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Optical wavelength discriminator based on a Sagnac loop with a birefringent fiber

***Abstract**. An optical wavelength discriminator based on a Sagnac loop is presented, intended for detecting signals from fiber Bragg gratings sensors. The Sagnac loop was created by connecting the output arms of a 3-dB coupler with a segment of a Panda type birefingent fiber and a fiber polarization controller. The results of measurements of the loop are given along with an example of its application for detecting the signal of a laser strain sensor.*

***Streszczenie**. Przedstawiono dyskryminator długości fali oparty na światłowodowej pętli Sagnaca, przeznaczony do detekcji sygnałów czujników ze światłowodowymi siatkami Bragga. Pętlę Sagnaca wykonano przez połączenie wyjściowych ramion sprzęgacza 3-dB z odcinkiem światłowodu dwójłomnego typu Panda i światłowodowym kontrolerem polaryzacji. Przedstawiano wyniki pomiarów pętli i przykład jej zastosowania do detekcji sygnału laserowego czujnika odkształcenia. (**Optyczny dyskryminator długości fali oparty na pętli Sagnaca ze światłowodem dwójłomnym**).*

Słowa kluczowe: optyczny dyskryminator długości fali, pętla Sagnaca, światłowód dwójłomny, czujnik laserowy
Keywords: optical wavelength discriminator, Sagnac loop, birefringent fiber, laser sensor.

Introduction

Fiber Bragg gratings used as measurement transducers convert the measured quantities into changes of the Bragg wavelength. Fiber Bragg gratings are therefore transducers with a frequency output.

To detect such signals, optical wavelength detectors are used. These are circuits, whose input is fed with light of variable wavelength and whose output signal is proportional to the AC component of the momentary wavelength. There are several solutions for optical wavelength detectors intended for detecting output signals of fiber Bragg gratings. They can be divided into the following categories: detectors with wavelength discriminators, detectors with tunable optical filters, with tunable light sources, spectrometric detectors. In detectors with wavelength discriminators, an optical signal of variable wavelength is converted into an optical signal of variable amplitude and subsequently subject to amplitude detection using a fotodetector. As optical wavelength discriminators devices such as bulk optical filters: band-pass filter, narrow-band filter, edge filter, interferometric filter [1], WDM couplers [2], highly overcoupled couplers [3], fiber Bragg gratings [4,5], and unbalanced fiber interferometers [6] are used. Application of wavelength discriminators is limited due to difficulties of achieving the required sensitivities and converting ranges.

To detect signals from fiber Bragg gratings tunable optical filters and tunable light sources are also used. Both wavelength detector types can operate in the tracking mode (with feedback) and in the scanning mode. Detectors with tunable filters (Fabry-Perot and acousto-optic filters) feature a wide tuning range and a wavelength resolution better than 1 pm [7]. Detectors with tunable lasers have a relatively narrow tuning range. The main limitation of those detectors in sensor applications is their high price. The task of developing an inexpensive optical wavelength detector, with good metrological properties, for cooperation with fiber Bragg grating sensors, is still of interest. It seems that an optical detector fulfilling the above requirements could be the fiber optic Sagnac loop with a fiber of high birefringence. The results of investigations of such a loop, constructed from a Panda type birefringent fiber, and its application for detecting output signals of a Bragg grating laser strain sensor are given.

The operation of the loop with a birefringent fiber

A detailed description of operation of the loop with a birefringent fiber is given in [8]. Below the fundamental relationships of the description are presented. The fiber loop is created by connecting a segment of a birefringent fiber to the ends of the output arms of a 3-dB directional coupler.

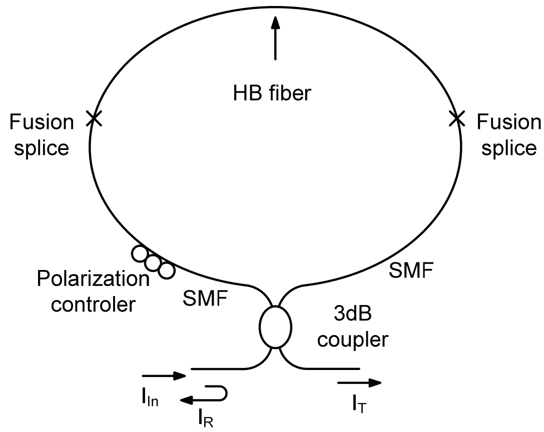

Fig.1. Diagram of the Sagnac loop with a birefringent fiber

The coupler splits the input signal into two waves of equal intensity propagating in opposite directions, which after passing through the loop interfere in the coupler. The result of this interference depends on the length of the fiber and its birefringence. The phase difference δ of the polarization components propagating in the fiber of length L is determined by the relation:

(1) $$\delta = \frac{2\pi \cdot L \cdot B}{\lambda},$$

where the birefringence $B = |n_f - n_s| = \lambda_0 / L_B$, n_f and n_s denote the the effective refraction coefficients for the fast and the slow axis of the fiber, λ denotes the wavelength, L_B is the beat length measured for the wavelength λ_0. Due to the dependence of δ on the wavelength, the Sagnac loop with the birefringent fiber acts like a comb filter. Neglecting the attenuation of the birefringent fiber, the single mode fiber and the loses in the 3-dB coupler, the reflection coefficient and the transmission coefficient of the birefringent fiber are periodic functions of wavelength, which are described by the formulas [8]

(2) $$R(\lambda) = cos^2\left(\frac{\delta}{2}\right), \qquad T(\lambda) = sin^2\left(\frac{\delta}{2}\right).$$

The period of the functions $R(\lambda)$ and $T(\lambda)$ is given by the relation [8]

$$\Delta\lambda = \frac{\lambda^2}{B \cdot L}. \tag{3}$$

Measurements and results

To construct the Sagnac loop, a 91,5 cm long segment of a Panda-type birefringent fiber PM1550-HP (Nufern) was used, a fiber polarization controller, and a 3-dB fiber coupler. The ends of the birefringent fiber were fusion spliced to the SMF28 single mode fiber. The polarization controller enables to increase the extinction ratio of the beams reflected and transmitted by the loop. The characteristics of the produced Sagnac loop were determined by utilizing a LED with a central wavelength of 1520 nm, a 3-dB bandwidth of 54 nm and a power of 40 µW, and an AQ-6315A optical spectrum analyzer from Ando.

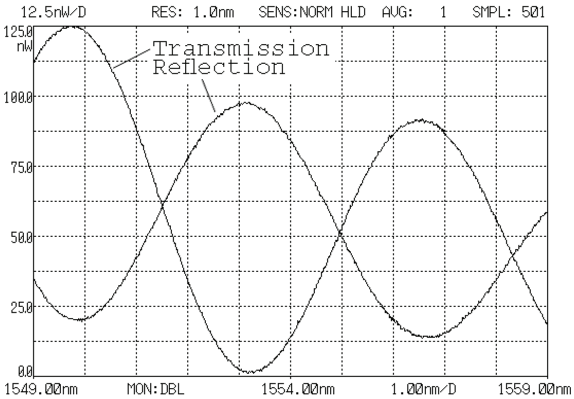

Fig.2. Spectrum of the transmitted and the reflected beam of the Sagnac loop with a birefringent fiber

In figure 2 the measured spectra of the reflected and the transmitted beams of the loop with a birefringent fiber are shown in linear scale, in the range 1549÷1559 nm. They are periodic functions of wavelength in accordance with equations (2). The change in amplitude of these functions results from spectral characteristic of the LED, which illuminated the loop. On the basis of the spectrum measurements performed, the period and the extinction ratio were determined; they are respectively 6,83 nm and 20 dB.

The points of intersection of the reflected beam spectrum and the transmitted beam spectrum are the midpoints of the linear ranges of the spectra. If the loop is adjusted in such a way, that the wavelength of the Bragg grating sensor, corresponding to the rest state, is equal to the wavelength at which one of the points of intersection occurs, then the intensities of the reflected beam and the transmitted beam are linear functions of the changes of the sensor's Bragg wavelength: a function decreasing (increasing) with wavelength and a function increasing (decreasing) with wavelength. Therefore in this case the loop with a birefringent fiber acts as a linear discriminator of the wavelength of optical bipolar signals. The linear conversion range of such a discriminator is determined by the period of the spectrum described by equation (3). A change of the conversion range can be accomplished by changing the length of the birefringent fiber; increasing the length of the fiber results in decreasing of the conversion range and vice versa. The conversion range of the discriminator is closely related to its conversion sensitivity; greater conversion range means lower sensitivity and vice versa – a narrow conversion range means greater sensitivity.

The shift of the Bragg wavelength, due to the measured quantity, causes in the discriminator linear changes of the reflected and the transmitted beam intensities in opposite directions. Therefore in further processing of the output signals of the discriminator, the well-known method of eliminating the effect of changes of the power fed to the discriminator on the signal after detection can be successfully applied, namely taking as the measured signal the ratio of the power difference and the power sum of the signals at the I_R and I_T outputs of the discriminator $(P_R - P_T)/(P_R + P_T)$.

Example of the application

An example of the application of the built loop with a birefringent fiber to detect the signal from the fiber laser strain sensor with a Bragg grating is shown in figure 3. The laser of the sensor comprises a Fabry-Perot resonator, in which the wideband mirror is constituted by the fiber loop constructed from a 3-dB coupler, and the tunable narrowband mirror is the Bragg grating. The grating is simultaneously the strain transducer. As the amplifying medium of the resonant cavity a segment of an erbium doped fiber was used with an absorption coefficient of 30 dB/m at the 1530 nm wavelength. The details regarding the strain laser itself are given in [5]. The output beam of the laser is fed from the Bragg grating, through ports 1 and 2 of the circulator, to the loop discriminator. The reflected beam, after going through ports 2 and 3 of the circulator, is found at the output I_R, the transmitted beam appears at the second output of the coupler I_T.

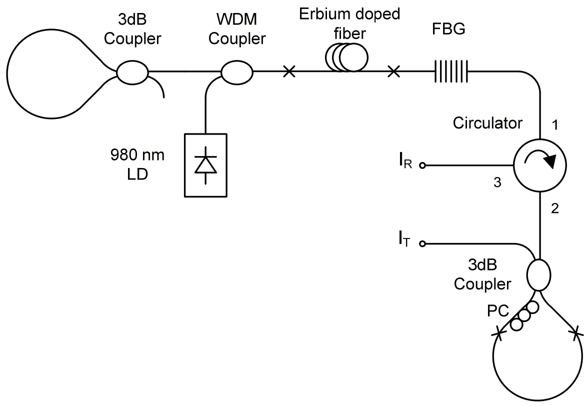

Fig.3. Diagram of the laser strain sensor with a Bragg grating and a fiber loop wavelength discriminator. The "x" indicates a fusion slice connection

After applying strains of predetermined values to the Bragg grating of the laser, the optical signals at the outputs I_R i I_T were measured. The results of these measurements are shown in figure 4. From the figure it is seen, that the change of the laser's wavelength in the direction of longer waves, caused by the tensile strain of the Bragg grating, produces linear changes of the intensity of the beams, the one reflected by the loop I_R and the one transmitted I_T, in opposite directions; the intensity of the reflected beam increases and the intensity of the transmitted one decreases. The spectra of the laser shown correspond to tensile strains of its Bragg grating of the following values 0, 218, 436 µε.

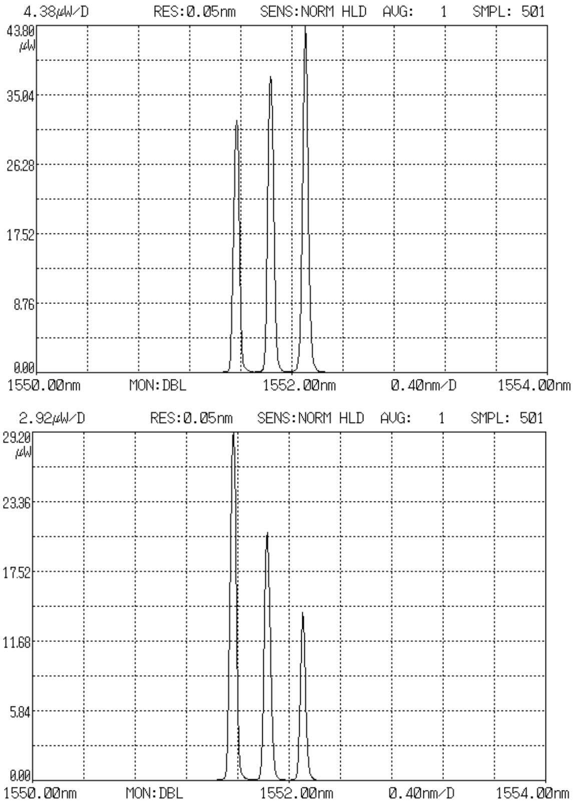

Fig.4. Laser beam spectrum at the I_R output (upper picture) and at the I_T output (lower picture) for the following Bragg grating strains: 0, 218, 436 µε

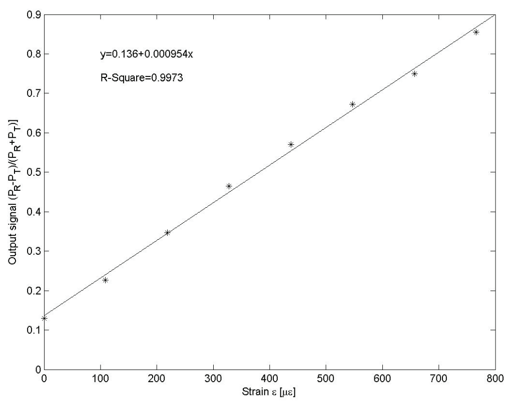

Fig.5. The relation of the output signal of the laser sensor $(P_R - P_T)/(P_R + P_T)$ to the strain of the Bragg grating

In figure 5, the static characteristic of the laser strain sensor with the fiber loop discriminator is shown, which is the relation of the ratio $(P_R - P_T)/(P_R + P_T)$ to the strain ε of its grating, in the range 0÷766 µε. The plot is linear in the strain range investigated, however it does not run through the origin of the coordinate system, which indicates, that the wavelength value of the sensor's laser in the state of rest does not coincide with the wavelength value corresponding to the point of intersection of the reflected beam spectrum and the transmitted beam spectrum of the discriminator. To achieve that, one needs to adjust the discriminator using the temperature method or the strain method.

The main disadvantage of the Sagnac loop with a birefringent fiber is the effect of temperature on its characteristics. It is caused by the change of the optical path as a result of changes of the refraction indices and the length of the fiber induced by the change of the ambient temperature. Because of this, the application of the discriminator with a Sagnac loop to detect slowly varying signals requires stabilizing its temperature.

Conclusions

The presented all-fiber optical wavelength discriminator based on the Sagnac loop with a birefringent fiber can be successfully applied to detect output signals of fiber Bragg grating sensors, especially laser sensors. It enables the detection of static and dynamic signals, both unipolar and bipolar. The detection range and the sensitivity can be easily changed by changing the length of the birefringent fiber, but one has to remember that those quantities are inversely related – the wider the detection range, the lower the sensitivity and vice versa. In static measurements the effect of temperature on the metrological properties of the discriminator needs to be reckoned in, because of the effect of temperature on the properties of the birefringent fiber. None the less owing to the simplicity of the design and the availability of fiber optic components needed for its construction, the device can become a useful passive discriminator of signals from fiber Bragg grating sensors.

REFERENCES

[1] Melle S.M., Liu K., Measures R.M.:A passive wavelength demodulation system for guided-wave Bragg grating sensors, IEEE Photon. Technol. Lett., No 5 (1992), 516-518
[2] Davis M. A., Kersey A.D., All-fibre Bragg grating strain-sensor demodulation technique using a wavelength division coupler, Electronics Letters, 30 (1994), No. 1, 75-77
[3] Zhang Q. at all. : Use of highly overcoupled couplers to detect shifts in Bragg wavelength, Electronics Letters, 31 (1995), No 6, 480-482
[4] Fallon R.W, et al., Identical broadband chirped grating interrogation technique for temperature and strain sensing, Electronics Letters, 33 (1997), No.8, 705-706
[5] Kaczmarek C., Światłowodowy czujnik laserowy odkształcenia z siatką Bragga, Pomiary Automatyka Kontrola, 56 (2010), No.9, 1071-1073
[6] Kersey A. D. at all. Fiber Grating Sensors, Journal of Lightwave Technol., Vol. 15, (1997), 1442-1461
[7] Kersey A. D., Berkoff T. A., Morey W. W.: Multiplexed fiber Bragg strain-sensor system with a fiber Fabry-Perot wavelength filter. Optics Letters, Vol. 18, (1993), 1370-1372
[8] Fang X., Claus R.O., Polarization-independent all-fiber wavelength-division multiplexer base on a Sagnac interferometer, Optics Letters, 20 (1995), No.20, 2146-2148

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