Using the Phase Response of Fiber Bragg Gratings for Measurement Applications

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Abstract

Fiber Bragg gratings have been used in optical sensor systems for a long time. The conventional read-out is based on an amplitude evaluation, recent studies consider also the utilization of the group delay characteristic. This paper proposes a novel read-out approach that incorporates the direct evaluation of a fiber Bragg grating's phase response. Experimental setups involving electronic vector network analyzers as well as just signal generators and analog-to-digital conversion are explained. The method has been evaluated with respect to real measurement tasks and shows promising results.

1 Introduction

Optical sensors are commonly used in a wide range of applications. Among different types of optical sensors, fiber based sensors offer versatile qualities, of which an important property is the resilience to interfering ambient electromagnetic fields. A well studied and widely used type of optical fiber sensors is the fiber Bragg grating (FBG) [1]. It is created by inducing a periodical change of the refractive index to a short segment of the fiber core. These interfaces cause reflection of a certain wavelength of incident light. According to the exact setup, which may be arranged in transmission or in reflection configuration, the FBG serves as an optical band-stop or an optical band-pass filter. This characteristic is primarily used in communication networks as notch filters or as part of multiplexing devices. However, it can also be utilized for sensing applications, as a change of the grating period will generate a wavelength shift of the filter function. Such a change of the grating period can be induced e. g. by variations of the fiber's temperature or by mechanical stress. The conventional read-out is realized by analyzing the optical spectrum and hereby determining the shift in wavelength from which the original variation of the measurand can be derived.

Recent activities of the authors propose a modulation of the light source in an FBG-based setup with a radio frequency (RF) signal and using the group delay characteristic of the FBG for read-out either alternatively or additionally to the amplitude characteristic [2, 3]. An advantage of this approach is the capability of diminishing the impact of environmental interferences to the amplitude e. g. in radio-over-fiber (RoF) setups.

While being calculated from phase measurements and therefore being mostly immune to amplitude noise, the group delay characteristic can only be applied when implementing at least two different frequencies for the modulation scheme at the same time. This is a potential downside of the principle as both, the efforts for RF signal generation (hardware) and for signal evaluation (software) may increase heavily.

In this contribution, the authors discuss a solution to the described challenges by proposing the direct evaluation of an FBG's phase response. After covering the process of reconstructing the original phase response characteristic, the application to a simple measurement setup is demonstrated and the findings are concluded by a discussion of the approaches' general applicability.

2 Methods

2.1 Overview of the Phase Response of Fiber Bragg Gratings

Fiber Bragg gratings are known to be dispersive elements and thus possessing a wavelength-dependent group delay characteristic. This property is not only frequently used for dispersion compensation in optical networks, but also has the theoretical background been studied in great detail [4, 5, 6, 7]. Originating from this point, the application of the group delay characteristic has been transferred to measurement tasks recently [8]. The mathematical description of the group delay is derived from the phase of the amplitude reflection coefficient according to the coupled-mode theory [9, 10, 11] and leads to the definition of the group delay

$$\tau_g(\omega) = -\frac{d\Phi(\omega)}{d\omega}. \quad (1)$$

Observing (1) makes clear that at least two measurements of signals with different frequencies ω have to be acquired to meet the requirements for performing a calculation of the group delay. Furthermore, it highlights that the group delay is being measured indirectly through the phase. Considering these two limitations and the fact that the phase information is already present in the setup, a simplification

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is to eliminate the need for different frequencies and to use the phase response of the FBG directly to accomplish the measurement task.

The phase response of FBGs has been studied for many years, focusing mostly on phase reconstruction methods. While first attempts relied on optical spectrum analyzers and sophisticated mathematics [12], a phase shift method [13] or an interferometric scheme [14], later approaches incorporated electro-optical single-sideband (SSB) modulation [15, 16, 17]. The SSB method allows for high resolution and low errors along with a comparably simple setup that bypasses the need of overly complex and expensive instruments.

In contrast to these publications, which focus on an exact reconstruction of the phase, the present work aims at a further reduction of hardware expenses in terms of costs and space. Following that, instead of a tunable laser source (TLS) and an external Mach-Zehnder modulator (MZM), an existing RoF setup [3] is adapted, using a directly modulated distributed feedback (DFB) laser diode. While DFB lasers are cost-effective and allow a high level of integration, they implement double-sideband (DSB) modulation which introduces another key difference to this work. As further consequence of the chosen setup, the sensor's characteristic curve is swept across the DFB laser diode's fixed central wavelength by manipulating the measurand. Here, a chirped FBG is used as sensor. It is designed for a full width at half minimum (FWHM) bandwidth of 8 nm around a central wavelength of 1536.5 nm. The FBG has a length of 7 mm, a chirp $\frac{d\Lambda}{dz}$ of $1\,\mathrm{nm\,mm^{-1}}$ and is apodized with a gaussian cosine function to provide a delay characteristic as linear as possible across the FWHM bandwidth. A cantilever, to which the grating is bonded, enables tuning of the spectrum by use of a fine threaded adjusting screw that is coupled to the cantilever's free tail. When the FBG is tuned across a certain bandwidth $\Delta\lambda$, the phase difference $\Delta\Phi$ of the modulation signal calculates according to

$$\Delta\Phi = 360^\circ \cdot f \cdot \frac{2 \cdot \Delta\lambda \cdot n}{\frac{d\Lambda}{dz} \cdot c_0} \tag{2}$$

with the modulation signal's frequency f, the propagating mode's effective refractive index in the grating n and the speed of light in vacuum c_0. In the following, experimental setups are explained for both, the determination of the original phase response and application related single shot measurements with even reduced hardware requirements.

2.2 Determining the Phase Response Characteristic

The experimental determination of the phase response is realized by the setup shown in Figure 1. In general, the electrical vector network analyzer (EVNA) outputs an RF signal to directly modulate the DFB laser diode. The latter is stabilized by a laser diode controller (LDC) and its optical output is connected to a circulator which inserts the modulated optical signal in the FBG sensor. Reflected light is then received by a photodiode. The opto-electrical converted signal is amplified and evaluated by the EVNA. Using the adjustment screw of the sensor, its spectrum

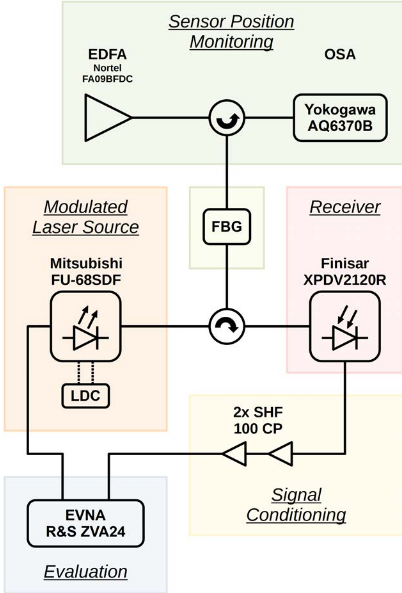

Figure 1 Experimental setup for determining the phase response with an EVNA.

is tuned across most of the FWHM range relative to the laser's wavelength. A fine step width of 200 pm is chosen for the tuning, leading to a resolution of 36 points across the tunable range of 7 nm. Because the adjustment screw does not provide any scale, the relative shift is monitored by connecting an erbium-doped fiber amplifier (EDFA) without any input signal (forming a broadband optical source) via a circulator to the FBG's second port and metering the reflected light with an optical spectrum analyzer (OSA). At each position of the sensor, a phase measurement is conducted by the EVNA.

Configuration parameters for the EVNA are: time sweep mode, frequency of 2.45 GHz, 1001 points, 10 dBm stimulus power, 1 kHz measurement bandwidth, no correction. A normalization is applied afterwards to all measurement results with the phase value at the FBG's center wavelength serving as reference. The OSA is set up to monitor a range from 1520 nm to 1560 nm with a resolution of 0.2 nm and 1001 points. At the same time, the broadband noise spectrum of the EDFA, stored in a separate trace beforehand, is subtracted from the OSA's input signal to allow for an analysis of the FBG's real spectrum regarding its position. This is implemented by a spectral width analysis at a threshold level of −5 dB. During this analysis, the DFB laser diode is turned off. When turned on for the measurement, it is operated at a forward current of 60 mA and a temperature of 21 °C. A settling time for the DFB laser diode of approximately 1 min after each power cycle is maintained. The photodiode and the amplifiers are operated according to their specifications. All relevant details regarding the manufacturers and models of the used components can be inferred from Figure 1.

2.3 Application to a Measurement Task

For the transfer to a measurement scenario, as it is the core component, the sensor is not changed. Although unneces-

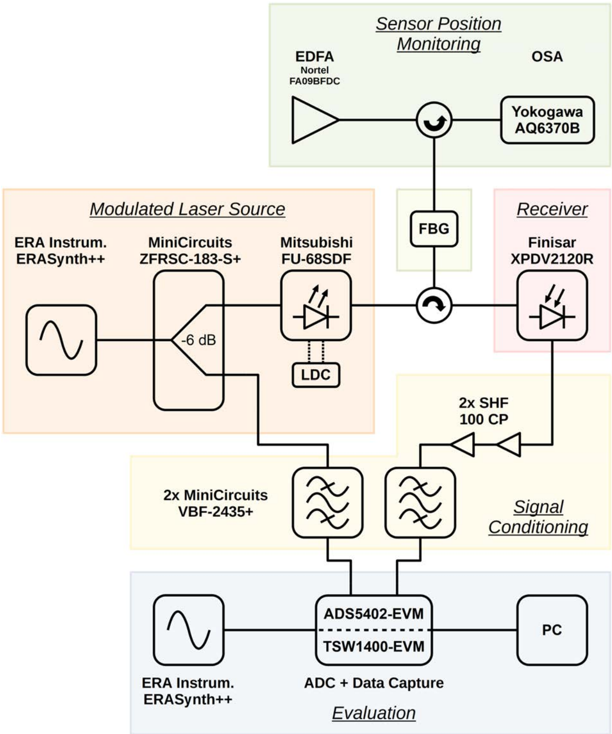

Figure 2 Experimental setup with simplified hardware effort for example measurements with an ADC.

sary for the measurement application, the optical position monitoring remains part of the setup to ensure comparability, too. Also, the laser diode and the photo diode plus the electrical amplifiers are still included to maintain a comparable signal quality. Consequently, all parameters regarding the listed components remain unchanged.

The focus in the second setup is on simplification of used electronic components. This relates to the signal generation and evaluation as incorporating an EVNA is not the first choice due to its high cost and its highly sophisticated capabilities of which only a small portion is needed. Therefore, it is substituted by a compact signal generator and an analog to digital converter (ADC) with a PC as control unit (Fig. 2). The ADC is run at 300 MHz, collecting 65 536 samples per channel for each single shot. In order to prevent aliasing due to the undersampling, anti-aliasing filters are integrated in both signal paths. The signal generator is set to a frequency of 2.45 GHz and an output power of 16 dBm in continuous wave mode. The – compared to the previous setup – higher output power compensates for a broadband -6 dB power divider that is introduced to provide a reference signal.

As before, at different tuning positions of the sensor, single shot measurements are performed, ten at each position. The digital values are processed by a python script that calculates the complex Fourier transform for the measurement signal and for the reference signal. Out of this, the phase values are determined for both signals and the reference phase is subtracted from the measurement signal's phase. Hence, all computed phase values stay correlated and a common normalization can be applied equivalent to subsection 2.2.

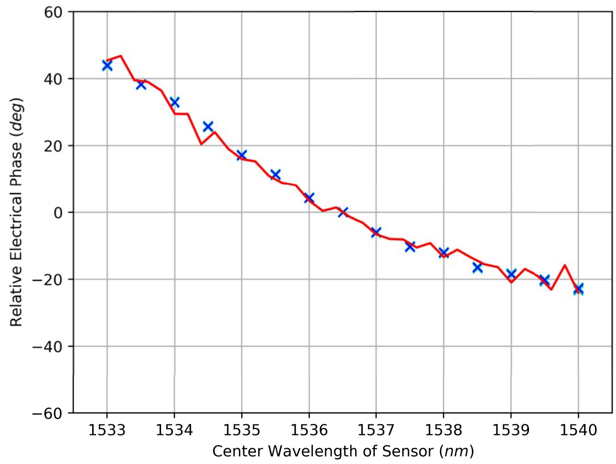

Figure 3 Measured dependency of the electrical phase from the center wavelength of the sensor; red: phase response derived with EVNA, blue: single measurements acquired with ADC.

3 Results and Discussion

Figure 3 shows the results for both measurements. Due to the low variation between the ten ADC measurements per wavelength, they are difficult to distinguish in the graph. They also correspond well with the reference curve acquired with the EVNA. A total phase difference $\Delta\Phi$ of 69.4° can be read from the EVNA measurements across the analyzed 7 nm broad bandwidth $\Delta\lambda$. For the given values and an refractive index of the fiber's core n of 1.4473 nm [18], the expected value calculates after (2) giving a result of 59.6°. The deviation between both values may be explained by manufacturing tolerances and interference phenomenons between the lower and the upper sideband resulting from the DSB modulation. As a consequence, unlike SSB modulation, DSB modulation does not make an exact determination of the phase response possible as has been discussed by the authors before [3]. Anyway, it is clearly visible that the method is suitable for measurement purposes when the same core setup is used for the reference curve determination and the measurement itself. For FBG-based sensors, this is the standard procedure in industry already. Another attribute of the derived phase response is its noticeable nonlinearity which is most likely related to the DSB modulation also. A better sensitivity could be achieved by designing an FBG with a steeper delay characteristic and thus a steeper phase response as long as the phase range does not exceed 2π to avoid ambiguity.

4 Conclusions

In this paper, the authors proposed a direct phase evaluation method of FBG sensors for measurement applications. The findings indicate a general applicability of the novel readout method. At the same time, variations from the expected values could be observed. Therefore, the approach does not permit a precise determination of the original phase response of the sensor but an unambiguous derived value in-

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stead. However, this does not involve a limitation to the measurement task while many advantages can be gained. Resilience to amplitude noise is a core aspect along with considerably reduced hardware expenses. Further studies could cover the origins of the deviations from theoretical values in terms of nonlinearity and overall phase sensitivity as well as an detailed analysis of the potential advantages of the novel scheme for the signal to noise ratio especially in RoF setups.

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