FOS based on the effect of the damping of optical radiation in the optical fiber. FOS based on the effect of the damping of optical radiation in the optical fiber are used to measure microscopic displacements. The main representative of this class of FOS is microbending sensors. The law of total internal reflection is broken due to bending of the fiber under pressure, and the volume of light, which is proportional to the magnitude of bending, comes from the core into the membrane; as a result, the intensity of light received by the photodetector is decreased, and increased with the decreased pressure.
Such microbending sensors are used in the applications where the measured variable (deformation, pressure, force, position, acceleration) can be mechanically converted into the movement of the device, which deforms the fiber. FOS of microbendings is shown in Figure 13. At the closing of the deforming device, radiation losses are increased and the amount of transmitted radiation is decreased.

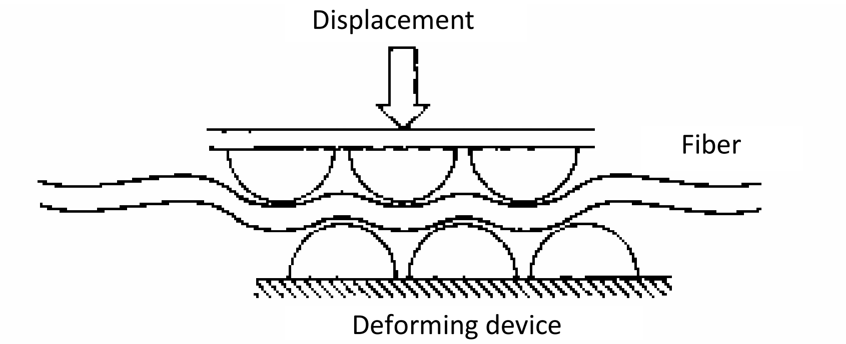

Figure 13 – Sensing element of microbending sensor.

Deforming device increases the losses in the fiber associated with the bending while displacement increase. An example of this optical sensor type is the invention called Overload protection for fiber optic microbend sensor US4871908 (Figure 14). This device uses two optical fibers, which allows compensating the external temperature influences by using the differential analysis of the optical signal. Figure 15 shows the design of the sensing element.

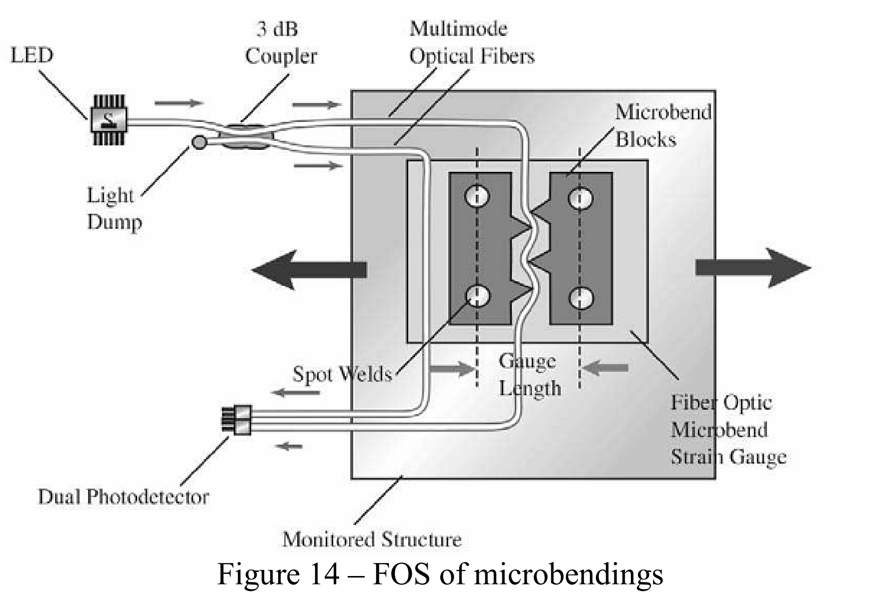

Figure 14 – FOS of microbendings

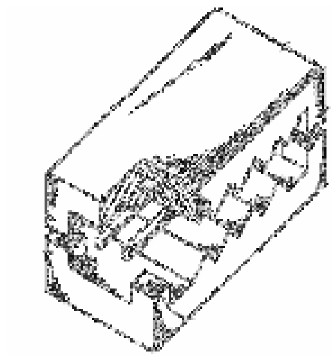
Figure 15 – Design of a sensing element of FOS of microbendings

Sensor type: closed channel.

Range of displacements detected: Up to 50 microns (depending on the material and thickness of the protective coating).

resolution: 0.1 micron.

Advantages:

- closed channel.

Disadvantages:

- measurement of micro-displacements;
- irregularities in a fiber, which distort the measured values;
- sensitivity to fluctuations in the input radiation.

FOS based on the modulation of the radiation flux. The largest class of FOS, based on the change of the radiation flux. One of FOS types based on the change in the optical radiation flux are position encoders, which use special plates (or discs) to measure the displacements. Binary coding scheme (as a rule, Gray code) is applied photographically on the transparent encoder disc, which provides a unique combination of marks for each position (Figure 16). The code is located on the tracks read by individual fibers. Both reflected and illuminated schemes can be used while work with the optical encoder

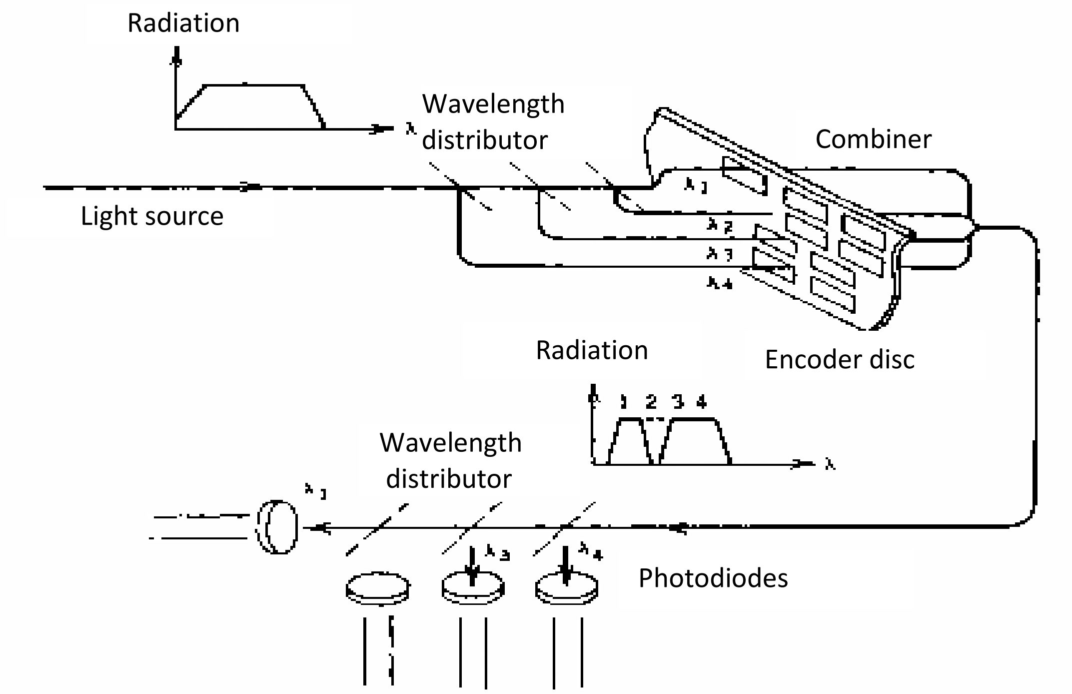

Figure 16 - Disc of encoder with a wavelength division used in the displacement sensor

Such sensors are most widely used in the aviation, where high resolution is required, usually 1 to 4096 = 2^{12}. Consequently, the simplest encoder reader requires 12 input and 12 output fibers.

The basic specifications for the mass-produced optical encoders.

Sensor type: open channel.

Measuring range: 50 m.

Resolution: 0.025 mm.

Wire speed: 4 m / s.

Operating temperature range: - 20 °C to 70 °C.

Linearity: 0.05%.

Advantages:

- wide displacement measurement range;
- high resolution;
- insensitivity to input radiation fluctuations.

Disadvantages:

- open channel;

– narrow operating temperature range.

Fiber-optic reflective sensors. Optical reflective sensors are widely used in various fields of engineering as displacement sensors, such as FOS, using the Fizeau interferometer. Such FOS uses a displacement measuring method that is binding of an object with a flexible stock with a thin layer Fizeau interferometer attached on its side (Figure 17). Moving an object causes a change in the intensity of reflected light. This method is implemented in a commercially available displacement sensors but it requires precise alignment of the optical fiber and a mirror, high-purity optical surfaces. Furthermore, an open optical channel of such sensor is exposed to contamination, and gases from the air are condensed on the surfaces of optical components at cryogenic temperatures. This sensor can measure displacements of up to 20 mm. With an accuracy of 0.02 mm in the temperature range of - 40 to +80 ^{0}C.

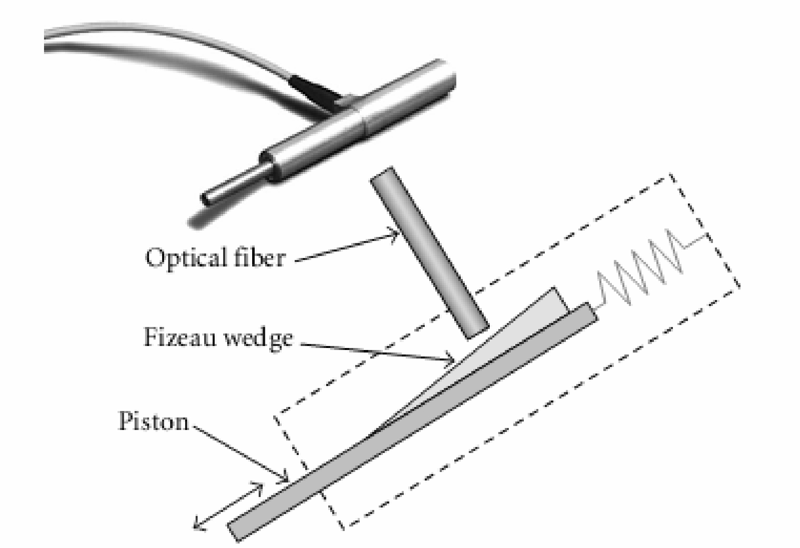

Figure 17 - Reflective optical sensor based on Fizeau interferometer

Another example of mass-produced type FOS is shown in Figure 18. The sensor is used to measure the shift and the vibrations of physical bodies. The linearity is ± 5% and the maximum resolution is 0.014 microns when measuring the shift up to 100 microns in the operating temperature range of - 75 °C to 150 °C. As a vibration sensor, such construction provides measurement in the frequency range from DC to 200 kHz.

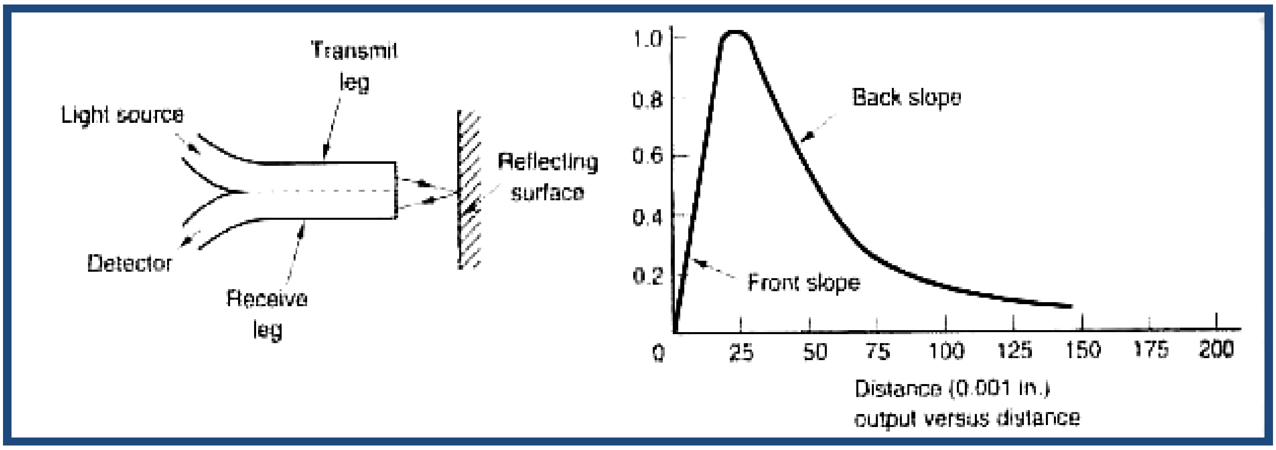

Figure 18 – FOS of shifts

Sensor type: open channel.
Range of registered displacements: Up to 100 microns.
Resolution**:** 0.014 microns.
Advantages:

– high resolution;
– non-contact measurement method.

Disadvantages:

– small range of measured displacements;;
– open channel;
– sensitivity to fluctuations in the input radiation.

FOS based on Fabry–Pérot resonator. Optical Fabry-Pérot resonators are used to measure small displacements. They consist of two semi-reflective mirrors arranged opposite each other at a distance *L* (Figure 19). Light enters the cavity from a source with known characteristics, such as from a laser. Photons come into the cavity and begin to reflect from the mirrors. During these reflections, they interfere with each other. In fact, the cavity acts as a light accumulator. Only photons of certain frequencies can fall outside the resonator. The frequency of the emitted light is changed accordingly to change in the cavity length. If one of the mirrors is movable, it is possible to determine very small changes in the cavity length by measuring the output frequency of light pulses. The frequency of the output pulses is a divisible of Δν interval, inversely proportional to the cavity length:

where c — speed of light;
L — distance.

In practical terms, the distance between the cavity mirrors is about 1 micron, and typical Δν values are in the range of 500 MHz to 1 GHz. Thus, difference between the frequencies of output radiation and the signal from the standard optical source indicate the change of the cavity length with accuracy comparable to the wavelength of light. The measurement object may be any physical value, change of which leads to the change in cavity size (displacement of mirrors), for example, mechanical stress, force, pressure, and temperature.

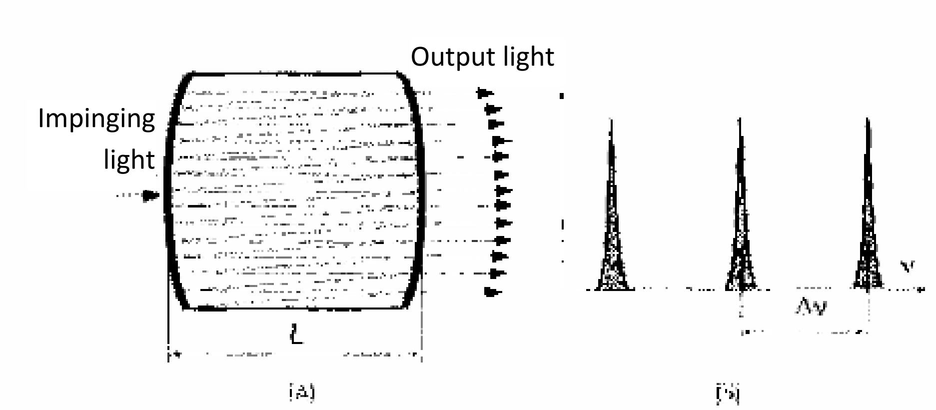

Figure 19 - Multiple interference within the Fabry-Pérot cavity (A) Pulses of light inside the cavity (Б)

The design of such FOS is described in the invention RUGGED FABRY-PÉROT PRESSURE SENSOR US7423762B2. The sensing element is shown in Figure 20. The pressure affecting on the side membrane causes the diaphragm to flex, thereby decreasing the cavity base *L*. The cavity is made in the form of a monolithic crystal by microfabrication techniques, so the mirrors are either dielectric or metal layers applied on a suitable substrate. To obtain the desired characteristics of the sensor, the thickness of each layer must be strictly controlled. This sensor has a very low coefficient of temperature sensitivity (less than 0.03%) and has an outer diameter of 0.55 mm.

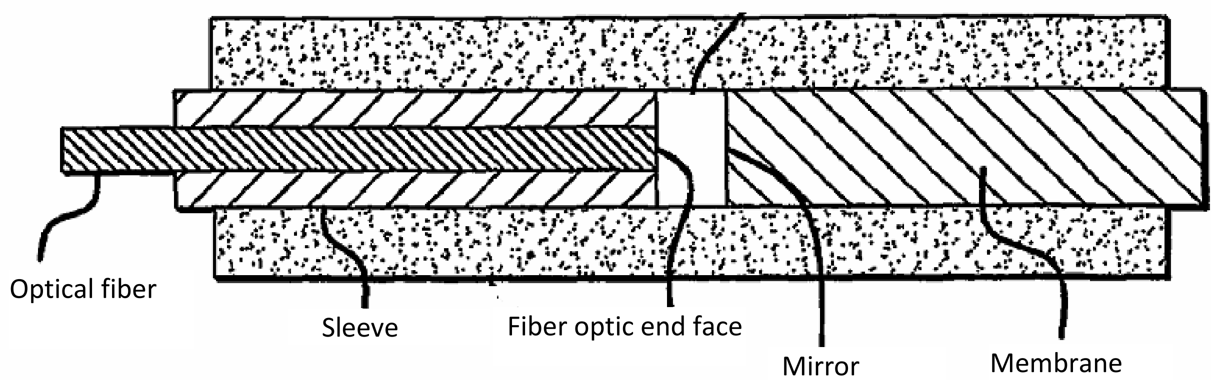

Figure 20 – Design of Fabry-Pérot sensor US7423762B2

An example of such FOS is the European patent EP0456681B1, the design of the sensing element is similar to the previous sample and the optical converter scheme is shown in Figure 21. The principle of operation is to determine the absolute value of the interferometer base. The sensing element of the device is a Fabry-Pérot interferometer, which reflects the broadband light source (LED) radiation. The sensor for measuring the mechanical movement of the surface is formed of the fiber end face and a controlled surface.

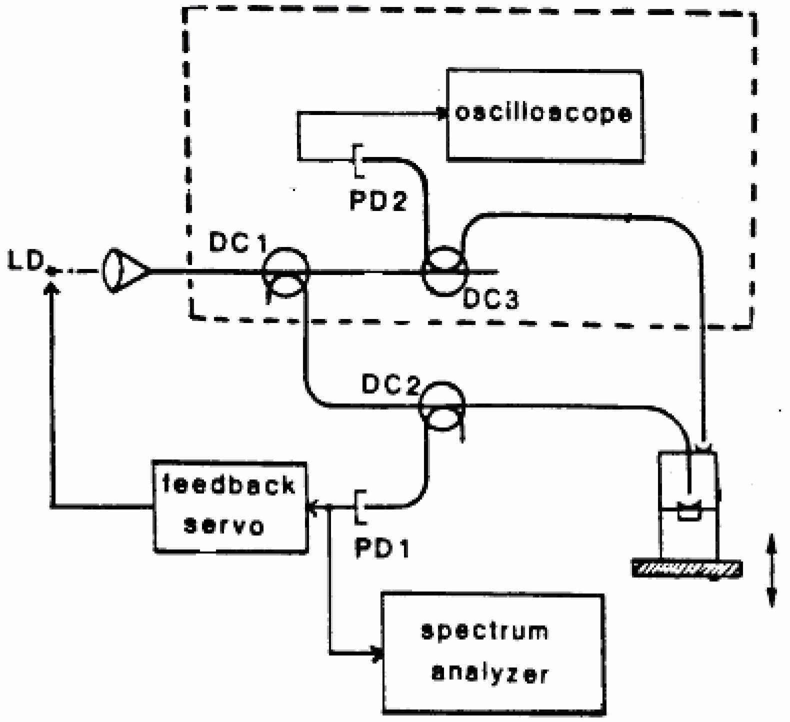

Figure 21 – Optical sensor with Fabry-Pérot cavity

Sensor type: open channel.
Range of registered displacements: 100 microns.
Resolution: 0.01 microns.
Advantages:

- insensitive to fluctuations of the input light;
- universality, i.e. the ability to measure various external influences by one and the same tool;;
- wide dynamic range (1:15000);
- high resolution.

Disadvantages:

- nonlinear reflectivity limits the effectiveness of its use;
- open channel.

Fiber Optic Sensors on the effect of magnetostriction

Magnetostriction is a phenomenon of body deformation (changing of its size, shape) when changing their magnetic state. This term also denotes the value of linear magnetostrictive deformations λ, i.e. the relative change in length of the sample ($\frac{\Delta L}{L}$) in a magnetic field. Magnetostrictive effect is strongly expressed in ferromagnetic materials and some ferrites, which reaches 10^{-4} + 10^{-3}, and 10^{-2} in individual cases (group of rare-earth metals and their alloys).

For example, the saturation magnetostriction λ_S of polycrystalline nickel (isotropic structure) measured in different directions relatively to H in the plane of the sample having a disk shape is shown in Figure 22.

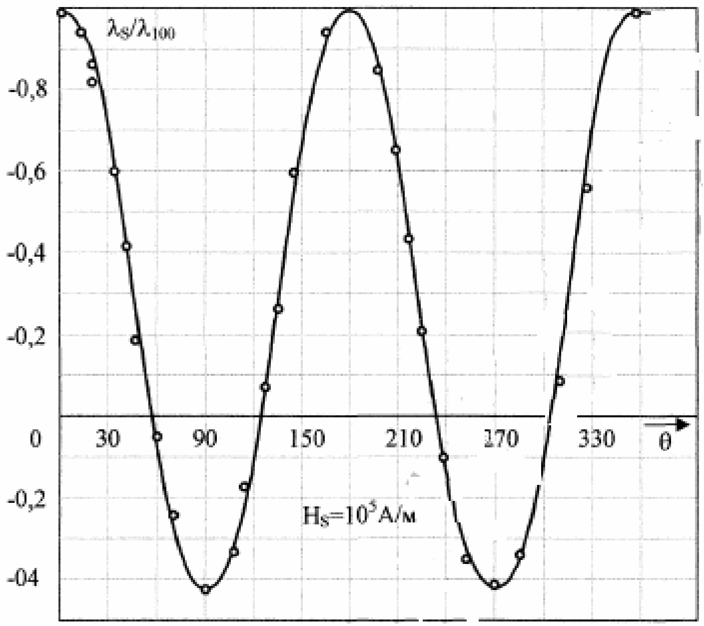

Figure 22 - Dependence $\lambda(H)$ for nickel in a plane perpendicular to H (transverse magnetostriction)

Table 3 shows the parameters of the most widely used in engineering and some promising magnetostrictive materials.

Table 3 - Parameters of promising magnetostrictive materials

Materials	$\rho * 10^3$,	E_{yu}, hPa	λ_s, 10^{-6}	$\frac{\delta\lambda}{\delta H}$, 10^{-9},	μ^r	B_s, T		Ohm*m	$\alpha_t * 10^{-6}, K^{-1}$
Nickel (HP2T)	8.9	19,5	-37	4,2	35	0,61	6	0,07	13
Nicosia	8,8	19	-27	28	210	0,62	20	0,18	-
Permendur (49KF)	8,15	23	70	27	400	2,35	160	0,4	9,2
Permendur (65K)	8,2	20	90	7	500	2,3	100	0,08	-
Alfer (14Yu)	6,6	16,3	40	-	110	1,2	25	1,2	12
Ferrite VIBROKS-2	5.1	17	-30	2,8	22	-	-	$4*10^5$	6
Tb	-		22000	-	-	-	-	-	-
Dy	-		21000	-	-	-	-	-	-
$SmFe_2$	-	14	-4500 -1560	- 1,5	- 2,5	-	-	- 1,2	-
$TbFe_2$	-	13,1	4700 1600	- 2	- 2,5	-	-	- 0,95	-
$ErFe_2$	-	-	-400	1	3,0	-	-	-	-

The magnetic properties of the materials vary with temperature changes, although this effect is not essential and can be neglected away from the Curie point and with low intensity magnetic field H .

Magnetostrictive materials are widely used in FOS. The use of magnetostrictive converters for displacement control may be implemented by using the external sources of a magnetic field, such as coils and magnets, and a ferromagnetic object changing the parameters of the magnetic field. Under the influence of object displacement, the sensing magnetostrictive element is deformed. The sensing element may be formed as a coating applied on the optical fiber, or as a segment of magnetostrictive material with the fixed optical fiber. It should be emphasized that implementation of an optical converter with the use of magnetostrictive materials is possible by several modulated parameters on optical radiation phase and optical radiation specter.

FOS on Bragg's gratings. FOS can be implemented with the modulated spectrum. Such sensors use Bragg's optical fiber gratings (BOG). Fiber grating is a section of optical fiber waveguide (typically, a single mode), which has in its core the periodic structure of refractive indexes (RI) with a period of L, having a certain spatial distribution, shown schematically in Figure 23. Typically, the grating is formed in a photosensitive core of an optical fiber waveguide 1, while the refractive index of the quartz cover 2 remains unchanged. Such structure has unique spectral characteristics, which determine its wide application in a variety of fiber optic devices. The most important property of Bragg's fiber gratings is a narrowband reflection of optical radiation, the relative spectral width of which may be 10^{-6} or less.

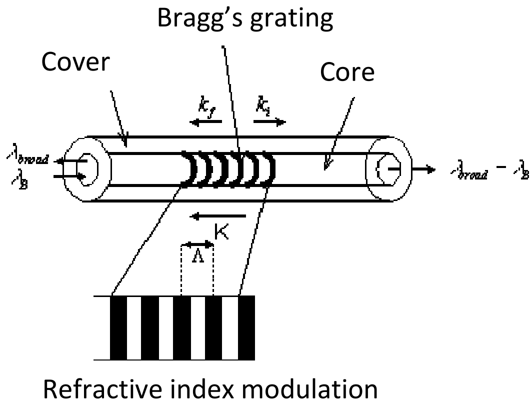

Figure 23 - Schematic representation of refractive index fiber gratings

The advantages of fiber photoinduced gratings in comparison with alternative technologies (e.g., interference mirrors and volume gratings) are obvious: a wide variety of obtained spectral and dispersive characteristics, many of which can be only implemented based on RI fiber gratings; fully fiber construction; low optical losses; relative ease of manufacturing, and many others. Currently, BOG is considered as one of the most promising sensitive elements of fiber-optic sensors of physical values. Among the main advantages are protection against exposure to electromagnetic fields, high sensitivity, reliability, reproducibility and wide dynamic measuring range, the possibility of spectral and spatial multiplexing of sensitive elements arranged in one or more optic fiber waveguides, a significant distance to the measurement location, a small response time to changes of the measured value, high corrosion and radiation resistance, small size and weight, and several others.

The reflection coefficient *R* at the resonant wavelength λ_{BG} for a homogenous grating of the length *L* is expressed as:

$$R = \mathrm{th}^2(kL),$$

where $k = pDn_{mod}h / \lambda_{BG}$ - coupling coefficient (Dn_{mod} - amplitude of the sinusoidal modulation of the refractive index, h - part of the power of the fundamental mode, which is distributed on the fiber core).

The resonance wavelength of Bragg's gratings λ_{BG} depends on the optic fiber waveguide temperature and attached thereto mechanical tensile or compressive stresses. This dependence is described by the following equation:

$$\Delta\lambda_{BG} = 2n\Lambda\left(\left\{1 - \left(\frac{n^2}{2}\right)[p_{12} - \nu(p_{11} + p_{12})]\right\}\varepsilon + \left[\alpha + \frac{1}{n}\frac{\Delta n}{\Delta T}\right]\Delta T\right),$$

$$\Delta\lambda_{BG} = 2n\Lambda\left(\left\{1 - \left(\frac{n^2}{2}\right)[p_{12} - \nu(p_{11} + p_{12})]\right\}\varepsilon + \left[\alpha + \frac{1}{n}\frac{\Delta n}{\Delta T}\right]\Delta T\right), \quad (3.28$$

where ΔT - temperature change,

ε - applied mechanical stress,

P_{ij} - Pockels coefficients of elastic-optical tensor,

n - Poisson's ratio,

α - coefficient of thermal expansion of quartz glass,

n - the effective refractive index of the fundamental mode.

This ratio gives typical values of the shift λ_{BG} depending on the temperature ~ 0.01 nm / K and the relative fiber elongation of an optic fiber waveguide ~ 103 x DL / L (nm).

A large number of ways to measure the displacement λ_{BG} is proposed. The most direct way is to measure the transmittance/reflection spectrum of a grating with a broadband light source and spectrum analyzer or by using a narrowband tunable laser and a photodetector. This method is insensitive to optical losses, which may occur in the optical path during measurement, and provides accurate λ_{BG} measurements. However, such a registration scheme requires expensive equipment and its operation speed is limited.

A higher performance is provided by the measurement schemes where a spectral shift of the grating is transformed into a change of intensity of the optical signal falling into the photodetector. This may be implemented, for example, by using an additional spectral filter with an inclined transmission characteristic. A long-period fiber grating can be used as such filter. The slope of the filter spectral dependence determines the dynamic range and sensitivity of the fiber sensor.

These schemes allow measuring the physical quantity at the BOG location; however, there are also problems of measuring the spatial distribution of this value. For this purpose, special schemes were designed to allow multiplexing of the sensing elements including ones located in one optic fiber waveguide. Such schemes include:

- spectral multiplexing of channels, wherein the sensing elements are spaced at different wavelengths;
- the use of optical switch connecting this or that sensing element to the measurement system;
- space-time multiplexing, wherein the response from each of the gratings is recorded at different times;
- combined schemes comprising several multiplexing channels listed above.

These λ_{BG} measurement schemes typically provide measurement accuracy of temperature ~ 0.1ºC and elongation ~ 10^{-6}.