Chapter 5
Fiber sensor

In the preface, we have introduced the fiber sensors briefly.

The fiber sensors can be divided into the following two types:

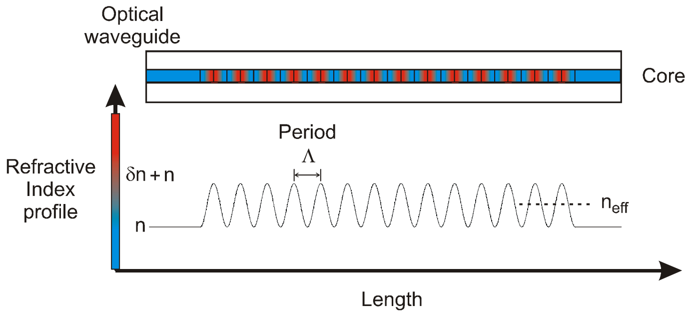
(1) Fiber Bragg grating based fiber sensors
- **Single-point fiber sensor**
- **Multi-point (quasi-distributed) fiber sensor**

(2) Distributed fiber sensors

Fiber Bragg grating based fiber sensors
Applications

Railway monitoring **Bridge monitoring**

Fiber Bragg grating based fiber sensors
What is the fiber Bragg grating?



The refractive index of the fiber core is modulated in a certain way.

When a Ge-doped silica core fiber is exposed to UV light (λ =190-266 nm), this leads to a change in refractive index (Δn) of the exposed region of the fibre.

Photosensitivity:

UV exposed Ge-doped silica fibre $\Delta n = 10^{-4}$

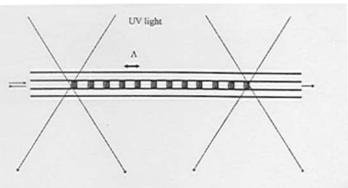
UV exposed B/Ge-doped silica fibre $\Delta n = 10^{-3}$

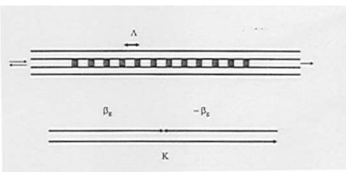
UV exposed H_2-loaded B/Ge-doped silica fibre $\Delta n = 10^{-2}$

This can be utilized to UV-write Bragg grating structures in fibers.

Fibre Bragg grating (FBG) - periodic index modulation in fiber core

$$n(z) = n_{co} + \delta n\left[1+\cos(2\pi z/\Lambda)\right]$$





Such structures can couple the light from the forward propagating mode (β_g) to the backward propagating mode ($-\beta_g$) when they are phase matched-forming reflection at resonant wavelength.

Phase match condition

$$\beta_g - (-\beta_g) = K = \frac{2\pi}{\Lambda} \quad \text{or} \quad \lambda_B = 2\Lambda n_{eff}$$

Λ - the period of the graing

n_{eff} - the effective mode index.

In the optic fibre communication window region (1.55 mm)
Typical $L \sim 0.75$ mm

(a) Reflectivity

$$R = \tanh^2 \kappa L$$

κ - couling coefficient, L - grating length

$$\kappa \approx \frac{\pi \Delta n I}{\lambda_B}$$

Δn - index modulation

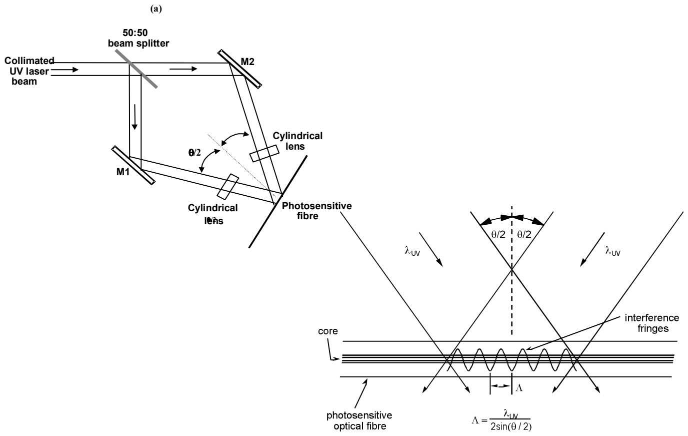
I - mode overlapping integral ($I < 1$).

(b) Bandwidth

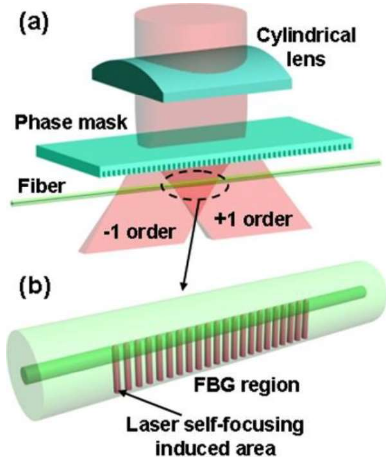
FWHM (3-dB) - full width at half maximum (typical 0.2-0.5nm).

$$\Delta\lambda = \frac{\lambda_B^2}{\pi n_{eff} L}\left(\kappa^2 L^2 + \pi^2\right)^{1/2}$$

Fabrication of fibre Bragg gratings
(a) Two-beam holographic writing



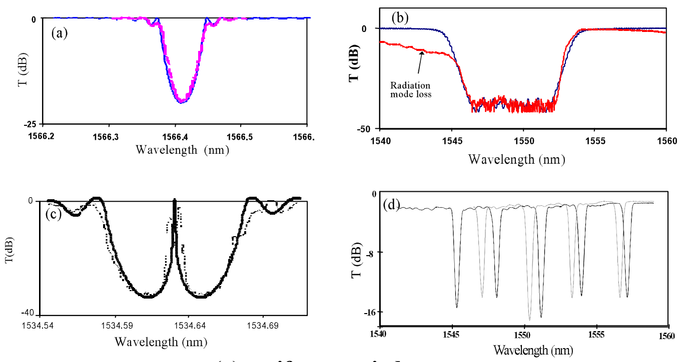
(b) Phase mask method



$$\lambda_B = 2n_{eff}\Lambda_g = n_{eff}\Lambda_{PM}$$

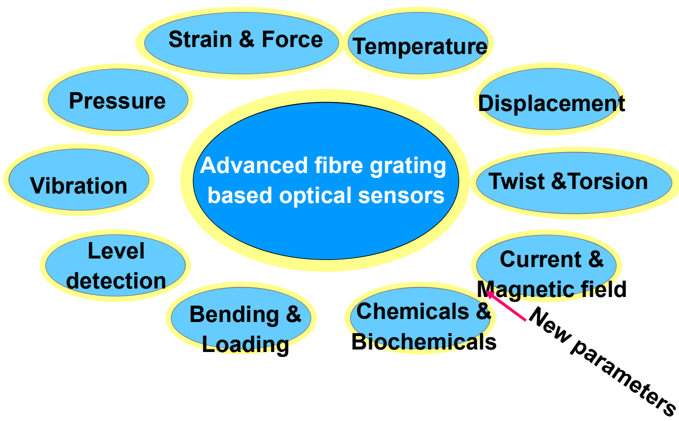
$$\Lambda_g = \frac{\Lambda_{PM}}{n_{eff}}$$

Complex grating structures



(a) uniform-period
(b) chirped
(c) bandpass (resonant)
(d) grating array

What properties FBG sensors can measure



For example:

Strain and temperature sensing

The sensing function of an FBG is related to the changes of both refractive index and grating period.

$$\lambda_B = 2\Lambda n_{eff} \rightarrow \Delta\lambda_B = 2n_{eff}(\Delta\Lambda) + 2\Lambda(\Delta n_{eff})$$

These changes are from externally applied mechanical and thermal perturbations, respectively.

Therefore, the peak reflected wavelength shifts $\Delta\lambda_B$ in response to change of strain $\Delta\varepsilon$ and temperature ΔT is given by

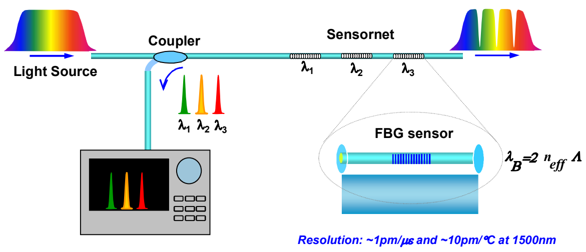
$$\frac{\Delta\lambda_B}{\lambda_B} = P_e\Delta\varepsilon + \left[P_e\left(\alpha_s - \alpha_f\right) + \varsigma\right]\Delta T$$

P_e – strain-optic coefficient

α_s and α_f – thermal expansion coefficients

ς- thermal-optic coefficient

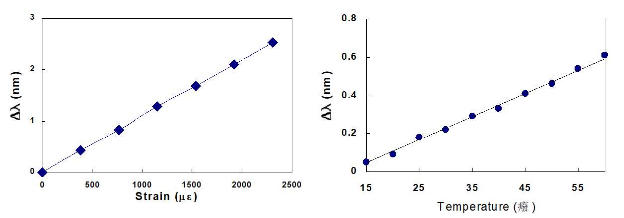
Advantages:



- Inherently sensitive to strain and temperature
- Absolute, linear response
- Small size and light weight, stable and durable
- Immune to EM interference
- Operate in a wide range of environmental conditions
- Can be easily embedded
- Easy to multiplex (sensornet technology)
- Ideal candidates for SMART structure applications

For grating produced in silica fibers, representative values of the strain- and temperature- induced wavelength shifts are ~1 pm/με and ~10 pm/°C at 1300 nm, respectively

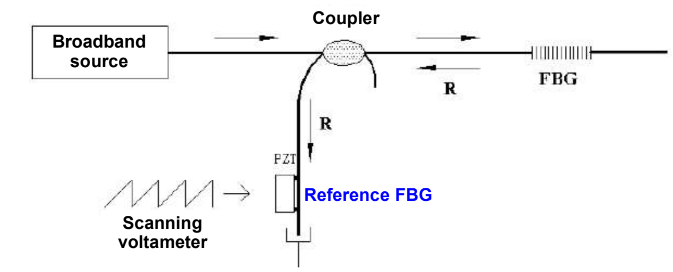
Typical Bragg wavelength shift responses to the applied strain and temperature



Demodulation methods of the FBG based sensors

- The method based on matched reference FBG
- The method based on tunable laser
- The method based on F-P filter

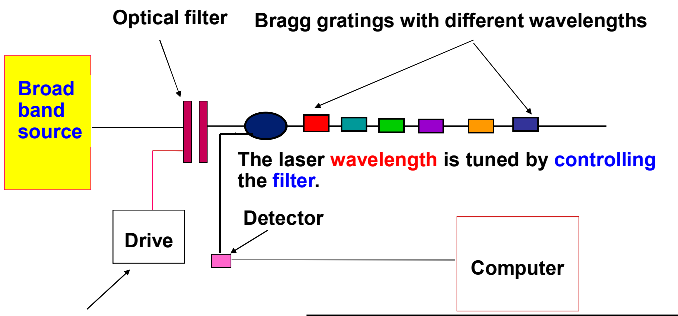
matched reference FBG



PZT can control the center wavelength of the reference FBG.

When the center wavelength of reference FBG matches with the reflected wavelength, the light will transmit.

The demodulation method based on tunable laser



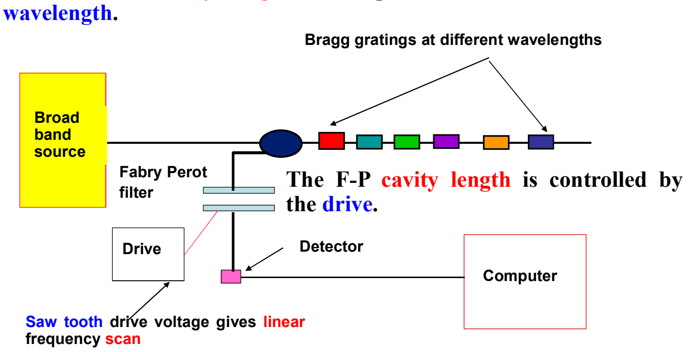
Saw tooth drive voltage gives linear frequency scan

锯齿波形提供线性频率扫描

When the output wavelength from the tunable laser is same as the center wavelength of the Bragg gratings, the light will be detected.

The demodulation method based on F-P filter

Different F-P cavity lengths correspond to different transmission wavelength.



When the transmission wavelength of the FP filter is same as the center wavelength of one of the Bragg gratings, the light will be detected.

Distributed fiber sensors

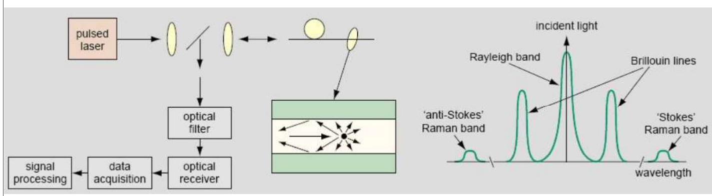
The distributed fiber sensors can be used to measure the temporal and spatial distributions of the physical quantities along fiber axis continuously.

Classification:

- Backward scattering type
- Transmission type

Here we mainly focus on the distributed fiber sensors based on backward scattering.

Distributed fiber sensors based on backward scattering



This type of sensors mainly utilize the backward scattering signal (e.g., Raleigh scattering, Raman scattering, Brillouin scattering) to realize the sensing.

•Raleigh scattering—Intensity monitoring—Fiber loss-strain, stress

•Raman scattering—Intensity monitoring—Temperature

•Brillouin scattering—Frequency or intensity—Strain, stress, temperature

Applications: Gas pipe monitoring & Landslide and mud-rock flow monitoring

The detection techniques of distributed fiber sensors
光学时域/频域/时间相干检测技术

The technique based on optical temporal domain detection:

OTDR、POTDR、ROTDR、BOTDR

The technique based on optical frequency domain detection:

OFDR、POFDR、ROFDR

The technique based on optical temporal coherence:

COTDR、ø- OTDR

Here we focus on the technique based on optical temporal domain detection

OTDR technique

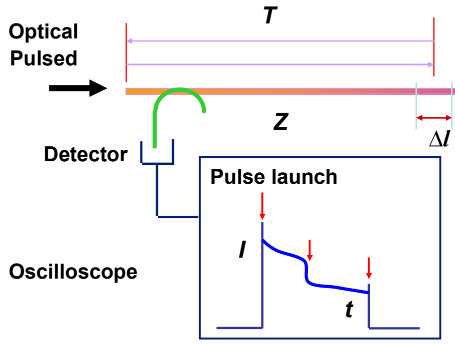
This technique is performed by collecting the backward scattering light signals that are launching into the fiber.

The distance between the input and disturbance point can be obtained according to the time delay between the input and returned signals:

$$d = \frac{cT}{2n}$$

c is the light speed in vacuum, *n* is the refractive index, *T* is the time delay

Time corresponds to distance



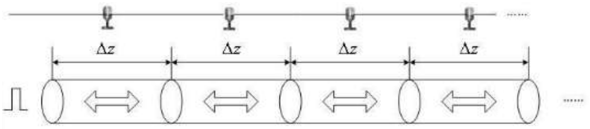
$$Z = \frac{1}{2} T \cdot \frac{c}{n}$$

System can be operated from one end

Spatial resolution of OTDR technique 空间分辨率

$$\Delta l = \frac{ct}{2n}$$

c is the light speed in vacuum, *n* is the refractive index, *t* is the pulse duration 脉冲持续时间



Distributed fiber sensors based on Raleigh scattering

Optical temporal domain detection techniques:

•Common OTDR

•Phase sensitive OTDR (φ-OTDR)

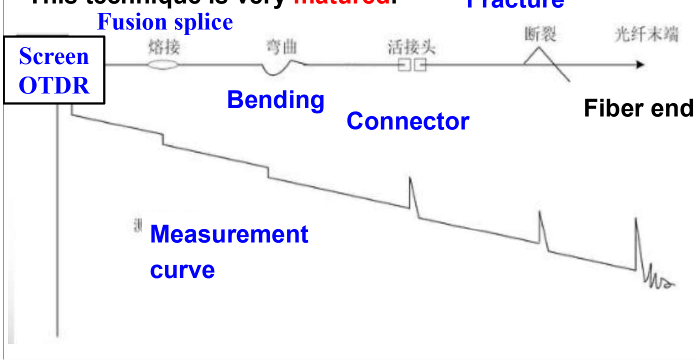
•Coherent OTDR (COTDR)

•Polarized OTDR (POTDR)

Common OTDR

It is usually used to measure or detect the loss and position of the fusion splice and connector.

This technique is very matured.

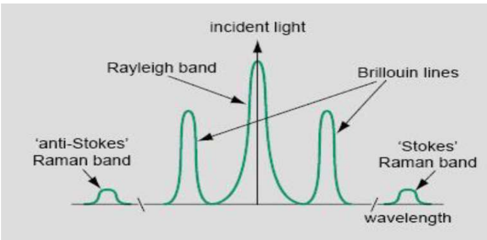


Distributed fiber sensors based on Raman scattering

This type of distributed fiber sensors are called as ROTDR.

ROTDR is usually applied in the temperature sensing at a large range and long distance

The relationship between the intensity ratio of Stokes light to anti-Stokes light and temperature is utilized to demodulate the signal.



The principle of ROTDR

For the Raman scattered lights, the intensity of Stokes light is not relative to temperature, but the intensity of anti-Stokes light varied with temperature.

The intensity ratio of Stokes light I_s to anti-Stokes light I_{as} as a function of temperature can be expressed as

$$\frac{I_{as}}{I_s} = a \cdot e^{-\frac{hc\nu_0}{kT}}$$

Temperature changes → I_{as} changes

Temperature changes → I_s no changes

a is a coefficient relative to the temperature, *h* is the Plank constant, *c* is the light speed in vacuum, ν_0 is the frequency of input light, *k* is the Boltzmann's constant, *T* is the absolute temperature

Therefore, the temperature can be calculated by measuring the intensity of Stokes and anti-Stokes lights

$$T = \frac{hc\nu_0}{k} \cdot \frac{1}{\ln a - \ln\left(\frac{I_{as}}{I_s}\right)}$$

The structure of ROTDR used for temperature sensing

In practical, the filters can be used to obtain the Stokes and anti-Stoke lights, respectively.

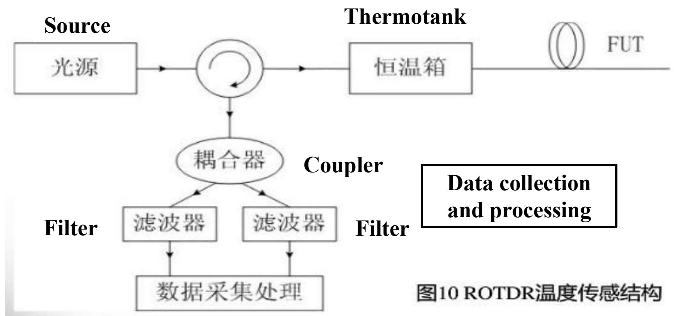


图10 ROTDR温度传感结构

Characteristics of ROTDR [与瑞利散射相比]

Intensity of Raman scattering is about 20~30 dBm lower than that of Raleigh scattering, thus high pulse peak power is required.

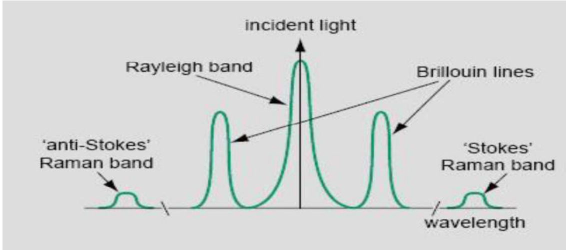
Intensity of Raman scattering is only relative to environment temperature, it is not sensitive to the strain.

Distributed fiber sensors based on Brillouin scattering

This type of distributed fiber sensors are called as BOTDR.

It detects the backward Brillouin scattering signals.

The Brillouin shifted light components are relative to the local temperature and strain.



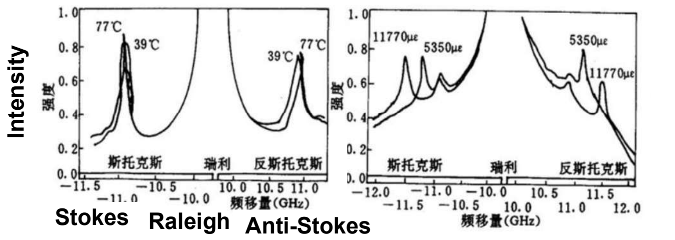
The temperature and strain will lead to the linear shift of the Brillouin frequency.

$$f_B = f_{B0} + f_T T(^oC) + f_\varepsilon \varepsilon(\mu\varepsilon)$$

The power of the Brillouin light increases with the increased temperature and decreases with the increased strain.

$$P_B = P_{B0} + P_T T(^oC) + P_\varepsilon \varepsilon(\mu\varepsilon)$$

The temperature and strain at one position can be achieved by measuring the Brillouin shift and the power of Brillouin scattered light.



At different temperatures　　At different strains

Frequency shift (GHz)

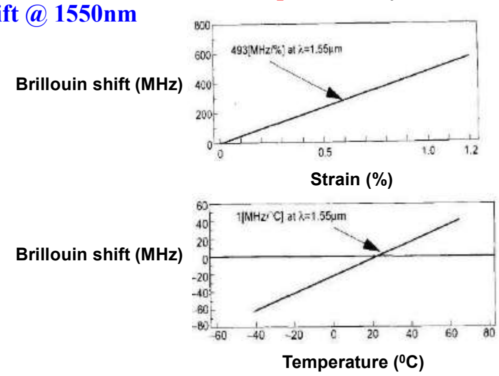
Brillouin shift coefficients of temperature are 1.22 MHz/°C (1310 nm) and 1 MHz/°C (1550 nm).

Brillouin shift coefficients of strain are 581 MHz/% (1310 nm) and 493 MHz/% (1550 nm).

Compared to strain, temperature has a comparatively little influence on the Brillouin shift.

For example:

To obtain the strain and temperature by measuring the Brillouin shift @ 1550nm



Structure of BOTDR

BOTDR exploits the spontaneous Brillouin scattering.[自发布里渊散射]

Issues:

–Intensity of Brillouin scattering signal is two order of magnitude smaller than that of Raleigh scattering signal, thus it is hard to detect. [功率较小，难以检测]

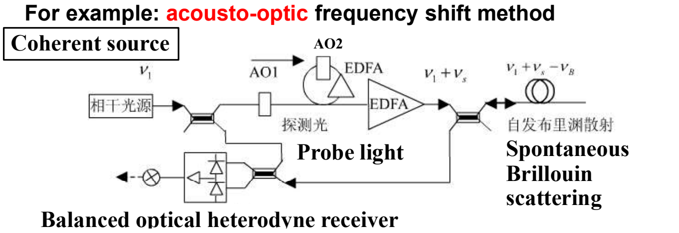
–Brillouin scattering shift are general 11 GHz and also hard to take out from Raleigh scattering signal.

Therefore, the approach of frequency mixing between the local light and scattering light is employed to realize the coherent reception.

因此，采用局部光和散射光混频的方法实现相干接收。

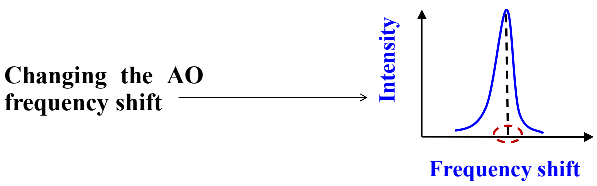
Demodulation of the BOTDR

For example: acousto-optic frequency shift method



The frequency shift ν_s from AOs is almost same as the Brillouin shift ν_B, thus the frequency of the backward Brillouin scattering light is close to that of the reference light.

Therefore the frequency difference is just located at the frequency bandwidth range of the optical heterodyne receiver. [光外差接收器]



Brilouin frequency spectrum can be obtained at the balanced optical heterodyne receiver.

The peak corresponds to the center of the Brillouin frequency shift.