Optical WGM Resonator Sensor of Earth Gravity Acceleration Inhomogeneities

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***Abstract*—We present a construction of the optical whispering gallery mode (WGM) resonator gravimeter. The sensitive element of the device is a resonator, placed on a cantilever, which moves with the change of gravity, variating the distance with coupling element. The gravity acceleration is measured by the change of the resonator eigenmode parameters.**

***Keywords*—optical gravimeter, gravity measurements, WGM resonator**

I. INTRODUCTION

The WGM resonators represent miniature disks, spheres, or rings of a diameter from microns to millimeters, made from optical materials, such as silica, MgF_2, CaF_2 etc. [1,2]. The laser light is coupled into a resonator using a coupling element, such as prism or tapered fiber (Fig. 1 a)) [1,2]. These compact optical devices are used as temperature, vibrating or bio-sensors [3]. The gravity measurements using WGM resonators are possible due to high sensitivity of the resonator to the change in the distance d between the resonator and coupling element.

The important parameter of the resonator is the total quality factor Q_{tot}, which characterizes the ability of the resonator to store photons. The total quality factor consist of two main parts: the internal quality factor Q_{in}, characterizing the photon losses inside and on the boarder of the resonator; and external quality factor Q_{ext}, characterizing the losses on a coupling. The total quality factor is: $1/Q_{tot}=1/Q_{in}+1/Q_{ext}$. Since the resonator were made and coupled, the only external quality factor can be changed by change of a distance d (not including the special constructions on the boarder of the resonator, which are not discussed in this article):

$$Q_{ext}(d)=102\left(\frac{R}{\lambda}\right)^{5/2}\frac{n^3\left(n^2-1\right)}{4q-1}e^{d(4\pi/\lambda)\sqrt{n^2-1}}. \quad (1)$$

Here q is a radial mode number and λ is a pump wavelength.

The resonator eigenmode has three main parameters [4]: the central frequency ω_ℓ (ℓ is the mode label), the amplitude T, and the width $\Delta\omega_\ell$. The central frequency mainly depends on a resonator radius R: $\omega_\ell = c\ell/Rn$, there n is a refractive index. The mode width depends on a resonator quality factor: $\Delta\omega_\ell = \omega_\ell/Q_{tot}$. The eigenmode amplitude also depends on a quality factor:

$$T=\frac{4Q_{in}Q_{ext}\left(\Delta d\right)\Gamma^2}{\left(Q_{in}+Q_{ext}\left(\Delta d\right)\right)^2}. \quad (2)$$

Here Γ is the mode matching between the resonator and coupling element, for the ideal mode matching Γ=1.

As we can see, the eigenmode parameters depend on the resonator parameters, so by registration of the eigenmode parameters on the output of the resonator we can calculate, which resonator parameter has been changed. If the resonator is made from elastic material and its R is changing with the influence of gravity, we can calculate the gravity acceleration controlling the shift of the eigenmode central frequency [5]. And if the distance d changes with the influence of gravity, we calculate the gravity acceleration using the measurements of the width and/or the amplitude of the eigenmode (Fig. 1 b), c)). This phenomenon is used in the current work for the gravity measurements.

For the gravity measurement the WGM resonator is placed on the end of the elastic cantilever, which is displaced with the influence of the gravity acceleration. The coupling element is placed on the fixed platform. If the gravity changes, the cantilever moves the resonator closer or further from the coupling element. The gravity acceleration is calculated using the eigenmode parameters on the output of the resonator.

Such gravimeters with the WGM resonators presented earlier [6-8] show the possibility to detect the change in acceleration up to $0{,}7\times10^{-6}$ g. But these systems have limits of

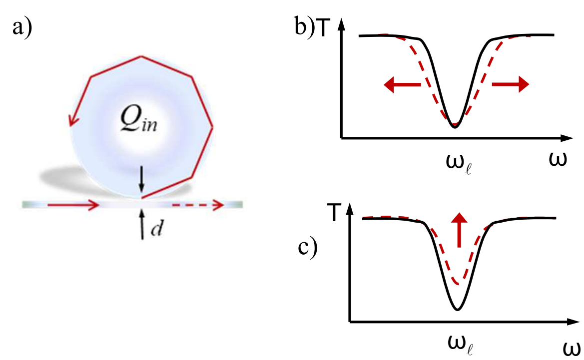

Fig. 1 a) WGM resonator and a coupling element, d – coupling distance. b) Change of eigenmode width. c) Change of eigenmode amplitude.

the cantilever displacement. It is limited from one side by the coupling element, which can be destroyed by the touch of the resonator, and from another side by the maximum gap, when the coupling of light inside the resonator will be lost. It limits a range of measurements and possibilities for displacements of the device. To predict these situations, we add to the construction the controller and the cantilever mover (see Fig. 2). This solution allows to protect the construction from the damages during vibrations, and to expand the range of the gravity measurements.

Here we show a construction of an optical gravimeter, which allows to expand the range of gravity measurements and to protect the device from damages during displacements or measurements. We also study the cantilever materials, making comparison between soft and hard materials.

II. METHODS/RESULTS

The construction of the optical gravimeter is shown at Fig. 2. The laser light is coupled into the WGM resonator using a coupling element (tapered fiber, prism or other). The advantage of the construction is that the type of the resonator or coupling element can vary, the only limit is the weight of the resonator (to be study in the future works). The signal from the output of the resonator goes to the measurement block, including, for example, OSA, there the eigenmode amplitude and/or width are measured. The results of measurements proceed at the main computer and at the controller of the cantilever mover. If the resonator reaches the limits of displacement, the controller gives a command to the cantilever mover to move the cantilever closer or further from the coupling element. The signal from controller goes to the main computer. The main computer calculates the change of gravity, taking in the account the results of eigenmode parameters measurements and the controller commands.

In fact, the part of the gravimeter, which reacts at the gravity change, is a cantilever. That is why we are concentrated to its study. The cantilever should be enough elastic to bend with the impact of gravity, and elasticity gives the sensibility for the device. But from the other point, the cantilever should be enough solid to hold the resonator.

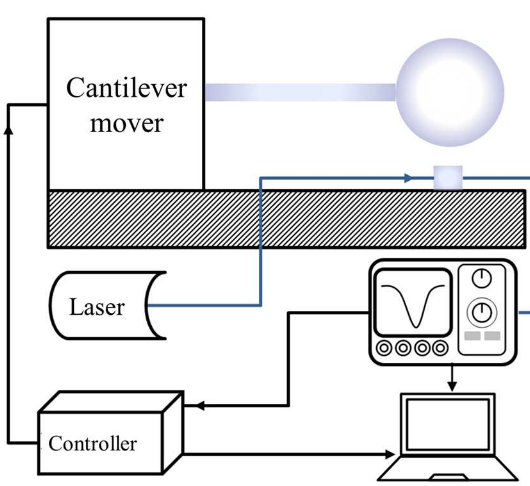

Fig. 2 The construction of the optical gravimeter with the WGM resonator

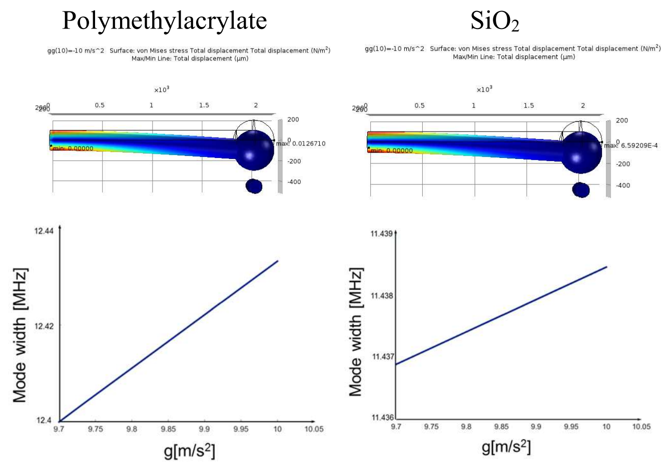

Fig. 3 The cantilever from polymethylacrylate (left column) and SiO_2 (right column).

We provide computer simulations of the cantilever and resonator. We change cantilever material from elastic organic glasses, as polymethylacrylate (PMA) to hard ones. The results for two materials are shown at Fig. 3. The resonator had the same parameters for both measurements: it is a sphere of a radius 200 μm, made from SiO_2. The cantilever is a cylinder of a radius 100 μm and length 2 mm. The g changed from 9.7 to 10. We calculate the change of eigenmode width with the change of *g*

We can see from our results (Fig. 3), that for the PMA cantilever we need to measure the change in eigenmode width of tens GHz, then for SiO_2 cantilever – one GHz. Means, the cantilever material can increase the sensitivity of the gravimeter in 10 times.

III. CONCLUSIONS

We presented the construction of the optical gravimeter with the WGM resonator as a sensitive element with expanded range of measurements, and protection from damages during exploitation and displacements. We studied different materials for the cantilever and showed the possibility to manage the device sensitivity using the cantilever material. We continue to study other parameters of the gravimeter parts such as resonator materials and radius, which gives different weight. The goal of our work is to create a compact, sensitive, and fast gravimeter, resistant to the real conditions of an exploitation.

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