Application of a LED–photodiode optocouple for the study of human respiratory function

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Abstract. Application of a LED-photodiode optocouple for the study of human respiratory function is considered. The optocouple operating in the middle-infrared part of the spectrum (with the peak of the LED emission at 4.1 μm at 300 K) was applied for monitoring changes in CO₂ concentration during respiration of a human. Studies were carried out simultaneously with the measurements of pressure in the left and right halves of the nose cavity. The results of the study open possibilities for using infrared optocouples as sensitive elements in compact and cheap sensors detecting breath abnormalities associated with respiratory and other diseases.

1. Introduction

Early diagnostics of respiratory diseases and development of its methods are among the important trends in modern otorhynolaryngology. According to the data by The Ministry of Healthcare of Russian Federation (2013), nearly 39% of population in Russia suffer from respiratory diseases. Also, diagnosed are asthma (1%), allergic rhinitis (0.2%) and chronic obstructive pulmonary disease (0.6%) [1]. All these diseases are accompanied with nasal breath anomalies. At the present time, anterior active rhinomanometry is considered to be a clinically approved method of unbiased investigation of nasal breath (Fig. 1(a,b)) [2]. Measured datum in this method is the nasal airway resistance, which is the ratio of pressure difference to flux difference in the tube supplied to the organs of the respiratory system. Non-invasiveness of the measurements and the compactness of the equipment are the advantages of the method. However, this method distorts natural breathing because of using a tube, thus reducing the chances of accurate early diagnostics. Working with such diagnostic equipment demands a high professional level of staff. The equipment is quite expensive ($ 10 000 per piece at average) and only specialized clinics can afford it. Using that kind of equipment in Russian Federation for prevention remains rather difficult.

For early diagnosis of respiratory diseases, it is relevant to study natural breathing without additional tube. The results of the studies carried out earlier [3] showed a non-linear dynamic character of such diagnostic parameters of natural breathing as airflow velocity, temperature, and pressure. Therefore, the basic requirements for the sensor element are high sensitivity and fast response. The method described in [3] had a significant drawback: the quick response was achieved at the cost of the miniature size of the sensor (a thermistor). Such miniature elements are brittle and not suitable for wide use. Replacement of the sensors described in [3] by optical sensors should be more beneficial. For example, Russian company "LED Microsensor NT", Ltd., produces infrared (IR) light-emitting...
diodes (LEDs) and photodiodes with fast response (dozens of nanoseconds), miniature size of the LED chip (0.3×0.3 mm), small angular divergence of LEDs (±3°), low power consumption (about 1 mW in a pulsed mode), long service life (80 000-100 000 hours), and reasonably low cost. These LEDs and photodiodes can be easily integrated into optocouples (Fig. 1(c)) [4].

Figure 1. Anterior active rhinomanometry equipment (a) and diagnostic result (b), IR optocouple (c).

2. Materials and method
This work presents the results of the study of the possibility of using a LED–photodiode optocouple ("LED Microsensor NT", Ltd.) as a sensor device for contactless measurements of the dynamic fluctuations of CO₂ concentration in the human breath. Carbon dioxide plays a leading role in the humoral mechanism of the regulation of respiration. It is known that the concentration of CO₂ changes during respiration: the proportion of CO₂ at inhalation is 0.03% and that at exhalation is 4.00%. This parameter is important in the breath diagnostics and is very informative.

The basic absorption band of CO₂ corresponds to the spectral region between 4200 and 4320 nm. Weaker absorption bands are located at 2700 nm and 2000 nm. In our study, we have used LEDs with dominating wavelength at 3.4, 3.8 and 4.1 μm at the temperature 300 K. First, we have studied their spectral characteristics. For this purpose, pulse excitation with a pulse width of 1 μs and pulse repetition frequency of 1 kHz was applied. Electroluminescence (EL) spectra were recorded with the use of cooled InSb photodiode. During the measurements, the LEDs were placed in a liquid nitrogen cryostat with a sapphire window. A lock-in amplifier was used for signal detection.

One of the studied IR LEDs was used as a part of LED-photodiode optocouple for the measurements of CO₂ during the breathing of a patient. The photodetector used in the optocouple was based on the same semiconductor material system as the LED, namely narrow-gap semiconductor InAs(Sb,P) system. To test the sensitivity of the method, the measurements of CO₂ concentration oscillations during the breathing were performed synchronically with those of pressure changes. Sensing device made on the basis of pressure sensors and gain block are shown in Fig. 2(a) [5]. The
experimental scheme of synchronous measurements is presented in Fig. 2(b). Clip with pressure and temperature sensors tap was attached to the nasal septum. The board has been placed near to patient’s nose, at a distance of ~5 cm. The signal from the pressure sensors and the optocouple was analyzed with the LeCroy WaveSurfer 3000 oscilloscope.

3. Results
The results of the study of the spectral characteristics of IR LEDs with dominating wavelengths at 3.4, 3.8 and 4.1 µm are shown in Figs. 3 and 4. As can be seen, at 300 K (Fig. 3), which should be the working temperature of the sensing device, only emission of the LED with dominating wavelength at 4.1 µm (Fig. 3(c)) corresponded to the strong absorption band of a gas present in the air, namely, CO₂. While the other LEDs could have been used for detecting other gases in the human exhalation, for our purposes it seemed reasonable to use the LED emitting at 4.1 µm, as low power of IR LEDs (typically just tens of µW) makes it difficult to obtain a strong signal at 300 K. For comparison, spectra of the same LEDs recorded at 77 K are shown in Fig. 4. The emission intensity of the LEDs at this temperature was much higher than at 300 K (the driving currents used at 77 K were much smaller, which is the reason for noise seen in the spectra), the spectra were narrowed and red–shifted. Comparison of the results obtained at 300 K and 77 K suggested that the reason for low power of the studied IR LEDs at the room temperature was the dominating contribution of non–radiative (Auger) recombination. Another problem with this type of LEDs is related to carrier leakage over the barriers [6]. To increase the quantum efficiency of these LEDs, one needs to improve their design so the Auger recombination and carrier leakage would be suppressed.

Figure 3. Electroluminescence spectra of three LEDs at T=300 K.

Note, that while the LEDs emitting at 3.4 and 3.8 µm were based on p-n junction structures with the active layer made of InAs (3.4 µm) or InAsSb (3.8 µm), the studied LEDs emitting at 4.1 µm were based on a multiple quantum well InAs/InAsSb structure with size quantization for holes in the well. This type of IR LEDs structure is considered to be very promising in future applications [7].

Figure 4. Electroluminescence spectra of three LEDs at T=77 K.

The example of the application of the LED-photodiode optocouple for the study of human respiratory function is shown in Fig. 5. As mentioned above, the sensitivity of the optocouple in the dynamic measurements of CO₂ concentration was studied simultaneously with the measurements of pressure in the left and right halves of the nose cavity using the sensor developed earlier [5].
results of the present study showed the high sensitivity of the optocouple in respect to the changes of CO$_2$ concentration during respiration (Fig. 5). The graphs of power spectral density revealed a coincidence of the main frequency peaks registered with the two methods (Fig. 5). Thus, the results of our study open possibilities for using LED-photodiode optocouple as a sensitive element in the breath diagnostics sensor.

![Figure 5](image)

**Figure 5.** The results of the measurements of respiration fluctuations and the graphs of the power spectral density: (a) for measured pressure in the right nasal cavity; (b) for measured pressure in the left nasal cavity; (c) for optocouple.

4. Conclusion

Application of a LED-photodiode optocouple for the study of human respiratory function was considered. The optocouple based on InAs(Sb,P) heterostructures and operating in the middle-infrared part of the spectrum (with the peak of the LED emission at 4.1 µm at 300 K) was applied for monitoring changes in carbon dioxide concentration during respiration of a human. Studies were carried out simultaneously with the measurements of pressure in the left and right halves of the nose cavity according to the method developed earlier and based on a thermistor. The results of the study open possibilities for using infrared optocouples as sensitive elements in compact and cheap sensors detecting breath abnormalities associated with respiratory and other diseases. Parameters of the sensor
need to be improved, and in particular, quantum efficiency of the LED should be increased. For this purpose, Auger recombination processes and carrier leakage over the barriers should be suppressed.

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