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Optical Resolution Enhancement with Phase-Sensitive Preamplification

Oo-Kaw Lim,[1*] Gideon Alon,[1] Zachary Dutton,[2] Saikat Guha,[2] Michael Vasilyev,[3] and Prem Kumar[1]

[1] *Center for Photonic Communication and Computing, EECS Department, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208*
[2] *Raytheon BBN Technologies, 10 Moulton St., Cambridge, MA, 02138*
[3] *Department of Electrical Engineering, University of Texas at Arlington, Arlington, TX 76019*
[*] *olim.nu@gmail.com*

Abstract: We demonstrate enhanced resolution in image detection by phase-sensitive preamplification. In one-versus-two-target experiment we distinguish otherwise unresolved images with higher probability after such amplification than is possible without amplification.

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1. Introduction

In the context of resolving power of an optical imaging system, the resolution is intrinsically tied to the signal-to-noise ratio (SNR) of a detected signal. Maximum achievable resolution depends on the amount of spatial information lost at the image plane across all spatial frequencies. Spatially-broadband optical preamplification can recover some of the lost resolution by bringing the signal level above the detecting pixels' noise floor across a range of spatial frequencies. The achievable SNR and hence the ultimate resolution depends on the type of optical preamplifier used. Phase-sensitive amplifiers (PSAs) are known for their capability to provide noise-free signal gain [1]. They can out-perform phase-insensitive amplifiers (PIAs) in SNR by 3 dB at large gains [2]. A spatially broadband signal such as that from a LADAR can also be noiselessly amplified with a PSA [3, 4]. However, the connection of the improved SNR with resolution enhancement has not been previously explored experimentally. Here we demonstrate, for the first time to our knowledge, enhanced resolution in direct image detection by use of a PSA. We show that in a one-versus-two-target experiment, images that are otherwise unresolved can be distinguished with higher probability after phase-sensitive amplification than is possible without amplification. Comparisons between the phase-sensitive and phase-insensitive cases will be presented at the conference.

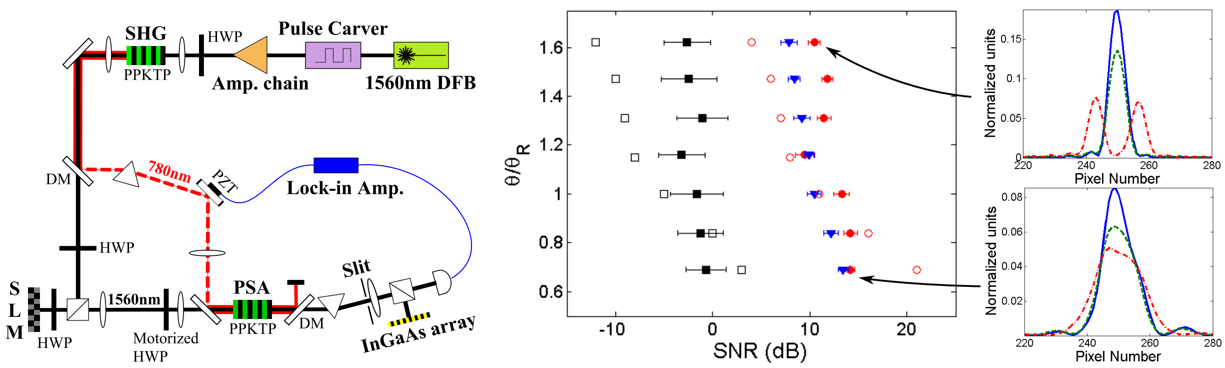
A common sensing scenario requiring high spatial resolution involves determining whether some received signal originated from one or two closely-spaced targets. A receiver's performance in this scenario can be quantified by postulating two equally likely hypotheses: H_1 assumes one target on boresight and H_2 assumes two identical targets symmetrically displaced about the boresight. Assuming the same total number of received signal photons in either case, the maximum likelihood decision criterion (for large detected photon number) can be expressed as [5]

$$\sum_1^K \left[\frac{1}{2}r_i^2\left(\frac{1}{\sigma_1^2(x_i)}-\frac{1}{\sigma_2^2(x_i)}\right)+r_i\left(\frac{\mu_2(x_i)}{\sigma_2^2(x_i)}-\frac{\mu_1(x_i)}{\sigma_1^2(x_i)}\right)\right] \underset{H_1}{\overset{H_2}{\gtrless}} \frac{1}{2}\sum_1^K\left[\frac{\mu_2(x_i)^2}{\sigma_2^2(x_i)}-\frac{\mu_1(x_i)^2}{\sigma_1^2(x_i)}-\ln\left(\frac{\sigma_1(x_i)}{\sigma_2(x_i)}\right)\right], \quad (1)$$

where the sum is over the total number K of pixels used and r_i is the measured data value at pixel i. The noise term $\sigma_j^2(x_i)$ accounts for contributions from the detector dark noise, signal shot noise, and excess noise on each pixel x_i for hypothesis H_j. For N_i number of photons detected on pixel i, the SNR is defined as $(\sum_1^K N_i)^2/\sum_1^K\langle\Delta N_i^2\rangle$. For a fixed error probability, one can find the required SNR to discriminate between the one- and two-targets cases.

2. Experimental Configuration and Results

The layout of the PSA imaging experiment is illustrated in Fig. 1(a). Optical pulses with near flat-top profile at 1560 nm (10 MHz repetition rate and 160 ps pulse duration) were generated with a homemade electro-optic pulse-carving system. The pulses were boosted in power with a chain of Erbium-doped-fiber amplifiers to produce 780-nm pump pulses (1kW peak power) via second-harmonic generation (SHG). The residual 1560 nm beam was used to illuminate a slit pattern of 6.67 lines/mm defined on a spatial light modulator (SLM). An image of the pattern was formed at the center of a 20-mm-long periodically-poled potassium-titanyl-phosphate (PPKTP) crystal via a 4-f lens system. The image was amplified phase-sensitively (8-dB gain) and relayed 1-to-1 onto a 1-d InGaAs detector array.



(a) (b)

Fig. 1. (color online) (a) Experimental setup. DM, dichroic mirror; PZT, piezo-electric transducer. (b) Resolution enhancement with PSA. Filled markers are experimental data; open markers are Monte-Carlo simulations. In the experiments SNR is determined from 5,000 data samples taken with the detector array for 1.4μs exposure time each, whereas in the simulations it was determined from 10,000 Monte-Carlo runs. Red circles–baseline (no PSA gain), black squares–PSA-enhanced. Plots on the right are measured baseline slit functions $\mu(x_i)$ for one slit (green dashed) and two-slit (red dot-dashed) patterns for the marked apertures. Because of a Gaussian pump profile, the one-slit PSA-enhanced patterns (blue solid line) deviate slightly from the baseline. For comparison we also show the baseline SNR results for the deviated one-slit patterns (blue triangles).

To change the Rayleigh resolution condition of the system we varied the imaging lens' aperture by adjusting the opening of a mechanical slit preceding it. For each aperture size D, we used a normalized parameter θ/θ_R to characterize the imaging resolution condition (θ is the line-pair angular separation and θ_R=λ/D is the equivalent Rayleigh limit for that aperture). In the experiment, we estimated identifying H_1 given H_2, i.e., we estimated the error probability (P_E) of identifying one target when two were present. For each θ/θ_R setting, the input signal power was varied via a motorized half-wave plate (HWP) to establish P_E=10^{-2} with the PSA-pump blocked (baseline). With the PSA turned on (pump unblocked), we further attenuated the input signal power to reclaim P_E=10^{-2} (PSA-enhanced). To properly compare the baseline and PSA-enhanced cases, in Fig. 1(b) we plot the resolution θ/θ_R, in both cases, versus the measured *input SNR*, i.e., the SNR as defined above with the PSA-pump blocked. The data in Fig. 1(b) clearly show the improvement of resolution, i.e., targets that are otherwise unresolved because of low input SNR become identifiable with use of the PSA.

To verify our interpretation of these results, we further performed Monte-Carlo (MC) simulations of the baseline and PSA-enhanced measurements. We generated photo-detection counts at each pixel according to the expected signal mean and variance, including light-count variance, mean dark counts, dark-count variance, and the noise due to sub-unity quantum efficiency. The hypothesis patterns were obtained from the experimentally measured slit patterns [panels in Fig. 1(b)]. The effective quantum efficiency of our system was estimated to be 8%. We find reasonable agreement with our experimental results. We furthermore verified that the errors were symmetrical with respect to the two hypotheses (choosing H_1 when H_2 is true and vice versa).

3. Conclusion

We experimentally demonstrated improvement of imaging resolution with phase-sensitive gain. Preservation of SNR in the amplification process can facilitate better performance than phase-insensitive amplification as it can provide noise-free gain. Additionally, a PSA can be an indispensable component in amplification of non-classical image signals that are critically sensitive to detection losses unlike ordinary coherent-state signals [6]. This work was supported in part by the DARPA Quantum Sensors Program.

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