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Fiber sensor for non-contact estimation of vital bio-signs

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ABSTRACT

Continuous noninvasive measurement of vital bio-signs, such as cardiopulmonary parameters, is an important tool in evaluation of the patient's physiological condition and health monitoring. On the demand of new enabling technologies, some works have been done in arterial pulse monitoring using optical fiber sensors. In this paper, we introduce a novel device based on single mode in-fibers Mach-Zehnder interferometer (MZI) to detect heartbeat, respiration and pulse wave velocity (PWV). The introduced interferometer is based on a new implanted scheme. It replaces the conventional MZI realized by inserting of discontinuities in the fiber to break the total internal reflection and scatter/collect light. The proposed fiber sensor was successfully incorporated into shirt to produce smart clothing. The measurements obtained from the smart clothing could be obtained in comfortable manner and there is no need to have an initial calibration or a direct contact between the sensor and the skin of the tested individual.

1. Introduction

Basic parameters relevant for human health monitoring, such as strain, displacement, crack width, vibrations or moisture can be measured by optical fiber (OFs) sensors [1]. OFs used for optical communications are highly flexible waveguides composed of nearly transparent dielectric materials [2]. Moreover, due to the large core diameters, OFs could be used together with cheap low precision connectors allowing reduction of the total cost associated with a complete system [3]. Being immune to electromagnetic interference, chemically inert, lightweight, small in size, easy to integrate and providing galvanic isolation often makes them the only option for certain sensing applications. Standard fibers and cables for data transmission can be used for many sensor applications and are available at a low price [1]. Dielectric nature and small diameter of the OFs also allow easy incorporation into miniaturized devices or embedment into medical textiles [4].

Monitoring of vital bio-signs using nonintrusive methods, such as application of OFs based medical textiles, is an important tool in healthcare monitoring. The continuous measurement of cardiopulmonary parameters, allows timely evaluate patient's physiological condition and to take appropriate steps using various applications such as telemedicine, critical care, diagnostic imaging, home, and rehabilitative care. Due to the mentioned above, a rapid emergence of multi-parameter physiologic monitors operating on a nonintrusive platform was developed in the recent years. The new monitors are more comfortable and easy for patient's and enable automatic measurement of vital bio-signs [4].

In order to measure cardiopulmonary parameters, OFs could be also used. At each heartbeat, blood is forced through the peripheral vessels, causing variation of the vessels diameter. The blood vessel movement causing corresponding tiny movements of the skin, especially near the arteries [5]. OFs can be used to sense both skin vibrations related to blood pulsation and pulse pressure. Until now, optical blood pressure measurement methods involve optics fibers and a light source/detector pair placed either in contact or in close proximity to the surface of the skin [6].

Based on the new enabling technologies, number of papers were published in relation to arterial pulse monitoring using OF sensors [7]. Zhihao Chen et al. [4,8] measured breath rate and heart rate using a micro bend multimode fiber optic sensor. The working principle behind this sensor is based on the theory of micro bending optical fibers. Contact with the body is needed for proper response from such sensors. A fiber optic that measure blood pressure invasively across a coronary artery stenosis was develops by Nan Wu et al. [9]. Pulse wave was measured with optic fiber, but the quality of the pulse wave signals was found highly dependent on sensor positioning and the fiber contact with the skin [6,10]. A. Grillet et al. [11] reported on OF sensors embedded into textile fabrics for the monitoring of respiratory movements. The authors evaluated different textiles fiber sensors. The

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sensing principle is based on measurement of the abdominal circumference elongation during breathing movements. L.G. Lindberg et al. [12] used Photo Plethysmo Graphy (PPG) methods in order to monitor respiratory and heart rates using fiber-optic sensor. The measurements were obtained here by illuminating the skin and tracking changes in light absorption. It requires direct skin illumination.

In this paper, we introduce a novel device based on single mode in-fibers MZI, to detect several biomedical parameters simultaneously without obvious skin contact. We are reporting on the detection of heartbeat, respiration and PWV. The introduced interferometer represents the new scheme effectively replacing the conventional MZI. The sensing principle is based upon insertion of discontinuities into the fiber causing light scattering and collection. The measurements are comfortable and initial calibration or direct illumination or contacts with the skin are not required. Also unlike in the case of the PPG measurement, our sensing principle is based upon interference and not upon spectral absorption and thus we are less sensitive to the exact wavelengths that are used in the sensing device. Wearing a shirt containing an integrated fiber sensor and collecting and processing the output signal is enough for the measurement. The PWV is calculated by simultaneous measurements of heart beat on both heart area and wrist. The measurements of PWV are obtained by integrating two fibers in two fixed locations along the shirt and obtaining shift in pulse wave peaks.

2. Theoretical background

Skin vibration produced by the heartbeat is either induced on the sensing fiber or affects the photons that are scattered form the fiber due to the discontinuities. Those changes will result in phase and polarization modulation of the photons of light traveling along the fiber as well as on the photons interacted with the vibrating tissue. This modulation can be detected by the MZI scheme [13,14] as the interaction with the reference photons converts the phase and polarization modulation into an amplitude modulation. Aharoni et al. [15] introduced a fiber based MZI, in order to detect sound pressure wave caused by speech. It was shown [15] that the phase of the light wave after traveling through a fiber having propagation constant β and length L, equals to:

$$\varphi = L\beta \tag{1}$$

When straining the fiber by ΔL in the axial direction the phase could be expressed by the following equation:

$$\Delta\varphi = \beta\Delta L + L\Delta\beta \tag{2}$$

It was shown [15] that the second term of the equation is negligible in respect to the theorem of interference. The experimentally tested MZI was based on separating a wave into two equal components via Y couplers. The two waves traveled along separate optical paths resulted in phase difference between the two arms. In order to obtain phase changes the MZI contained two arms- one arm is regarded as a reference arm and the second is the sensing arm. In this way, two waves traveled along separate optical paths resulting in a phase difference according to:

$$\Delta\varphi = 2\pi\frac{(L + \Delta L)(n + \Delta n)}{\lambda} - 2\pi\frac{Ln}{\lambda} \tag{3}$$

where λ is the light wavelength, n is the refraction index of the core of the fiber [15].

Same principles are used in this paper, but the interferometric realization is an in-fiber one. The main difference between the systems is related to the incorporation of three ports optic circulator working as MZI and also as an optical coupler. This can be seen in Fig. 1.

The optical circulator allows light to travel in only one direction and achieve bi-directional optical signal transmission over a single fiber. Signal entering port 1 will exit from port 2 with minimal loss, while signal entering port 2 will exit from port 3 with minimal loss. The first port of the circulator that is connected to the fiber which is free of deformation, will act as the first reference arm of the MZI, and the second port being connected to the fabric integrated fiber, and which is being subjected to the deformation caused due to the skin's movement, will act as the sensing arm of the MZI.

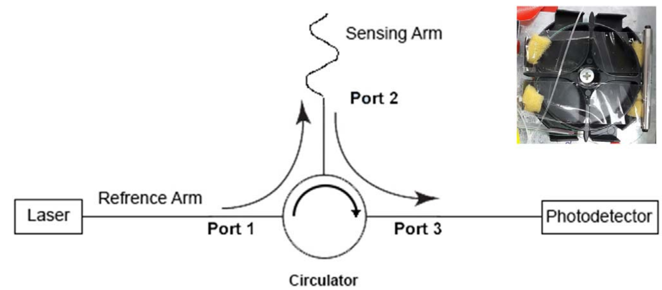

Fig. 1. Three ports circulator assembly with the image of the fabricated circulator in the right upper corner.

The third port will collect light from both ports: the cross talk light from port 1 and the back reflections of light from port 2 (affected by the discontinuities generated along the sensing arm of the fiber). Similarly to MZI and according Eq. (3), the output of the circulator (port 3) will contain phase difference between the two paths –the phase accumulated along the reference arm (port 1) and the phase accumulated along the sensing arm (port 2). The interference that occurs by using MZI, when two or more wave fronts are superimposed, and which provides resultant wave amplitude that depends on their relative phases [15], occurs also in the circulator system. Comparison of MZI and the three-port circulator elements is shown in Table 1.

Light passing directly from the first port to the third port passes in an attenuation level of 40–50 dB. As described, the light's entering port 2 is connected to the sensing arm ended up with the connector. Connectors with SPC (super PC) and UPC (ultra PC) polish quality result in back reflections of −40 to −55 dB and < −55 dB, respectively. These polished types of connectors are used in high-speed, digital fiber optic transmission systems. Therefore, the light reaching in the connector from both paths has the same power. To further clarify the operation principle of the circulator in particular [16] and the optical setup in general one may see the image of our setup presented in Fig. 2(a).

Previous works showed that aortic PWV is strongly associated with the presence and extent of atherosclerosis and constitutes a forceful marker and predictor of cardiovascular risk in hypertensive patients [17]. In this article PWV was calculated by the equation:

$$PWV = X/T \ [m/\sec] \tag{4}$$

While X is the path length of the pulse wave (length of the arterial pass between the two measurement fibers that are integrated in the shirt) and T is the time for the pulse wave to travel distance X. The heart rate was calculated according to the following equation:

$$HR = n/t \times 60 \ [BPM] \tag{5}$$

While n is the number of detected heart beat per period of time t.

3. Experiments

Image of our constructed optical setup is shown in Fig. 2(a). The schematic configuration of the experimental setup is shown in Fig. 2(b). The system contains laser connected to the fiber optic sensor built on the base of single mode fibers and 3 ports optical circulator functioning both as fiber coupler and as MZI. As mentioned above, the first and second ports are used as two arms - the first is for the reference arm and the second is used as the sensing arm. The circulator is connected to switchable gain detector, transmitting the signal to the computer.