Spin–orbit laser mode transfer via a classical analogue of quantum teleportation

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Abstract
We translate the quantum teleportation protocol into a sequence of coherent operations involving three degrees of freedom of a classical laser beam. The protocol, which we demonstrate experimentally, transfers the polarization state of the input beam to the transverse mode of the output beam. The role of quantum entanglement is played by a non-separable mode describing the path and transverse degrees of freedom. Our protocol illustrates the possibility of new optical applications based on this intriguing classical analogue of quantum entanglement.

Keywords: quantum teleportation, classical non-separability, spin–orbit laser modes

(Some figures may appear in colour only in the online journal)

1. Introduction
The tensor product structure of the vector space describing composite quantum systems is the key to the very definition of quantum entanglement. It was noticed many years ago [1] that the same mathematical structure arises in the description of classical optical fields, yielding what has been called classical entanglement or non-separability. This analogue of quantum entanglement allows us to translate quantum information concepts to the classical domain. Our first contribution to this topic was the demonstration of a topological phase acquired by maximally entangled qubits in the spin–orbit modes of a classical laser beam [2, 3]. Later, we investigated a Bell inequality to characterize the non-separability between polarization and the spatial mode structure of classical paraxial beams [4]. This investigation was also later taken up in the single photon regime by other groups [5, 6]. Recently, the role of Bell inequalities in classical optics has drawn a fair amount of attention, being addressed in a series of papers [7–9]. This new understanding of classical non-separability resulted in new optical applications inspired by quantum information [10–17].

The possibility of using the polarization degree of freedom to control spatial modes has resulted in a number of applications both in classical and quantum optics. Examples include quantum image control [18], spin to orbital degree of freedom information transfer [19–21], quantum cryptography [22–24], controlled gates [25, 26], quantum games [27], environment-induced entanglement [28], quantum teleportation [29]. The coherent superposition of different transverse modes carrying orthogonal polarizations creates polarization vortices that have been proved useful for classical and quantum encoding of information [30–32].

One of the chief uses of quantum entanglement is information distribution based on quantum teleportation [33]. It enables one party (Alice), to transfer an arbitrary, unknown quantum state to a second party (Bob) via the use of previously shared quantum entanglement and classical communication [34–38]. In 2001, Spreeuw proposed a classical optical scheme mimicking quantum teleportation, with the goal of transferring the state of the path degree of freedom of a laser beam to its polarization [39]. More recently, there have been a few experimental demonstrations of various classical optical analogues of the quantum teleportation protocol. In [40], the role of Alice’s qubit state to be teleported was played by two independent, and incoherent, light beams, with the classical information being transferred via a classical laser beam. In [41], the state transfer was performed from the orbital angular momentum of a laser beam to its polarization, whereas in the very recent paper [42] the transfer was from the path degree of freedom to its transverse mode structure. These investigations have been responsible for the introduction of new techniques to enable precise, robust control...
between the different degrees of freedom addressable in optical experiments.

Here we report on experiments in which we perform the interferometric transfer of arbitrary polarization modes to the transverse spatial structure of a paraxial, classical laser beam; as far as we know, this is the first teleportation-like protocol implemented between these degrees of freedom. This is achieved by mapping the steps of a single-qubit quantum teleportation protocol into a sequence of controlled optical mode operations. In our experiments, the role of quantum entanglement is played by a classical non-separable joint state of the path and transverse spatial degrees of freedom of the laser beam. Our set-up is relatively simple and translates the relative ease of polarization preparation into the possibility of high-quality and fast preparation of arbitrary states of transverse modes of a laser beam. Our results push further the analogy between classical and quantum entanglement, showing new optical applications are possible if we explore this analogy in depth.

Our paper is organized as follows. In section 2 we introduce the optical modes we use to describe the different degrees-of-freedom we manipulate in our experiment. In section 3 we translate the steps of the quantum teleportation protocol to a series of operations on a classical laser beam. In section 4 we describe the experimental setup and results, with some concluding remarks in section 5.

2. Optical mode structure

Our experiment involves interference and polarization measurements on first-order paraxial beams. We will work in the computational basis of Laguerre–Gaussian modes of width \(w\), carrying orbital angular momentum. Inside an interferometer, these modes are distributed between two alternative paths determined by the longitudinal propagation axes of the modes. For simplicity, we assume two axes lying parallel to the \(z\) direction of the coordinate system, lying a distance \(d \gg w\) apart from each other, so that the overlap between transverse modes belonging to different paths is negligible. We shall refer to these paths as 0 and 1 and designate their locations on the \(x-y\) plane by the coordinates \((0, 0)\) and \((d, 0)\), respectively.

We describe the transverse modes in the normalized Laguerre–Gaussian basis and focus on the first order, two-dimensional vector space. Their functional form is

\[
\psi_{\xi, \eta}(\xi, \eta) = \frac{2}{\sqrt{\pi}} (\xi \pm i\eta) e^{-\left[(\xi^2 + \eta^2)(1 + z^2) - i\phi(\xi)\right]},
\]

(1)

where

\[
\bar{\xi} = \frac{z}{z_0}, \\
(\xi, \eta) = (x, y)/w(\bar{\xi}), \\
w(\bar{\xi}) = w_0\sqrt{1 + \bar{\xi}^2}, \\
\phi(\bar{\xi}) = \arctan(\bar{\xi}),
\]

(2)

\(z_0 = k w_0^2/2\) is the Rayleigh distance and \(w_0\) is the beam waist. The transverse coordinates \((\xi, \eta)\) are relative to the path axes and normalized by the beam width. This arrangement is depicted in figure 1.

Transverse modes lying on different paths do not overlap and are orthogonal, regardless of their functional form. Therefore, we can formally represent the path modes as an independent degree of freedom and describe them by a pair of column vectors

\[
\chi_0 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad \chi_1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}.
\]

(3)

We then build the path-transverse mode structure as a tensor product \(\{|\psi_{x+}, \psi_{y+}\} \otimes \{\chi_0, \chi_1\}\). Finally, each transverse mode lying on each path has two possible polarizations described by horizontal and vertical unit vectors \(\{\hat{e}_H, \hat{e}_V\}\). Thus, our complete workspace will be

\[
W = \{\psi_{x+}, \psi_{y+}\} \otimes \{\chi_0, \chi_1\} \otimes \{\hat{e}_H, \hat{e}_V\}.
\]

(4)

These three degrees of freedom can be operated separately or in a combined way in order to implement controlled operations. In the polarization degree of freedom, unitary transformations are implemented with waveplates, and projections onto linear basis vectors are performed by polarizers. Transverse modes can be transformed by astigmatic mode converters or Dove prisms. Path modes can be operated on with beam splitters (BSs) and phase shifters. Controlled operations are easily performed when transverse mode or polarization transformations are applied on one path only. With this set of operations we will implement the steps of a quantum teleportation protocol to transfer an arbitrary polarization superposition to the transverse mode, using the resource of classical, non-separable states of the path and transverse degrees of freedom.

3. The protocol

The teleportation protocol involves three steps. First, an arbitrary polarization mode is prepared on the laser beam impinging on path 0. Then, the transverse mode is entangled with the path degree of freedom with a conditional operation. Finally, a Bell projection is performed on the path and polarization degrees of freedom, resulting in four transverse mode superpositions at the different outputs. One of them (the successful output) will carry a transversal mode state which

![Figure 1](image-url)
directly corresponds to the initial polarization state. The other three outputs will correspond to the initial polarization state changed by Pauli operations, in direct correspondence with the one-qubit quantum teleportation protocol. In what follows we describe each step in more detail.

3.1. Polarization preparation

In order to demonstrate the protocol, we sent a sequence of twelve different polarization modes prepared with a half and a quarter waveplates. This sequence is represented in the Bloch sphere shown in figure 2, where the corresponding transverse modes produced are also represented. By rotating the orientations of the waveplates, we prepare polarization states which interpolate between three mutually unbiased modes: (i) linear horizontal (point 1), (ii) linear at 45° (point 5) and (iii) left circular (point 9). Each point corresponds to a polarization superposition

$$\hat{\varphi}_n = \alpha_n \hat{e}_H + \beta_n \hat{e}_V$$  \hspace{1cm} (1 \leq n \leq 12),

with $\alpha_n$ and $\beta_n$ determined by the polar and azimuthal angles on the sphere.

3.2. Path-transverse mode entanglement

A non-separable path-transverse mode state can be created by applying a path Hadamard operation followed by a conditional transverse mode flip. This is achieved with a Dove prism inserted on path 1 after the BS, as sketched in figure 3.

3.3. Path-polarization Bell projection

An essential ingredient of the protocol is the ability to perform a Bell measurement in the degrees of freedom corresponding to the polarization and beam path. This can be done via a controlled unitary gate between them, followed by a projection on single-system bases. In our scheme, we make a path dependent polarization transformation followed by a beam splitter operation (which corresponds to a Hadamard gate on the path mode), followed by polarization measurements with polarizing BSs. The path-polarization Bell measurement scheme is described at the top of figure 4. The controlled polarization transformation is implemented with a half waveplate oriented at 45°, placed on path 1.

$$\chi_0 = \varphi_{n},$$

with $\varphi_{n}$ in the Bloch sphere viewed in figure 2. This corresponds to a CNOT gate that flips the polarization (target) conditioned to the path mode (control). Then, the two path modes are combined in a 50/50 BS, corresponding to a Hadamard gate. One can easily verify that this sequence transforms the four path-polarization Bell modes as follows:

$$\chi_0 \hat{e}_H + \chi_1 \hat{e}_V / \sqrt{2} \rightarrow \chi_0 \hat{e}_H,$$

$$\chi_0 \hat{e}_H - \chi_1 \hat{e}_V / \sqrt{2} \rightarrow \chi_1 \hat{e}_H,$$

$$\chi_0 \hat{e}_V + \chi_1 \hat{e}_H / \sqrt{2} \rightarrow \chi_0 \hat{e}_V,$$

$$\chi_0 \hat{e}_V - \chi_1 \hat{e}_H / \sqrt{2} \rightarrow \chi_1 \hat{e}_V.$$  \hspace{1cm} (6)

Finally, a polarization measurement performed at each output path can discriminate the four input Bell modes. These operations can be summarized as a quantum circuit, as shown at the bottom of figure 4.

4. Experimental setup and results

The experimental setup is described in figure 5. A horizontally polarized TEM$_{00}$ mode produced by a He–Ne laser is diffracted by a holographic mask to prepare a Laguerre–Gaussian transverse mode $\psi_n$ propagating on path $\chi_0$. Two waveplates convert its polarization to a chosen superposition

$$\hat{\varphi} = \alpha \hat{e}_H + \beta \hat{e}_V,$$  \hspace{1cm} (7)
thus preparing the initial separable supermode
\[ \Psi_A = \psi_+(\eta, \xi) \chi_0 \hat{\varphi}. \] (8)

For simplicity, we shall omit the arguments in the transverse modes from now on. A BS is used to perform a Hadamard gate in the path mode, and a Dove prism is inserted in output path 1 of the BS to flip the transverse mode propagating on this path. This operation is modelled by a CNOT gate on the transverse mode (target), controlled by the path; it creates the non-separable transverse-mode/path state which plays the role of a pair of maximally entangled qubits in the quantum teleportation protocol. This supermode is described by:
\[ \Psi_B = \left[ \psi_+ \chi_0 + \psi_- \chi_i \right] \hat{\varphi}. \] (9)

After the controlled operation between path and transverse mode, we start the sequence of operations that will perform the Bell projection on the path and polarization modes, as described in section 2. First, a second controlled gate is performed by a half-wave plate oriented at 45° (Pauli \( \sigma_X \) operation on polarization), inserted on path 1. It is equivalent to a CNOT gate on the polarization mode (target) controlled by the path, producing the supermode
\[ \Psi_C = \psi_+ \chi_0 (\alpha \hat{e}_H + \beta \hat{e}_V) + \psi_- \chi_i (\beta \hat{e}_H + \alpha \hat{e}_V). \] (10)

Then, a Hadamard operation is performed on the path degree-of-freedom by a BS, resulting in the output supermode
\[ \Psi_D = [ (\alpha \psi_+ + \beta \psi_-) \chi_0 \hat{e}_H + (\beta \psi_+ + \alpha \psi_-) \chi_0 \hat{e}_V + (\alpha \psi_- - \beta \psi_+) \chi_i \hat{e}_H + (\beta \psi_- - \alpha \psi_+) \chi_i \hat{e}_V ] / \sqrt{2}. \] (11)

To complete the Bell measurement a polarization projection is performed with a polarizing BS placed in each output path, giving output transverse modes
\[ \psi_y(\eta, \xi) = (\chi_j^\dagger \hat{e}_j) \cdot \Psi_D, \] (12)

with \( i = 0, 1 \) and \( j = H, V \). The four output transverse modes are
\[
\begin{align*}
\psi_{0H} &= \alpha \psi_+ + \beta \psi_- \\
\psi_{0V} &= \beta \psi_+ + \alpha \psi_- \\
\psi_{1H} &= \alpha \psi_- - \beta \psi_+ \\
\psi_{1V} &= \beta \psi_- - \alpha \psi_+ 
\end{align*}
\] (13)

Output port 0H is the successful one, which does not require any unitary correction, while ports 0V, 1H and 1V, must be corrected with \( \sigma_X, \sigma_Z \) and \( \sigma_X \sigma_Z \) operations, respectively.

The four outputs were registered with a CCD camera. First we prepared the input beam with left circularly polarized light, which corresponds to \( \alpha = 1 / \sqrt{2} \) and \( \beta = i / \sqrt{2} \). This setting is expected to produce four Hermite–Gaussian beams oriented at \(-45°\) on port 0H, \(45°\) on port 0V, \(45°\) on port 1H and \(-45°\) on port 1V, which is in very good agreement with the results shown in the top four images of figure 6.

The bottom images are theoretical density plots of the transverse mode superpositions given by equation (13).

Then, a sequence of polarization modes was prepared by rotating the quarter and half waveplates at different orientations. This produced twelve polarization modes, forming a closed path in the Poincaré sphere, represented in figure 2. The images obtained in the successful port for these twelve input polarizations were registered on the CCD camera and shown in figure 7 together with the corresponding theoretical density plots of the expected transverse modes on this port. The experimental images are in good agreement with the numerical simulations.

To better evaluate the quality of our implementation of the protocol, we have measured the parameters characterizing the transferred superposition, namely the absolute values and...
the relative phase of $\alpha$ and $\beta$. By blocking each arm of the path-transverse-mode entanglement stage and measuring the output intensity in the successful port, we could estimate $|\alpha|^2$ and $|\beta|^2$ from the ratio between the partial and total intensities. We have done this for a sequence of input polarizations, starting on the north pole of the Poincaré sphere and going down to the south pole, following the great circle passing through points 1–5 of figure 2. These input polarization modes were prepared with a half waveplate. In figure 8 we show the experimentally measured values of $|\alpha|^2$ and $|\beta|^2$ as a function of the waveplate orientation $\theta$. The expected, theoretical values $|\alpha|^2 = \cos^2 2\theta$ and $|\beta|^2 = \sin^2 2\theta$ are shown with dashed lines.

The relative phase $\phi$ between $\alpha$ and $\beta$ determines the spatial orientation of the images of the two transverse mode lobes produced on the successful port. This is an important advantage of using Laguerre–Gaussian modes as the computational basis. In order to evaluate the phase transfer, we have measured the orientation of the Hermite–Gaussian lobes formed on the equatorial path connecting points 5 and 9. The input polarization was prepared with a half waveplate at a variable orientation $\theta$ and a quarter waveplate fixed at 45°. The orientation of the HG lobes is given by the line connecting their intensity peaks. The results are shown in figure 9. The error bars were evaluated from a sequence of twenty images for each point. The theoretical values expected for this path is $\phi = 2\theta - 45^\circ$, indicated by the dashed line in figure 9. For all points from 5 to 9, we also measured $|\alpha|^2 \approx |\beta|^2 \approx 0.5$. Combining the estimates of $|\alpha|^2$, $|\beta|^2$ and the relative phase $\phi$, we have calculated the fidelities achieved in the protocol for all points from 5 to 9. They are shown on table 1.

**Table 1.** Measured fidelities of the mode transfer for points lying on the equatorial path 5 to 9.

| Point | Fidelity     |
|-------|--------------|
| 5     | 0.96 ± 0.05  |
| 6     | 0.97 ± 0.04  |
| 7     | 0.98 ± 0.04  |
| 8     | 0.99 ± 0.05  |
| 9     | 0.99 ± 0.04  |

**Figure 7.** Experimental (top) and theoretical (bottom) images obtained at the successful output port for the twelve input polarizations indicated on the Bloch sphere of figure 2.

**Figure 8.** $|\alpha|^2$ (black) and $|\beta|^2$ (red online) as a function of the half waveplate orientation. The dashed lines correspond to the expected theoretical values.

**Figure 9.** Relative phase $\phi$ between coefficients $\alpha$ and $\beta$ as a function of the half waveplate orientation $\theta$ for the equatorial path 5–9. The dashed line corresponds to the expected theoretical values.
5. Conclusion

We have proposed and experimentally demonstrated a scheme to transfer an arbitrary polarization state to the first order transverse structure of a paraxial laser beam. The scheme mirrors the quantum teleportation protocol and uses operations on three internal degrees of freedom of a paraxial laser beam. It can be used as a practical way of generating arbitrary first order transverse modes either for classical optical processing or quantum cryptography in the photonic count regime.

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