Abstract Teleportation describes the transmission of information without transport of neither matter nor energy. For many years, however, it has been implicitly assumed that this scheme is of inherently nonlocal nature, and therefore exclusive to quantum systems. Here, we experimentally demonstrate that the concept of teleportation can be readily generalized beyond the quantum realm. We present an optical implementation of the teleportation protocol solely based on classical entanglement between spatial and modal degrees of freedom, entirely independent of nonlocality. Our findings could enable novel methods for distributing information between different transmission channels and may provide the means to leverage the advantages of both quantum and classical systems to create a robust hybrid communication infrastructure.

Demonstration of local teleportation using classical entanglement

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1. Introduction

Quantum teleportation allows a sender to share information with a receiver by encoding it into a quantum state that both parties can access. In general, the counter-intuitive aspects of this type of protocols stem from the fact that, in contrast to all conventional forms of communication, the state itself is not being transmitted between the two [1]. Following the first landmark experiments employing photonic quantum states as information carriers [2–4], teleportation has been implemented in a wide variety of different physical systems [5–8]. Teleportation is therefore considered to be a fundamental building block for quantum communication and computation architectures. At the core of its ability to distribute information through potentially vast and far-reaching networks is entanglement, which allows the nonlocal interaction that is necessary for a transfer of information to occur [9].

For many years, entanglement was viewed as the epitome of a quantum effect, seemingly lacking any analogue in classical systems. Only very recently it became clear that the underlying algebraic structure giving rise to entanglement can indeed be reproduced in the classical domain [10–16]. Very recently, moreover, state transfer protocols based on the classical entanglement concept between the orbital angular momentum and the polarization states of the electromagnetic field have also been proposed [17,18]. As it turns out, the key distinction between classical and quantum systems is not their capability to support entanglement, but rather the (non-) locality of the same [14]. As subsequent works have demonstrated [19–22], these notions may help to infuse classical physics with the potentialities offered by quantum entanglement to drive novel and interesting applications. In this work, we extend the concept of teleportation beyond its well-known quantum context. To this end, we propose and experimentally demonstrate a photonic setting in which classical entanglement can be harnessed to teleport information between the spatial and modal degrees of freedom of a purely classical light field. While non-locality remains the differentiating feature between quantum and classical configurations, our results illustrate that teleportation-based protocols can bridge the gap between these two realms.

2. Theoretical background

On a conceptual level, teleportation involves at least three degrees of freedom, which henceforth will be labelled as A, B and C. Whereas an entangled Bell state is established between A and B, the information one desires to transmit is contained in C. The actual teleportation process is facilitated by the application of a controlled-NOT (C-NOT) operation with respect to A and C, followed by a Hadamard

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Figure 1 (a) Generation: A continuous-wave He-Ne laser is prepared in a classically entangled state with radial polarization by a rotating polarization wave plate (RPWP). The initial state $|\psi\rangle$ is then obtained using a beam splitter (BS1). Two density filters ($F_\alpha$ and $F_\beta$) are used to encode the information in the cebit $C$. Preparation: The initial state $|\psi\rangle$ is then sent through a C-NOT gate, realized using two Sagnac interferometers with a polarizing beam splitter. The lower interferometer, corresponding to $|1\rangle_C$ also contains a half-wave plate (HWP) to rotate the polarization. The two parts of the beam are then recombined through a second beam splitter (BS2), which implements a Hadamard operation for the cebit $C$. Measurement: The correct output state is selected by choosing the $x$-polarization (PBS3) of the lower output channel of BS2. The reflected beam from a third beam splitter (BS3) is sent to a CCD camera (Cam2) for direct acquisition of the intensity profile and angle measurement. The transmitted beam from BS3 is instead sent to the modal decomposition stage, consisting of a computer generated hologram (CGH) a lens and a second CCD camera (Cam1). (b) Exemplary scanning electron microscope image of a nanograting-based polarization rotating wave plate such as the RPWP used to generate the classically entangled beam with radial polarization.

The entanglement, initially shared between the cebits A and B, has been transferred to C and A. To realize the teleportation of information between the cebits C and B, $|\psi_{out}\rangle$ is then projected onto one of the four basis states spanning the joint Hilbert space of the two entangled cebits A and C. A readout of the information contained in the cebit B will therefore give us access to the information initially encoded in the cebit C.

### 3. Experimental setup

To implement such a protocol, we employ the experimental setup shown in Fig. 1, where the information can be teleported from the path (C) to the spatial (B) Hilbert space. First, we need to generate a classically entangled beam with radial polarization. To do that, light from a 594 nm He-Ne laser is sent to a custom-designed rotating polarization wave plate (RPWP) fabricated using a femtosecond laser waiting technique. It essentially consists of a $\lambda/2$ plate with locally varying anisotropy, realized by inscribing periodic sub-wavelength nano-gratings in the bulk of a fused silica substrate [23, 24]. By tuning the polarization of the inscribing laser, moreover, it is possible to control the orientation of the nano-gratings, therefore allowing a great degree of control over the polarization pattern imprinted.
on the impinging beam at the micron scale. A scanning electron microscope image of the nano-grating pattern forming a RPWP is shown in Fig. 1(b). In our specific case, the RPWP has been designed in such a way to obtain a classically entangled beam with radial polarization, namely \[ |\Phi^{+}\rangle_{AB} = \frac{1}{\sqrt{2}} [\psi_{10}(x, y)\hat{x} + \psi_{01}(x, y)\hat{y}] \]. \tag{3}

Therein, $\psi_{10}$ and $\psi_{01}$ are the first-order Hermite-Gaussian solutions of the paraxial equation [25], and $\hat{x}, \hat{y}$ denote the horizontal and vertical polarization eigenstates, respectively.

To implement the third cebit C, we employ a 50/50 beam splitter (BS1 in Fig. 1) to create two identical copies of $|\Phi^{+}\rangle_{AB}$, which then propagates along different paths. One path then represents $|0\rangle_{C}$, and the other $|1\rangle_{C}$, respectively [14]. To encode the initial information in the cebit C, two density filters $F_{\alpha}$ and $F_{\beta}$ are placed at each output of the beam splitter BS1.

The output state $|\Psi_{out}\rangle$ described by Eq. (2) therefore corresponds to the two output channels of BS2. Note that each of its four unique mode structures can be individually extracted with a simple measurement operation. Consider, for example, the first term in Eq. (2), which can be written, in terms of optical modes, as follows

\[
|00\rangle_{CA} \otimes (\alpha |0\rangle_{B} + \beta |1\rangle_{B})
\]

\[
= \hat{x} [\alpha \psi_{10}^{u}(x, y) + \beta \psi_{01}^{u}(x, y)].
\tag{4}
\]

The path cebit C is here implemented by labelling the upper and lower beams with the superscript $u$ and $l$, respectively. Then, $|0\rangle_{C}$ corresponds to the beam being in the upper path, while $|1\rangle_{C}$ corresponds to the beam being in the lower path [14]. A closer inspection to the above equation reveals that in order to project the output state $|\Psi_{out}\rangle$ onto the state $|00\rangle_{CA}$, it is sufficient to take the $\hat{x}$-polarization eigenstate of the beam in the upper path, i.e., $|0\rangle_{C}$. This guarantees access to the information encoded in the cebit B. In our experimental setup, this projection operation is realized by placing a polarizer (PBS3) at the output of BS2 corresponding to $|0\rangle_{C}$. In terms of optical beams, the projected state $|00\rangle_{CA} |0\rangle_{out}$ assumes the following form:

\[
M(x, y) = \alpha \psi_{10}(x, y - y_{0}) + \beta \psi_{01}(x, y - y_{0}).
\tag{5}
\]

The beam $M(x, y)$ is then split into two parts by a beam splitter (BS3). While the reflected beam is directly acquired by a CCD camera (Cam2), the transmitted beam is instead sent through a computer-generated hologram (CGH) that decomposes it in its different Hermite-Gaussian constituents [26]. Subsequent imaging onto a second CCD camera (Cam1) allows for the extraction of both the amplitude and the phase of the modal coefficients $\alpha$ and $\beta$.

\[\text{To retrieve the information encoded in the spatial cebit B, we use the following approach. First, we look at the intensity distribution acquired by Cam2. If the intensity profile of the acquired image appears as a Hermite-Gaussian mode $\psi_{01}$ rotated by an angle $\theta$ with respect to the y-axis (see, for example, on of the insets in Fig. 2), the information can be directly retrieved from the acquired image by means of a digital algorithm. First, we evaluate the slope of the line parallel to the horizontal axis. As can be seen, the retrieved angles (black points) are in good agreement with the theoretical prediction (red solid line), namely $\cot \theta = |\beta/\alpha|$. The insets show the acquired intensity distribution (single realization) corresponding to $\theta = 47^\circ, 55^\circ, 62^\circ$ and $76^\circ$, respectively.}\]
angle $\theta$. In order to solve this issue, and to be able to retrieve the phase information encoded in the coefficients $\alpha$ and $\beta$ in Eq. (5), a full modal decomposition technique is needed. For this, we employ the so-called correlation filter method (CFM) technique [26]. This essentially amounts to taking the scalar product between the modal function described by Eq. (5) and the Hermite-Gaussian basis functions $\psi_{lm}$, i.e.,

$$\langle \psi_{lm}|M\rangle = \int \int_{-\infty}^{\infty} \psi_{lm}^*(x, y)M(x, y)dxdy. \quad (6)$$

Therefore, since the Hermite-Gaussian functions $\psi_{10}$ and $\psi_{01}$ are the complete basis set that spans the two dimensional Hilbert space associated to cebit B, this method allows to extract the information encoded in this cebit by simply calculating $\langle \psi_{01}|M\rangle = \alpha$ and $\langle \psi_{10}|M\rangle = \beta$, respectively. This is realized in our experimental setup by using a computer-generated hologram (CGH) with appropriately designed transmission functions [26]. The integration appearing in Eq. (6) has been then carried out using a 2$f$ system, which performs the Fourier transform of the incoming signal. The intensity distribution in the focal plane therefore provides access to the amplitude of the coefficient $\alpha$ and $\beta$. With this method, it is then possible to retrieve the relative phase difference $\Delta\phi$ between $\alpha$ and $\beta$ by means of a three-way interference between different replicas of the two mode functions with known phase difference. In addition, in order to provide real-time access to both $\alpha$ and $\beta$ simultaneously, we employed an angular multiplexing technique similar to the one described in Ref. [26].

Although the results presented in Fig. 3 are in very good agreement with the expected ones, it has to be noted that the measurement error increases with the measured ratio $\beta/\alpha$. To obtain a good correlation signal, in fact, the scalar product (6) needs to be evaluated at a single point (e.g., along the optical axis of the system), where the signal originating from the two Hermite-Gaussian modes are truly independent of one another. Fluctuations of the position of this point due to small fluctuations of the position where the two beams recombine (BS2) are the main source of measurement errors and can be minimized by ensuring a sufficient contrast in signal strengths between the modes.

### 4. Discussion

The results presented in this manuscript allow us to draw some important conclusions about the concept of teleportation. It is worth noticing, in fact, that Eq. (2) is completely independent on the classical or quantum nature of the three systems A, B and C used to implement the teleportation protocol. This is also proven by the fact that the only essential ingredient for realizing a teleportation protocol is entanglement. However, entanglement alone cannot distinguish between a classical and a quantum system, as it manifests itself in the same way in both cases [14]. Therefore, the gate sequence typical of a teleportation experiment is universally valid, and, once implemented, can teleport either classical or quantum information. These observations lead us to interpret Eq. (2) as simply the teleportation equation.

To properly distinguish between the classical and the quantum case, then, one has to invoke the concept of non locality, namely if the considered system is obeying or violating the principle of local realism. This, in fact, contextualizes the experiment in either the classical and strictly local world or in the nonlocal realm of quantum mechanics. In our case, this means that we can teleport information only between different degrees of freedom belonging to the same classical system.

### 5. Conclusions

With this work we have extended the concept of teleportation to the classical realm by implementing a photonic setting in which classical entanglement allows to teleport information between path and spatial degrees of freedom of a purely classical light field. In doing so, we have shown that teleportation is a general concept, that transcends the
distinction between classical or quantum systems, and that non-locality ultimately differentiates between these two realms. Along these lines, our results may pave the way towards the realization of a hybrid classical-quantum communication infrastructure.

Supporting Information

Additional supporting information may be found in the online version of this article at the publisher’s website.

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References

[1] C. H. Bennett, G. Brassard, C. Crépeau, R. Jozsa, A. Peres, and W. K. Wootters, Phys. Rev. Lett. 70, 1895 (1993).
[2] D. Bouwmeester, J.-W. Pan, K. Mattle, M. Eibl, H. Weinfurter, and A. Zeilinger, Nature 390, 575 (1997).
[3] L. Vaidman, Phys. Rev. A 49, 1473 (1994).
[4] A. Furusawa, J. L. Sorensen, S. L. Braunstein, C. A. Fuchs, H. J. Kimble, and E. S. Polzik, Science 282, 706 (1998).
[5] M. Riebe, H. Häffner, C. F. Roos, W. Hönsl, J. Benhelm, G. P. T. Lancaster, T. W. Körber, C. Becher, F. Schmidt-Kaler, D. F. V. James, and R. Blatt, Nature 429, 734 (2004).
[6] H. Krauter, D. Salart, C. A. Muschik, J. M. Petersen, Heng Shen, T. Bernholz, and E. S. Polzik, Nature Phys. 9, 400 (2013).
[7] W. Pfaff, B. Hensen, H. Bernien, S. B. van Dam, M. S. Blok, T. H. Taminiau, M. J. Tiggesman, R. N. Schouten, M. Markham, D. J. Twitchen, and R. Hanson, Science 345, 532 (2014).
[8] A. Z. Khoury and P. Milman, Phys. Rev. A 83, 060301(R) (2011).
[9] M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information (Cambridge University Press, 2000).
[10] R. J. C. Spreeuw, Found. Phys. 28, 361 (1998).
[11] A. Luis, Opt. Commun. 282, 3665 (2009).
[12] A. Holleczek, A. Aiello, C. Gabriel, C. Marquardt, and G. Leuchs, Opt. Express 19, 9714 (2011).
[13] X.-F. Qian and J. H. Eberly, Opt. Lett. 20, 4110 (2011).
[14] A. Aiello, F. Töppel, C. Marquardt, E. Giacobino, and G. Leuchs, New J. Phys. 17, 043024 (2015).
[15] P. Ghose and A. Mukherjee, Rev. Theor. Sci 2, 1 (2014).
[16] R. J. C. Spreeuw, Phys. Rev. A 63, 062302 (2001).
[17] S. M. H. Rafsanjani, M. Mirhosseini, O. S. Magana-Loaiza, and R. W. Boyd, Phys. Rev. A 92, 023827 (2015).
[18] B. Pinheiro da Silva, M. A. Leal, C. E. R. Souza, E. F. Galvao, and A. Z. Khoury, “Spin-orbit mode exchange via a classical analog of quantum teleportation”, arXiv:1509.06826v2.
[19] F. Töppel, A. Aiello, C. Marquardt, E. Giacobino, and G. Leuchs, New. J. Phys. 16, 073019 (2014).
[20] C. V. S. Borges, M. Hor-Meyll, J. A. O. Huguenin, and A. Z. Khoury, Phys. Rev. A 82, 033833 (2010).
[21] E. Karimi, J. Leach, S. Slussarenko, B. Piccirillo, L. Marucci, L. Chen, W. She, S. Franke-Arnold, M. J. Padgett, and E. Santamato, Phys. Rev. A 82, 022115 (2010).
[22] L. J. Pereira, A. Z. Khoury, and K. Deichoum, Phys. Rev. A 90, 053842 (2014).
[23] L. P. R. Ramirez, M. Heinrich, S. Richter, F. Dreisow, R. Keil, A. V. Korovin, U. Peschel, S. Nolte, and A. Tünnermann, Appl. Phys. A 100, 1 (2010).
[24] M. Beresna, M. Gecevicius, P. G. Kazansky, and T. Gertus, Appl. Phys. Lett. 98, 201101 (2011).
[25] O. Svelto, Principles of Lasers (Springer, 2010).
[26] T. Kaiser, D. Flamm, S. Schröter, and M. Duparré, Opt. Express 17, 9347 (2009).