Noise-Free Amplification: Towards Quantum Laser Radar

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QUANTUM IMAGING LADAR: THEORY

The architecture of a Quantum Imaging LADAR is shown in Fig. 1. Without the elements depicted by dashed lines, it is equivalent to current state-of-the-art JIGSAW LADAR [1], where 3D pictures (2 transverse dimensions + time-of-flight information) of the target are collected from different points to permit foliage cover penetration. In the quantum configuration, a Quantum Image Enhancer (QIE) is added between the light-collecting optics and the detector array and is supplied with an optical reference beam from the transmitter. QIE operation, detailed below, leads to two independent mechanisms of resolution improvement: a) quantum enhancement of high-spatial-frequency content and b) quantum recovery of information lost by the detector array.

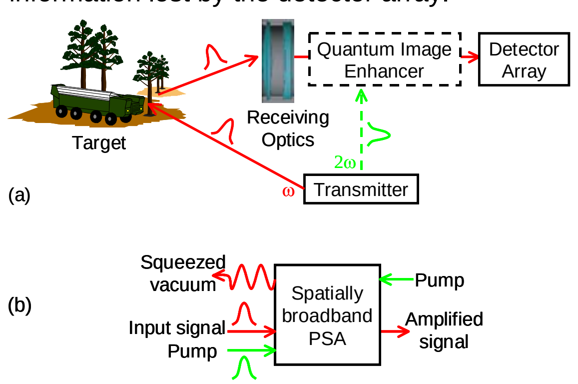

Figure 1. (a) Quantum Imaging LADAR as a quantum enhancement of its classical-sensor counter-part, the JIGSAW LADAR. Dashed lines: Elements added by the quantum sensor. b) Details of the Quantum Image Enhancer; PSA – phase-sensitive amplifier ("squeezer / anti-squeezer").

Quantum Enhancement of High-Spatial-Frequency Content

One of the limits on maximum achievable resolution comes from the fact that a finite aperture of the objective attenuates the high spatial frequencies responsible for fine features of the image. Quantum-mechanically, this is equivalent to adding vacuum noise to these frequency components via an equivalent beamsplitter (see Fig. 2). The input aperture can be either hard (rectangular low-pass filter; shown in Fig. 2 by solid black lines on both sides of the objective) or soft (e.g., Gaussian or Lorentzian low-pass filter; shown by gray shading inside the objective), or a combination of the two. An attempt to overcome Rayleigh resolution limit can be made by de-convolving the spatial-response function from the image data (for soft apertures) or by extrapolating signal spectrum into the stop-band via analytic continuation (for hard apertures). In either case, the signal-to-noise ratio of the detected spatial frequency components will ultimately determine the degree of success of such a procedure, i.e., maximum recoverable resolution of

$$\lambda/(D\sqrt{\mathrm{SNR}}) = \lambda/(D\sqrt{N}),$$

since the classical coherent-state SNR is given by the # of detected photons N.

Although the information lost by hard-aperturing cannot be recovered, the effect of soft-aperturing (if it comes from increased reflection or scattering losses at high-spatial frequencies, or from their deliberate attenuation / apodization) can be mitigated quantum-mechanically. Indeed, if the vacuum input to the equivalent beamsplitter in Fig. 2(a) is replaced by locally generated spatially broadband (i.e., multimode) squeezed vacuum with appropriate phase, SNR of the light passing through the aperture will remain almost unchanged by soft attenuation. More specifically, for transmittance T, SNR will decrease by a factor

$$[1 + (1-T)/(ST)],$$

which can be made arbitrarily close to unity by using squeezing factor $S \gg 1/T$. For example, in order to recover the spatial frequency content attenuated 100 times by a Lorentzian low-pass filter with effective (–3-dB) aperture size *D*, we will need S>100, which will extend the effective spatial bandwidth of the filter 10 times (i.e., produce an effective aperture size 10*D*), leading to 10-fold improvement in the resolution beyond the classical limit of $\lambda/(D\sqrt{N})$.

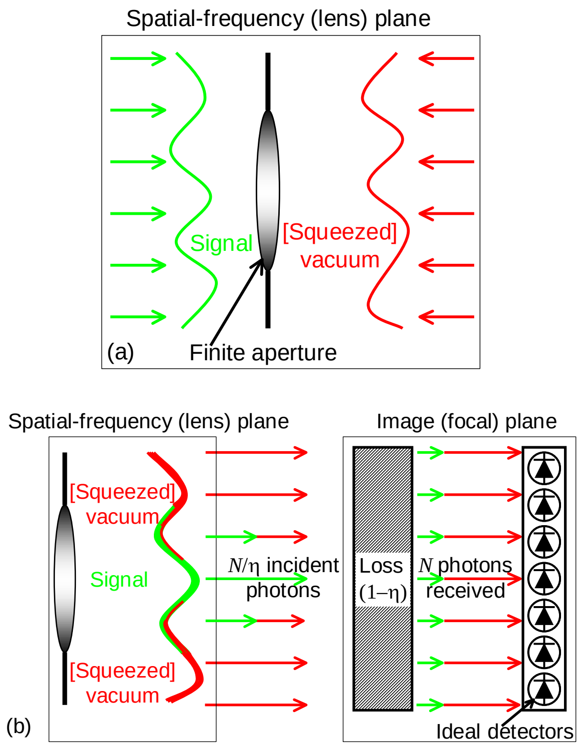

Figure 2. Illustration of quantum noise degrading the resolution. a) Cutting off of high-spatial-frequency components by finite aperture size is equivalent to using a beamsplitter adding vacuum fluctuations at these frequencies. b) In addition to vacuum-noise degradation due to finite aperture size in spatial-frequency plane, the signal-to-noise ratio of all spatial-frequency components is further degraded by quantum efficiency η of the photodetector in image plane.

Quantum Recovery of Information Lost by the Detector Array

The second mechanism of loss of spatial information, limiting maximum achievable resolution, takes place in the image plane, i.e., it impacts all spatial frequency components to the same extent. The focal-plane photodetector array has non-unity quantum efficiency, η, whose effect is equivalent to adding vacuum noise and degrading the signal-to-noise ratio needed for successful de-convolution operation. While individual *p-i-n* photodiodes can approach η = 1, low-received-light requirements of LADAR applications (such as the DARPA JIGSAW program) demand the use of avalanche photodiode (APD) arrays, for which only η = 0.2 has been obtained so far [1]. This 20% quantum efficiency benchmark of JIGSAW LADAR has only been achieved in visible wavelength range, where silicon APD arrays can be fabricated. For infrared applications (beyond the range of silicon), η values of the detector arrays are significantly (orders of magnitude) lower.

The proposed QIE will recover the image information lost due to low η, improving the SNR by 1/η and resolution by $1/\eta^{1/2}$, which potentially enables greater than ×10 resolution enhancement in low-quantum-efficiency infrared applications. The key element of QIE is a spatially broadband phase-sensitive amplifier (PSA), e.g., an optical parametric amplifier [2–5]. Depending on the relative phase between the input signal and the reference (pump) beam, it either amplifies or attenuates the spatially broadband signal (image). In contrast to any other known optical amplifier, PSA has unique quantum properties that allow it to perform amplification and attenuation without adding any noise, which leads to converting coherent-state input signal into phase-squeezed or amplitude-squeezed one, respectively. For a PSA gain of *G*, the improvement of SNR at the detector is given by a factor

$$G / (G\eta + 1 - \eta) \approx 1/\eta$$

for *G* >> 1 [4]. Thus, if without QIE the detected number of photons was *N* and resolution was $\lambda/(D\sqrt{N})$, the QIE-enhanced resolution estimate becomes $\lambda\sqrt{\eta}/(D\sqrt{N})$.

The same PSA can also be used with no input to generate [e.g., via bi-directional pumping as in Fig. 1(b)] spatially broadband squeezed vacuum discussed in the preceding sub-subsection.

In addition to the quantum resolution enhancement, the use of PSA also offers two classical advantages over the existing JIGSAW configuration: a) the phase/frequency (Doppler shift) information can now be recovered from the data, because of the phase-sensitivity of the QIE; b) QIE is optically gated by pump pulses (e.g., pico- or femto-second pulses), so that the range resolution is no longer limited by ~3-ns speed of APD gating [6]; c) the exotic APD arrays can be replaced by more common focal-plane-array technology (e.g., by CCD or photovoltaic arrays).

Summary

The Quantum Imaging LADAR concept described above can enhance the resolution by recovery of some of the high-spatial-frequency content rejected by a soft aperture (using locally generated squeezed vacuum) and by recovery of image information lost due to low quantum efficiency of the detector array (using receiver-side phase-sensitive amplification / phase squeezing). As exemplified by the cases of Lorentzian soft aperture and infrared detection, the resolution improvement offered by the proposed configuration can exceed a factor of 10.

QUANTUM IMAGING LADAR: EXPERIMENTS

An experiment is to demonstrate the feasibility of resolution enhancement by a spatially broadband PSA can be carried out with available technology. The schematic of an experimental setup is shown in Fig. 3(a). Signal from a pulsed laser source is reflected from a closely spaced two-slit (1D) or two-hole (2D) object pattern, combined with pump (at second harmonic frequency), and imaged into the center of a nonlinear crystal comprising phase-sensitive optical parametric amplifier (OPA). The phase-sensitively-amplified signal is then imaged onto a detector array having low quantum efficiency. By reducing the receiving aperture size, we can realize a situation where the object separation is below the Raleigh resolution limit, and post-detection processing (de-convolution) based on high SNR is needed to resolve the two objects. When the pump (green trace in Fig. 3a) is turned off, the arrangement becomes classical (PSA is transparent with gain of unity). Thus, both classical and quantum resolution limits can be measured and compared in this setup. Figure 3(b) illustrates the principle of operation of the spatially broadband optical parametric amplifier. OPA amplifies signals with *k*-vectors within the cone determined by phase-matching conditions. If the transverse component of *k*-vector has a magnitude of *q* (spatial frequency), then all spatial frequencies up to

$$q_{max} \approx (k_p/\text{length})^{1/2},$$

where k_p is the magnitude of the *k*-vector of the pump, will be amplified. By exiting the input of the OPA with signal and idler beams having opposite values of *q* (Fourier-domain equivalent of an image with a constant phase), one can put the OPA into a phase-sensitive regime, leading to noiseless amplification or attenuation.

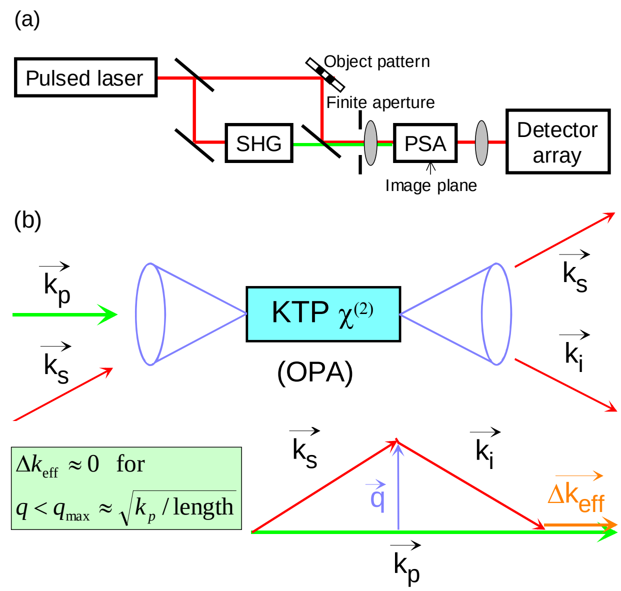

Figure 3. (a) Schematic of the setup for a proposed experiment. (b) Illustration of broad spatial bandwidth of an optical parametric amplifier.

Two of the authors have previously utilized a spatially broadband PSA to demonstrate noiseless image amplification (see experimental setup in Fig. 4a) [4]. A two-slit pattern imaged into a KTP crystal serving as a PSA was phase-sensitively amplified and scanned over by a single photodetector. The scanned intensity and noise profiles of the detected pattern are shown in Fig. 4(b). After comparing the SNRs with and without the pump and taking into account the detector's quantum efficiency, the intrinsic noise figure of the PSA was determined to be NF = (–0.2 ± 0.6) dB at PSA gain of 2.5 (i.e., 4 dB), as opposed to 2.2-dB NF limit of a conventional phase-insensitive optical amplifier with the same gain.

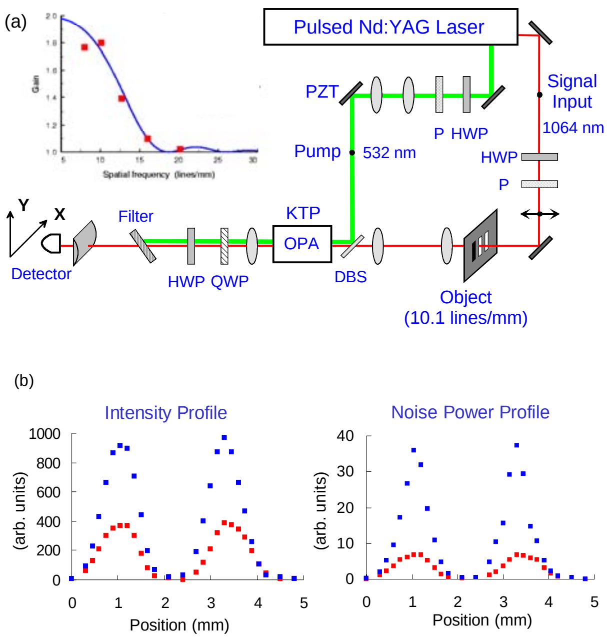

Figure 4. (a) Schematic of the experiment [4] using PSA for noiseless amplification of images. Graph on the inset illustrates the measured spatial bandwidth of the amplifier. (b) Measured intensity and noise profiles of the signals at PSA input (red) and output (blue). Measured gain G = 2.5 (4 dB) and NF = (–0.2 ± 0.6) dB.

While the setups of Fig. 3(a) and 4(a) look similar, the foci of the previous and proposed experiments are different. Our prior work concentrated on demonstration of noiseless image amplification property of the PSA, i.e., on sensitivity improvement. In the proposed experiment, we will directly address the problem of resolution enhancement and demonstrate the conversion of the PSA SNR advantage into the improvement of resolution. Instead of a single scanning detector, we will employ an array, such as a linear *p-i-n*-diode array or a CCD, with post-detection processing leading to the resolution limit. Note also that, in some situations, using the PSA in the Fourier plane [5, 3] might be more beneficial for resolution enhancement, and such situation can be easily implemented in the proposed setup.

The spatial bandwidth of the PSA is determined, primarily, by the crystal length. Thus, using newer high-nonlinearity crystals such as periodically-poled KTP and lithium niobate will allow us to achieve large spatial bandwidths at moderate pump power levels.

Summary

We have proposed an experimental effort to demonstrate that the PSA-assisted quantum recovery of information lost by a low-quantum-efficiency photodetector array will lead to improvement of the resolution beyond the classical limit. This work builds upon our prior demonstrations of superior SNR properties of the spatially broadband PSA and intends to convert this SNR advantage into resolution enhancement.

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