

A space-time transcoder

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Light with phase front carrying an orbital angular momentum (OAM) is useful in many fields, such as optical tweezers, astronomy. In optical communication, light encoded information in its OAM degrees of freedom enables networks to carry significantly more information and increase their capacity significantly. However, light with OAM has a difficulty in propagating in commercial optical fibers, while light in Gaussian mode encoded with time-bin is most suitable for transmission in fiber. Therefore it is crucially important to build up a bridge for interfacing lights with OAM and time-bin. Here, we report the realization of a photonic space-time transcoder, by which light with an arbitrary OAM superposition is experimentally converted into a time-bin Gaussian pulse and vice versa in principle. Furthermore, we clearly demonstrate that the coherence is conserved very well and there is no crosstalk between orthogonal modes. Such a photonic device is simple and theoretically can be built up in a scalable architecture. Our experimental demonstration paves a primary step towards mixed optical communication in free-space and optical fibre.

Structured vortex beams have many interesting physical properties [1, 2]. Allen et al. firstly recognized that light beams with phase front $\exp(i l \alpha)$ carry an orbital angular momentum (OAM) of $l \hbar$ per photon, where l being a topological charge, α representing an azimuthal angle [3]. The unique properties of helically phased light beams are useful in many fields, such as optical tweezers, astronomy and optical information processing [4-6]. Because of the inherent infinite dimension of OAM, the photon's OAM has the potential for encoding a photon in a

high-dimensional space, enabling the realization of high channel capacity communication [7]. Recent progress based on photonic OAM and polarization multiplexing for high-speed data transmission clearly shows the advantages of OAM beams in classical optical communications [8]. In quantum information science, besides high-capacity, light encoded in OAM degree of freedom enables more security in quantum communications. However, light with OAM has a difficulty in propagating in commercial optical fibers, it is more suitable for transmission in free space.

As a basic information encoding in communications, time-bin encoding is a technique widely used in classical information processing and quantum information science, where the information is encoded in different time bin of light in Gaussian mode, therefore it is suitable for long distance transmission in fiber due to its robustness against optical decoherence [9]. In addition, the time-bin degree of freedom is essentially unlimited, therefore can consist of a high-dimensional space, like the OAM degree of freedom.

A global communication network should be the combination of the subnetwork in free space and the subnetwork in fibre system, therefore it is very promising to convert the information between OAM and time-bin degrees of freedom vice versa freely, which are spanned in spatial and time domain respectively. In this work, we report on the realization of a space-time transcoder, by which, the information encoded in OAM degree of freedom is converted to the information encoded in time domain, and vice-versa. Furthermore, we demonstrate that the light coherence is also conserved during the conversion. Additionally, the conversion efficiency in our scheme can reach 100% in principle. Some other schemes can detect several different l states in time domain but with an efficiency that cannot exceed the reciprocal of the number l theoretically, and the conservation of coherence has not been proved [10, 11]. This transcoder has important applications in connecting traditional fiber-based communication system with the satellite-based network, and also in quantum key distribution without reference frame alignment [12]. The demonstrated space-time device is very simple and also scalable for high OAM states, and holds a promise in future classical mixed communications with large degrees of freedom of photons.

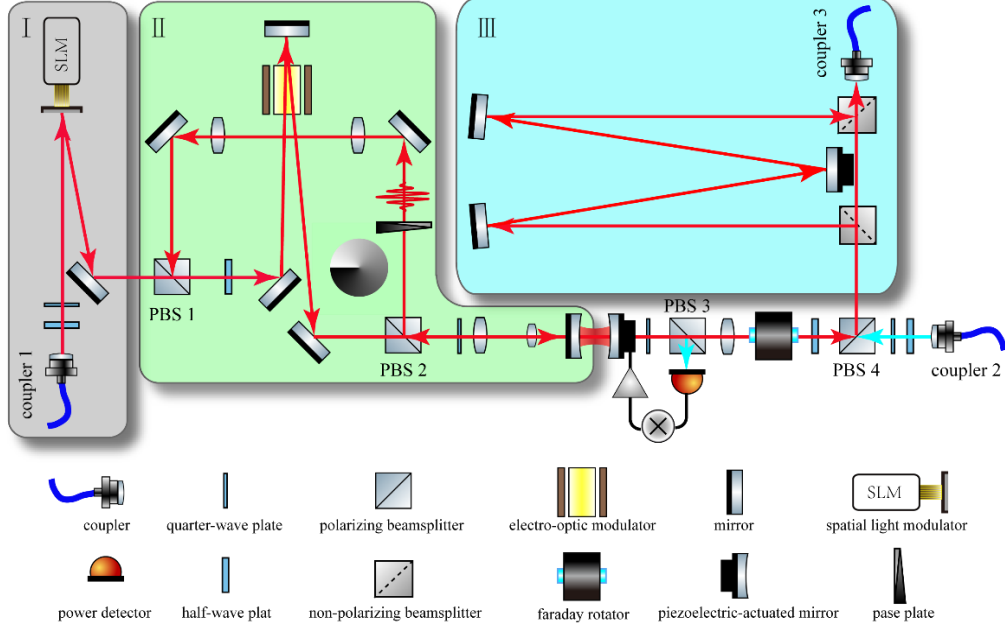


Fig 1. Schematic of the transcoder. Part 1 is used to generate arbitrary superposition of LG modes. Part 2 transforms photonic pulse with different OAM spatial modes into different time bins with Gaussian modes. Part 3 is used for checking spatial coherence. The cavity is locked on the Gaussian mode by using laser beam from coupler 2.

Space-to-time conversion

Our space-time photonic transcoder consists of an optical cavity and an optical loop. The mode selection property of an optical cavity, that light with different OAM value corresponds to different eigenfrequency within the cavity, ensures a high extinction ratio between different OAM states of light (See Appendix). When a cavity is locked to the fundamental Gaussian mode, it will let the light with zero OAM transmit and reflect the rest of light back effectively. An optical loop with a vortex phase plate (VPP) inside is used to trap light pulse and decrease the OAM value of light by 1 per loop. A pulse with l OAM can't pass through the cavity until its OAM becomes zero after l loops. Thus, an optical pulse with different OAM will exit the transcoder at different time $t_0 + T * l$, with T being the round trip propagation time in the loop. Optical cavity is usually used for purifying a Gaussian laser beam [13], so it could vastly reduce the crosstalk between different OAM. The transformation process is described as follow:

$$\sum_l \alpha_l |l\rangle \rightarrow \sum_l \frac{\beta \alpha_l}{\gamma^l} |t_0 + T * l\rangle \quad (1)$$

where, α_l is the proportion of the component with OAM value l , γ is the circulation loss of the optical loop, t_0 is the output time of a Gaussian input pulse, β is the normalization coefficient.

In our experiment, the initial continuous wave (CW) laser beam is from a Ti: sapphire laser (Coherent MBR 110) centered at 795nm. We use two Pockels cells (Cleveland Crystals, Inc IPD-2545) as fast optical switches to cut CW laser beam into pulses with a duration of 5 ns at 1 kHz repetition rate. Fig .1 shows a schematic overview of the experimental setup. The optical system mainly consists of three parts: Part 1 is used to generate an arbitrary superposition of LG modes. Part 2 transforms an optical pulse with OAM modes into time bins with Gaussian mode. Part 3 is used for checking whether OAM coherence is preserved or not during the conversion. See more details in Supplement.

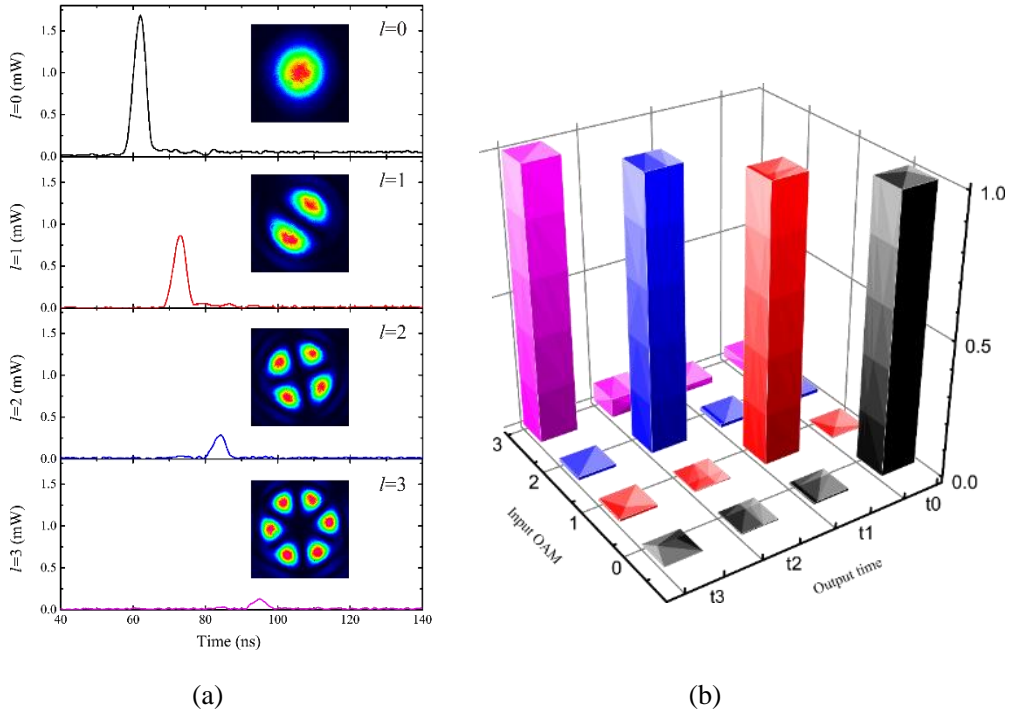


Fig 2. Experimental results. (a) The curves represent the generated different time bins from the input pulses with different OAM, the time interval between the generated adjacent bins is 11 ns. Insets: The interference patterns of input light beam with different OAM values, generated by part 1. (b) Normalized matrix of OAM to time-bin conversion.

In order to show the OAM of the generated light beam from part 1, we interfere the light

beam with its own mirror image. A Mach-Zehnder (M-Z) interferometer with even and odd numbers of reflections in different arms can achieve this goal, since the sign of the OAM is inverted at each reflection. In the case of light with l OAM, the interference pattern has $2l$ radial fringes. The insets in Fig 2(a) show the interference patterns of light beam with different OAM values, which are generated by part 1. Pulses with different OAM values are inputted to the transcoder at the same time and pass through the cavity at different time, then are coupled into a single mode fiber by coupler 3. Finally, the output from the coupler 3 is detected by a fast photodiode (Thorlabs SUV-7) connected to a 500 MHz oscilloscope for time-domain detection. The curves in Fig 2(a) show the converted Gaussian pulses at different time. From the curves we can clearly see the relationship between the output time (t_l) of the Gaussian pulse and the OAM (l) of the input pulse:

$$t_l = t_0 + T * l \quad (2)$$

In our experiment the time interval (T) between the generated adjacent bins is 11 ns. The intensity attenuation of the pulse is mainly caused by the optical loss in the optical loop, which can be improved by using high quality optical components, and thus it can work for higher OAM orders.

To check whether there is the crosstalk in the process of conversion, we integrate the intensity under each peak versus the input OAM state l and the output time bin t_l . The result is shown in Fig 2(b), where each row has been renormalized to the peak of the correct detection. The crosstalk is defined as the ratio between the neighboring incorrect detections and the correct detection. From the normalized matrix shown in Fig 2(b), we can get the nearest neighbor crosstalk among four OAM states, and the average crosstalk is below -20dB experimentally. Low crosstalk means low bit error rate, this property can also be utilized to measure the OAM spectrum.

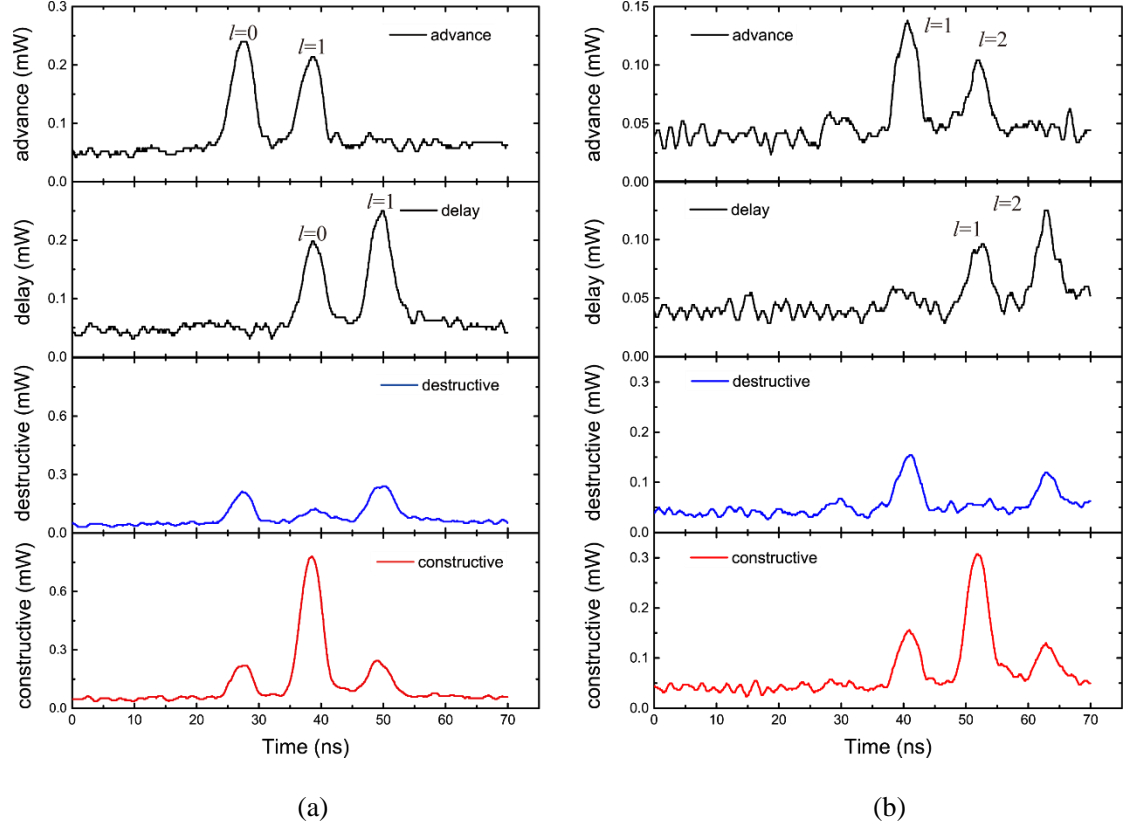


Fig 3. The results for checking the coherence during the conversion. The advance and delay curves represent the detected pulses from the short arm and long arm of the M-Z interferometer in part 3 of Fig. 1 respectively. Pulses from different arms have a component overlapping on time, the components interfere with each other when they get together. (a) The interference result for a pulse in superposition of OAM $l=0$ and $l=1$. (b) The interference result for a pulse in superposition of OAM $l=1$ and $l=2$.

. We use an unbalanced M-Z interferometer to interfere the adjacent pulses to verify whether the coherence is maintained in the transformation process or not. One arm of the interferometer is 3.3 m longer than the other one. A pulse in superposition of OAM $l=0$ and $l=1$ states: $\sin \beta |0\rangle + \cos \beta |1\rangle$ is translated to the superposition state in time-domain: $\gamma \cdot \sin \beta |t_0\rangle + \frac{\cos \beta}{\gamma} |t_0 + T\rangle$, where γ stands for the different optical loss between the two components. When the pulse output from the M-Z interferometer in Fig 1. Part 3, the two components interfere with each other. In Fig 3(a) the advance and delay curve represent the detected pulses from the short arm and long arm respectively. In the experiment, we make the two components have approximately equal strength by adjusting the proportion of different

components and the optical loss in one arm of the interferometer. Due to the fluctuation of the arm-length difference of the interferometer, we observe that the interference slowly changes between constructive and destructive. In Fig 3(a) the blue and red curves show the constructive and destructive interference results respectively. The interference visibility reaches 0.795 after the background electrical noise corrected, which demonstrates that the coherence unchanged in the transformation process. Further test with the superposition of OAM $l=1$ and $l=2$ states comes to the same conclusion, and the interference visibility is 0.806, see Fig 3(b). Since the coherence in the transformations is conserved, the transcoder is suitable for coherent optical communication system.

Time-to-spatial conversion

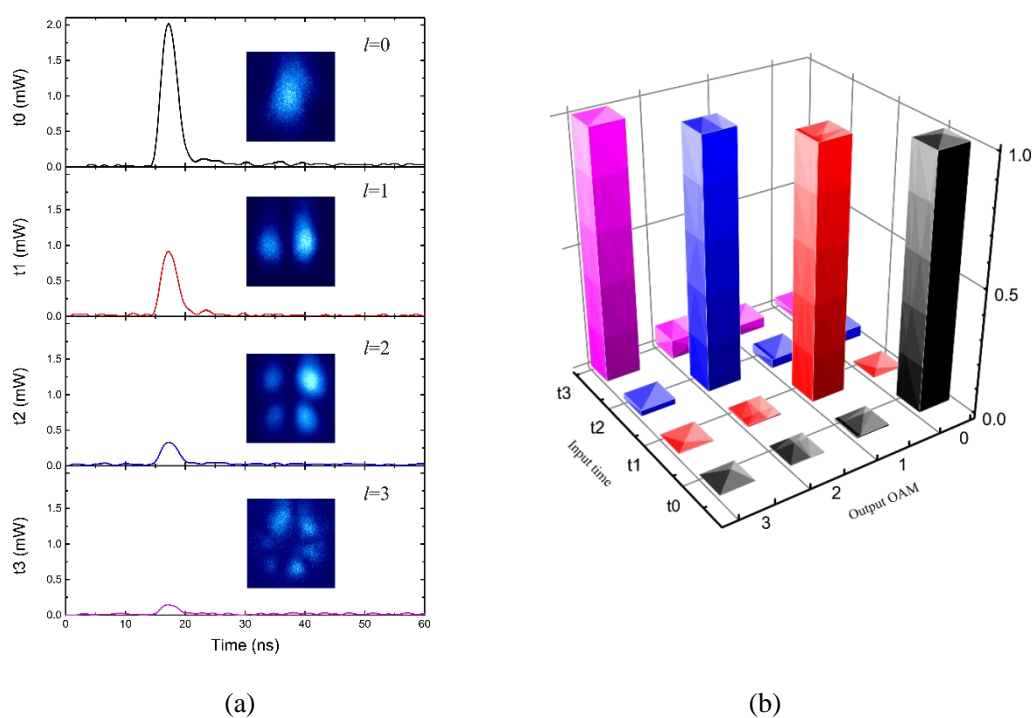


Fig 4(a) The curves are the projective measurement results of the generated pulses with different OAM from pulses inputted at different time, and the detected pulses in corresponding OAM mode. The insets show the interference patterns of the generated pulses with its own mirror image. (b) Normalized matrix of time-to-OAM conversion.

Even more interestingly, when the same setup works under inverse cycling, pulses inputted at

specific times could be transformed into the corresponding OAM mode. In this way, the functions of the optical system have been changed. Part 3 is used to generate two coherence pulses with a time interval of 11ns. Part 2 introduces a phase front $\exp(il\alpha)$ to the pulse inputted at time $t_0 - T * l$. Finally, part 1 performs projective measurement for the spatial structural of the generated pulse. The transformation process could be described as follow:

$$\sum_l \alpha_l |t_0 - T * l\rangle \rightarrow \sum_l \frac{\beta \alpha_l}{\gamma^l} |l\rangle \quad (3)$$

where, α_l is the proportion of the component inputted at time $t_0 - T * l$, γ is the circulation loss of the optical loop, t_0 is the input time for a Gaussian output pulse, β is the normalization coefficient. See more details in Supplement.

As shown in Fig.4(a), pulses inputted at different time (t_i) can be converted to output pulses at the same time with a specific OAM ($l=i$) corresponding to the input time. In order to show the OAM of the generated pulses intuitively, we use the M-Z interferometer mentioned before to interfere the generated pulses with its own mirror image. The insets in Fig 4 (a) show the interference patterns of the generated pulses, these patterns are detected by a fast-gated intensified CCD camera (ANDOR iStar 334T) with a gating speed of 6 ns. The interference pattern with $2l$ radial fringes clearly indicates that the pulse carried the OAM $l=i$.

To check the crosstalk in this transformation process, we measure the OAM content of the generated pulse for each input time via a projective measurement. The integrated intensity under each peak versus the input time bin t_i and the component with OAM l is shown in Fig 4(b), where each row has been renormalized to the peak of the correct detection. The average nearest neighbor crosstalk among four OAM states is -19.5dB. The same setup, when used in reverse, generate pulses with OAM at high frequency. In our experiment the frequency is 1 kHz, it is much higher than the Image Frame Rate (60Hz) of spatial light modulator (SLM) and could be improved easily.

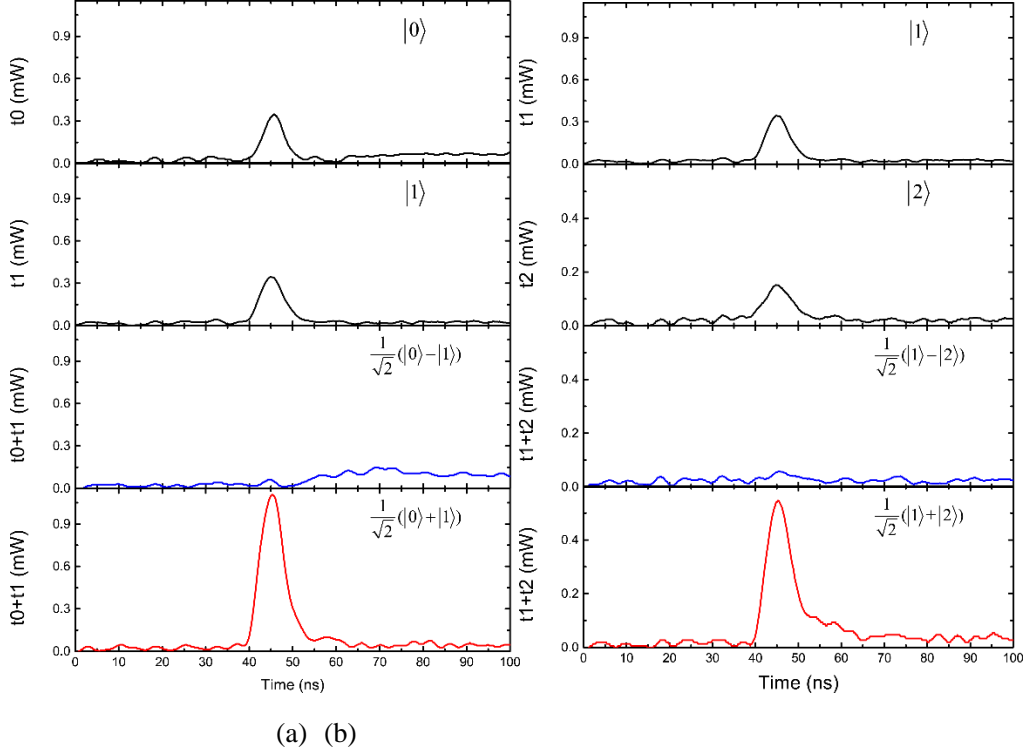


Fig 5. t_i represent the input time of the pulse, The curves are the projective measurement result on OAM state $|i\rangle$. (a) The interference result for pulses inputted at time t_0 and t_1 . (b) The interference result for pulses inputted at time t_1 and t_2 .

To verify whether the coherence is maintained in the transformation process or not, the M-Z interferometer in Fig 1. Part 3 is used to prepare a pulse in superposition of time bin $|t_i\rangle$ and $|t_{i+1}\rangle$ states. Different time bin will be converted into pulse with different OAM. When they outputted at the same time, the generated pulse will be in superposition state of OAM $l=i$ and $l=i+1$. Performing projective measurement on superposition states $\frac{1}{\sqrt{2}}(|i\rangle - |i+1\rangle)$ and $\frac{1}{\sqrt{2}}(|i\rangle + |i+1\rangle)$, we get the destructive and constructive interference result as shown in Fig 5. The interference visibility reached 0.92 and 0.792 for $i=0$ and $i=1$ respectively. Obviously, the coherence is maintained in the transformation process, and the transcoder can prepare pulse in superposition of OAM state.

Discussion

Due to the serious optical losses in the imperfect optical loop, we only demonstrate the

optical conversion with just four OAM modes at present. In principle, one can convert unlimited topological charge of OAM modes by improving the efficiencies. What's more, this photonic device could work for shorter pulses by changing the parameters of the cavity, then, we can miniaturize the optical loop, as thus, this device can be worked in more scalable architecture.

Our designed transcoder can be regarded as an OAM sorter or a high frequency OAM generator, which also can be used in studying photonic entanglement within OAM and time-bin degrees of freedom, also maybe useful in studying quantum simulation with OAM modes. By this way, one can easily prepare the hybrid entanglement with OAM and time-bin based general nonlinear processes of spontaneously parametric down conversion and spontaneously four-wave mixing.

Conclusions

We realize the conversion of pulses with spatial information encoded in OAM degree of freedom into the time domain vice versa, and further demonstrate the preservation of the coherence during the conversion. The demonstrated space-time device is very simple and scalable for high OAM states. A high extinction ratios between different OAM states have been achieved, and the main limit for high-order OAM transformation comes from the efficiency of the components. Our work is very promising in future classical mixed communications with large degrees of freedom of photons.

Acknowledgments

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Supplement

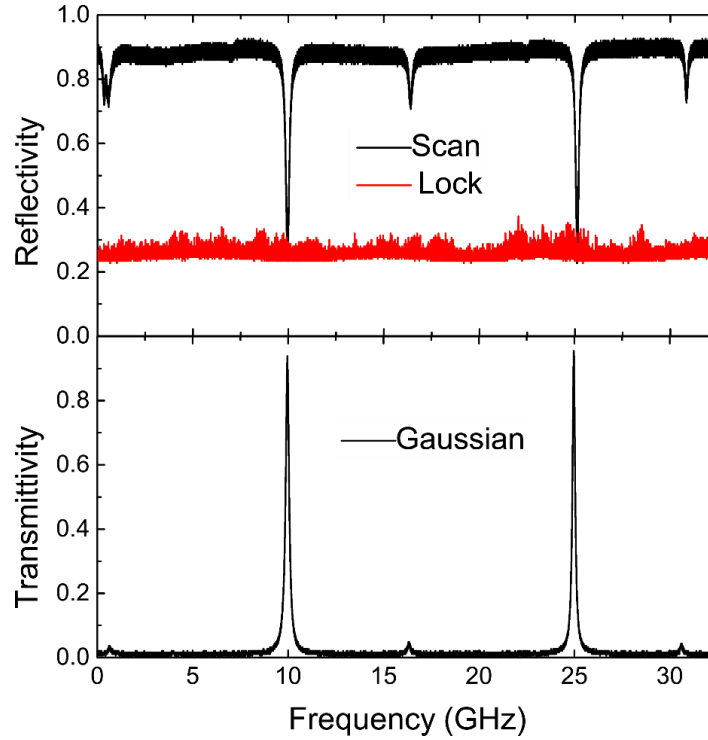
Optical system of space-to-time transformation

In the experimental setup shown in Fig. 1, the pulsed Gaussian laser beam from coupler 1 diffracted off computer-generated fork-diffraction patterns on a SLM (Holoeye LETO LCoS) shown in Part 1, the fork dislocation in the patterns introduces helical phase fronts ($\exp(i l \alpha)$) to the first-order diffracted pulse, therefore the pulse carries the OAM of l . Part 2 is the core of our scheme. We make the diffracted pulse from Part 1 to be in state $|H, l\rangle$, it indicates that the pulse carries OAM l and is in horizontal (H) polarization. The polarizing beam splitter (PBS) is assumed to transmit the H polarization and reflect the V polarization, so the pulse could transmit through the PBS 1. Since the electro-optic modulator (EOM) is triggered just after the pulse double-passes through it for the first time. So the pulse is still in state $|H, l\rangle$, and goes through PBS 2 to the optical cavity. The optical cavity consists of two mirrors with radii of 50 mm separated by 10 mm. Since the cavity is locked to the LG_{00} mode, the pulse could pass through efficiently if and only if $l = 0$, otherwise it will be reflected back almost totally. The experimentally measured transmissivity for Gaussian mode is 90% and the reflectivity for nonzero OAM mode is 90%. Even though part of the Gaussian mode is reflected back, high extinction ratios between different OAM states can still be achieved, because the reflected part will get back with nonzero OAM, which can't pass through the cavity. The reflected pulse becomes in state $|V, l\rangle$ after it double-passes the quarter-wave plate (QWP). Then, it is reflected to the vortex phase plate (VPP) by the PBS 2. The VPP introduces a phase $\exp(-i \alpha)$ to the pulse after it passes through, so the state becomes $|V, l-1\rangle$. A 4-f system is used to erase the detrimental effect on the beam quality after a round trip. The EOM changes the polarization of the pulse when it double-passes for the second time, now the state becomes $|H, l-1\rangle$. The pulse will get back to the optical cavity again and again with lower OAM, only if its OAM becomes zero, then it could pass through the cavity. The total number of reflections in the optical loop is even, so we can ignore the sign inversion at each reflection. The round trip propagation time of the optical loop is T (11ns). By this way the optical loop converts the pulse with OAM l into a Gaussian pulse at a specific time which correlated with the OAM value of the input pulse. Assume that a Gaussian input pulse come out of

the optical loop at time t_0 , so a pulse with OAM l need to undergo multiple passage through the VPP and out at time $t_0 + T * l$.

Cavity locking

A faraday rotator cooperating with a HWP is used to change the H polarization laser beam from cavity into V polarization, and keeps the polarization of laser beam from coupler 2 unchanged. Laser beam from couple 2 is reflected to a power detector by the optical cavity. Error signal generated from the reflectance spectrum is fed back to the piezoelectric-actuated mirror to suppress the distance fluctuations between the cavity mirrors, in other words, the cavity is locked on the Gaussian mode of the laser beam.



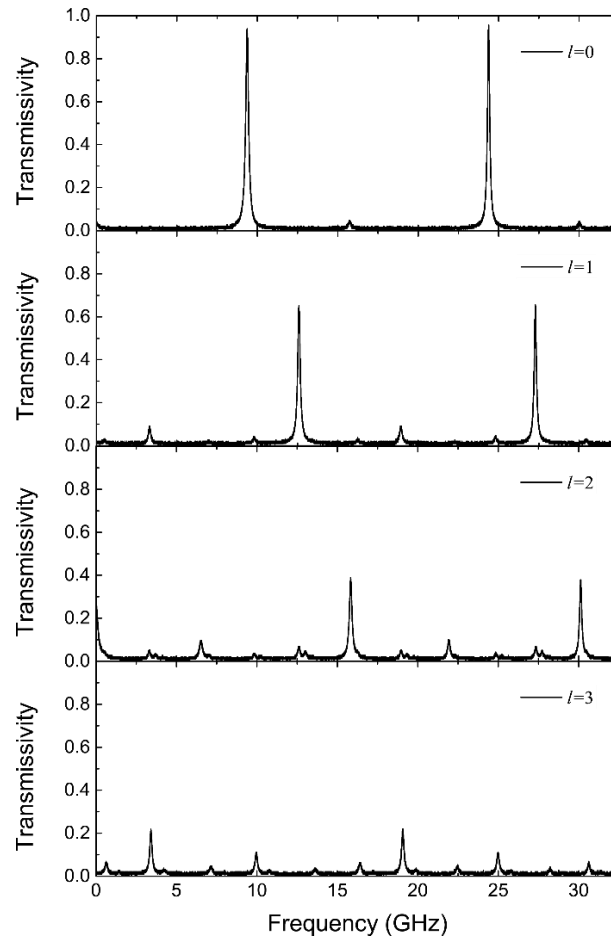
The figure above shows the reflectance spectrum of Gaussian mode and the locked spectrum. The one below is the transmission spectrum of Gaussian laser beam.

Even though laser beam from coupler 2 mode matched with the cavity not very well, the valley of the reflectance spectrum and the peak of the transmission spectrum still corresponds to the same frequency. When the cavity locked on the valley, the experimentally measured transmissivity for Gaussian mode is 90%, and the reflectivity for nonzero OAM mode is 90%. The transmissivity and reflectivity can be very close to 100% theoretically.

Optical system of time-to-spatial transformation

Firstly, we block one arm of the Mach-Zehnder interferometer, a pulsed Gaussian laser beam from coupler 3 mode matches with the cavity, Laser beam from couple 2 is used to lock the cavity on the Gaussian mode. Since the peak power of the pulse is much stronger than the laser beam from coupler 2, the influence of the lock-cavity laser beam to the pulse is ignorable. Assume that the EOM is triggered to change the polarization of the pulse at time t_0 , and a HWP is inserted into the optical loop to keep a pulse traveling inside before the EOM triggered. A pulse arrived at EOM for the first time at $t_0 - T * l$, it will travel in the optical-loop and multiple passage through the same VPP. Then, the pulse get out of the optical-loop at time t_0 with OAM l . The output pulse is diffracted off fork-diffraction patterns on the SLM, the fork-diffraction pattern displayed on the SLM can be used to “flatten” the phase of the component with a specific incident OAM, which can be coupled efficiently to a single-mode fiber. Finally, we use a fast photodiode to measure how much power was carried by the mode we are projecting into.

Optical Cavity



The transmission spectrums of the cavity for laser beam with different OAM values.

The electric field of LG modes in cylindrical coordinates.

$$LG_{pl} = \sqrt{\frac{2p!}{\pi(p+|l|)!}} \frac{1}{w(z)} \left(\frac{r\sqrt{2}}{w(z)}\right)^{|l|} \exp\left(\frac{-r^2}{w^2(z)}\right) L_p^{|l|}\left(\frac{2r^2}{w^2(z)}\right) \exp(il\alpha) \exp\left(\frac{ik_0 r^2 z}{2(z^2+z_R^2)}\right) \exp\left(-i(2p+|l|+1)\tan^{-1}\left(\frac{z}{z_R}\right)\right) \quad (4)$$

The finesse of the cavity is $F = \frac{\pi\sqrt{R}}{1-R} = \frac{\pi\sqrt{0.95}}{1-0.95} \approx 61.24$, where R is the reflectivity of the cavity mirror. The free spectral range (FSR) is $\Delta\nu = \frac{c}{2nd} \approx \frac{3 \times 10^8 \text{ m/s}}{2 \times 1 \times 0.01 \text{ m}} = 15 \text{ GHz}$, where d is the distance between the cavity mirror. The full width at half maximum (FWHM) of the transmission peak is $FWHM = \frac{\Delta\nu}{F} \approx 245 \text{ MHz}$. The linewidth of a 5 ns laser pulse is 16 MHz, which is less than the FWHM, that ensure the transmission of the pulse.

$(2p+|l|+1)\tan^{-1}\left(\frac{z}{z_R}\right)$ in Equation (4) is Gouy phase, it is caused by the propagation in transverse direction. The phase shift result in the eigenfrequencies of LG modes within a resonator are different with that of Gaussian modes. The eigenfrequencies of LG modes within a resonator:

$$\nu_{l,p,m} = \frac{c}{2nd} \left(m + \frac{2p+|l|+1}{\pi} \cos^{-1}(\sqrt{g_1 g_2})\right) \quad (5)$$

Where l and p are the transverse quantum number, m is the longitudinal quantum number, and $g_i = \left(1 - \frac{d}{R_i}\right)$ is the stability parameter. In our experiment $g_i = 0.8$, then:

$$\nu_{l,p,m} = \frac{c}{2nd} (m + (2p+|l|+1) \times 0.2048) \quad (6)$$

Even though, the eigenfrequencies of some OAM values are close to Gaussian modes, the frequencies difference could be bigger than FWHM for a wide range of OAM values. In our experiment the range is OAM $l < 201$. Experimentally measured reflectivity is greater than 85%, and the transmittivity is 6×10^{-5} for OAM $l=5$. It is better for laser beam with other OAM values.