_{m1}$)
- DC pump component >> DC probe component

$$H(\omega) = -\exp\left[-2\left(j\frac{\omega}{\mathrm{v}} + \alpha\right)L\right]\int_0^L g(z'')I_{P0}(z'')\times$$

$$\exp\left[\int_{z''}^{L} g(z')\left[I_{P0}(z') - I_{S0}(z')\right]dz'\right]\exp\left[2\left(j\frac{\omega}{v} + \alpha\right)z''\right]dz''$$

This formulation eliminates the need for solving a system of coupled differential equations!

Reconstruction in the Frequency Domain: Novel Approach

- The unknown strain or temperature profile is expressed as the sum of harmonic functions:

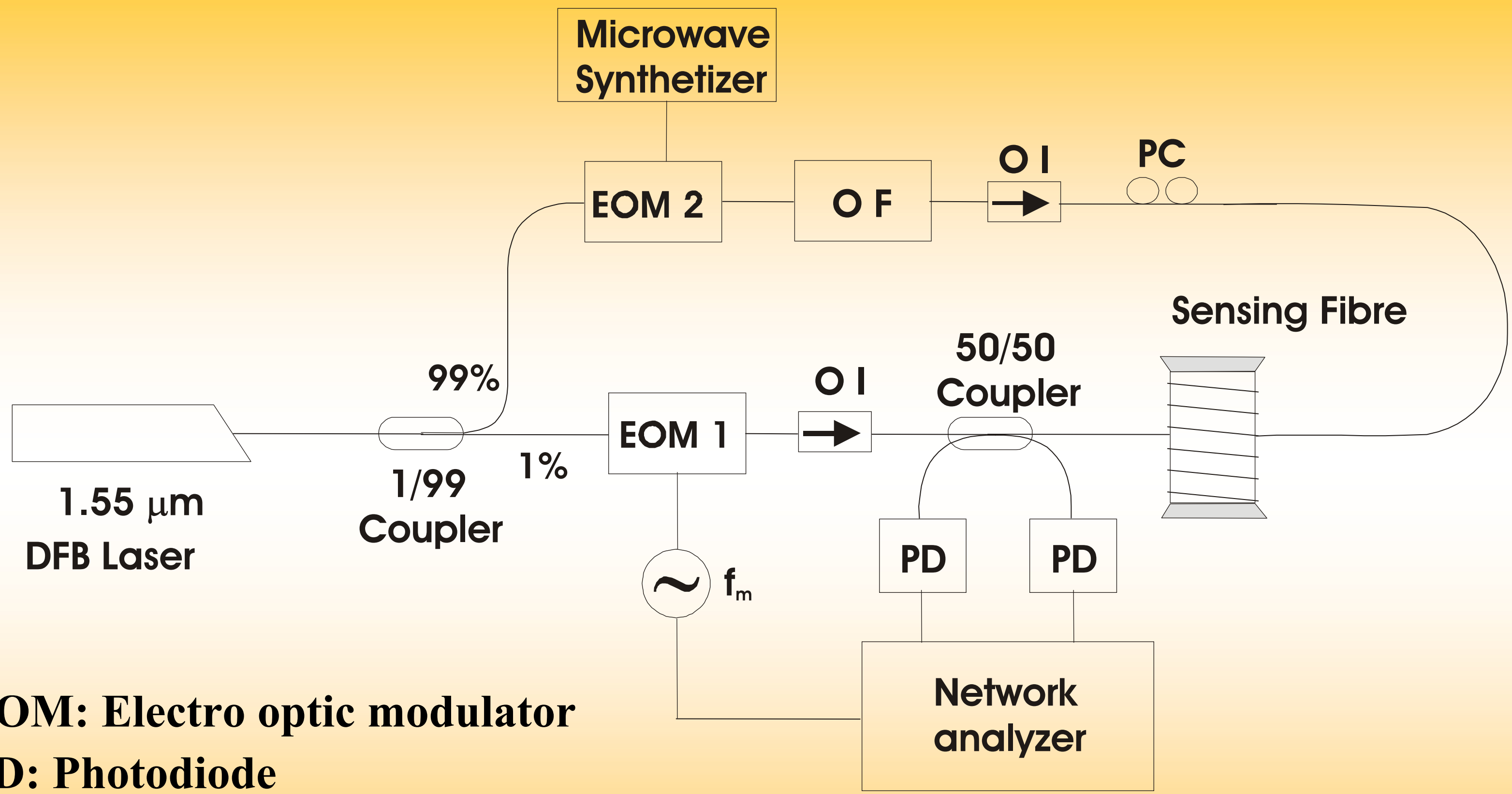
$$\Delta f(z) = f(z) - f_{impert.} = f_0 + 2\,\mathrm{Re}\left(\sum_{n=1}^{N-1} f_n e^{jn\frac{2\pi}{L}z}\right) \quad 0 \le z \le L$$

where L is the sensing length

Novel Approach Advantages

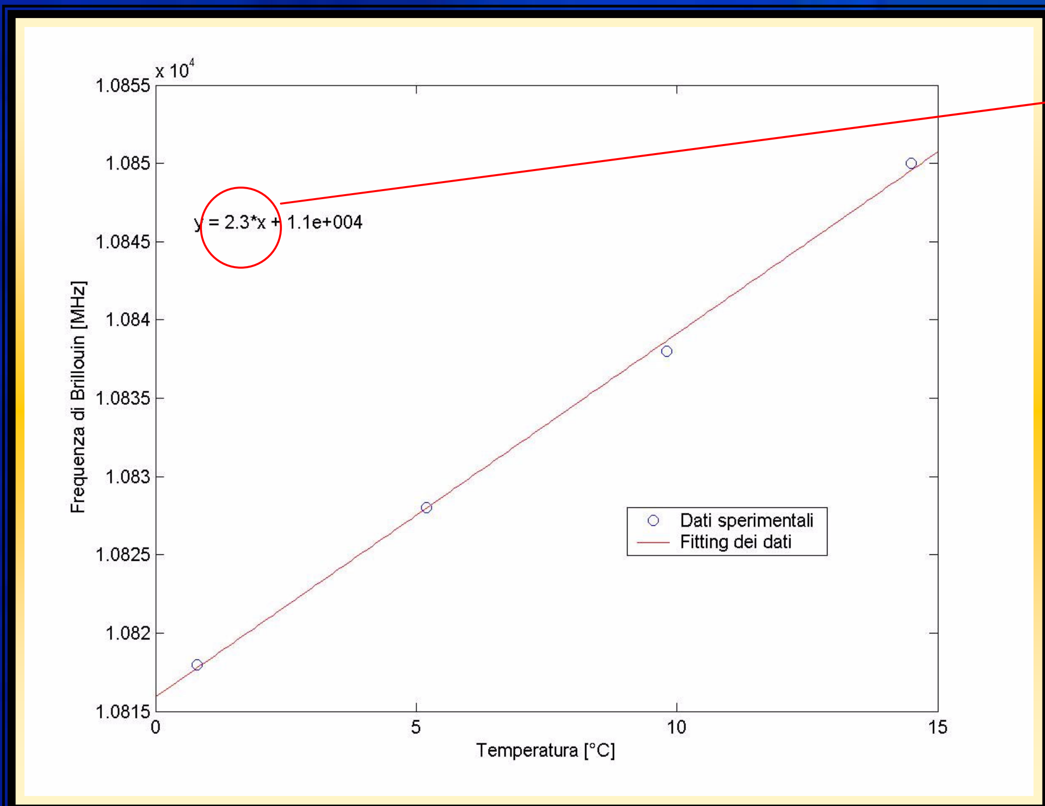
- ✓ Both data processing and measurements are performed in the frequency domain
- ✓ The nonlocal effects are compensated for
- ✓ Measurements can be taken with few pump-probe frequency offsets
- ✓ The influence of noise is strongly reduced

Experimental set-up



EOM: Electro optic modulator
PD: Photodiode
OF: Optical Filter
OI: Optical isolator
PC: Polarization controller

Temperature calibration

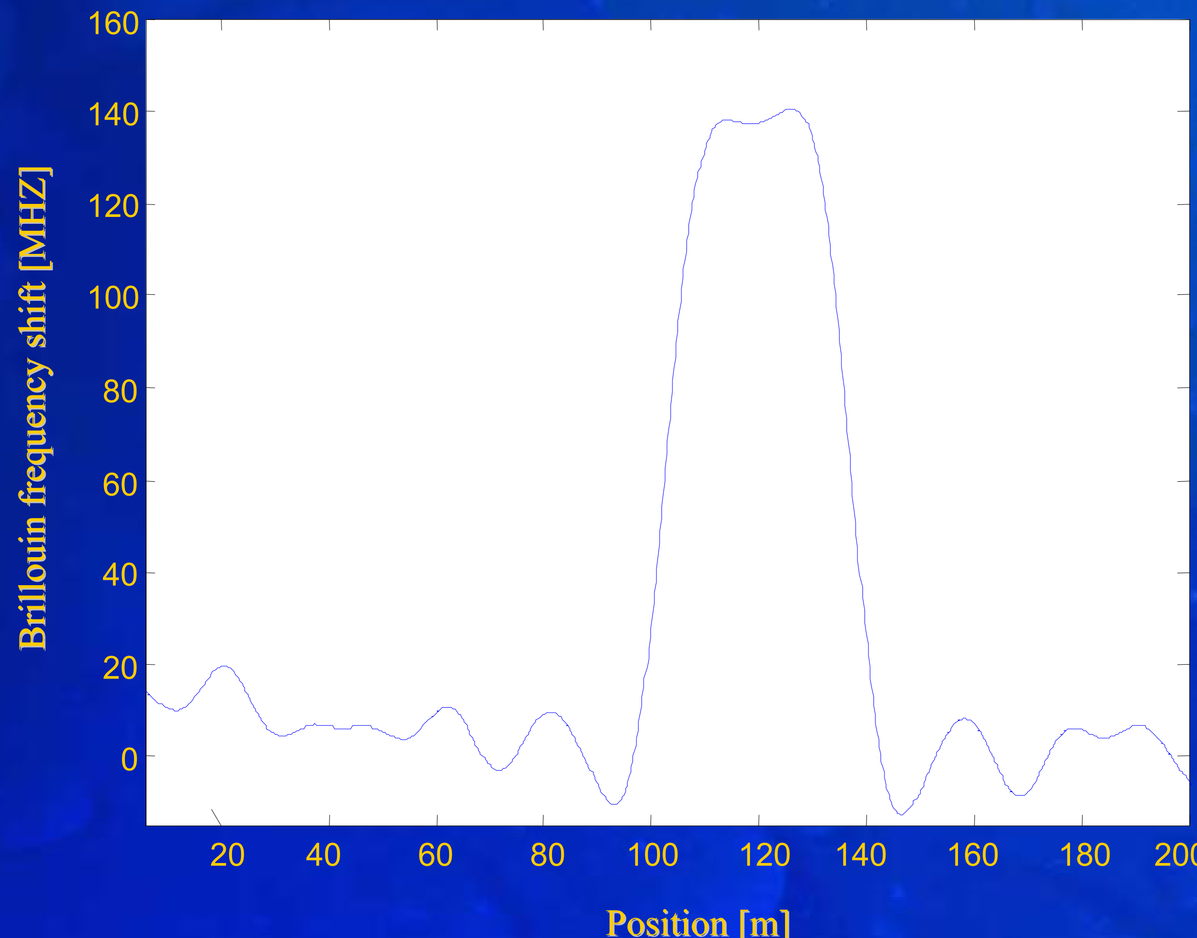


$$C_T = 2.3 MHz/°C$$

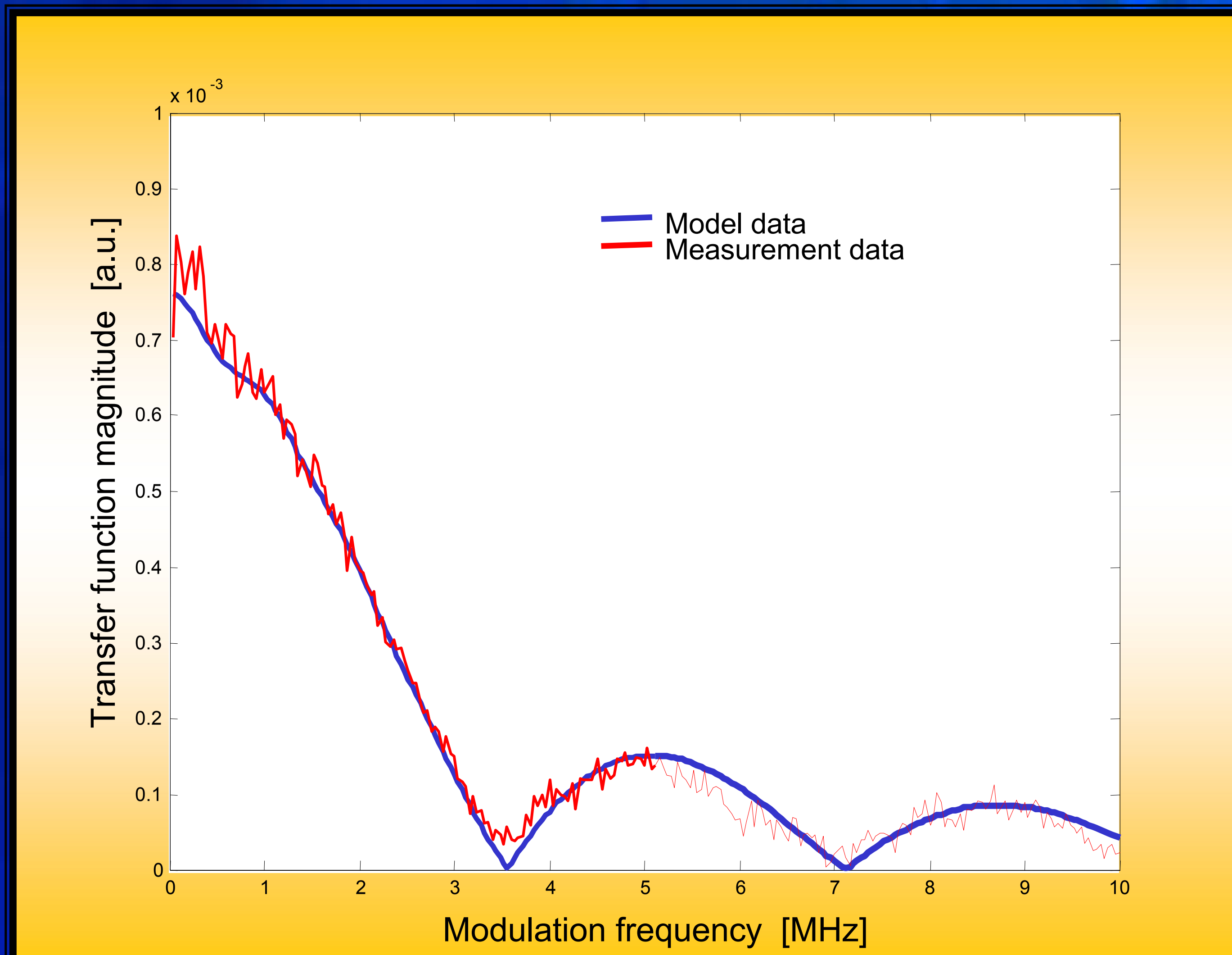
$$\Delta T = \frac{\Delta f}{C_T}$$

Experimental results

30m-long fiber with a 140MHz Brillouin shift difference between two 100m-long fibers

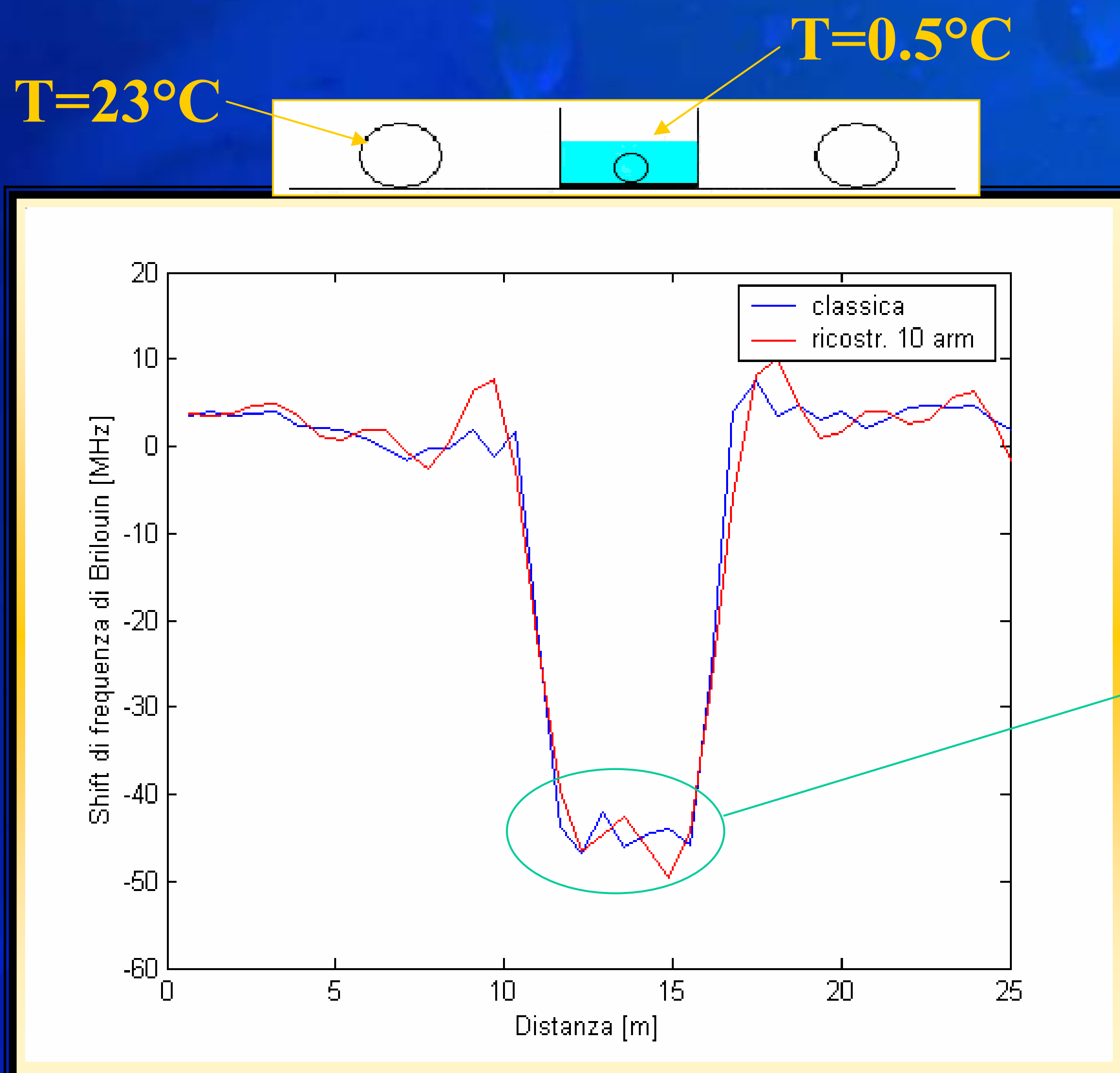


Experimental results



Experimental results

One fiber region (5m-long) immerged into melting ice



$\Delta f = -49\text{MHz}$

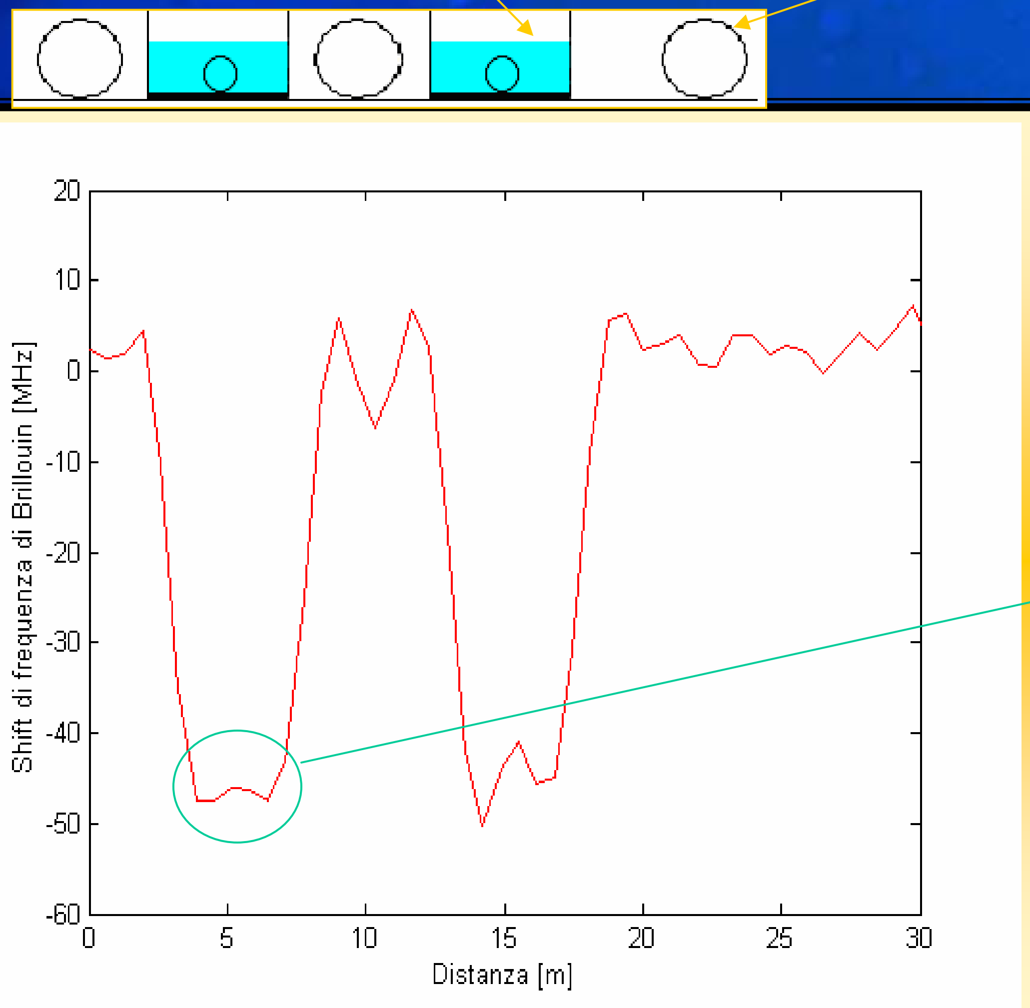
$\Delta T = -21.3°C$

Experimental results

Two fiber regions (5m-long) immerged into melting ice

T=1.6°C

T=23°C (temp. ambiente)

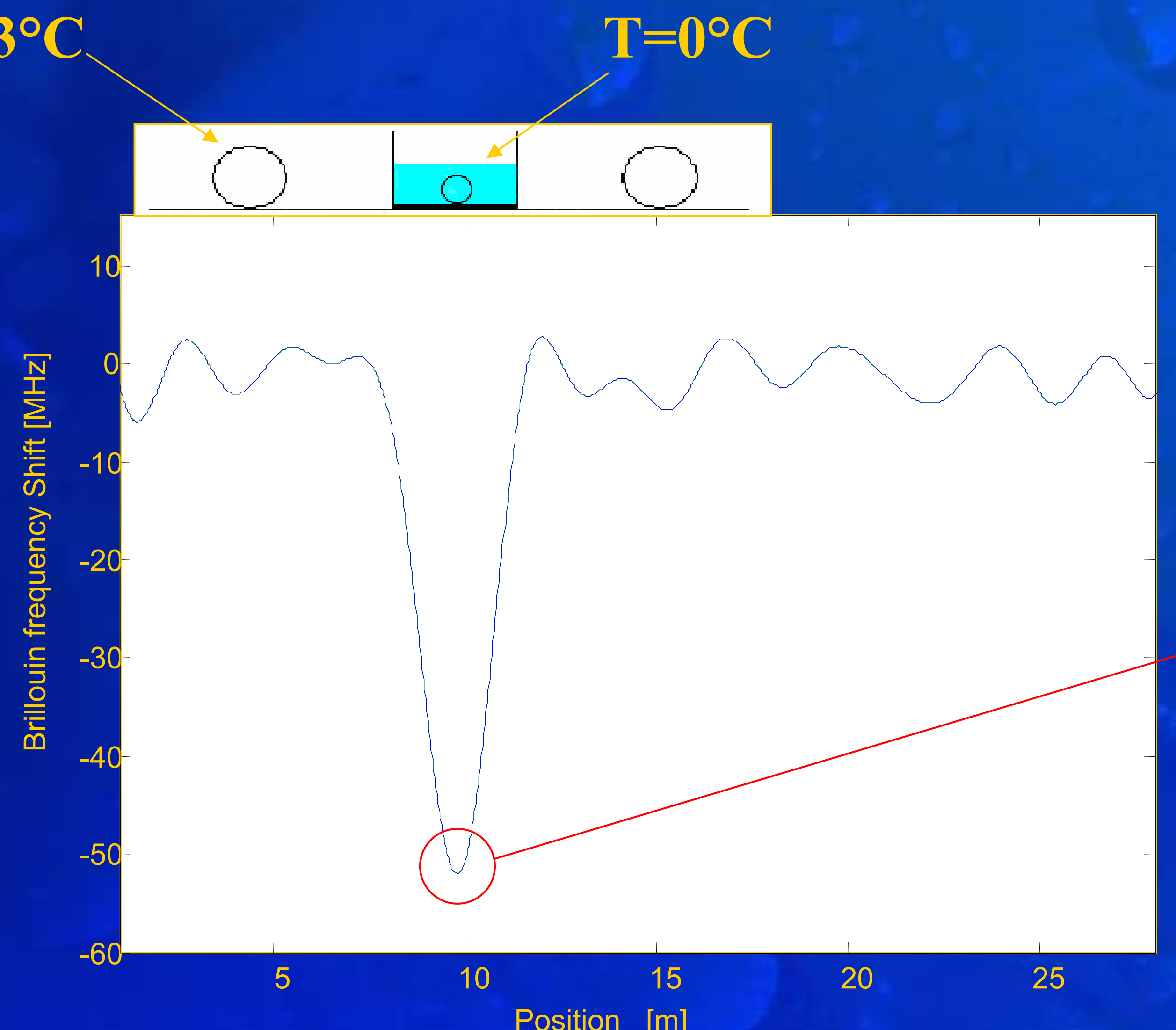


$\Delta f = -49MHz$

$\Delta T = -21.3°C$

Experimental results

One fiber region (2m-long) immerged into melting ice



Δf = -52MHz

ΔT= -22.6MHz

Experimental results

two fiber regions (1m and 1.5m long) immerged into melting ice