Enhanced absorption microscopy with correlated photon pairs

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By harnessing the quantum states of light for illumination, precise phase and absorption estimations can be achieved with precision beyond the standard quantum limit. Despite their significance for precision measurements, quantum states are fragile in noisy environments which leads to difficulties in revealing the quantum advantage. In this work, we propose a scheme to improve optical absorption estimation precision by using the correlated photon pairs from spontaneous parametric down-conversion as the illumination. This scheme performs better than classical illumination when the loss is below a critical value. Experimentally, the scheme is demonstrated by a scanning transmission type microscope that uses correlated photon illumination. As a result, the signal-to-noise ratio (SNR) of a two-photon image shows a 1.36-fold enhancement over that of single-photon image for a single-layer graphene with a 0.98 transmittance. This enhancement factor will be larger when using multi-mode squeezed state as the illumination.

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I. INTRODUCTION

Low-energy illumination imaging is necessary when treating photosensitive samples, including biological cells [1,2], quantum gases [3], and atomic ensembles [4]. The qualities of the images can be measured by their signal-to-noise ratios (SNRs), where the signal is the contrast between the sample and background and the noise is the fluctuation of the detected signal. According to the theory of statistics [5], the estimation precision Δt is limited by Δt ≥ 1/√MF(t), where M is the number of repeated measurements, F(t) is the value of the Fisher information. For low-photon-level coherent state illumination, the shot-noise limit appears to be dominant, and the measurement precision can be improved by repeating the measurements [6]. Fortunately, quantum metrology [7–12] further improves the parameter estimation precision [13]. By carefully choosing the probe quantum state and projection detection basis, the Fisher information of single measurement could be improved, and the Heisenberg limit of the strategy enhancement of the Fisher information can be potentially approached [13]. It has already been demonstrated that the quantum N00N state [14] can be used to measure the optical phase such that the measurements precision exceeds the standard quantum limit [15–18]. Recently, such methods were introduced to build microscopes with quantum light illumination that outperform the same type of interference microscope with classical illumination [20–22]. However, such methods have limited applications and depend on the target samples, additionally, the quantum entanglement is fragile in a noisy environment. The apparatus also requires a high stability for interference.

For direct absorption measurements, theoretical and experimental works have demonstrated that the heralded single-photon source from parametric down-conversion [20] can exceed the shot-noise limit when estimating the transmittance of highly transparent samples [27]. In the protocol named “quantum illumination”, the heralded single photons are sent to a low reflectivity target in a high background-noise environment, and an enhanced SNR for the detection can be obtained [28,29]. Recently, Matthews and coworkers experimentally demonstrated that the sub-Poisson distribution of quantum states can reduce the noise when estimating lossy samples [30,31]. Their work used a high-quality heralded single-photon source from a spontaneous down-conversion (SPDC) process to measure the transmittance beyond the classical shot-noise limit. Such a method is suitable for the commonly used transmission or reflection microscopes and does not rely on quantum entanglement or quantum interference. However, the quantum advantages are sensitive to the heralding efficiency of the single-photon source, which is limited by the optical loss and inefficient detector in the reference arm. Unfortunately, the quality of the heralded probe single-photon source is far from perfect in most situations.

In this letter, we propose a scheme to obtain an enhanced precision absorption microscope by sending both correlated photons to the sample to probe the transmittance. Our scheme can surpass the coherent state limit without heralding apparatus when the transmittance is near unity. Above a critical value of the transmittance, it performs better than the classical illumination in the same measurement system. The enhancements are demonstrated experimentally with a scanning microscope, achieving an enhancement factor of 1.36 for a graphene sample transparency of 0.98. Using direct measurements, the scheme is stable and could be used for applications in photosensitive biological imaging.

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II. PRINCIPLE

For a direct absorption measurement, the probability of the input photon passing the sample is a function of the transmittance $t$. Representing the bosonic operator for input and output photon modes as $a_i$ and $b_i$, respectively, the linear absorption can be effectively treated as a beam splitter (BS) with transmission $t$, and thus, $b_i = \sqrt{t a_i} + \sqrt{1-t} c$, where $c$ is the operator of the vacuum noise input mode. By measuring the expectation value of an appropriate physical observable $O$ as a function of $b_i$, we can estimate the transmittance $t$ of the absorptive sample such that the uncertainty is written as

$$\Delta t_M = \frac{\sqrt{\langle \Delta O^2 \rangle}}{\sqrt{M} |\partial O/\partial t|}$$

(1)

where the fluctuation $\langle \Delta O^2 \rangle = \langle O^2 \rangle - \langle O \rangle^2$ and $M$ is the number of repeated measurements. Generally, $O$ is chosen to be an expression of the photon number operators that correspond to the photon coincidence detection, which can be easily realized experimentally.

Fig. 1(a) shows two schemes for the absorption measurement. A sequence of correlated photon pairs is generated and then sent to the observers, Alice and Bob. In the left case, only the signal photons sent to Bob pass through the absorptive sample; this case is called the “single-pass” scheme. In the right case, both the signal and idle photons pass through the sample; this case is called the “double-pass” scheme. Similar to quantum entanglement-assisted dense coding, we question whether the correlation can obtain more information in the “double-pass” scheme than that in the “single-pass” scheme, with the same illumination photon number. Therefore, we compare the two schemes shown in Fig. 1(a), where the photon source is a two-mode squeezing state with $|\phi \rangle = (|1 \rangle + |0 \rangle)/\sqrt{2}$, corresponding to the non-degenerate down-conversion sources, such that $\beta$ is related to the squeezing parameter and $\alpha$ is the normalization factor. For both cases, we perform the $k_1$-th and $k_2$-th order correlation measurements of each mode, i.e., the physical operator we measure can be expressed as $O = (b_1^\dagger)_{k_1} b_1^{k_1} (b_2^\dagger)_{k_2} b_2^{k_2}$ with the subscript 1(2) denotes the path to Alice (Bob). Let the transmittances be $t_1$ and $t_2$, we then have $\langle O \rangle = t_1^{k_1} t_2^{k_2} \langle a_1^{k_1} a_1^{k_1} a_2^{k_2} a_2^{k_2} \rangle$ and $\langle O^2 \rangle = \sum_{m_1} k_1 C_{k_1, m_1} C_{k_2, m_2} t_1^{k_1 + m_1 + k_2 + t_2} \langle (a_1^{k_1 + m_1 + k_2 + t_2}) (a_1^{k_1 + m_1 + k_2 + t_2}) \rangle$,

where $C_{k_1, m_1}$ is the parameter transforming $O^2$ to normal order operators. Introducing the precision of the absorption estimation for $t_2$

$$\Delta t = \sqrt{R} \frac{\sqrt{\langle \Delta O^2 \rangle}}{|\partial O/\partial t|}$$

(2)

where $R = \sum_j \langle \phi | b_j^\dagger b_j | \phi \rangle$ is the averaged photon number of the input state ($j = 1$ for “single-pass” scheme, $j = 1, 2$ for “double-pass” scheme). Therefore, $\Delta t$ can also be understood as the normalized precision of the estimation per input photon.

For the simplest case, we choose an ideal photon pair state $|\phi \rangle = |1, 1 \rangle$ and $k_1 = k_2 = 1$. The precision $\Delta t_{SP}$ for the “single-pass” scheme ($t_1 = 1$), $\Delta t_{DP}$ for the “double-pass” scheme and $\Delta t_{CS}$ for a coherent state input are calculated as follows:

$$\Delta t_{SP} = \sqrt{t_2 (1-t_2)}$$
(3)

$$\Delta t_{DP} = \sqrt{(1-t_2^2)/2}$$
(4)

$$\Delta t_{CS} = \sqrt{t_2}$$
(5)

These precision as well as the enhancement factor $\Delta t_{SP}/\Delta t_{DP}$ are plotted in Fig. 1(b). It is shown that both schemes outperform the classical case of the coherent state for high transmittance and that the “single-pass” scheme shows the best performance for all transmittance values, which is the same with single photon state. For such an ideal input quantum state, the minimal photon number uncertainty of the quantum state results in the suppression of the noise in the direct absorption parameter estimation. In this case, the “double-pass” scheme shows no advantage over the “single-pass” scheme.

However, the advantage of single photons requires high-performance heralding apparatus on the SPDC source and the imperfections in the operation and detection will degrade the quantum advantage. The “double-pass” scheme can reveal the quantum advantage without making heralding on the SPDC source. Usually, the SPDC source works with $\beta << 1$ to avoid multiple photon pair generation, generating a state that can be approximated as $|\phi \rangle = \alpha |0 \rangle + \beta |1, 1 \rangle$. For such a practical source,

$$\Delta t_{SP} = \sqrt{t_2 - t_2^2 \beta^2} \approx \sqrt{t_2}$$
(6)

$$\Delta t_{DP} = \sqrt{(1-t_2^2 \beta^2)/2} \approx 1/\sqrt{2}$$
(7)

The equations indicate that the estimation precision of “single-pass” scheme approximately equals $\Delta t_{CS}$ and the estimation precision of “double-pass” scheme is almost independent on the transmittance. So, the precision of “single-pass” can be approximately treated as the classical bound for coherent state illumination in the same apparatus. In Fig. 1(c), we use the estimated value from experiment $\beta = 10^{-2}$ and calculate the precisions $\Delta t_{SP}$ and $\Delta t_{DP}$ as well as the enhancement factor $\Delta t_{SP}/\Delta t_{DP}$. It is shown that the “double-pass” scheme outperforms the “single-pass” scheme when $t_2$ is higher than the critical value $t_{critical}$. The maximum enhancement factor is $\sqrt{2}$ when $t_2$ approaches unity. The enhancement can be understood by Eq. (2). For both schemes, the probe state and the detection are the same. The differences of the “single-pass” and “double-pass” schemes are two folds: (i) The main difference between the two schemes is that they measure different quantities. The “single-pass”
scheme measures $t$ while the “single-pass” scheme measures $t^2$. The sensitivity increases by a factor 2 for the later scheme. (ii) When the transmittance of the sample approaches to unity, the means and variances of the coincidence detection rates in the two schemes are nearly the same. The average number of photons passing through the sample in the “double-pass” scheme is twice that in the “single-pass” scheme, resulting the decrease of the sensitivity by a factor of $\sqrt{2}$. Therefore, the precision is finally enhanced by $\sqrt{2}$ times when the sample is nearly transparent. By solving the equation $\Delta t_{\text{DP}} = \Delta t_{\text{SP}}$, we derive the relation between the critical point $t_{\text{critical}}$ and $\beta$ as

$$t_{\text{critical}} = \frac{1 - \sqrt{1 - \beta^2}}{\beta^2} \approx \frac{1}{2} + \frac{1}{8} \beta^2.$$  

(8)

Our analysis indicates that the “double-pass” scheme can be used to suppress the probe state fluctuation and improve the precision of the estimation without performing additional heralding on the photon source, when the sample transmittance exceeds a critical value $t_{\text{critical}}$. Throughout our analysis, we have assumed the detection efficiency to be unity. For a non-ideal detection process, the inefficiency of the detectors can be summarized as the loss of the sample and does not affect the validity of the calculations.

### III. EXPERIMENTAL RESULTS

In this section, we experimentally carry out both “single-pass” and “double-pass” absorption microscope measurements and give a proof of principle demonstration of the advantage of the “double-pass” scheme. The experimental setup is shown in Fig. 2. A periodic pooled KTP crystal is pumped by a 404 nm continuous-wave laser, and the wavelength degenerate photon pairs with orthogonal polarizations at 808 nm are generated via a type-II SPDC process. To satisfy the quasi phase-matching condition [37] for the wavelength degenerate SPDC, the nonlinear crystal is put in a temperature controlled oven. Filtered by a 650 nm long-pass filter and 808 nm interference filter, photon pairs are separated from the pump and are further divided by a polarization beam splitter (PBS) before been finally coupled into different single-mode fibers before the sample (for “single-pass” scheme) or after the sample (for “double-pass” scheme).

The scanning absorption microscope is composed of a fiber-collection lens and two objective lenses, with N.A.s of 0.75 and 0.8, respectively. The test samples to are few-layer graphene films. The illumination photons are focused on the sample by the first objective lens, and the transmitted photons are collected by the second objective lens behind the sample. There are two reasons for choosing a few-layer graphene film as the sample: (a) The transmittance is nearly unity for a monolayer; (2) The thickness of the sample is quantized and uniform in different areas, which gives a distribution of the transmittance for the scanning measurement.

Both schemes shown in Fig. 2(a) are performed in our experiment. The scanned images are shown in Figs. 3(a) and (b), in which each pixel is measured by recording the coincidence counts within a certain period. It should be noted that the durations of the experiments for two schemes are different to ensure the same photon numbers. There are three distinct areas of different transmittances in the sample that correspond to different numbers of layers. In our experiment, we make a post-selection by adjusting the wait times in each scheme in area A to remove the influences of other losses within the apparatus and to ensure that the detected photon numbers are the same. Therefore, the illumination state after the area A can be treated as the input. To characterize the quality of the image, we calculate the SNRs in area $B$ and area $C$, both
FIG. 2: Experimental setup. HWP: half-wave plate; Filter1: 650 nm long-pass filter; Filter2: 808 nm interference filter. PBS: polarization beam splitter. A 404 nm laser is focused on the periodic pooled potassium titanyl phosphate (KTP) crystal to generate twin photons with orthogonal polarizations (H, V). We use a temperature controller to tune the wavelength of the photons. “Single-pass” scheme: After filtering and PBS, the photons are separated and coupled into different single mode fibers. One photon is used as the trigger, and the other is used as the illumination. “Double-pass” scheme: After filtering, the two photons are coupled to one fiber and then the two-photon source is used as the illumination and is focused on the sample. The coincidence measurement is performed by splitting the photons with the PBS. The difference between the two schemes is the position of the PBS. The “Single-pass” scheme is realized by moving the PBS in the black dashed box upwards.

The measured transmittance of area $A$, whose averaged photon number is approximately 5000 counts. In the following experiments, the signal is defined as the average photon number difference between the input and output counts $\langle O_{in}\rangle - \langle O_{out}\rangle$, where $O_{in} = a_{1}^{+}a_{1}a_{2}^{+}a_{2}$, $O_{out} = b_{1}^{+}b_{1}b_{2}^{+}b_{2}$. The uncertainty of the counts is $\langle \Delta O^{2}\rangle = \sqrt{\langle \Delta O_{in}^{2}\rangle + \langle \Delta O_{out}^{2}\rangle}$, where $\langle \Delta O_{in}^{2}\rangle$ and $\langle \Delta O_{out}^{2}\rangle$ can be calculated from the standard deviations of the counts in each pixel. The SNR is defined as

$$SNR = \frac{\langle O_{in}\rangle - \langle O_{out}\rangle}{\sqrt{\langle \Delta^{2}O_{in}\rangle + \langle \Delta^{2}O_{out}\rangle}},$$

which is the ratio of the expectation value of $O_{in} - O_{out}$ and the square root of its variance.

For the “single-pass” scheme, the idler photon is used as a trigger since it can eliminate the influence of the environment noise, and the signal photon is used to illuminate the sample. The measured transmittance of area $B$ and $C$ are $0.87 \pm 0.012$ and $0.66 \pm 0.011$, respectively. The calculated SNRs for $B$ to $A$ and $C$ to $A$ are 13.18 and 30.54, respectively, which are higher than those of the “single-pass” case. The enhancement factors are 1.268 and 1.231, respectively. We have also measured a single-layer graphene film with a transmittance of 0.98, resulting in a 1.36-fold enhancement of the SNR. These experiment results ambiguously demonstrate the enhancement of the absorption microscope with the use of “double-pass” correlated photons.

We plotted the SNR enhancements derived from Eq.9 for different schemes in Fig.3(e). From the plot, the higher transmittance gives a greater enhancement, with an upper bound of $\sqrt{2}$ when the sample is nearly transparent. In our experiment, the enhancement factors 1.36, 1.27 and 1.23 correspond to the transmittance of 0.98, 0.87 and 0.66, respectively, which well fit our analyses.

IV. DISCUSSION

For realistic applications, it is important to optimize the efficiencies of every component of the microscope, including the input quantum photon source and the detector efficiencies. Any losses in the state preparation, evolution and detection processes can degrade the photon correlation, and the advantage of the “double-pass” scheme is only valid when the whole transmittance is greater than the critical transmittance $t_{critical}$. An possible method of achieving greater enhancements is utilizing the higher-order correlations of multiphoton input probe states. A theoretical analysis shows that the maximum enhancement over the classical bound (“single-pass” scheme) can be promoted to $\sqrt{N}$ by using $N$-photon correlated illumination state.
In summary, we propose and experimentally demonstrate the “double-pass” scheme for direct absorption measurements using correlated two-photon source, which achieves a higher precision and outperforms the “single-pass” case with the same resource consumption. This method can be used to achieve low noise images in transmission microscopy better than the coherent state illumination without building high-quality heralded single photon sources. Such transmission microscopes are very robust for practically applications since they have no specific requirements for the stability of their environments, unlike those required for the interference protocols. Another advantage of this method is that the coincidence technology is immune to optical background noise, which is quite important for low photon number illumination measurements. The proof of principle demonstration of this method opens a new avenue for weak field imaging without fragile quantum interference and is promising for the practical applications of quantum enhanced imaging.

VI. APPENDIX

The “double-pass” scheme can be extended to the “multiple-pass” scheme with multiple correlated photons impinging on the sample. The physical observable is chosen as

\[ O = \prod_{i}^{N} (b_i^\dagger b_i^b_i^h_i), \]

(10)

corresponding to the N photon coincidence measurement. The expectation values of \( O \) and \( O^2 \) at the detector are

\[ \langle O \rangle = \prod_{i}^{N} \prod_{i}^{N} (a_i^\dagger a_i^k_i) \]

(11)

\[ \langle O^2 \rangle = \sum_{m_1}^{k_1} \sum_{m_2}^{k_2} \ldots \sum_{m_N}^{k_N} C_{k_1,m_1} C_{k_2,m_2} \ldots C_{k_N,m_N} \prod_{i}^{N} (a_i^\dagger a_i^k_i, b_i^h_i, c_i^b_i) \]

(12)

where \( k_i \) is the order of the correlation measurement of the \( i \)-th path. The normalized estimation precision with respect to the resource \( R \) is given by

\[ \Delta t = \frac{1}{\sqrt{R}} \sqrt{\frac{\langle O^2 \rangle - \langle O \rangle^2}{\frac{d\langle O \rangle}{dt}} \sum_{i}^{N} Tr\{n_i \rho \}. \]

(13)

Here, suppose the illumination state to be a multimode squeezing state \( |\phi\rangle = \sum_{n} \beta_n |n, n, \ldots n\rangle \). For \( N = 3 \) and \( k_1 = k_2 = k_3 = 1 \), the estimation precision for the “triple-pass” scheme shows a maximum \( \sqrt{3} \)-fold enhancement over the “single-pass” scheme when \( t \) approaches unity.

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[1] D. J. Stephens and V. J. Allan, Light microscopy techniques for live cell imaging. Science 300, 82 (2003).
[2] M. A. Taylor, W. P. Bowen, Quantum metrology and its application in biology. Phys. Rep. 615, 1–59 (2016).
[3] K. Eckert, O. Romero-Isart, M. Rodriguez, M. Lewenstein, E. S. Polzik, and A. Sanpera, Quantum nondemolition detection of strongly correlated systems. Nat. Phys. 4, 50 (2007).
[4] F. Wolfgramm, C. Vitelli, F. A. Beduini, N. Godbout, and M. W. Mitchell, Entanglement-enhanced probing of a delicate material system. Nat. Photonics 7, 28 (2012).
[5] P. Kork, B. W. Lovett. Introduction to optical quantum information processing. (Cambridge University Press, 2010), Chap. 13.
[6] C. W. Gardiner and P. Zoller, Quantum Noise (Springer-Verlag, Berlin, 2004), 3rd ed., p. 322.
[7] Y. Giovannetti, S. Lloyd and L. Maccone, Quantum-enhanced measurements: beating the standard quantum limit. Science 306, 1330–1336 (2004).
[8] K. Goda, N. Miyakawa, E. E. Mikhailov, S. Saraf, R. Adhikari, K. McKenzie, R. Ward, S. Vass, A. J. Weinstein, N. Mavalvala, A quantum-enhanced prototype gravitational-wave detector. Nat. Phys. 4, 472–476 (2008).
[9] P. M. Anisimov, G. M. Raterman, A. Chiruvelli, W. N. Plick, S. D. Huver, H. Lee, and J. P. Dowling, Quantum metrology with two-mode squeezed vacuum: parity detection beats the Heisenberg limit. Phys. Rev. Lett. 104, 103602 (2010).
[10] T. Ono and H. F. Hofmann, Effects of photon losses on phase estimation near the Heisenberg limit using coherent light and squeezed vacuum. Phys. Rev. A 81, 033819 (2010).
[11] V. Giovannetti, S. Lloyd and L. Maccone, Advances in quantum metrology. Nat. Photonics 5, 222–229 (2011).
[12] D. S. Simon, G. Jaeger and A. V. Sergienko, Quantum Metrology, Imaging, and Communication, (Springer 2017).
[13] S. Slussarenko, M. M. Weston, H. M. Chrzanowski, L. K. Shalm, V. B. Verma, S. W. Nam and G. J. Pryde, Unconditional violation of the shot-noise limit in photonic quantum metrology. Nature Phot. 11, 700–703 (2017).
[14] M. J. Holland and K. Burnett, Interferometric detection of optical phase shifts at the Heisenberg limit. Phys. Rev. Lett. 71, 1355 (1993).
[15] I. Afek, O. Ambar, and Y. Silberberg, High-NOON states by mixing quantum and classical light. Science, 328, 879–881 (2010).
[16] A. Kuzmich, L. Mandel, Quantum Semiclassical Opt. 10, 493–500 (1998).
[17] J. G. Rarity, E. Tapster, E. Jakeman, T. Larchuk, R. A. Campos, M. C. Teich, E. A. Saleh, Two-photon interference in a Mach-Zehnder interferometer. Phys. Rev. Lett. 65, 1348–1351 (1990).
[18] E. Fonseca, C. Monken, and S. Padua, Measurement of the de Broglie wavelength of a multiphoton wave packet. Phys. Rev. Lett. 82, 2868–2871 (1999).
[19] K. Edamatsu, R. Shimizu, and T. Itoh, Measurement of the photonic de Broglie wavelength of entangled photon pairs generated by spontaneous parametric down-conversion. Phys. Rev. Lett. 89, 213601 (2002).
[20] T. Nagata, R. Okamoto, J. L. O’Brien, K. Sasaki, S. Takeuchi, Beating the standard quantum limit with four-entangled photons. Science 316, 726-729 (2007).
[21] R. Okamoto, H. F. Hofmann, T. Nagata, J. L. O’Brien, K. Sasaki, and S. Takeuchi, Beating the standard quantum limit: phase super-sensitivity of N-photon interferometers. New J. Phys. 10, 073033 (2008).
[22] G. Y. Xiang, B. L. Higgins, D. W. Berry, H. M. Wiseman, G. J. Pryde, Entanglement-enhanced measurement of a completely unknown optical phase. Nat. Photonics 5, 43–47 (2010).
[23] G. Y. Xiang, H. F. Hofmann, and G. J. Pryde, Optimal multi-photon phase sensing with a single interference fringe. Sci. Rep. 3, 2684 (2013).
[24] T. Ono, R. Okamoto, and S. Takeuchi, An entanglement-enhanced microscope. Nature commun. 4, (2013).
[25] Y. Israel, S. Rosen, and Y. Silberberg, Supersensitive polarization microscopy using NOON states of light. Phys. Rev. Lett. 112, 103604 (2014).
[26] X. S. Ma, J. Koiller, and A. Zeilinger, Delayed-choice gedanken experiments and their realizations. Rev. Mod. Phys. 88, 015005 (2016).
[27] A. Meda, E. Losero, N. Samantaray, F. Scafrimuto, S. Pradyumna, A. Avella, I. Ruo-Berchera and M. Genoves, Photon number correlation for quantum enhanced imaging and sensing. J. Opt. 19, 094002 (2017).
[28] S. Lloyd, Enhanced sensitivity of photodetection via quantum illumination. Science 321, 1463-1465 (2008).
[29] S. H. Tan, B. I. Erkmen, V. Giovannetti, S. Guha, S. Lloyd, L. Maccone, S. Pirandola and J. H. Shapiro, Quantum illumination with Gaussian states. Phys. Rev. Lett. 101, 253601 (2008).
[30] J. H. Shapiro, S. Lloyd, Quantum illumination versus coherent-state target detection. New J. Phys. 11, 063045 (2009).
[31] Z. Zhang, S. Mouradian, F. N. Wong, and J. H. Shapiro, Entanglement-enhanced sensing in a lossy and noisy environment. Phys. Rev. Lett. 114, 110506 (2015).
[32] Z. Zhang, M. Tengner, T. Zhong, F. N. Wong, and J. H. Shapiro, Entanglement’s benefit survives an entanglement-breaking channel. Phys. Rev. Lett. 111, 010501(2013).
[33] S. Barzanjeh, S. Guha, C. Weedbrook, D. Vitali, J. H. Shapiro, and S. Pirandola, Microwave quantum illumination. Phys. Rev. Lett. 114, 080503 (2015).
[34] R. Whittaker, C. Erven, A. Neville, M. Berry, J. L. O’Brien, H. Cable, and J. C. F. Matthews, Absorption spectroscopy at the ultimate quantum limit from single-photon states. New J. Phys. 19, 023013 (2017).
[35] P. A. Moreau, J. Sabines-Chesterking, R. Whittaker, S. K. Joshi, P. Birchall, A. McMillan, John G. Rarity and Jonathan C. F. Matthews, Demonstrating an absolute quantum advantage in direct absorption measurement. Sci. Rep. 7, 6256 (2017).
[36] J. Sabines-Chesterking, R. Whittaker, S. K. Joshi, P. M. Birchall, P. A. Moreau, A. McMillan, H. V. Cable, J. L. O’Brien, J. G. Rarity, and J. C. F. Matthews, Sub-Shot-Noise Transmission Measurement Enabled by Active Feed-Forward of Heralded Single Photons. Phys. Rev. Appl. 8, 014016 (2017).
[37] N. B. Nasr, S. Carrasco, B. E. Saleh, A. V. Sergienko,
M. C. Teich, J. P. Torres, L. Torner, D. S. Hum and M. M. Fejer, Ultrabroadband biphotons generated via chirped quasi-phase-matched optical parametric down-conversion. Phys. Rev. Lett. 100, 183601 (2008).