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Quantum microwaves/Micro-ondes quantiques

Non-classical radiation emission by a coherent conductor

Rayonnement non classique émis par un conducteur cohérent

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ABSTRACT

We report experimental evidence that the microwave electromagnetic field generated by a normal conductor, here a tunnel junction placed at ultra-low temperature, can be non-classical. By measuring the quadratures of the electromagnetic field at one or two frequencies in the GHz range, we demonstrate the existence of squeezing as well as entanglement in such radiation. In one experiment, we observe that the variance of one quadrature of the photo-assisted noise generated by the junction goes below its vacuum level. In the second experiment, we demonstrate the existence of correlations between the quadratures taken at two frequencies, which can be stronger than allowed by classical mechanics, proving that the radiation at those two frequencies are entangled.[1]

RÉSUMÉ

Nous rapportons des preuves expérimentales de ce que le champ électromagnétique micro-ondes généré par un conducteur normal, une jonction tunnel placée à ultra-basse température, peut avoir un comportement non classique. Nous démontrons l'existence de compression d'état ainsi que d'enchevêtrement dans cette radiation en mesurant les quadratures du champ électromagnétique à une ou deux fréquences de l'ordre du GHz. Dans une expérience, nous observons que la variance d'une quadrature du bruit photo-assisté généré par la jonction descend sous son niveau de vide. Dans une deuxième expérience, nous démontrons l'existence de corrélations entre les quadratures observées à deux fréquences, corrélations qui peuvent être supérieures à ce qui est permis par la mécanique classique, prouvant que la radiation à ces deux fréquences est enchevêtrée.[1]

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[1] Inspired from previous works/Inspiré de travaux antérieurs [1,2].

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1. Introduction

A great effort is currently deployed to find sources of quantum light. A light with properties beyond that of classical physics is indeed essential to the development of quantum information technology [3,4] and has direct applications in metrology [5]. Quantum light can be non-classical in several ways. Squeezed light offers the possibility of observing fluctuations lower than that of vacuum along one quadrature: the rms fluctuations ΔX^2 of the (in phase) amplitude of $X\cos(2\pi f_1 t)$ can be smaller than that of vacuum at the expense of an increase of the rms fluctuations ΔP^2 of the (quadrature) amplitude of $P\sin(2\pi f_1 t)$; this is necessary in order to preserve Heisenberg's uncertainty principle (for a review on squeezing, see [6–8]). Two-mode squeezed light refers to the existence of correlations between the quadratures of the electromagnetic field taken at two different frequencies f_1 and f_2 that go beyond what is allowed by classical mechanics [2]. A strong enough two-mode squeezing can lead to entanglement between the two frequencies [9].

Many systems have been devised to produce squeezed light, based for example on non-linear crystals, atomic transitions and non-linear cavities in optics [10], but also with parametric amplifiers and qubits in the microwave domain [11–14]. The key ingredient in all these systems is the existence of a nonlinearity, which allows the mixing of vacuum fluctuations with the classical, large field of a coherent pump. Here we use the discreteness of the electron charge e as a source of non-linearity: A tunnel junction (two metallic contacts separated by a thin insulating layer) has *linear* $I(V)$ characteristics at low voltage and thus cannot be used as a non-linear element to mix signals. There is no photo-assisted dc transport, i.e. no rectification. However, electrical current $I(t)$ flowing in a conductor always fluctuates in time, a phenomenon usually referred to as "electrical noise". Interestingly, this noise can be *non-linear* as a function of voltage, even if the $I(V)$ characteristics itself is linear.

While the dc current corresponds to the average $\langle I(t)\rangle$, current fluctuations are characterized by their statistical properties such as their second order correlator $\left\langle I(t)\, I\left(t'\right)\right\rangle$ or, in frequency space, the noise spectral density $S(f)=\left\langle |I(f)|^2\right\rangle$ where $I(f)$ is the Fourier component of the current at frequency f. Here the brackets $\langle\cdots\rangle$ represent the statistical average. The tunnel junction, as well as most coherent conductors, exhibits shot noise: the variance ΔI^2 of the current fluctuations generated by the junction depends on the bias voltage. For example, at low frequency and high current, the noise spectral density is given by $S(f_1=0)=e\,|I|$ (for a review on shot noise in mesoscopic conductors, see [15,16]), a strongly non-linear function. When under ac excitation, the junction exhibits photo-assisted noise [17–19] as well as a dynamical modulation of its noise [20,21]. We use this modulation of the *intrinsic* noise of the junction by an external ac excitation to generate squeezing.

An alternate approach is to consider that the time-dependent current fluctuations in the sample generate a random electromagnetic field that propagates along the electrical wires. Both these descriptions are equivalent. For example, the equilibrium current fluctuations (Johnson–Nyquist noise [22,23]) correspond to the blackbody radiation in one dimension [24]. More precisely, the power radiated by a sample at frequency f in a cable is proportional to the spectral density $S(f)$ of current fluctuations which, at high temperature and at equilibrium (i.e. with no bias), is given by $S(hf \ll k_\mathrm{B}T)=2k_\mathrm{B}T/R$, where T is the temperature and R the electrical resistance of the sample [25].

In short samples at very low temperatures, electrons obey quantum mechanics. Thus, electron transport can no longer be modeled by a time-dependent, classical number $I(t)$, but needs to be described by an operator $\hat{I}(t)$. Current fluctuations are characterized by correlators such as $\left\langle \hat{I}(t)\,\hat{I}\left(t'\right)\right\rangle$. Quantum predictions differ from classical ones only when the energy hf associated with the electromagnetic field is comparable with energies associated with the temperature $k_\mathrm{B}T$ and the voltage eV. Hence for $hf \gg k_\mathrm{B}T, eV$, the thermal energy $k_\mathrm{B}T$ in the expression of $S(f)$ has to be replaced by that of vacuum fluctuations, $hf/2$. Some general link between the statistics of current fluctuations and that of the detected electromagnetic field is required beyond the correspondence between spectral density of current fluctuations and radiated power [26–30]. In particular, since the statistics of current fluctuations can be tailored by engineering the shape of the time-dependent bias voltage [31], it is possible to induce non-classical correlations in the electromagnetic field generated by a quantum conductor. For example, an ac bias at frequency f_0 generates correlations between current fluctuations at frequencies f_1 and f_2, i.e. $\left\langle \hat{I}(f_1)\hat{I}(f_2)\right\rangle \neq 0$, if $f_1 \pm f_2 = nf_0$ with n, an integer [20,21,32]. This is responsible for the existence of correlated power fluctuations [33] and for the emission of photon pairs [34] recently observed. For $f_1=f_2$, $\left\langle \hat{I}^2(f_1)\right\rangle \neq 0$ leads to vacuum squeezing.

Entanglement of photons of different frequencies has already been observed in superconducting devices engineered for that purpose in [35,14,36], where frequencies f_1 and f_2 are fixed by resonators and the entanglement comes from a non-linear element, a Josephson junction. What we show here is that a quantum conductor excited at frequency f_0 can emit entangled radiation at *any* pair of frequencies f_1, f_2 such that $f_0=f_1+f_2$. This property is demonstrated using a tunnel junction but our results clearly stand for any device that exhibits quantum shot noise. The key ingredient for the appearance of entanglement is the following: noise at any frequency f_1 modulated by an ac voltage at frequency f_0 gives rise to sidebands with a well-defined phase. These sidebands, located at frequencies $\pm f_1 \pm nf_0$ with n, an integer, are correlated with the current fluctuations at frequency f_0. The particular case $f_2=-f_1+f_0$ we study here corresponds to the maximum correlation.

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