Spatial mode detection by sum-frequency upconversion

Adam Vallés[1], Bereneice Sephton[1], Fabian Steinlechner[2,3], Thomas Konrad[4,5], Juan P. Torres[6,7], Filippus S. Roux[1,8], and Andrew Forbes[1]

[1] School of Physics, University of the Witwatersrand, Private Bag 3, Wits 2050, South Africa
[2]Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Str. 7, 07745 Jena, Germany
[3]Friedrich Schiller University Jena, Abbe Center of Photonics, Albert-Einstein-Str. 6, 07745 Jena, Germany
[4]School of Physics, University of KwaZulu-Natal, Durban, South Africa
[5]National Institute of Theoretical Physics, UKZN Node, Durban, South Africa
[6]ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels, Barcelona, Spain
[7]Department of Signal Theory and Communications, Universitat Politecnica de Catalunya, Campus Nord D3, 08034 Barcelona, Spain
[8]National Metrology Institute of South Africa, Meiring Naudé Road, Brummeria, Pretoria 0040, South Africa
adam.vallesmari@wits.ac.za

The efficient creation and detection of spatial modes of light has become topical of late, driven by the need to increase photon bit-rates in classical and quantum communications. Here we put forward a new spatial mode detection technique based on the nonlinear optical process of sum-frequency generation, also showing that the method can be used to transfer an image from the infrared band to the visible, which implies the efficient conversion of many spatial modes.

There has been a great development in methods to create and detect optical spatial modes, fuelled for example, by the desire for higher bit-rates in classical and quantum communication, among other applications [1]. Such mode creation and detection processes are traditionally achieved with tools based on linear optics. However, mode creation has also been demonstrated with nonlinear optics. With spontaneous parametric down-conversion (SPDC), the method of choice to introduce the concept, one can create photon pairs entangled in their spatial degree of freedom. It is instructive to outline how SPDC generates correlated modes, as schematically depicted in Fig. 1(a) for a Gaussian pump and orbital angular momentum (OAM) modes as an example. When a Gaussian beam pumps the SPDC process, it mediates the generation of paired entangled down-converted photons, signal (A) and idler (B), embedded into spatial modes satisfying ℓ_A=-ℓ_B, as shown in the simulated spiral bandwidth of Fig. 1(b). In this work we make use of the dual process sum-frequency generation (SFG) for the detection and selection of spatial modes, contrasting the similarity with the anticorrelated relation obtained with its analogous nonlinear process, the SPDC.

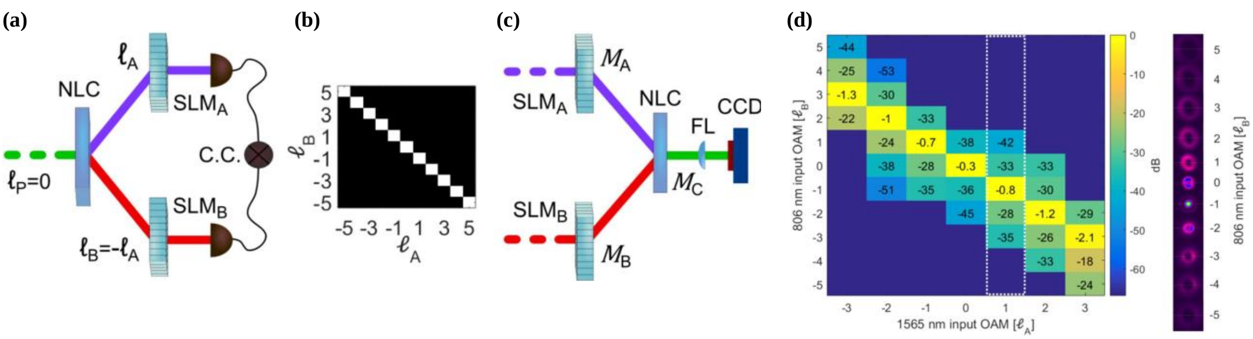

FIG. 1 **(a)** Traditional quantum experiment where a Gaussian mode pumps a nonlinear crystal (NLC) mediating the generation of two entangled photons with opposite OAM values. **(b)** Simulated modal spiral spectrum of the down-converted photon pairs. **(c)** Setup used to demonstrate the spatial mode detection by frequency upconversion. **(d)** Experimental cross talk results after performing a modal decomposition varying the helical charge of the input OAM mode for 806 nm (ℓ_B), when setting a particular input OAM mode for 1565 nm within the range ℓ_A=[3,-3].

In the frequency upconversion process, schematically depicted in Fig. 1(c), two incoming signals (M_A and M_B) are engineered to be in specific states. The upconverted signal is detected in the far field, so that there is a nonzero signal only when the phases are conjugate. In this scheme the nonlinear crystal (NLC) is the detector rather than the generator. Our results shown in Fig. 1(d) confirm the concept of spatial mode detection by upconversion using intense beams carrying orbital angular momentum (ℓ_A and ℓ_B) as example. To quantify the quality of this spatial mode detection technique, a cross-talk matrix measurement was performed, finding a -30 dB cross-talk on average, showing how well we can distinguish between the desired mode and the rest of the orthogonal modes [2].

Even though we have demonstrated the technique with high intensity signals, the results are immediately applicable to single photon states too by employing single photon counting detectors and single mode fibres.

[1] H. Rubinsztein-Dunlop, et al., "Roadmap on structured light," J. Opt. **19**, 013001 (2017).
[2] B. Sephton, A. Vallés, F. Steinlechner, T. Konrad, J. P. Torres, F. S. Roux, A. Forbes "Spatial mode detection by frequency upconversion," Opt. Lett. **44**, 586 (2019).