Back action evading electro-optical transducer

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Electro-optical transducers are utilized for upconversion of radio frequency (RF) signals to the optical frequency domain to study the RF signals with optical tools. The transducers frequently impact on the RF system and introduce additional noise, including optical shot noise as well as quantum back action noise, limiting the measurement accuracy. In this paper we theoretically study a technique based on a high efficiency electro-optical phase modulation effect that allows back action evading detection of an RF field quadrature. The main idea of proposed method is independent homodyne detection of two (Stokes and anti-Stokes) optical modes. It allows subsequent postprocessing of the detected signals, which, in turn, results in a broadband back action evading measurement leading to the high sensitivity evaluation of the RF signals.

INTRODUCTION

Photonics is instrumental for generation [1–3], synthesis [4], detection and distribution [5, 6] of RF, microwave and millimeter wave signals. Significant attention has been attracted recently to the nonlinear cavity-enhanced microwave photonic devices utilized for the purpose [7–11]. The monolithic optical microcavities, on one hand, enable efficient phase matching of the nonlinear conversion processes due to the small cavity size and, on the other hand, enable high conversion efficiency due to the high quality (Q-) factors.

Quantum operation of the electro-optic transducers became feasible because of the high efficiency of the resonant electro-optical processes [5, 12–14], availability of room temperature single photon detectors as well as quantum processors operating in the RF domain. The quantum electro-optical transducers provide a way of low loss transfer and detection of the microwave quantum states [7, 13, 15].

The electro-optical transduction involves the linear electro-optic effect which corresponds to the dependence of the index of refraction of some optical crystals on an electric field amplitude of the RF signal of interest. The effect leads to the phase sensitive modulation of light. The electro-optical modulation effect was noticed as a process physically similar to the optical rectification [16–19]. The effect was utilized for electro-optical modulation at microwave frequencies more than a half century ago [20]. The modulators constitute one of the building blocks of RF photonics, as can be seen from the multiple detailed reviews [21–25].

Reported previously methods assume that there is a single parametric channel transferring information from an RF photon to an optical photon. An ultimate high fidelity parametric transducer that converts RF photons to the optical frequency domain enables counting the photons with an accuracy limited by the RF photon shot noise. However, the single RF photon counters were not realized experimentally in a devices based on monolithic microcavities because of technical restrictions.

In this paper we introduce a back-action evading technique for detection of RF signals using a simple low loss resonant phase modulator capable of producing multiple optical harmonics when an RF signal is present. The upconversion of the RF signal to optical domain corresponds to establishing a photonic gain in the system [7]. For instance, if an RF photon with carrier frequency \(\omega_{RF}\) is upconverted to optical frequency \(\omega_0\), the power of the RF source is increased by \(\omega_0/\omega_{RF}\). We show that unlike early electro-optical transducers, the device based on the phase modulation allows generation of a few optical photons per one RF photons which further increases the photonic gain in the device. This parametric amplification is accompanied by a back-action noise that masks the signal. We found that the back action can be removed from the measured signal due to quantum correlation among the optical modulation harmonics.

MODEL AND BASIC EQUATIONS

Let us consider physical system depicted in Figure (1). An anti-reflection coated electro-optical crystal is inserted into an optical resonator supporting three optical modes only. The frequency difference between each consecutive pair of modes corresponds to the frequency of the RF signal fed into the electro-optical crystal. The central optical mode is pumped with monochromatic light. As the result of the electro-optical interaction the light exiting the optical resonator becomes modulated. The modulation harmonics are generated in the corresponding optical modes of the resonator. To perform the measurements of the RF signal entering the electro-optical crystal we independently detect and analyze the modulation harmonics leaving the resonator. The goal of the
measurement is to achieve as high as possible measurement sensitivity of the amplitude and phase components of the RF field. The three-mode configuration is introduced for the sake of simplicity of the description of the proposed measurement technique.

Let us start from the Hamiltonian of the system. We consider three optical modes including central one, described with annihilation operator \( c \) and carrier frequency \( \omega \), red shifted one, described with annihilation operator \( c_m \) and carrier frequency \( \omega_m \), and blue shifted one, described with annihilation operator \( c_p \) and carrier frequency \( \omega_p \). The modes are coupling through the RF field described by annihilation operator \( d \) with carrier frequency \( \omega_d \).

\[
H = H_0 + V, \quad (1a)
\]
\[
H_0 = \hbar \omega c^\dagger c + \hbar \omega_m c_m^\dagger c_m + \hbar \omega_p c_p^\dagger c_p + \hbar \omega_d d^\dagger d, \quad (1b)
\]
\[
V = \hbar \eta (c_m^\dagger d^\dagger + c_p^\dagger d) c + \hbar \eta^*(c_m d + c_p d^\dagger) c^\dagger. \quad (1c)
\]

For the sake of simplicity we assume that the optical frequencies are equidistant and their frequency difference is equal to the frequency of the RF cavity:

\[
\omega_p - \omega = \omega - \omega_m = \omega_d. \quad (2)
\]

The coupling constant is measured in frequency units and is defined as

\[
\eta = \frac{1}{2} \omega n_c^2 r \sqrt{\frac{2\pi \hbar \omega_d}{n_d^2 \nu_d}} \xi, \quad (3)
\]

where \( n_c \) and \( n_d \) are the refractive indexes of the optical and RF modes, correspondingly, \( r \) is the electro-optic coefficient of the material for the selected polarizations of the modes, \( \nu_d \) is the volume of the RF mode,

\[
\xi = \frac{1}{V} \int dV |\Psi|^2 \quad (4)
\]

is the overlap integral of the optical and RF fields, \( |\Psi|^2 \), \( |\Psi_m|^2 \), and \( |\Psi_d|^2 \) are the spatial distributions of the power of the optical and microwave fields respectively,

\[
(1/V) \int |\Psi|^2 dV = 1, \quad V \text{ is the mode volume for the optical cavity. We assume that the optical modes are nearly identical, i.e. } \omega \approx \omega_{p,m} \gg \omega_d, \text{ and } V \approx V_{p,m},
\]

\[
\int dV |\Psi|^2 \Psi_d = \int dV |\Psi|^2 \Psi_m. \quad (d)
\]

Using the Hamiltonian we derive the equations for the fields, assuming all the resonant coupling. We also introduce the attenuation constants and external pumping, following the general rules of the Langevin equation formalism

\[
\dot{c} + \gamma c = -i \eta^* (c_m d + c_p d^\dagger) + \sqrt{2\gamma a}, \quad (5a)
\]
\[
\dot{c}_m + \gamma c_m = -i \eta d^\dagger c + \sqrt{2\gamma a_m}, \quad (5b)
\]
\[
\dot{c}_p + \gamma c_p = -i \eta d c + \sqrt{2\gamma a_p}, \quad (5c)
\]
\[
\dot{d} + \gamma_M d = -i \eta c^\dagger_m c - i \eta^* c^\dagger_p c^\dagger + \sqrt{2\gamma_M q} + i f_s. \quad (5d)
\]

The external signal can be presented in form

\[
f_s = e^{-i \phi_s} \sqrt{\frac{2 P_d \gamma_M}{\hbar \omega_d}}, \quad (6)
\]

where \( P_d \) is the power of the RF signal and \( \phi_s \) is the phase of the RF signal. The set of equations has to be supplied with expressions for the fields leaving the optical resonator:

\[
b_{p,m} = -a_{p,m} + \sqrt{2\gamma} c_{p,m}. \quad (7)
\]

It is important to note that the signal depends on the attenuation coefficient \( \gamma_M \). We cannot consider a lossless mechanical system to perform the measurements discussed here.

**SOLUTION OF THE LANGEVIN EQUATIONS**

The steady state equations for the expectation values of the field amplitudes in the case of the all-resonant tuning can be written as

\[
\gamma C = -i \eta^* (C_m D + C_p D^*) + \sqrt{2\gamma} A, \quad (8a)
\]
\[
\gamma C_m = -i \eta D^* C, \quad (8b)
\]
\[
\gamma C_p = -i \eta D C, \quad (8c)
\]
\[
\gamma_M D = -i \eta C_m^* C - i \eta^* C_p C^*. \quad (8d)
\]

Let us assume that the RF signal is weak (\( D = 0 \)). In this case \( C = A \sqrt{2\gamma} \), and \( C_m = C_p = 0 \).

Let us show that the solution is stable. We write a set of the equations neglecting by the external pumping:

\[
\dot{c} + \gamma c = 0, \quad (9a)
\]
\[
\dot{c}_m + \gamma c_m = -i \eta d^\dagger C, \quad (9b)
\]
\[
\dot{c}_p + \gamma c_p = -i \eta d C, \quad (9c)
\]
\[
\dot{d} + \gamma_M d = -i \eta c^\dagger_m C - i \eta^* c_p C^*. \quad (9d)
\]
Separating Eq. (9a) from the set we obtain the characteristic equation
\[
\left| \begin{array}{ccc} 
    
    \lambda + \gamma & 0 & i\eta C^* \\
    0 & \lambda + \gamma & i\eta C \\
    i\eta C & i\eta C^* & \lambda + \gamma_M 
  \end{array} \right| = 0
\]
(10)
which has all negative roots \(\lambda_{1,2} = -\gamma < 0, \lambda_3 = -\gamma_M < 0\), confirming that the solution is stable.

The set of equations for the Fourier amplitudes of the fluctuation parts of the operators can be written as
\[
(\gamma - i\Omega)c_m^\dagger = i\eta d^\dagger C^* + \sqrt{2}\gamma d_m^\dagger,
\]
(11a)
\[
(\gamma - i\Omega)c_p = -i\eta d C + \sqrt{2}\gamma a_p,
\]
(11b)
\[
(\gamma_M - i\Omega)d = -i\eta c_m C - i\eta c_p C^* + \sqrt{2}\gamma M q + if_s,
\]
where \(c_p \equiv c_p(\Omega), \ c_m^\dagger \equiv c_m^\dagger(-\Omega)\) and so on.

Introducing quadrature amplitudes
\[
c_{pa} = \frac{c_p e^{i\phi} + c_m^\dagger e^{-i\phi}}{\sqrt{2}}, \quad c_{p\phi} = \frac{c_p e^{i\phi} - c_m^\dagger e^{-i\phi}}{i\sqrt{2}},
\]
(12a)
\[
c_{ma} = \frac{c_m e^{i\phi} + c_m^\dagger e^{-i\phi}}{\sqrt{2}}, \quad c_{m\phi} = \frac{c_m e^{i\phi} - c_m^\dagger e^{-i\phi}}{i\sqrt{2}},
\]
(12b)
\[
d_a = \frac{d + d^\dagger}{\sqrt{2}}, \quad d_{\phi} = \frac{d - d^\dagger}{i\sqrt{2}}.
\]
(12c)
where \(\eta C = |\eta C|e^{-i\phi}\). Using Eq. (11) we derive
\[
(\gamma - i\Omega)c_m = -|\eta C|d_{\phi} + \sqrt{2}\gamma a_{ma},
\]
(13a)
\[
(\gamma - i\Omega)c_{m\phi} = -|\eta C|d_{\phi} + \sqrt{2}\gamma a_{m\phi},
\]
(13b)
\[
(\gamma - i\Omega)c_{pa} = |\eta C|d_{\phi} + \sqrt{2}\gamma a_{pa},
\]
(13c)
\[
(\gamma - i\Omega)c_{p\phi} = -|\eta C|d_{\phi} + \sqrt{2}\gamma a_{p\phi},
\]
(13d)
\[
(\gamma_M - i\Omega)d_a = -|\eta C|c_{ma} + |\eta C|c_{p\phi} + \sqrt{2}\gamma M q_{a} - f_{\phi},
\]
(13e)
\[
(\gamma_M - i\Omega)d_{\phi} = -|\eta C|c_{ma} - |\eta C|c_{pa} + \sqrt{2}\gamma M q_{\phi} + f_{a}.
\]
(13f)

Let us assume that we are able to measure output waves from modes \(c_m\) and \(c_p\) separately. This is reasonable since the microwave frequency can exceed tens of GHz and low loss filters with narrower bandwidth exists. Let us introduce linear combinations of the quadrature amplitudes
\[
\alpha_{\pm a} = \frac{d_{pa} \pm a_{ma}}{\sqrt{2}}, \quad \alpha_{\pm \phi} = \frac{d_{p\phi} \pm a_{m\phi}}{\sqrt{2}},
\]
(14a)
\[
g_{\pm a} = \frac{c_{pa} \pm c_{ma}}{\sqrt{2}}, \quad g_{\pm \phi} = \frac{c_{p\phi} \pm c_{m\phi}}{\sqrt{2}},
\]
(14b)
\[
\beta_{\pm a} = \frac{b_{pa} \pm b_{ma}}{\sqrt{2}}, \quad \beta_{\pm \phi} = \frac{b_{p\phi} \pm b_{m\phi}}{\sqrt{2}},
\]
(14c)
and rewrite set (13) in form
\[
(\gamma - i\Omega)g_{+a} = \sqrt{2}\gamma \alpha_{+a},
\]
(15a)
\[
(\gamma - i\Omega)g_{-a} = \sqrt{2}|\eta C|d_{a} + \sqrt{2}\gamma \alpha_{-a},
\]
(15b)
\[
(\gamma_M - i\Omega)d_{a} = -\sqrt{2}|\eta C|g_{+a} + \sqrt{2}\gamma M q_{a} + f_{a},
\]
(15c)
\[
(\gamma - i\Omega)g_{+\phi} = -\sqrt{2}|\eta C|d_{a} + \sqrt{2}\gamma \alpha_{+\phi},
\]
(15d)
\[
(\gamma - i\Omega)g_{-\phi} = \sqrt{2}\gamma \alpha_{-\phi},
\]
(15e)
\[
(\gamma_M - i\Omega)d_{a} = \sqrt{2}|\eta C|g_{-\phi} + \sqrt{2}\gamma M q_{a} - f_{\phi}.
\]
(15f)

In addition, for the output fields we get using (7)
\[
\beta_{+a} = -\alpha_{+a} + \sqrt{2}\eta C a_{+a} = \gamma + i\Omega \alpha_{+a},
\]
(16a)
\[
\beta_{-a} = \frac{\gamma + i\Omega}{\gamma - i\Omega} \alpha_{-a} + \frac{2\sqrt{\gamma C} |\eta C|}{\gamma - i\Omega} d_{\phi},
\]
(16b)
\[
\beta_{-\phi} = -\alpha_{-\phi} + \sqrt{2}|\eta C|g_{-\phi} = \gamma + i\Omega \alpha_{-\phi},
\]
(16c)
\[
\beta_{+\phi} = \frac{\gamma + i\Omega}{\gamma - i\Omega} \alpha_{+\phi} + \frac{2\sqrt{\gamma C} |\eta C|}{\gamma - i\Omega} d_{a}.
\]
(16d)

Introducing notations
\[
\beta = \frac{\gamma + i\Omega}{\gamma - i\Omega}, \quad K = \frac{4|\eta C|}{\gamma^2 + \Omega^2},
\]
(17a)
we rewrite Eqs. (16) as
\[
\beta_{-a} = \beta \alpha_{-a} - \frac{\beta K}{(\gamma M - i\Omega)} \alpha_{+a} + \frac{\sqrt{3}K}{(\gamma M - i\Omega)} (\sqrt{2}\gamma M q_{a} + f_{a}),
\]
(18a)
\[
\beta_{+\phi} = \beta \alpha_{+\phi} - \frac{\beta K}{(\gamma M - i\Omega)} \alpha_{-\phi} - \frac{\sqrt{3}K}{(\gamma M - i\Omega)} (\sqrt{2}\gamma M q_{a} - f_{\phi})
\]
(18b)
Here the terms proportional to \(K\) result from the back action.

**MEASUREMENT STRATEGY**

We see that sum \(\beta_{+a}\) of output quadratures contains only input fluctuations \(\alpha_{+a}\), whereas difference \(\beta_{-a}\) contains both input fluctuations \(\alpha_{-a}\) and term proportional to RF phase quadrature \(d_{\phi}\). In turn, \(d_{\phi}\) (15c) depends on back action \(\alpha_{+a}\). Hence, post processing of independent measurements of \(\beta_{+a}\) and \(\beta_{-a}\) gives us possibility of complete exclusion of back action. For this we have to take the following combinations
\[
\beta_a = \frac{K}{(\gamma M - i\Omega)} \beta_{+a} + \beta_{-a} = \beta \alpha_{-a} + \frac{\sqrt{3}K}{(\gamma M - i\Omega)} (\sqrt{2}\gamma M q_{a} + f_{a})
\]
(19a)
\[
\beta_{\phi} = \frac{K}{(\gamma M - i\Omega)} \beta_{+\phi} + \beta_{-\phi} = \beta \alpha_{+\phi} - \frac{\sqrt{3}K}{(\gamma M - i\Omega)} (\sqrt{2}\gamma M q_{a} - f_{\phi})
\]
(19b)
In this scheme the SQL arises when we measure only one combination $\beta_{-a}$ or $\beta_{+\phi}$. For the case when we measure $\beta_{-a}$ (16b) we get

$$S_n(\Omega) = 2\gamma_M(2n_T + 1) + \left(\frac{\gamma_M^2 + \Omega^2}{K}\right) + K \geq 2\gamma_M(2n_T + 1) + S_{SQL},$$

$$S_{SQL} = 2\sqrt{\gamma_M^2 + \Omega^2}, \quad K_{SQL} = \sqrt{\gamma_M^2 + \Omega^2}.$$ (22)

The sensitivity is restricted by SQL. The first term $2\gamma_M(2n_T + 1)$ corresponds to the RF limit (33), discussed below. We should note that in this scheme even in the case of zero temperature ($n_T = 0$) we can not set the attenuation coefficient $\gamma_M = 0$ to fully neglect the RF fluctuations and redefine the SQL. It is because the $\gamma_M$ serves as the coupling between the RF signal and the electro-optical crystal (6).

If we rewrite Eq. (19a) in form

$$\beta_a = \sqrt{\frac{\beta}{\gamma_M - i\Omega}} \left(\frac{\gamma_M + i\Omega}{\sqrt{\beta K}}\right) \alpha_- + \sqrt{2\gamma_Mq_\phi + f_\alpha},$$ (23)

which results in the normalized spectral power density of the quantum noise. In this case the detection condition becomes

$$S_n(\Omega) = 2\gamma_M(2n_T + 1) + \frac{\gamma_M^2 + \Omega^2}{K}$$ (24)

Here we assume that the single sided spectral density of $\alpha_-$ is equal 1. The power spectral densities are illustrated by Fig. 2.

The detection condition

$$f_{so} \geq \sqrt{\frac{S_n(\Omega)}{2\pi}} \frac{\Delta\Omega}{\Omega}$$ (25)

indicates that the suggested here measurement procedure leads to a broadband force measurement with sensitivity better than the SQL. We note that the external signal is defined in a way that $f_{so}$ is a generalized force acting on the RF oscillator. It can be recounted into the actual RF power or the number of RF photons using the definition (6).

However, we should note that in the case of zero temperature ($n_T = 0$) and resonant signal ($\Omega = 0$) the SQL (22) is equal to the RF limit (33) $S_{SQL_0} = S_{SQL}(0) = S_{RF} = 2\gamma_M$. So even though we can beat the SQL when measuring the other spectral components of the signal, we can only reach the SQL for the resonant component, as it can be seen on Fig. 3.

Eq. (22) shows that the SQL gets higher with the increase of $\Omega$. This is the reason why we can beat the SQL at the nonresonant frequencies. It would be more natural to watch the value $S/S_{SQL_0}$. If we compare the sensitivity in such way, we can say that it actually gets worse when we measure the offresonant components. It is presented on Fig. 4 (the plots on Fig. 2 will not change because they are plotted for the given value of $\Omega$).

The back action is excluded completely in output quadrature $\beta_a$. This is a consequence of the separate measurements of the correlated output waves escaping modes $\epsilon_m$ and $\epsilon_p$. This is the main result of our paper.

![Figure 2. Noise power spectral densities $S$ as a function of power parameter $K$. Measurement of only $\beta_{-a}$ or $\beta_{+\phi}$ (20) (red line) does not allow to surpass the sum of SQL and RF limit (21) (dashed green line). Measurement of combination $\beta_a$ (24) (orange line) allows to evade back action and surpass SQL, but the sensitivity is limited by the RF limit (33) (dashed blue line). The plots are presented for $\Omega/2\pi = \gamma_M/2\pi = 1 MHz$ and $n_T = 0$.](image)

![Figure 3. Noise power spectral densities $S$ as a function of frequency $\Omega$ for different power parameters $\kappa = K/K_{SQL}$. Measurement of combination $\beta_a$ (24) (red, orange and purple lines) allows to evade back action and surpass SQL, but the sensitivity is limited by the RF limit (33) (dashed blue line). The plots are presented for $\gamma_M/2\pi = 1 MHz$ and $n_T = 0$.](image)
In the frequency domain the set is transferred to resonator during the ringdown time and where plots are presented for beat it and offresonant sensitivity is worse than resonant. The sideband is given by RF signal the averaged number of photons in an optical microwave photons. Indeed, for a relatively strong it allows generation of multiple optical photons per sin-

In this case the contribution of the shot noise described by Eq. (31b) can be dropped and the detection condition (25) is defined by the noise spectral density

\[ S_{RF} = 2\gamma M (2n_T + 1) \]

It means that the sensitivity of the measurement involving the single optical sideband is defined by the RF fluctuations only. The optical fluctuations practically do not contribute to the measurement noise. To achieve similar conditions in the case considered in this paper we have to use high enough pump power \((K \gg 1)\).

The power of the signal in the single sideband case is limited by the input RF power. The optical harmonic power is \(P_d(\omega/\omega_d)^2\). In our case the power of each harmonic is \(P_d(\omega/\omega_d)^2/(K/4)\). Therefore, even though the sensitivity in both measurement schemes is similar, our system is capable of producing higher power signals being easier to detect.

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