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A fiber-optic Doppler blood flow-velocity sensor

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Abstract

A mock-up of a fiber-optic Doppler blood flow-velocity sensor has been made and described. The principle of its operation is based on the recording of the Doppler shift of scattered radiation of a monofrequent single-mode semiconductor laser. The radiation was inserted into a blood vessel model using a fiber-optic probe. The performance data of the mock-up in the blood vessel model was measured. The designed apparatus was shown to make possible the reliable measurement of the blood flow velocity in the blood vessels through inserting the fiber optic probes. The measurement accuracy depends on the accuracy of the used recording equipment. The performance data of the designed apparatus, that obtained using the blood vessel model, meets all modern requirements.

Keywords: Sensor; Optical fiber; Interferometry; Blood flow-velocity sensor; Semiconductor laser.

Volumetric blood flow has been studied for over half a century; blood flow measurements were employed in surgical practice since the 1920s. A method for recording volumetric blood flow was first proposed in Rein's study [1]. Radionuclide diagnostics was later developed, and non-contact electromagnetic and ultrasonic flow meters were devised. These methods are still currently in use.

Laser radiation that can be delivered into a blood vessel via a fiber optic light guide extends the possibilities offered by the traditional methods. Measuring the intensity fluctuation spectra under quasi-elastic scattering of laser radiation by moving cells allows to determine their speed and other parameters using the Doppler effect [2,9].

Technological advances in laser physics, electronics and computing opens up new opportunities for creating devices with improved characteristics, i.e., increased measurement accuracy, low power consumption, smaller sizes and longer service life.

This paper describes a mock-up of a fiber optic Doppler blood flow velocity sensor that we have constructed. The sensor records the Doppler frequency shift of scattered radiation from a monofrequent single-mode semiconductor laser, emitted into a blood vessel via a fiber optic probe. We have

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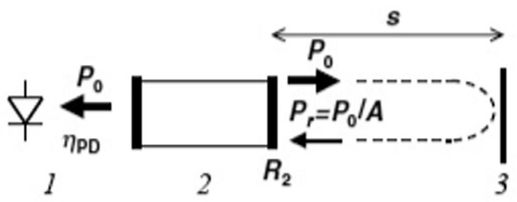

Fig. 1. Schematic for self-mixing laser interferometry [7]: *1* is the monitor photodiode, *2* is the laser diode, *3* is the scattering object; P_0 and P_r are the emitted and the back-scattered laser power; η_{PD} is the quantum yield of the photodiode; R_2 is the power reflectivity of the laser's output facet.

measured the characteristics of the sensor in a model of a blood vessel.

The operational principles of the device are based on laser interferometry which is widely used in industrial and laboratory conditions for measuring displacement, velocity of solid or liquid objects, vibration and distance. Intracavity self-mixing laser interferometry adopted in this study, where the radiation of a semiconductor diode laser scattered by the object is returned into the cavity, was first introduced in 1986 [3, 4]. The advantages of this approach include compact design, signal recording by a photodiode built in the laser module, high sensitivity (the device can be brought to operate as a single-photon counter during module cooling), remote measurement, in particular, for diffusely scattering objects.

Optical feedback in laser diodes was previously extensively studied both theoretically and experimentally. Acket et al. [5] proposed a classification of different feedback modes, considered the changes in the emission spectra and examined the noise characteristics. Wang et al. [6] performed a theoretical analysis of self-mixing detection modes.

Scattered laser radiation with a frequency ω, shifted by $\Delta\omega$ due to the Doppler effect, is directed back into the optical fiber; the radiation is amplified as it passes through the laser medium, interferes with the initial radiation with the frequency ω, and the amplitude-modulated signal with the frequency $\Delta\omega$ is recorded by the built-in photodetector (Fig. 1).

In the general case, this back-scattered radiation alters the lasing threshold, which in turns modulates the amplitude and the phase of laser radiation. Additionally, since the change in the lasing threshold is associated with charge carrier density, the lasing spectrum changes as well. The time scale for this change lies in the sub-nanosecond range.

The analytical stationary equation describing this modulation has the following form:

$$P(\phi) = P_0(1 + mF(\phi)), \tag{1}$$

where P_0 is the initial lasing power, m is the modulation parameter, $F(\phi)$ is the periodic function of phase ϕ.

The modulation parameter and the form of the $F(\phi)$ function depend on the so-called feedback parameter C [6]:

$$C = ks\frac{\sqrt{1+\alpha^2}}{L_{las}n_{las}}, \tag{2}$$

where α is the linewidth enhancement factor; L_{las} is the cavity length; n_{las} is the refractive index of the lasing medium; k is the coefficient equal to

$$k = \frac{\varepsilon}{\sqrt{A}}\frac{1-R_2}{\sqrt{R_2}}$$

Here $\varepsilon \le 1$ is the difference between the emitted and the back-scattered mode; A is the total attenuation of lasing power outside the cavity; R_2 is the power reflectivity of the laser's output facet (see Fig. 1).

Thus, the value of the parameter C depends both on the amount of feedback, and the distance s to the scattering object. This parameter determines the feedback mode. In this case, $C << 1$, the feedback mode is very weak, the function has a cosine form, and the index $m << \sqrt{A}$.

The analytical expression for the beat signal recorded by the photodetector has, for the case $C << 1$, the following form [7]:

$$S_I = \eta_{PD}\frac{q}{h\nu}P_0\frac{2\varepsilon\tau_p(1-R_2)}{\tau_{las}\sqrt{A}\sqrt{R_2}}\cdot\frac{I/I_{th}-N_0/N_{th}}{I/I_{th}-1}, \tag{3}$$

where $\eta_{PD} = \eta_q\eta_c$ (the product of the quantum efficiency η_q of the built-in photodiode multiplied by the coupling efficiency η_c); τ_p is the photon lifetime in the cavity; τ_{las} is the cavity round-trip time; I and I_{th} are, respectively, the pumping current and the threshold current; N_0/N_{th} is the ratio of the transparency carrier density to the density threshold (usually equal to 0.8).

The signal amplitude S_I is measured as the peak-to-peak ratio with the back-scattered radiation phase varying by 2π.

The curves calculated in Ref. [5] for beat signal versus power attenuation exhibited a wide range of linear response, limited from below by the signal-to-noise ratio. For our system, the photocurrent noise whose main component is shot noise is described by