# Photonics
# 5a FBG (Fiber Bragg Grating) Sensors



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## *Summary*

- Impact of fiber optics on modern sensory systems
- Bragg's effect
- Introduction of Fiber Bragg Grating (FBG)
- FBG mathematical model
- Reflection and Transmission in FBG
- FBG Structure
- FBG sensors
- FBG sensor applications

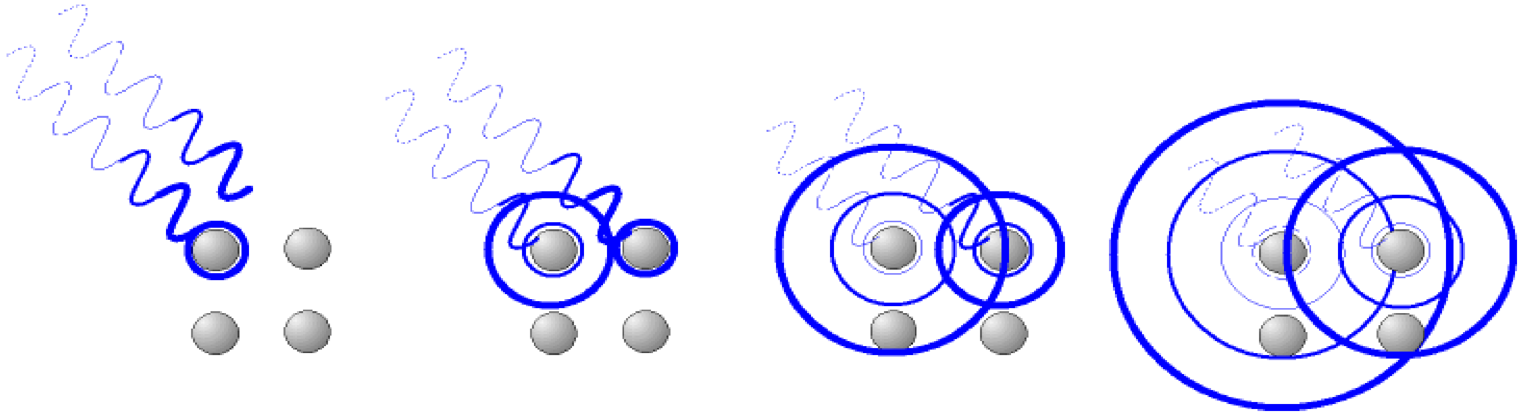
## ❖ Impact of fiber optics on modern systems

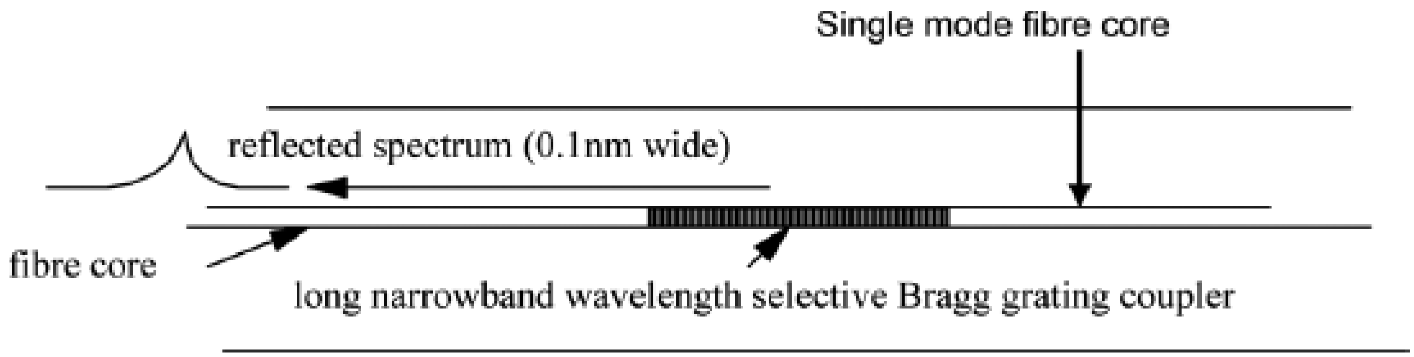
It is clear from the revolution of the year 2000 that optical fibers have made an enormous impact on modern telecommunication systems. The capacity of optical fiber systems is forever moving upward and distances longer, fueled by the exploding demand for the Internet. As we move into the next millennia, the need for interactive long distance communications will increase, pressured by the need to reduce the demand for energy and the effects of global warming.

## ❖ Bragg's law

In physics, Bragg's law gives the angles for coherent and incoherent scattering from a crystal lattice. When X-rays are incident on an atom, they make the electronic cloud move as does any electromagnetic wave. The movement of these charges re-radiates waves with the same frequency (blurred slightly due to a variety of effects); this phenomenon is known as Rayleigh scattering (or elastic scattering). **The interference is constructive when the phase shift is a multiple of 2π; this condition can be expressed by Bragg's law:**

$$n\lambda = 2d\sin\theta$$






## Fiber Bragg grating—basics.

# ❖ Introduction to FBG

A **Fiber Bragg Grating (FBG) is an optical fiber for which the refractive index in the core is perturbed forming a periodic or quasi periodic index of modulation profile.** A narrow band of the incident optical field within the fiber is reflected by successive, coherent scattering from this index of modulation variations. When the reflection from a crest in the index of modulation is in phase with the next one, we have maximum mode coupling or reflection.

**Bragg effect condition:**

$$\lambda_B = 2n_{eff}\Lambda$$

**where**

- **$\lambda_B$ is the Bragg wavelength**
- **$n_{eff}$ is the effective modal index of refraction**
- **$\Lambda$ is the perturbation period**

## ❖ FBG basic properties

1. Pasive fiber optic component exhibiting basic functional **attributes of reflection and filtering**
2. Simple to manufacture
3. Small in dimension
4. Low cost
5. Exhibit good immunity to changing ambient conditions and EM radiation
6. FBG replace bulk optic mirrors & beam splitters in equipments which increases system stability and portability

## ❖ FBG mathematic model

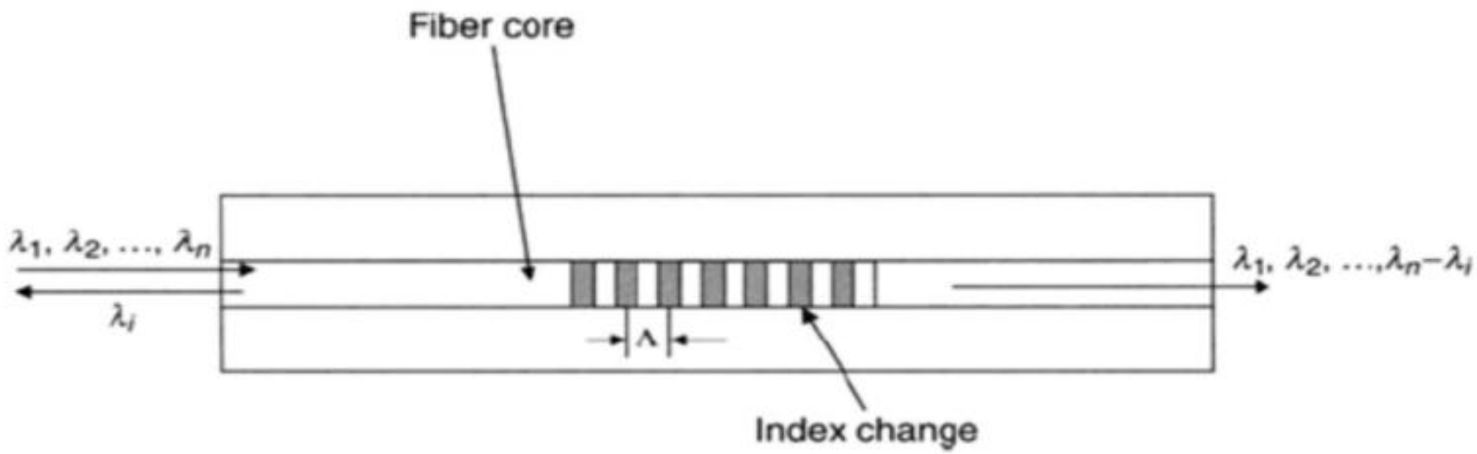
The relation between the spectral dependence of a fiber grating and the corresponding grating structure is usually described by the **coupled-mode theory**.

The forward and backward propagating field envelopes are mutually coupled by **the coupled mode equations**

$$\frac{du(z;\delta)}{dz} = +i\delta u + q(z)v$$

$$\frac{dv(z;\delta)}{dz} = -i\delta v + q^{*}(z)u,$$

## ❖ FBG structure

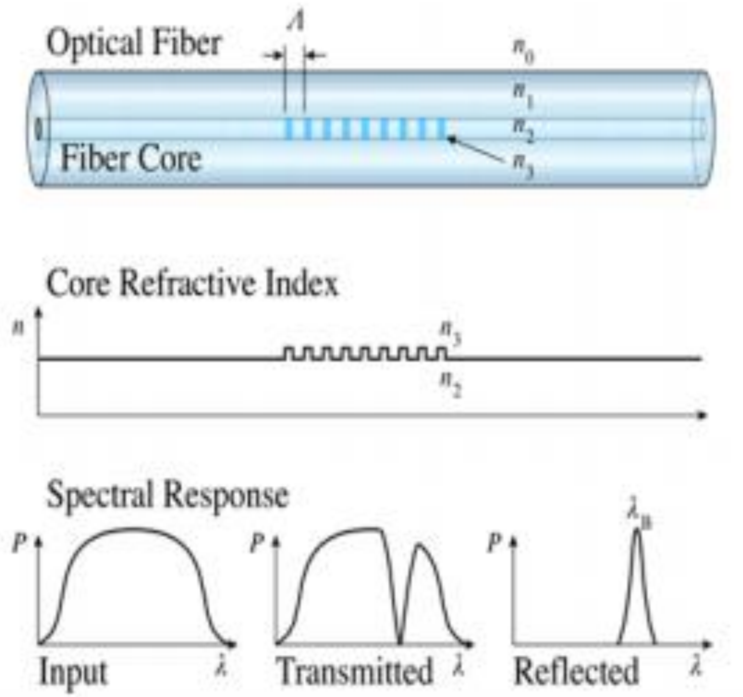


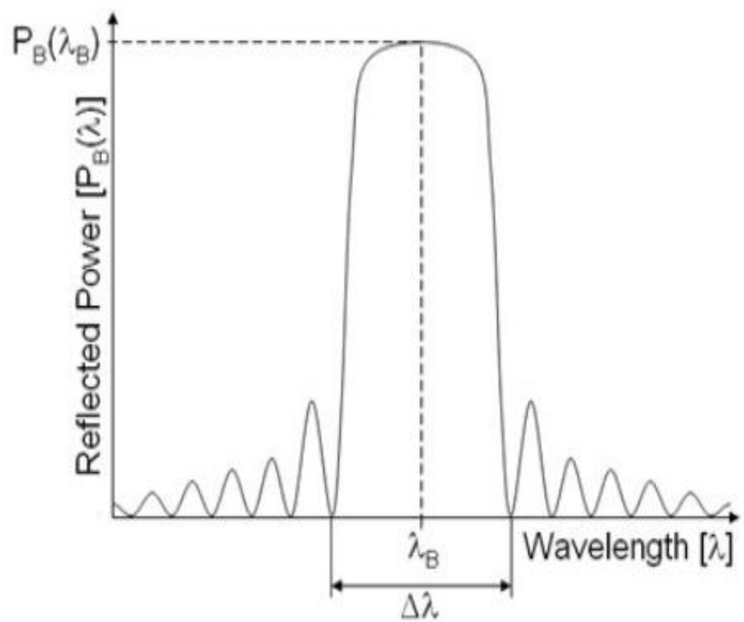

Schematic diagram of a fiber Bragg grating.

The refractive index of the fiber core is **modulated with a period of Λ.** When a light with a broad spectrum is launched into one end of fiber containing a **FBG**, the **part of the light with wavelength matching the Bragg grating wavelength will be reflected back to the input end**, with the rest of the light passing through to the other end.

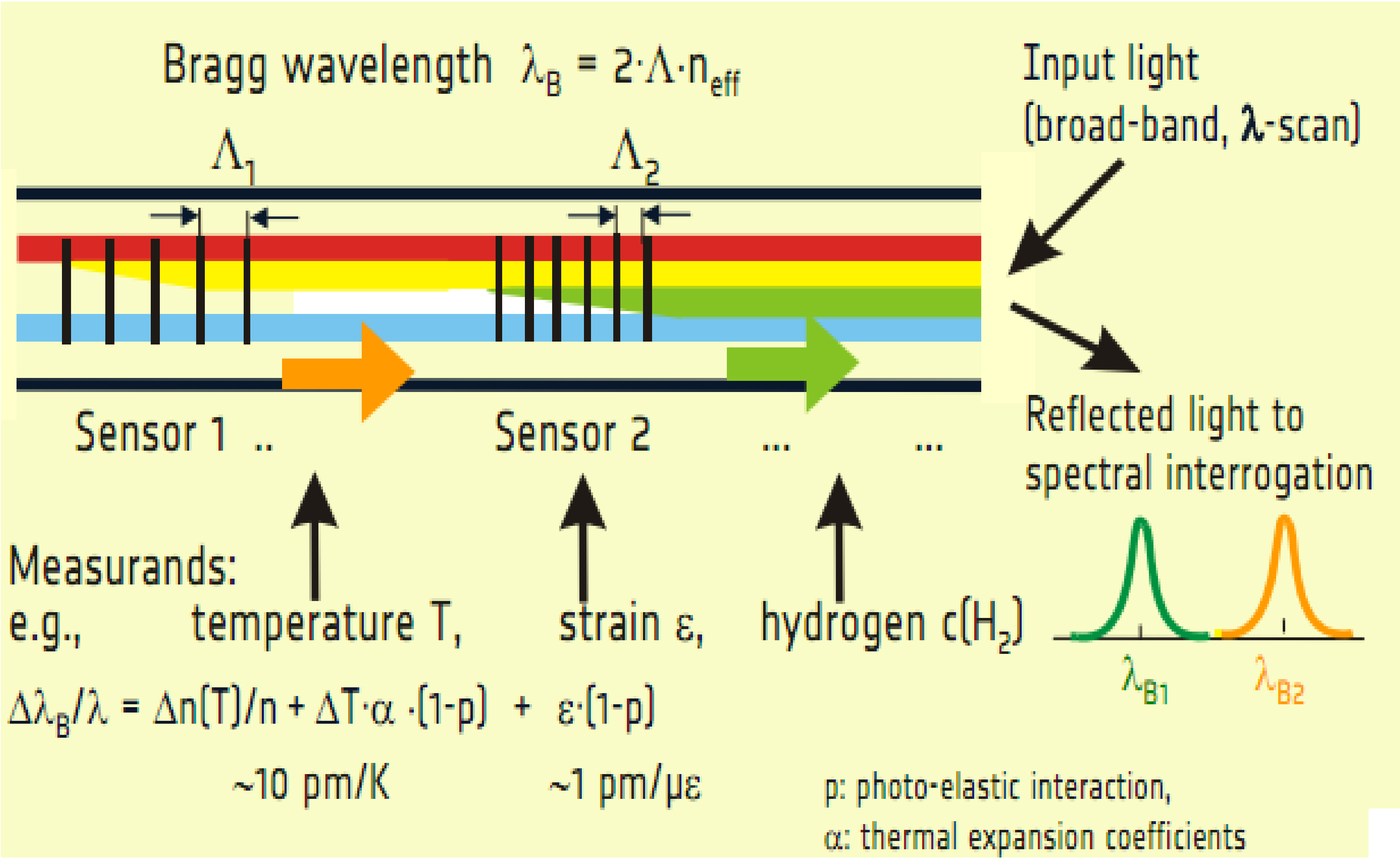
## ❖ Reflection and Transmission in FBG

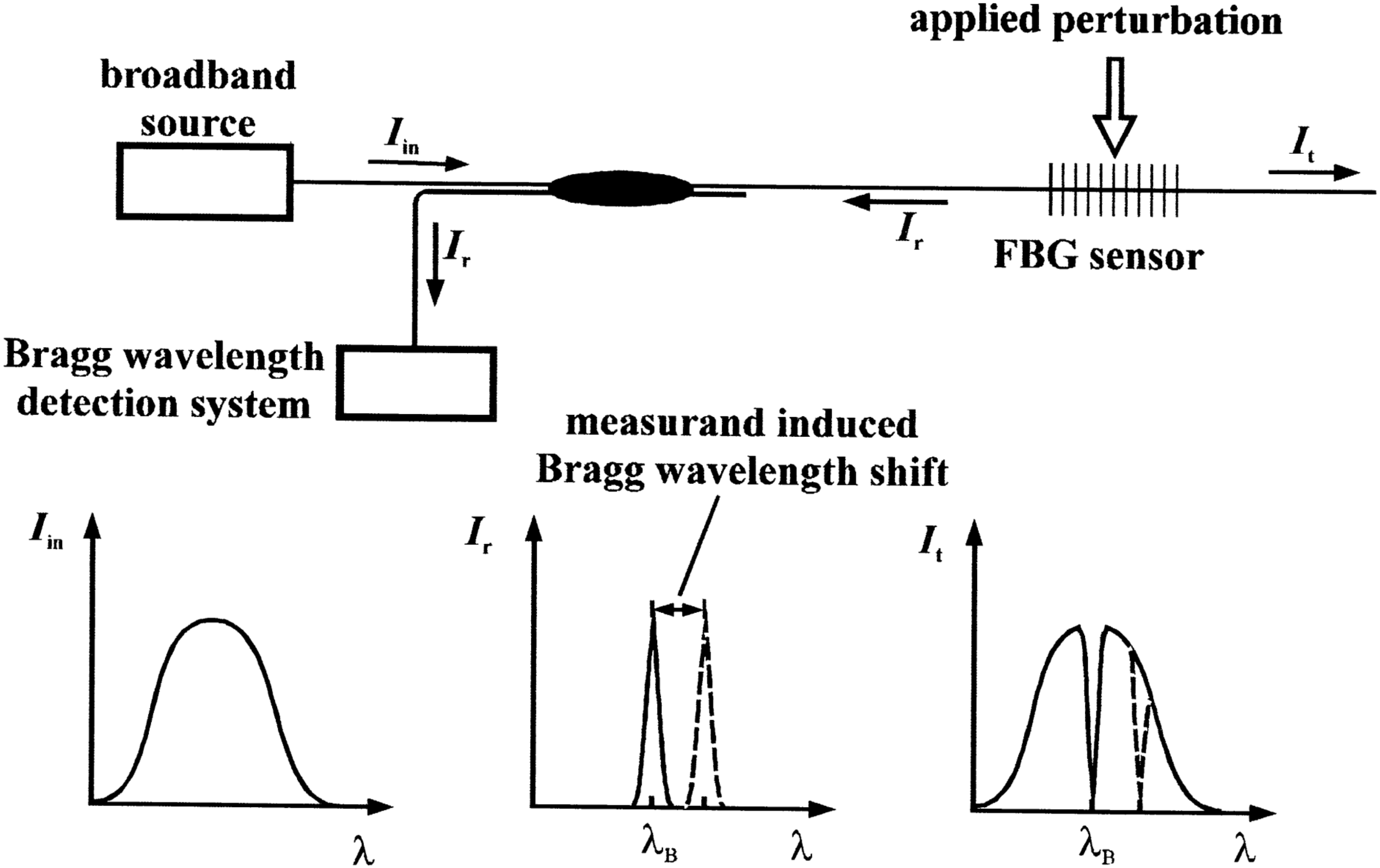
**The fundamental principle behind the operation of FBG is Fresnel reflection**. Where light traveling between media of different refractive indices may both reflect and refract at the interface. The **FBG** will typically have a sinusoidal refractive index variation over a defined length.



## ❖ FBG sensory function






**Basic Bragg grating-based sensor system with transmissive or reflective detection options.**

## ❖ FBG Structures

The structure of the FBG **can vary via the refractive index,** or the **grating period.** The grating period can be **uniform or graded**, and either **localised or distributed** in a superstructure.

| FBG TYPES | CHARACTERSTICS | APPLICATIONS |
|---|---|---|
| Simple reflective gratings | Creates gratings on the fiber that meets the Bragg condition | Filter for DWDM, stabilizer, locker |
| Long period gratings | Significant wider grating periods that couples the light to cladding | Gain flattening filter, dispersion compensation |
| Chirped fiber Bragg gratings | A sequence of variant period gratings on the fiber that reflects multiple wavelengths | Gain flattening filter, dispersion compensation |
| Slanted fiber gratings | The gratings are created with an angle to the transmission axis | Gain flattening filt |

## ❖ FBG construction basic operations

| Select Proper fiber | H2 loading | Laser writing | Annealing | Athermal packaging | Testing |
|---|---|---|---|---|---|
| Different FBG requires different specialty fiber | Increase photo sensitivity for easier laser writing | Optical alignment & appropriate laser writing condition | Enhance grating stability | For temperature variation compensation | Spec test |

## ❖ FBG device fabrication

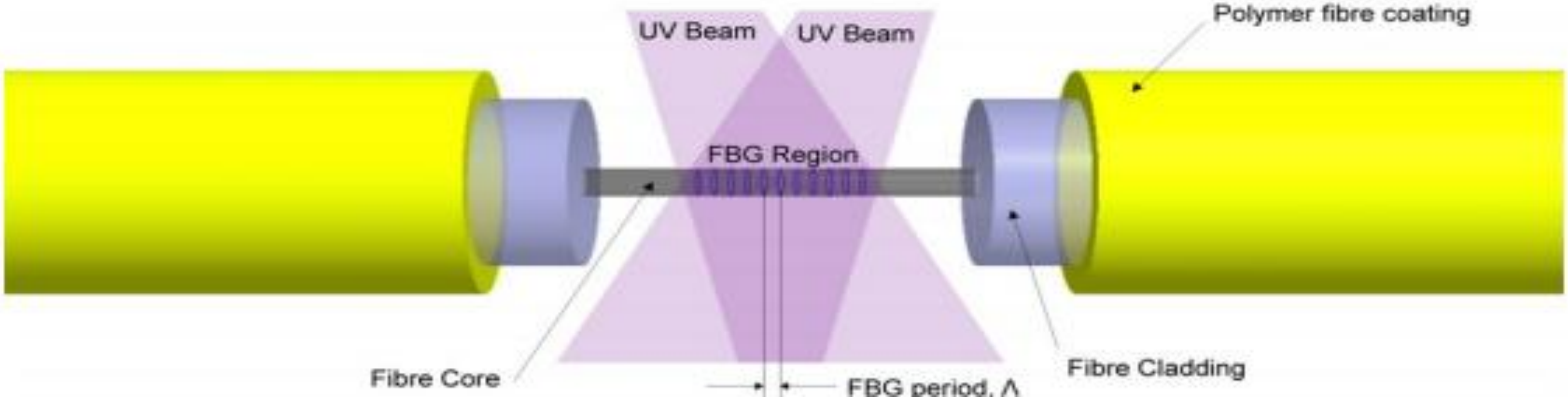
**FBGs, are fabricated by techniques that broadly fall into two categories:**

**a) Holographic**

**b) Noninterferometric**

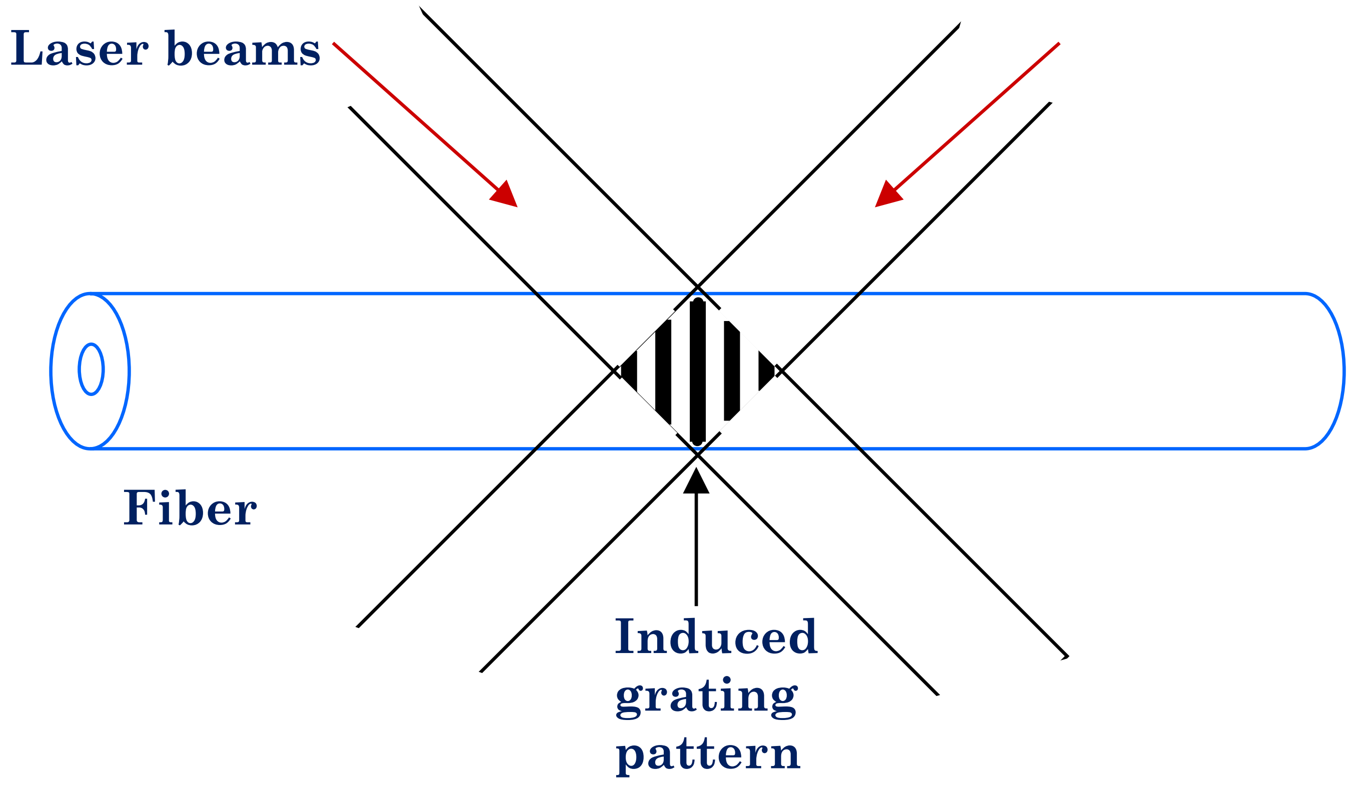
***Holographic techniques*** **use a beam splitter to divide a single input UV beam into two, interfering them at the fiber core**

**Noninterferometric techniques depend on periodic exposure of a fiber to pulsed sources or through a spatially periodic amplitude mask. Here we only introduce the holographic approach with a bulk interferometer**



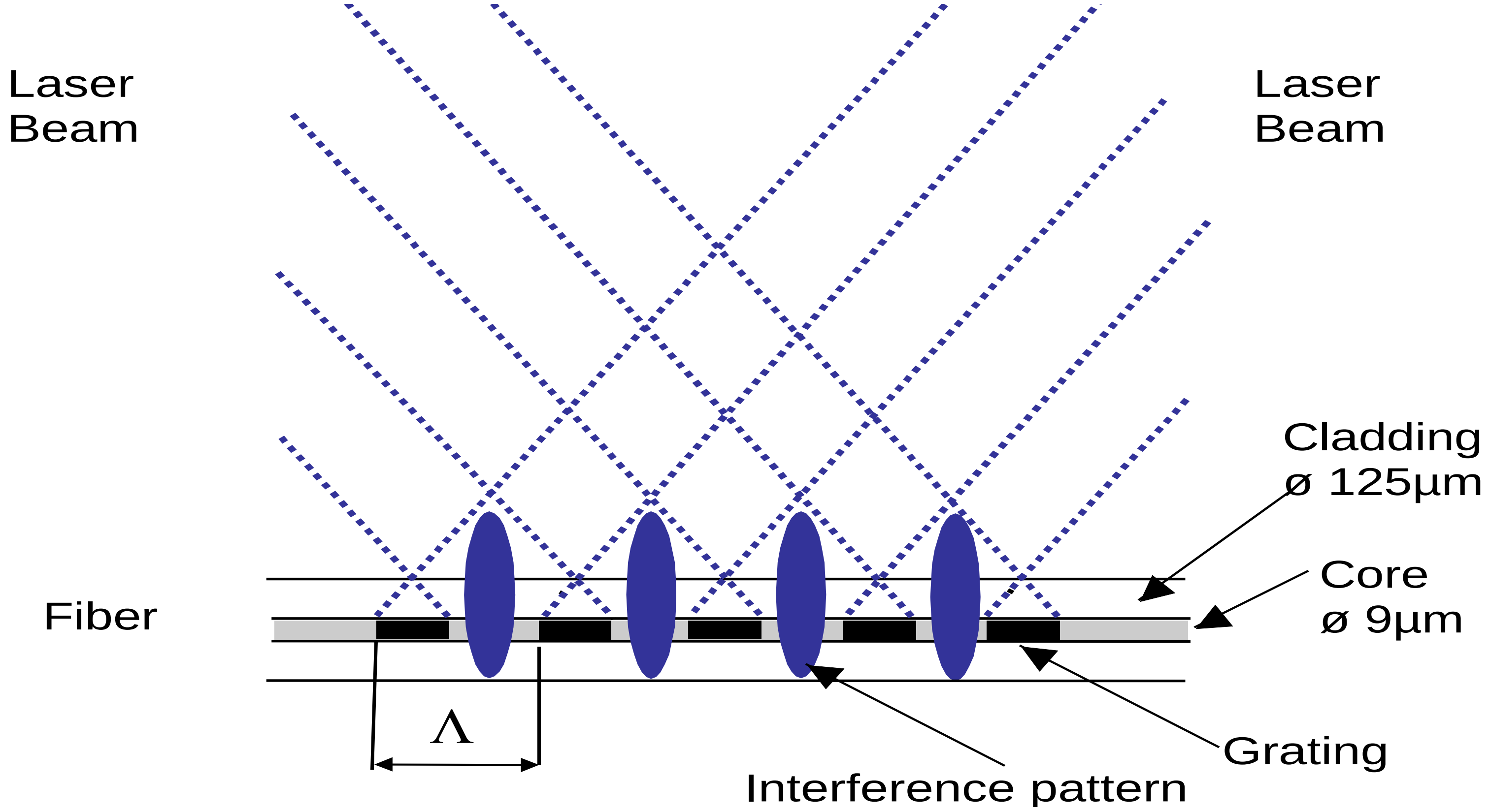
## ❖ FBG device fabrication

**Split Beam Interferometer Method**



## ❖ FBG device fabrication

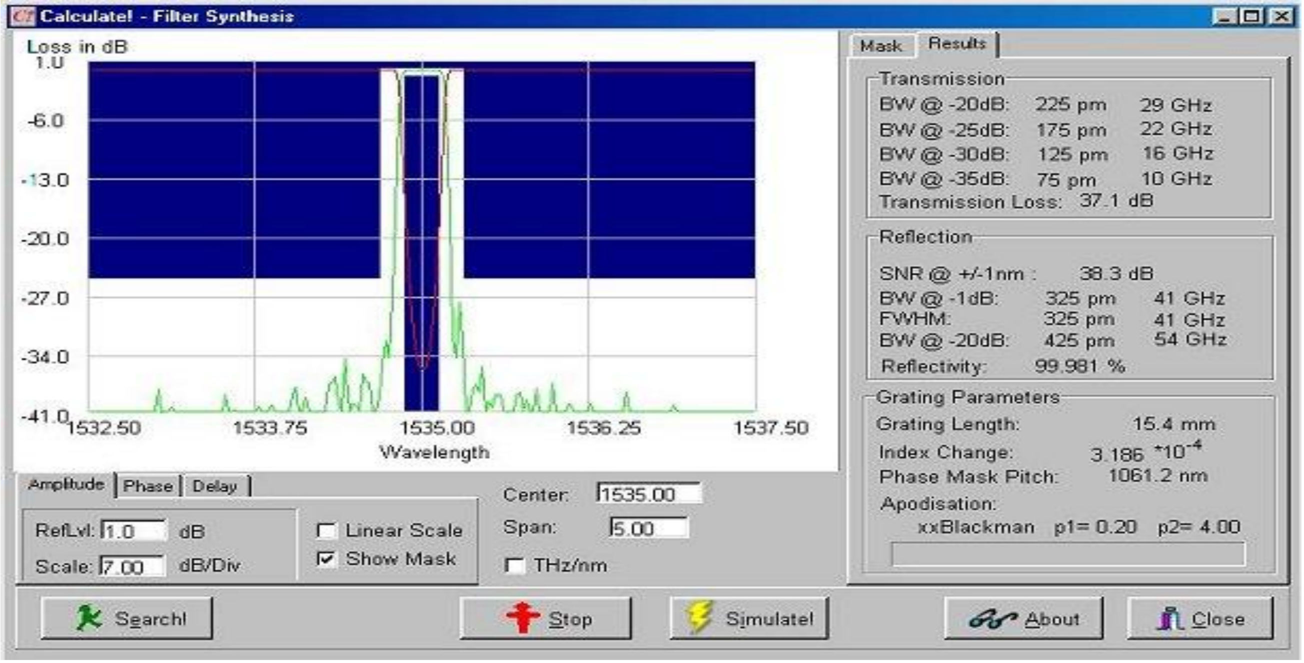
### <u>Split Beam Interferometer Method detail</u>



# ❖ FBG device fabrication

## Phase Mask Technique

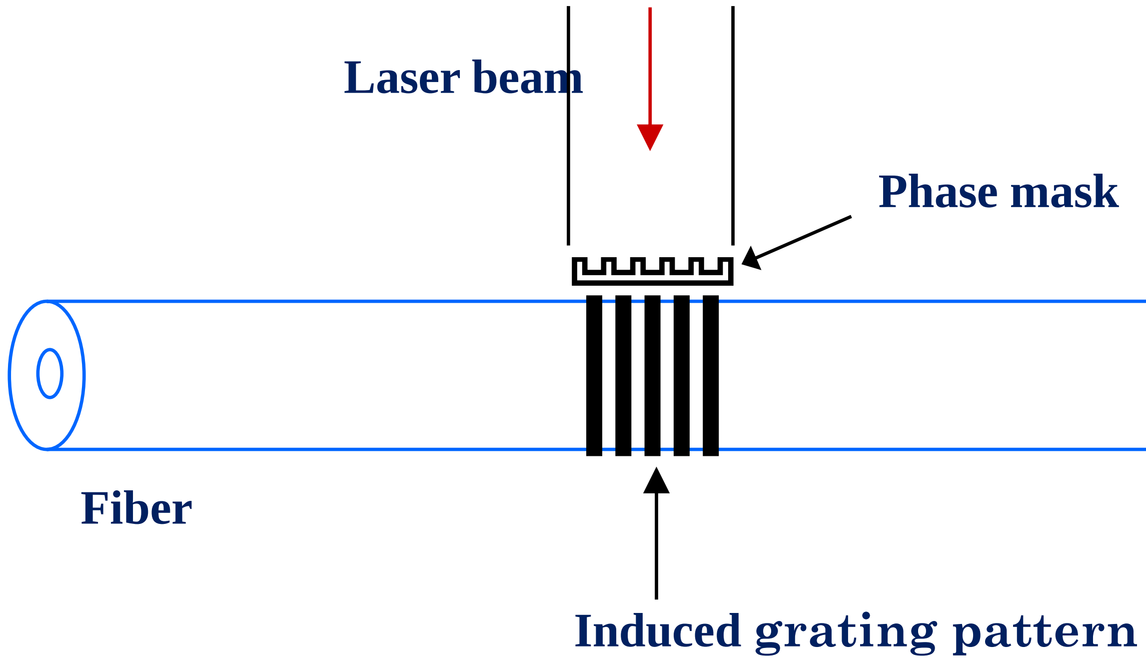
- **UV is diffracted into –1,0,1 orders by relief grating**
- **Input mask is wavelength specific**
- **Different $\lambda_B$ require different phase masks**



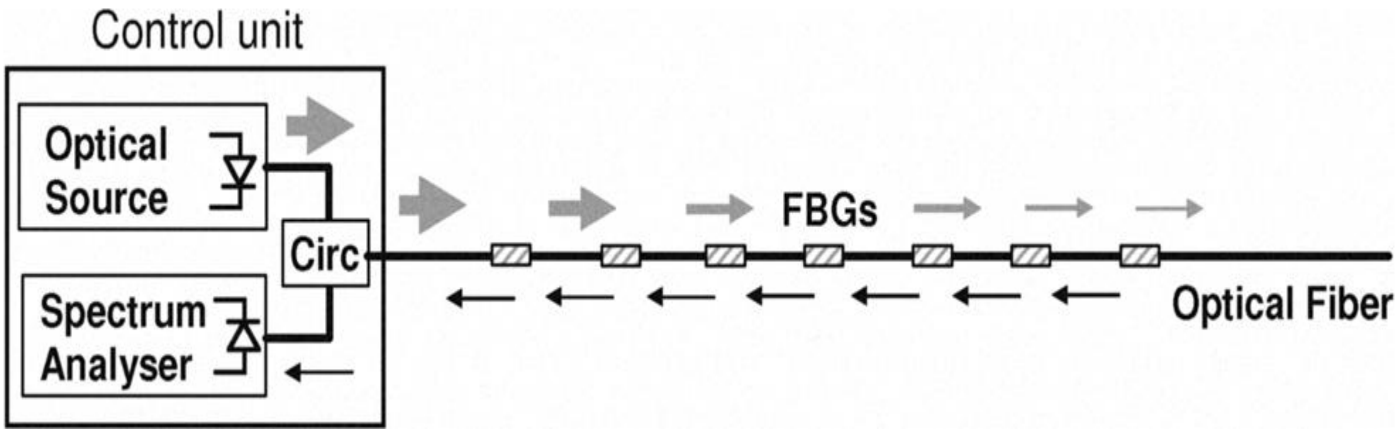

**FBG custom design software**

## ❖ FBG device fabrication

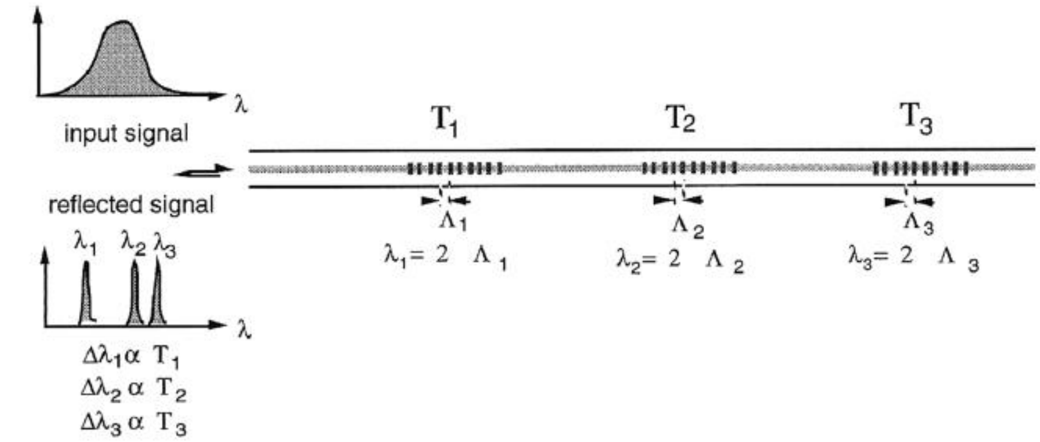
### Phase Mask Technique

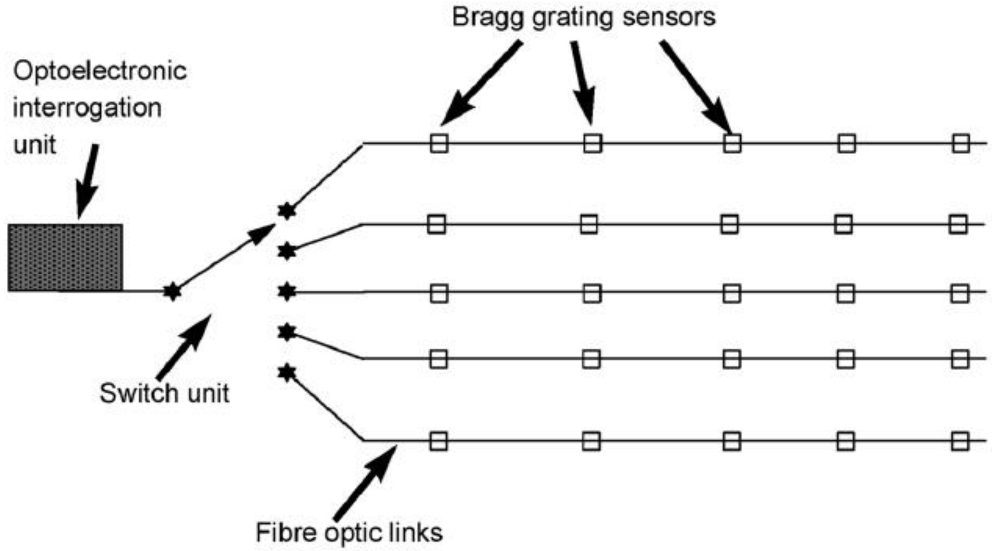


# ❖ FBG sensory system




- Interrogation of several FBGs based on WDM in the reflection mode
- Specific Bragg wavelength shifted by each FBG can be read in real time
- Coupling light from a broadband source: Edge-emitting LED, Super luminescent solid state or fiber amplified spontaneous emission (ASE) source
- Returned signal is generally analyzed by using an optical spectrum analyzer
- Very important advantage - FBG wavelength shift is insensitive to attenuations in fibers, optical connectors and splices – resulting in a robust technique




**Fiber Bragg grating arrays for very large passive sensor systems. There can be many tens of gratings on a single fiber.**

## ❖ FBG sensory system

- Estimation of range distance of FBG interrogations system
- OF attenuation 0.25 dB/km
- Optical power source around -10 dBm/channel
- Detector sensitivity of -40 dBm
- Optical power dynamical range 30 dB
- Maximum sensing distance up to 100 km accounting the splice and devices losses

## ❖ FBG sensory system

- FBG is small, robust and durable for operating in harsh environments
- FBGs are optically written into OF, they are small enough to embed or laminate into composite materials

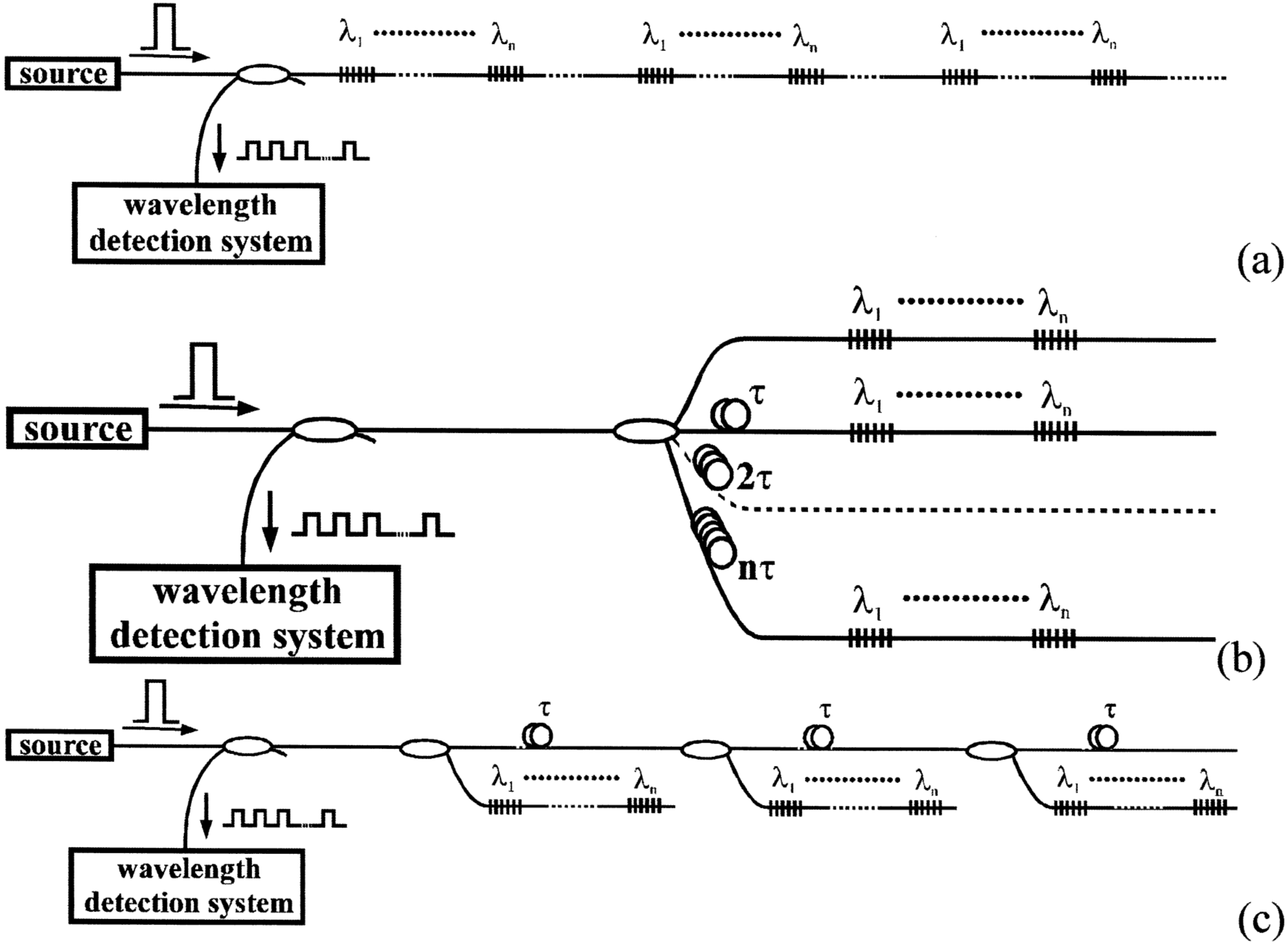
- One disadvantage of FBG sensing technique is that FBG sensors are sensitive to the temperature and for other sensing than temperature is necessary to use a compensation technique to obtain correct values of the parameter under evaluation

## ❖ FBG sensory system

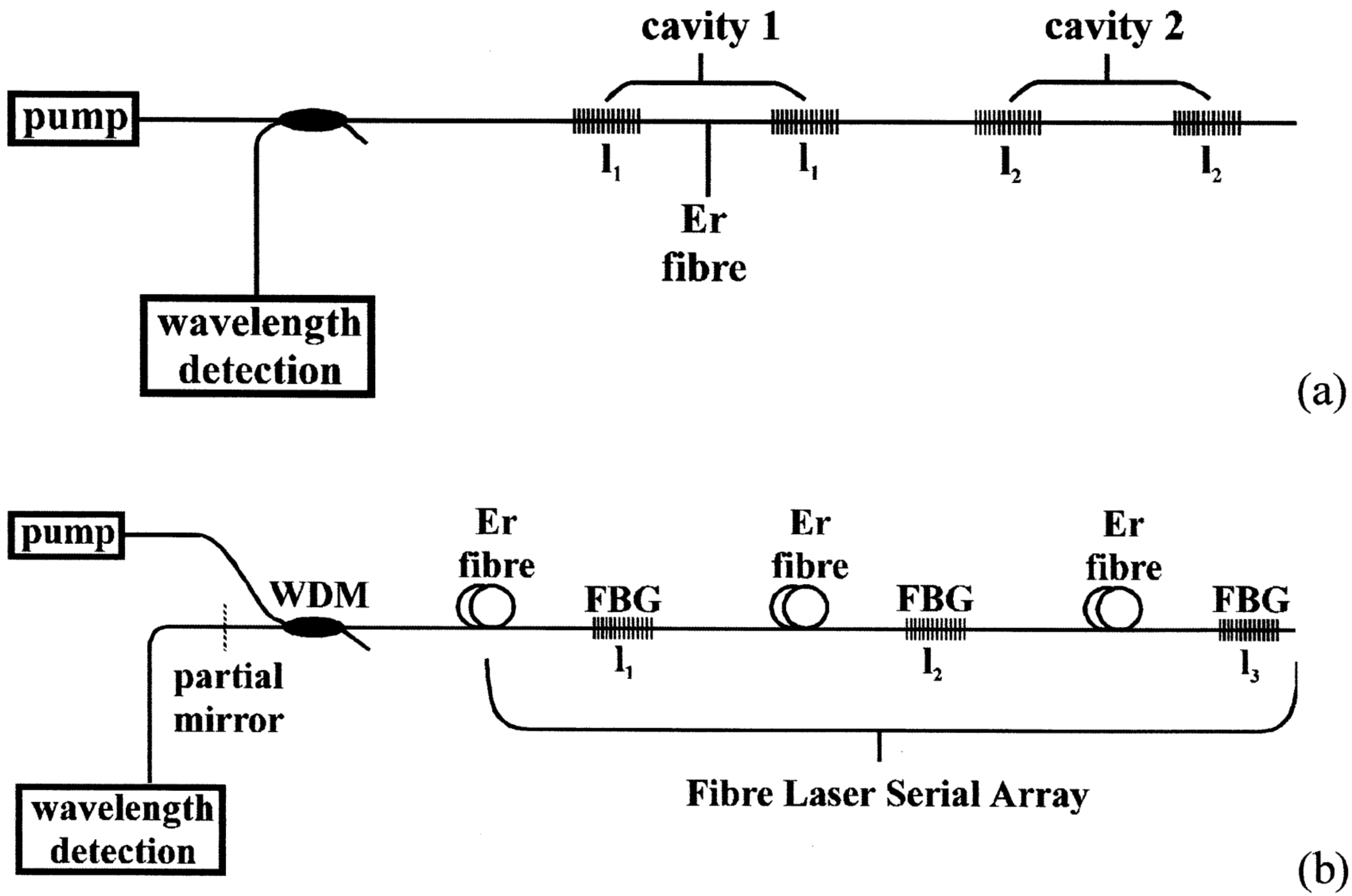
- Telecom market boom in the late1990s has developed methods for automated production of FBGs
- Today FBGs can be manufactured in volume at a relatively low cost
- The cost of FBG sensors can vary from dozen dollars for non packaged sensors to a hundred dollars for packaged sensors
- Normally FBGs are specified using ITU-T grid frequencies but can be fabricated any frequency of fiber optic transmission spectrum
- Typical interrogator cost is 1.5 k USD

## ❖ FBG sensory system

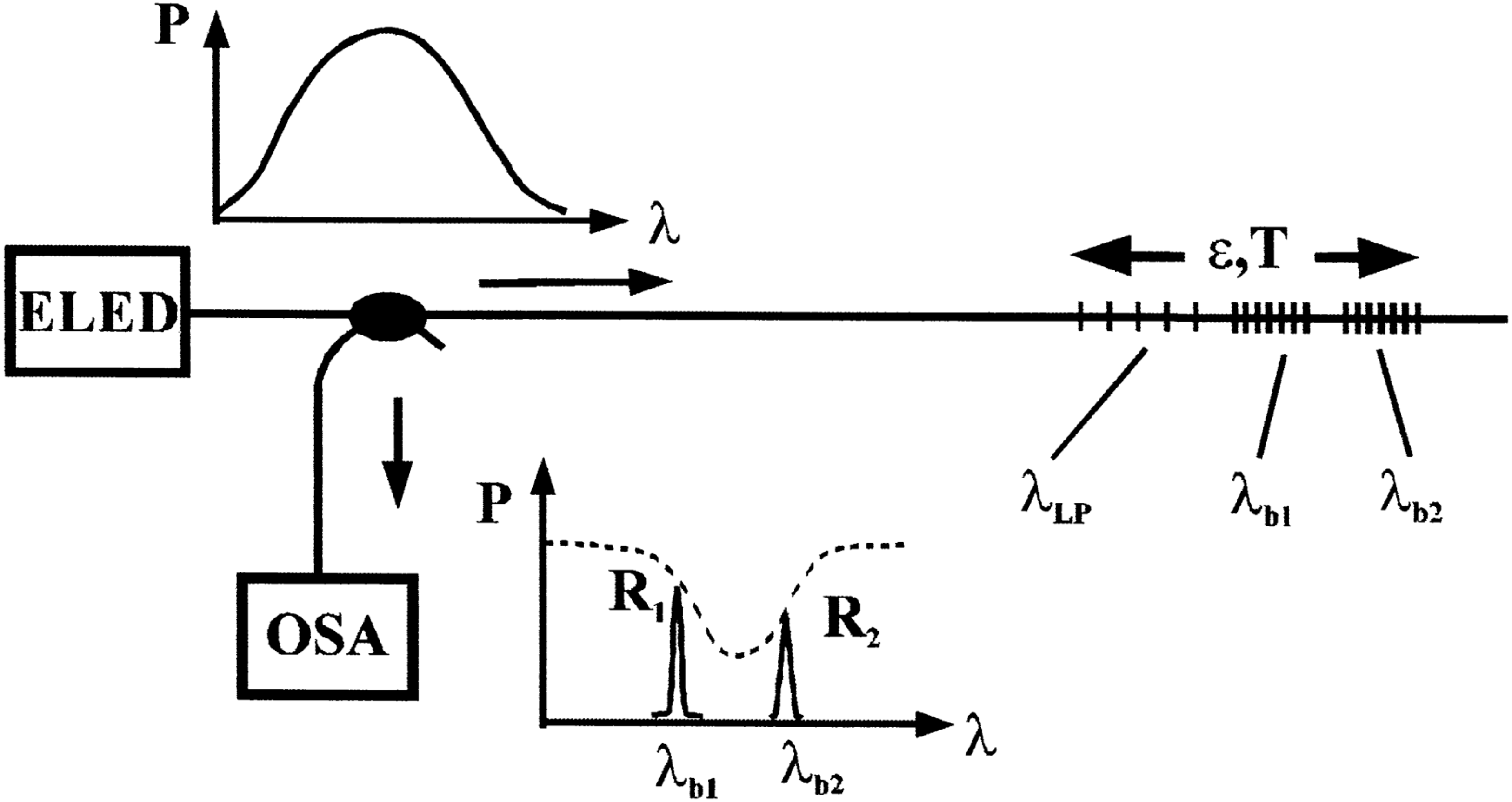
- Bandwidth for FBG sensing technique is measured mainly in the third window
- Common range used is from 1510 to 1590 nm
- Each sensor can use 3 nm of this spectrum range
- Around 16 FBGs can be multiplexed in just one single OF
- FBG control unit (interrogator) to uses optical switch to increase its capacity
- Optical switches from 4 to 16 ports are used



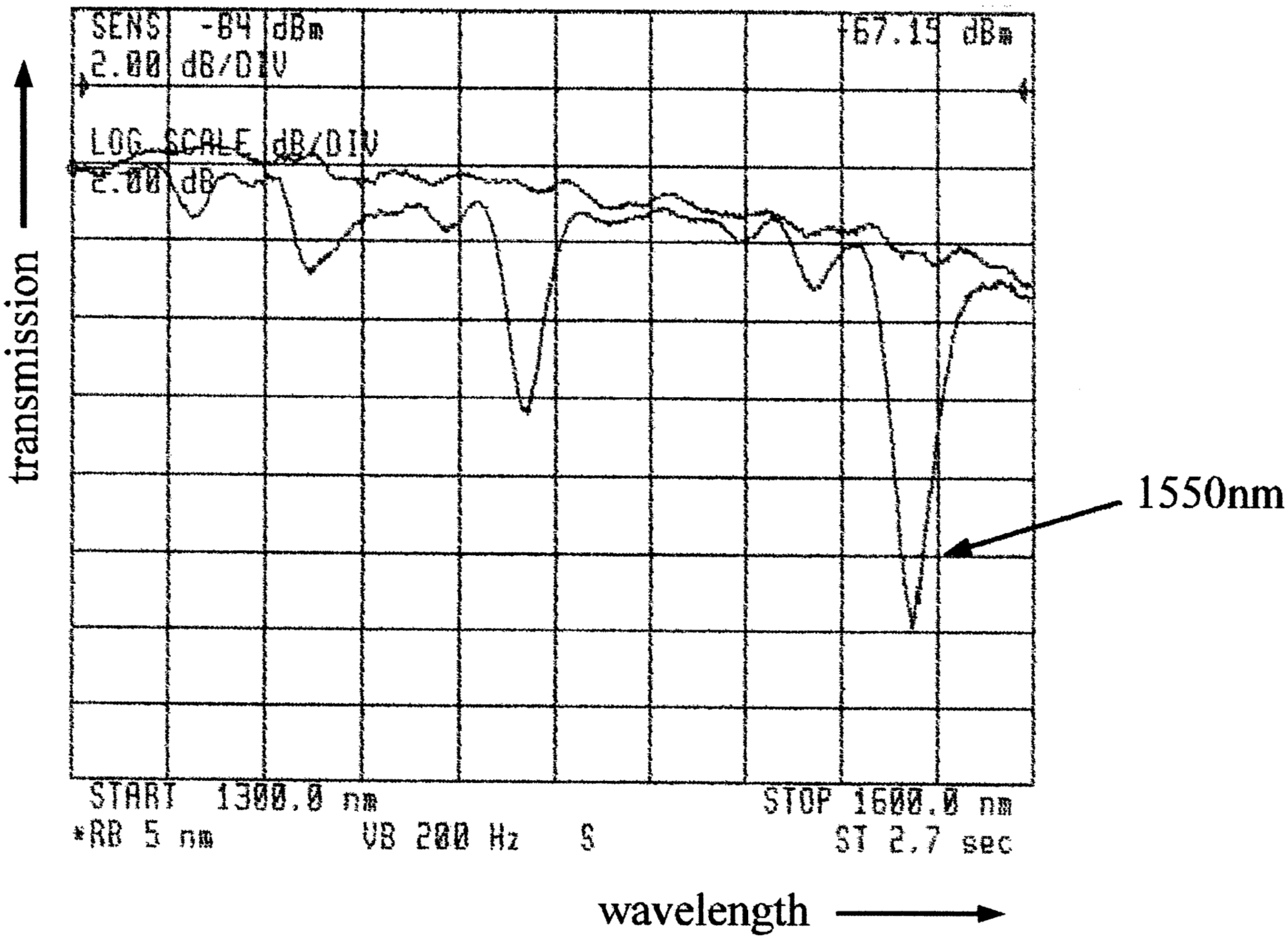

**T/WDM addressing topologies for FBG arrays:**
**a) Serial system with low reflectivity gratings,**
**b) Parallel network, and c) Branching network.**




**Basic fiber Bragg grating laser sensor systems:**
**a) Short cavity FBG-pair lasers,**
**b) Extended cavity FBG lasers.**




**Schematic of hybrid FBGrLPG sensor for simultaneous strain and temperature measurement.**




**Transmission spectrum of an LPG.**

# ❖ FBG Sensors


**Pressure FBG Sensor**
Range:+/-1 to 2.5MPa (please specify the range)
Accuracy: <=5%
Wavelength: 1525 to 1565nm
Working Temperature: -30 to 70degC
Dimension: 80x300mm (diameter x length)

**High Temperature Pressure FBG Sensor**
Working Temperature: up to 250degC

**Earth Pressure FBG Sensor**
Dimension: 160mm dia, 25mm thickness
Wavelength Range:anyway wavelength between 1510 to 1590nm
Measure range: 0.6MPa
Accuracy: 3%
Resolution: 0.66%
Repeatability: <1.32%
Linearity: <0.66%
Reflectivity: >90%

# ❖ FGB Sensors

**Embedded FBG Strain Sensor**
Center Wavelength: any wavelength between 1510 to 1590nm
Strain Range: +/-3000με
Resolution: 1 με
Installation: Embedding
Dimension: 35x60 or 100mm
Operating Temperature Range: -30 to 80 degC

**Weldable FBG Strain Sensor**
Center Wavelength: any wavelength between 1510 to 1590nm
Strain Range: +/-3000με
Resolution: 1 με
Installation: Arc Weldable
Dimension: 65x35mm
Operating Temperature Range: -30 to 80 degC

**Temperature FBG (standard)**
Wavelength: any wavelength between 1525 to 1565nm
Temperature Range: -20 to 150 degC
Resolution: 0.1degC
Accuracy: 1degC
Fiber: SMF-28 or compatible
Dimension: □8x100mm

## ❖ Measuremet with FBG sensory system

1) FBG sensors

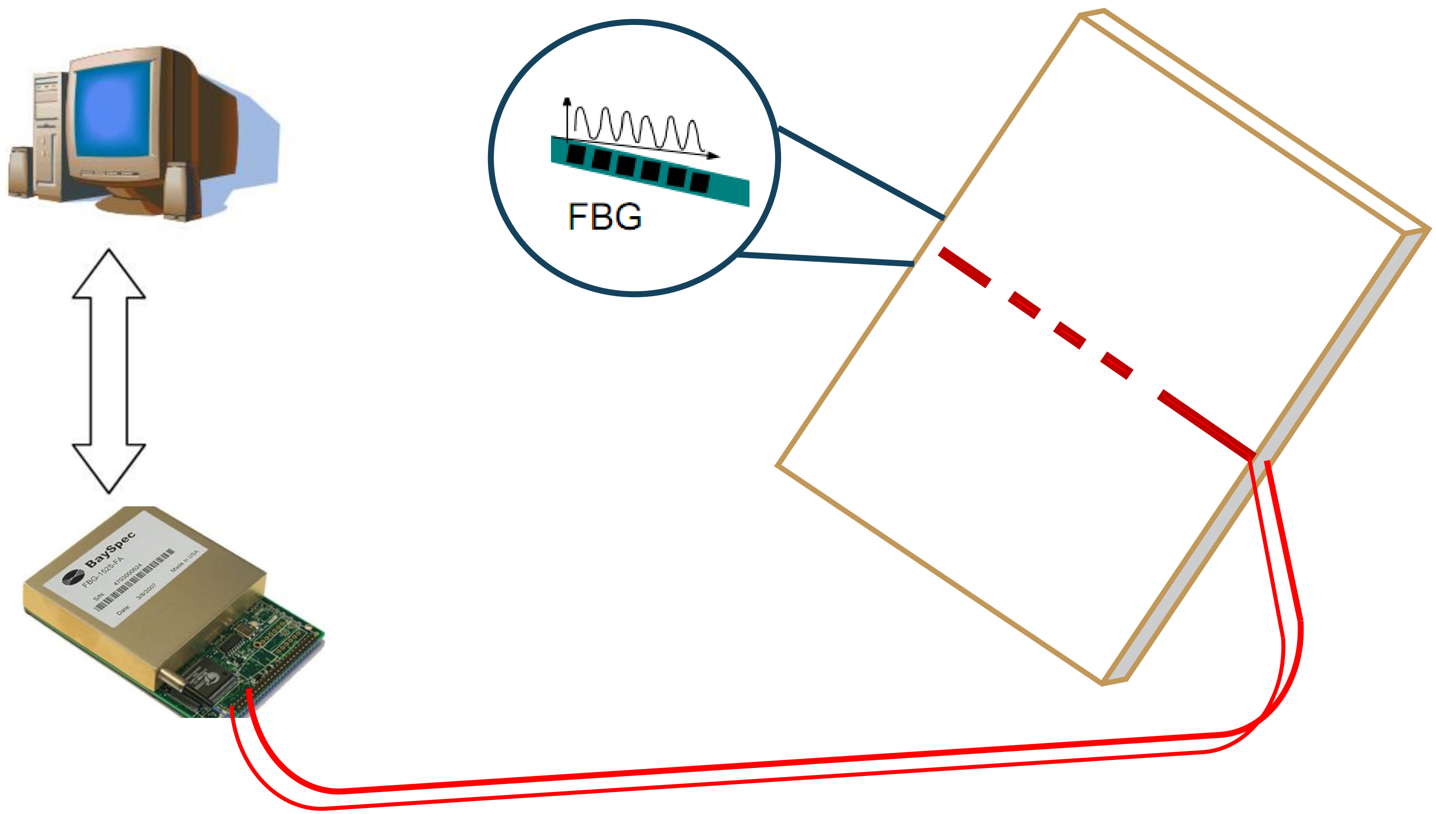
2) Fiber optic cable connection between the sensors and control electronics

3) Control electronics

4) PC connected to the control electronics via a local cable, local area network, Internet, or GSM modem


## ❖ Measuremet with FBG sensory system

**The FBG sensors are bound to the object to be monitored so as to reproduce the movements or deformations of its surface: the changes induced in the structure of the bragg grating is encoded in the form of changes in wavelength, the optical signal that reaches the 'electronic control.**



## ❖ FBGs sensors advantages

- Immunity to electromagnetic interference
- Small size
- Narrowband with wide wavelength operating range
- Environmentally stable (compared to copper)
- Long distance
- Remote sensing
- Can be multiplexed in a single fiber
- Totally passive

## ❖ FBGs sensors advantages

- Suitable for long-term permanent Structural Health Monitoring (SHM)
- No calibration needed
- One optical cable can have up to 64 sensors
- Simple installation
- Cable can run kilometres, up to 60 - 70 km
- No electrical sparking, intrinsically safe to oil or flammable environment
- No Electro Magnetic Interference (EMI), suitable for electrical, power and nuclear plants, etc.

## ❖ Application of FBG sensors

- Strain & temperature measurement, structural health monitoring
- Aerospace
- Aircraft structures, wing and hull (embedment in composites, light weight)
- Spacecraft (no safety objections, EMC)
- Airship (electrical insulation, lightning safe)
- Energy industry (electrical insulation, immunity to electromagnetic interference)
- Power generators, transformers, switches (multi-sensor)

## ❖ Application of FBG sensors

- Superconductors, nuclear fusion experiment (electrical insulation, EMC)
- Transportation
- Railway overhead contact lines, railway pantographs (electrical insulation)
- Geo-technical & civil engineering (long transmission lines, multiplexing)
- Coal mining, petrol & gas exploration (explosion-proof, remote sensor)
- Rock-bolts
- Opto-chemical monitoring

## ❖ Application of FBG in monitoring systems

***Monitoring of building structures and geotechnical,*** **SOFO (Smartec SA—Switzerland) technology**

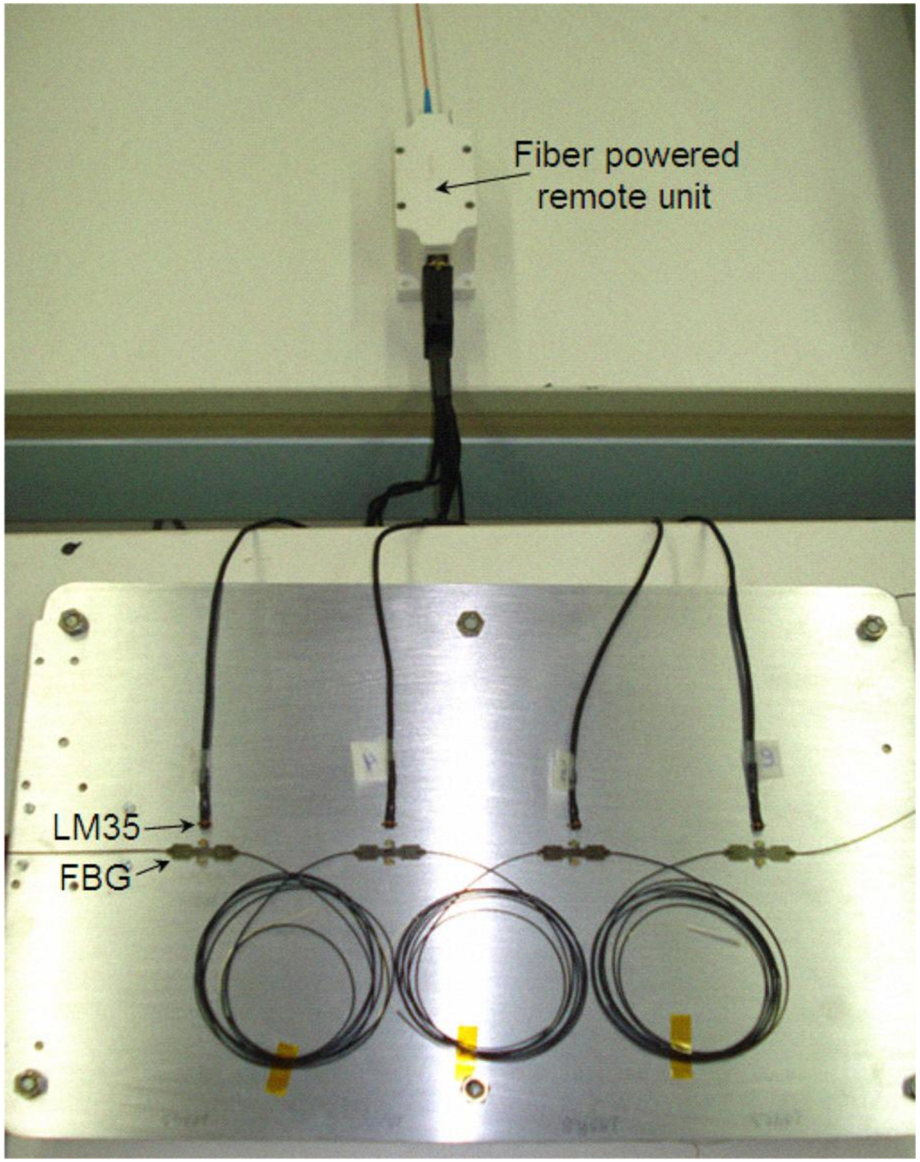
- **Proven and reliable technology measuring strain, bending, vertical and horizontal displacements of structural elements**
- **Used during construction to measure the solidification and shrinkage of concrete and concrete interactions between old and new structure**

## ❖ Application of FBG in monitoring systems

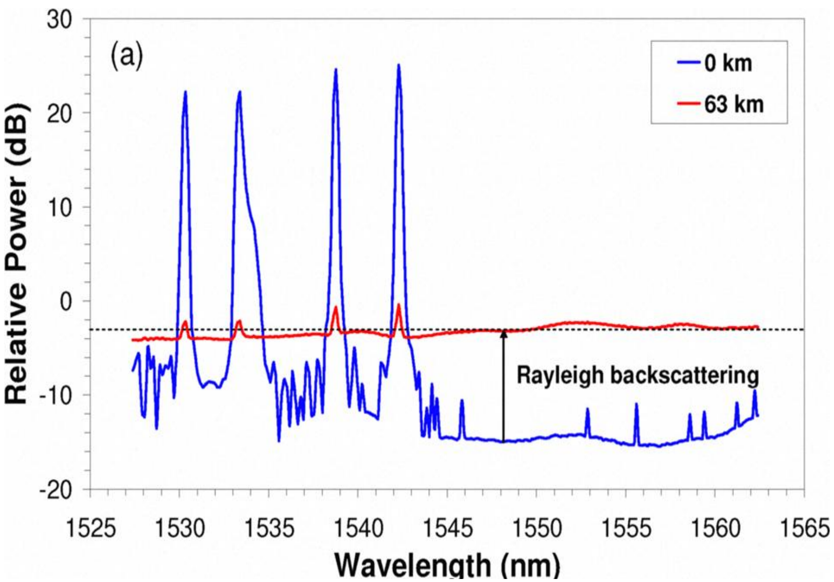
### *What can be monitored*

- **Monitoring of mechanical stress, deformations, horizontal and vertical, shifts and bends**
  **(Static and dynamic)**
- **Deformation monitoring during construction**
  **(Hardening and curing of concrete, characteristics of pre stressed concrete)**
- **Monitoring of cracks in the structure**
- **Long-term monitoring of structures**
- **Monitor the impact of environmental conditions**
  **(Snow load, ice, temperature changes, wind)**

## ❖ FBG temperature sensor



## ❖ FBG temperature sensor




**Sensor response**

- **Spectral characteristics transmitted by the FBGs**

**The characteristics of the optical sensor os4100 FBG:**

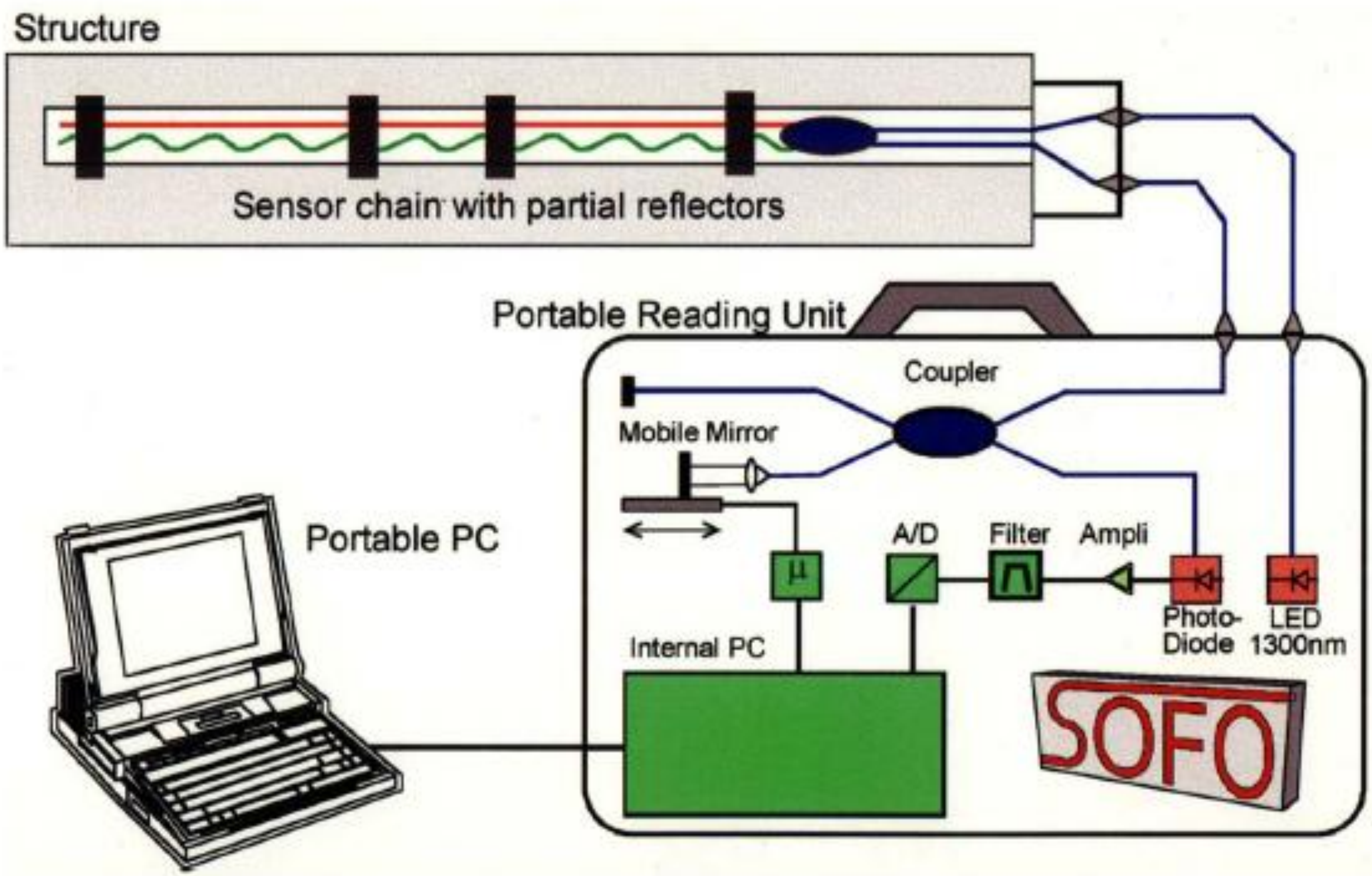
- **Temperature operation range = - 40 to 120 $^0$C**
- **Repeatability = ±0.75 $^0$C**
- **Sensitivity = 28.9 pm/ $^0$C**
- **Drift = ± 1.0 $^0$C**

Joao Batista Rosolem, Claudio Floridia, Antonio Arnauri Ju riollo and Edson Wilson Bezerra: Comparative Analysis of Fiber Grating Versus Fiber Powering for Fiber Optical Sensing Applications( IMOC 2009).

- Application of FBG sensors (monitoring)
- SOFO (Smartec SA—Switzerland) technology

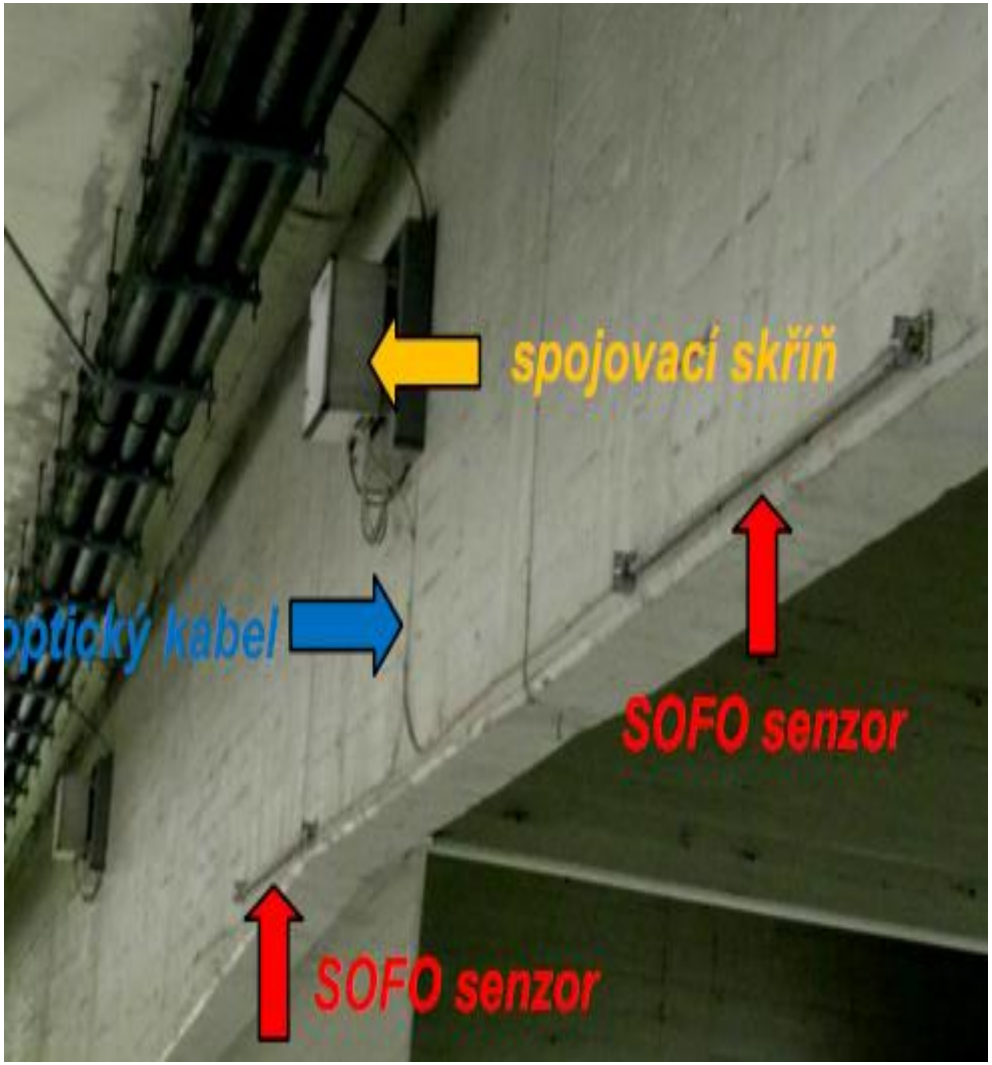
## SOFO system elements

- *SOFO senzors*
- *Optical cables*
- *Interconnecting cabinets*
- *Evaluation unit, channel switch*
- *Evaluation software*
- *Visualization software*




**SOFO (Smartec SA—Switzerland) white light interferometer displacement sensor—conceptual diagram.**

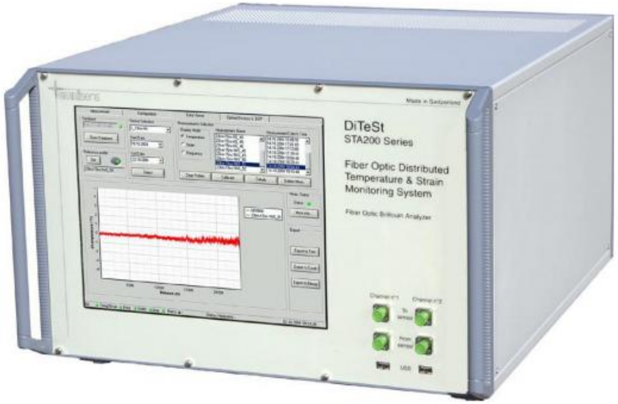
## ❖ Application of FBG sensors (monitoring)



## ❖ Application of FBG sensors (monitoring)

***Monitoring civil structures***: The potential for FBG sensors to measure both the health of a structure and provide useful data for traffic monitoring and control comes from their ruggedness, unobtrusive size, distributed sensor capability, stability, and long operating life.

# ❖ Application of FBG sensors (monitoring)



# ❖ Application of FBG sensors (monitoring)

In recent years, to monitor the status of infrastructure and of building in general, such as bridges, tunnels, dams, power plants, stadiums, etc. is used systems using FBG sensors.

- Highest measurement quality
- Higher reliability
- Replaces the manual readings
- Automatic measurement
- Insensitivity to environmental noise

SOFO sensors can be installed prior to pouring concrete

## ❖ Application of FBG sensors (monitoring)

***SOFO*** **is a technology used in buildings all over the world for over 10 years, during which several thousands of sensory systems were installed. Its biggest advantage is to monitor the construction of the building essentially a long time. The physical principle of the sensor is that you can not alter the initial zero, the sensor is designed to be independent of the surrounding temperature.**

SMARTEC

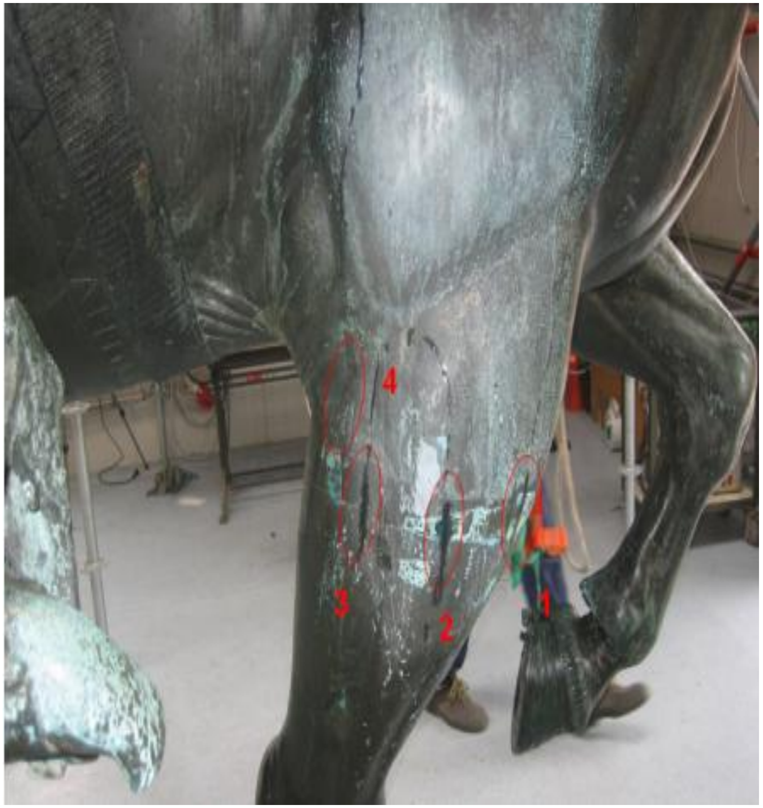
# ❖ Application of FBG sensors (monitoring) (distribution of energy)

**In the electricity transmission system can be used for monitoring cable temperature. Alarm software monitors cables, minimizing the risk of false alarms.**

## ❖ Application of FBG sensors (architectural)

**For the restoration of architectural property :**

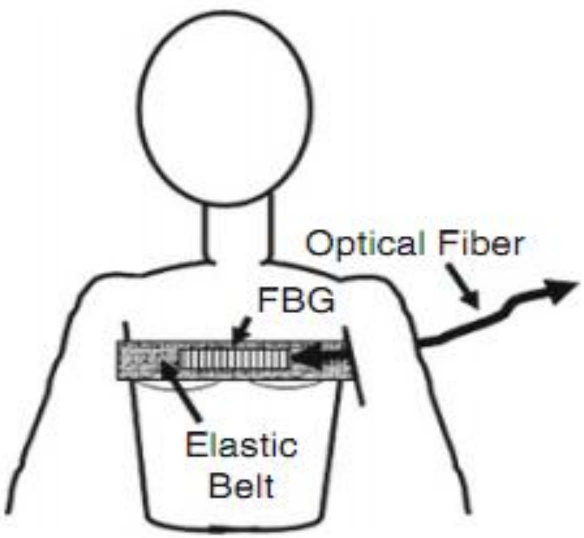
**An innovative field of application of FBG sensors is the preservation of architectural and artistic works. In fact, the durability of ancient buildings, whether they are themselves the artistic to be protected.**




## ❖ Application of FBG sensors (medical monitoring)

### Application in medicine - Respiration Monitoring

In this application, an FBG is attached to an elastic belt, which is held in position just above the breast. As the patient breathes, the thorax cage distends and deflates rhythmically, providing a method for monitoring respiration. In addition, the frequency of the signal can be used to trigger corrective action should the patient be under stress.



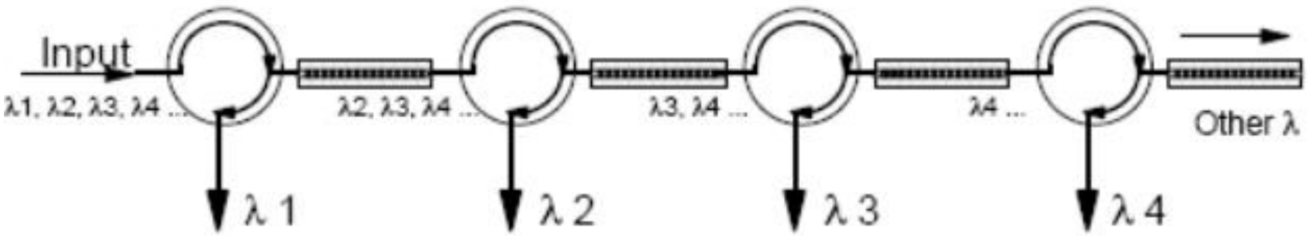
## ❖ Application of FBG sensors (health monitoring)

### Traffic and Structural Health Monitoring

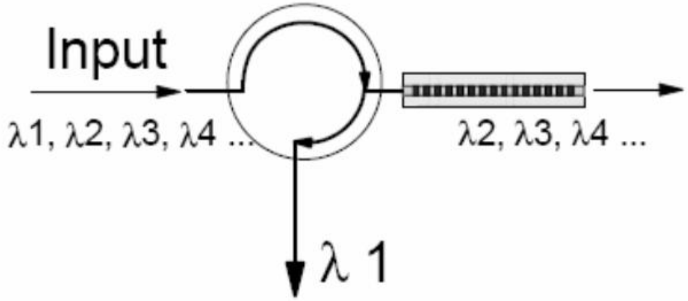
**Applications of FBGs include monitoring the curing of concrete, as it is important to know when the chemical reaction is completed. A system of distributed FBGs was used to monitor the traffic and the structural health of a bridge.**

# ❖ Application of FBG (Photonics)

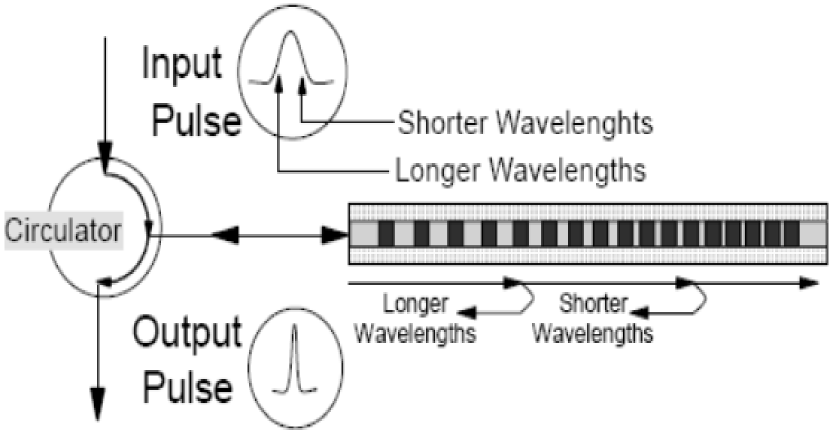
## Demultiplexor Using FBG




## FBG Filter




## FBG in OF Dispersion Compensation



# ❖ Application of FBG (other applications)






## ❖ Conclusions and future prospects

**FBGs are appearing in a variety of sensing applications. In fact, the market for sensors is now either matching or exceeding the volume of applications in telecommunications. Certainly, the complete FBG sensor system remains expensive so long as it is based on spectrally resolved sensing; however, simpler techniques for sensing using FBGs are being proposed, which are based on amplitude and transmission measurements using discrimination.**

**The field of sensing with FBGs is certainly secure, growing rapidly, and appears set for a long, steady, and healthy future in an increasing number of areas.**

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