Photonic sensor with radio frequency power detection for body pressure monitoring*

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(Received 20 June 2023; Revised 4 August 2023)

A photonic sensor with radio frequency (RF) power detection for body pressure monitoring is proposed. The sensor based on two fiber Bragg gratings (FBGs) can transfer the wavelength shift to the change of RF power. The pressure can be measured by modulating and processing one single frequency RF signal. The theoretical analysis and experimental results of the photonic sensor are presented and discussed. The pressure sensitivities are acquired with 2.62×10^{-5} mW/kPa at 2.14 GHz, 2.46×10^{-5} mW/kPa at 2.21 GHz, 2.81×10^{-5} mW/kPa at 2.37 GHz, and 3.02×10^{-5} mW/kPa at 2.45 GHz, respectively. Furthermore, the pressure measurements of pressed body parts are also obtained by the sensor.

Document code: A **Article ID:** 1673-1905(2023)12-0752-4
DOI https://doi.org/10.1007/s11801-023-3110-1

Pressure ulcer is a very serious problem for the long-term bedridden patient in clinical medicine[1-3]. In order to prevent pressure ulcer, the pressure levels of pressed body parts, such as occiput, sacrum and heel, need to be monitored in time. According to the measured pressure information, the evolution of pressure ulcer can be evaluated, and the effective treatment will be applied accurately[4-7]. Optical fiber pressure sensors are used for measuring body pressure. One popular method is based on fiber Bragg grating (FBG), which records the reflection wavelength shift to obtain force change[8-10]. In 2019, DOMINGUES et al[11] proposed an FBG-based sensing cell for foot pressure monitoring. A normal force applied to the top area of the sensing cell would compress the cell, inducing a positive Bragg wavelength shift. The sensitivity of 7.6 pm/kPa is achieved. Since the sensed physical information is encoded into wavelength, the spectrum resolution of the wavelength interrogator determines the FBG sensing performance. To monitor the wavelength shift, some expensive optical instruments, such as optical spectrum analyzer and tunable laser, are often used as the wavelength interrogator. Because of the limited speed and wavelength resolution for the wavelength interrogator, it is still a challenge for traditional FBG sensors with higher performance nowadays. Therefore, FBG sensors for body pressure monitoring are greatly restricted in precise treatment of pressure ulcer.

Recently, radio frequency (RF) photonic sensors are presented to realize better performance[12,13]. RF photonic sensors translate the optical signals from the optical domain to the RF signals in the RF domain, and process the RF signals to obtain the sensed information. The tiny optical wavelength shift in these methods can be obtained by measuring the frequency or intensity variation of the RF signal using a vector network analyzer (VNA) or spectrum analyzer. As most sensing methods, RF unbalanced Mach-Zehnder interferometer and RF photonic filter have been built[14,15]. The wavelength shift can be obtained by measuring the resonant frequency or the free spectrum range (*FSR*) of the RF signal. In 2022, SHE et al[15] demonstrated a distributed strain sensor with high resolution based on a two-tap RF photonic filter. By detecting the resonance frequency shift of the RF photonic filter, the strain value can be measured.

For most RF photonic sensors with frequency response detection, the scanning and processing of RF signals in wide frequency range are realized by VNA in laboratory. Because of high complexity and cost, it is a barrier for VNA to be applied in the practical sensing fields. In addition, RF photonic sensors have been achieved for monitoring temperature or strain. However, pressure

* This work has been supported by the Key R&D Project of Science and Technology Department of Sichuan Province (No.2023YFS0122), and the Health Research Project for Cadres of Sichuan Province (No.2022-204).
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measurement by RF photonic sensors is still not reported in biomedical domain.

In this paper, we propose a photonic sensor with RF power detection for body pressure monitoring. The sensor based on two FBGs can transfer the wavelength shift to the change of RF power by introducing a wavelength-dependent RF phase difference. The photonic sensor can be realized by modulating and processing one single frequency RF signal, which leads to a low-cost and efficient sensing solution in clinical medicine. Both theoretical analysis and experimental results of the photonic sensor are presented and discussed, and some pressures of pressed body parts are also measured by the RF photonic sensor.

The sensing system is shown in Fig.1. An amplified spontaneous emission (ASE) source with polarization maintaining (PM) fiber is modulated by an electro-optic modulator (EOM). The EOM is driven by an RF signal generator. The modulated optical signal is fed into two serial FBGs. The first FBG with the Bragg resonance of 1 547.49 nm and the reflectivity of 95% is used as the sensing head. The second FBG with the Bragg resonance of 1 539.22 nm and the reflectivity of 95% is used as the reference head. The two FBGs are separated at some distance.

Two reflective light beams from the two FBGs pass through a long optical fiber, and are detected by a wideband photodiode (PD). The RF signal from the PD is amplified by an amplifier, and then received by an RF spectrum analyzer.

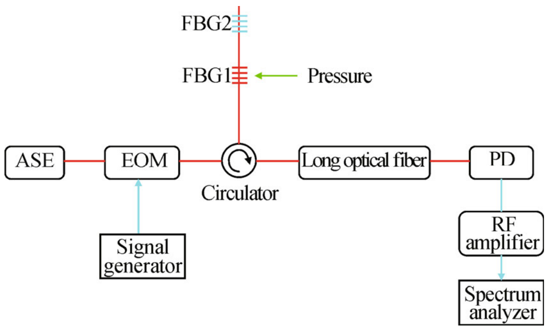

Fig.1 Experimental setup of the sensing system

For such a sensor configuration, the delay time between the sensing and reference signals can be written as

$$\tau=\tau_0+\Delta\tau, \tag{1}$$

where τ_0 is the initial delay time caused by the separation of the two FBGs, and $\Delta\tau$ is the dispersion delay time between the two optical carriers caused by the chromatic dispersion.

When the pressure is applied to the sensing FBG, the dispersion delay time can change with the increase of the wavelength difference between the FBGs. The dispersion delay time can be given by

$$\Delta\tau=DL\Delta\lambda, \tag{2}$$

where D is the chromatic dispersion, L is the length of the long optical fiber, and $\Delta\lambda$ is the wavelength difference.

The output RF signal of the sensing system can be expressed as

$$S(f)=A\cos(\pi f\tau)\cos\left(2\pi f\left(t-\frac{\tau}{2}\right)\right), \tag{3}$$

where f is the signal frequency, τ is the delay time between the sensing and the reference signals, and A is the amplitude coefficient. This equation shows that the transfer function follows cosinoidal rule for the sensing system in Fig.1.

The output RF power can be expressed as

$$P(f)=K\left(1+\cos(2\pi f\tau)\right), \tag{4}$$

where K is the scaling factor.

When a modulation RF signal with proper frequency is used for the sensor, the output RF power can change linearly with the delay time in a certain range. Thus, the pressure can be determined by simply detecting the output RF power.

The setup of the sensing system is shown in Fig.2. In the experiment, the central wavelength of the ASE source is 1 542.48 nm, and the spectrum bandwidth of 3 dB is more than 30 nm. The separation of the two FBGs is about 0.5 m for the clinical measurement. The single mode fiber is used as long optical fiber, and the length is about 10 km.

To improve the pressure sensitivity, the two FBGs are packaged into cubic structures with organic polymer, respectively. The picture of the packaged FBG is shown in Fig.3. The structure has the length of 30 mm, the width of 10 mm and the height of 10 mm. The vertical force is uniformly acted on the top area of the sensing structure. The pressure is equal to the certain force divided by the top area.

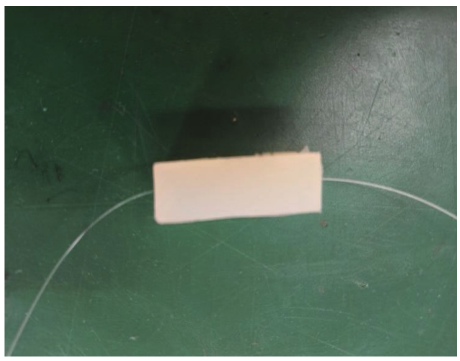

Fig.2 Picture of the packaged FBG

Fig.3 shows the RF transfer response from the initial state (free from the pressure) and the state with about 42 kPa pressure to the sensing FBG. The measurement is realized by a VNA with the sweeping frequency range from 2 GHz to 2.5 GHz. The interference pattern and the RF power with one frequency are observed to shift considerably when the pressure of the sensing system is changed, which agrees well with the previous analysis.

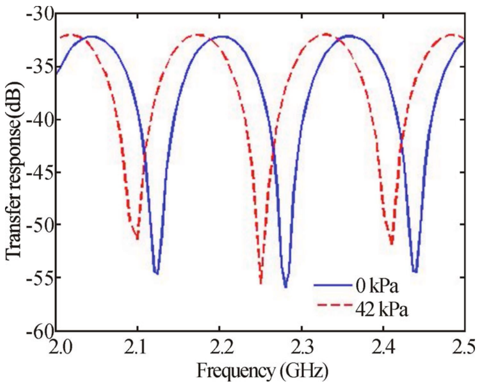

Fig.3 RF transfer responses with different states

The characteristics of the output RF power and pressure are then measured. The RF signal from an RF signal generator is injected to the EOM, and the RF power from the amplifier is detected by a spectrum analyzer. The resolution bandwidth of the spectrum analyzer is set at 100 Hz for measuring the RF power precisely.

According to the results obtained by the VNA, appropriate signal frequencies are selected for pressure sensing test. At each frequency, the pressure is increased from 0 to 42 kPa. The relationship between the output RF power and pressure is shown in Fig.4. When the pressure is changed from 0 to 42 kPa, the output RF power increases or decreases monotonously. The curves show linear variation within certain range. For the frequencies of 2.14 GHz and 2.45 GHz, the RF powers vary positively with the pressures, and the sensitivities are about 2.62×10^{-5} mW/kPa and 3.02×10^{-5} mW/kPa, respectively. For the frequencies of 2.21 GHz and 2.37 GHz, the RF powers vary negatively with the pressures, and the sensitivities are about 2.46×10^{-5} mW/kPa and 2.81×10^{-5} mW/kPa, respectively. When the signal frequency increases, the measurement sensitivity is improved significantly for the same change rule. In the experiment, the power unit of dBm from the spectrum analyzer is transformed to the power unit of mW. The experimental results can satisfy the rule described by Eq.(4). In order to enhance the pressure accuracy, more pressure measurements can be averaged with more different frequencies.

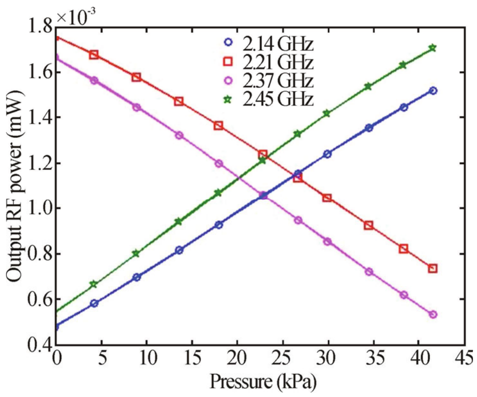

Fig.4 Relationship between output RF power and pressure

The stability of the output RF power is also observed. The output RF power is recorded every 1 min with the pressure of 18 kPa. The result is shown in Fig.5. The RF power change is less than ±0.04 dB, which proves good stability of the sensing system.

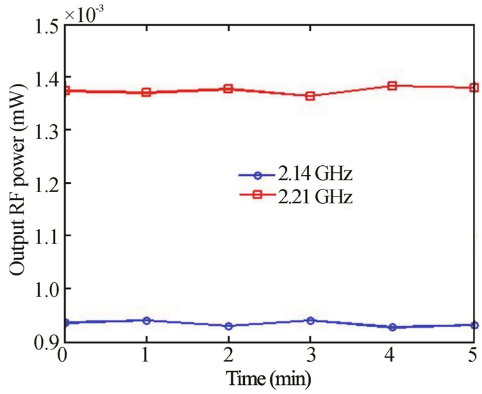

Fig.5 Output RF power stability

The two FBGs are placed and fixed on a bed. Five persons lie on the sensing FBG for test, respectively. The sensing system can monitor the pressures of the key pressed body parts including occiput, sacrum and heel. Fig.6 shows the pressure measurements of different body parts. The pressures of the key body parts for each person distribute differently. The pressure range is from 16 kPa to 33 kPa. According to the measured pressure data, the changing process of pressure ulcer can be analyzed and predicted with a risk prediction model[16,17]. Thus, pressure ulcer for each person can be prevented and treated in time.

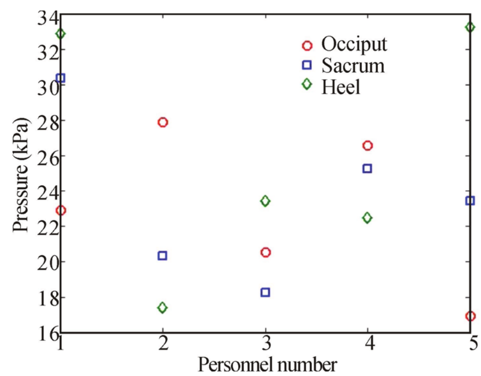

Fig.6 Pressure measurement results for body parts

In summary, a photonic sensor with RF power detection for body pressure monitoring has been demonstrated. The sensing system is realized by modulating and processing the single frequency RF signal without scanning and analyzing spectrum in wide frequency range. In the experiment, the pressure sensitivities reach 2.62×10^{-5} mW/kPa at 2.14 GHz, 2.46×10^{-5} mW/kPa at 2.21 GHz, 2.81×10^{-5} mW/kPa at 2.37 GHz, and 3.02×10^{-5} mW/kPa at 2.45 GHz, respectively. The output

RF power change is less than ±0.04 dB in 5 min. The sensing system is applied to monitor body pressure, and some measured data are obtained in practice. The proposed sensor possesses remarkable advantages of low cost, high flexibility and potentially high sensitivity. It is expected that the photonic sensor has important applications in biomedical domain.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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