Impact of Phase-Sensitive-Amplifier's Mode Structure on Amplified Image Quality

Muthiah Annamalai,[1] Michael Vasilyev,[1*] and Prem Kumar[2]
[1]*Department of Electrical Engineering, University of Texas at Arlington, Arlington, TX 76019*
[*]*E-mail: vasilyev@uta.edu*
[2]*Center for Photonic Communication and Computing, EECS Department, Northwestern University, 2145 Sheridan Rd., Evanston, IL 60208*

Abstract: We study phase-sensitive image pre-amplification versus pumping conditions and number of signal modes. We see image improvement by pre-amplification, and high-spatial-frequency enhancement for "higher-order-pump," "nonzero-wavevector-mismatch" cases.

OCIS codes: (190.4970) Parametric oscillators and amplifiers; (280.3640) Lidar; (999.9999) Optical image amplification.

The wide spatial bandwidth [1] of traveling-wave phase-sensitive optical parametric amplifiers (PSAs) can be used for noiseless amplification of faint images [2,3]. This makes the PSA pre-amplifiers attractive for direct-detection-based or coherent LIDARs, where they can overcome the readout noise and low quantum efficiency of infrared detectors [4,5]. However, the analysis of the modal structure of the traveling-wave PSAs is very difficult. This is because their single-pass nature requires the use of a tightly focused pump beam to achieve any noticeable gain. The resulting spatially varying PSA gain, along with finite spatial bandwidth, couples and mixes up the modes representing the informational content of the image [6].

We have recently developed a method for finding the orthogonal set of independently amplified modes of the traveling-wave PSA [7,8]. We have obtained the shapes of these eigenmodes for Hermite- and Laguerre-Gaussian pumps (HG_{00} and LG_{00}) of various spot sizes [8,9], with and without on-axis wavevector mismatch, as well as for higher-order Gaussian pumps (HG_{mn}) [10]. In this paper, we describe how such eigenmode structure of the PSA affects the quality of the amplified image.

We consider a 2-cm-long PSA with nonlinear coefficient d_{eff} = 8.7 pm/V and zero on-axis wavevector mismatch Δk, pumped by a Gaussian beam with 1/*e* intensity radii $a_{0px} = a_{0py}$ = 200 μm, power P_0 = 4 kW, and wavelength 780 nm, whose modes have been described in [8]. Under these conditions, the PSA provides gain of 15 (11.8 dB) for the most-amplified mode and supports 6 modes with gains within 3 dB of this value and ~ 15 modes with gains within 6 dB of this value. These first 15 eigenmodes can be represented by the sub-space of Laguerre-Gaussian modes LG_{pl} of 1/*e* intensity radius a_0 = 62 μm, with radial index *p* varying from 0 to 14 and azimuthal index *l* varying from –5 to 5 [9]. The top of Fig. 1(a) shows the input image of letter "N" (left) and the same image represented by such 15×11 space of LG_{pl} modes. Below that, Fig. 1(a) shows the intensity map of the input image (3D view and top view) amplified by the first *M* eigenmodes of the PSA (*M* = 3, 6, 10, or 15), while the gains of the remaining eigenmodes are artificially set to unity. The lowest image of Fig. 1(a) corresponds to *M* = 15, but with the gains of all 15 modes artificially set to equal that of the most-amplified mode. Although the image of the letter "N" is easily identifiable even for the PSA with *M* = 3 or 6, this is only due to the presence of the original undistorted and un-amplified image in the output field (the Green's function of the PSA is a sum of the contribution of the PSA and a delta function representing the input image [6]). In order to properly judge the contribution added by the PSA, we also show on the right of Fig. 1(a) the intensity of the light obtained by subtracting the input image field from the PSA output field (after accounting for passive propagation). One can easily see that the PSA contribution resembles letter "N" only at the highest number of *M* = 15 modes (with or without equalization).

Next, we show in Fig. 1(b) how the PSA pre-amplification with *M* = 15 modes can help in identifying the faint image in the presence of noise. We assume a specular target returning an average number of *N* coherent-state photons for the whole image, which is detected by a homodyne receiver with quantum efficiency η. One can see that, while the image can be identified as letter "N" even without the PSA under good signal-to-noise-ratio (SNR) conditions (large *N* and η), the PSA greatly improves image quality under moderate SNR (two middle rows) and enables identification of the letter in the low SNR case (bottom row), which is impossible to do without the PSA.

Finally, we explore the advantages of the PSA with either a non-zero on-axis wavevector mismatch Δk or with higher-order Hermite-Gaussian pump HG_{mn}. As we found in [10], these conditions shift the maximum PSA gain to the eigenmodes with significant high-spatial-frequency content. This is attractive for images relying on high spatial frequencies, such as the bulls-eye pattern shown in Fig. 2. From this figure, one can easily see that, at the same a_{0p} = 200 μm and P_0 = 4 kW as the HG_{00}, $\Delta k = 0$ case, the non-zero Δk and HG_{22}-pump cases yield better image quality.

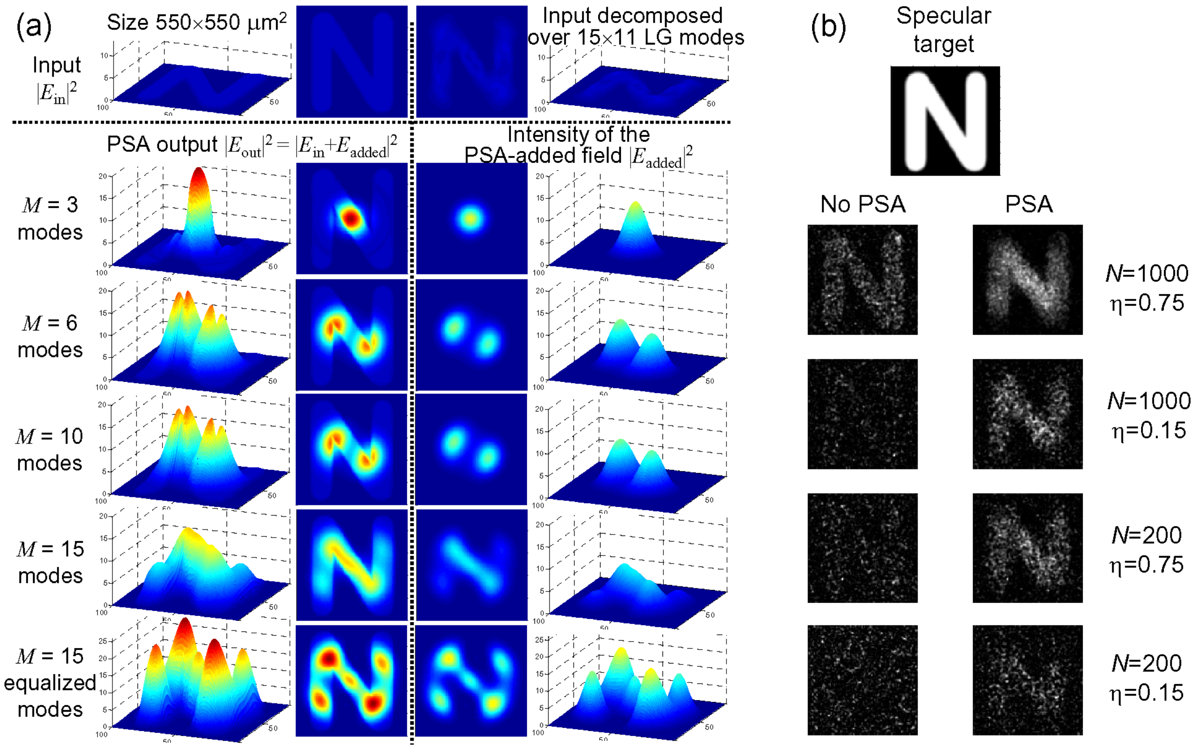

Fig 1. (a) Illustration of the impact of the number of PSA modes M on the quality of the amplified image. Left panel shows the intensity images of a specular target (letter "N") before and after the PSA, in which the gains of all eigenmodes with indices greater than M are artificially set to unity. Right panel shows the intensity of the field added by the PSA under the same conditions. (b) Images of a specular target obtained in homodyne detection with N return photons and detection efficiency η, either with or without phase-sensitive pre-amplification using M = 15.

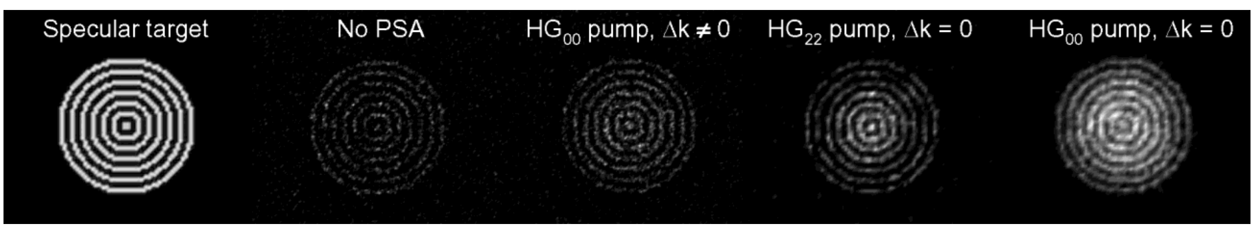

Fig. 2. Images of a bull's-eye target (outer radius ~75 μm) obtained in homodyne detection with $N = 10^4$ return photons and detection efficiency η = 15%, with or without phase-sensitive pre-amplification for three different pumping cases.

To summarize, we have shown that a meaningful image (letter "N") can be amplified by a phase-sensitive parametric amplifier supporting ~15 modes, even without gain equalization among the modes. This is sufficient to overcome the loss of SNR due to low detection efficiency and to identify the faint images that are not recognizable in the absence of the PSA pre-amplifier. We have shown that non-zero on-axis wavevector mismatch or higher-order Gaussian pumping can be used to tune the PSA to images with significant high-spatial-frequency content. Although our analysis has relied on specular targets, the effect of amplifier's mode structure on image quality will be similar for speckle targets as well, but the SNR might be different [5].

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