

Measuring fluorescence by observing field quadrature noise

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We perform balanced homodyne detection of the electromagnetic field in a single-mode tapered optical nanofiber surrounded by rubidium atoms in a magneto-optical trap. Resonant fluorescence of atoms into the nanofiber mode manifests itself as increased quantum noise of the field quadratures. The autocorrelation function of the homodyne detector's output photocurrent exhibits exponential fall-off with a decay time constant of 26.3 ± 0.6 ns, which is consistent with the theoretical expectation under our experimental conditions. **To our knowledge, this is the first experiment in which fluorescence has been observed and measured by balanced optical homodyne detection.** © 2018 Optical Society of America

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1. INTRODUCTION

A tapered optical nanofiber (TNF) [1] is manufactured by heating and elongating a regular optical fiber, reducing its diameter below the optical wavelength. A significant fraction of the optical mode guided by such a fiber propagates as an evanescent field, which can interact with atoms or artificial atom-like objects placed in the neighborhood of the fiber. Because the field stays focused over a macroscopic length determined by the profile of the TNF, it can interact with a large number of such objects [2, 3]. This makes TNF an attractive tool for various quantum light-matter interfacing applications, such as quantum-optical memory [4, 5] and cavity quantum electrodynamics [6].

The TNF has the property to “suck in” spontaneous emission from atoms in its direct neighborhood: due to Purcell-like effects, a significant fraction of that emission occurs via the guided mode [7, 8]. This effect has been utilized, for example, for measuring the temperature of magneto-optical traps [9–11] as well as sensing position of atoms in optical lattices [11]. It is also an excellent tool to study the undesired process of atom's condensation on the nanofiber's surface [12]. Resonant fluorescence,

an inherently multimode phenomenon, can be detectable in a single mode of the TNF, even if produced by only a few emitters. This makes fluorescence amenable to homo- and heterodyne methods, which can detect light only in the optical mode of the local oscillator. So far, heterodyne detection of the fluorescence into the nanofiber has been performed by observing the statistics of correlation events from two single-photon detectors exposed to an interference signal between the fluorescence signal and a microscopic local oscillator [13].

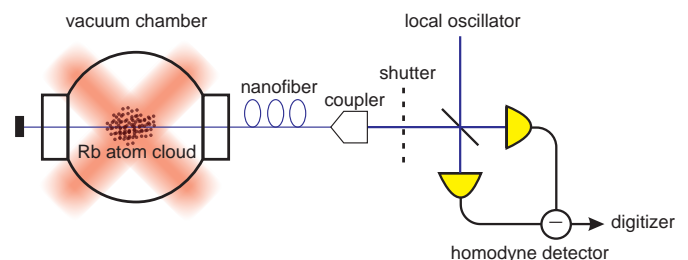


Fig. 1. Schematic diagram of the experiment. The cold atomic cloud is overlapped over the TNF in the vacuum chamber. The shutter alternates the acquisition of the vacuum field and the signal from atoms by the BHD.

Here we measure resonant fluorescence into a TNF by means of “classic” balanced homodyne detection with a strong local oscillator (Fig. 1), which obviates the need for single-photon detectors. Balanced homodyne detection is a powerful approach capable of completely characterizing an arbitrary quantum state of light [14] by analyzing the noise statistics of the detector's output photocurrent. If, in addition, the temporal autocorrelation behavior of that photocurrent is analyzed, one can obtain the information about the temporal mode in which a given optical state (e.g., a single photon) is generated [15–17].

Our experiment consists in continuous measurement of the output photocurrent of the detector, which is proportional to the instantaneous measurement of the electric field quadrature of the single TNF mode. We extract the information about the fluorescence spectrum from the autocorrelation statistics of this photocurrent. Specifically, the difference between the autocorre-

lation profiles in the presence and absence of rubidium atoms around the nanofiber reproduces the exponential temporal profile of the photons emitted thanks to resonant fluorescence.

2. MEASURING TEMPORAL PROFILE BY HOMODYNE DETECTION

A simple way to visualize our technique is to think of the optical field spontaneously emitted by the atoms into the fiber as a stationary stochastic process. The balanced homodyne detector (BHD)'s output voltage $V(t)$ is proportional to the amplitude of that field in the fiber mode as a function of time; hence, the autocorrelation $\langle V(t)V(t + \Delta t) \rangle_t$ can be calculated. According to the Wiener-Khinchin theorem, the Fourier transform of this autocorrelation is equal to the power spectrum of the resonant fluorescence, which is a Lorentzian line whose width, γ , is evaluated below. The autocorrelation function can be expected to be double-exponential with a decay constant of $2/\gamma$.

However, the measured signal is microscopic, and hence contaminated by the shot noise of the local oscillator. In order to quantitatively predict the spectrum and amplitude of the signal, we apply the quantum analysis of Refs. [15–17]. In this analysis, time is treated in terms of short discrete bins of duration τ in order to accommodate the discrete nature of digital data acquisition: the k th bin corresponds to the moment $t = k\tau$. Suppose photons with the same temporal density matrix ρ_{jk} are repeatedly emitted into a certain spatial mode. The time-dependent electromagnetic field quadrature in this mode is being measured with a BHD with the quantum efficiency η . The mean autocorrelation of the quadrature values at time bins j and k is then given by [15–17]

$$\langle X_j X_k \rangle = \frac{1}{2} \delta_{jk} + \eta \text{Re} \rho_{jk}. \quad (1)$$

Here the first term corresponds to the shot noise (the vacuum field whose quadrature variance is normalized to $\langle X^2 \rangle = \frac{1}{2}$) and the second term to the field of the photon [17]. In the case of spontaneous emission,

$$\rho_{jk} = \theta(j)\theta(k)\gamma\tau e^{-\frac{\gamma}{2}(j+k)}, \quad (2)$$

where $\theta(\cdot)$ is the Heaviside step function and the factor of $\gamma\tau$ is due to normalization, so that $\text{Tr} \rho_{jk} = 1$ for $\gamma\tau \ll 1$.

Equation (1) assumes that the photons are repeatedly emitted at the same time with respect to a certain reference. In our case, the emission occurs at random times, so the autocorrelation has to be averaged over random moments m of the emission

$$\langle X_j X_k \rangle = \frac{1}{2} \delta_{jk} + \eta \text{Re} \langle \rho_{j-m, k-m} \rangle_m. \quad (3)$$

If $f \ll \gamma$ is the average frequency at which photons are emitted, m can be assumed to be uniformly distributed in the interval from $-1/(2f\tau)$ to $1/(2f\tau)$. Substituting the density matrix (2), we find $\langle X_j X_k \rangle = \frac{1}{2} \delta_{jk} + \eta f \tau e^{-\frac{\gamma}{2}|j-k|}$, which can be rewritten as

$$A_X(l) \equiv \langle X_j X_{j+l} \rangle_j = \frac{1}{2} \delta_{l,0} + \eta f \tau e^{-\frac{\gamma}{2}|l|}. \quad (4)$$

Remarkably, the quadrature variance ($A_X(0)$) does not depend on the spontaneous emission rate γ . This is because the pulse associated with each photon (whose height is proportional to γ , and width is inversely proportional to γ) is randomly distributed over a time interval that is much larger than its duration.

It remains to account for the electronic noise and bandwidth of the BHD. The role of the electronic noise is equivalent to an

optical loss of about 10% [18], and therefore insignificant for our treatment. The effect of the final bandwidth is to relate the BHD output voltage to the field quadratures by the convolution $V_j = \sum_{j'} X_{j'} R_{j-j'}$, where R is the detector's temporal response function [19]. Accordingly, the autocorrelation profile of the voltage is related to that of the quadratures via the convolution

$$A_V(l) \equiv \langle V_j V_{j+l} \rangle_j = \sum_{l'} A_X(l') A_{V0}(l-l'), \quad (5)$$

where $A_{V0}(l-l') = \sum_i R_i R_{i+l-l'}$ is the convolution of the response function with itself. This function is equal to the autocorrelation exhibited by the BHD output voltage in response to the vacuum field, in which case only the first term in Eq. (4) is present, and can therefore be easily measured [Fig. 2(a)]. The difference between the voltage autocorrelation profiles in response to the atomic fluorescence and the vacuum field yields the second term in Eq. (4) which is of interest to us. Although this second term is also distorted by the convolution with A_{V0} , this effect is negligible because, as evidenced by Fig. 2(a), the response time of the detector is ~ 5 ns, much shorter than the relevant lifetime of the D_2 transition in Rubidium-87 ($T_1 = 26$ ns) [20]. Therefore we can approximately write

$$A_V(l) \approx \frac{1}{2} A_{V0}(l) + \eta f \tau e^{-\frac{\gamma}{2}|l|}. \quad (6)$$

The first term in Eq. (6) provides us with natural means to find the proportionality coefficient between the experimentally observed output voltage of the BHD and the corresponding quadrature. Knowing this coefficient, we can then determine the magnitude of the second term and hence the rate f of photon emission into the nanofiber.

3. EXPERIMENT AND RESULTS

The tapered nanofiber (TNF) is manufactured by pulling a commercial single mode fiber by flame brushing technique [21]. This technique allows flexibility in choosing the radius and length of the waist of the TNF. For our experiment, we keep a radius of 230 ± 20 nm and a waist length of 10 mm. The TNF is loaded in an ultra high vacuum chamber where Rubidium-87 atoms are prepared in a magneto optical trap (MOT). The position of the MOT is manipulated by three orthogonal compensating coils to ensure the best coupling.

The TNF collects fluorescence of the atoms excited by the MOT beams. We take the output signal from one end of the TNF and connect it to a 90:10 fiber beam splitter. The 10% output is directed to a single photon counting module to monitor the photon emission rate. The other output of the beam splitter is taken as the signal for homodyne detection, which is realized by a home-made BHD [19, 22, 23] with the local oscillator tuned to the expected emission frequency. The BHD output data are collected by a 8-bit digitizer card (Acqiris DP-240) with a resolution of $\tau = 2$ ns. A few samples of the collected data are shown in Fig. 2(b).

The MOT cooling laser is resonant to the $6S_{1/2}, F = 2 \rightarrow 6P_{3/2}, F' = 3$ cycling transition (selection rules prohibit the atom to decay into the $F = 1$ ground state). Those atoms that do decay outside $6S_{1/2}, F = 2$ are repumped by the MOT repumping beam. Thus, majority of the photons coupled into the fiber are at the frequency of the cooling transition. The observed photon count rate of the SPCM is ~ 10 KHz, giving a photon emission rate of $f \sim 150$ KHz. This means that the ratio between the signal from the atoms, given by the second term in Eq. (6), and the shot

noise, given by the first term, is on a scale of $2f\tau/2 \approx 3 \times 10^{-4}$ (the factor of 1/2 is because the homodyne detector is only sensitive to a specific polarization direction). In the experiment, we observe this ratio to be $\sim 2.5 \times 10^{-4}$.

In order to obtain a better signal to noise ratio, we acquire large sets of data. Specifically, the data corresponding to 5×10^{10} 2-ns bins are acquired and analyzed. This corresponds to a relative uncertainty of $\sim 5 \times 10^{-6}$ for each point of the autocorrelation profile. But because the atomic signal itself is very small in comparison with the vacuum autocorrelation, this signal has a relative statistical uncertainty on a scale of 2%, and is hence visibly noisy [Fig. 2(c)]. Additionally, the variance of the shot noise current drifts due to fluctuations in the LO power. To circumvent this issue, we alternate the acquisition of the signal from atoms and vacuum with the help of a shutter as seen in Fig. 1 with a period of 2 s. The difference in autocorrelation functions is calculated for alternate sets and averaged over multiple sets.

Figure 2(c) shows the difference of the BHD voltage autocorrelation in the presence and absence of atoms. The autocorrelation profile resembles an exponential decay with the time constant of $2/\gamma = 26.3 \pm 0.6$ ns. This is about twice as fast as one would expect for a free spontaneously decaying rubidium atom, for which $1/\gamma_0 = 26.24$ ns [20].

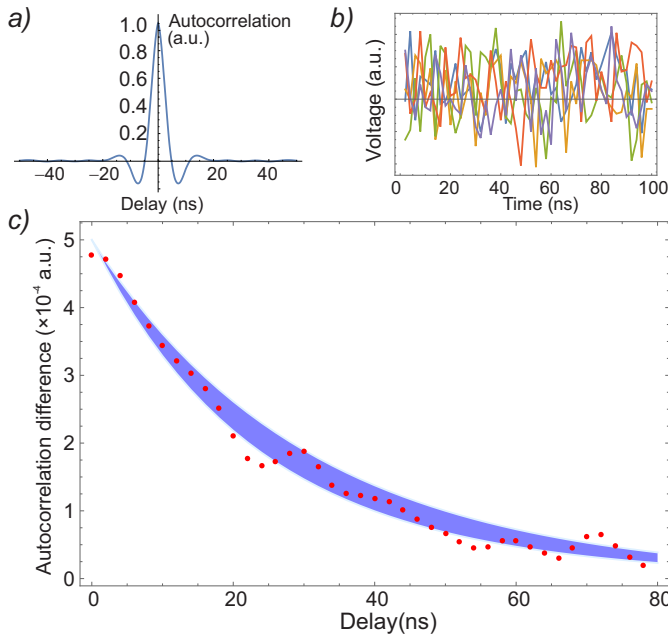


Fig. 2. Experimental results. a) Auto-correlation $A_{V0}(l)$ of the signal from the BHD without atoms. b) Five samples of the BHD output signal. c) Difference $A_V(l) - A_{V0}(l)$ between the BHD signal autocorrelation profile in the presence and absence of atoms, corresponding to the resonance fluorescence. The red dots indicate the experimental data and the blue region is the theoretical prediction. The uncertainty in the theory is due to the uncertainty in the fiber radius. The vertical axis units in (a) and (c) are consistent with each other.

4. THEORETICAL MODEL

We ascribe this discrepancy to two factors. First, the field we observe is resonant fluorescence rather than spontaneous emission: the atom is being excited at the same time as it is emitting.

The spectrum of the resonance fluorescence is described by the central peak of the Mollow triplet, whose width depends on the Rabi frequency of the pump field as well as its detuning from the resonance. In our case, we estimate the Rabi frequency of the MOT trapping beams as 2.2γ and their detuning as -2.6γ , which yields the peak width of $1.6\gamma_0$ [24].

Second, the TNF modifies the electromagnetic mode structure around an atom, and therefore alters the atomic spontaneous emission rate due to Purcell-like effects [25]. The theoretical analysis of this modification is done by considering a classical oscillating dipole in the vicinity of the TNF. The spontaneous decay rate of an emitter is directly proportional to the power emitted by such a classical dipole [26]. We evaluated this power by finite-difference time-domain simulation using the software package Meep [27].

The Purcell enhancement is evaluated by taking the ratio of the total flux emitted by the dipole in the presence and absence of the TNF. It exhibits dependence on the orientation of the emitter and its distance from the TNF as seen in Fig. 3. The effect fades within ~ 400 nm from the fiber surface.

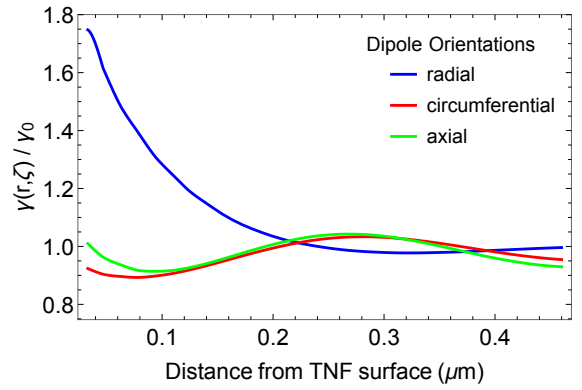


Fig. 3. Theoretically calculated ratio of the electromagnetic power produced by a classical emitter in the neighborhood of a TNF to that without TNF as a function of the atomic distance from the fiber surface. The TNF has a radius of 230 nm. The three plots correspond to different orientations of the dipole with respect to the TNF.

Since our system contains many atoms, the autocorrelation function of the BHD photocurrent is obtained by averaging all possible positions and orientations, so Eq. (2) takes the form

$$\rho_{jk} = \frac{1}{3} \theta(j) \theta(k) \sum_{\zeta=1}^3 \int \gamma(r, \zeta) \alpha(r, \zeta) \tau e^{-\gamma(r, \zeta) \tau(j+k)/2} n(r) dV, \quad (7)$$

where $\gamma(r, \zeta)$ is the net decay rate as a function of the dipole orientation ζ and its distance r from the fiber surface (Fig. 3), $n(r)$ is the atomic number density, which we assume spatially independent and $\alpha(r)$ is a weight factor which defines the fraction of the emission that goes into the guided mode. The coupling into the guided mode depends on the dipole's orientation and its distance from the surface [28]. Mathematically, it is given by

$$\alpha(r) = \frac{\gamma(r, \zeta) - \gamma_0}{\gamma(r, \zeta)} \quad (8)$$

Since the atoms closer to the TNF give a stronger contribution to the intensity, we expect a rapidly decaying weight factor. Averaging the density matrix according to Eq. (7), we obtain a

decay profile that is very well approximated by an exponential with the decay rate $\gamma_{\text{avg}} \approx (1.25 \pm 0.1)\gamma_0$, where the uncertainty is due to that in the fiber radius.

The aggregate action of the two factors modifying the decay rate gives a factor of $1.6 \times 1.25 = 2.0 \pm 0.15$, consistent with our experimental observation.

Our experimental data permit us to estimate the mean number of photons emitted into the nanofiber by the surrounding atoms. The average quadrature variance associated with the single-photon state is three times that of the vacuum. That is, if each time interval τ in the measured mode contained a photon, we would observe $A_V(0) - A_{V0}(0) = 2A_{V0}(0)$. In fact, we observe $A_V(0) - A_{V0}(0) = 2.5 \times 10^{-4}A_{V0}(0)$. This means the photons arrive at an average rate of $r = 1.25 \times 10^{-4}\tau^{-1} = 6.25 \times 10^4 \text{ s}^{-1}$. This is consistent with our estimate made with the SPCM, given that the BHD is sensitive to only one polarization mode.

The MOT has a density of about $10^{10} - 10^{11} \text{ atoms/cm}^3$ resulting in around 30 – 300 atoms within a radius of 500 nm around the 3-mm TNF waist. The average weight factor $\alpha(r, \zeta)$ integrated over this neighbourhood of the TNF is about 10^{-3} . Estimating about a half of the population to be in the excited state at any given time, we expect the photon emission rate into the fiber mode to be on a scale of 50 – 500 KHz. This is consistent with the measured photon count rate.

The use of evanescent dipole traps [29] would enhance the average atom number by 3–4 orders of magnitude, making the contribution of the atomic fluorescence to the homodyne signal comparable to the shot noise. Under these circumstances, not only the temporal properties, but also complete quantum state characterization of the spontaneously emitted light would become possible to measure. As a final comment, we believe this to be the first experiment in which atomic fluorescence has been measured with balanced homodyne detection. This may appear paradoxical because fluorescence is seen as an inherently incoherent phenomenon whereas nonzero autocorrelation of the BHD output voltage indicates the presence of some degree of coherence in that emission. Of course, this coherence is nothing but a consequence of a finite spectral width of the fluorescence [30].

5. FUNDING INFORMATION

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