

Supplementary Information for “Efficient ultrafast homodyne detection of quantum light”

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Supplementary Note 1. SIMULATION OF WEIGHTING-VECTOR OPTIMIZATION

We simulate the SNR improvement achieved by the optimization method described in the main text, using a realistic homodyne circuit model. First, we assume that the electronic noise is stationary, meaning that $E_{lm} = \langle \hat{v}_e(t_l) \hat{v}_e(t_m) \rangle = \langle \hat{v}_e(t) \hat{v}_e(t + \Delta t_{lm}) \rangle$, where $\Delta t_{lm} = t_m - t_l$. Thus, the electronic-noise matrix $\mathbf{E}$ can be regarded as an autocorrelation matrix whose elements depend only on Δt_{lm} . According to the Wiener-Khinchin theorem, this stationary autocorrelation matrix is the inverse Fourier transform of the power spectral density of the electronic noise $S_e(f)$:

$$E_{lm} = \mathcal{F}^{-1}[S_e](\Delta t_{lm}), \quad (1)$$

where $\mathcal{F}^{-1}$ denotes the inverse Fourier transform, defined as $\mathcal{F}^{-1}[G](t) = \int_{-\infty}^{\infty} df G(f) e^{i2\pi ft}$. Furthermore, R_{lm} is proportional to the product of impulse response functions at different times, provided that detector response functions from different pulses have negligible overlap (see Eq. (15) in the main text). The impulse response in the frequency domain is given by the transfer function $\tilde{r}(f) = \mathcal{F}[r](f)$. Combining this expression with Eq. (15) in the main text, R_{lm} is rewritten as

$$R_{lm} = \eta_{PD} e^2 |\alpha_p|^2 \mathcal{F}^{-1}[\tilde{r}](t_l - jT) \mathcal{F}^{-1}[\tilde{r}](t_m - jT), \quad (2)$$

for $t_l, t_m \in [jT, jT + T]$.

We use the homodyne circuit model in Ref. [1]. In this model, the photodiode is regarded as a current source with an additional variable capacitor C_p in parallel. The power spectral density of the electronic noise $S_e(f)$ and the response function $\tilde{r}(f)$ of this circuit are given by

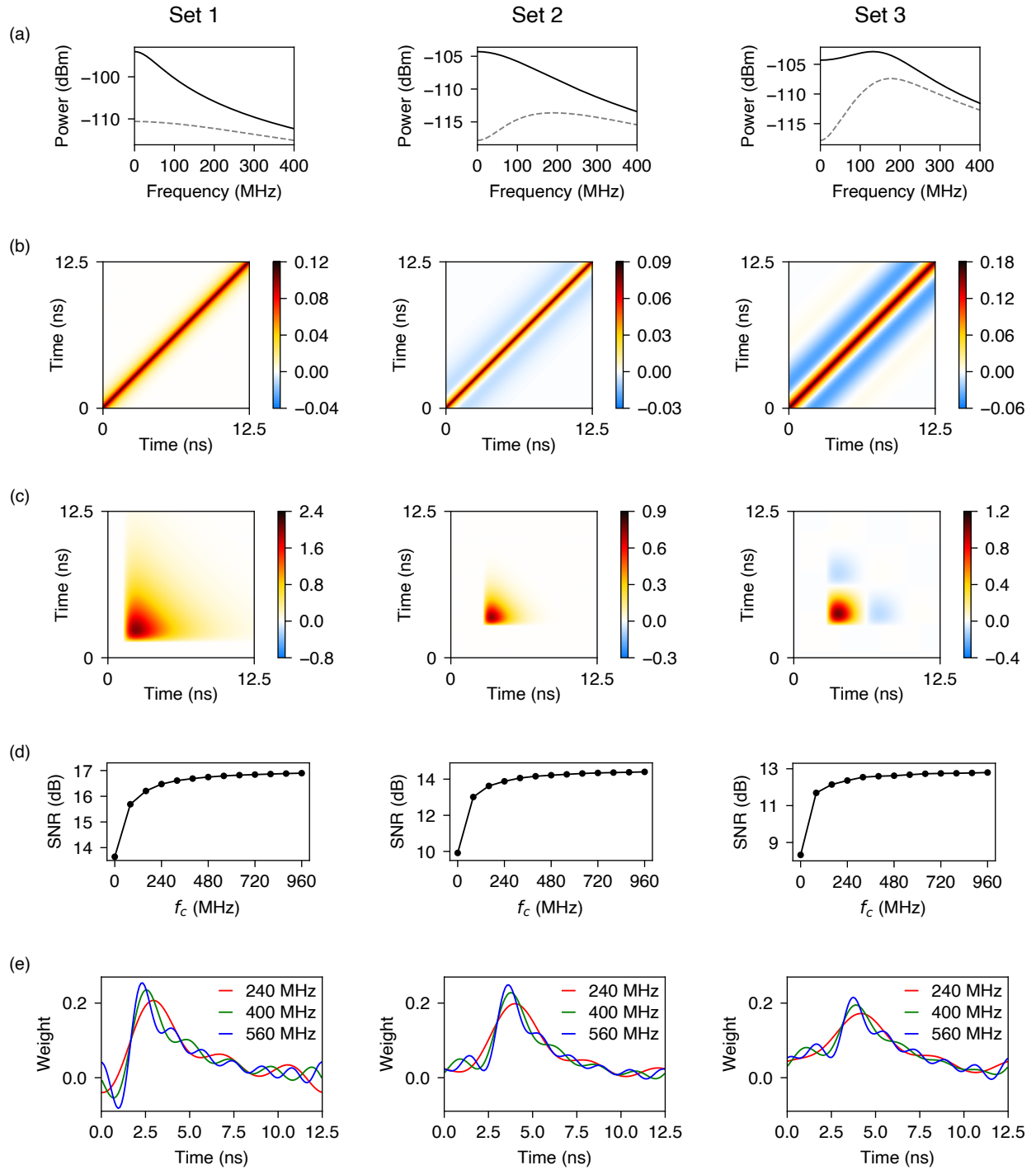
$$S_e(f) = \frac{n_c + n_f \bar{f}^2}{1 + (p^2 - 2)\bar{f}^2 + \bar{f}^4} \quad (3)$$

$$\tilde{r}(f) = \frac{R_f}{1 + ip\bar{f} - \bar{f}^2}, \quad (4)$$

respectively, where a normalized frequency $\bar{f}$ is defined as $\bar{f} = f/f_0$, $p = f_0(2\pi R_f C_f + 1/\text{GBW})$ and $f_0 = \sqrt{\text{GBW}/(2\pi R_f C_t)}$. The noise coefficients are given by $n_c = e_n^2 + 4k_B T_e R_f + i_n^2 R_f^2$, and $n_f = 4\pi^2 e_n^2 R_f^2 C_t^2 f_0^2$, where k_B is the Boltzmann constant and T_e is the temperature. Here, GBW is the gain-bandwidth product, and i_n and e_n are the input noise current density and voltage density of the op-amp, respectively. The circuit parameters R_f and C_f represent the feedback resistance and the capacitance of the transimpedance amplifier, respectively. C_a is the input capacitance of the op-amp, and $C_t = 2C_p + C_f + C_a$ is the total capacitance.

We simulate this homodyne detector model using an OPA847 op-amp and varying R_f , C_f , and C_p , which are given in Supplementary Table 1. The differences in the characteristic frequency f_0 and damping parameter p determine the impulse responses of each parameter set. We set $\eta_{PD} = 0.9$, the LO power to 2.7 mW, and $T_e = 298.15$ K (25 °C). The following values are taken from the datasheet of the OPA847: $i_n = 2.5$ pA/ $\sqrt{\text{Hz}}$, $e_n = 0.89$ nV/ $\sqrt{\text{Hz}}$, GBW = 3.9 GHz, and $C_a = 2$ pF. Using these parameters and Eqs. (3)–(4), we first plot the spectra of shot noise and electronic noise, shown in Supplementary Figure 1(a). Their shapes depend on f_0 and p : f_0 determines the time and frequency scale, whereas p sets the damping behavior. For larger p , $S_e(f)$ and $|\tilde{r}(f)|^2$ monotonically decrease with frequency, whereas they show non-zero maximum peaks as p decreases. Moreover, in the time domain, both the autocorrelation of the electronic noise and the detector response are underdamped for $p < 2$, critically damped for $p = 2$, and overdamped for $p > 2$. These behaviors are reflected in the structures of $\mathbf{E}$ and $\mathbf{R}$, shown in Supplementary Figure 1(b) and (c),

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Supplementary Figure 1. Simulation results of weighting-vector optimization for three different parameter sets of a homodyne detector (left: Set 1, center: Set 2, right: Set 3, as defined in Supplementary Table 1). (a) Power spectrum of the shot noise at an LO power of 2.7 mW with $\eta_{PD} = 0.9$ (black), and the electronic noise (gray, dashed). Both spectra are calculated for a resolution bandwidth of 10 kHz. (b) Electronic-noise matrices $\mathbf{E}$. (c) Detector response matrices $\mathbf{R}$ at $\eta_{PD} = 0.9$ and LO power of 2.7 mW. (d) SNR as a function of the cutoff frequency up to $f_c = 960$ MHz. (e) Optimal weighting vectors for $f_c = 240$ MHz (red), 400 MHz (green), and 560 MHz (blue).

Supplementary Table 1. Circuit parameter sets used in homodyne detector simulations.

Parameter	Set 1	Set 2	Set 3
R_f (k Ω)	3.3	1.0	1.0
C_f (pF)	1.0	1.5	1.0
C_p (pF)	4.0	5.0	8.0
f_0 (MHz)	130.8	214.4	180.7
p	2.74	2.08	1.18

respectively. Since E_{lm} is determined by the autocorrelation function, whereas R_{lm} is proportional to the product of the response functions at different times, R_{lm} is more localized in time.

Using $\mathbf{E}$ and $\mathbf{S} = \mathbf{E} + \mathbf{R}$, we evaluate the SNR as a function of the cutoff frequency f_c , shown in Supplementary Figure 1(d). The SNRs of the three parameter sets obtained with the constant weighting vector are 13.8 dB, 9.9 dB, and 8.3 dB, respectively. These values increase to 16.6 dB, 13.9 dB, and 12.4 dB for $f_c = 240$ MHz, and to 16.9 dB, 14.3 dB, and 12.7 dB for $f_c = 560$ MHz. Supplementary Figure 1(e) shows the corresponding optimal weighting vectors for three cutoff frequencies: $f_c = 240$ MHz, $f_c = 400$ MHz, and $f_c = 560$ MHz for each circuit parameter set. As f_c increases, high-frequency oscillations are observed in the optimal weighting vectors.

SUPPLEMENTARY REFERENCES

- [1] Masalov, A. V., Kuzhamuratov, A. & Lvovsky, A. I. Noise spectra in balanced optical detectors based on transimpedance amplifiers. *Rev. Sci. Instrum.* **88**, 113109 (2017).