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IMAGING AT THE LIMITS

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Monday Morning

MANIPULATION OF QUANTUM NOISE IN OPTICAL MEASUREMENTS

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Uncertainty, as is well-known, plays a central role in Quantum Mechanics and limits our knowledge of any physical system. But this does not mean that one cannot measure perfectly (at least in theory) a given quantity. One can for example prepare the system in the eigenstate of the observable associated to the measurement, or take advantage of the quantum correlations existing between the quantity to measure and another one.
This tutorial paper will briefly review the implementation of these ideas in the optical domain, in which the quantum noise, or photon noise, is a limit which is indeed reached in many high sensitivity measurements. It will deal successively intensity measurements, interferometric techniques, polarisation measurements, and show how one can reduce the quantum fluctuations by an appropriate tailoring of the quantum state of the light used in the system.
We will then turn our attention to the measurements which do not depend on the total intensity of a light beam, but on the detail of its repartition in the transverse plane, i.e. to images, and show that it is also possible in this case to find eigenstates of the measurement, which are now quantum states of different transverse modes of the field. Figure 1 gives an example of the improvement of a measurement performed in an image using an appropriate tailored light state. The problem of the role of quantum noise in optical resolution will also be addressed.
We will finally discuss in which respect these methods can be implemented in real and practical measurements.

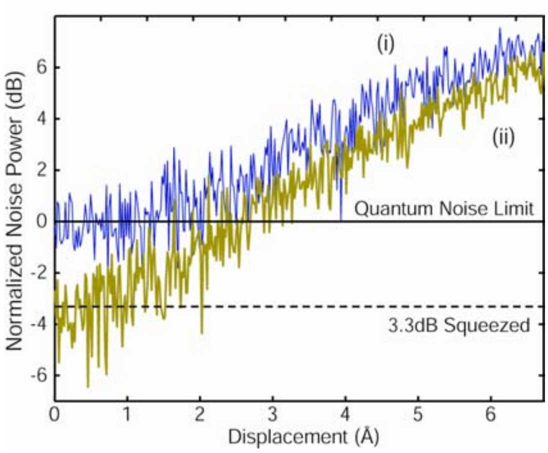

Figure 1 : optical signal used for the measurement of a very small transverse displacement of an optical beam as a function of the imposed displacement (in Angstroem). The noise floor is reached for smaller displacement values when one uses appropriately squeezed light (ii), instead of an ordinary laser beam (i)
*(N. Treps et al, Science **301,** 940 (2003))*

TUTORIAL

Spatial Squeezing and Correlations

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The field of Quantum Imaging has received a lot of attention in the recent years. It aims to exploiting the spatial quantum properties of light for applications to Imaging and, more in general, to parallel Inormation Processing.
A physical process which plays a central role in this field is optical parametric down-conversion. One can distinguish two opposite regimes that have been the object of intensive study. The first, and largely more common in the literature, is the case of extremely low gain, in which one pair of signal-idler photons is emitted at a time, and one detects coincidences in the arrival of signal and idler photons, for example the image is obtained from the arrival of a huge number of photon pairs.. In this talk, instead, I will focus on the opposite regime of medium/large gain, in which a macroscopic number o photon pairs is emitted and/or detected at a time.
The first part of the talk concerns the analysis of the spatial quantum properties of parametric down-conversion in the macroscopic regime. Both the case of Type I materials and of Type II materials will be considered showing, in each case, the phenomena of spatial squeezing and spatial quantum correlation which arise in the near and in the far field. The spatial correlations are intrinsically quantum and correspond to phenomena of spatial quantum entanglement. The discussion will be mainly based on the use o the input-output relations of the nonlinear crystal (Heisenberg picture) but, in order to illustrate the entanglement properties, I will occasionally use the Schroedinger picture.
The second part of the lecture will be devoted to the illustration of some techniques of Quantum Imaging, which exploit the spatial quantum properties of parametric down-conversion.
Special and extensive attention will be dedicated to the approach of Entangled Imaging, which is also known in the literature as Ghost Imaging. The signal and idler beams propagate in distinct arms of an imaging system. An object, about which information needs to be extracted, is located in the signal arm. Information about the spatial distribution of the object is not obtained by direct detection of the signal beam but, rather, from the spatial correlation of signal and idler beams and, what is most surprising, by scanning the idler beam which never passed through the object. The two-arm configuration of this technique will be illustrated for the two cases of detection of the image of an object and of detection of the Fourier transform of an object.
I will mention the recent debate on whether quantum entanglement is necessary to perform ghost imaging or not, and show that, in the macroscopic regime, it is possible to obtain substantially the same performances by using, instead of the entangled signal-idler beams, two classically correlated beams obtained by splitting a thermal (or thermal-like) beam with the help o a beam splitter. This result will be first shown theoretically and numerically and, last but not least, will be substantiated by an experiment just realized by Fabio Ferri and Davide Magatti at University of Insubria in Como.

Detection of sub-shot noise spatial correlation in high-gain parametric down-conversion

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Spatial quantum optical fluctuations are studied because of new potential applications of quantum optical procedures in parallel processing and multi-channel operation. There is a large literature on spatial effects in the spontaneous regime of parametric down-conversion (PDC) where photons are created one pair at a time [1]. The experimental results we present are instead in the *high-gain* regime, and show a twin-beam-like *spatial quantum correlation* between pairs of symmetrical signal and idler pixels. To date, most quantum correlation measurements in PDC have been performed with low-to-medium pump-power lasers and usually rely on statistical ensembles from different *temporal* replica of the quantum system. With increasing gain a transition from the quantum to the classical regime has been observed [2]. However, recent theoretical investigations predict multi-mode spatial quantum correlations also in the high-gain limit, precisely sub-shot noise photon number correlations between symmetrical portions of signal and idler, when detection areas exceed the typical size of the mode (coherent area) [3].

Here we report on the first quantum measurements performed by using a low-repetition rate (2 Hz) pulsed high-power laser (1GW-1ps). This enables us to tune the PDC to the high-gain regime (up to one hundred photons per mode) while keeping a large beam size (1mm). The huge number of transverse modes (measured using a high quantum-efficiency CCD [4]) allows us to identify areas of the signal and idler beams where symmetrical signal-idler pixel pairs correspond to independent *spatial* replica of the quantum system. A single-shot statistics is then obtained by averaging over the pixel pairs.

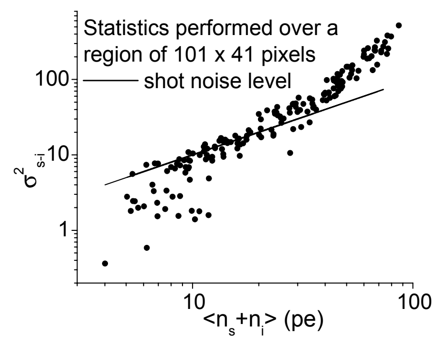

Fig. 1. Noise in the difference of photoelectrons in the signal and idler pixel pair plotted vs. the mean photoelectron counts of the pixel pair. The points are averaged over pixels in the selected areas in single shot. Pump: 352 nm, 0.2-0.4 mJ, 1ps, 1mm FWHM. Crystal: 4mm type-II β-barium-borate.

Figure 1 shows the measured correlations in the far-field radiation of PDC. Plotted is the variance σ_{s-i}^2 of the photon-number difference of the signal and idler pixel pair versus the mean photon number of the signal-idler pixel pair, which represents the shot noise (SN). In case of perfect quantum correlation $\sigma_{s-i}^2=0$, while the full line gives the classical SN limit. The measurements are performed by changing the pump power and show correlations below the SN limit when the gain is lower than 15 photons per pixel. This result never observed before is in accordance with the predictions of a fully 3D model that includes the finite beam size. The quantum nature of the correlations tends to disappear for higher gain in accordance with the fact that the pump waist size decreases when increasing the power with a consequent increment of the coherence areas size of the PDC radiation. Moreover, instead of pixel pair correlations, correlations between larger spatial areas reaching the size of the coherence area of (or bigger than) the spatial modes are under current investigation.

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All-optical image processing with type-II Second Harmonic Generation

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Nonlinear optical effects may provide a way to perform all-optical parallel processing of images. Here, we investigate the possibilities offered by type-II second harmonic generation both in intracavity and traveling wave configurations.

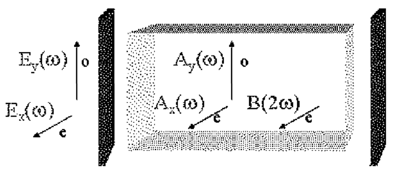

FIG. 1. Intracavity setup

The intracavity configuration is represented in Fig. 1: A crystal with a $\chi^{(2)}$ nonlinearity is placed in an optical cavity. Assuming a type-II phase matching, second-harmonic field will be generated if the cavity is pumped at two orthogonal polarizations x and y. We will assume that the image to be processed will be injected in x-polarization, with an homogeneous pumping amplitude E_y in the orthogonal y-polarization[1].

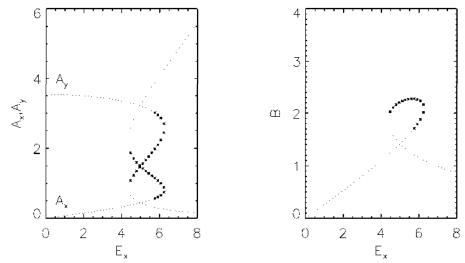

FIG. 2. Steady state solution for asymetric pumping, as a function of E_x. $E_y = 5$.

Fig. 2 represents the steady state solution for the system of nonlinearly coupled equations governing the time evolution of the intracavity fields[2], as a function of the amplitude E_x of the x-polarized pump for a fixed E_y. The pecular S-shape of these curves can be exploited for image processing purpose and suggests two different operating regimes. If the intensity of the signal in x-polarization remains always below the value of the y-polarized pump field, the steady state intracavity field $A_x(x)$ never leaves the lower branch of the curve $A_x(E_x)$ (Fig. 2), and follows in a quasi linear way the spatial dependence of the input signal, while the output $B(x)$ at frequency 2ω reproduces the spatial distribution of the input signal. Therefore, the device allows to transfer an input signal from the fundamental up to second-harmonic frequency (Fig. 3). If, on the contrary, the intensity of the signal in x-polarization is increased so that it locally exceeds the pump E_y, the S-shaped dependence of $A_x(E_x)$ comes into play: we show that the transmitted image at polarization x reproduces the input image of the part where E_x exceeds E_y with an enhanced contrast, while the second-harmonic field distribution displays the contour of this image (Fig. 4)[1].

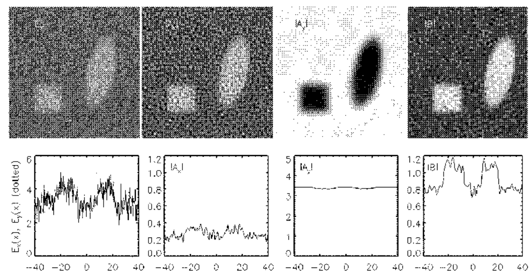

FIG. 3. Frequency Transfer of a two dimensional optical image in the noisy case. From the left to the right: $E_x(x)$,$A_x(x)$, $A_y(x)$ and $B(x)$.

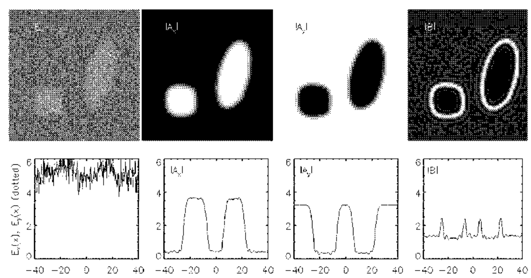

FIG. 4. Contrast enhancement and contour recognition in the case of a noisy image. E_y is the same as in Fig. 3.

In the traveling wave configuration we explore from the point of view of quantum imaging the possibilities offered by type II second harmonic generation. The polarization degree of freedom alows for a variety of operating regimes. In the simple frequency addition regime, a degradation of the signal to noise ratio occurs, but our quantum treatment allows to find out ways to improve the noise behavior of the system. For a pump polarized along the diagonal, the possibility of noiseless up-conversion of an input image with the same polarization from fundamental to Second Harmonic frequency is predicted, whereas an image with the orthogonal polarization can be without modifying the experimental setup, noiselessly amplified.

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Measurements of intensity correlations in the transverse plane of the output from a confocal optical parametric oscillator

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We study the correlations in the output of a triply resonant as well as a doubly resonant (single pass pump or pump enhanced) confocal OPO. Multimode generation requires a pump beam with a wide beam waist in the nonlinear crystal; thus mode match of the pump beam is not required and is not a realistic assumption. A triply resonant configuration is thus complicated by the fact that the generating pump field is also a complicated multimode field. For this reason we prefer the single pass doubly resonant configuration or the pump enhanced doubly resonant configuration.

We have chosen to study the intensity correlations in the transverse plane by performing true auto- and cross-correlation measurements of the fluctuations relative to a mean intensity profile.

Some of the challenges encountered in these measurements are

- Stability of the OPO setup while registering signal/idler, near field/far field.
- Repeatability of measurements from shot to shot.
- Validity of correlation measurements; what to correlate: within a single shot or fluctuations from shot to shot (assuming same mode structure).

In our setup we work on the following innovations:

- 4-way pictures containing both near field and far field for both signal and idler.
- Stabilization of the OPO-cavity.
- 2-D auto- and cross correlation computed on single shot measurements or on the fluctuating part of multiple shot measurements.

We obtain simultaneous imaging of near field and far field by splitting the output from the OPO in two beams and separately adjusting the focal distance of each. We then recombine the beams to propagate nearly concentric and parallel, but with an angle difference adjusted to give two separate images (image split in the horizontal direction) on the same CCD-chip. Furthermore, we split the two polarizations apart by placing a Wollaston prism just in front of the CCD-detector. The Wollaston prism is oriented to split the vertically and horizontally polarized beams in the vertical direction. We thus obtain far field registration of signal and idler just above each other and next to that near field registration of the same.

The fact that we can now obtain near field / far field images of both signal and idler beams on the same CCD-frame insures validity of correlations between these fields. A separate, but related, question is if we can assume stability and repeatability between the mode structures from shot to shot. So far this has been nearly impossible to obtain due to the instability of the OPO-setup. A confocal cavity is particularly unstable due to its ability to support many off-axis modes, and the usual stabilizing methods designed for single transverse mode (Gaussian beam) fail in our case, where the mode structure does not provide a unique error signal. We propose to solve this problem by using a so-called pump enhanced cavity. This is a cavity, where the pump is in weak resonance (e.g. 50% reflection for the pump light). The signal and idler can still both be resonant, so we could term the cavity 2½-times-resonant. The pump resonance is used to provide an error signal for stabilizing the cavity. This stabilization still does not affect the signal and idler beams, which are still free to form the mode structure and pattern generated by the nonlinear gain, but the conditions under which they evolve would be stabilized.

The pump laser for the experiments is a frequency doubled YAG-laser at 532 nm (5 W CW Coherent VERDI). The confocal cavity consists of two concave mirrors with radius of curvature $R = -100$ mm. The two mirrors have a transmittance of 50% for the pump (532nm) and high reflectance for the signal and idler (1064nm). The nonlinear medium is a KTP crystal cut in the xy-plane according to the degeneracy point at $\phi = 23.5^o$.

We have shown that a degenerate confocal, pump enhanced OPO can be stabilized and can oscillate in a superposition of many transverse modes. We observed complex patterns in the near and far field. We compared the performance of the triply resonant cavity to that of the pump-enhanced double resonant cavity. Furthermore, we have developed correlation methods for measuring correlations within a single shot or correlations between the fluctuating parts of multiple images.

Monday Afternoon

The Generation of Non-Classical States of Light with Resonant-Cavity Light-Emitting Diodes (RCLEDs): A Perspective for Quantum Imaging ?

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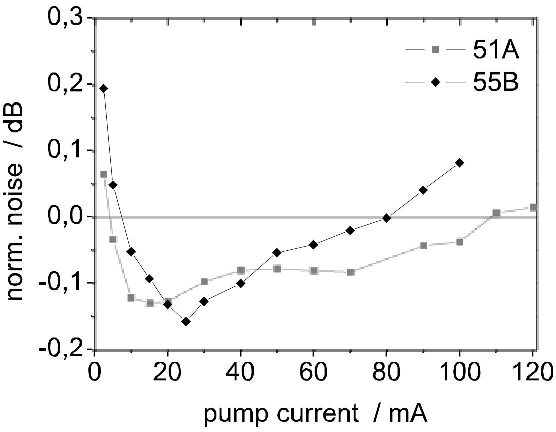
The resonant-cavity light-emitting diode (RCLED) or microcavity LED /1/ does not only represent an elegant and sophisticated technological approach with improved impact on efficiency, available emission spectrum, higher power and speed for illumination and short-range telecommunications applications, but is also interesting with respect to its fundamental quantum optics point of view. We apply the “quiet pumping” idea of generating non-classical states of light with sub-shot amplitude noise fluctuations (amplitude squeezing) with semiconductor optoelectronic emitters as demonstrated a few years ago theoretically and experimentally /2/ onto RCLEDs.

We present results of comprehensive investigations of the intensity noise and the angular-resolved spectral emission characteristics of RCLEDs, demonstrating an interesting interplay between these two properties. First, we find that the intensity noise of the investigated RCLEDs, detected within a full solid angle of detection, is up to -0.15 dB below the shot noise in a quite large pumping regime, as depicted in Fig. 1 for two RCLEDs, i.e. we demonstrate the successful generation of squeezed states of light with these optoelectronic devices.
Second, we investigate the spectral and angular emission characteristics and find that the cavity-like character of the Bragg mirrors and the quantum well active medium manifests itself in a temperature-tunable blue shift of the central emission wavelength from 847 nm at zero degree to 825 nm at an emission angle of sixty degree.
Third, we measure the angular-resolved intensity noise. From its super-shot noise behavior we deduce anticorrelations between the intensity noise of different radial beam components, as shown in Fig. 2 for the correlations between the central and peripheral noise. Finally, these experimental results, the possible origin of the observed anticorrelations, as well as possibilities of these non-classical states of light with respect to spatially quantum correlated optical beams /3/ and their applications in sensing, spectroscopy and imaging are discussed.



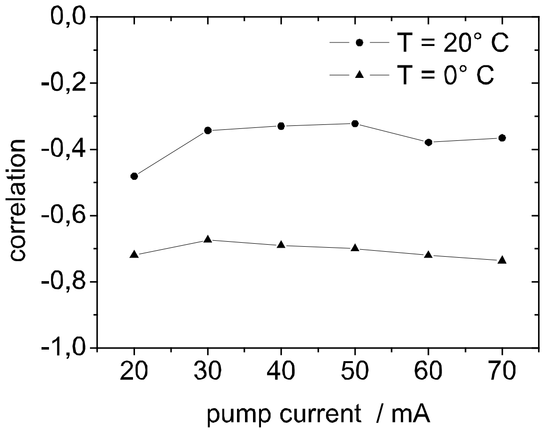


Fig. 1 Shot noise normalized intensity noise as a function of pump current for 2 devices.

Fig. 2 Correlation coefficient between the fluctuations of the central and peripheral beam for 20 ° C and 0°C.

We would like to acknowledge the excellent resonant-cavity light-emitting diodes provided by Christian Jung from OSRAM Opto Semiconductors, Regensburg (Germany).

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Polarization patterns and singularities in imaging and focusing

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Summary

When focusing light with a high aperture, a standard linearly polarized TEM 00-mode does not lead to the smallest possible spot size. Instead, the focus becomes elliptical, the long axis being oriented in the direction of the initial polarisation [1]. The focal spot is minimized by using a radial polarized donut mode. This has linear polarization locally, but the direction of linear polarization varies across the beam always oriented in the radial direction. At beam centre one finds a polarization singularity. The predicted reduction of the spot size [2] has been demonstrated experimentally [3]. This suggests that all optical systems operating with large numerical apertures are potential candidates for performance enhancement by polarization optimization.

Using a Linnik interference microscope we studied the light field in the vicinity of small structures down to sub-wavelength dimensions. Close to these structures one finds lines of phase singularities which can be imaged into the far field and measured with great precision [4]. With the reference arm closed we also studied small grooves of the type used in CD-ROM's for data storage. Generally, some improvement is expected from using radial polarization for illumination in the Linnik microscope.

In the presentation it will be shown that polarization and singularities are important parameters in the interaction between wavelength scale structures and light.

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Super-resolution in optical imaging by classical means

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The tutorial talk discusses ways of achieving optical super-resolution in classical means. In particular we shall be looking at the definition of “resolution” and its different version depending on whether coherent or incoherent imaging is considered. A particular context of “two point resolution” is in astronomy so first the definition of angular resolution is given. Aberrations are known to severely affect resolution and so their effect is discussed in some detail. An alternative way of evaluating resolution in optical systems is via their transfer functions. Hence, the talk will present a short introduction to transfer functions, their roles and how they can be manipulated in order to improve on resolution.

The second part of the talk concentrates on practical means of achieving super-resolution. Thus we will be discussing solutions due to Toraldo di Francia and Frieden and the extension of these works to high numerical aperture optical systems. Confocal microscopy will prominently feature in the tutorial as one of the most elegant embodiments of superresolving optical systems. Methods of manipulating the point spread function of such imaging systems are described. These include 4Pi and theta-microscopy. We shall restrict our discussions to linear light-specimen interactions because fluorescence and other non-linear techniques will be the subject of another tutorial presentation.

The optical resolution in confocal microscopy is partly determined by the lateral size of the detector. Of course the noise level present in the system is also partly determined by the detector size. We present a simple analysis of confocal microscopes on the basis of signal and noise level revealing that, from classical optics point of view, there is an optimum detector size that does not correspond to the one determined when noise level considerations are not included.

The talk will also discuss methods of increasing “resolution” in optical data storage. We will point out that it is not necessarily the best way to widen the transfer function to achieve higher data density. Also, we will draw a parallel between imaging and detection and show that when *a-priori* information of the object being imaged is available this fact alone can, in certain circumstances, lead to superresolution.

Quantum limits on optical super-resolution

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Quantum imaging is a newly born branch of quantum optics which studies ultimate performance limits in optical imaging, allowed by the lows of quantum mechanics [1]. One of the problems recently addressed in this context is about the quantum limits of the optical resolution [2].

The conventional concept of resolving power of an optical instrument was developed at the end of the nineteen century in classical works of Abbe and Rayleigh. The classical resolution limit was formulated in terms of the overlap of the images of two closely spaced points at the input of the optical system. This classical limit is based on the presumed resolving capabilities of human eye, and is not a fundamental limit imposed by quantum mechanics. Today one can obtain the resolution better than the Rayleigh limit by recording the images at the output of the optical system with modern CCD cameras and subsequent electronic processing for reconstruction of the input objects [3].

In the framework if the modern Fourier optics the resolving power of an optical system is characterised by its spatial-frequency transmission band. Classical super-resolution is an attempt to restore the spatial Fourier components of the object outside the transmission band of the system. It appears to be possible when one has some *a priori* information about the object, for example, that the object has a finite size [4].

In this tutorial lecture it will be demonstrated that the ultimate performance of the super-resolution technique is determined by the quantum fluctuations of light inside the area of the object and the vacuum fluctuations outside it. We shall give an overview of the quantum theory of super-resolution developed recently in terms of the prolate spheroidal functions [1]. We shall formulate the standard quantum limit of super-resolution and demonstrate that one can go beyond this limit using spatially multimode squeezed light [5].

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Tuesday Morning

Tutorial:
Classical Coherence Imaging and Quantum Two-Photon Imaging

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Imaging by measurement of the optical coherence function at pairs of separated points has been well known since the early days of the development of partial coherence theory in the 1950s and 1960s. The Michelson stellar interferometer (MSI) relies on the interferometric measurement of the second-order coherence function and the Van Cittert-Zernike theorem. The Hanbury Brown-Twiss (HBT) interferometer is based on measurement of the fourth-order (intensity) coherence function (or the photon coincidence rate). For thermal light, because of the photon bunching effect, this latter function is directly related to the second-order coherence function via the Siegert relation. Imaging of non-self-luminous objects by measurement of the coherence function has also been pursued as applications to light scattering were developed. In 1963, Goldberger, Lewis and Watson recognized that the measurement of the coincidence rate of photons scattered in *two* directions from an object illuminated by *two* optical beams yields information on the *amplitude* scattering coefficient, so that the system provides information about phase objects.

This venerable subject is being rediscovered as a result of the strong interest in quantum imaging, particularly imaging with a two-beam light source in a two-photon quantum state. Generated by spontaneous parametric down-conversion in a second-order nonlinear medium, such light has found applications in communication, cryptography, metrology, and imaging. In 2000, Saleh *et al*. [1] established a duality between imaging using light in a two-photon state and imaging based on measurement of the classical coherence function. This duality established a correspondence between the various two-photon imaging configurations and the old/newly-discovered imaging schemes based on measurement of the coherence function.

The underlying physics of this duality is the correspondence between the first-order coherence function $G^{(1)}(\mathbf{x}_1,\mathbf{x}_2) = <\hat{E}^{-}(\mathbf{x}_1)\,\hat{E}^{+}(\mathbf{x}_2)>$ for light in any state, and the wavefunction $\psi(\mathbf{x}_1,\mathbf{x}_2) = \langle 0|\hat{E}^{+}(\mathbf{x}_2)\hat{E}^{+}(\mathbf{x}_1)|\Psi\rangle$ for light in a two-photon pure state $|\Psi\rangle$, where $|0\rangle$ is the vacuum state. Here, $\hat{E}^{+}(\boldsymbol{x})$ and $\hat{E}^{-}(\boldsymbol{x})$ are, respectively, the positive- and negative-frequency components of the electric field operator at the position $\boldsymbol{x}$. In the classical coherence-imaging system, $G^{(1)}$ is measured interferometrically, e.g., using an MSI, or its magnitude $|G^{(1)}|$ is inferred from measurement of the intensity coherence function, as in the HBT interferometer (if the light is in a thermal state). In the two-photon imaging system, the magnitude $|\psi(x_1,x_2)|^2$, which is the probability of two-photon coincidence, is measured using a coincidence detector. The analogy between the two imaging systems stems from the almost identical rules governing the propagation of $G^{(1)}(\mathbf{x}_1,\mathbf{x}_2)$ and $\psi(\mathbf{x}_1,\mathbf{x}_2)$ through linear systems. Both originate from the relations between the fields $\hat{E}^{(\pm)}(\mathbf{x})$ at the detectors and at the source. Thus, all imaging configurations in one imaging modality have their counterparts in the other, including the van Cittert–Zernike theorem of classical partial coherence and ghost imaging of two-photon systems. This duality has many interesting ramifications. For example, the limit $G^{(1)}(\mathbf{x}_1,\mathbf{x}_2) \sim \delta(\mathbf{x}_1 - \mathbf{x}_2)$, which corresponds to a spatially incoherent source, is the dual of the limit $\psi(\mathbf{x}_1,\mathbf{x}_2) \sim \delta(\mathbf{x}_1 - \mathbf{x}_2)$, which corresponds to a maximally entangled two-photon state!

In this tutorial, we compare and contrast imaging systems based on measurement of the classical coherence function, and those based on two-beam two-photon light and the measurement of photon coincidence rates.

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Quantum Imaging

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The phenomenon of ghost imaging was demonstrated at UMBC ten years ago [1]. The experiment exploited an apparent "spooky action at a distance" of an entangled photon pair and offered an entirely novel kind of imaging. Although questions regarding fundamental issues of quantum theory still exist, quantum imaging has brought a great deal of attention from the view point of practical applications, in which measurements and imaging may achieve the fundamental limits by means of greater resolution and by means of nonlocal behavior.

Recently, Gatti et. al. proposed using thermal radiation to create ghost images [2]. Like the historical Hanbury Brown-Twiss experiment, this phenomenon is another example of two-photon effects [3]. The experimental demonstration of thermal light ghost imaging has been realized at UMBC recently [4].

Can thermal light ghost imaging replace ghost imaging using entangled states? This will be the first question to be addressed.

We classify quantum imaging into two basic categories – coherent two-photon imaging and incoherent two-photon imaging (1) Coherent two-photon imaging: Typical experiment was demonstrated by using entangled photon pairs generated via spontaneous parametric down conversion (SPDC) [1]. The ghost image is the result of coherent superposition of the two-photon amplitudes. It is the coherent superposition of the two-photon amplitudes that makes the ghost image very special. It is nonlocal while achieving spatial resolution even beyond the classical limit. (2) Incoherent two-photon imaging: Typical experimental setup of two-photon ghost imaging using thermal light is similar to the ghost imaging experiment of SPDC, except the light source and a slightly different Gaussian thin lens equation to determine the image plane [4]. However, thermal state is a mixed state. Instead of coherent superposition of two-photon amplitudes, it is the incoherent addition of the second order correlation function that makes the ghost image possible. Due to the incoherent nature, spatial resolution of the thermal light ghost image cannot go beyond the classical limit. In addition, we have also identified problems that may hinder the realization of thermal light imaging applications. One of them is the low visibility of the images. Similar to Hanbury Brown-Twiss experiment, the maximum visibility of thermal light $G^{(2)}$ is 33% (a 1:2 constant background) and drop quickly when the object has more features [4]. In our measurement, the image visibility dropped from about 1/3 to a few percent when the number of slits on the object plane increased. These problems will be discussed during the report of the experiment.

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Image formation using quantum-entangled photons

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Abstract: Coincidence (ghost) imaging forms an image using photons that have never encountered the object. We present experimental results showing which aspects of this process result from quantum entanglement and which can be understood classically.

Quantum imaging [1,2] can be used to construct images that are sharper or are more sensitive to features of low contrast than is allowed by conventional imaging techniques. In this contribution, we describe an experimental and theoretical investigation of the process of coincidence (or "ghost") imaging with the goal of establishing any limitations to the usefulness of this method and of establishing which features of the coincidence imaging process are quantum and which can be understood in terms of classical correlations.

The process of coincidence imaging using an entangled light source [3] is illustrated in Fig. 1. Here a laser beam excites a second-order nonlinear optical crystal, and through the process of parametric downconversion a pair of entangled photons is created. One of these photons illuminates an object, and a non-imaging detector (a "bucket" detector) registers the scattering of the photon from this object. The other photon of the pair is directed onto an imaging device, a photodetector array. A coincidence circuit records the output of the imaging detector only when triggered by the bucket detector. In this manner, a sharp image of the object is obtained, even though the photons that fall onto the imaging detector have never interacted with the object to be imaged.

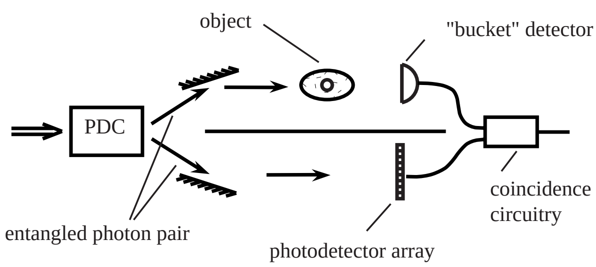

Fig. 1. Illustration of the process of coincidence imaging.

There has been a spirited discussion [4,5] in the literature regarding the conditions under which coincidence imaging can occur and in particular on whether coincidence imaging is an intrinsically quantum process or whether it can be understood in terms of classical correlations. Recently, Gatti et al. [6] have argued theoretically that coincidence imaging can be performed using classical correlations for an object at a known distance from the apparatus, but that quantum entanglement is required if one wants to obtain a sharp image of an object that might be either in the near or far field of the light source. We have performed an experiment to test this idea, and find results [7] in full agreement with these predictions.

Our experimental setup and results are shown in Fig. 2. In part (a) of the figure, an object in the form of a two-bar mask is imaged onto the plane of the parametric downconverter. In part (b), the object is placed in the far field of the downconverter. In both cases a sharp image of the object is obtained by the coincidence circuit. We have also obtained results for the situation in which the parametric downconverter is replaced by a classically correlated source. In this case, we obtain sharp images for an object in either the near or far field but not in both. These results can be understood from the point of view that, in the quantum case, the observer can wait until the photon pair is emitted before deciding whether the measure the position or (transverse) momentum of one of the photons. The analogous quantity for the other photon is then precisely determined. The relation between coincidence imaging and the EPR effect [8] and additional applications of entangled photon pairs emitted by the process of parametric downconversion will also be described in our presentation.

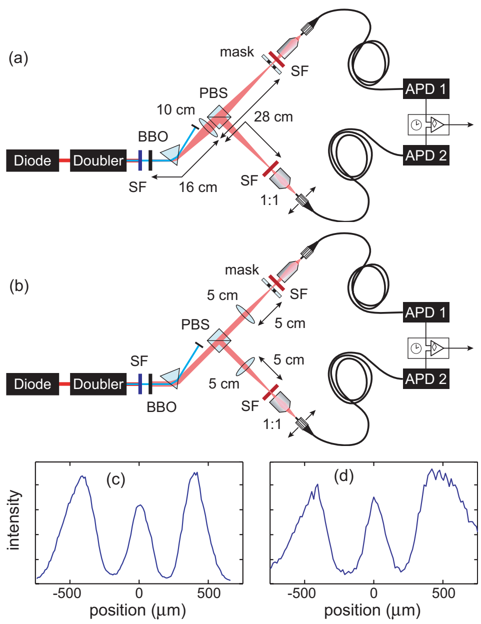

Fig. 2. Experimental setups (a,b) and measurements (c,d) showing coincidence images of a two-bar masks in both the near (a,c) and far (b,d) fields.

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Manipulation and Transmission of Quantum Images

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The twin photons produced in the parametric down-conversion, can be prepared in entangled states that can be used for instance, in quantum communication [1]. Most of the projects related to the use of entangled photons for quantum communication, rely on the manipulation of the photon polarization as the entangled degree of freedom [2]. In particular, the capability of reliably transmitting an entangled photon pair through a long distance have been pursued, with and without the use of optical fibers [3]. Optical fibers are a very convenient and robust medium for transmitting optical signals. However, sometimes it is not possible to use it. One nice example is the project for transmitting entangled photon pairs via satellite [4]. As a first approach, it has been demonstrated that it is possible to share an entangled photon pair through about 600m of free air [5]. In all the cases mentioned, the entangled degree of freedom was the polarization. However, this is not the only degree of freedom that we can prepare entangled states with twin photons. Twin photons can be entangled in the transverse momentum, giving rise to the so called *Quantum Images*. The term quantum image has been used for the correlated images in optical fields [6]. A discussion on the issue of the quantum character of these correlated images is actually in progress [7]. Some kinds of correlated images are prepared by transferring the angular spectrum of the pump beam to the correlated twin beams [8]. In this case, it is possible to show that some correlated images, have transverse correlations that violate a classical inequality, leading to spatial photon anti-bunching [9,10]. Here we work with this kind of correlated images and we are going to call them quantum images, even though there may have place for further discussion on the issue.

We demonstrate that the quantum image can be prepared partially through the nonlinear interaction and partially by propagation of signal and idler beams through lenses [11]. Using this kind of preparation it is also possible to use a telescope for transmitting the quantum image with an almost divergence-free system [12].

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Correlated Imaging in the macroscopic regime: fast and broadband

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The Correlated Imaging technique, based on two spatially correlated beams, is interesting because the image of an object or its diffraction pattern can be obtained with a degree of flexibility superior to standard imaging techniques. For example, illuminating the object by one beam the processing of the image is done by changing only the optical setup in the path of the other beam. Most remarkably, the diffraction pattern can be observed despite the fact that both beams taken separately are incoherent. This technique was first formulated by Klyshko for the case of entangled beams (hence under the name Entangled Imaging) generated by spontaneous parametric down conversion (PDC) in a regime where coincidences are detected between the signal and the idler photons (see [1] and references quoted therein). We generalized the technique to the macroscopic regime of a very large number of photon pairs emitted in each pump pulse [2].

Recently a very lively debate has developed on whether the quantum entanglement of the two beams is necessary to achieve such results or whether a classical correlation is sufficient [3,4]. We demonstrate both analytically and numerically that such a scheme can be implemented using incoherent classical light. Precisely, thermal (or thermal-like) radiation is injected onto a beam splitter and the two outgoing beams are treated in the same way as the signal and idler beams in Entangled Imaging. Based on a parallel treatment of the two cases of entangled beams and classically correlated thermal beams, we show that in the macroscopic regime all the imaging performances of the entangled source can be emulated by the classically correlated beams [5].

We illustrate the results for Correlated Imaging in the macroscopic regime of PDC through realistic numerical simulations. For the reconstruction of the diffraction pattern a spatial averaging technique is introduced which greatly improves the imaging bandwidth with respect to the natural spatial bandwidth of PDC. In addition it reduces the convergence rate of the correlations by several orders of magnitude. These effects are found for both amplitude and phase objects [6].

Using a homodyne detection scheme the full phase information can be reconstructed. Moreover, the spatial averaging technique mentioned above works particularly well in the homodyne scheme, since from measurements of the spatial correlations one can obtain both the real and the imaginary part of the diffraction pattern (in contrast, the direct intensity detection scheme gives information about the modulus of the diffraction pattern). Thus, by taking the inverse Fourier transform one can retrieve the image of the object. Due to the large spatial bandwidth available in the reconstructed diffraction pattern owing to the spatial averaging technique, complex images can be retrieved with high resolution after a number of pump pulses on the order of 100 (see Fig. 1) [7].

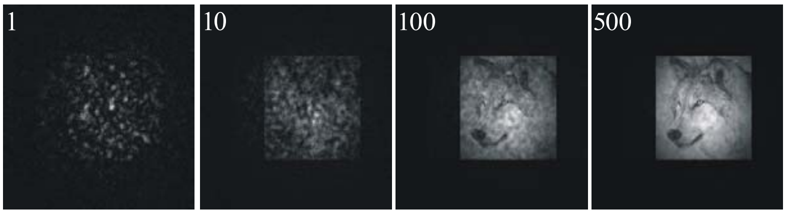

Fig.1*: Reconstructing an image located in one arm from the correlations in the homodyne detection case. The modulus of the inverse Fourier transform of the correlations containing the diffraction pattern is shown, using the spatial average technique as well as averaging over the number of shots indicated in each image.*

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Resolution and self-apodization in quantum Image

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PACS numbers:

Quantum coincidence imaging [1] is a method used for generating and detecting the image of an object by using light in the two-photon entangled state and coincidence detection. These photons are generated by the incidence of a pump (p) laser beam in a nonlinear crystal. This nonlinear optical process is called spontaneous parametric down conversion (SPDC). The photon pairs are generated simultaneously ("twin photons") and are called signal (s) and idler (i). Recently, we derived theoretically [2] the mathematical expression that describes the amplitude of probability to detect simultaneously two photons in the image plane of an object illuminated by a twin photons source. In this work, we show experimentally that an image of an object is obtained when one of the photons of a parametric down-converted pair illuminates the object and the two photons are detected in coincidence after they have been transmitted by two lenses. The image is mathematically described by a quantum fourth-order correlation function that differs from the classical image description in two aspects. The quantum image is produced by a non-local effective lens whose aperture is described by a compressed convolution of the magnitude of the lens transmission functions [2]. The image is generated by the entangled state two-photon light source in which the effective wavelength is equal to the de Broglie wavelength $\lambda/2$, where λ is the wavelength associated to the individual photons. Better resolution and strong apodization effects are observed. All the experimental setups used for generating the image of an object are shown in Fig. 1. In Fig. 1.(a), we used a classical light source, a diode laser with $\lambda = 826$nm. In Fig. 1.(c), we also used a classical a light source, a laser with $\lambda = 413$nm. Fig. 1.(b) shows the experimental setup that uses the twin photons as a light source. Each photon has individually wavelength around 826 nm. The involved longitudinal distances had been chosen to obey the thin lens equation for image formation. The pump laser beam was focused at the object plane. The experiment was performed by using a double slit as an object. The slit width is 89 μm, and the separation between the slits is 175 μm. For the setups shown in Fig. 1.(a), 1.(b) and 1.(c), the results are shown in Fig. 2.(a), 2.(b) and 2.(c), respectively. The continuous lines are the theoretical predictions [2]. By comparing Fig. 2.(a) and 2.(b), that use equals wavelength, we observe that the image made with twin photons has a resolution better than the one generated with the classical source, being therefore better than the diffraction limit. Moreover, the secondary maxima present in the classical image are absent in the quantum image (apodization effect). In spite of this, the quantum image resolution is not as good as the resolution of the image produced by the *pump* classical light source because the transmission function of the effective lens is not equal to the transmission function of the original lenses.

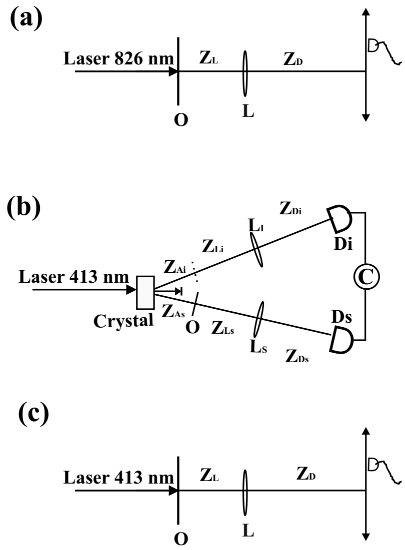

FIG. 1: Outline of experimental setup used for generating the image of an object (O) using a classical infrared light source (a), infrared twin photons (b) and a classical violet light source (c).

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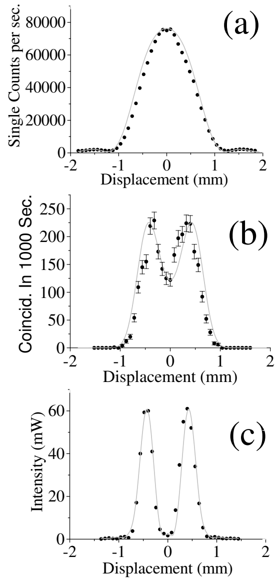

FIG. 2: Image of a double slit obtained by using classical infrared light source (a), infrared twin photons (b) and classical violet light source (c).

Tuesday Afternoon

Retrodictive states in two-photon quantum imaging

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The usual way to calculate probabilities in quantum theory is to use a prepared state and evolve this forward in time from the preparation time to the measurement time. In two-photon quantum imaging the prepared state is the crystal two-photon state. The two photons are separated in the experiment into two different arms, pass through different optical systems, and fall upon separate detectors. The forward time-evolution of the initially-prepared state allows a calculation of the joint probability of two detections, one in each arm, at particular spatial positions in the plane of detection. This is a fully predictive calculation.

Recently, we have developed a fully consistent formulation of retrodictive quantum theory. In this more unusual formulation the state of the system at any time is the detected state evolved backwards in time from the measurement. It is especially efficient for calculating retrodictive conditional probabilities - the probability, say, that a particular state was prepared earlier, given that the system is measured to be in a certain state.

In two-photon quantum imaging experiments the measurement corresponds not to a joint probability of detection in the two arms, but to a conditional probability of detection in the second arm, given a detection in the first. This suggests that a retrodictive type of calculation will be more natural. In fact we can formulate the state of the system at any time in this manner. The state evolves retrodictively from the first-arm detection through the system to the nonlinear crystal, where a partial collapse occurs, leaving a predictive conditioned state in the second arm. This state evolves forward in time until it is measured at the second detector. This state gives the conditional detection probability in a natural way.

In this paper will look at the similarities and differences between the predictive and retrodictive approches.

Adaptive Optics

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As the diameter of an astronomical telescope increases so does its diffraction limited resolution. However, in practice, beyond a certain pupil size (typically around 10cm in the visible at a good observing site) the actual resolution does not improve, but is limited by the aberrations introduced by turbulence in the Earth's atmosphere. This "seeing"-limited resolution is typically around one arc-second in visible wavelengths. The turbulence aberrations themselves are random and dynamic with timescales on the order of milliseconds, frustrating static correction, and result in a time-varying aberrated speckle image. The problem was recognized by Newton, but in the early 1950's adaptive optics was proposed as a solution, and has been developed during the subsequent half-century. The principle is to use dynamic correction, continually updated to compensate for the aberrations in real-time. Wavefront control is provided by an active deformable mirror—a mirror with an array of mechanical actuators that can be used to alter the spatial figure of the mirror's optical surface. The random nature of the aberrations requires some method to estimate the required correction: a wavefront sensor is used to monitor the wavefront of light passing through the aberrations. The typical arrangement is a closed-loop system. The wavefront sensor measures the residual wavefront error after the correction and the figure of the mirror is updated from this error signal.

Adaptive optics is now firmly established for ground-based astronomy, however its usefulness extends well beyond astronomy. In retinal imaging, the optical quality of the eye, which is itself a highly dynamic system, limits resolution. By correcting in real-time for the eye's aberrations, it is possible to image individual photoreceptors in the fovea. The technique can, in principle, be applied to many other optical systems that suffer from (unknown) aberrations.

Classically, the diffraction limit requires aberrations to be corrected down to $\lambda/14$ (the Marechal criterion). The degree to which this correction is achieved depends on a large number of factors: the statistics of the aberrations; the number, layout and the mechanism of the deformable mirror actuators; the speed of the correction; and crucially the accuracy with which the aberrations can be measured or estimated. In fact, it is probably fair to say that most of the "technology" of adaptive optics is in the wavefront sensing, and it is the wavefront sensing aspects of adaptive optics where most research is currently focused.

Fabricating and inspecting sub-half-wavelength devices with partially-coherent technology.

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Light with wavelengths of 248nm and 193nm is used today to manufacture and inspect integrated circuits with dimensions <55nm. Destructive interference creates the narrow dark features and high contrast photoresist transfers them to the chip.

The electronics industry today depends on optical methods for printing many millions of transistors and billions of interconnects, each of them much less than a wavelength in dimension, on square kilometers of silicon, to make chips which sell for a few Euros each. The smallest dimensions (as small as ~45nm today) correspond to dark features in the optical image. By arranging for the electric field to change phase by 180 degrees at the location of such dark features, chip and photomask designers can use destructive interference to create robust images that print in photoresist as narrow linear gates and tiny circular vias. When image variations are small enough, processing can also trim dimensions further. The wavelength of light only constrains the pitch of repeating patterns formed in a single exposure. Near term plans include liquid immersion lithography to shrink the effective wavelength even further.

All of this works because of the remarkable properties of today's chemically amplified photoresists. While these materials cannot compute photon correlations, they do break or form bonds in polymer matrices with a quantum efficiency much greater than unity, thereby dramatically altering film dissolution rates. The resist development process is more nonlinear than nonlinear optics, except that its rate depends on the integrated exposure. The statistics of dissolution, however, introduces roughness (noise) and diffusion limits resolution!

While sub-half-wavelength transistor gates have been printed for a few years as resist walls in positive photoresist, contacts and vias - which require sub-wavelength holes in developed resist films - remain problematic. They can be printed - even at the tightest spacings - in negative resist using optical vortices. Multiple exposures with multiple resist processes can overcome even basic linear optics limits!

While the problems of printing sub-wavelength features in photoresist films appear to be under control, inspecting and measuring those films - and the masks needed to project them - is not. Inspection and metrology are very important, both in order to qualify production processes and to reject defective resist patterns before errors are etched permanently into chips. Among the difficult challenges are assessing phase errors on masks, finding 50nm scale defects on wafers (while scanning at rates measured in 100's of sq. cm./hr), or 100nm diameter vias that go 300nm down, but are not open at the bottom, and measuring sub-nanometer roughness at the edges of resist features. Optical methods are still preferred for a variety of reasons and quantum imaging may have an important role to play in future inspection and metrology.