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Generation of highly entangled states of light based on quantum optical frequency comb

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14. ABSTRACT

In this project, we generate highly entangled states of light for scalable quantum information technologies. Light has various advantages as a carrier of quantum information, e.g. fast transmission speed and high quantum state fidelity, but it has limitations on scalability due to a low generation rate and small degrees of freedom for quantum states. We have solved those limitations by two methods. One is to employ deterministic generation of quantum light (squeezed vacuum), and the other is to exploit large degrees of freedom associated with frequency modes of optical frequency comb. To integrate the two methods, we engineer a quantum process in an optical parametric oscillator that is compatible with optical frequency comb. The generated light from the device is a complexly entangled quantum state in multiple frequencies (central wavelength: 800 nm), so called quantum optical frequency comb (QOFC):
it exhibits multipartite quantum correlations (or entanglement) among many frequency modes. We have experimentally characterized the QOFC by using homodyne detection in multiple frequency modes, and construct the associated covariance matrix. As quantum correlations are a key quantum resource for quantum technologies, the quantum optical frequency comb will have broad applications for quantum technologies with scalability, such as multiple-player quantum communication and measurement-based quantum computing.

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Abstract

In this project, we generate highly entangled states of light for scalable quantum information technologies. Light has various advantages as a carrier of quantum information, e.g. fast transmission speed and high quantum state fidelity, but it has limitations on scalability due to a low generation rate and small degrees of freedom for quantum states. We have solved those limitations by two methods. One is to employ deterministic generation of quantum light (squeezed vacuum), and the other is to exploit large degrees of freedom associated with frequency modes of optical frequency comb. To integrate the two methods, we engineer a quantum process in an optical parametric oscillator that is compatible with optical frequency comb. The generated light from the device is a complexly entangled quantum state in multiple frequencies (central wavelength: 800 nm), so called *quantum optical frequency comb (QOFC)*: it exhibits multipartite quantum correlations (or entanglement) among many frequency modes. We have experimentally characterized the QOFC by using homodyne detection in multiple frequency modes, and construct the associated covariance matrix. As quantum correlations are a key quantum resource for quantum technologies, the quantum optical frequency comb will have broad applications for quantum technologies with scalability, such as multiple-player quantum communication and measurement-based quantum computing.

Introduction

Light can carry quantum information which can be transmitted with the fastest speed, and the encoded quantum information can be controlled and measured with a high precision. Light therefore has played important roles in developing quantum technologies [1]. For example, quantum communication, such as quantum key distribution and quantum network, exploits quantum features and quantum correlations of light [2]. Quantum metrology employs an engineered quantum light to enhance measurement precision [3]. Quantum light can be used to exhibit computational speed up; a notable example is BosonSampling [4].

A next stage for light-based quantum technologies is scaling-up of the capacity of a quantum information carrier. This goal is, however, considered to be challenging because a typical quantum-light generation process is non-deterministic [5]: a common method is a spontaneous parametric down conversion process which generates a pair of photons, but it has success probability of 0.001. Furthermore, entangling independent photons requires a nonlinear interaction or a post selection which limits a success probability up to 50 %.

An alternative approach is to harness quantum features of electric fields (or light quadratures) rather than photons. An important quantum state for those observables is a squeezed vacuum state [6], which exhibits reduced fluctuation of an electric field. Such a quantum state can be generated on demand (i.e. 100 % success probability). Interestingly, quantum interference of many squeezed vacuum states at linear optics can result in multipartite entangled states; this process again succeeds with 100 % probability. It is therefore possible to generate large-scale entangled states of light by exploiting multiple optical modes and on-demand generation of quantum light [7].

An optical frequency comb provides an ideal platform of such multiple modes as it can support more than 10^5 frequency modes. Tailoring the multiplicity of optical modes with controlled quantum processes can lead to generation of large-scale entangled states of light: the resultant light is thus called *quantum optical frequency comb (QOFC)*. Recently, QOFC was generated in frequency modes up to the number of twelve [8], but it is far below the full potential of optical frequency comb [9]. It is, therefore, necessary that optimization and engineering of QOFC should be developed furthermore.

Large-scale entangled states by QOFC will be a key quantum resource for developing quantum technologies with scalability. For example, QOFC provides increased capacity of quantum information, which is beneficial for *quantum communication* [2]. In quantum sensing, QOFC can be employed to measure several parameters with enhanced precision: *distributed quantum sensing* [10]. Finally, QOFC can be used to show quantum advantage in quantum simulation: *Gaussian BosonSampling* [11].

In this project, we have generated highly-entangled states of light (central wavelength: 800 nm) based on QOFC. To this end, we develop several techniques in controlling and characterizing QOFC:

1) We generated QOFC in multiple frequency modes by building a synchronously pumped optical parametric oscillator. The device is carefully designed to achieve a broadband operation for QOFC.

2) We developed a technique to access and control an individual frequency mode or a superposition of different frequency modes. For a fine control of the frequency modes, we achieved a frequency resolution of 0.07 nm.

3) We investigated a method to characterize the generated QOFC. To do so, we developed a detector that can selectively measure specific frequency modes. In addition, we developed a method of quantum state tomography that is applicable to multimode Gaussian quantum states.

Research Activities

Let us start by explaining generation of QOFC. For the generation, a synchronously pumped optical parametric oscillator (SPOPO) is employed. SPOPO is resonant on multiple frequencies simultaneously, which is compatible with optical frequency comb. In addition, we implement a pulse shaper to have control over multiple frequency modes. At the final part, we develop homodyne detection with selectivity of measurement on frequency modes. Finally, we characterize the generated QOFC. In the following, details of the research activities are explained.

(1) Generating quantum optical frequency comb by implementing SPOPO

To generate QOFC, we have built a synchronously pumped optical parametric oscillator (SPOPO), as shown in Fig. 1(a). As the main laser, we employ a Ti-Sa pulse laser, and the cavity length of SPOPO is matched with that of Ti-Sa laser. As a result, SPOPO can accommodate a broad range of frequency modes emitted from the Ti-Sa laser. SPOPO contains a nonlinear crystal, which generates a nonclassical light based on a parametric down conversion, and the generated light makes many round trips inside SPOPO before leaving the cavity.

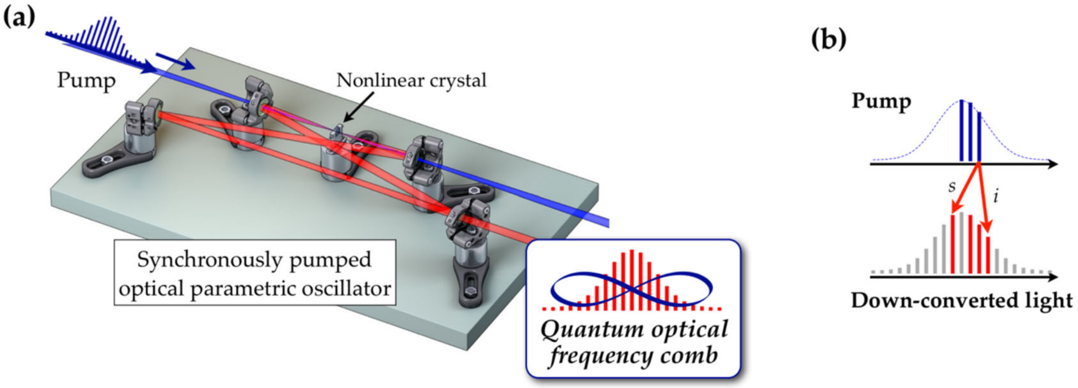


Figure 1 (a) Scheme of a synchronously pumped optical parametric oscillator. (b) Many frequency modes in the pump laser can be down-converted into numerous ways to generate highly entangled states of light.

The generated light is QOFC, which exhibits quantum correlations among different frequency modes. As shown in Fig. 1(b), one frequency mode in optical frequency comb of pump can be down-converted into two frequency modes (signal *s*, idler *i*), and they correspond to an entangled state called an EPR state. In general, there are multiple possibilities of down conversion into a pair of frequency modes, where all the possibilities exist simultaneously as a quantum superposition. In addition, pump laser contains many frequency modes, and each of them is converted in a similar way. As a result, the quantum optical frequency comb contains a complexly entangled state of multiple frequency modes.

Figure 2 shows the actual SPOPO implemented in the laboratory. The cavity round trip length is set to 3.75 m to match with the repetition rate of the Ti-Sa laser (80 MHz); the length is implemented by optical reflections on 13 mirrors (a plane or a curved mirror) inside the cavity. At the location of the nonlinear crystal, the beam radius is designed for 40 μm for an efficient nonlinear interaction, and it is then increased to 800 μm for the free space propagation of 3.75 m. All the coatings for the optics have a broadband antireflection coating (reflectance >> 99.99 %) to minimize loss in the operation wavelength range (790 nm ~ 810 nm). For maintaining the resonance on the cavity, the cavity length is precisely adjusted (Δx) using a mirror controlled by a piezoelectric actuator. All of these efforts have been required to make the multiple-frequency-modes operation of SPOPO, which in turn generates QOFC in multiple frequency modes.

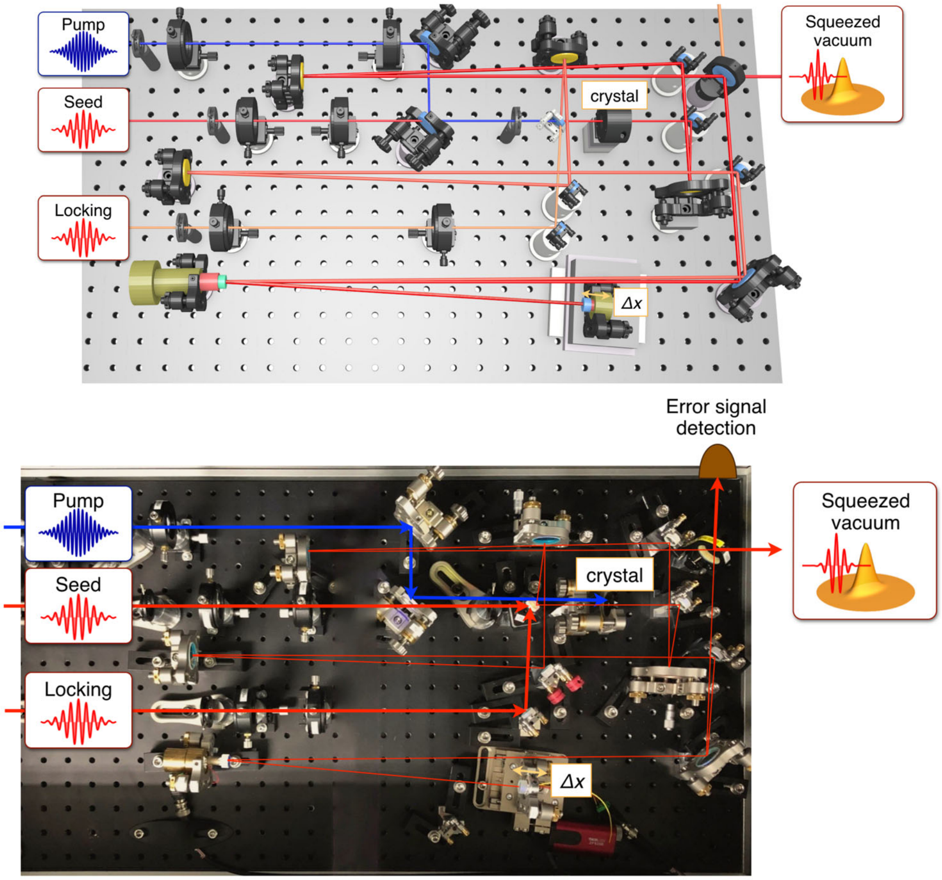


Figure 2 Synchronously pumped optical parametric oscillator. Design (the upper one) and experimental implementation (the lower one).

To investigate a proper functioning of SPOPO, we first inject the seed beam (Fig. 2) into the input coupler of SPOPO. The transmittance of the beam through SPOPO was measured as varying the cavity length using a piezoelectric transducer. We find that the transmittance measurement (shown in Fig. 3; the blue graph) show the dominating main peak due to the Gaussian spatial mode, and the side peaks by higher-order spatial modes are negligible, which means a proper alignment of the cavity and an excellent spatial mode matching between the seed and SPOPO.

Next, we implemented the cavity length locking using the locking beam in Fig. 2. Similar to the seed beam, the locking beam is injected to the input coupler and the transmitted beam is measured; the difference from the seed is that the locking beam travels in SPOPO in the opposite direction with respect to the seed beam. As a result, the locking beam and the seed beam can be separated at the output of SPOPO. To obtain the error signal for the cavity locking, the locking beam has been phase-modulated (at around 1 MHz) before entering SPOPO, and the electronic signal by detecting the output light is demodulated with the same frequency. Fig. 3 shows the error signal (the red graph), which provides a feedback signal to adjust the piezoelectric transducer using a proportional-integral device. Once the locking is established, SPOPO can operate in a stable condition during more than 10 mins.

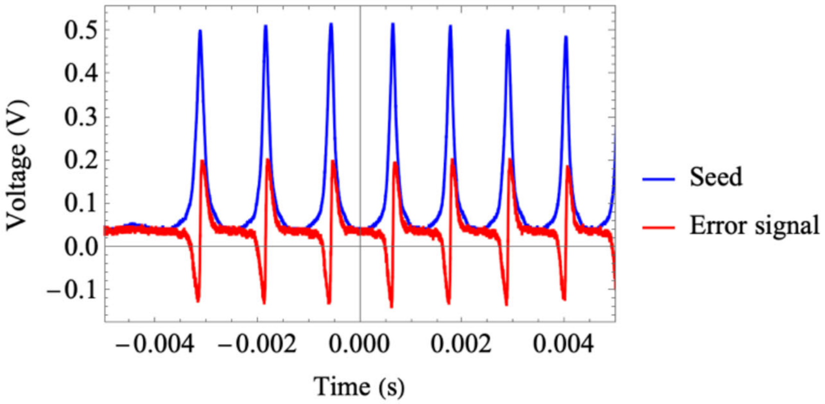
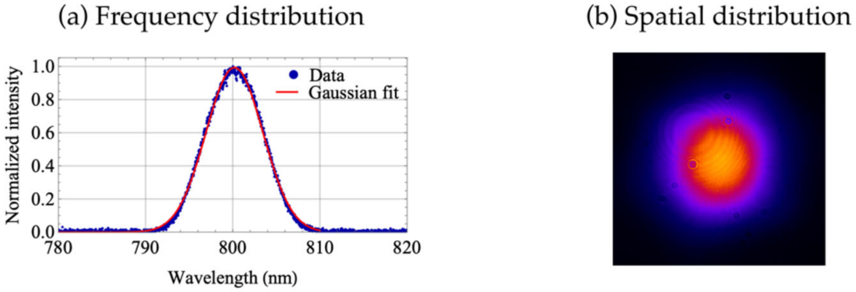


Figure 3 Measurement of the transmitted light through SPOPO. Seed beam (blue), error signal (red).

After that, we supplied a pump laser to SPOPO to make nonlinear down-conversion process. The pump laser has a central wavelength of 400 nm, which is generated via second harmonic generation of 800 nm laser. When the pump laser power exceeds 130 mW (called the threshold power), we have observed lasing at 800 nm due to a down-conversion process. Figure 4 shows the measurement results of the generated laser: (a) the Gaussian spectral distribution and (b) the Gaussian transversal profile, as expected.


(a) Frequency distribution

(b) Spatial distribution

Figure 4 Laser generated by an optical parametric oscillation process in SPOPO. (a) spectral mode (b) spatial mode.

Finally, we investigate the quantum property of the light from SPOPO. For this purpose, we need to operate SPOPO not in the lasing regime (as described in the previous paragraph) but in the quantum regime. For operating in the quantum regime, we reduce the pump power to 50 mW, where quantum squeezed light is generated from SPOPO. To characterize its quantum property, we employed homodyne detection which measures observables associated with electric fields (electric field quadratures). We have developed our own homodyne detectors in the lab, and more details will be explained in a next section.

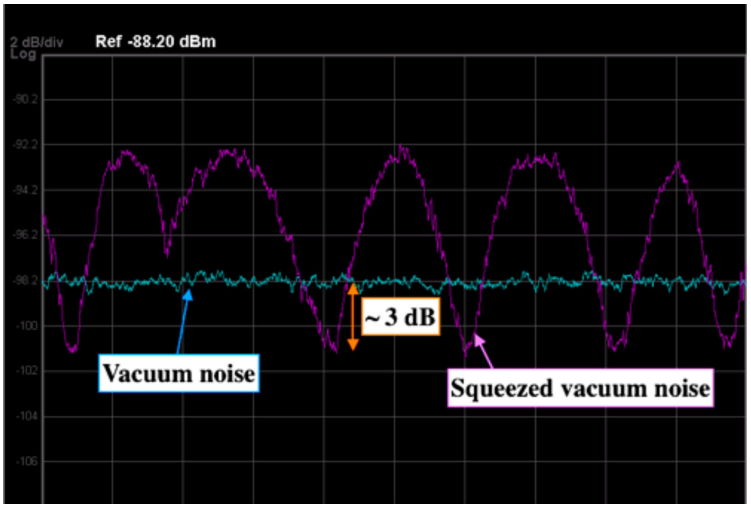


Figure 5 Observation of squeezed light

We have observed a nonclassical noise suppression by squeezed light, as presented in Fig. 5. We used an electronic spectrum analyser to obtain the variance of electric field quadratures (analysis frequency: 1 MHz). The cyan curve corresponds to the variance of the vacuum state, which was taken as a reference. The purple curve was then obtained by sending squeezed light as varying the phase in homodyne detection. One can observe that the nonclassical noise suppression takes place for the squeezed light: the observed suppression ratio was about 3 dB.

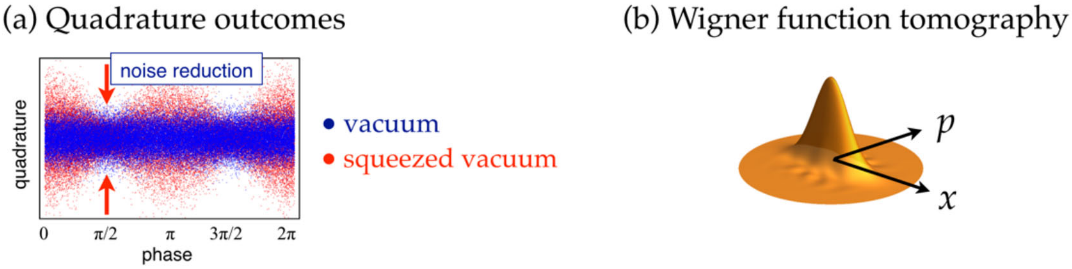


Figure 6 (a) Obtaining individual quadrature outcomes by squeezed light. (b) Quantum state tomography.

Extending the variance measurement, we furthermore obtain the individual quadrature outcomes by measuring squeezed light. Fig. 6(a) shows the results (red: squeezed vacuum, blue: vacuum). At the phase of π/2, the quadrature outcomes of squeezed light show a narrower distribution than that of the vacuum state. Such noise reduction can be directly used in quantum metrologies. Based on the quadrature outcomes, we also develop a method to reconstruct a quantum density matrix with physical conditions, called a quantum state tomography. The tomography result is shown in Fig. 6(b), which is drawn in a phase space. As expected, the distribution in the *p* quadrature is squeezed while *x* quadrature shows antisqueezing.

(2) Controlling QOFC

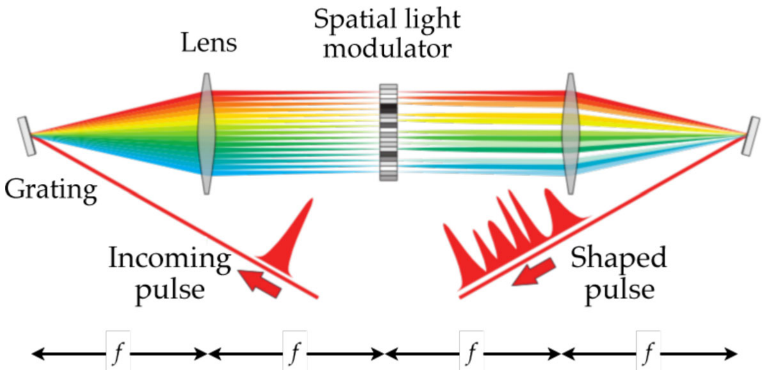


Figure 7 Scheme of a pulse shaper

To control or access multiple frequency modes of QOFC, we have implemented a pulse shaper. Its basic working principle is to spread light depending on frequency and to control amplitude and phase of each frequency using a spatial light modulator. Figure 7 shows 4-*f* geometry to construct a pulse shaper. An optical grating diffracts incoming pulses, and a lens focuses the diffracted pulses on the Fourier plane, where a spatial light modulator (SLM) controls different frequency components of the light. *f* is the focal length of the lens. Another set of a grating and a lens transforms the diffracted light into a single beam.

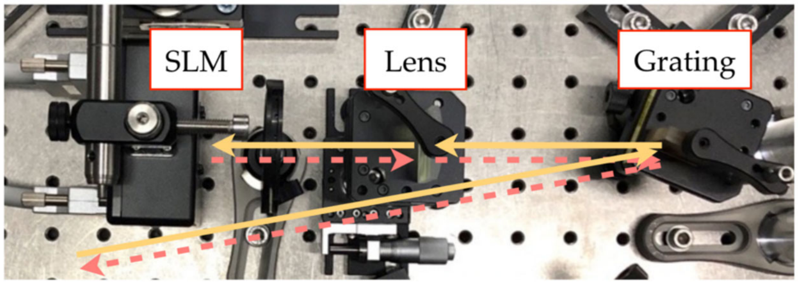


Figure 8 Implementation of a pulse shaper

We have implemented a pulse shaper as shown in Fig. 8. For actual implementation, we use the folded version of the geometry having a curved mirror and a reflection-type SLM to reduce optical aberrations. The grating has a groove density of 2200 lines/mm, and the focal length of the lens is 100 mm. SLM is located at the focal plane of the lens and has 800 pixels with a 20 μm pitch. To minimize the spatial chirp and temporal chirp, we adjusted the distances between the SLM, the lens, and the grating. Figure 9 shows the performance of the pulse shaper. Different wavelengths can be controlled by addressing different pixels in SLM (Fig. 9(a)). The wavelength resolution is measured to be 0.07 nm (Fig. 9(b)). Based on the pulse shaper, we have generated various spectral modes of light. Figure 10 shows the results of generating Hermite-Gaussian modes of light (intensity distributions are measured only).

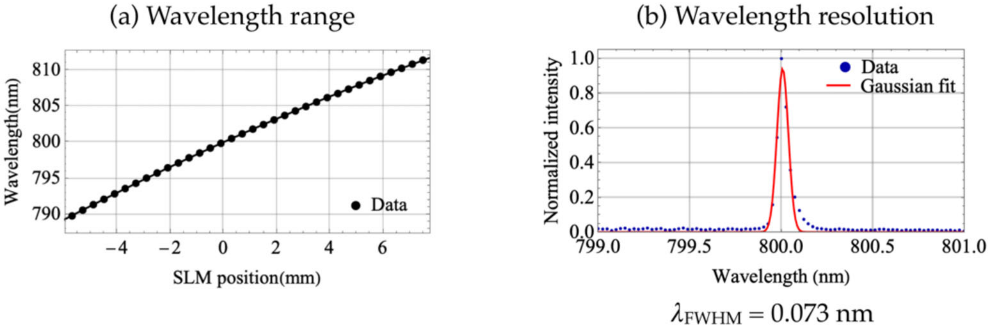


Figure 9 Performance of the pulse shaper. (a) control range. (b) control resolution.

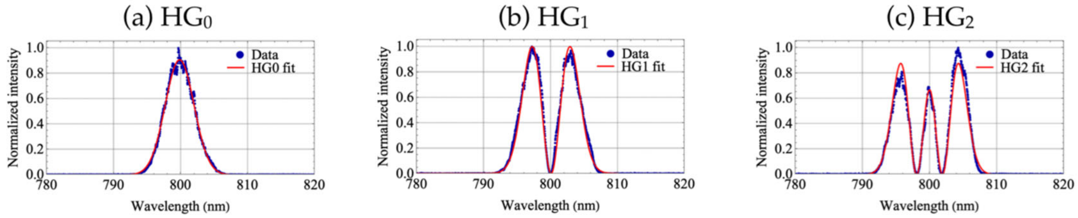


Figure 10 Generation of Hermite-Gaussian (HG) spectral modes: (a) HG_0 (b) HG_1 (c) HG_2

(3) Characterizing QOFC

To characterize QOFC containing multiple frequency modes, we have developed a homodyne detector that can select specific frequency modes. Homodyne detector measures electric field or light quadratures ($\hat{x}(\theta) = \hat{a} + e^{i\theta}\hat{a}^\dagger$), which can reveal quantum correlations contained in the generated QOFC. Figure 11(a) shows the homodyne detector developed in the laboratory. A quantum state ($\hat{\rho}$) is mixed with a local oscillator (LO) at a 50:50 beam splitter (BS), and then the resulting beams are detected by the homodyne detector. We have characterized a technical performance of the detector by measuring the clearance (shot noise/electrical noise). As shown in Fig. 11(b), the clearance has a broad frequency bandwidth (more than 20 MHz), and the maximum clearance of 17 dB has been achieved.

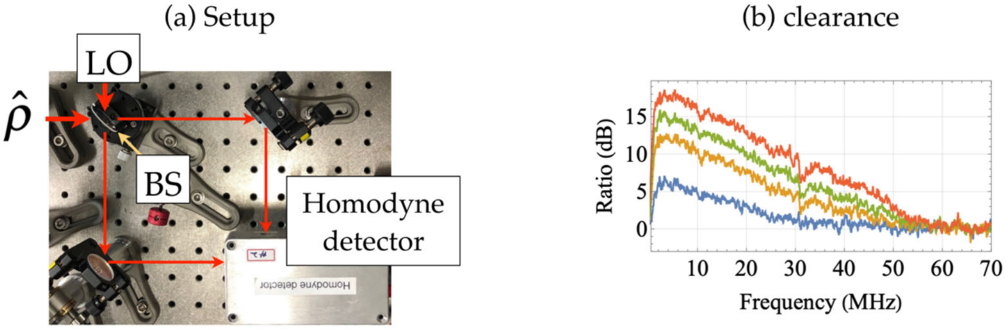


Figure 11 (a) Setup of a homodyne detector. (b) Clearance of the homodyne detector (LO power: 0 mW for blue, 1 mW for orange, 5 mW for green, and 10 mW for red)

To measure various spectral modes of light using the homodyne detector, we employ a local oscillator prepared by the pulse shaper described in the previous section. As the local oscillator defines the detection mode, one can access various spectral modes (e.g. HG modes, frequency-band modes, or a superposition of two different modes) using the pulse shaper. We have measured the multimode characteristics of the QOFC using the homodyne detector with the pulse shaper. Based on the eight frequency-band modes in Fig. 12(a), we have obtained a covariance matrix of QOFC. The covariance matrix, shown in Fig. 12(b), has the full information of a multimode Gaussian quantum state in QOFC, which is an analog of quantum state tomography for Gaussian states. The diagonal elements show noise properties of individual modes, and the off-diagonal elements shows correlations between different modes.

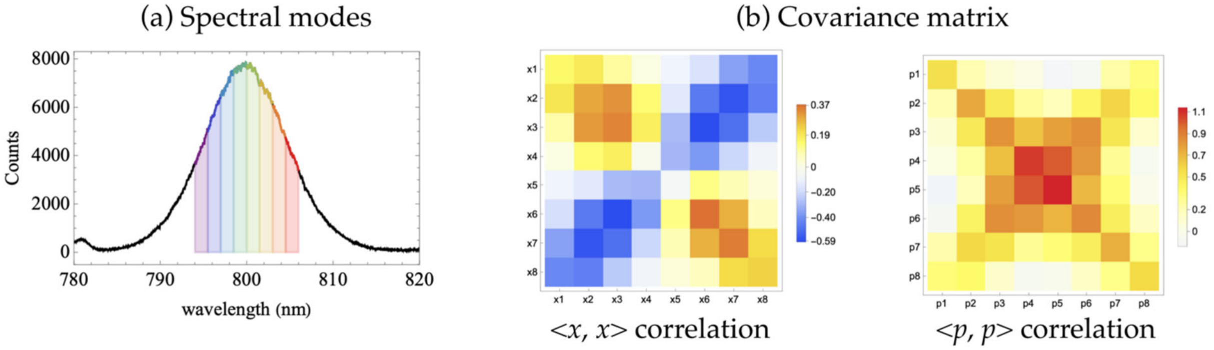


Figure 12 Characterization of multimode correlations in QOFC. (a) Eight spectral modes used (mode index from 1 to 8 for the shorter to the longer wavelength). (b) The obtained covariance matrix.

Conclusions and Impact

In this project, we have experimentally generated entangled states of light by exploiting multiple frequency modes of light. We implemented SPOPO for an efficient nonlinear parametric down-conversion process in a broad frequency range. For measuring multimode quantum light, we developed a pulse shaper (having a resolution of 0.07 nm) and a homodyne detector (clearance of 17 dB). As a result, we observed a quadrature noise reduction of 3 dB by squeezed light. We furthermore characterized multimode correlations in the QOFC by obtaining a covariance matrix. In this case, eight frequency-band modes are used, which are prepared by the pulse shaper.

The results of this project provide a quantum resource required for developing quantum technologies with scalability. Quantum entanglement is at the heart of many quantum technologies (e.g. quantum network and quantum computing), and its extension to multiple parties (or multiple modes) make it possible to enhance the capacity of quantum technologies.

Currently, a large part of optical quantum technologies is based on entanglement of photons, but it has limitations in increasing the number of entangled photons. On the other hand, our result uses electric fields of quantum light, whose number can be readily extended without suffering from a reduction in the generation probability.

We have achieved a basic step to generate QOFC, but we anticipate that further studies are required for versatile applications of QOFC in quantum technologies, e.g., reconfigurable generation of QOFC. Continual development of QOFC will give a promising solution for the next generation of scalable quantum technologies.

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