Crossing the diffraction limit with an optical amplifier

Gal Gumpel and Erez N. Ribak

Department of Physics, Technion - Israel Institute of Technology

ABSTRACT

Heisenberg's uncertainty principle tells us that it’s impossible to determine simultaneously the position of a photon crossing a telescope's aperture as well as the angle of its momentum. A new technique suggests to overcome the diffraction limit via optical amplification. A number of entangled photons, created by amplification of a single photon, behaves as a single quantum system with respect to the uncertainty principle. Unfortunately, spontaneous emission contributes noise and negates the possible gain from this stimulated emission. The spontaneous photons guarantee the uncertainty principle.

Thus the problem of low resolution is replaced by the problem of low SNR. The detection of spontaneous photons follows the same Poisson statistics in time and space. However, the stimulated photons are spatially and temporally coherent with the incoming photons. A pixel with additional hidden thermal signal will slightly modify the Poisson statistics, and only within the diffraction pattern of the photon packets.

We characterise the average number of spontaneous photons in all pixels, and subtract it from the stimulated photons. This algorithm is applied on simulated detection events of an amplified signal. The reconstructed image is resolved beyond the limit of the same optical system in the absence of amplification.

We produced a number of samples of a wide-band solid-state dye (DCM within PMMA), because the expected number of (stellar) photons is small, and a solid-state dye is easier to handle compared to a dye solution. Initial results with a white light source and a laser pump depict the parameters of the method.

Keywords: astronomical super-resolution, optical amplification

1. Introduction

Optical resolution is limited to λ/D, and there are no proven super-resolution imaging systems in astronomy, as opposed to microscopy. This limit of λ/D, is set by quantum calculations, and was related initially to the uncertainty principle. The calculation is not trivial for quantum states of light, but it can go below this limit. We wish to use light amplification to increase the resolution. This was suggested before [1-4] but not realised yet. Here we show that the idea can be proven to work, even under simplifying assumptions.

We used an optical amplifier to increase the number of stellar photons. In doing so, we also created spontaneous photons, which outnumber the amplified photons by orders of magnitude. However, since we know the arrival times of the stellar photons, we can limit our observation to these times. At the same time, we can characterise the mean number of spontaneous photons so as to subtract them from the resulting image. In contrast to previous works, which use dedicated photon tagging detectors, we employ a simple camera, where the sheer number of pixels allows us to statistically differentiate between spontaneous and stimulated photons (Figure 1).

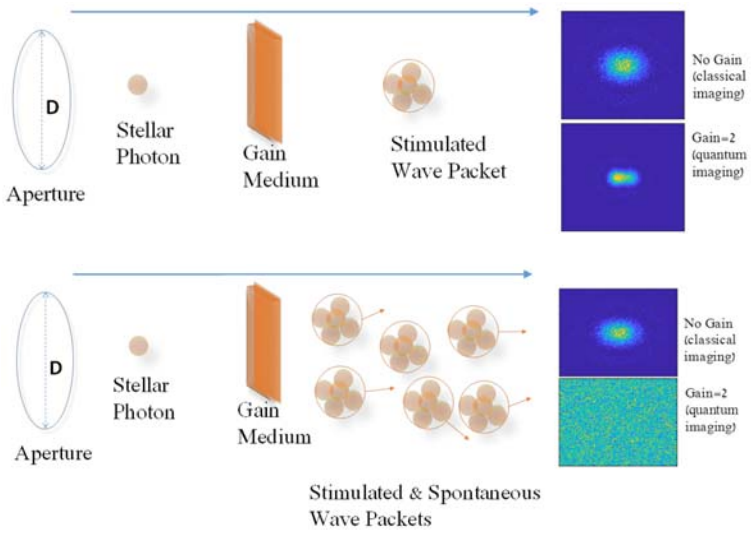

Fig 1. Simulation of the experiment, without (top) and with (bottom) spontaneous photons. Results on the right are from extensive simulations.

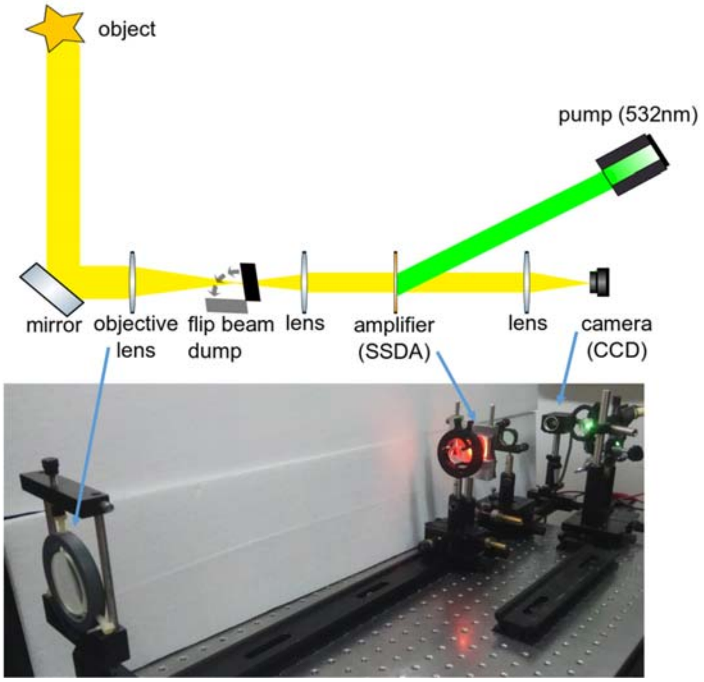

Fig 2: An object is imaged by the objective lens, amplified, and re-imaged on the camera. The pump beam comes from a green laser. A shutter (not pictured) blocks the object image half the time.

2. Experiment

The optical setup is pretty straightforward: a remote white-light object is imaged and then re-collimated onto the amplifier. A laser beam pumps the amplifier, and the result is imaged onto a large format camera. A slow chopper turns the object beam on and off, with synchronised camera frames. The two sets of frames, without and with the object, are subtracted from each other, and the remainder is the requested signal (Figure 2).

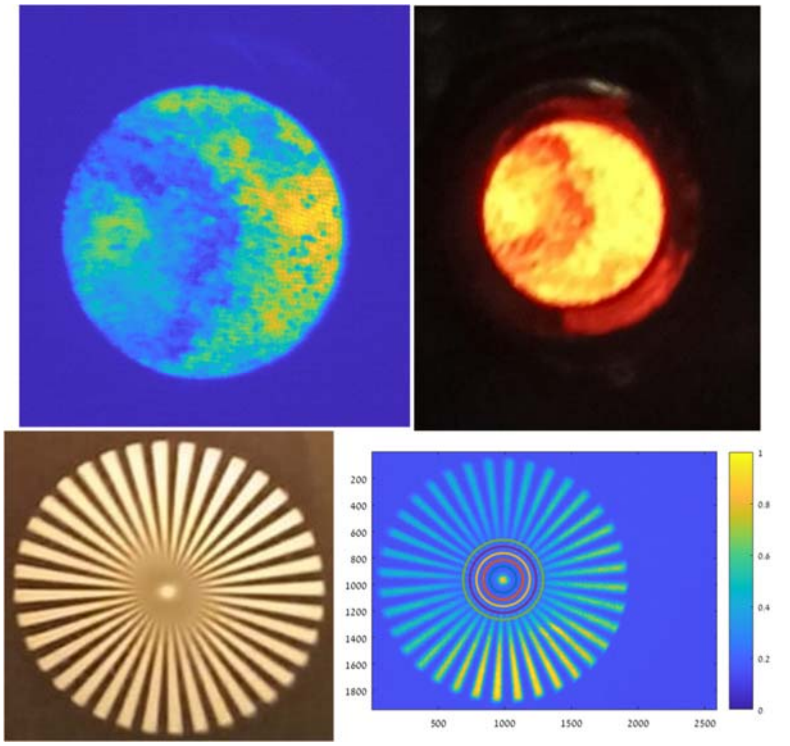

Fig 3: Top: Fibre bundle (direct and amplified). Bottom: Spoke wheel (direct and amplified).

We employed two types of object: a fine multi-fibre bundle, where the fibres themselves were barely resolved, and a spoke wheel pattern (Figure 3). Both provide different spatial frequency components, and the spoke wheel allows a direct estimation of their cut off frequency.

3. Amplifier

The requirements for the amplifier (wide band, visible, bulk) forced us to manufacture our own. We chose a solid one, as it does not have maintenance or toxicity issues. It had 67 nm band width, compared to the usual monochromatic amplifiers, such as in fibres. Once we produced such an amplifier, it was polished for us by Shamir-Eyal. Then they were able to prepare one by themselves, and finally we received one from the Austrian Institute of Technology (see materials in Figure 4). We were worried about mode competition (as in lasers), and we limited the rate to 10^{10} photons/s $\approx$ 3 nW. At the low level of stellar light, this issue is mute. The surface and bulk properties were such that we were not able to get diffraction limited images, and the point spread function was wider than expected. However, we were still able to show that the final resolution after amplification was improved compared to the original one. When used in astronomy, this would require either an amplifier of better optical quality, or adaptive optics (which exist anyway at most telescopes) to minimise wave front aberrations.

Fig 4: From left: DCM:PMMA fabricated in our lab and polished by Shamir-Eyal Ltd; DCM:CR7 fabricated by Shamir-Eyal Ltd; PMN:PMMA top layer fabricated at the Austrian Institute of Technology.

4. Results, Fibre Bundle

Images of the fibre bundle, such as in Figure 3, were compared for their Fourier content. The comparison was between imaging when the pump beam was off (regular imaging) to the case when the pump beam was on (amplified imaging). We could clearly see signal at higher frequencies in the latter case. A vertical cut through the power spectrum (Figure 5) clearly shows fibre-to-fibre signal, which is not interferometric: the light source was an incandescent lamp, devoid of lateral coherence. Even in case that some fringes do exist, they are too dense to notice in the regular image, but resolved in the amplified one.

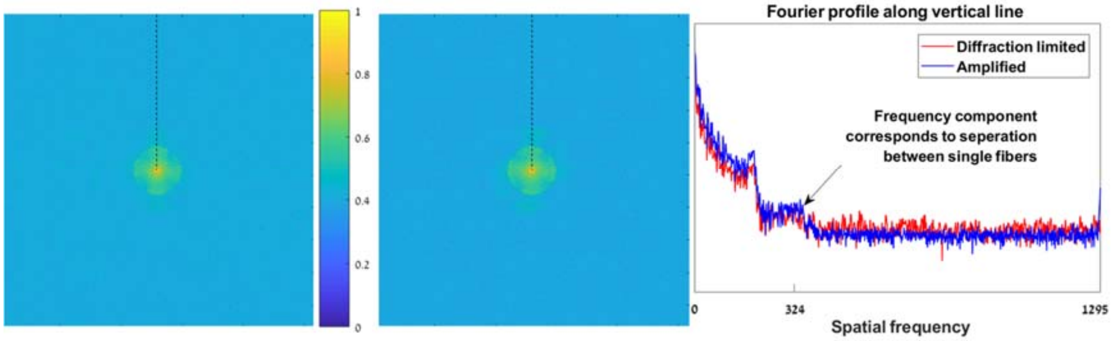

Fig 5: Fourier transform of the fibre bundle output. From left: regular imaging, amplified imaging, and vertical cut comparison of the two.

5. Results, Spoke wheel

Next we analysed the spoke wheel target, and here we took a different approach. We took circular cuts at different radii (marked in colours in Figure 3) and Fourier transformed their intensity. With 36 spokes, one should get that frequency easily marked. We show results for PMN:PMMA and DCM:CR7 amplifiers (Figure 6). When getting closer to the centre (circle number decreasing) noise takes over and the number of spokes is not clear any more. However, the effect of other frequency is reduced when using amplified imaging.

To compare these values quantitatively, we calculated the contrast transfer function (CTF) which is a good proxy for the modulation transfer function [5]. The cut-off frequency (when the signal drops to the background level) for the DCM:CR7 is 13% higher with amplified imaging when compared to regular imaging. For PMM:PMMA the difference is much more decisive: 67% (Figure 7).

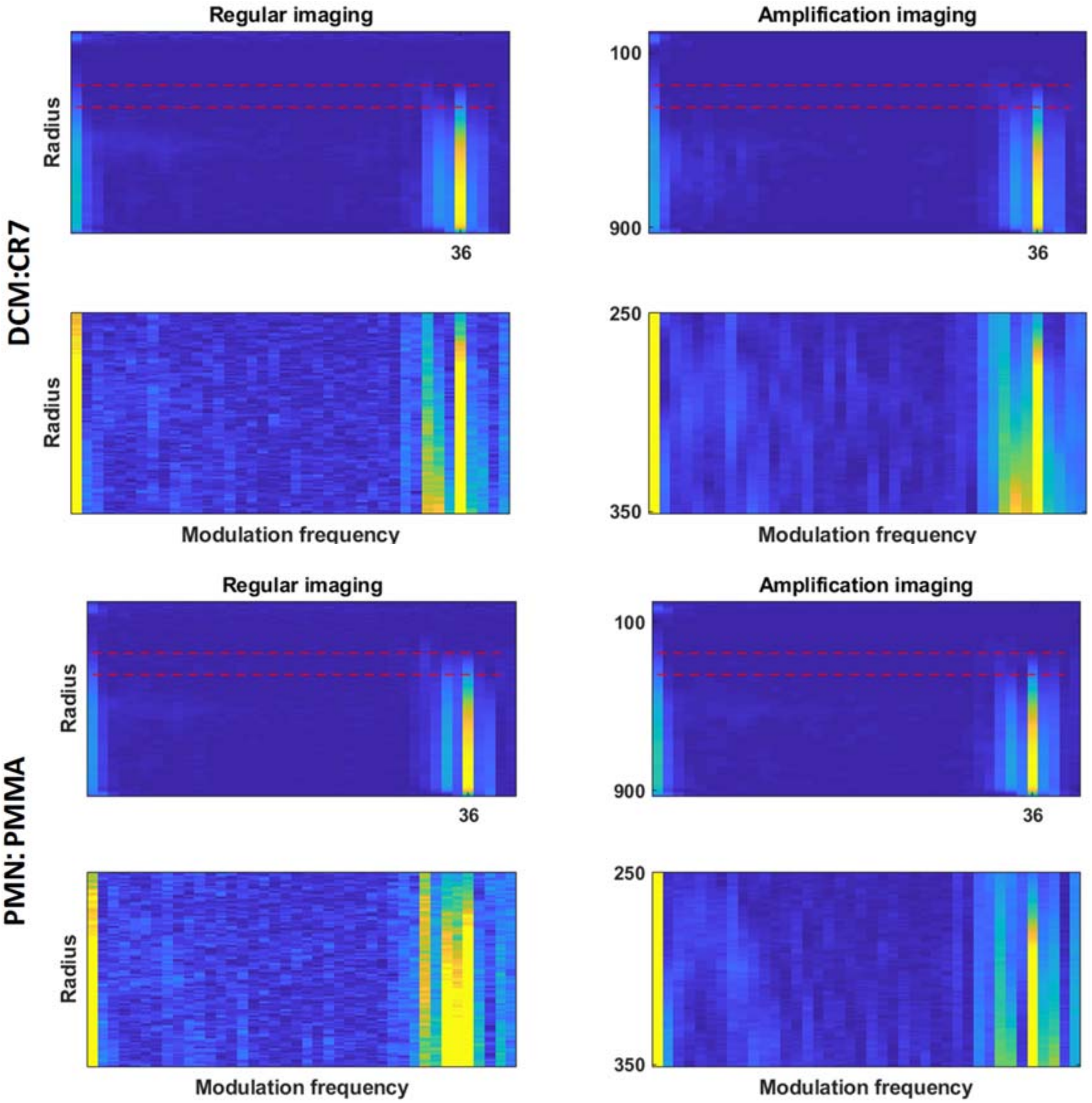

Fig.6. Comparison of the spoke frequency for all (rows 1,3) and selected (rows 2, 4) radii (Fig. 3). For both materials, in amplified imaging, the signal is much clearer than with regular imaging.

6. Summary

We describe a new method to overcome the diffraction limit in astronomy, by amplification of photon wave packets. A wide band amplifier produces stimulated and spontaneous photons, within the original stellar wave packet. By modulation of the stellar signal, we characterise the spontaneous noise, until its level drops below the true, stimulated signal. This is always the tension in super-resolution [6, 7], how much improvement do we get, and at what price (especially noise)? Our experimental results prove the improvement of the modulation transfer function of white-light objects, despite wave front aberrations in the amplifier.

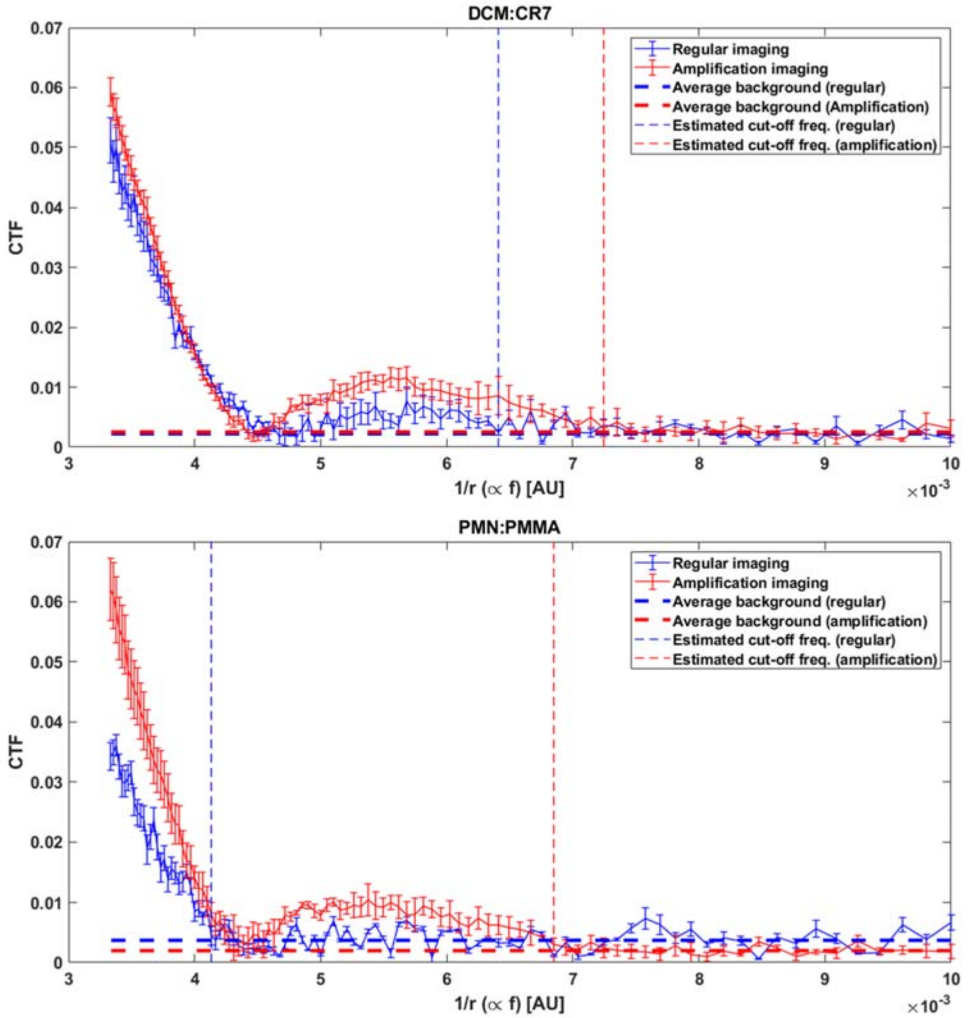

Fig.7. Higher cut off frequency in the circular transfer function (related to the modulation transfer function), for amplified *vs*. regular imaging. The difference in cut off is 13±3% for DCM:CR7, and 67±10% for PMN:PMMA.

References

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