Use of narrow optical resonances for measuring small displacements and for building gravity-wave detectors

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The first results of the use of narrow optical resonances for precise measurements of small displacements are reported. The experiments were conducted using an He-Ne laser at $\lambda = 3.39\ \mu$m with a methane cell. The nonlinear resonances in methane with a width of 50 kHz and an intensity of about 1 mW were used. A periodic perturbation was supplied to one of the laser cavity mirrors. The absolute sensitivity of the measurements was 6×10^{-6} Å along a base of 5×10^{2} cm.

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1. Optical methods, which make it possible to detect small phase changes of optical signals that occur with a change in the optical path length due to the action of various factors, are used to solve many applied problems and to perform precise physical experiments. The possibilities of double-beam and multiple-beam interferometry were recently investigated in conjunction with the problem of detecting gravity waves. The methods of double-beam laser interferometry made it possible to measure small changes of $\sim 10^{-7}$ rad in optical phase and $\sim 10^{-12}$ cm in length.[1] The use of Michelson interferometers with a large number of beam traversals in each arm,[2,3] multiple-beam interference systems,[4] as well as lasers with a Fox-Smith cavity,[5] makes it possible to improve significantly the measurement sensitivity.

Changes of the optical phase or lasing frequency, which occur with small displacements of the mirror, can be measured by using narrow optical resonances and frequency-stable lasers.[4,6] We report in this paper the use of narrow optical resonances for measuring small periodic displacements with a relative sensitivity of 10^{-16}.

2. The measurement method is based on the detection of small changes in laser frequency that occur with changing cavity length or of the refractive index of the medium due to perturbations. The method is shown schematically in Fig. 1. A periodic perturbation, which acts on one of the laser cavity mirrors, changes the cavity length l by an amount Δl and, consequently, changes the lasing frequency ν by an amount $\Delta \nu = \frac{\Delta l}{l}\nu$. A change in the lasing frequency by means of narrow saturated-absorption resonances changes the laser-radiation power ΔP, which is then recorded by a photodetector (see Fig. 1). The laser frequency must be tuned to the region of maximum steepness of the resonance to obtain the maximum sensitivity. The conversion sensitivity increases with increasing resonance intensity and decreasing width.

The minimum detectable change in cavity length is determined by the noise of the

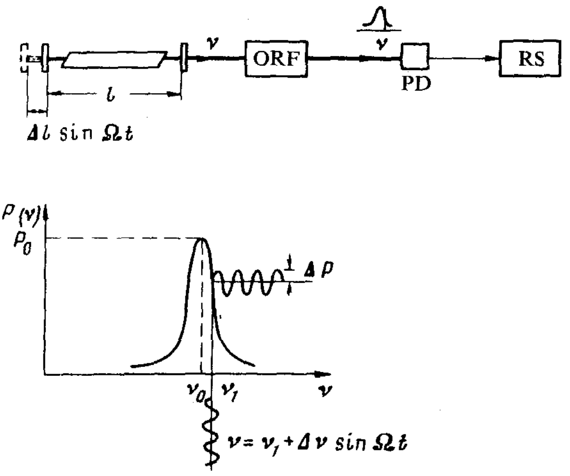

FIG. 1. Schematic of a device for measuring small displacements by means of optical resonances. *ORF*, optical-resonance filter; *RS*, recorder system; *PD*, photodetector.

laser radiation and of the measurement channel. In principle, the photon noise due to the quantum nature of laser radiation is the limiting factor. Simple calculations show that the minimum detectable displacement Δl for a Lorentz-type resonance, which is restricted only by the fluctuational noise of the photons, is defined by the expression

$$\Delta l_{min} \approx \frac{4}{3\sqrt{3}} \lambda \frac{\Gamma}{\nu_m} \frac{1}{k} \sqrt{\frac{h\nu}{P_0}\Delta f}\,, \qquad (1)$$

where λ is the radiation wavelength, Γ is the resonance half-width, $\nu_m = c/2l$ is the intermode spacing, k is the resonance contrast, P_0 is the laser-radiation power, and Δf is the bandwidth of the measurement channel.

We can see in Eq. (1) that, in contrast to the Michelson interferometer method,[1] the use of the optical resonance makes it possible to increase the sensitivity of the measurements by a factor of ν_m/Γ. An estimate of $\Delta l_{\min}$ from Eq. (1) for the known parameters of the He-Ne laser at $\lambda = 3.39\ \mu$m and the nonlinear resonance in methane[7] gives $\Delta l_{\min} \approx 10^{-16}$ cm/Hz$^{1/2}$($\Delta l/l \approx 10^{-18}$). Under actual experimental conditions the measurement sensitivity decreases because of the presence of additional noise caused by fluctuations of the radiation power due to instability of the lasing frequency and of the discharge plasma, photodetector noise, etc. The magnitude of this noise, which depends on the specific experimental conditions, may exceed the photon noise by a significant amount.

3. Experiments were conducted with an He-Ne laser at $\lambda = 3.39\ \mu$m with a methane absorption cell. We used the nonlinear resonance in methane with a width of 5×10^4 Hz, a contrast of $\approx 70\%$, and an intensity of ≈ 1 mW. The cavity length was 5×10^2 cm. The experimental apparatus, shown schematically in Fig. 2, includes the stable-frequency He-Ne/CH_4 laser 1 with a narrow emission line, which was described

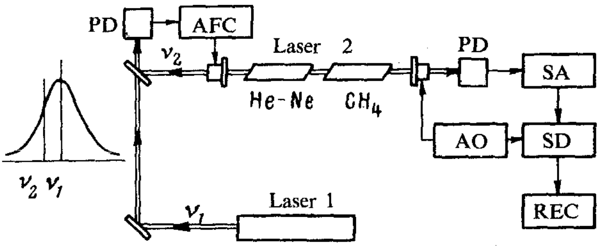

FIG. 2. Schematic of the experimental apparatus. *SA*, selective amplifier; *SD*, synchronous detector; *AO*, acoustic oscillator; *REC*, recorder; *AFC*, automatic frequency control; *PD*, photodetector.

in Ref. 7, and the laser 2, which is now under investigation. The frequency of laser 2 was locked into the frequency of laser 1 by means of an electronic automatic-frequency-control (AFC) system. The frequency of laser 2 was set precisely in the region of maximum resonance steepness. The periodic perturbation of the cavity was provided by applying a sinusoidal signal to a precalibrated piezoceramic element, to which one of the cavity mirrors was attached. The frequency Ω of the perturbing signal must be separated from the bandwidth of AFC action in order to avoid the influence of the latter on the measurement results. In our case Ω was equal to 15 kHz. The intensity-modulated radiation of laser 2 struck the photodetector, whose output signal was traced on the recorder after synchronous detection.

Figure 3 shows a characteristic signal trace for different periodic perturbations. The averaging time was 10 sec. The minimum detectable amount of mirror displacement, as determined by the noise level, was 6×10^{-6} Å. In this case the relative sensitivity was $\approx10^{-16}$. The measurements show that the observed noise is fully attributable to the photodetector noise, which amounts to $3\times10^{-7}\ \mathrm{V/Hz}^{1/2}$ and is about three orders of magnitude greater than the photon noise.

4. The use of narrower saturated-absorption resonances to increase the sensitivity is limited because of the decrease in their intensity. It may prove promising to use two-photon resonances without a Doppler shift[8] in the short-wave region of the spectrum, in which the intensity saturation does not occur even at a power of $\sim$ 1 W. The use of two-photon resonances requires the development of frequency-stable, tunable lasers. An estimate from Eq. (1) of the following parameters of the system: $\lambda=0.5\ \mu$m, $P_0\sim1$W, $l\sim1$ cm, $k\approx1$, $\Gamma\approx1$ kHz, and $\Delta f=1$ Hz gives $\Delta l\sim10^{-21}$cm $(\Delta l/l\sim10^{-21})$.

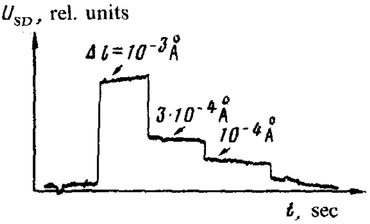

FIG. 3. Trace of a signal at *SD* output for different mirror displacements Δl.

The experimental and estimated results indicate that detectors for recording gravity waves with use of narrow optical resonances can be built.

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