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Unsolved problems in quantum optics (several short notes)

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Abstract. The possible prospects for the improvement of the resolution and of the sensitivity in quantum-optics experiments are discussed as well as possible applications of quantum-optics methods for the solution of fundamental physical problems.

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Quantum optics at present is one of the flourishing parts of modern physics. The scientists who worked in this area have invented and realized many elegant and very effective methods, which, on the one hand, permitted observation of new physical phenomena and, on the other, permitted deeper understanding of nonlinear interaction of electromagnetic radiation with a chosen object. The main features of these methods are: *(i)* the very high level of isolation of the object (single atom or group of atoms or molecules) from the uncontrolled external perturbation, *(ii)* the time of interaction of the photons with the objects was substantially extended and controlled. In these type of experiments, the following should be underlined: the discovery of Rabi beatings in the exchange of a single photon between one atom and a mode in a resonator (one atom maser), the quantum Zeno effect, the preparation of the non-classical state of electromagnetic radiation, the suppression and redistribution of quantum fluctuation, and the new records in frequency stability.

From my point of view, it is irrational to try to separate quantum optics (with "heavy" photons of the optical band) from optoelectronics or quantum electronics (with "light" photons of the microwave band). These fields ideologically create an integer body. The following short and almost evident notes are about some prospects in this area, which do exist from the point of view of the author, who is an admirer.

1 Sensitivity

The achieved sensitivity in many existing schemes of experiments is defined by the level of isolation of the mode of the electromagnetic resonator (the quality factor). From my point of view, for all optical, infrared and microwave resonators there exists a very substantial, potential reserve to increase the quality factor. The realizable reflectivity of mirrors today (which differs from unity at the level, of 10^{-6} [1]) is three orders of magnitude better than the experimentalists had at their disposal two decades ago. Meanwhile, there are no real fundamental limitations which forbid substantial improvement of this parameter. The predicted limit of dissipation which is defined by zero-point oscillation [2], is many orders smaller. At the same time it is worth noting that even with the existing level of the mirror's finesse, in the so-called full-scale laser-interferometric antenna (LIGO, VIRGO, GEO [3]), it is possible to reach the quality factor of the mode exceeding 10^{15}. In these optical resonators the relaxation time has to be close to $\tau_e^\star \simeq 10\,\mathrm{s}$.

The situation in the microwave band is similar. The resonators, relatively recently realized, with whispering gallery modes in high purity dielectrical discs have quality factors close to 10^{10} at liquid-helium temperature [4]. However, this value is due to the finite level of impurities in the dielectrics. It was only possible above 30 K to register the level of losses due to fundamental processes of nonlinear photon – phonon interaction. If it will be possible to reduce the level of impurities, one may expect to obtain the quality factor at the level $10^{14} - 10^{15}$. This corresponds to relaxation times of $\tau_e^\star \simeq 10^4 - 10^5\mathrm{s}$.

Summing up the above arguments it is possible to expect the increase of the quality factors of the elecromagnetic resonators by at least several orders above the present values.

2 Quantum non-demolition

The substantial increase of the relaxation time $\tau_e^\star$ may lead to the quantitative change of the situation with the non-classical states of electromagnetic radiation and with Quantum-Non-Demolition measurements (QND). In other words, it is possible to expect a substantial increase in sensitivity in many experiments.

It is well-known that the non-classical states (sometimes the term squeezed state is used) may give substantial advantage in different measurements. For example, in the above-mentioned laser-gravitational antennae, which have to detect

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Dedicated to H. Walther on the ocassion of his 60th birthday the bursts from astrophysical catastrophes, it is necessary in the first step of the program to measure the perturbation of the metric $h \simeq 3 \times 10^{-21}$ which produces the small "detuning" of an optical Fabry-Perot resonator. This "detuning", in turn, produces a phase shift $\Delta\varphi \simeq h\omega_e\tau_{gr}/2$ (where ω_e is the pump frequency and τ_{gr} is the duration of the gravitational burst). For the advanced version of these antennae, the expected sensitivity is $h \simeq 3 \times 10^{-22}$. Thus, for $\omega_e \simeq 2 \times 10^{15}$rad/s and $\tau_{gr} \simeq 1 \times 10^{-3}$s it will be necessary to register $\Delta\varphi \simeq 3 \times 10^{-10}$rad. If the classical (coherent) state in the resonator is used then it is necessary to have inside the resonator at least $N \simeq (\Delta\varphi)^{-2} \simeq 10^{19}$ photons. This value is relatively large. On the other hand, from the point of view of the quantum theory of measurements there are no principal restrictions to prepare a completely phase-squeezed quantum state in a resonator, for which $N \simeq (\Delta\varphi)^{-1}$. In this case it will be sufficient to use only 10^{10} optical photons.

The QND measurements, as is well known, permits the attainment of very high sensitivity; in particular, to beat the so-called Standard Quantum Limits (SQL) [5]. The situation in the QND measurements may be described as the very beginning of the "events" (the reader may find some parts of information about QND measurements in quantum optics only in the review [6]). For example, recently, three groups of experimentalists have reported that, using the QND methods, they achieved a resolution better than $\sqrt{N}$ in the measurements without absorption of photons (for this case SQL is equal to $\sqrt{N}$). But in these experiments, the number N was very large. On the other hand, the theory of QND measurements permits not only counting a single photon without absorption but to measure its energy with an error of $\hbar/\tau$ (where τ is the time of measurements).

Another example of the possible future developments of the "events" is the present state-of-the-art of frequency stabilization and the prospects in this area. The existing secondary frequency standards have the level of relative instability 3 – 4 orders of magnitude larger than the SQL for this value for the used size and other parameters of the installations. The theory of QND measurements gives definite recommendations how to reach the level of instability much lower than the SQL ones.

Summing up these remarks it is possible to expect substantial improvements in sensitivity, resolution, etc. in quantum optics, when non-classical states and QND methods will be converted from "toys" into "tools".

3 Outlook

Many of the recent discoveries in quantum optics (not all of them) are very impressive and important but, nevertheless, they have some kind of "weakness": these discoveries are in complete agreement with the existing theories (in particular with QED). Much more important were and will be the experimental discoveries which either disprove the existing theories or became the basis of new theories in a completely new field. From this, very "fundamentalistic", point of view, quantum optics may and must be regarded as one of the most powerful "tools" in the hand of the experimentalists. And this "tool" may become much more powerful, as it was mentioned above.

From my point of view, there are many new very attractive programs of research, where quantum optics is playing a role of a "tool". Besides the above-mentioned problem of detecting the bursts of gravitational radiation (and later, when the shape of the bursts will be registered, of learning how the neutron stars and the black holes are merging), there are several others which seem to me to be very "tasty". These are the attempts to find the electrical dipole moment of neutrons and attempts to find the distribution of the electrical charge in the proton and several other programs.

In the end of these notes I want to attract the attention of the experimentalists in quantum optics to the potentially existing and very interesting fundamental problem. The beginning of existence of this problem was "established" by J.A. Wheeler in the 1950s, when he noted that in space there may exist topologically different ways of coupling between two separate areas (the wormholes). Three decades later, Hawking [7], developing this idea, proposed the possibility of the existence of topological fluctuations, which either couple different parts of this world or couple it with another one. These fluctuations have to be "produced" by the appearence and the disappearence of micro black holes with fundamental Planck's mass $(\hbar c G^{-1})^{1/2} \simeq 10^{-5}$g where c is the speed of light and G is the gravitational constant), during a very short time $\simeq 10^{-43}$s. The next logical step was the idea that, as any black hole, these micro ones even appear as fluctuations, and have to absorb information. In other words: to act as a classical observer. The latter has to produce decoherentization of any object's behavior. The articles which presented the elaboration of this idea [8 – 10] are very controversal: The predictions of the time of decoherentization of elementary particles and of macroscopic masses are very different. This controversy may be in part regarded by the community of the experimentalists as a logical result of the fact that there is no solid theory of quantized gravity, as well as there is no experimental proof that the gravity is quantized. On the other hand, this controversy is an evident sign that this problem is a direct challenge for the experimentalists to try to find the unexpected decoherentization of micro or macro objects. It may be done, in principle, in a very simple scheme. The experimentalist has to do his best in the isolation of the chosen object from the heat bath and then, using one of the QND observables (for a free mass this is the speed and the energy), register it as long as the perturbation from the heat bath will not be recorded. If he will observe perturbation of the quantum state *before* the expected time due to the thermostat, he will have the reason to claim the discovery of a new essence.

It is worth adding here that, until now, nobody analyzed the possible action of these topological fluctuations on the electromagnetic radiation.

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