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Observation of Kerr Effects in On-Chip Optical Parametric Oscillators

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Abstract: Cross quadrature correlations are observed from the spectral matrices of two-mode bright states generated in an integrated optical parametric oscillator. We attribute degradation of amplitude difference squeezing with increasing pump intensities to this effect.

Silicon-based materials have been in the heart of the microelectronics industry for decades. Taking advantage of an already developed manufacturing industry, low losses waveguides are routinely fabricated in the micro scale. Optical cavities are among several optical elements that can be imbued in small chips. Such devices are commonly used as a feedback system to enhance nonlinear interactions of light and matter, in this case the material waveguides. By respecting dispersion conditions, which depend on the material and the geometry of the waveguides [1], the integrated micro-cavities act as an optical parametric oscillator (OPO). Operating above threshold, bright modes are excited, which are of special interest for the study of nonclassical light.

The deterministic character of bright light is in contrast to the probabilistic generation of discrete photon states, usually based on spontaneous emission processes. Hence, continuous variables nonclassical states, such as squeezed and entangled states, are ideal to quantum communications with high data transmission rates. The sensibility of such correlations to optical losses may preclude efficient long distance communication. Nevertheless, intense nonclassical light can be effectively employed to interconnect different on-chip quantum systems in future integrated quantum networks [2].

In the present work, we will investigate the correlations of signal and idler beams generated in a fully integrated silicon-based third order ($\chi^{(3)}$) OPO. As summarized in figure 1, our light source consists of a 1560 nm wavelength commercial RIO laser. After amplification, we use a filter cavity to produce a near coherent pump. We couple the pump into the bus waveguide with a tapered fiber. Pumping the integrated micro-ring resonator above threshold, intense signal and idler fields are generated by a four-wave mixing process at the respective frequencies of 1544 nm and 1577 nm, as shown in the inset of figure 1.

The micro-cavity resonance is tuned by thermo-optical effect with the aid of an integrated micro-heater. A lock-in system is used to actively maintain the oscillation condition of the system stable. The generated fields are monitored by an optical spectrum analyzer to which we send a fraction of the chip output. The spatially overlapped output fields are then separated with a diffraction grating and send to individual analysis cavities. The optical resonators beat the carrier fields with their sidebands in a self-homodyne process [3]. Balanced detections are then carried in order to simultaneously access the noise and the standard quantum limit of each field. The two-mode correlations are then investigated by computational analysis.

By synchronously sweeping the cavities we directly access correlations between equivalent quadratures of the fields, from which we directly observed up to 2.30 ± 0.03 dBm of amplitude difference squeezing. Still, excess of noise of more than 20 units of shotnoise was measured for the phase sum fluctuations. Although entanglement is predicted for $\chi^{(3)}$ OPOs [4], the excessive noise hindered any evidence of such correlation.

In order to obtain the full tomography of the two-mode state, we also need to measure the correlations between different quadratures of the fields. We fixed a cavity far from resonance as we continued to scan the other (and vice-versa) in a sequence of three consecutive measurements. From this procedure, and following the demodulation chain proposed in [3], we were able to recunstruct the two-mode spectral matrix. Amplitude-phase correlations were clear from non-zero off-diagonal terms, which is equivalent to a rotation in the axis of the noise ellipse. This effect is expected from self- and cross-phase modulations present in the third order interaction dynamics [4, 5]. From this phenomenon, better correlations are expected when in the rotated axis, that is, when we diagonalize the

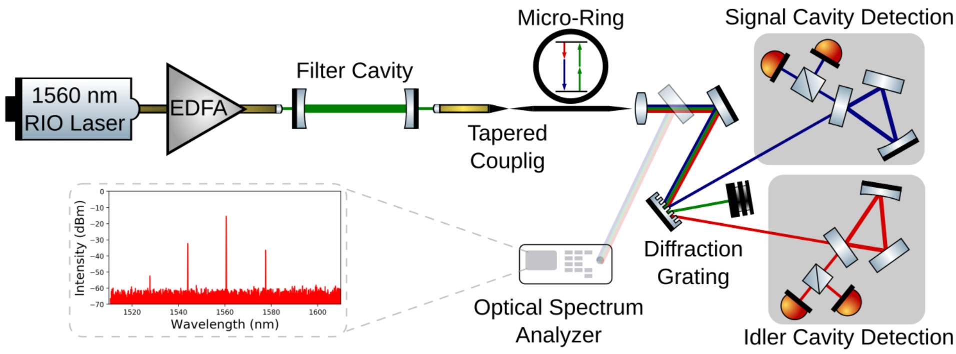

Fig. 1. Experimental setup scheme. The micro-ring oscillator is pumped with a filtered intense field. Operating above threshold, signal and idler are generated by a four-wave mixing process, as illustrated in the inset of the microcavity. After separation, resonator assisted detection schemes are used to characterize the fields states. Further details are given in the main text. EDFA: Erbium Dopped Fiber Amplifier.

spectral matrix.

The two-mode correlations were monitored for a range of different pump intensities above threshold, up to the saturation of our detectors. Cross correlations between different quadratures are clearly present, as significant rotation angles, between 10 and 45 degrees, are observed for all of our measurements, as shown in figure 2 (a). While the individual amplitude noises are reduced in the rotated frames, figure 2 (b), the phase noise systematically increase, figure 2 (c). Despite the clear presence of strong (classical) correlations, the amplitude difference squeezing is completely lost in the new frames, figure 2 (d). This is a consequence of the noisy, highly mixed states at the output of our OPO. Furthermore, degradation of squeezing for the original quadratures is also observed. This behavior is not expected for amplitude difference squeezing obtained from $\chi^{(2)}$ OPOs [6]. This effect can be explained by the distortion of the noise ellipse, where the mixture with the phase quadrature impact the robustness of the amplitude difference quadrature.

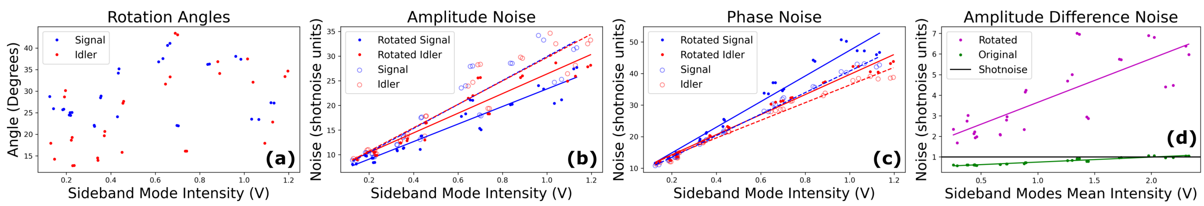

Fig. 2. **(a)** Rotation angles for signal (blue) and idler (red) fields for several output powers of the fields. **(b,c)** Comparison between the amplitude (b) and phase (c) quadratures of the measured fields with the rotated frames. **(d)** Squeezing degradation of amplitude difference with the increasing sideband mean field intensity and the excess of noise observed in the rotated frame. Fitted lines are included for visualization aid.

In summary, from the reconstruction of two-mode covariance matrices we identified cross correlations between different quadratures of the field, an expected effect related to self- and cross-phase modulations present in $\chi^{(3)}$ nonlinear interactions [5]. This effect explains the lack of robustness of the amplitude difference squeezing, which is in contrast to $\chi^{(2)}$ OPOs. Further investigations are being carried out to mitigate the excess of phase noise. We then expect to observe an enhancement in the squeezing for rotated quadratures as well as quantum entanglement between signal and idler beams.

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