Free-space information transfer using light beams carrying orbital angular momentum

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Abstract: We demonstrate the transfer of information encoded as orbital angular momentum (OAM) states of a light beam. The transmitter and receiver units are based on spatial light modulators, which prepare or measure a laser beam in one of eight pure OAM states. We show that the information encoded in this way is resistant to eavesdropping in the sense that any attempt to sample the beam away from its axis will be subject to an angular restriction and a lateral offset, both of which result in inherent uncertainty in the measurement. This gives an experimental insight into the effects of aperturing and misalignment of the beam on the OAM measurement and demonstrates the uncertainty relationship for OAM.

OCIS codes: (090.1970) Diffractive optics; (010.3310) Laser beam transmission; (060.4510) Optical communications.

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1. Introduction

Optical encoding is now being applied to free-space communication links. Such links have been demonstrated at both the classical [1] and single photon level [2]. Most of these links rely on modulation of intensity (or photon number), frequency, or polarisation of the light. Here we encode the data on the orbital angular momentum of the light and show that this leads to an improved security that can be implemented at both the classical and single photon level.

Light beams can carry both spin and orbital angular momentum (OAM) associated, respectively, with circular polarisation and the helicity of their phasefronts [3, 4]. As identified by Allen *et al*., a beam comprising l helical phasefronts, described by a phase term $\exp(il\phi)$, carries an OAM of $l\hbar$ per photon, where l can take any integer value [5].

Light's spin has long been used in quantum-mechanical experiments [6, 7]. The quantum nature of OAM was demonstrated by Mair *et al*. [8], who observed entanglement of OAM between down-converted pairs of photons, and Leach *et al*. [9] developed an interferometric device that can sort single photons according to their OAM. Optical spin can be described in the two-dimensional basis of right and left circular polarisation with an angular momentum of $\pm\hbar$ per photon, respectively. It is therefore a suitable physical realisation of a qubit. By contrast, OAM has an infinite number of eigenstates, corresponding to the different values of l, and the number of bits the OAM of a single photon can represent is therefore, in principle, unlimited. This makes OAM a promising parameter onto which classical or quantum information may be encoded [10].

Light carrying OAM can be described in terms of Laguerre-Gaussian (LG) modes [5] which contain an $\exp(il\phi)$ phase term describing an on-axis phase singularity of strength l. In addition to the number l, LG modes are characterised by their radial index p and their waist size w_0. Here we use LG modes with $p = 0$; for $l \neq 0$, their intensity cross-sections consist of one bright ring with no on-axis intensity. For a given waist size w_0, the radius of the ring scales with $\sqrt{l}$. All optical systems have finite apertures and it is only this that restricts the maximum value of l that may be used.

It is important to consider how the rapid modulation of one observable impacts on other properties. We have recently observed a relationship for OAM states that links a restriction in angular position, $\Delta\phi$, to a spread in OAM, Δl [11]. The distribution of l-states is predicted from a discrete Fourier-transform of the azimuthal dependence of the aperture function. The key

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implication is that the error-free measurement of the OAM of a light beam requires a measurement aperture without any angular restriction. This has implications for the integrity/security of a data link based on OAM: a potential eavesdropper with a receiver placed some distance from the beam axis and spanning an angular range of less than 2π cannot measure with certainty the OAM of the beam.

In this paper we report a free-space optical link that uses OAM to transmit and receive data. We operate the link over 15 meters and demonstrate that the data recoverable by most eavesdroppers is corrupted.

2. Optical setup

We encode and measure optical OAM via phase holograms. Phase holograms are typically designed to incorporate a spatially dependent phase retardation in the range 0 to 2π. To convert a plane-wave input to a helical phase front therefore requires a hologram pattern described by $l\phi \bmod 2\pi$. Invariably such holograms are only partially efficient, resulting in a number of different diffraction orders, all of which are collinear.

Our transmitter unit is based on a HeNe laser, a computer-controlled phase hologram implemented using a reflective spatial light modulator (SLM, Boulder Nonlinear Systems, 512×512 pixels) and a telescope. We chose an “alphabet” consisting of the values $l = -16, -12, -8, -4, 4, 8, 12, 16$; this separation in l values is compatible with our chosen method of compensating for small perturbations in alignment. In addition, the cross-talk between channels is decreased while keeping the size of the beams within the aperture of the system. The corresponding beams are generated by a set of pre-calculated hologram patterns. The SLM is illuminated with a 6mm-diameter collimated beam from a HeNe laser. The afocal telescope expands the reflected beam to approximately 4cm diameter, ensuring eye-safe intensity levels. As discussed above, the hologram patterns are designed to operate on-axis such that the specified first-order beam comprising the desired LG mode is superimposed on the residual zero-order beam, i.e. a fundamental Gaussian. This fundamental Gaussian beam provides a reference signal at the $l = 0$ detector from which the system can be aligned.

The receiver unit comprises a similar telescope, SLM and CCD array detector. The beam from the transmitter is collected by the telescope and reduced to 6mm diameter and reflected from the SLM, programmed with the analysing-hologram pattern. If the l value of the beam is minus the l value of the hologram then the resulting beam has planar phase fronts and therefore can be focussed through a pin hole. Changing the l value of the analysing hologram allows the beam to be analysed for its OAM. Hologram designs can be refined such that a single hologram can test for a number of OAM states simultaneously [12]. Our analysing hologram is designed to diffract the light into nine beams, each with a different helicity, arranged in a 3×3 grid. The helicity of the incident beam results in one of the nine beams having a high on-axis intensity, thereby establishing its OAM state. All nine beams are imaged onto the CCD array, from which we determine the on-axis intensity of each beam. The experimental configuration is shown in Fig. 1.

The analysing hologram in the receiver unit is calculated as the sum (modulo 2π) of two phase patterns: a vertical phase grating with a central dislocation of order 4, blazed such that the power is equally distributed in the -1st, 0th and +1st diffraction order, and a similarly blazed horizontal phase grating with a central dislocation of order 12. This gives eight diffraction orders corresponding to the chosen alphabet. To compensate for small perturbations in alignment associated with atmospheric turbulence etc., we define the measurement axes relative to the observed position of the central $l = 0$ channel. The choice of every fourth $l-$value avoids the overlap of the $l = 0$ alignment spot with the rings resulting from non-diffracted light of the transmitted “alphabet” modes. Using a different alphabet set as an example, Fig. 2 shows how

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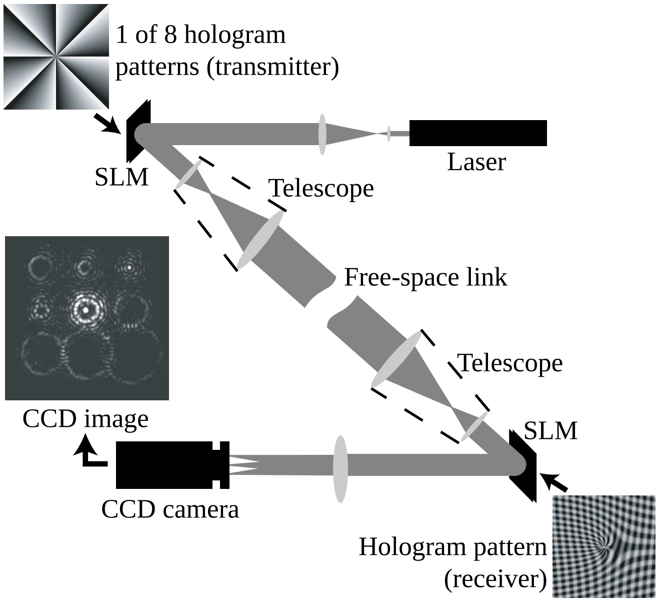

Fig. 1. Optical configuration of the free-space optics (FSO) demonstration system. Shown here is the case of a beam with $l = 8$.

the design of an analysing hologram can be derived from two individual holograms that separate modes horizontally and vertically. The hologram design is covered in more detail in ref. [13].

Figure 3 shows typical images recorded by the CCD array and the corresponding on-axis intensities associated with each of the channels. The $l = 0$ component confirms correct alignment of the system and the additional component identifies the transmitted OAM state.

We are able to measure accurately the OAM states up to a transmission range of 15m. When used over longer ranges the integrity of the beam helicity is degraded and the contrast between channels is gradually reduced. We believe that this degradation arises from atmospheric turbulence, which introduces aberrations degrading the phase structure, and hence the purity of the OAM state. The range and reliability of conventional free-space optics (FSO) systems is limited by many factors also including turbulence, building sway [14] and fog [15]. The range of a conventional FSO system can be significantly improved by using adaptive optics to correct for the aberrations introduced by the atmosphere [16]. Adaptive optics can also be used within our system by correcting for the aberrations introduced to the l=0 component of the beam.

Helical beams are also highly sensitive to aberrations in the medium through which they are propagating. Beams with l=1 are extremely resilient to distortion since the on-axis phase singularity simply cannot disappear. Beams with $|l| > 1$ are in general unstable to perturbation (especially astigmatism), an l=N singularity collapsing to N× l=1 singularities [17]. Within our communication system, which relies on high l states, this collapse is triggered by atmospheric aberration and sets a limitation to the operating range. However, we believe that the same aberration correction optics as used in conventional FSO systems will give similar benefits to our own.

The use of CCD arrays and SLMs is convenient for the purposes of our demonstration, but it places severe limitations on the bandwidth of the optical link. The CCD array could be replaced with an array of discrete photodiodes aligned to monitor the on-axis intensity of each beam. The need to modulate the SLM could be removed by using a static hologram pattern in the trans-

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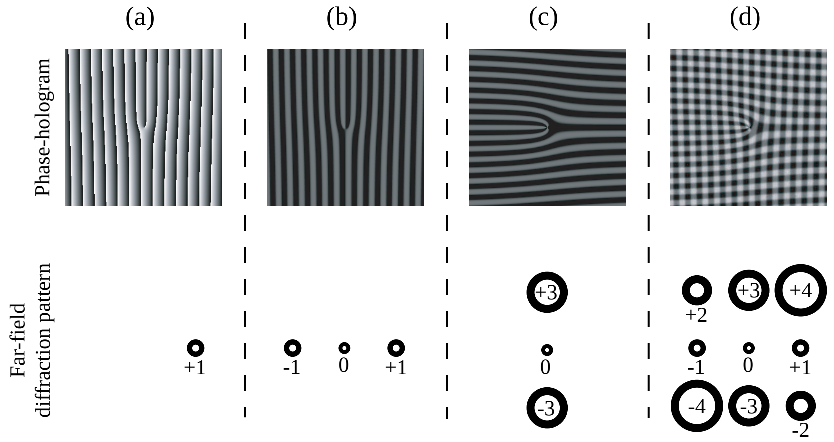

Fig. 2. Some examples of phase-hologram designs (top) and schematic representation of the corresponding far-field diffraction patterns under plane wave illumination (bottom). The phase-hologram patterns are represented in grey-scale. (a) Horizontally shifted l=1 beam. (b) Setting the phase at each point in the hologram pattern for the horizontally shifted $l = 1$ beam to either 0 or π (whichever is closest) gives three horizontally separated beams with l= -1, 0 and +1. (c) Similarly, we can obtain three vertically separated beams with l= -3, 0 and +3. (d) The sum of the two phase patterns that create the horizontally and vertically separated beams gives a 3×3 array of beams with l= -4, -3, ..., +3, +4.

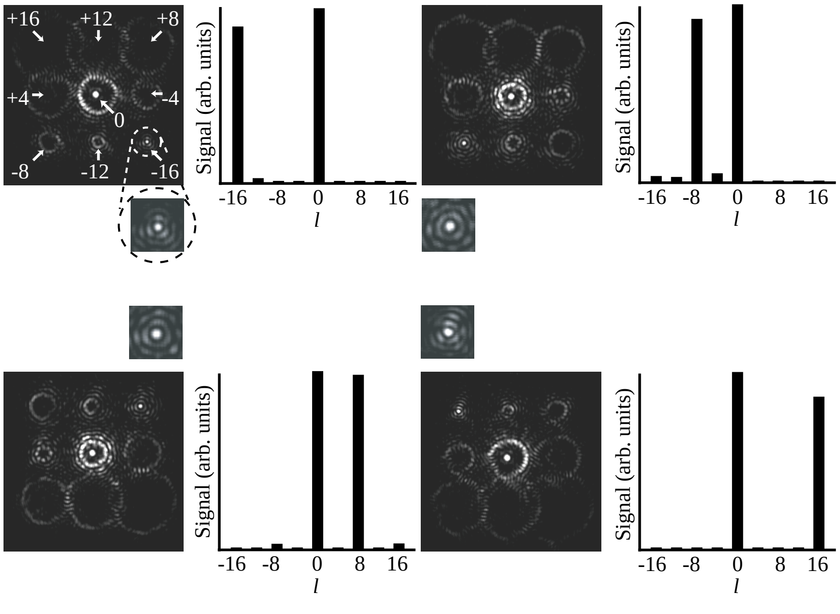

Fig. 3. A subset of results from transmitting a data set using OAM. We have used a data transmission set corresponding to the azimuthal indices $-16, -12, -8, -4, 0, +4, +8, +12, +16$. We have defined a matrix of detectors by measuring the intensity at specific points on the CCD image.

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mitter similar to that used in the receiver. Rather than acting as a "fan-out", the same hologram design could then combine the beams from various laser diodes into a single transmitted beam with chosen helicity. Each laser diode could then be modulated at its full bandwidth giving multi-channel transmission ("OAM multiplexing").

3. Security advantages

The security of conventional free-space communication is compromised by atmospheric scattering, allowing the beam to be covertly intercepted using an additional receiver. For this reason, security has to rely on mathematical encryption of the data. Our method using OAM to encode the data offers an inherent security enhancement as it is difficult to read the data without positioning the detector directly in the path of the intended receiver. The OAM data is extremely difficult to recover from the light that is scattered by the atmosphere since the time dependent scattering process randomises the phase structure of the beam. Light scattered from optical components, although not subject to temporal variation, is still highly complex and recovery of the original OAM data is non-trivial. Even if positioned within the beam there are several ways in which an eavesdropper may have difficulty in establishing a system to measure the OAM.

As discussed in the introduction, the width of an angular aperture through which a beam passes and the light's associated OAM are conjugate variables and their measurement precision is related by an uncertainty relationship [11]. Within our communication system, this manifests itself as an inherent uncertainty in the measurement of OAM when the angular extent of the beam during the measurement is restricted. Figure 4 shows the effect of inserting different segment masks into the path of an l=1 laser beam, each mask transmitting segments of size 360°, 270°, 180° and 90° of the beam, respectively. The detected OAM values are shown for each mask along with the theoretical values, obtained from the power spectrum of the Fourier transform of the azimuthal aperture function. For the case of no angular restriction, the receiver measures the value of OAM with high probability. Reducing the aperture size increases the spread in the measured OAM as predicted from the Fourier transform of the aperture function. This shows that if a measurement covers only a restricted angular range of the beam the precision of the OAM measurement is degraded. Given sufficient time and/or signal it would still be possible to infer the true value of OAM from the mean of the measured distribution. However, in situations where the signal to noise is more marginal, the confidence with which the mean value of OAM can be estimated is decreased. Clearly, this potential corruption of data due to beam obstruction also applies equally to the intended recipient as it does to the eavesdropper. Consequently for reliable data transfer it is essential that the line of sight between transmitter and receiver is not obstructed, a requirement that is also relevant to conventional FSO systems. In the extreme case of encoding on a single photon, the spread in OAM means that the probability of error-free measurement is small. Such a single photon system could be implemented by using a single-photon source as reported by Shields *et al*. [18].

Another way in which the eavesdropper could be compromised is by alignment error with respect to the transmitter. Due to the finite diameter of the collection optics, a lateral misalignment results in an aperturing of the beam and hence a broadening similar to that observed in the case of the angular restriction discussed above. Alternatively, an angular misalignment of the receiver means that the detected beam is no longer described by a single value of OAM, but rather a superposition of different OAM states centred about the original value [19]. Figure 5 shows the effect of angular misalignment of an l=1 beam between detector and receiver, comparing the measured results to those predicted by a decomposition of the detected beams in terms of cylindrical harmonics. Combining an angular misalignment with a small lateral displacement is mathematically more complex. In essence the beams linear momentum, acting about the measurement axes gives rise to an addition extrinsic angular momentum, indistinguishable

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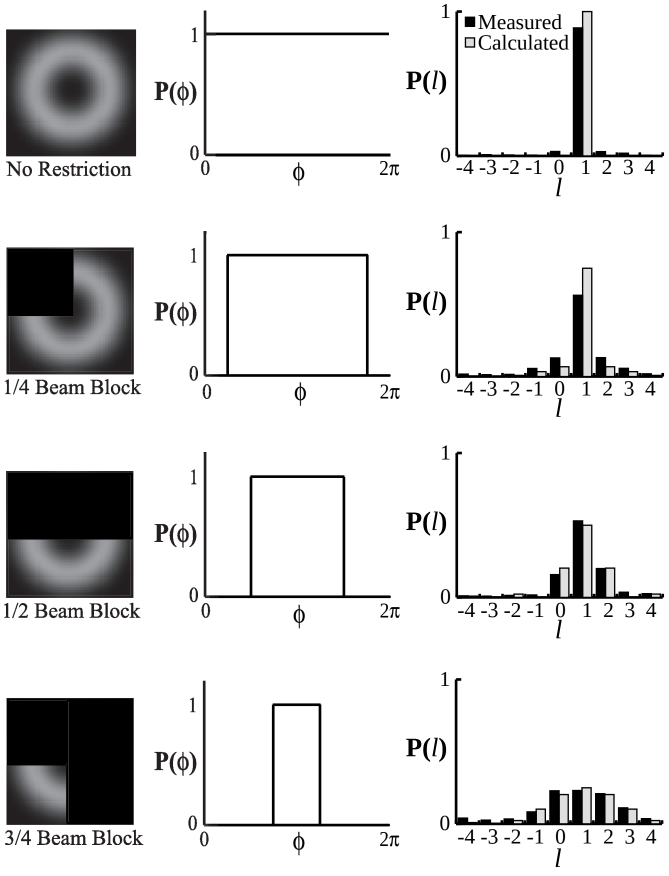

Fig. 4. Spread – or uncertainty – in the measured values P(*l*) for various apertures inserted into the path of an *l*=1 beam. The beam immediately after the aperture is shown in the left column. The measured spread in *l*-values (dark bars) compares well with the power spectrum of the aperture function P(ϕ) (light bars).

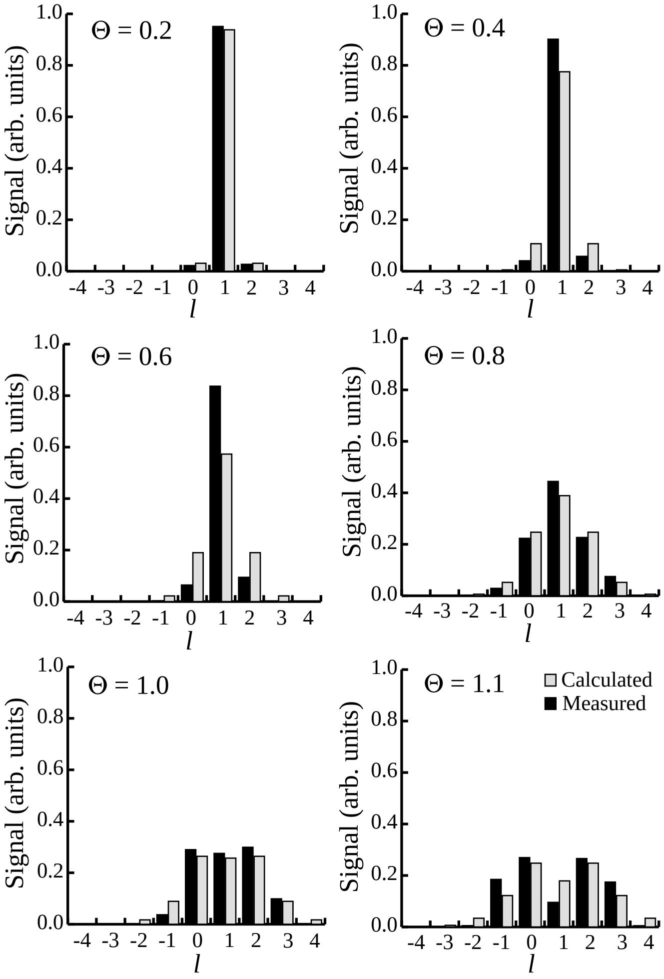

Fig. 5. Spread in the values of *l* for various angular misalignments of an *l*=1 beam. Θ is the angular misalignment as a fraction of the beam divergence. The measured results (dark bars) are compared to those predicted by a decomposition of the detected beams in terms of cylindrical harmonics (light bars).

from the intrinsic OAM [20]. The effect on the measurement is to both broaden the angular momentum distribution and displace the mean value. In such situations, the OAM content of the beam is extremely difficult to infer and the security of the link is enhanced. Obviously, to take full advantage of this security enhancement, the OAM values used for encoding need to be closely spaced. The channel separation of $\Delta l = 1$, as used in the experiments shown in Fig. 5, offers a higher degree of security than the configuration based on $\Delta l = 4$ as shown in Fig. 3.

The corruption of intercepted OAM data due to potential aperturing of the beam and uncertainty in alignment result in an optical communication system for which data integrity is only maintained, in practice, along the line of sight between transmitter and intended receiver. This is in complete contrast to a communication system based on measurement of the spin angular momentum (i.e polarisation state), where the intrinsic nature of the spin angular momentum means that its measurement and associated data is unchanged by angular restriction, a lateral

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shift or angular misalignment of the measurement axis.

4. Conclusions

We have demonstrated that OAM can be used to encode data onto a laser beam for transmitting information in free-space optical systems. We have shown that this system offers a level of security that does not depend on mathematical or quantum-mechanical encryption methods. We believe that our technique is compatible with current FSO techniques like wavelength-division multiplexing, the use of adaptive optics for the correction of atmospheric effects and quantum cryptography with single photons. Our work has also brought up many interesting questions, some of which we discuss in this paper, and which need to be fully addressed before our ideas can be realised in a commercial FSO system.

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