Gravitational-wave detection through the use of competing resonances of ring lasers

M. V. Danileĭko, A. M. Fal', V. P. Fedin, and L. P. Yatsenko
Institute of Physics, Academy of Sciences of the Ukrainian SSR

(Submitted 21 March 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **39**, No. 9, 428–430 (10 May 1984)

Nonlinear competing resonances in the output of ring lasers might be used to detect ultrasmall changes in optical path length. Because of the competition between the oppositely directed waves, these resonances are considerably sharper than those in linear lasers. An absolute sensitivity of 5×10^{-7} Å has been achieved in the detection of periodic perturbations of the position of one of the resonator mirrors with a baseline of 0.85 m in a He-Ne/CH_4 ring laser.

Bagaev *et al.*[1] have suggested making use of the narrow resonances in the output from gas lasers with a nonlinear absorption to develop devices for detecting gravitational waves. The idea is to detect that alternating component of the laser output power which arises upon periodic displacements of one of the resonator mirrors. The output frequency is maintained on the steepest part of a resonance. The sensitivity of this method, which is limited by photon noise, is better than that of laser interferometric methods[2,3] by a factor of $k\,(\Omega_m/\Gamma)$, where k and Γ are the contrast and width of the nonlinear resonance, and Ω_m is the mode spacing. An absolute sensitivity of 6×10^{-6} Å over a 5-m baseline has been achieved[1] in a linear He-Ne/CH_4 laser.

Attempts to further improve the sensitivity, in linear lasers with in-resonator absorption by reducing the widths of the resonances run into the difficulty that the contrast decreases simultaneously. In the present letter we wish to suggest that small changes in the optical length of a resonator might be detected by making use of the nonlinear competing resonances in the output of ring lasers; because of the competition between the oppositely directed waves, these resonances are considerably more intense and narrower. Their slopes are thus considerably steeper than those of resonances in a linear laser.[4]

Near the center of the gain line in a single-mode gas ring laser, lasing involving a single traveling wave may be preferred from the energy standpoint.[4] When a nonlinearly absorbing medium is placed in the resonator, the region of single-wave generation expands, but in a narrow interval of the difference $\Delta\omega = \omega - \omega_0$ between the laser output frequency ω and the center of the absorption line, ω_0, a regime of lasing involving two oppositely directed waves remains stable. The intensities of the oppositely directed waves is given by the following expression in the region of the competing resonance in the approximation of a slight saturation of the gain[5]:

$$P_{1,2} = \frac{P_0}{2}\left[1 \pm \frac{\delta}{\chi - \mu\zeta\Delta\omega^2/(\gamma^2+\Delta\omega^2)}\right], \tag{1}$$

where $\delta = \{[2(\eta_1 - \eta_2)]/[\eta_1 + \eta_2]\} \ll 1$ is the relative difference between the extents $(\eta_{1,2})$ to which the pump level exceeds the thresholds for the oppositely directed waves, the small parameter χ is a measure of the competition between the oppositely directed waves, μ is the ratio of the linear absorption coefficient and the linear gain, ζ is the ratio of the saturation parameters of the absorbing and gain media, γ is the homogeneous width of the absorption line, and P_0 is the resultant intensity. The width of competing resonance (1) is determined by

$$\delta\omega = 2\sqrt{\frac{\chi-\delta}{\mu\zeta - \chi + \delta}}\,\gamma. \tag{2}$$

The resonances of most interest for the detection of small displacements are "table-shaped" resonances, with an essentially flat top and a rapid change in intensity at $\Delta\omega \simeq \pm\delta\omega/2$. Such resonances arise under the conditions $\delta \ll \chi \ll \mu\zeta$, and these conditions can be satisfied experimentally quite simply.

The minimum observable amplitude of a periodic change in the laser perimeter $L = L_0 + \Delta L \cos\Omega t$ is determined by the fluctuational photon noise, which is a fundamental limiting factor for all laser methods for measuring small displacements. Assuming that the laser is tuned to the region of the maximum slope of the competing resonance, $\Delta\omega \simeq \delta\omega/2$, we easily find the following expression for $\Delta L_{\min}$ under the conditions $\delta \ll \chi \ll \mu\zeta$:

$$\Delta L_{min} = \frac{\lambda}{2}\,\frac{\delta\omega}{\Omega_m}\,\frac{\delta}{\chi}\sqrt{\frac{\hbar\omega}{P_0}\Delta f}, \tag{3}$$

where λ is the wavelength, and Δf is the passband of the detection system. Expression (3) is analogous to expression (1) of Ref. 1, but when competing resonances are used, the role of the contrast $k \lesssim 1$ is played by the quantity $\chi/\delta \gg 1$, and the width $(\delta\omega)$ of the competing resonance is considerably smaller than that $(\Gamma \simeq \gamma)$ of the resonance in a linear laser.

In the present experiments we used a $He\text{-}Ne/CH_4$ ring laser at the wavelength 3.39 μm. The resonator perimeter was 0.85 m; the length of the absorbing cell was 0.3 m; the methane pressure was 3 mtorr; and the output power was 0.5 mW. The width of the competing resonance was 50 kHz, and the parameter δ/χ was $\simeq 10^{-1}$. The output frequency was stabilized at the zero of the second derivative of the output power with respect to the frequency; this stabilization kept the apparatus tuned to the

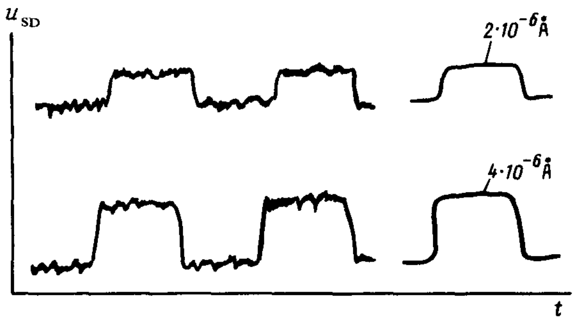

FIG. 1. Output signal from the synchronous detector (at the left) and output signal from the automatic system for data acquisition and preliminary processing (at the right).

part of the resonance with the greatest slope. The spectral width of the laser output was $\simeq 1$ kHz; the bandwidth (Δf) of the detection system was 1 Hz; and the bandwidth of the automatic-frequency-control system was 800 Hz. The position of one of the resonator mirrors was modulated by applying a 200-kHz sinusoidal voltage to a piezoelectric ceramic. The detection system consisted of a cooled low-noise photodetector, a tuned amplifier, a synchronous detector, and an automatic system for data acquisition and primary processing. The piezoelectric ceramic was calibrated beforehand in the working frequency range. Figure 1 shows the experimental results. The sharp change in the output voltage of the synchronous detector corresponds to the point at which the mirror position begins to be modulated, and the step in the output signal is proportional to the displacement amplitude. The smallest amplitude detectable is 5×10^{-17} m. The sensitivity of these measurements is limited by the noise that results from the conversion of frequency fluctuations of the laser into amplitude fluctuations with the tuning to the region of the rapid change in intensity. The use of an optical system with a stabilized reference laser, a heterodyne laser, and systems for phase automatic frequency control[1] made it possible to substantially reduce this noise component and to achieve a sensitivity $\sim10^{-19}$ m, which is determined by the photon noise for the particular competing resonances used in these experiments.

These results demonstrate that the use of competing resonances of ring lasers holds promise for detecting ultrasmall periodic displacements and for developing gravitational-wave detectors.

[1] S. N. Bagaev, A. S. Dychkov, and V. P. Chebotaev, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 85 (1981) [JETP Lett. **33**, 79 (1981)].
[2] G. E. Moss, L. R. Miller, and R. L. Forward, Appl. Opt. **10**, 2495 (1971).
[3] R. L. Forward, Phys. Rev. **D17**, 379 (1978).
[4] N. G. Basov, É. M. Belenov, M. V. Danileĭko, and V. V. Nikitin, Zh. Eksp. Teor. Fiz. **60**, 117 (1971) [Sov. Phys. JETP **33**, 66 (1971)].
[5] M. V. Danileĭko, A. M. Fal', V. P. Fedin, M. T. Shpak, and L. P. Yatsenko, Kvantovaya Elektron. (Moscow) **9**, 2013 (1982) [Sov. J. Quantum Electron. **12**, 1307 (1982)].

Translated by Dave Parsons
Edited by S. J. Amoretty