Non-Invasive Fiber Optic Probe Encapsulated Into PolyDiMethylSiloxane for Measuring Respiratory and Heart Rate of the Human Body

Jan NEDOMA[1], *Marcel FAJKUS*[1], *Petr SISKA*[1], *Radek MARTINEK*[2], *Vladimir VASINEK*[1]

[1]Department of Telecommunications, Faculty of Electrical Engineering and Computer Science, VSB–Technical university of Ostrava, 17. listopadu 15, 708 33 Ostrava, Czech Republic
[2]Department of Cybernetics and Biomedical Engineering, Faculty of Electrical Engineering and Computer Science, VSB–Technical university of Ostrava, 17. listopadu 15, 708 33 Ostrava, Czech Republic

jan.nedoma@vsb.cz, marcel.fajkus@vsb.cz, petr.siska@vsb.cz, radek.martinek@vsb.cz, vladimir.vasinek@vsb.cz

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Abstract. *This article describes the design and the functional verification of fiber optic system with an innovative non-invasive measuring probe for monitoring respiratory and heart rate. The measuring probe is based on Fiber Bragg Grating (FBG), and it is encapsulated in the PolyDiMethylSiloxane polymer (PDMS). PDMS offers a unique combination of suitable properties for the use in biomedical applications. The main advantages include inert to human skin and immunity to electromagnetic interference. The measuring probe is a part of contact strip which is placed on the chest of the patient. The measurement is based on sensing the movements of the thoracic cavity of the patient during breathing. Movement (mechanical stress) is transferred to FBG using the contact strip. Respiratory and heart rate are analyzed using the spectral evaluation of the measured signals. This monitoring method is fully dielectric; thus the absolute safety of the patient is ensured. The main contributions of the article are a design of non-invasive probe encapsulated into a PDMS polymer and implementation of the probe for humans using a contact strip. This combination forms an essential element of the measuring system. The set of experimental measurements verified functionality with respect to the position of the patient. Performed experiments proved the functionality of the presented solution so it can be utilized for further research in biomedical applications.*

Keywords

FBG, Fiber Bragg Gratings, fiber optic sensor, Heart Rate (HR), Non-invasive, PolyDiMethyl-Siloxane (PDMS), Respiration Rate (RR).

1. Introduction

The current trend of developments clearly indicates that future monitoring essential vital functions of the human body tend to sophisticated diagnostic equipment and methods in biomedical applications. The aim is to merge more diagnostic parameters to a single universal probe or a universal measuring system. Recently, the utilization of Optical Sensors has been growing in variety of emerging biomedical applications [1] and [2]. Based on the study of the literature review, authors of this article introduce an innovative combination of non-invasive measuring probe encapsulated into PDMS and implementation into the clamping contact strip. Monitoring respiratory and heart rate can be performed using one universal probe. The measuring probe based on Bragg grating technology and the probe encapsulated in a particular shape into a PDMS polymer. Fiber-optical sensors have been increasingly utilized in the biomedical applications, e.g. for measuring respiratory and cardiac activity [3], for specific heart rate monitoring [4], for early detection of health deterioration through a network of FBG [5], or for sensing respiratory parameters and the chemical reactions of human skin to external influences by using a sensor based on an enlarged-taper tailored Fiber Bragg Grating [6]. This fact is mainly due to characteristic features of the optical sensor-power supply independence and electromagnetic immunity. The optical fiber sensors can be utilized without electrical interference in the presence of other electrical equipment. Thus, the safety of patient monitoring is not affected, or more precisely, it makes the measurement more safety. The combination with PDMS material further enhances comfort during monitoring parameters. Biocompatibility is one of the primary factors for the patient comfort. PDMS is inert to the human skin, and it does not affect the patient's body. Authors focus on both description of the innovative non-invasive measuring probe and on implementation of the probe for measurement on human. The aim is not a comparison with existing diagnostic tools and methods.

2. Gait Motion Capture

Siloxanes are the compounds which contain a Si-O-Si bond in the molecule. This chemical group is specific for its stability; therefore, one can prepare an endless chain with composed of -(O-Si-O-Si-O)-. The last two free bonds of the silicon atom can be occupied by various -HO groups or organic ligands such as -CH_3. The most commonly used compound is PolydDiMethylSiloxane which is defined by the chemical formula in the form: $(CH_3)_3SiO[SiO(CH_3)_2]nSi(CH_3)_3$. The siloxanes are completely stable in standard conditions and are not subject to degradation in the presence of water or oxygen. The resulting products are solid or liquid substances according to the number of ligands and siloxane groups. Their other properties are both hydrophobicity and almost complete inertness to living organisms.

The production of PDMS involves three elements, namely technical silicon, hydrochloric acid, and methanol. This combination creates the so-called chloromethane. The manufacturing process contains four chemical phases: synthesis, rectification, hydrolysis, and polycondensation. Figure 1 describes chemical composition of PDMS. Methyl (CH_3) [7] and [8] represents the organic substituent in most cases.

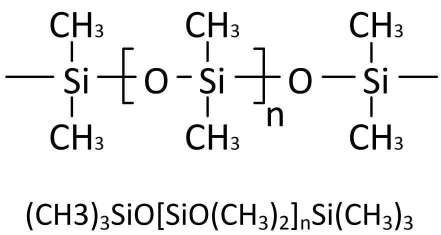


Fig. 1: Chemical composition of PDMS.

Encapsulation of measuring probe was made by PDMS with the designation of Sylgard 184. Sylgard 184 is a two-component casting compound; wherein A component creates own pre-polymer and B component is a curing agent. Both components are mixed according to datasheet in a weight ratio of 10:1 (A:B). Bubbles and microbubbles which result from the combination of the pre-polymer and the curing agent can be removed using an ultrasonic bath. Homogeneity of connection is provided using a laboratory shaker.

Sylgard 184 belongs to the moderately viscous liquid elastomers. The primary characteristic of PDMS is its temperature stability. PDMS is formed by the bonds Si-CH_3 and Si-O having a high binding energy ($452\ \mathrm{kJ} \cdot \mathrm{mole}^{-1}$). PDMS withstands temperatures ranging from -60 °C through 200 °C, in short-term processes to 350 °C. At temperatures around 100 °C, curing of Sylgard 184 can be performed within several minutes.

Fiber-optical Bragg gratings are most commonly used fiber-optical sensors for their spectral characteristics [9] and [10]. Repeated changes in refractive index of the core of an optical fiber creates the grating. Spectral reflection of a selected wavelength, known as Bragg wavelength, occurs on periodic interfaces. All the other wavelengths pass through the Bragg grating without damping. Figure 2 shows the structure of the FBG.

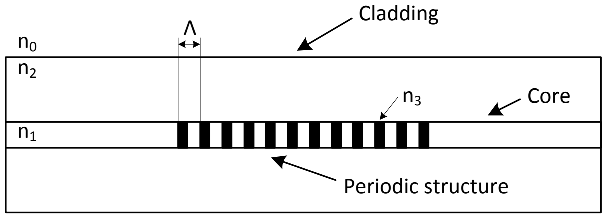


Fig. 2: Example of structure of Fiber Bragg Grating.

The Bragg wavelength λ_B is given by following equation:

$$\lambda_B = 2n_{eff}\Lambda, \tag{1}$$

where n_{eff} is the effective refractive index of the optical fiber with Bragg grating and Λ is the period of changes in the refractive index pitch for the fiber's core. The effective refractive index in a single-mode optical fiber can be approximated using the formula:

$$n_{eff} \cong \sqrt{n_2 + \frac{\lambda^2}{4\pi^2 r^2} \cdot (1.1428V - 0.996)^2}, \tag{2}$$

where n_2 is the refractive index of the cladding, λ is the wavelength of transmitted light, r is the core diameter and V is the normalized frequency.

The primary use of FBG is based on the deformational and temperature sensitivities. Based on the temperature evolution of mechanical stress, the Bragg wavelength shift can be defined as:

$$\frac{\Delta\lambda}{\lambda_0} = k\varepsilon + (\alpha_\Delta + \alpha_n)\Delta T, \tag{3}$$

where k is the deformational coefficient, α_n is the optical temperature coefficient, α_Δ is the coefficient of thermal expansion, ΔT is the temperature change and ε is the applied deformation. Deformational dependence and temperature dependence are determined both by the parameter values and the central Bragg wavelength. Normalized deformational and temperature coefficients [11] are introduced for determination of the individual sensitivities. Normalized deformational coefficient is given by:

$$\frac{1}{\lambda_B}\frac{\Delta\lambda_B}{\Delta\varepsilon} = 0.78 \cdot 10^{-6} \quad (\mu\varepsilon^{-1}), \tag{4}$$

and normalized temperature coefficient by:

$$\frac{1}{\lambda_B}\frac{\Delta\lambda_B}{\Delta\varepsilon} = 6.678 \cdot 10^{-6} \quad (^{\circ}\mathrm{C}^{-1}). \tag{5}$$

FBGs are single-point sensors, with multiplexing techniques we can join them together and obtain a multipoint measuring probe [12] and [13].

3. Results

Implemented manufacturing technology of FBG encapsulation is based on the casting of the liquid PDMS into the desired form (dimensions of the measuring probe). We take into account the size, weight, and shape within the design of the form. We create the rectangular shape with dimensions of 80×40×5 mm. The casting insert is created by a substrate into which is stored the bare FBG. Process of encapsulation is divided into three independent steps: the integration of FBG into liquid PDMS, the curing at a temperature of 100 °C ± 3 % in a temperature box for 60 minutes and 24 hour relaxation time. Results in the article [14] show that this type of encapsulation does not affect the structure of the FBG.

The measuring probe consists of the uniform FBG with polyamide protection with Bragg wavelength of 1554.1207 nm. The width of the reflecting spectrum is 2.3241 nm and reflectivity is 95.7 %. Monitoring of the basic parameters of FBG was performed during curing and after 24 hour relaxation time. Broad-spectrum LED (Light Emitting Diode) light source with a central wavelength of 1550 nm and an optical spectrum analyzer with a sampling frequency of 300 Hz were used for monitoring the parameters. The final probe is shown in Fig. 3.

Three different techniques for attaching the measuring probe were tested within the implementation of the probe on the human body. Based on the post-analysis, we defined the most efficient suitable method of attachment seems to be utilizing the contact strip placed around the chest of the patient. The position of the probe is in an area of the heart. The measurement is

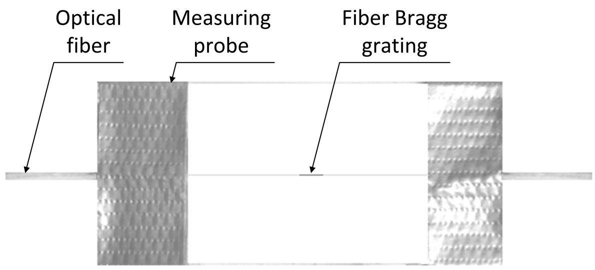


Fig. 3: The measuring probe for monitoring respiratory and heart rate.

based on sensing the widening of the ribcage of the patient during breathing. Movement (mechanical stress) is transferred to FBG using the contact strip. Respiratory and heart rate are analyzed by the spectral evaluation of the measured signals. Broad-spectrum LED with a central wavelength of 1550 nm ensures a source of light radiation. The methodology of the test was based on sensing a minute measurement of breath and heart rate with a sampling frequency of 300 Hz at five tested people. Three positions of patients were tested: static position in standing, static position in sitting, and static position on the back. Figure 4 shows measuring diagram for analyzing both heart and respiratory rate.

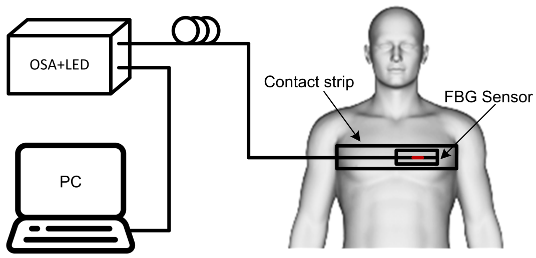
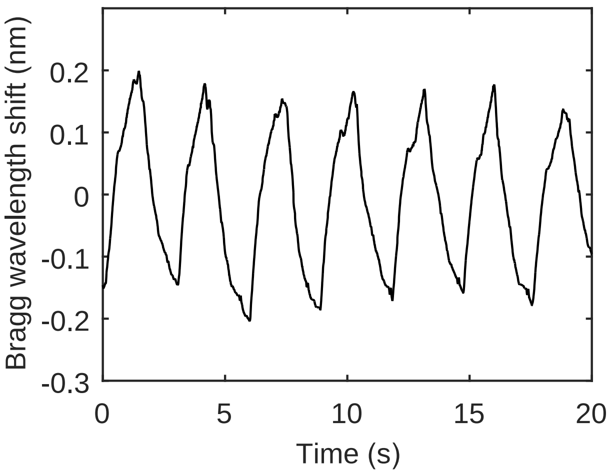


Fig. 4: Measuring diagram of respiratory and heart rate.

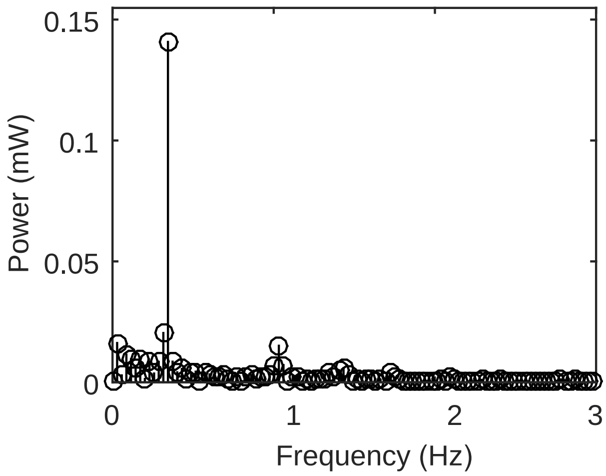
Figure 5 shows the measured changes of Bragg wavelength of the respiratory rate for the tested person in depending on the three selected positions. The respiratory rate was derived using the dominant frequency found via Fourier transform of the given waveform. A 20 second time is always shown for better clarity.

Based on the post-analysis, digital IIR (Infinite Impulse Response) filter utilized the measured waveforms of the respiratory rate. This IIR filter is bandpass of Butterworth type with a lower cut-off frequency of 1 Hz and upper cut-off frequency of 5 Hz. The magnitude response of the used digital IIR filter is shown in Fig. 7.

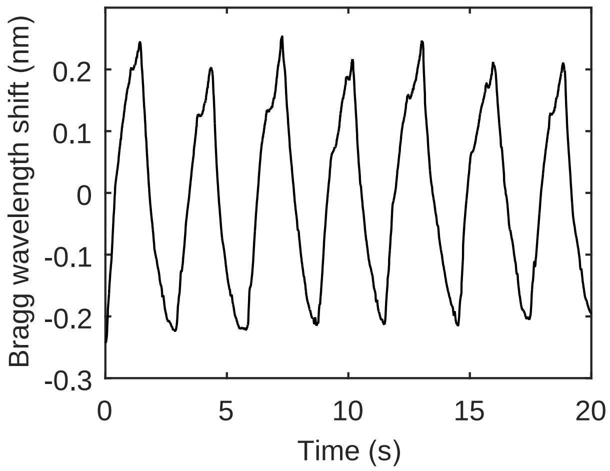
Figure 6 shows resulting superimposed courses of pulse activity over the courses of the breath for the tested persons in depending on the three defined positions. Heart rate was calculated based on the Fourier



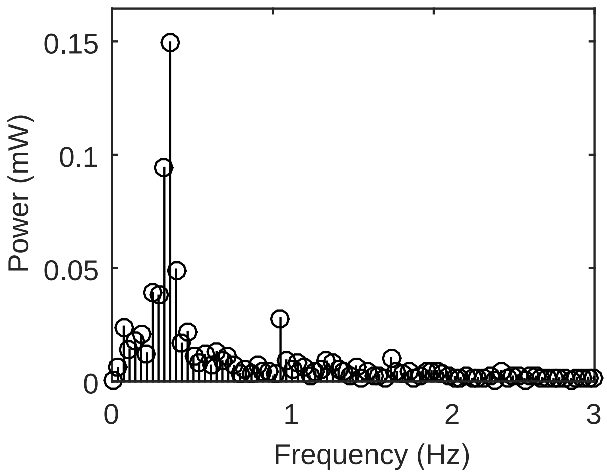
(a)



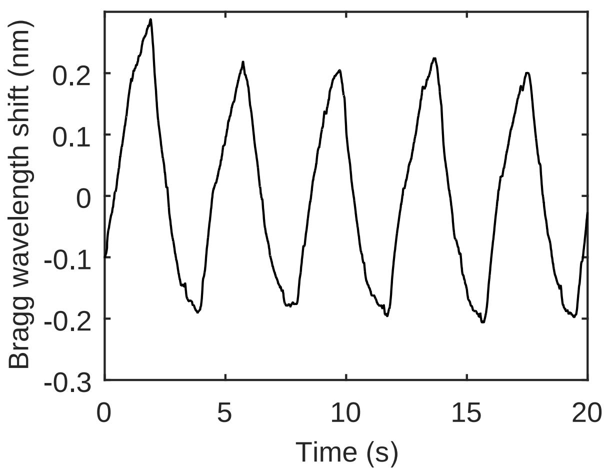
(b) FFT.



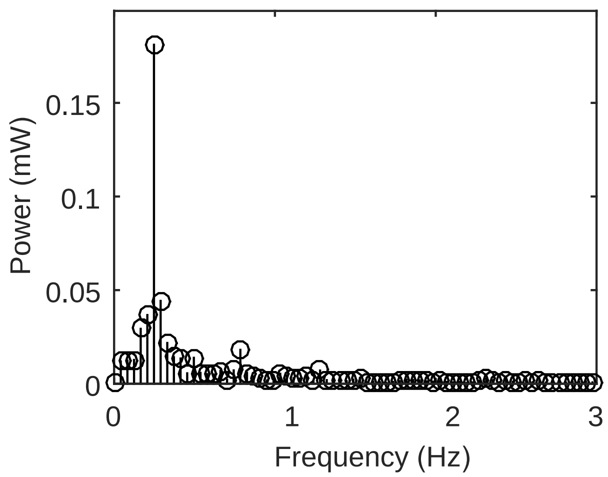
(c)



(d) FFT.

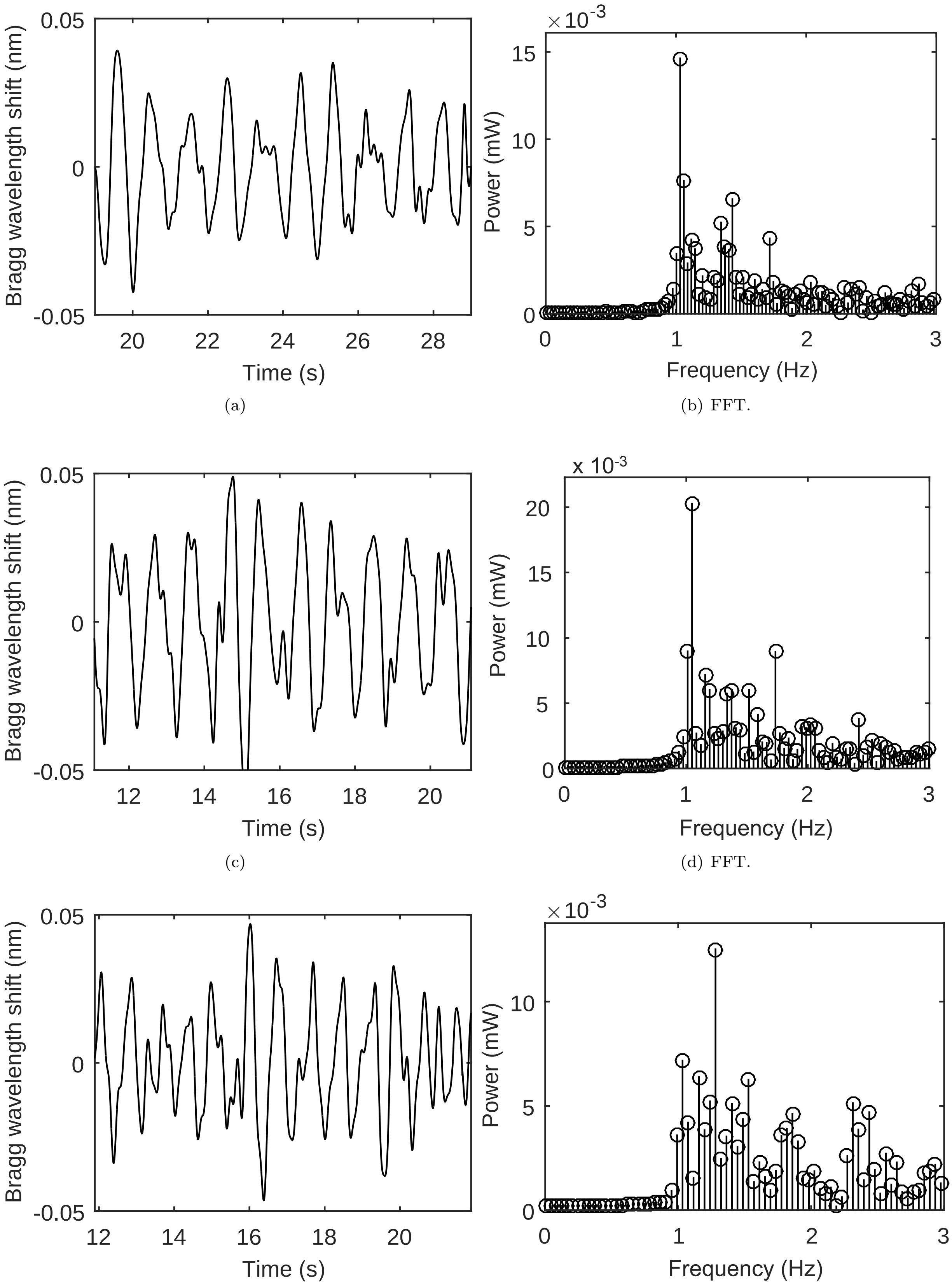


(e)



(f) FFT.

Fig. 5: Courses of respiratory rate and her frequency spectra: (a)–(b) static position in standing, (c)–(d) static position in sitting, (e)–(f) static position on the back.



(a) (b) FFT.

(c) (d) FFT.

(e) (f) FFT.

Fig. 6: Courses of heart rate and her frequency spectra: (a)–(b) static position in standing, (c)–(d) static position in sitting, (e)–(f) static position on the back.

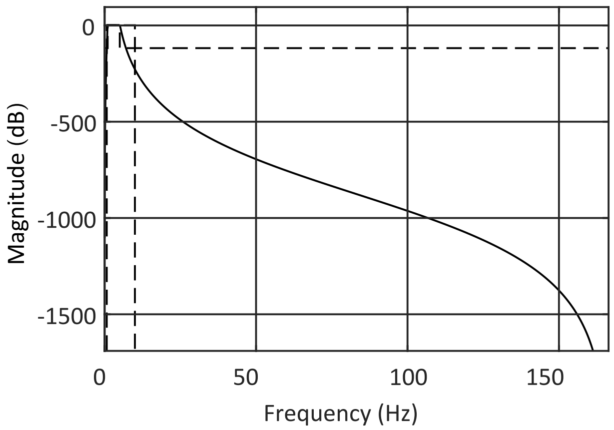


Fig. 7: The magnitude response of the used digital IIR filter.

transform, or more precisely, from the dominant frequency of the given waveforms. For clarity, only 10 seconds of the signal is plotted

Table 1 shows the dominant frequency and respiratory rate for the displayed courses in Fig. 5. Table 2 shows the dominant frequency and heart rate for the displayed courses in Fig. 6.

Tab. 1: Statistical data for courses of respiratory rate in Fig. 5.

Defined position	Dominant frequency (Hz)	Respiratory Rate (min^{-1})
Static position in standing	0.3611	21.6676
Static position in sitting	0.3439	20.6386
Static position on the back	0.2479	14.8741

Tab. 2: Statistical data for courses of heart rate in Fig. 6.

Defined position	Dominant frequency (Hz)	Heart Rate (min^{-1})
Static position in standing	1.0473	62.8363
Static position in sitting	1.0319	61.9159
Static position on the back	1.2808	76.8499

4. Conclusion

The authors described the design, implementation and verification (by experimental measurement) of the innovative prototype of the non-invasive measuring probe to monitoring respiratory and heart rate of the human body. PDMS has a unique combination of properties, and is suitable for use in biomedical applications. The main advantages include inert to human skin, immunity to electromagnetic interference, mechanical durability, and temperature stability. The main contribution of this paper are the design, implementation of non-invasive measuring probe encapsulated into PDMS, and implementation of the probe to the human using clamping contact strip. This combination creates a fundamental element of the measuring system. The repeated test of assembled prototype confirmed the functionality. Experimental results, which were carried out by the measuring probe in the laboratory, demonstrated the functionality of the proposed solution. Three general positions for measurements of mentioned vital parameters were analyzed. Based on the post-analysis, we can say that positions do not affect the functionality of the measuring probe. Respiratory and heart rate were derived based on the Fourier transform, or more precisely, from the dominant frequency component of the given waveform. The article does not include all aspects which can arise or affect monitoring of the mentioned fundamental life functions within the innovative measuring probe. It is the initial step to the new little-described medical field of non-invasive monitoring of the human body. The comprehensive characterization of our novel sensor and its comparison to other existing sensors, and the further signal processing will be the aim of our future articles.

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About Authors

Jan NEDOMA was born in 1988 in Prostejov. In 2012 he received a Bachelor's degree from VSB–Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of Telecommunications. Two years later, he received his Master's degree in the field of Telecommunications in the same workplace. He is currently employee and a Ph.D. student of Department of Telecommunications at VSB–Technical University of Ostrava. He works in the field of optical communications and fiber optic sensor systems.

Marcel FAJKUS was born in 1987 in Ostrava. In 2009 he received a Bachelor's degree from VSB–Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of

Telecommunications. Two years later, he received a Master's degree in the field of Telecommunications in the same workplace. He is currently employee and a Ph.D. student of Department of Telecommunications at VSB–Technical University of Ostrava. He works in the field of optical communications and fiber optic sensor systems.

Petr SISKA was born in 1979 in Kromeriz. In 2005 he finished M.Sc. study at VSB–Technical University of Ostrava, Faculty of Electrical Engineering and Computer Science, Department of Electronic and Telecommunications. Three years later, he finished Ph.D. study in Telecommunication technologies. Currently he is employee of Department of Telecommunications. He is interested in Optical communications, Fiber optic sensors and Distributed Temperature Sensing systems.

Radek MARTINEK was born in 1984 in Czech Republic. In 2009 he received Master's degree in Information and Communication Technology from VSB–TU of Ostrava. Since 2012 he worked here as a research fellow. In 2014 he successfully defended his dissertation thesis titled „The use of complex adaptive methods of signal processing for refining the diagnostic quality of the abdominal fetal electrocardiogram". He works as an assistant professor at VSB–TUO: Technical University of Ostrava since 2014. In 2016 he became the Layout Editor in journal Advances in Electrical and Electronic Engineering (ISSN 1336-1376).

Vladimir VASINEK was born in Ostrava. In 1980 he graduated in Physics, specialization in Optoelectronics, from the Science Faculty of Palacky University. He was awarded the title of RNDr. at the Science Faculty of Palacky University in the field of Applied Electronics. The scientific degree of Ph.D. was conferred upon him in the branch of Quantum Electronics and Optics in 1989. He became an associate professor in 1994 in the branch of Applied Physics. He has been a professor of Electronics and Communication Science since 2007. He pursues this branch at the Department of Telecommunications at VSB–Technical University of Ostrava. His research work is dedicated to optical communications, optical fibers, optoelectronics, optical measurements, optical networks projecting, fiber optic sensors, MW access networks. He is a member of many societies - OSA, SPIE, EOS, Czech Photonics Society; he is a chairman of the Ph.D. board at the VSB–Technical University of Ostrava. He is also a member of habitation boards and the boards appointing to professorship.