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Comments and Addenda

The section Comments and Addenda is for short communications which are not appropriate for regular articles. It includes only the following types of communications: (1) Comments on papers previously published in **The Physical Review** *or* **Physical Review Letters**. *(2) Addenda to papers previously published in* **The Physical Review** *or* **Physical Review Letters**, *in which the additional information can be presented without the need for writing a complete article. Manuscripts intended for this section must be accompanied by a brief abstract for information-retrieval purposes. Accepted manuscripts follow the same publication schedule as articles in this journal, and page proofs are sent to authors.*

Temperature effects in photodetection: Additional results

Annabella Selloni and A. Quattropani
Laboratoire de Physique Théorique, Ecole Polytechnique Fédérale Lausanne, CH-1006 Lausanne, Switzerland

P. Schwendimann
Institut für Theoretische Physik, Universität Bern, CH-3012 Bern, Switzerland

H. P. Baltes
Zentrale Forschung und Entwicklung, Landis & Gyr Zug AG, CH-6301 Zug, Switzerland
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We study the temperature dependence of the dark current and the quantum efficiency of photodetectors using our previous open-system detection model. We evaluate the joint contribution of these effects to the moments of the photoelectric current.

In our previous paper[1] we studied the effect of nonzero temperature of a photodetector on the measurement of the average radiation intensity and the photon statistics. We have shown how the quantum efficiency is reduced as a consequence of an increase of the field attenuation κ with increasing detector temperature. In Ref. 1, however, we overlooked that the dependence of the photoelectric signal on the *density of the photosensitive atoms* can be included in our model calculation. Since this dependence may lead to large dark currents, whose effect on the photocounting statistics can even exceed that of the temperature-dependent quantum efficiency, it is pertinent to add an appropriate discussion.

We recall that in our model the detector is represented by a collection of N two-level atoms (level-spacing ϵ) in a unit volume. The atoms are coupled to reservoirs which maintain the detector temperature (i.e., a certain relative population of the upper and lower levels), withdraw excited electrons, and repopulate the lower level. The reservoirs simulate the electronics and the cryostat. The effects of the atom-bath coupling are characterized by a constant γ. The photosensitive atoms are coupled to the incoming resonant monomode radiation field ($\hbar\omega = \epsilon$) by the usual dipole interaction Hamiltonian in the rotating-wave approximation (coupling constant λ).

In our previous analysis[1] we used the initial condition that no radiation field at all is initially present inside the detector, i.e., the thermal-equilibrium field corresponding to the detection temperature is built up in the course of the interaction of radiation and detector atoms. We now adapt the more realistic initial condition that a resonant thermal field with average photon number $\bar{n} = [\exp(\beta\epsilon) - 1]^{-1}$ (β is the inverse temperature) is already present at the beginning of the counting interval of length T. Using the method described in Ref. 1, we find that the νth factorial moment $N_A^{(\nu)}(T)$ of the photoelectric current after integration time T is related to the quasiprobability distribution $\mathcal{P}(\alpha)$ of the incoming radiation by

$$N_A^{(\nu)}(T) = \nu!\, u^\nu \int d^2\alpha\, \mathcal{P}(\alpha) L_\nu(-\eta|\alpha|^2/u) \ . \qquad (1)$$

Here L_ν denotes the Laguerre polynomial of order ν and η denotes the temperature-dependent quantum efficiency (see Fig. 1):

$$\eta = 1 - \exp(-2\kappa T), \qquad (2)$$
$$\kappa = \lambda^2\gamma^{-2} N \tanh(\beta\epsilon/2) \ .$$

By u we denote the average integrated dark current given by

$$u = 2\gamma T N_{2,\mathrm{eq}} \ , \qquad (3)$$

where $N_{2,\mathrm{eq}}$ is the density of excited atoms at thermal equilibrium, viz.,

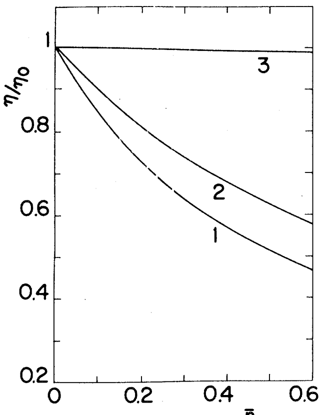

FIG. 1. Ratio η/η_0 versus mean thermal photon number $\bar{n}$. Curves 1, 2, and 3 correspond to $2\kappa_0 T = 0.1$, 1, and 10, respectively.

$$N_{2,\mathrm{eq}} = N[1 + \exp(\beta\epsilon)]^{-1} . \tag{4}$$

As one could expect, the dark current is proportional to γ (e.g., the applied potential) and to N (e.g., the density of photosensitive impurities in a doped semiconductor). In contrast to (3), the initial condition of the zero initial thermal field[1] leads to $u = 2\gamma T N_{2,\mathrm{eq}} - \eta\bar{n}$. Moreover, we point out that the factor N in Eq. (4) was disregarded in Ref. 1, so that the discussion of the numerical examples included only the temperature dependence of the efficiency, but did not appropriately account for the dark current. In the present note we account for both effects simultaneously. In principle, the two temperature effects superimpose in a complicated way as can be seen from Eq. (1), but the numerical evaluation with realistic parameters presented below shows that the dark current is much more important than the temperature dependence of the quantum efficiency.

We compare the cases of zero and nonzero detector temperature in terms of the ratio R_ν between the finite-temperature moments (1) and their zero-temperature values. In the case of a *coherent* incoming field of intensity $|\alpha_0|^2$ we obtain

$$R_\nu = \nu!(u/\eta_0|\alpha_0|^2)^\nu L_\nu(-\eta|\alpha_0|^2/u) , \tag{5}$$

where η_0 denotes the zero-temperature quantum efficiency. A *Gaussian* field of intensity $\mathfrak{N}$ leads to

$$R_\nu = (\eta/\eta_0)^\nu (1 + u/\eta\mathfrak{N})^\nu . \tag{6}$$

Finally, for a superposition of these two fields we find

$$R_\nu = (\eta/\eta_0)^\nu (1 + u/\eta\mathfrak{N})^\nu \times L_\nu(-\eta|\alpha_0|^2/u + \eta\mathfrak{N})[L_\nu(-|\alpha_0|^2/\mathfrak{N})]^{-1} . \tag{7}$$

In Fig. 2 we show the temperature effect on the first moment ($\nu = 1$), i.e., the average intensity of the photoelectric current, for an incoming field with average photon density $\mathfrak{N} = 10^8$ (we remark that the first moment does not depend on the incident field statistics). To this end we plot the ratio R_1 as a function of $(\beta\epsilon)^{-1}$ for fixed values $2\gamma T = 10$ $(2\kappa_0 T) = 1$, where κ_0 denotes the zero-temperature field-attenuation constant, and various values N of the density of photosensitive atoms. A similar plot of R_2, the ratio of the variances, is shown in Fig. 3 for Gaussian and coherent radiation with the same average intensity $|\alpha_0|^2 = \mathfrak{N} = 10^8$. Figures 2 and 3 show that for each

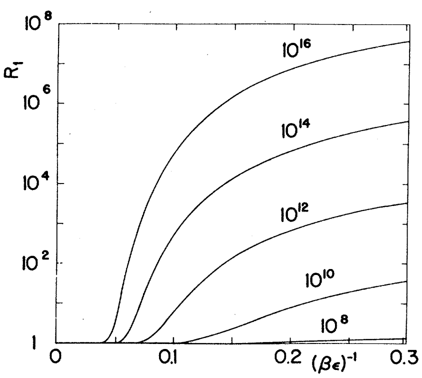

FIG. 2. Relative first moment of photoelectrons versus temperature measured in terms of $(\beta\epsilon)^{-1}$ for $2\gamma T = 10$ $(2\kappa_0 T) = 1$ and average photon density 10^8. Numbers labeling the different curves indicate the density N of the photosensitive atoms.

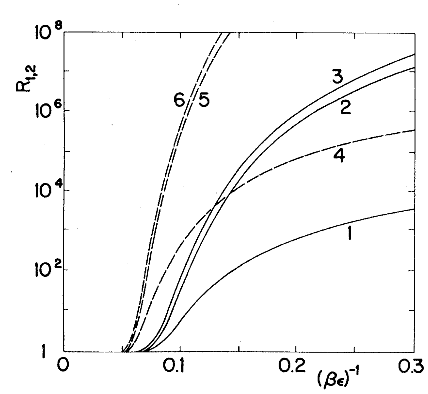

FIG. 3. Relative first and second moments, R_1 and R_2, versus $(\beta\epsilon)^{-1}$ for $2\gamma T = 10$ $(2\kappa_0 T) = 1$ and average photon density 10^8. Curve 1 corresponds to the first, curve 2 to the second moment for a Gaussian field, and curve 3 to the second moment for a coherent field. Curves 1, 2, 3 are for $N = 10^{12}$. Curves 4, 5, 6 are the same as 1, 2, 3, but with $N = 10^{14}$.

value $N/\mathfrak{N}$ there is a "threshold temperature" $(\beta\epsilon)^{-1}_{th}$ below which R_ν does not appreciably deviate from unity and above which the dark current contribution becomes more and more important. The values of $(\beta\epsilon)^{-1}$ where $R_1 - 1$ is of the order of say 10^{-2}, are $(\beta\epsilon)^{-1} = 0.062$, 0.048, 0.039, and 0.033 for $(N/\mathfrak{N}) = 10^4$, 10^6, 10^8, and 10^{10}, respectively. For instance, the value $(\beta\epsilon)^{-1} = 0.033$ for a CO_2 laser beam of 10.6-μm wavelength corresponds to a threshold temperature of 44 K, and for 1-eV photon energy the pertinent threshold is 380 K. These results show that the dark-current effect is predominant for all reasonable values of the ratio $N/\mathfrak{N}$ of the density N of photosensitive atoms to the density $\mathfrak{N}$ of incoming photons. An estimate of the dark current is essential for e.g., small signal detection. In principle, the dark current can be reduced by reducing $N/\mathfrak{N}$, e.g., by reducing the effective detector volume generating dark current. This technique is indeed currently applied.[2]

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[1]A. Selloni, P. Schwendimann, A. Quattropani, and H. P. Baltes, Phys. Rev. 18, 2234 (1978).

[2]S. R. Borello and M. A. Kinch, in *Utilization of Infrared Detectors*, Proceedings of the Society of Photo-Optical Engineers, edited by I. J. Spiro (Society of Photo-Optical Instrumentation Engineers, Palos Verdes Estates, California, 1978), Vol. 132, p. 27.