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I. SUMMARY

A. The effect of heating on dissipation of mechanical energy and changes of mode frequencies in fused silica fibers

V.P. Mitrofanov and K.V. Tokmakov have carried out measurements of the temperature dependence of Q-factors of the bending modes of unloaded fused silica fibers drawn from Heraeus Co. Suprasil 300 brand fused silica. These fibers demonstrated the irreversible and hysteretic dependence of the Q's on the temperature in the process of heating and subsequently cooling at the range $20 - 330°$C analogously to fibers fabricated from Russian brand KS4V fused silica studied previously. It was shown in this way that such a behavior is the general feature of fused silica fibers. The best $Q \simeq 1.2 \times 10^7$ for fibers with diameter of about 250μm were reached at temperature of about 60°C after baking. Room temperature Q's did not vary after baking. It was assumed that the changes of Q's are caused by adsorption and desorption of water molecules from the surface of the fiber. The loss mechanism is supposed to be associated with the relaxation process related to a change of the orientation of the adsorbed water molecules due to the deformation of the fiber. It was also found that the temperature coefficient of the fused silica Young's modulus in fibers reduces on 10% in comparison with those in a bulk material. One should take into account these properties of fibers when designing high-Q fused silica fiber suspension of the mirrors.

(see details in Appendix A; the article is submitted to Phys.Lett.A).

B. Measurements of variation of electric charge on a prototype of fused silica test mass for gravitational wave antenna

Variations of electric charge located on fused silica mirror can produce fluctuating force and correspondingly excess noise in the interferometric gravitational wave detector. V.P. Mitrofanov, K.V. Tokmakov and undergraduate student L.G. Prokhorov have carried out long-term measurements of electric charge on the fused silica test mass of 0.5 kg suspended by fused silica fibers.

The continuous rise of electric charge was observed as a rule after the evacuation of vacuum chamber when the initial charge density on the test mass was of the order of 10^{-13} C/cm^2. Besides, three large jumps of electric charge happened during about 10 months of observations. The jumps consisted of several charge step changes with a total rise upto about 10^{-11}C/cm^2. The jumps of electric charge were correlated with strong changes of the test mass oscillation amplitude (of about 25%) which were much larger than those usually observed in free decay. The jumps of the amplitude may be interpreted as a result of additional damping arising from the interaction of electric charges located on the test mass with the probe electrode. Possible cause of the electric charge variations may be associated with the cosmic ray effect.

To check this hypothesis V.P.Mitrofanov, K.V.Tokmakov and undergraduate student L.G.Prokhorov began the experimental investigation of correlations between the changes of the electric charge on the fused silica test mass and the flux of cosmic rays passing through the vacuum chamber with the test mass. They are doing these experiments in close collaboration with Phil Willems (Caltech). He developed the apparatus for the monitoring of cosmic rays on the base of the scintillation paddles detectors. At present eleven scintillation paddles supplied by photomultipliers are installed around the vacuum chamber and the system of data acquisition and processing is being tuned

(see details in Appendix B or Phys.Lett.A 300 (2002) 370).

C. Measurement of thermorefractive noise in fused silica

M.L.Gorodetsky and undergraduate student I.S.Grudinin in 2002 continued improving the accuracy of the installation for the measurement of fundamental thermorefractive noise in fused silica microspheres. Small volume occupied by optical field in these microspheres $V_{eff} \sim 10^{-9}$cm^3 permits to obtain large fluctuations of eigenfrequencies due to this type of noise which may be measured. In 2002 M.Gorodetsky and I.Grudinin were using He-Ne laser ($\lambda = 0.63\mu m$) instead of initially proposed Nd-YAG ($\lambda = 1.06\mu m$). This allowed them to identify the modes by observing, recording with CCD camera and post-processing speckle pictures of residual scattering. Knowing the mode it is possible to make direct comparison of theoretical calculations with measured spectra of the noise. Simple method of direct calibration of measured spectra by adding small known frequency modulation of the pump laser was also developed.

At present spectral density of thermorefractive noise was measured in many microspheres with the diameter $D = 90 \div 900\mu m$ in the frequency range $10 \div 10^5$ Hz. Most spectra are in good qualitative and quantitative agrement with theoretical predictions. Systematic differences found in very small microspheres for low frequencies deserve consideration. However they may be explained without requirement of other unknown noises.

Preliminary results of measurement were reported on the conference IQEC-2002 (Moscow). The work is now on the stage of analysis of obtained results and preparation for publication and report on the conference Photonics West-2003 (Jan.25-31, San Jose).

(See details in Appendix C).

D. The development and the improvement of methods of registration of excess noise in violin modes of all fused silica suspension

During 2002 I.A.Bilenko and postgraduate student N.Yu.Markova were continuing the improvement of the installation based on Fabry-Perot optical resonator with one mirror (a very small one) welded between two fused silica fibers.

Several modifications in this device have been made. In particular an external amplitude stabilization feedback loop was added to the pump laser. New design for the mounting of the fixed mirror and fiber-to-cavity matching lens was implemented. The computer data acquision system now includes five channels: main signal amplitude and phase, laser intensity, mirror adjustment feedback error signal and seismic monitor channels.

At present sensitivity to the displacement is equal to $S_x = 8 \times 10^{-13} cm/\sqrt{Hz}$ near the frequency 1 kHz and $S_x < 5 \times 10^{-13} cm/\sqrt{Hz}$ at frequencies higher than 2 kHz.

The pace of the modifications and of the improvements was substantially slowed by the failures of several elements of the installation (including ion pump).

E. Parametric Oscillatory Instability in Power Recycled LIGO Interferometer

S. P. Vyatchanin and postgraduate student S. E. Strigin continued to investigate undesirable effect of parametric instability (V.B.Braginsky, S.E.Strigin, and S.P.Vyatchanin, *Physics Letters* **A287**, 331 (2001); gr-qc/0107079) which may cause very substantial decrease of the antennae sensitivity and even may make the antenna unable to work properly. In 2002 the condition of parametric instability were formulated for topology of LIGO interferometer with power recycling mirror. From the one hand it was obtained that condition for parametric instability for LIGO topology can be fulfilled for substantially *lower* level of energy than in single FP resonator. From the other hand it was shown that possible presence of anti-Stokes optical modes can *increase* the energy at which parametric instability occurs.

This effect originates from the fact that in LIGO-II the high value of optical energy $\mathcal{E}_0$ is planned to be stored in arms of interferometer: $\mathcal{E}_0 > 30$ J (it corresponds to the circulating power W of the order of 0.8 megawatt).

Calculations for simplified model and three-dimensional consideration show that in resonance case parametric instability may take place when the value of optical energy is ~ 6300 times smaller than that planned in LIGO-II. The necessity to carry out an experimental program which may permit to evade this effect is emphasized.

(See details in Appendix E or Phys. Lett.A 305 (2002) 111).

F. Low Quantum Noise Tranquilizer for Fabry-Perot Interferometer

S. P. Vyatchanin has considered the possibility to introduce low noise optical damping into mechanical oscillator (one of Fabry-Perot (FP) resonator mirrors is a mechanical resonator). Pumping FP resonator with light detuned from resonance one can create positive or negative rigidity in mechanical oscillator. Such a rigidity being introduced with delay (of the order of relaxation time of FP resonator) is equivalent to additional low noise damping. This damping may tranquilize (depress) parametric oscillatory instability in FP interferometer which is undesirable in laser gravitational wave antennae.

(See details in Appendix F or Phys. Lett.A 293 (2002) 228).

G. The "optical lever" intra-cavity readout scheme for gravitational-wave antennae

Several years ago a new principle of *intra-cavity* readout scheme for gravitational-wave antennae has been proposed by the Moscow Group. It was suggested to register directly redistribution of the optical field *inside* the optical cavities using Quantum Non-Demolition (QND) measurement instead of monitoring output light beam by photodetectors. This principle allows to solve one of the main problems of contemporary large-scale gravitational-wave antennae: very high value of optical pumping power which also depends sharply on the required sensitivity.

One of possible realizations of this principle is the "optical bar" scheme, which allows to transfer displacement of the end mirrors of the gravitational-wave antenna caused by the gravitational wave to equal displacement of the local mirror, using ponderomotive optical rigidity which can exist in the antenna's arms. This displacement can be detected by a measurement device monitoring the position of the local mirror relative to reference mass placed outside the optical pumping field. A small-scale optical interferometric meter for example can be used as such a meter.

F.Ya.Khalili has proposed an improved version of the "optical bar" scheme, which differs from the original one by using Fabry-Perot cavities in the arms of the antenna, similar to ones used in traditional topologies of gravitational-wave antennae with extra-cavity measurement.

This scheme was called "optical lever" because it can provide a gain in displacement of the local mirror similar to the gain which can be obtained using ordinary mechanical lever with unequal arms. The value of the gain is proportional to the finesse of the Fabry-Perot cavities.

This gain by itself does not allow to overcome the standard quantum limit in wide-band regime. But it allows to use less sensitive local position meter and increases the signal-to-noise ratio for miscellaneous noises of non-quantum origin, making it easier to overcome the standard quantum limit using, for example, variation measurement in the local position meter.

Using this gain, it is possible to make the signal displacement of the local mirror close to the signal displacement of the end mirrors of hypothetical gravitational-wave antenna with arm lengths equal to the half-wavelength of the gravitational wave

(see details in Appendix G or Phys.Lett. A298 (2002) 308).

H. Stroboscopic Variation Measurement

Two well-known promising technologies which allow to obtain sensitivity better than the Standard Quantum Limit are stroboscopic measurement and variation measurement. Both of these methods, however, have their own disadvantages. The stroboscopic regime require to use short pulses of optical pumping with instant power much higher than the mean power. In order to use the variation measurement it is necessary to know shape and arrival time of the signal to be detected, or (in the case of so-called Spectral variation measurement), it is necessary to use additional Fabry-Perot cavities with the length comparable with the length of the main cavities of the antenna.

F.Ya.Khalili and postgraduate student S.L.Danilishin proposed new *stroboscopic-variation measurement* which combines time-dependent pumping of the stroboscopic measurement, time-dependent cross-correlation of the meter noises used in variation measurement, and discrete sampling method. Such a combined procedure allows to obtain sensitivity close to traditional forms of variation measurement and also close to the Energetic Quantum Limit which defines the ultimate sensitivity that can be achieved at given meter's energy.

The stroboscopic variation measurement does not require information about the signal shape and arrival time (as the usual variation measurement does). At the same time, sensitivity of the stroboscopic variation measurement does not depend crucially on the duration of the pumping pulses (as in the case of the usual stroboscopic measurement).

The stroboscopic variation measurement can be used most effectively in intra-cavity readout schemes for gravitational-wave antennae, where it is necessary to measure a small displacement of local test object with very high precision using, for example, a small (table-top scale) interferometric position meter

(See details in Appendix H or Phys.Lett.A 300 (2002) 547).

I. Quantum speed-meter and laser interferometric gravitational-wave antennae

It is well known that only so-called QND observables can be continuously monitored with arbitrary high precision. A free mass has two such variables: momentum p and variable with explicit time dependence $x - pt/m$. In both cases the meter must be able to "see" momentum of free mass. However, implementation of such meters at the quantum level of sensitivity does not seem possible for the contemporary level of technology.

At the same time, it is possible to measure velocity of a free test mass instead of momentum. Velocity is not a true QND observable, and it is perturbed by the meter during such a measurement. However, its properties are close to properties of the momentum and therefore the perturbation can be rather easily excluded from the output signal of the meter using cross-correlation between the measurement noise and back-action noise.

The velocity measurement can be performed by devices which use pairs of position measurements separated by small time τ — so-called quantum speed-meters.

F.Ya.Khalili proposed a new version of the quantum speed-meter scheme which can be used directly in large-scale gravitational wave antennae. It is based on the combination of a zero-area Sagnac interferometer with two large-scale Fabry-Perot cavities. It uses polarization of the pumping light in order to separate from each other two pumping beams which pass through the interferometer in clockwise and counter-clockwise direction.

Sensitivity of this version of optical speed-meter is typical for schemes with traditional (extra-cavity) topology. If pumping beam is used in coherent quantum state then it is necessary to have about one kilowatt (without power recycling) of the optical power in order to reach the Standard Quantum Limit, and the necessary pumping power depends on the required sensitivity as h^{-2}, where h is the signal amplitude which has to be detected.

This scheme, however, has the following advantages in comparison with other proposed schemes with extra-cavity topology:

- It allows to obtain sensitivity better than the Standard Quantum Limit in wide band (the bandwidth is limited by the bandwidth of the Fabry-Perot cavities only).
- It does not require exact information about the shape and arrival time of the signal.
- It does not require any large-scale modifications of the standard topology of the laser interferometric antennae.
- It does not require non-classical state of the pumping power (however, using squeezed quantum state it is possible to reduce the value of the pumping power)

Therefore, considered scheme looks as the promising option for the first step beyond the Standard Quantum Limit.

(See details in Appendix I or in F.Ya.Khalili, LANL preprint gr-qc/0211088).

J. Collaboration of MSU group with members of LIGO Lab

S. P. Vyatchanin and postgraduate student S. E. Strigin had very fruitful discussions about parametric instability with Bill Kells and Erika D'Ambrosio, pointed on importance to take into account anti-Stokes modes in parametric instability effect. These discussions stimulated them to make detail analysis of parametric instability in power recycling interferometer mentioned in section D.

The search of correlation between the changes of the electric charge on the fused silica test mass and the flux of cosmic rays passing through the vacuum chamber with the test mass was carried out by V. P. Mitrofanov and K. V. Tokmakov in close collaboration with Phil Willems. Phil Willems in particular developed the apparatus for the monitoring of cosmic rays on the basis of scintillation paddles detectors. At present eleven paddles supplied by photomultiplier are installed around the chamber and the system of data collection is tuning.

K. Collaboration of MSU group with group of K. S. Thorne

This part of researches are being done by S. P. Vyatchanin and his student S. E. Strigin in collaboration with Erika D'Ambrosio, Richard O'Shaughnessy and Kip S.Thorne.

Thermoelastic fluctuations of mirror's surface decrease considerably if beam with larger radius is used. This source of noise is very significant in sapphire test masses (as it was shown in *Physics Letters A* **A264** (1999) 1). In order to decrease the thermoelastic fluctuations of mirrors surface it was proposed to use so called "Mexican-hat" light beam in the LIGO interferometers. These beams has larger radius of beam than Gaussian beams at the same difractional losses and hence thermoelastic noise for such beams is smaller. It was also proposed to use conic shape of test masses (instead of cylindric one). Preliminary results show that both these modifications allow to decrease thermoelastic noise by factor $4 \div 8$.

The article is in preparation (see also LIGO documents G010151-00 and G010297-00).