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## Robust interferometer for the routing of light beams carrying orbital angular momentum

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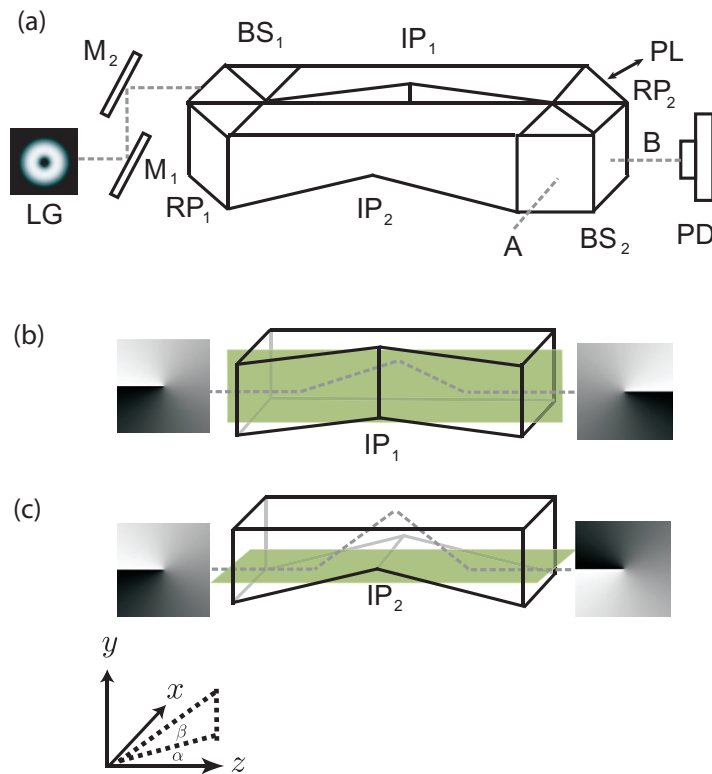
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**Abstract.** We have developed an interferometer requiring only minimal angular alignment for the routing of beams carrying orbital angular momentum. The Mach–Zehnder interferometer contains a Dove prism in each arm where each has a mirror plane around which the transverse phase profile is inverted. One consequence of the inversions is that the interferometer needs no alignment. Instead the interferometer defines a unique axis about which the input beam must be coupled. Experimental results are presented for the fringe contrast, reaching a maximum value of  $93 \pm 1\%$ .

The orbital angular momentum (OAM) carried by light is an extremely useful optical characteristic, with applications in many areas of optics. It was Allen *et al* who recognized that a helically phased light beam with a phase cross section of  $\exp(i\ell\phi)$  carries an OAM of  $\ell\hbar$  per photon [1, 2]. An example is Laguerre–Gaussian (LG) beams which have a helical phase structure. The integer  $\ell$  is unbounded, giving a large state space in which to encode information [3–5].

The use of diffractive elements containing an  $\ell$ -fold fork dislocation has become commonplace for the generation of helically-phased beams [6, 7]. The fork diffraction grating, when illuminated with a Gaussian beam, for example from a single-mode fibre, produces the helical mode in the first diffraction order. This grating can also be used in reverse to couple light with a helical phase into a single-mode fibre [8]. Sequentially changing the dislocation in the fork allows a range of  $\ell$  values to be measured, but checking for  $N$  states requires at least  $N$  photons [8]. Recently it has been shown that two diffractive optical elements can

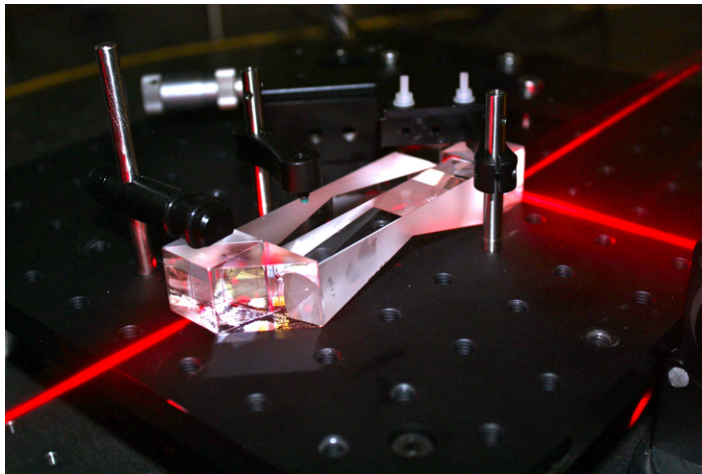


**Figure 1.** (a) Schematic of the robust odd–even OAM router (M, mirror; BS, beam-splitter; RP, right-angled prism; IP, inverting prism; PL, piezoelectric; A, output port A; B, output port B and PD, photo-diode). (b) and (c) illustrate the effect of the prisms on their own. It can be seen that the beams behind the two prisms are rotated by  $180^\circ$  with respect to each other. An inverting prism, like a Dove prism, has a mirror plane, indicated in green, around which any transmitted beam is flipped.

be used to transform OAM states into transverse momentum states. A lens can then separate the resulting states into a specified lateral position, allowing for the efficient measurement of multiple states simultaneously [9, 10]. In both of the above systems, however, the nature of a mode transformation means that the OAM of the light is changed during the measurement process.

A method to route OAM at the single-photon level was outlined by Leach *et al.* It is based on a Mach–Zehnder interferometer with a Dove prism in each arm [11]. When the two Dove prisms are orientated with respect to each other by an angle of  $\theta$ , there is a relative phase difference between the two arms in the interferometer of  $\Delta\psi = 2\ell\theta$  (figure 1(a)). In the specific case of  $\theta = 90^\circ$ , constructive interference will occur at one of the two output ports for all even  $\ell$ -valued states and then for odd  $\ell$ -valued states in the other output port. In principle, this routing can be achieved with 100% efficiency and with no loss of the input beam’s helical phase structure. Simultaneously maintaining the alignment of many such interferometers has proved technically challenging.

Preserving the structure of the input beam is important for many experiments, for example to demonstrate amplitude damping of Laguerre–Gaussian laser modes [12] and in the



**Figure 2.** Photo of the robust interferometer sketch in figure 1(a).

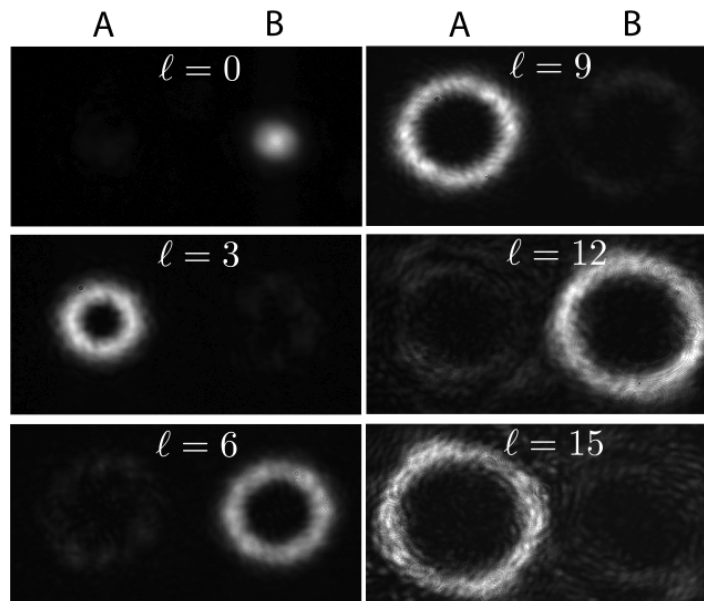
development of a linear optical CNOT gate for OAM [13, 14]. In each of these experiments interferometers similar to that outlined by Leach *et al* were used. Attempting to make this interferometric technique more robust, Slussarenko *et al* reconfigure the Mach–Zehnder interferometer as a Sagnac interferometer [15]. This approach reduces the number of degrees of freedom within the interferometer, but requires additional polarization optics.

In this paper we present a compact, robust interferometer, removing many of the previously required degrees of freedom. The technique outlined by Leach *et al* requires that the beams transmitted through the two Dove prisms are co-linear at the output of the interferometer ( $BS_2$  in figure 1(a)). This alignment was previously achieved by the accurate positioning of the Dove prisms, mirrors and beam splitters with the interferometer [11, 12, 14]. A Dove prism has a mirror plane, around which the transverse cross section of any transmitted beam is inverted (figure 1(b)). Considering these mirror planes, a different approach to alignment can be taken. The intersection of the mirror plane in each Dove prism defines the path an input beam is required to take for the two beams to be co-linear at the output ports. Hence, by controlling the direction of the input beam, the interferometer can be aligned without precise alignment of any of the constituent components. The requirement is that the whole beam is always contained within the aperture of the prisms. An additional fine control for the path length is required such that the integer  $\ell$  states completely constructively, or destructively, interfere at the output ports of the interferometer.

In our approach we use specially manufactured inverting prisms, previously discussed by Leach *et al* [16]. The beam enters and exits each inverting prism at an optical face perpendicular to the optical axis. This allows for the introduction of right-angled prisms, as opposed to mirrors, meaning all optical surfaces can be bonded into a single, robust unit, shown in figure 2.

We demonstrate the case of  $\alpha = 90^\circ$ , for the routing of states with even and odd  $\ell$  values. The intersection of the mirror planes of the prisms  $IP_1$  and  $IP_2$  (see figures 1(b) and (c)) was found through the use of external coupling mirrors,  $M_1$  and  $M_2$  in figure 1(a).

In our experimental implementation of the compact interferometer, we use a linearly polarized Gaussian beam with a complex phase profile  $\exp(i\ell\phi)$  as our basis set of OAM. These modes were prepared by expanding a HeNe laser beam to illuminate an  $\ell$ -fold fork diffraction grating, encoded with only phase information on a spatial light modulator (SLM)

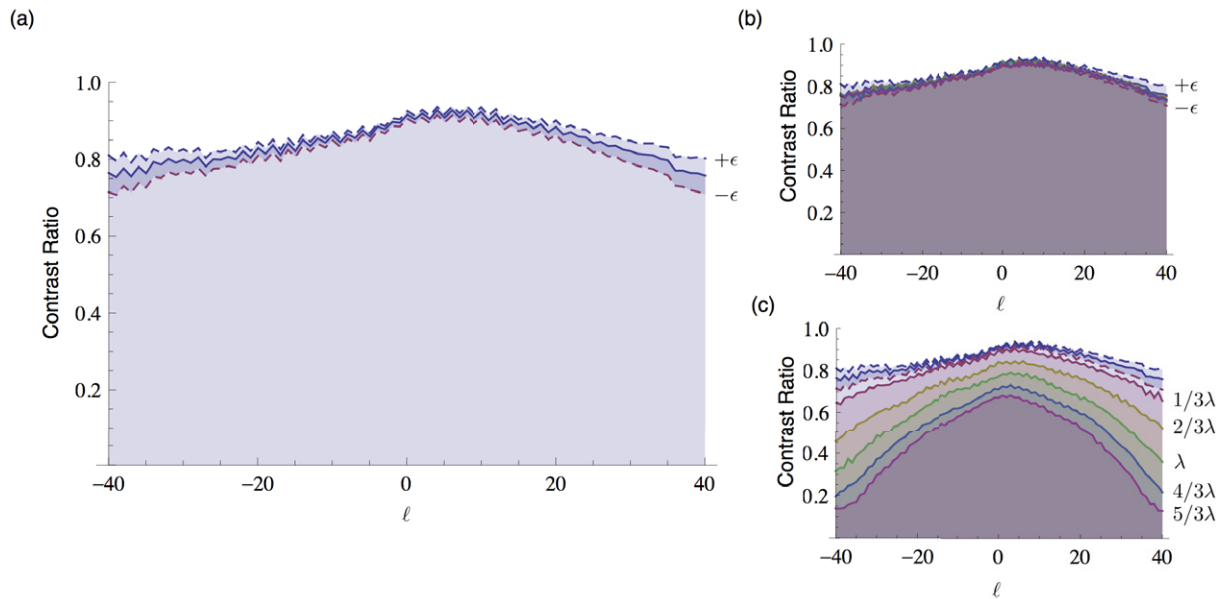


**Figure 3.** The interferometer routing odd and even helically-phased light beams into ports *A* and *B*, respectively. For demonstration purposes we also encode intensity information to the hologram pattern to generate the LG modes shown above.

as this gives a high diffraction efficiency over all  $\exp(i\ell\phi)$  modes. To allow the precise control of constructive and destructive interference in the interferometer, the second right-angled prism,  $RP_2$ , was attached to a piezoelectric mount, giving fine control over the path difference within the interferometer. When the input mode is correctly aligned, the routing of odd and even  $\ell$ -valued LG modes into the output ports *A* and *B*, respectively, is achieved. Experimental results are shown in figures 3 and 4. The large number of degrees of freedom previously required has been reduced to five degrees of freedom, position  $(x, y)$  and tilt  $(\alpha, \beta)$  of the input beam, and a small adjustment of the path length difference in the interferometer.

To test the performance of the interferometer in separating odd and even  $\ell$ -valued  $\exp(i\ell\phi)$  modes, the intensity of the interference pattern in one of the output ports was monitored with a photodiode, while the path length of the interferometer was oscillated back and forth between constructive and destructive interference by driving the piezoelectric stage. The ability of the router to separate the input modes can be characterized by the fringe contrast [17]. The contrast is defined as  $(v_{\max} - v_{\min}) / (v_{\max} + v_{\min})$ , where  $v_{\max}$  and  $v_{\min}$  are the measured maximum and minimum voltages from the photodiode.

In our assessment of the performance of our interferometer we recognize that a potential limitation is imposed by the purity with which  $\exp(i\ell\phi)$  modes can be produced by the SLM and associated optics. SLMs are themselves a source of aberration in the optical system since their flatness is typically specified at one or two optical wavelengths. In this experiment we use the central region of an optically-addressed SLM, which is typically flatter than the alternative technology, normally liquid crystal on silicon. Despite using the flattest of our SLMs and careful alignment of the associated optics it is likely that residual aberrations will lead to a degradation in the performance of the interferometer, especially at high values of  $\ell$ .



**Figure 4.** The contrast measured over the OAM mode range of  $\ell = -40$  to  $\ell = 40$ , (a) without and (b) with, additional aberrations. The error in the measured contrast ratio is determined by considering the standard deviation of the voltage received when no light is incident on the photodiode. In (b) and (c) the effect of aberration on the contrast is shown for astigmatism and trefoil, respectively. The magnitude of aberration was determined by the total phase height variation across the diameter of the beam incident on the SLM. The same magnitude of aberration was applied in the form of astigmatism and trefoil, with an approximate value of  $1/3\lambda$ ,  $1/3\lambda$ ,  $2/3\lambda$ ,  $\lambda$ ,  $5/3\lambda$  and  $4/3\lambda$ , where  $\lambda$  is the wavelength of the incident light.

To investigate the effect of aberrations we scan the input modes over the range of  $\ell = \pm 40$  for various degrees of additional astigmatism and trefoil aberrations which we encode on the SLM. For no additional aberrations, we observe that for low values of  $\ell$  the contrast is in the region of 90%, falling to around 75% at  $\ell = \pm 40$  (see figure 4). At these higher values of  $\ell$  we note that trefoil aberration (figure 4(c)) has significantly more impact on the contrast than astigmatism (figure 4(b)). When an aberration is added to a beam carrying OAM, the beam is no longer a single  $\ell$  valued mode and is instead a superposition of different  $\ell$  valued modes, centred about the original value. As astigmatism is two-fold rotationally symmetric, the result in a superposition containing further modes with  $\Delta\ell = \pm 2$ , resulting in no observable degradation of the contrast obtained from the even/odd separation (see figure 4(b)). In comparison, trefoil aberrations are three-fold rotationally symmetric, resulting in superposition containing further modes with  $\Delta\ell = \pm 3$ , and hence causing a noticeable degradation in the contrast of the even/odd separation.

In summary, we have developed a robust odd-even OAM router with a reduction in the number of degrees of freedom to simply that of the input light beam. A change in the orientation angle  $\alpha$  allows the routing of beams with different  $\ell$  values into the two output ports [11]. Cascading multiple interferometers, with coupling mirrors between each stage, would allow the



routing of a beam into one of many output ports where each corresponds to a different  $\ell$  value of the input beam [11]. The routing of an OAM beam with the preservation of the helical structure is useful for data processes and transfer, as multiple gates can be used sequentially to carry out more complex operations on a input beam.

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