High-dimensional quantum states are promising resources for quantum communication and processing. In this context the frequency degree of freedom of light combines the advantages of robustness and easy handling with standard classical telecommunication components. In this work we propose a method to generate and control the symmetry of broadband biphoton frequency states, based on the interplay of cavity effects and relative temporal delay between the two photons of each pair. We demonstrate it using an integrated AlGaAs semiconductor platform producing quantum frequency combs, working at room temperature and compliant with electrical injection. These results open interesting perspectives for the development of massively parallel and reconfigurable systems for complex quantum operations.

Since the emergence of the domain of quantum information, quantum optics plays an important role as an experimental test bench for a large variety of novel concepts; nowadays, in the framework of the development of quantum technologies, photonics represents a promising platform for several applications ranging from long distance quantum communications to the simulation of complex phenomena and metrology [1, 2]. In these last years a growing attention has been devoted to large scale entangled quantum states of light as key elements to increase the data capacity and robustness in quantum information protocols. Such states can be realized through qubits encoded in many-particles, but this approach suffers from scalability problems; an alternative strategy is to work with a lesser number of particles and to encode information in high-dimensional states. This has been implemented using different degrees of freedom of light: spatial or path modes [3, 4], orbital angular momentum [5, 6], time-energy [7], frequency [8, 9]. Among all these possibilities the frequency domain is particularly appealing thanks to its compatibility with the existing fibered telecom network [10]; moreover, it enables the development of robust and scalable systems in a single spatial mode, without the requirement of complex beam shaping or stabilized interferometers.

The most straightforward physical process to generate quantum states in the frequency domain is nonlinear optical conversion, widely used to produce photon pairs for quantum information and communications protocols.

A convenient way to handle the frequency continuous degree of freedom is to discretize it and generate biphoton frequency combs [11]. Such states have first been investigated exploiting spontaneous parametric down-conversion (SPDC) in dielectric crystals [12–14], by placing a resonant cavity either after or around the nonlinear material. In the latter case the state is shaped directly at the generation stage with the advantage of avoiding signal reduction [15]. More recently biphoton frequency combs have been generated in integrated optical micro-resonators via spontaneous four-wave mixing: this approach overcomes the drawbacks of low scalability and high cost of bulk systems. Interesting results on the generation and coherent manipulation of high-dimensional frequency states have been obtained in both Hydex [8] and silicon nitride micro-rings [9]. For the development of accessible processing of quantum frequency combs a handy control over their symmetry is desirable. The ability to switch from symmetric to anti-symmetric high-dimensional states opens the way to the implementation of qudits teleportation, logic gates as well as dense coding and state discrimination [6, 10, 17]. These concepts have started to be explored in [18, 19] making use of bulk Fabry-Perot cavities in Hong-Ou-Mandel (HOM) interferometry experiments.

In this work, we propose a method to generate and control the symmetry of biphoton frequency combs by combining the spectral filtering effect of a cavity with the control of the temporal delay between photons of a pair. We show that the simple tuning of the pump frequency allows to engineer the wavefunction symmetry. The advantage of our proposal is that it doesn’t rely on post-selection, as usual techniques based on coincidence measurements of photons emerging from a beam-splitter. We demonstrate our method on an integrated AlGaAs semiconductor device emitting broadband frequency quantum states in the telecom range, working at room temperature and compliant with electrical injection [20]. In Figure 1 we present the schematic of the experimental set up for the generation and symmetry manipulation of biphoton frequency combs. Each pair. We demonstrate it using an integrated AlGaAs semiconductor platform producing quantum frequency combs, working at room temperature and compliant with electrical injection. These results open interesting perspectives for the development of massively parallel and reconfigurable systems for complex quantum operations.
state at the output of the cavity is:

$$|\psi\rangle = \int_{-\infty}^{\infty} C_{PM}(\omega_p, \omega_-) \delta(\omega_- - 2n\bar{\omega}) d\omega_-$$

$$|H, \frac{\omega_p + \omega_-}{2} \rangle|V, \frac{\omega_p - \omega_-}{2}\rangle$$

By tuning of the pump frequency we have access to two classes of states, having different spectral pattern (See Figure 2(a)). For \(\omega_p = \omega_R = 2n\bar{\omega}\), with \(n\) integer number, we generate resonant states, whose JSI maxima are disposed at even multiple of \(\bar{\omega}\) (See Figure 2(b)). In the approximation of a cavity with perfect reflectivity, the resonant state is:

$$|\psi_R\rangle = \sum_m \int_{-\infty}^{\infty} C_{PM}(\omega_R, \omega_-) \delta(\omega_- - 2m\bar{\omega}) d\omega_-$$

$$|H, \frac{\omega_R + \omega_-}{2} \rangle|V, \frac{\omega_R - \omega_-}{2}\rangle$$

For \(\omega_p = \omega_{AR} = (2n+1)\bar{\omega}\), we generate anti-resonant states, whose JSI maxima are disposed at odd multiples of \(\bar{\omega}\) (See Figure 2(c)). In the same approximation of a cavity with perfect reflectivity the anti-resonant state is:

$$|\psi_{AR}\rangle = \sum_m \int_{-\infty}^{\infty} C_{PM}(\omega_{AR}, \omega_-) \delta(\omega_- - (2m+1)\bar{\omega}) d\omega_-$$

$$|H, \frac{\omega_{AR} + \omega_-}{2} \rangle|V, \frac{\omega_{AR} - \omega_-}{2}\rangle$$

The simulated JSI for intermediate values of the pump beam frequency is presented in the Supplementary Information (See Figure 1 Supplementary material).

In order to control the symmetry of the biphoton state, we introduce a third stage in the experimental setup, consisting of a polarizing beam splitter, separating deterministically the signal and idler photons into two different paths \(a\) and \(b\), and a delay line on one of the two paths (see Figure 1). The introduced temporal delay \(\tau\) modulates the JSI of the state \(|\psi\rangle\) with the periodic function \(f_{delay} = \exp(i\tau\omega_-)/2 = \cos(\tau\omega_-)/2 + i\sin(\tau\omega_-)/2\), consisting of a symmetric real part and anti-symmetric imaginary part in the \(\omega_-\) variable. For \(\tau = \pi/\bar{\omega}\), corresponding to half of the cavity round trip time, the periodicity \(f_{delay}\) is the double of the one of \(|\psi\rangle\) state JSI. In this case, the JSI of the resonant state \(|\psi_R\rangle\) is in phase with the symmetric part of \(f_{delay}\), resulting in the pattern of Figure 2(d). On the contrary the JSI of the anti-resonant state \(|\psi_{AR}\rangle\) is in phase with the anti-symmetric part of \(f_{delay}\) resulting in the pattern of Figure 2(e). The resonant and anti-resonant states after the optical delay stage are:
FIG. 2. a) Simulated JSI of the quantum state generated through type II SPDC filtered by a Fabry Perot resonator with mirror reflectivity 0.8, for a pump beam of linewidth \( \Delta \omega \gg \bar{\omega} \) and central frequency \( \bar{\omega}_0 \), coinciding with the cavity resonance closest to degeneracy. Dashed lines evidence two cuts of the JSI corresponding to a resonant and an anti-resonant state. (b-c) Corresponding simulation of the JSA (blue line: real part; red line: imaginary part), for \( \tau = 0 \) (d, e) and \( \tau = \pi / \bar{\omega} \) (d, e).

\[
|\psi_R\rangle = \sum_m C_{PM}(\omega_R, 2m\bar{\omega}) e^{im\pi} \\
|a, \omega_R/2 + m\bar{\omega}\rangle |b, \omega_R - m\bar{\omega}\rangle
\]

\[
|\psi_{AR}\rangle = \sum_m C_{PM}(\omega_{AR}, (2m + 1)\bar{\omega}) e^{i(m + \frac{1}{2})\pi} \\
|a, \omega_{AR}/2 + (m + \frac{1}{2})\bar{\omega}\rangle |b, \omega_{AR}/2 - (m + \frac{1}{2})\bar{\omega}\rangle
\]

(5)

We note that the state \( |\psi_R\rangle \) is symmetric under particles exchange, while \( |\psi_{AR}\rangle \) is anti-symmetric. Analog results occur for \( \tau \) values that are odd multiples of the cavity half round-trip time (see Figure 2 in Supplementary Information).

We have thus demonstrated that the proposed experimental setup allows to generate biphoton frequency combs and to control their spectral symmetry by tuning the pump beam frequency.

In the following, we experimentally demonstrate this method using an AlGaAs chip. This platform combines a large second order optical susceptibility, a direct bandgap and a high electro-optic effect, making it attractive for the miniaturization and the integration of several quantum functionalities in a single chip [22, 23]. The device consists of a Bragg reflection ridge waveguide optimized for efficient type II SPDC [20, 24, 25] (See Supplementary Table 1 for details on the structure). The modes involved in the nonlinear process are a TE Bragg mode for the pump beam around 765 nm and TE\(_{00}\) and TM\(_{00}\) modes for the photon pairs in the C-telecom band. Note that, for this device, the group velocity mismatch between the two photons of each pair is so small that no off-chip compensation is required to preserve their indistinguishability [23, 24]. The photon pairs are thus emitted in very good approximation with a joint spectral amplitude centered in \( \omega_- = 0 \) and symmetric in the \( \omega_- \) variable, enabling a direct implementation of our method. Moreover, the refractive index contrast between the semiconductor and the air, leads to a modal reflectivity at the waveguide facets of 0.27(0.24) for the TE(TM) polarized mode, creating a Fabry-Perot cavity surrounding the nonlinear medium. Our chip thus integrates the generation and the cavity stage of the experimental scheme represented in Figure 2 leading to an extremely simple and compact solution. Photon pairs are generated by pumping the device with a continuous wave laser having a linewidth of \( \Delta \omega = 2\pi \cdot 100 \text{ kHz} \), which is much smaller that the free spectral range of the cavity (\( \bar{\omega} = 2\pi \cdot 19.2 \text{ GHz} \)).

FIG. 3. JSI of the state generated by the AlGaAs chip measured by stimulated emission tomography for two values of the pump beam frequency, \( \omega_p = \omega_R \) and \( \omega_p = \omega_R - \bar{\omega} \) corresponding to a resonant and an anti-resonant state, respectively. \( \bar{\omega} = 2\pi \cdot 19.2 \text{ GHz} \), \( \omega_R = 2\pi \cdot 196.1 \text{ THz} \) (765 nm)
can extract the emission bandwidth of the photon pairs, 
by taking into account the chromatic dispersion of the 
output ports are connected to single photon avalanche 
receiver. Generated photons are separated with a fibered 
beam splitter and by choosing a temporal delay $\tau = \pi/\bar{\omega}$. These results prove that the device emits a biphoton frequency comb and that the tuning of the pump frequency controls the transition from an resonant state to an anti-resonant one.

In order to quantify the level of mirror symmetry of the JSA function, we implement a HOM interferometer. Generated photons are separated with a fibered polarizing beam splitter, delayed by $t_{\text{HOM}}$, their polarization aligned with a half wave-plate, and they are recombined at a fibered 50/50 beam splitter. The two output ports are connected to single photon avalanche photodiodes having a detection efficiency of 25% and the coincidences counts are recorded with a time-to-digital converter. The obtained results for $|\psi_R\rangle$ are reported in Figure 4, a dip having a width of $52\pm2$ fs is observed. Similar results are obtained for $|\psi_{AR}\rangle$. Its visibility defined as $(N_r - N_s)/N_r$, where $N_r$ is the coincidences rate far from the interference region and $N_s$ the coincidence rate at the minimum of the dip, is 86%. This value is limited by residual modal birefringence. The oscillating behavior observed around the dip is well-described by taking into account the chromatic dispersion of the sample, as shown by the result of the numerical simulation reported in Figure 3. From this simulation we can extract the emission bandwidth of the photon pairs, $\Delta\omega = 2\pi\times21.82$ THz, corresponding to a signal and idler bandwidth of $\Delta\lambda_{\text{sys}} = 170.9$ nm around 1530 nm (see details in Supplementary Information Figure 3-4). This result demonstrates that the device generates a broadband biphoton frequency comb, where the photons of each pair are in a coherent superposition of more than 500 peaks.

The control of the symmetry of the generated state is done by implementing the last stage of the experimental scheme presented in Figure 1, that is by adding a delay line on one of the output ports of the polarizing beam splitter and by choosing a temporal delay $\tau = \pi/\bar{\omega}$. This leads to the generation of the state $|\psi_R\rangle$ for the resonant case and $|\psi_{AR}\rangle$ for the anti-resonant case.

In order to evaluate the symmetry of the JSA of these states, we rely on HOM interferometry: photon pairs described by a symmetric JSA are expected to anti-bunch, whereas photon pairs described by an anti-symmetric wave function are expected to anti-bunch. Figure 5 reports the experimental results of the HOM experiment: when we inject in the beam splitter the state $|\psi_R\rangle$ a dip is observed, while when we inject in the beam splitter the state $|\psi_{AR}\rangle$ we obtain a peak. The observed visibility is $\approx 10\%$, due to the combined effect of reflectivity, birefringence and chromatic dispersion. Taking into account these effects, we predict that a spectral filter, centered at the frequency degeneracy and having a bandwidth of 25 nm, together with a reflection coating increasing the facets reflectivity to 0.5, would allow to reach a visibility of $70\%$. We discuss the estimated visibility in the ideal case of zero birefringence (or compensated birefringence) and zero chromatic dispersion as a function of the reflectivity in the Supplementary material Figure 5.

We underline that the use of frequency anti-correlations and of a pump beam with a narrow spectral profile ($\Delta\omega <\ll \bar{\omega}$) are essential elements for the manipulation of the state symmetry: a broad pump would generate an uncorrelated state, consisting of a superposition of resonant and anti-resonant patterns, incompatible with this symmetry manipulation protocol.

In conclusion, we have proposed and demonstrated a method to generate and manipulate the symmetry of biphoton frequency combs based on the interplay between cavity effects and a delay line. The method can...
be adapted and applied to a large variety of systems, either bulk or integrated, thus increasing their flexibilit
ity and the richness of the generated states. In addition
since it doesn’t rely on post selection, it can generate on
demand anti-symmetric states. We have shown that Al
GaAs Bragg reflector waveguides are a particularly con
venient system to implement this method, thanks to the
emission of photon pairs via type II SPDC (leading to a
deterministic separation of the photon pairs), small bire
fringence of the generated modes (leading to a symmetric
JSA with respect to frequency degeneracy and avoiding
the requirement of off-chip compensation), and to the
natural presence of a cavity (due to facets reflectivity).
Further progress is possible in different ways: a full in
tegration of the setup could be obtained by developing
an on-chip polarizing beam splitter, as already demon
strated in Si-based devices [29], and by controlling the
relate delay between the orthogonally polarized pho
tons through the electro-optic effect [30]. Moreover, the
compliance AlGaAs chip with electrical injection at room
|temperature [20] paves the way towards the integration
of the laser source within the chip, resulting in an ex
tremely miniaturized and versatile system. These results
open the way to new quantum protocols exploiting high-
dimensional frequency states with controllable symme
try, such as the implementation of quantum logic gates
through coherent manipulation of entangled frequency-
bin qubits [31], high-dimensional one-way quantum pro
cessing [32] or error correction in high-dimensional re
dundant states [33].

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