# Scientific session of the Division of General Physics and Astronomy of the Academy of Sciences of the USSR (27 September 1989)

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A scientific session of the Division of General Physics and Astronomy of the USSR Academy of Sciences was held on 27 September 1989 at the S. I. Vavilov Institute of Physics Problems of the USSR Academy of Sciences. The following two reports were presented at the session:

1. *V. B. Braginskiĭ, V. S. Il'chenko, and M. L. Gorodetskiĭ.* Optical microresonators with modes of the whispering gallery type.

2. *M. I. Klinger.* Low-temperature properties of nonmetallic glasses.

Brief summaries of the papers are given below.

**V. B. Braginskiĭ, V. S. Il'chenko, and M. L. Gorodetskiĭ.** *Optical microresonators with modes of the whispering gallery type.* A discussion is given of the properties of optical microresonators (MR) with modes of the whispering gallery (WG) type, results are presented of the experimental investigation of these microresonators and prospects of their applications are discussed.

Ultra-high-frequency dielectric microresonators with WG modes have been extensively studied[1] and are successfully utilized in technology.[2] With their aid it became possible to attain the basic limit of UHF losses in perfect dielectric crystals and to achieve a quality factor of $Q \approx 10^8$ at $T = 77$ K and $Q \approx 10^9$ at $T = 4$ K (disc resonator made of leucosapphire of diameter $D = 10$ cm; wavelength $\lambda = 3$ cm).[3] By reducing the dimensions of the dielectric resonator by 3–4 orders of magnitude and by using dielectrics with a sufficiently low optical absorption one can obtain an optical resonator with a high quality factor. In so doing the use of the WG modes (confined waved undergoing multiple total internal reflection from the boundary of an axially-symmetric dielectric body) provides, apparently, the only possibility of achieving a quality factor $Q \geqslant 10^8$ in the optical range with the resonator dimensions being comparable to a wavelength. Since the high quality factor is in this case combined with a small physical volume $V_{\rm eff}$ of localization of light fields the nonlinearity of the material in such a system must be manifested at a very low pumping power. This property of optical WG modes is of interest for some experiment programs.

1. The existence of optical WG modes was confirmed for the first time in early experiments on stimulated emission in spherical samples of $CaF_2{:}Sm^{2+}$ [4] and in microdroplets of aerosols.[5] An indirect estimate of the quality factor of the WG modes in these experiments did not exceed $Q = 10^4$. It is not difficult to show that the value of $Q$ in the optical range can be higher by several orders of magnitude.

With the use of fused quartz (optical absorption in fibers $\alpha = 10$ db/km at $\lambda = 0.63$ m) the internal losses in the material and radiation from the curved side surface of the resonator do not prevent achievement of a quality factor of $10^{10}$ with a diameter of the MR of $D \geqslant 15$ $\mu$m. The principal factor in limiting the quality factor must be scattering by surface inhomogeneities. Estimates show that it also does not prevent achievement of $Q = 10^9$ for $D = 150$ $\mu$m and $Q = 10^5$ for $D = 15$ $\mu$m in the case of an average size of an inhomogeneity typical for glass surfaces of $\sigma = 50$ nm.

2. Optical bistability, i.e., a histeretic amplitude and frequency characteristic of the resonator arises when an amplitude-dependent shift of the eigenfrequency $\omega$ of an individual mode as a result of the cubic nonlinearity of the material $4\pi\omega\chi^{(3)}E^2/n^2$ ($n$ is the index of refraction, $E$ is the electric field, $\chi^{(3)}$ is the cubic nonlinear susceptibility) exceeds the width of the resonance curve $\omega/Q$. The threshold bistability power is determined by the expression

$$W_{\rm bist} \approx \frac{n^4\omega V_{\rm bist}}{32\pi\chi^{(3)}Q^2}. \tag{a}$$

For a quartz resonator ($\chi^{(3)} = 1\times10^{-14}$ electrostatic CGS units, $n = 1.45$) with $E_{l l 1}$, $H_{l l 1}$ modes for $\lambda = 0.63$ $\mu$m ($\omega = 2\pi\cdot4.7\cdot10^{14}$ rad/s) the effective volume must amount to $V_{\rm eff} \approx 3\cdot10^{-11}$ cm$^3$ ($l = 100$, $D = 15$ $\mu$m) and $V_{\rm eff} \approx 2\cdot10^{-9}$ cm$^2$ ($l = 1000$, $D = 150$ $\mu$m). For a quality factor of $Q = 10^8$ it corresponds to a threshold bistability power of $W_{\rm bist} \approx 4\times10^{-7}$ W and $W_{\rm bist} \approx 4\times10^{-5}$ W for $l = 100$ and $l = 1000$ respectively. We note that in the existing bistable Fabry-Perot resonators typical values of $W_{\rm bist}$ amount to $10^{-2}$–$10^{-3}$ W

3. Samples of spherical microresonators made of fused quartz of diameter from 40 to 400 $\mu$m were investigated experimentally. Using a tunable single-frequency He–Ne laser, and introducing radiation into the samples by means of prisms, effectively excited WG modes were observed with a typical quality factor of $10^7$–$10^8$. The maximum measured value of the quality factor was $Q = (3 \pm 0.3)\times10^8$ in one of the resonators with a diameter of 150 $\mu$m. The majority of the modes observed in MR of diameter less than 200 $\mu$m had bistable properties with a pumping power from $10^{-5}$ W to $10^{-4}$ W. Two types of bistability were observed in quartz

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MR – a slow one with a response time of $\tau = 10^{-3}$–$10^{-6}$ s and an equivalent susceptibility of $\chi^{(3)} = 10^{-11}$–$10^{-13}$ electrostatic CGS units which corresponded to a thermal nonlinearity of the MR and also a fast one with $\tau < 10^{-8}$ s (the estimate is limited by the experimental methodology), for which the estimate of the cubic susceptibility amounted to $\chi^{(3)} = (1.3 \pm 0.7) \times 10^{-14}$ electrostatic CGS units, in good agreement with the well-known value of the Kerr nonlinearity of quartz. A more detailed description of the experiment can be found in Ref. 6.

4. In addition to the obvious prospect of utilizing optical MR with WG modes as miniature narrow-band optical filters (in the linear regime) one should distinguish two other important fields of their possible application.

1) The cross interaction of the WG modes due to the nonlinearity of the material enables one to propose a procedure for the quantum-nonperturbing measurement of the number of quanta in a single mode $N_i$ by the shift of the resonance frequency $\omega_k$ of another mode.[7] Estimates have shown that the combination of the small effective volume with the high quality factor of the WG modes enables one, in principle, to realize such measurements with an error of $\Delta N_i \leqslant 1$.

2) The small dimensions and record-low threshold bistability power enable one to propose the microresonators with whispering gallery modes to be the basic element in a real optical computer. A microresonator based on glass with an admixture of $CdS_x Se_{1-x}$ ($\chi^{(3)} \approx 10^{-9}$ electrostatic CGS units, $\alpha = 10^4$ db/km) would almost completely satisfy the set of requirements[8] being imposed at the present time on a discrete bistable element of an optical computer. Thus, with the size of $D = 4\ \mu$m ($l = 30$) it can have a quality factor $Q = 3 \cdot 10^4$, a rapid action of $\tau \approx Q/\omega \approx 10$ ps, a threshold bistability power $W_{\text{bist}} = 4 \times 10^{-5}$ W and an operating energy per switching of $\mathscr{E}_0 \approx 4 \cdot 10^{-16}$ J (a thousand photons). On relaxing the requirement on rapid action ($\tau \approx 3$ ns) and using MR with a higher quality factor (losses in the glass with $CdS_x Se_{1-x}$) make possible a quality factor of $Q \approx 10^7$, the value of $\mathscr{E}_0$ can, in principle, be reduced down to $10^{-18}$ J (single-photon control).


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