FIBRE OPTIC SENSOR OF ELECTROSTATIC FIELD WITH MECHANICAL RESONATOR.

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ABSTRACT

New type of fibre optic sensor of electrostatic field is considered. Using the interferometric detection technique the sensitivity of about 0.2 $(V/m)/\sqrt{Hz}$ was achieved. Theoretical evaluation yields the thermal fluctuation limit of sensitivity of about $2.5\cdot 10^{-4}$ $(V/m)/\sqrt{Hz}$.

1. INTRODUCTION

The interferometric optical systems have found a wide application in research and industry as providing the displacement sensitivity of parts of angstrom. With the creation of fibre optic interferometers, the new opportunities for the development of resonator-based devices have appeared. The fibre optic Fabry-Perot interferometer has a number of advantages as compared with interferometers of other types (Mihelson and Mach-Zahnder), such as simplicity and insensitivity to phase fluctuations of light in fibre and couplers [1-3]. At present, the development of fibre optic sensors of electric field follows generally the way of optical signal modulation by means of piezoelectric action on the fibre [4-6]. In spite of simplicity of the scheme, the sensitivity of these sensors is rather low and equals about 10 V/m.

In this paper a new fibre optic sensor of electrostatic field is considered. Using the interferometric detection technique the sensitivity of about 0.2 $(V/m)/\sqrt{Hz}$ was achieved. In many cases the physical limitation for the sensitivity of interferometer-based sensors originates from thermally generated vibrations [7,8]. It is shown in this paper that the thermal fluctuation limit of sensitivity is about $2.5 \cdot 10^{-4}$ $(V/m)/\sqrt{Hz}$.

2. PRINCIPLE OF OPERATION

The scheme of the sensor is shown in Fig.1. The resonator in the form of a cantilever beam made of metallic glass is placed between the isolated capacitor plates. The alternating voltage $U_\omega \cos \omega$ t is applied to the capacitor, so that the alternating electric field emerges between the edges of the capacitor plates. When the measured electric field E_0 is applied to the resonator, the electric charges are induced on it. The alternating field of the capacitor acts on these charges giving rise to excitation of resonator flexural vibration. The amplitude of oscillation is proportional the induced charge and, hence, to E_0. The partially reflecting surface of the cantilever and the output end of the fibre form the low contrast Fabry-Perot cavity. Oscillation of the resonator modulates the path length of the interfering rays, so that an intensity-modulated light is propagating back along the fibre and the directional coupler to the photodetector, when the cavity is illuminated with CW radiation of laser diode. As a result, the amplitude of phase modulation of output signal is proportional to E_0. To increase the signal-to-noise ratio the oscillation was excited at the resonator natural frequency ω and detected with the aid of lock-in amplifier.

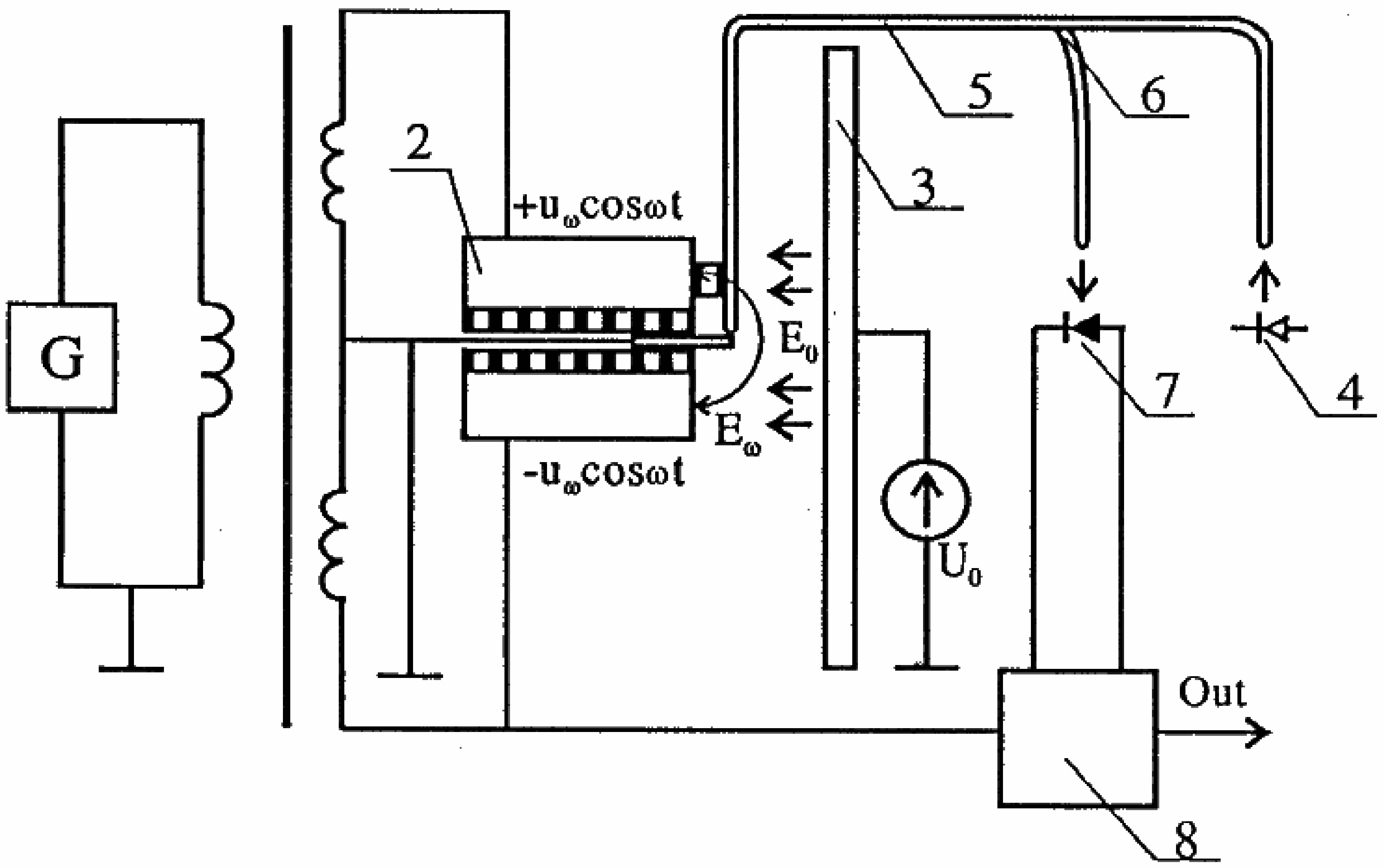

Fig.1 The scheme of fiber optic electric field sensor.
1-resonator, 2-cubic capacitor, 3-test plate, 4-CW laser diode, 5-optical fiber, 6-directional coupler, 7-photodiode, 8-lock-in amplifier.

3. EXPERIMENTAL RESULTS

The sensitive element used in the experiment consists of the cubic capacitor with length a=2 cm and the isolated cantilever beam which is placed between the capacitor plates. The resonator of length l=5 mm, width b=2 mm and thickness h=35 μ m was made of metallic glass. Met-glass was chosen as a material of the resonator because of its excellent mechanical properties and high reflectivity. Partially reflecting surface of the resonator and the end of single-mode fibre form the cavity of Fabry-Perot resonator, which is illuminated by CW semiconductor laser source of wavelength $\lambda = 0.85\,\mu$ m. We adjusted the fibre to equalize the amplitudes of the waves reflected from the fibre tip and from the resonator surface. The perpendicularity of the fibre and the cantilever beam was controlled by of microscope over the mirror image of the fibre on the plate of resonator. When the alternating voltage of amplitude U_ω =170 V was applied to the capacitor, the oscillation at the resonator natural frequency f=672 Hz was excited. The oscillator quality factor was measured to be Q=167. The coefficient of conversion S of the electric field E_0 into the amplitude of phase modulation was measured by applying the constant voltage U_0=17 V on a test plate, which generated an uniform electric field near the sensitive element. The plate was placed at the distance 8 cm from the capacitor. The intensity of modulated light $I(t)$ was proportional to $\sin\varphi(t)$, where $\varphi(t) = \varphi_0 + \Delta\varphi \sin \varphi t$. The value $\Delta\varphi$ was proportional to the applied voltage U_0, and the measured conversion coefficient was $S = \Delta\varphi / E_0 = 7.4 \cdot 10^{-4}$ rad/(m/V). The value φ_0 was adjusted by applying the magnetic field perpendicular to the resonator plate to maintain $\varphi_0 = 2\pi k$ (where k is an integer constant).

Small permanent signal was also observed after removing the constant voltage U_0 from the test plate. The reason was probably in an electric charge accumulated at the tip surface of the fibre used in interferometer.

4. THEORETICAL MODELLING

A stationary uniform electric field with the intensity E_0 induces the charge distribution on the metal surface of cubic capacitor. Therefore, the cantilever beam will be acted upon by resultant electric field, the intensity of which exceeds E_0. To calculate the stationary charge distribution on the sensitive element we replace the cube with the edge $2a$ by an imaginary cylinder of length $2a$ and radius a. Since the characteristic resonator size is much smaller than that of capacitor, we may suggest that such a replacement has a small effect on the electric field near the resonator. In such a formulation the problem allows analytical solution by solving two-dimensional Laplas equation, which is invariant with respect to conform mappings [13]. We find finally the following expression for the linear density of charge distribution:

$$\sigma(x) = 12\,\varepsilon_0\,E_0\left\{\sin\left[\pi\left(1-\frac{x}{l}\right)\right]+\frac{2x}{a}\left[1+\exp\left(\frac{a}{l}\left(\frac{2x}{l}-1\right)\right)\right]\right\} \qquad (1)$$

where ε_0 is the dielectric constant.

When an alternating voltage is applied to the capacitor, the electric field E_ω is induced near the capacitor ends. The field has the form of concentric circles with centers on the line joining two capacitor plates [9]:

$$E_\omega = \frac{u_\omega}{\pi r}\cos\omega t \qquad (2)$$

where r is the radius of circle. Under the action of E_ω the charged resonator is acted upon by harmonic force $F(x,t) = F_\omega(x)\cos\omega t = \sigma(x)E_\omega$, which excites mechanical transverse oscillations.

The Fourier projection Φ of the exciting force F_ω on the fundamental flexural mode of oscillation $\psi(x)$ is given by the following expression [10]:

$$\Phi = \frac{\int_0^l F_\omega(x)\,\psi(x)\,dx}{\int_0^l \psi^2(x)\,dx} \qquad (3)$$

Thus, the resonance displacement of the cantilever is described by the expression [11]:

$$Y(x,t) = \frac{Q\,\Phi}{\mu\,\omega^2}\,\psi(x)\cos\omega t \qquad (4)$$

where $\mu = m/l$, and m is the mass of the resonator. From the equations (1)-(4) we can find the expression for the amplitude of resonator tip vibrations $Y(l)$.

The oscillation of the resonator modulates the phase of interferometer output signal. The coefficient of conversion of applied electrostatic field into the interferometer phase modulation is

$$S = (4\pi/\lambda)\,(Y(l)/E_0) \qquad (5)$$

Substituting the parameters of the sensor in (4) and (5) we have found the theoretical prediction for conversion coefficient $S_t = 9.5\cdot 10^{-4}$ rad/(V/m), which appeared to be in a good correspondence with the coefficient $S_e = 7.4\cdot 10^{-4}$ rad/(V/m) observed experimentally.

Finally, the minimum detectable electric field limited by thermal vibrations of the resonator was evaluated from fluctuation-dissipation theorem [12]. Taking the signal-to-noise ratio equal to 1, we find the minimum detectable intensity of field $E_{min} = 2.5\cdot 10^{-4}$ (V/m)/$\sqrt{\text{Hz}}$.

5. REFERENCES.

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