Cezary KACZMAREK[1]

Politechnika Lubelska, Katedra Elektroniki

Fiber optic Sagnac loop with a polarization maintaining photonic crystal fiber as an optical wavelength demodulator for fiber Bragg grating sensors

***Abstract**. The properties of a fiber optic Sagnac loop with a polarization maintaining photonic crystal fiber are presented, which is utilized as an optical wavelength demodulator. Owing to the use of a photonic crystal fiber, which has high birefringence and a very low temperature coefficient of birefringence, a temperature-stable optical wavelength demodulator circuit was obtained. The constructed demodulator was applied in a fiber optic force sensor with a Bragg grating. The nonlinearity error of the sensor with the demodulator does not exceed 1 %.*

***Streszczenie**. Przedstawiono właściwości światłowodowej pętli Sagnaca ze światłowodem fotonicznym przenoszącym polaryzację wykorzystanej jako optyczny demodulator długości fali. Dzięki zastosowaniu światłowodu fotonicznego o wysokiej dwójłomności i bardzo małym współczynniku temperaturowym dwójłomności uzyskano stabilny temperaturowo układ demodulatora długości fali optycznej. Zastosowano wykonany demodulator w światłowodowym czujniku siły z siatką Bragga. Błąd nieliniowości tego czujnika z demodulatorem nie przekracza 1 %. (**Światłowodowa pętla Sagnaca ze światłowodem fotonicznym przenoszącym polaryzację jako optyczny demodulator długości fali dla czujników z siatkami Bragga**).*

Słowa kluczowe: demodulator długości fali, pętla Sagnaca, światłowód fotoniczny przenoszacy polaryzację, czujnik siły, światłowodowa siatka Bragga.
Keywords: wavelength demodulator, Sagnac loop, polarization maintaining photonic crystal fiber, force sensor, fiber Bragg grating.

Introduction

Fiber Bragg gratings have gained more and more significance in the field of fiber optic sensors. It is due to their advantages, which include small size and mass, and a frequency output signal. To detect output signals from fiber Bragg gratings many detection circuits have been developed, which feature different degrees of complexity and detection accuracy. They do not, however, fulfill the requirements with respect to the costs and metrological properties to be commonly utilized in fiber Bragg grating sensors. That is why new configurations of such detectors, that fulfill the metrological and price expectations, are being continuously researched. A fiber optic Sagnac loop with a birefringent fiber is an interesting fiber optic device often used in telecommunication systems and fiber optic sensors. It features a periodic variation of the reflection coefficient and the transmission coefficient as a function of wavelength, which creates the possibilities to utilize it, among other things, as a multi frequency grating filter in fiber lasers, and as a wavelength demodulator in fiber Bragg grating sensors [1-4]. In a Sagnac loop, the effect of the outside environment on the two light waves propagating in opposite directions inside the same segment of the fiber, is the same. For this reason the interfering effect of the environment on the operation of the Sagnac loop is minimized. Nevertheless the ambient temperature changes cause changes of the optical path length in the loop as a result of the temperature dependence of the refractive index and the thermal expansion of the fiber.

A significantly smaller effect of temperature in comparison to conventional fibers is exhibited by photonic crystal fibers (PCFs). These fibers constitute a new class of fibers, intensively developed over the last years. A typical PCF is made of pure silica glass. It comprises an array of regularly arranged air holes, running along the axis of the fiber, and having a diameter of the order of micrometers and distances between the air holes also of the order of micrometers. Two main types of PCFs are distinguished: fibers with a solid core, and fibers with a hollow core. They differ in their optical properties and in the way they guide the light. Great possibilities of modifying the structure of these fibers allow to achieve extraordinary optical properties. PCFs with a solid core are manufactured as single mode, multi mode, nonlinear and polarization maintaining fibers. Polarization maintaining photonic crystal fibers (PM PCFs) feature a several times higher birefringence and a more than an order of magnitude lower temperature coefficient of birefringence than conventional polarization maintaining (PM) fibers, like the types Panda and Bow-Tie [5]. Presented are the results of measurements of the optical wavelength demodulator created on the basis of a Sagnac loop with a PM PCF with a solid core. Given is an example of application of the created demodulator to detect the output signal of a fiber optic force sensor with a Bragg grating.

Sagnac loop with a birefringent photonic crystal fiber

The Sagnac loop is constructed from a 3 dB coupler, a polarization controller and a segment of a single mode PM PCF (figure 1).

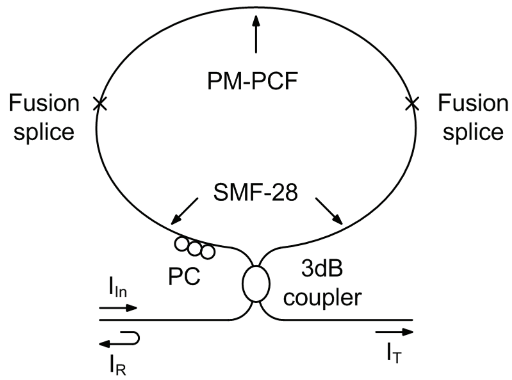

Fig.1. Diagram of the Sagnac loop with a PM PCF

The transmission coefficient $T(\lambda)$ and the reflection coefficient $R(\lambda)$ of the Sagnac loop with a polarization maintaining fiber are periodic functions of wavelength, which are described by the formulas [6]

(1) $$T(\lambda) = [1 - cos(\delta)]/2 \qquad R(\lambda) = [1 + cos(\delta)]/2 ,$$

while the period of these functions is governed by the relation

(2) $$\Delta\lambda = \lambda^2 / BL ,$$

where δ is the phase difference between the polarization components, propagating in the polarization maintaining fiber of length L, and determined by the relation $\delta=(2\pi/\lambda)BL$; B is the linear birefringence of the fiber $B=|n_f - n_s|$ and λ is the wavelength, n_f and n_s denote the effective refractive indices for the fast and the slow axis of the fiber.

In the constructed Sagnac loop, a segment of a single mode PM PCF "PM-1550-01" was used, with a length of 42,4 cm, manufactured by NKT Photonics A/S. The fiber contains, in the region of the photonic structure, two holes of greater diameter on both sides of the core. The high birefringence of the fiber was obtained by combining a non circular core and an air-glass cladding with a large refractive index step. The basic parameters of the fiber are: beat length of 1,8 mm, linear birefringence of 8,65 x 10^{-4} for λ=1,55 μm, polarization extinction ratio greater than 30 dB for 100m, small attenuation (1,5 dB/km for λ=1,55 μm), the temperature coefficient of birefringence more than 30 times lower than for conventional highly birefringent fibers [7,8].

The connection of the PCF with the telecom fiber SMF28 was performed by fusion splicing, using an electric arc splicer. Splicing PCF fibers this way causes a lot of problems, mainly the collapse of PCF structure because of the high temperature of splicing, which results in very high attenuation of such a connection [9]. By selecting a suitable arc duration, a SMF28 - PM-1550-01 - SMF28 path cord was produced, whose attenuation amounts to 4,2 dB. The attenuation of the produced Sagnac loop is ~10 dB. Similar values of attenuation of fusion splices for the same pairs of fibers were obtained by splicing using a CO_2 laser [6].

To determine the characteristics of the constructed Sagnac loop a wideband light source in the form of a LED, and the optical spectrum analyzer ANDO AQ-6315A were used. The parameters of the LED are: central wavelength of the emitted beam - 1520 nm, 3dB bandwidth - 54 nm, optical power - 40 μW. In figure 2, the measured spectrum of the reflected beam and the transmitted beam of the Sagnac loop with a PM PCF, in the range 1530 - 1540 nm, is presented in linear scale. On the basis of the performed measurements, the period of the spectrum variation and the dynamic range was determined, which are respectively 6,4 nm and 25 dB.

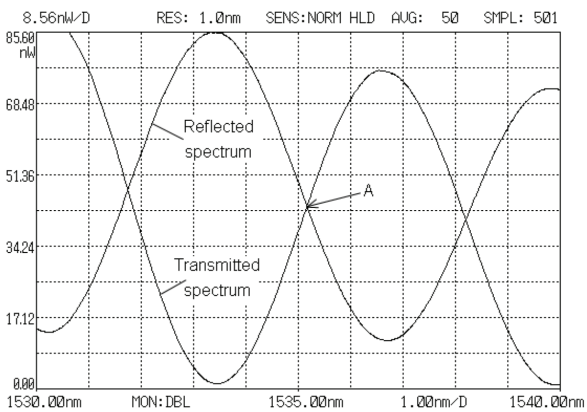

Fig. 2. Spectrum of the reflected and the transmitted beam of the Sagnac loop with a 42,4 cm long segment of a PM PCF

To apply the Sagnac loop as a wavelength demodulator of a Bragg grating sensor, the loop's operating point, indicating one of the points of intersection of the spectral characteristics, should correspond to the Bragg wavelength of the sensor, when no input is acting on it (point A in figure 2). The acting of the input causes variations of the Bragg wavelength of the sensor and proportional variations, in opposite directions, of the intensities of the transmitted and the reflected beams. The variations of the intensities of the beams will be proportional to the acting input quantity, if the range of the variations is not too wide. The nonlinearity of the functions describing the spectrum of the transmitted and the reflected beams of the demodulator, determined from their point of quadrature, is not greater than 0,5 % for deviation from the quadrature not greater than 11 degrees. For the produced Sagnac loop this corresponds to a deviation from the quadrature of ±0,4 nm. The Bragg grating force sensor was designed for that exact range of wavelength variation.

The full usefulness of the Sagnac loop as an optical wavelength demodulator of fiber Bragg grating sensors requires the satisfaction of the condition of stability of its optical characteristics; the effect of temperature on these characteristics must be negligible. This condition is not satisfied by the Sagnac loop with a conventional birefringent fiber [4]. A conventional PM fiber is produced from different kinds of glass with different thermal expansion coefficients, which results in a low thermal stability of its birefringence. This leads to the temperature dependence of the characteristics of the Sagnac loop with a conventional birefringent fiber. In order to utilize the Sagnac loop with a conventional birefringent fiber as a wavelength detector in FBG sensors, it is necessary to use circuits for temperature stabilization of the operating point of the detector, which leads to the circuit becoming more complex, and the sensor more expensive. The birefringent PCF is produced from a single type of glass; the variation of its optical properties with temperature is small. The applied, type PM-1550-01, highly birefringent PCF features a 30 times lower temperature coefficient of birefringence than a conventional birefringent fiber.

Figure 3 shows the transmission spectrum of the produced Sagnac loop, incorporating the PM-1550-01 PCF, in the wavelength range 1529 - 1541 nm, recorded every 6 minutes for 90 minutes, in laboratory conditions. From the obtained results it follows, that the variations of the spectrum period are imperceptible, smaller than the resolution of the spectrum analyzer that was used for measurements.

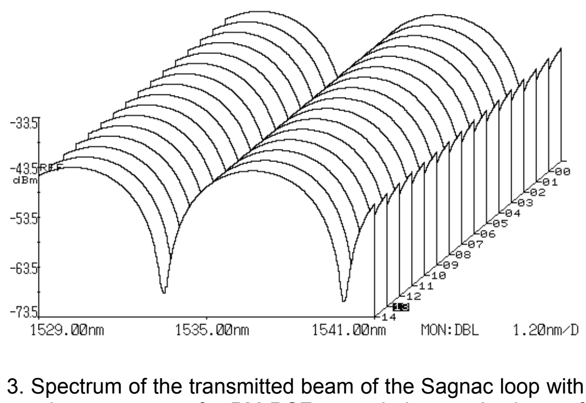

Fig. 3. Spectrum of the transmitted beam of the Sagnac loop with a 42,4 cm long segment of a PM PCF, recorded every 6 minutes for 90 minutes, plotted in semi logarithmic scale

Example of application

The constructed wavelength demodulator was applied in a fiber Bragg grating force sensor with a range of 50 N. As the elastic element of the sensor, a cantilever with a constant strength was used, on which a uniform, apodized fiber Bragg grating was installed, which had the following parameters: central wavelength λ_c = 1535,18 nm, 3 dB bandwidth $\Delta\lambda$ = 0,35 nm, reflection coefficient R = 0,99, The circuit diagram of the sensor is shown in figure 4.

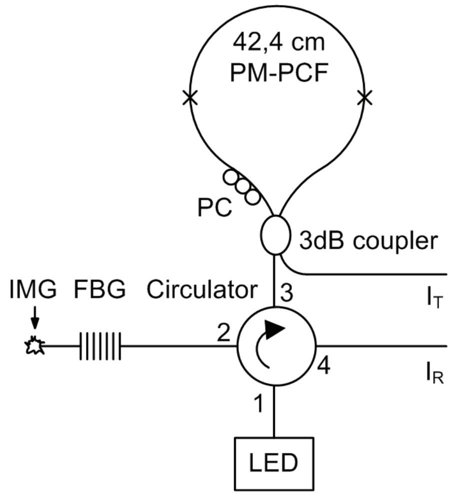

Fig. 4. Diagram of the compressive force sensor featuring a FBG and a loop wavelength discriminator. FBG – fiber Bragg grating, IMG – index matching gel. The ”x” symbol signifies a fusion splice

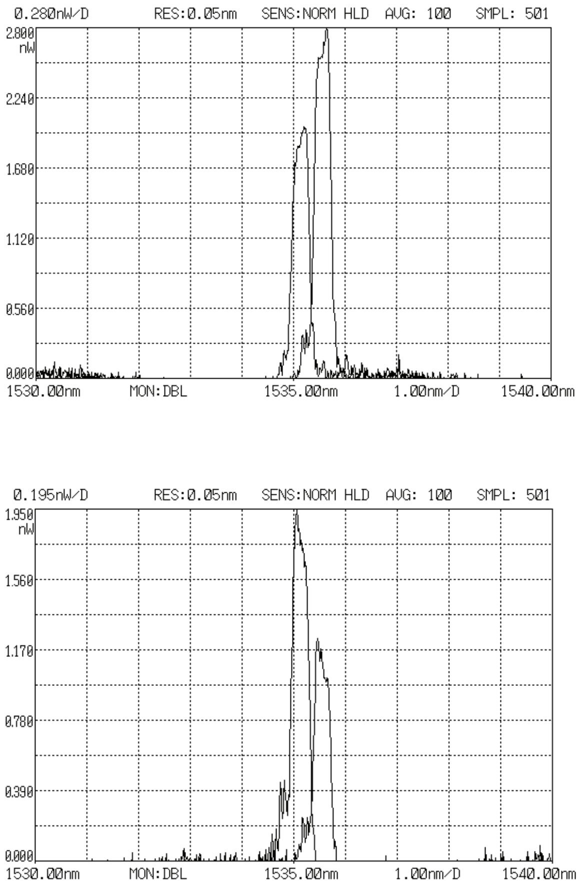

Fig. 5. Spectrum of the reflected beam of the FBG at the transmitting output P_T of the demodulator (the upper graph) and at the reflecting output P_R (lower graph), for the following loads of the sensor: 0 N and 50 N

The fiber Bragg grating is illuminated by the beam from the LED through ports 1 and 2 of the optical circulator. The beam reflected by the grating is fed through port 3 of the circulator to the first input port of the Saganc loop’s coupler. The transmitted beam of the loop is obtained at the second input port of the coupler, and the beam reflected by the grating is obtained at port 4 of the circulator. The index matching gel was used at the bare fiber end of the Bragg grating to minimize the Fresnel reflection. The operating point of the wavelength demodulator was adjusted to the value of the central wavelength of the non loaded sensor, equal to 1535,18 nm. Under the effect of the nominal load, applied by a compressive force with a value of 50 N, the central wavelength of the Bragg grating of the sensor will shift by 0,40 nm. This means, that the operating point of the demodulator will shift in the direction of longer waves by 1/16 of the period of its spectrum, and its conversion nonlinearity in this range is not greater than 0,5 %. While changing the load of the sensor in the range 0 - 50 N, measurements were performed of the power in the beam reflected by the Bragg grating of the sensor, at the outputs of the demodulator: the transmitting P_T and the reflecting P_R. The spectrum of the reflected beam of the Bragg grating of the sensor at the demodulator outputs for two values of the force acting on the sensor: 0 N and 50 N is shown in figure 5.

This figure is the graphical illustration of the operation of the demodulator when the spectrum of the Bragg grating is shifted by 0,40 nm in the direction of longer waves. Having at disposal the two output signals of the wavelength demodulator P_T and P_R, which vary in opposite directions, the well known method of making the output signal of the sensor independent of the intensity fluctuations of the light illuminating the grating can be applied by creating the quotient of the sum and the difference of the signals $(P_T-P_R)/(P_T+P_R)$ as the output signal. The static characteristic of the constructed fiber Bragg grating force sensor in the range 0 - 50 N is shown in figure 6. The nonlinearity error of the sensor determined on the basis of the characteristic does not exceed 1 %.

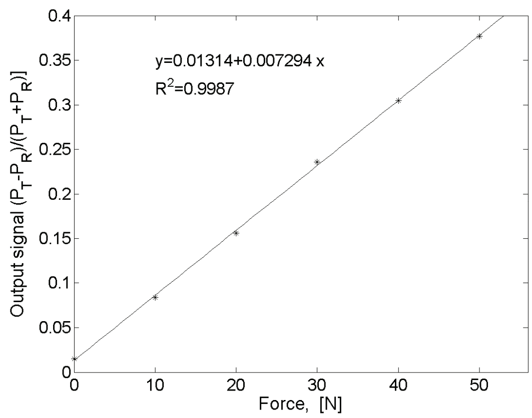

Fig. 6. Static characteristic of the fiber optic force sensor with a Bragg grating

Conclusions

The results of measurements of the wavelength demodulator based on the Sagnac loop with a PM PCF and the measurements of the characteristics of a force sensor using the demodulator show, that it can make an inexpensive detector circuit with good metrological properties for Bragg grating sensors. Thanks to the application, in the demodulator, of a PM PCF, whose birefringence is more than two times higher and the birefringence temperature coefficient more than thirty times lower then that of a conventional birefringent fiber, one obtains a stable wavelength demodulator circuit. The fixed operating point of the demodulator depends on the temperature only to a small degree and the segment of the fiber used is more than two times shorter than a conventional birefringent fiber, if it was used for the same purpose. The range of linear conversion of the demodulator can be easily altered by changing the length of the segment of the PM PCF, while keeping in mind, that increasing the conversion range of the demodulator decreases its sensitivity and vice versa. To construct the presented wavelength demodulator care needs to taken when fusion splicing the birefringent PCF to the telecommunication fiber, to ensure small splice losses. This can be accomplished using a conventional fusion splicer, which utilizes an electric arc, by optimizing the duration and power of the arc.

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***Autor**: dr inż. Cezary Kaczmarek, Politechnika Lubelska, Katedra Elektroniki, ul. Nadbystrzycka 38 A, 20-618 Lublin, E-mail: c.kaczmarek@pollub.pl;*