Eur. Phys. J. D **61**, 237–239 (2011)
DOI: 10.1140/epjd/e2010-10616-x

THE EUROPEAN PHYSICAL JOURNAL D

Regular Article

Spatial reshaping of a squeezed state of light

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Received 24 October 2010
Published online 3rd December 2010 – © EDP Sciences, Società Italiana di Fisica, Springer-Verlag 2010

Abstract. Reshaping the spatial profile, or mode, of a quantum state of light is one of the challenges in many quantum optics applications. We test the noise properties of a universal programmable mode converter and demonstrate that it can reshape the spatial mode of a beam while retaining its quantum properties. No detectable amount of noise is added to the light and only the standard transmission losses through conventional optical elements are found to affect the non-classical nature of the transformed light.

The properties of continuous variable (CV) non-classical states of light such as squeezed states or multimode entangled states contradict classical postulates like locality [1] and separability [2]. These quantum states are valuable resources for fundamental tests of quantum mechanics and for many protocols in communications [3], sensing [4] and quantum information processing [5]. In many practical applications it is important to match the spatial shape, or mode, of the light at every stage of the optical setup: state preparation, manipulation, and detection. The output mode of the non-classical state source can differ from the conventional TEM_{00} mode [6] or be different from the optimal modes for manipulation and detection. Consider an optical parametric oscillator producing squeezed light to enhance measurement; the squeezed state is generated in the resonant mode of the cavity [7], and to use the full noise reduction this has to be matched to the mode that contains the information to be measured [8]. For optimal detection, this mode then needs to be matched to the detector mode [9], which is either the local oscillator mode in a standard homodyne detection system [10], or a more complex mode in the case of specifically shaped multi pixel detectors [11]. In the case of CV non-classical states, it is important that the spatial mode is reshaped with very high mode matching efficiency, without any addition of noise in the relevant frequency band, and preferably with low optical losses, in order to maintain the quality of the state. More generally, even for non-CV experiments, good mode matching to complex modes can be critical [12]. It can, for example, improve the overall efficiency of devices based on single photon correlation detection [13]. In [14], we presented the unitary programmable mode converter (UPMC), a device potentially able to perform any spatial mode transformation with low losses. In this study we focus on the question: how will squeezed states of light be altered in this device? Here we provide quantitative answers, reporting the efficiency of reshaping the spatial mode of a non-classical state.

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We use squeezed states to characterize the UPMC. Squeezed states are states of light which have Gaussian Wigner functions with a width along one of the quadratures (the squeezed quadrature) below the quantum noise limit; this property makes them non-classical [15]. The quantum state of squeezed light can be fully characterized by its variances along its squeezed and anti-squeezed quadratures. This variance is given in dB with the reference (0 dB) set at the quantum noise limit.

We produce squeezed states in an optical parametric amplifier (OPA) aligned in a bow-tie configuration. The OPA is pumped with 532 nm light from a frequency-doubled diode-pumped Nd:YAG laser operating at 1064 nm. A periodically poled $KTiOPO_4$ (PPKTP) crystal is employed as the non-linear medium [7].

The squeezed light at the output of the OPA has the spatial profile of a transverse electro-magnetic fundamental mode (TEM_{00}), and we want to characterize the ability of the UPMC to transform this TEM_{00} into another spatial mode without altering its quantum state. We use two separate homodyne detections (HD_1 and HD_2, as described in Fig. 1) to characterize the quantum state of the light before and after the UPMC. The local oscillator (LO_1) for HD_1 is in the TEM_{00} mode that matches the output of the OPA. HD_2 uses a local oscillator (LO_2) in a different spatial mode that defines the desired output mode of the UPMC and is used to measure its quantum state.

To produce a spatially stable LO_2 we use a high finesse mode cleaning cavity as a Gaussian mode selector (GMS). This cavity is seeded with a misaligned beam in order to lock it on resonance with a higher order TEM mode (TEM_{n0}). Using a GMS restricts the set of spatial transforms upon which to benchmark the UPMC, from the input TEM_{00} to a TEM_{n0}. The results from this subset

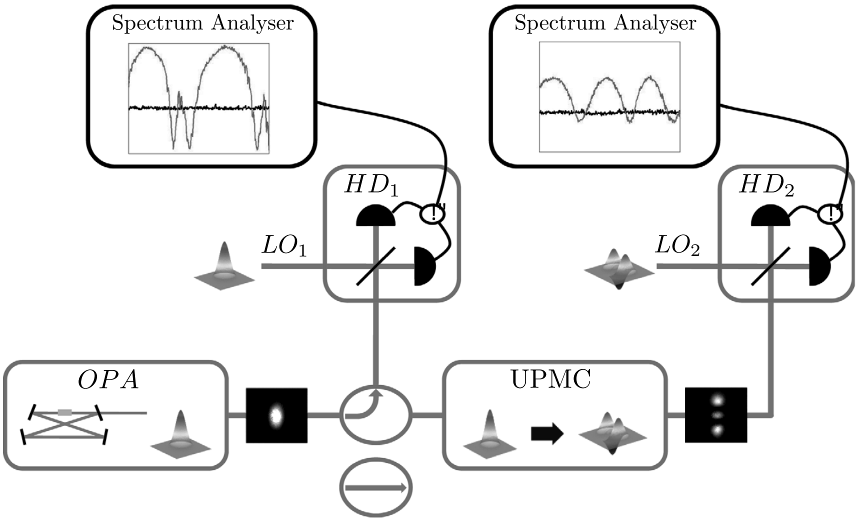

Fig. 1. (Color online) General schematic of the experiment. The output of the optical parametric amplifier (OPA), a squeezed state in the TEM_{00} mode, is either sent directly to be measured on the first homodyne detection HD_1 using a local oscillator in the TEM_{00} mode or sent through the UPMC. The UPMC changes the spatial profile of the light, in this specific example to a TEM_{20}. The squeezing levels in the TEM_{20} output mode are then measured using HD_2.

Table 1. Measured variances before (HD_1) and after (HD_2) the UPMC for a range of transforms.

Output mode:	TEM_{00}		TEM_{10}		TEM_{20}		TEM_{30}	
Homodyne	HD_1	HD_2	HD_1	HD_2	HD_1	HD_2	HD_1	HD_2
Squeezed quadrature, in dB	−5.1	−1.7	−5.0	−1.6	−4.9	−1.3	−5.0	−1.4
Anti-squeezed quadrature, in dB	6.3	4.4	6.4	4.4	6.3	3.3	6.6	4.0

may then be generalized to predict the performance of the UPMC for all transforms.

To create the signal beam to be measured at HD_2 the output of the OPA is first mode-matched via a combination of spherical and cylindrical lenses into the UPMC. It then undergoes a succession of 3 reflections on independent computationally addressed deformable surfaces, with Fourier transforms (FT) taking place between each reflection. We use a single deformable mirror (DM) from Boston Micromachine for the three successive reflections by focusing the beam on to three designated areas, with negligible cross talk between the areas. The face of the DM is a 12 by 12 pixel array, with the four corner elements disabled – hence controlled by 140 actuators. The three highly elliptical beam spots focused on to the DM have column widths of 2 pixels each. A DM is chosen over a liquid crystal on silicon spatial light modulator because of its absence of phase flicker [16].

A complete treatment of the UPMC is provided in reference [14], suffices to say here that with an unlimited number of reflections on deformable surfaces with infinite pixel counts separated by FTs, any unitary transform of the spatial profile can be performed. When the number of pixels and the number of reflections are limited, simulations predict how well the transform will be performed. For our proof of principle UPMC, the size of the DM restricts us to vertical transforms with 3 reflections on 12 pixels.

Each spatial transform requires a different profile of the DM to be programmed. In order to find the optimal DM shape for a given transform we use a stochastic optimization algorithm. The output of the UPMC is made to interfere with LO_2 on the half beam splitter of HD_2. We vary the overall phase of LO_2 via a piezo and use the visibility derived from this interference as the optimization criterion. We change repeatedly the shape of the DM, measure visibility, and once a maximum is reached the DM shape is held constant. Once optimal DM shapes have been found that correspond to given transforms, it is possible to select these shapes within milliseconds by sending the required commands to the actuators.

We test the UPMC for a range of transforms, using TEM_{00}, TEM_{10}, TEM_{20} and TEM_{30} modes as LO_2. We find that no additional noise can be detected on HD_2 compared to HD_1 in the 1–6 MHz bandwidth. We then measure the squeezing and anti-squeezing variances on HD_2, having measured the variances on HD_1, before the UPMC, as a reference. This procedure is implemented to correct for fluctuations of the quantum state produced by the OPA. We measure the noise variance in a band of width 300 kHz around the center frequency 2.7 MHz. Table 1 presents the variances measured on HD_1 and HD_2.

As can be seen in Table 1, when the UPMC is set to convert the output of the OPA to a TEM_{30}, the variance along the squeezed quadrature of the TEM_{30} is 1.4 dB below the quantum noise limit. To our knowledge, this is the first measurement of squeezing in such a high order mode. It shows that even this proof of principle UPMC gives access to high squeezing levels in complex spatial profiles. It is also noteworthy that the shape of the desired output mode seems to have a limited influence on the quality of the transform.

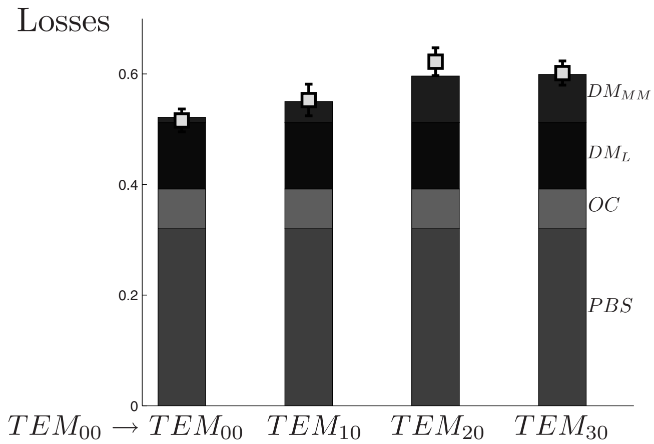

Fig. 2. (Color online) Comparison between the losses calculated from the quantum variance measurements and the losses in power, for different transformations of the spatial profile. PBS shows the losses from the polarizing beamsplitters and OC the losses from the other optical components. DM_L shows the losses from the reflections on the DM and DM_{MM} represents the loss due to the spatial profile mismatch. Finally, the squares represent the losses calculated from the quantum variance measurements.

In order to explain the difference of squeezing levels between HD_1 and HD_2, we measure the beam power at different points in the beam path. Overall, from the input to the output of the UPMC, we find 51% loss. Each reflection on the deformable mirror is responsible for a 4.2% loss; this value is consistent with the reflectivity of the gold membrane of the DM and the coatings used on the protective window. Thus, the three reflections on the deformable mirror introduce 12.1% losses. The polarizing beamsplitters each introduce 5% loss when used in transmission; accounting for a total 31% loss in the case of three reflections. Finally, the remaining 18% loss is consistent with the number of optical elements in the beam path and the specifications of their coatings. Additionally, because this proof of principle UPMC is limited to three reflections, the spatial profile of the output of the UPMC is not perfectly matched to LO_2. This mode mismatch is equivalent to an additional loss, the value of which is derived from the visibility of the interference between the UPMC's output and LO_2.

We find that the differences between the quantum states measured before and after the UPMC can be accounted for by these power losses alone. Under this assumption, we use the measured noise variances to compute values of passive loss for each of the different transforms. In Figure 2, we compare the losses calculated from these quantum measurements, to the losses in power we measured directly on the beam. As can be seen in Figure 2, the two values are in good agreement, well within the error bars derived from the quantum measurements. This validates the assumption that the UPMC only introduces passive losses on the quantum state.

As a conclusion, our results confirm that the UPMC can transform the spatial profile of the light while retaining its quantum properties, excluding passive losses introduced by its optical components. Convincingly, the UPMC does not add noise, and allows for high quality mode matching. It must be noted here that our device is a proof of principle UPMC. A lossless transform is indeed possible given access to higher quality optical components; there is nothing fundamental in the UPMC's design that destroys the quantum state of the light. To that extent, the UPMC is a useful link between the quantum resource and its manipulation. Moreover, the programmable nature of the UPMC makes it a flexible device, allowing for example the same OPA and optical set-up to be used for a wide range quantum enhanced detections.

This work was funded by the Center of Excellence program of the Australian Research Council. It was supported by the Australian Research Council Discovery Project DP0985078 and the NCI National Facility at the ANU. We acknowledge the financial support of the Future and Emerging Technologies (FET) programme within the Seventh Framework Programme for Research of the European Commission, under the FET-Open grant agreement HIDEAS, number FP7-ICT-221906.

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