Optoelectronic system for monitoring physiological parameters of patients under MRI diagnosis

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In this work an optoelectronic system for monitoring of basic physiological parameters of patients under MRI diagnosis is presented and discussed. The system comprises a set of fiber Bragg gratings as the strain sensors and an optoelectronic interrogator. Initial measurement results prove the possibility of the heart and respiratory rates detection with no influence of the magnetic field.

Introduction

The magnetic resonance imaging (MRI) technique is a diagnostic tool which is nowadays commonly used in almost every field of medicine. In some cases, when a patient experiences increased discomfort or fear, MRI examination requires continuous monitoring of basic physiologic parameters, such as the heart rate, the respiratory rate and the temperature. Due to the harsh environment, i.e. strong magnetic field present within the MRI chamber, the monitoring system requires application of non-standard solutions. Furthermore, the installed equipment cannot negatively affect the results of the MRI scan. Such requirements clearly suggest that monitoring system based on photonic components, totally immune to external electromagnetic field might be an interesting alternative to presently used MRI compatible electronic systems.

In this work we demonstrate and discuss a concept of a novel system, based on a network of fiber Bragg gratings (FBGs) and photonic integrated circuits (PICs) as interrogating devices, dedicated for non-invasive monitoring of the heart rate and the respiratory rate of the patient under the MRI scan.

System concept

The proposed monitoring system comprises a set of fiber Bragg gratings used as the strain sensors. The network of sensors, differing in the Bragg wavelength, are connected in series to provide sufficient measurement data – multiple sensors increase the effective area where the patient movements induce detectable stress on the deployed optical fiber. This enables also proper positioning of the sensors with respect to the patient, as the relative angular orientation influences the heart and the respiratory rate detection. A broadband C-band optical signal from a superluminescent LED is launched to the fiber through an optical circulator. The remaining circulator port is connected to a multi-channel FBG interrogator, to enable reading out the current Bragg wavelengths of all gratings simultaneously. The obtained measurement data is then analyzed by dedicated software. In the final design, the light source and the interrogator are assumed to be replaced by a dedicated application specific photonic integrated circuit (ASPIC), however for the proof-of-the-concept tests a commercially available devices have been used.

Fiber Bragg gratings

The series of 10 mm long FBGs have been inscribed in a single-mode germano-silicate optical fiber using a 248 nm KrF excimer pulsed laser. Then, the accelerated aging process has been used to stabilize the FBGs spectral parameters. All gratings have been written using specially designed phase mask that consists of an array of sub-masks. The difference in periods between the adjacent sub-masks is 3 nm, which corresponds to 4.28±0.03 nm grid in Bragg wavelengths (Fig. 1a). Such a wavelength separation ensures that reflected spectra of adjoining FBGs do not overlap. The detailed reflected spectrum of a single FBG (FBG 6) is presented in Fig. 1b.

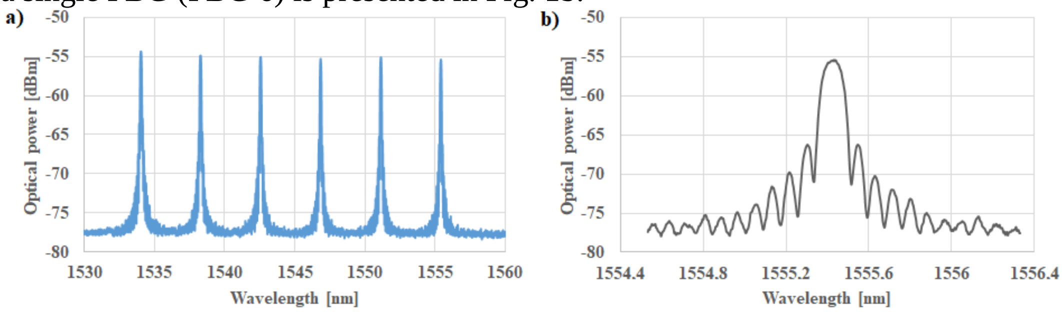

Fig. 1. Measured reflected spectra of six FBGs written in hydrogen-loaded fiber (left) and the detailed spectrum of a single FBG (right).

Reflection coefficients of the gratings (73±7%) have been chosen to provide satisfactory signal-to-noise radio and well-defined reflection peaks. It ensures that Bragg wavelength changes vs. strain/temperature can be reliably monitored using fiber-optic interrogators.
Both temperature and strain responses of the gratings exhibit linear changes of Bragg wavelengths vs measured parameter (strain/temperature). The temperature and strain coefficients have been experimentally determined to be 10.2±0.2 pm/°C and 1.1±0.1pm/με, respectively. It means, that the temperature measurement resolution of 0.1 °C is possible while using commercially available interrogators. Furthermore, the feasible strain resolution is up to a few με within the c.a. ±1800 με range. However, in the proposed sensing system, where only tensile forces are applied to the FBGs, the strain measurement range from 0 με up to 3600 με can be obtained, with no spectral overlap.

Interrogation system

Time dependent values of the central FBG wavelength are recorded using the interrogation system based on the I-MON 256 USB analyzer by *Ibsen Photonics*. This device provides real-time (up to 6 kHz) measurements of the spectrum with high resolution (wavelength fit resolution below 0.5 pm) in a wavelength range of 1525-1570 nm. A superluminescent diode (SLED) is used as the light source (wavelength range of 1515-1576 nm). A circulator is used to connect the SLED with the FBG sensors and the interrogator. The measurement system is schematically depicted in Fig. 2.
In the presented configuration of the system (Fig. 2.) the reflection spectrum of the FBG is acquired. The essential element of the spectrum analyzer is a system of multiple transmission gratings, which allows separating the input signal spatially into its wavelength components by turning the light by 360 degrees inside a compact housing. The individual channels of separated wavelengths are directed toward the photodiode array of 256 pixels, converted to digital form and transmitted to the computer. Any deviations from the linearity of the wavelength of the diode array are corrected by the analyzing software with the use of polynomial functions. As the average wavelength spacing of the interrogator diode array is about 170 pm and the full width at half maximum of the reflection spectrum of FBGs used in the presented system is around 300 pm, the FBG spectrum peak is sampled with only 6-8 wavelength values. Therefore, the software used for data processing determines the center frequency of the grid with

Gaussian profile estimation and a three-point least squares fitting procedure. The time-dependent changes of the Bragg wavelength yield the input signal for further analysis.

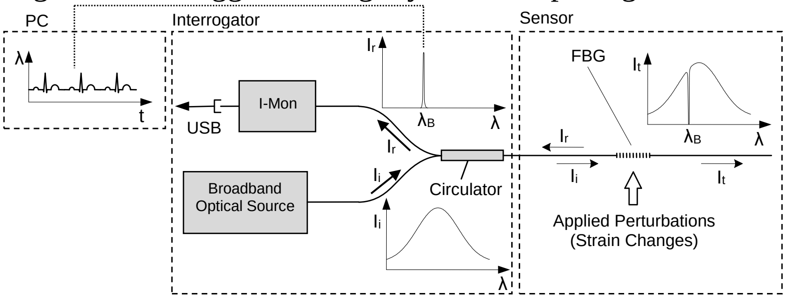

Fig. 2. Interrogation system of the FBG-based sensor network.

Integrated interrogator

Apart from the presently deployed optoelectronic interrogator, the integrated 36-channel C-band ASPIC-based spectrometer was designed and fabricated using the generic InP process provided by Smart Photonics [1]. The wavelength-selective element of the interrogator is an arrayed waveguide grating (AWG) demultiplexer. The interrogator was designed in two variants using a 2×36 AWG with a channel spacing of 50 GHz and 75 GHz, respectively. Both interrogators have two access waveguides, one of them is connected directly to the AWG, while the second is connected to the AWG through an optical pre-amplifier. Each of the AWG outputs is connected to a PIN photodiode. A microscope picture of the fabricated photonic chip is shown in Fig. 3.

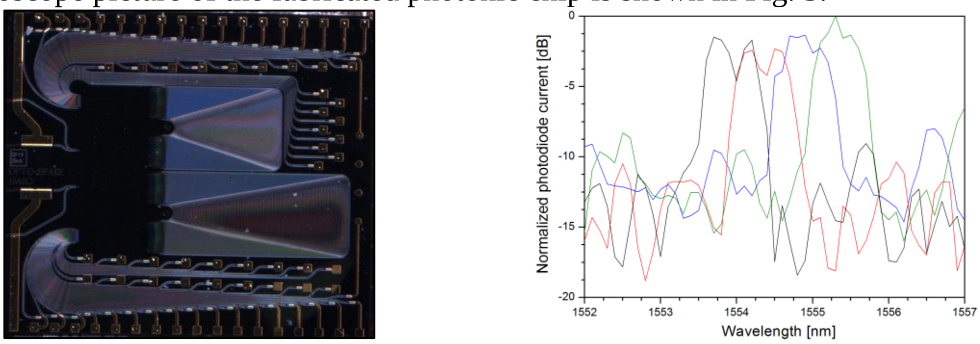

Fig. 3. The microscope picture of the AWG-based integrated interrogators (left) and the measured transmission characteristic of the 50 GHz AWG wavelength demultiplexer (right).

The device performance was characterized by injecting a TE-polarized optical signal from a tunable laser diode and monitoring the photodiode currents. Fig 3 presents introductory results of the wavelength response of four neighboring photodiodes of the 50 GHz demultiplexer, while injecting the signal to the non-amplified input of the interrogator. The signal to noise ratio in this case is relatively small (ca. 10-15 dB), however it should improve when the amplified input is used. The central wavelengths of the transmission peaks are separated by about 0.4 nm which corresponds well to the designed channel spacing of 50 GHz. Due to relatively broad transmission peaks (FWHM > 0.5 nm) there is a substantial inter-channel crosstalk present in the AWG wavelength spectrum. This feature, which in principle is disadvantageous for WDM telecom applications, may be profitable for FBG interrogation, as it allows monitoring of the Bragg wavelength using a smaller number of photodiodes.

Measurement results

Initial tests of the monitoring system were performed using a single fiber Bragg grating as the strain sensor. The fiber with the inscribed FBG was mounted using an epoxy glue on a PMMA board and deployed under the patient subjected to MRI diagnosis. Fig. 4 presents the obtained measurement results – the deviation of the Bragg wavelength is plotted as the function of time. The high, slowly-varying peaks are caused by the breath movements of the patient, while small and fast-varying peaks are a result of the cardiac activity. No influence of magnetic field of MRI instrument on the sensing system have been observed.

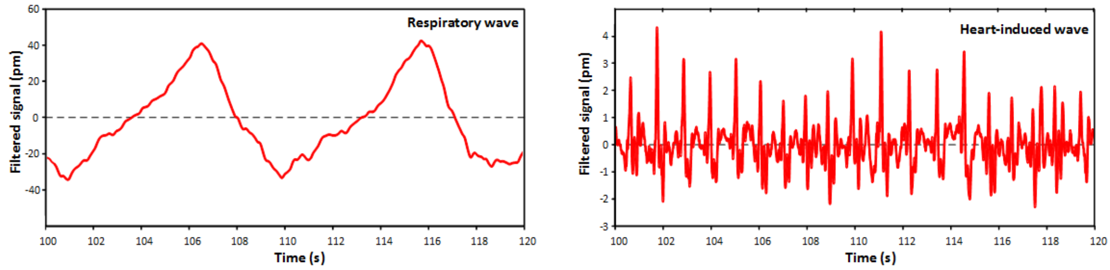

Fig. 4. Measurement results obtained using the test setup - respiratory and heart-induced waves plotted as a function of the deviation of the Bragg wavelength in the time domain.

It should be noted that in the recorded signals the respiration-induced artifacts as well as heart-induced waves are present. They were extracted with the use of digital filters. Fourth order band-pass Butterworth digital filter with cutoff frequencies of 0.1 Hz and 2.1 Hz was used to extract the respiration wave. A similar filter with cutoff frequencies of 20 Hz and 300 Hz was used for determination of the wave reflecting the heart work. In the acquired signal samples, the peak to peak amplitudes of heart induced characteristic waves are in the range of 10 to 15 pm. At the same time the amplitudes of respiratory cycle induced waves lie in the range of 50 to 70 pm. These values are significantly above the noise floor. The estimated signal to noise ratio (SNR) was about 34 dB for the respiratory wave and 27 dB for the heart wave respectively.

The extraction of the heartbeat and respiratory cycles characteristic peaks from the strain sensor signals is a complex task, mainly due to interferences originating from other body movements as well as interferences between heart and thorax movements. Nevertheless, the initial measurements showed possibility of extracting the basic vital signs parameters, i.e., breathing and heart rates. The methods of analysis of the signals collected in a similar way were presented previously in [2,3]. The signal recorded by the proposed device requires intense post processing, but the method becomes advantageous in high EM field environment such as MRI examinations, which do not affect the optical signal propagation in the fiber nor disturb the sensor operation.

Summary

An experimental optoelectronic system for monitoring of basic physiological parameters of patients under MRI diagnosis has been demonstrated and briefly discussed. The initial measurement results confirm both the general correctness of the proposed approach and the applicability of the system to continuous monitoring of the patient's physical condition in a strong magnetic field, without influencing the results of the MRI scan.

Acknowledgement

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