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## Observation of chromatic effects near a white-light vortex

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**Abstract.** Using a spatial light modulator to modify the phase of a light beam we create a spatially coherent, white-light beam containing an optical vortex. All the spectral components are helically phased; hence the beam carries an orbital angular momentum that is an integer multiple of  $\hbar$  per photon. A low-dispersion prism, positioned after the modulator, ensures that the vortices associated with each spectral component are co-axial. In addition, deliberate introduction of slight spectral dispersion means that the vortices associated with each wavelength no longer overlap. Subsequent examination near the beam axis reveals the chromatic effects predicted by Berry (2002 *New J. Phys.* **4** 66; 74).

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### 1. Introduction

Phase dislocations or singularities are found throughout optical physics [1, 2, 20]. They arise naturally within diffraction patterns, speckle fields and various natural optical phenomena. The spectral patterns in the vicinity of the phase singularities which arise from white-light sources have been analysed and observed [3–8]. More recently, studies into the colours of white-light phase singularities have revealed dramatic effects in the region of the dislocation [9, 10].

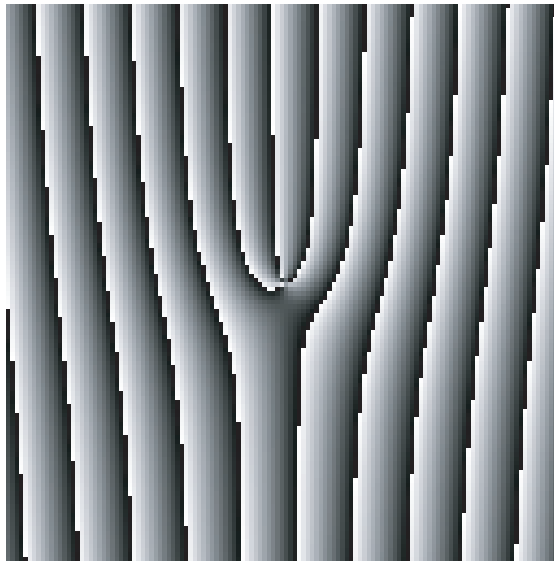
A screw dislocation, or optical vortex, is one type of singularity that runs parallel to the beam axis [11–14]. The phase around the vortex is given by  $\exp(il\phi)$ , where  $l$ , typically  $\pm 1$  in natural phenomena, can in fact be any integer value. The associated phase-fronts are inclined with respect to the beam axis resulting in an azimuthal component to the momentum flow and hence an angular momentum in the direction of propagation. For cylindrically symmetric beams, where the vortex is collinear to the beam axis, the phase-fronts are helical and the ‘orbital angular momentum’ is  $l\hbar$  per photon [11]. This orbital angular momentum is independent of the light’s polarization state and in recent years has been the subject of many experimental and theoretical studies [15]. Although seemingly a property of the beam’s phase structure it is worthwhile to emphasize that the orbital angular momentum is a measurable property of each photon within the beam [16, 17].

## 2. Method

Helically phased beams can be generated in a number of ways, perhaps the most adaptable of which is the use of spatial light modulators that modify the phase structure of a transmitted or reflected beam [18]. A modulator used in this way is frequently termed a computer-generated hologram and is equivalent to a diffraction grating, which gives a specific beam structure in the first diffraction order. Although, in principle, such an element can be blazed to diffract all the incident energy into the first-order, in practice, the desire to use a wide range of wavelengths and other imperfections in the modulator limits the diffraction efficiency into the chosen order. Consequently, it is usual practice to design the element to give angularly displaced orders so that the desired order can be selected using a spatial filter positioned in the Fourier plane of the modulator.

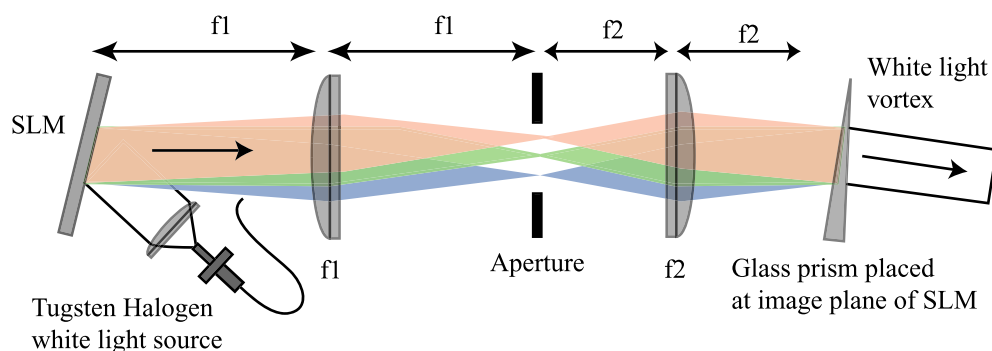
For producing helically phased beams, the most common hologram design is a forked diffraction grating with an  $l$ -pronged dislocation on the beam axis (see figure 1) [12, 14]. When illuminated with a Gaussian beam, the first-order diffracted beam is a close approximation to a Laguerre–Gaussian beam with the desired  $\exp(il\phi)$  phase structure. Although ideal for transforming monochromatic laser beams into ones carrying orbital angular momentum, when applied to broad-band sources the spectral components are angularly dispersed. We show that this can be corrected by imaging the plane of the modulator on to a prism that introduces the opposite angular dispersion.

Figure 2 shows the experimental configuration used for producing the white-light vortex. A 200 W tungsten halogen bulb is focused into a single-mode optical fibre, the output from which is collimated with a 30 mm focal length lens to give a 10 mm diameter white-light beam with a high degree of spatial coherence. The collimated beam is incident on a nematic liquid-crystal spatial light modulator that can be addressed to give the desired hologram (Hamamatsu). The diffracted light is collected and focused with a 600 mm lens, a spatial filter positioned in the Fourier plane of which allows the first-order to be selected. A subsequent 250 mm focal length lens recollimates the light and forms an image of the hologram in the plane of a small-angle prism. The number of lines on the hologram is adjusted such that, allowing for the relay magnification, the angular dispersion introduced by the hologram is exactly compensated by the prism. The result is a white-light beam with each spectral component having helical phase-fronts about a common beam axis.



$l=3$  hologram

**Figure 1.** A typical holographic pattern for producing a beam with helical phase-fronts. For plane-wave illumination, this example would give an first-order diffracted beam with an azimuthal-phase term.

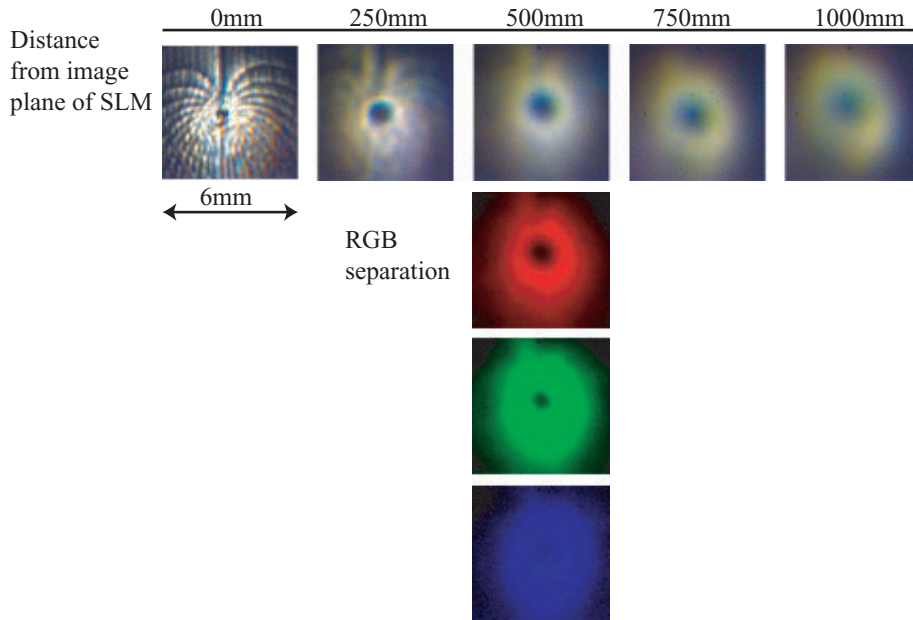


**Figure 2.** The experimental configuration used for producing the white-light vortex and subsequent investigation into chromatic effects near the beam axis.

### 3. Results

Figure 3 shows images of beam cross-sections at various distances after the prism; the RGB separations from the colour camera show that their spectral deviation is well compensated. Despite the broad-band nature of the source, the orbital angular momentum is still precisely defined by  $l\hbar$  per photon. We note that the hologram and prism combination performs a similar transformation for orbital angular momentum as an achromatic quarter-wave plate would for spin angular momentum. Other methods where a birefringent crystal has been used to produce an incoherent light with an optical vortex have also been reported [19].

Although of interest as a white-light optical vortex, our primary motivation for generating such beams is to investigate experimentally the predicted chromatic effects that occur in the



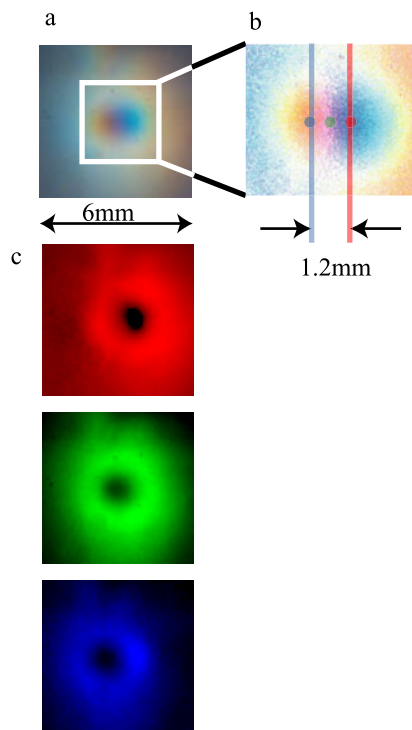
**Figure 3.** Image cross-sections of the white-light vortex beam recorded at various distances from the image plane of the spatial light modulator. The striations in the image plane arise from a residual intensity modulation within the spatial light modulator.

region of an optical vortex with slight dispersion between the wavelengths. As has been pointed out, this is typically the case when the vortices are a result of a natural optical phenomenon [9, 10]. However, since the vortices themselves are points of zero intensity, the predicted chromatic effects are extremely subtle and can only be observed in the cases of extremely high light intensity or better, by processing the resulting image to boost the intensity of the dark regions.

As perceived by the eye, the colour of a point within an image is an extremely complicated process. Even judging the colour of a light source is dependant on the spectral distribution of the light, the response of the eye's colour receptors and in the case of an extended scene the colour of the surrounding region. If this image is to be reproduced, then additional concerns are the printing pigments and the spectral properties of the light subsequently used to view the reproduction. In our case, we adopt the same algorithm as proposed by Berry [9, 10]. To record the image of the white-light vortex, we use a standard colour CCD with an RGB colour response approximately matching that of the eye. To reveal the chromatic detail of the dispersed vortex structure, we apply a colour correction such that at every pixel in the image, the RGB values are increased to make the largest of them fully saturated but maintaining their ratios. For a 24-bit colour image (8 bits per channel) this corresponds to

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} \Rightarrow \begin{pmatrix} R \\ G \\ B \end{pmatrix} / \max(R, G, B). \quad (1)$$

The action of this operation on an image is termed a 'chromascope'.

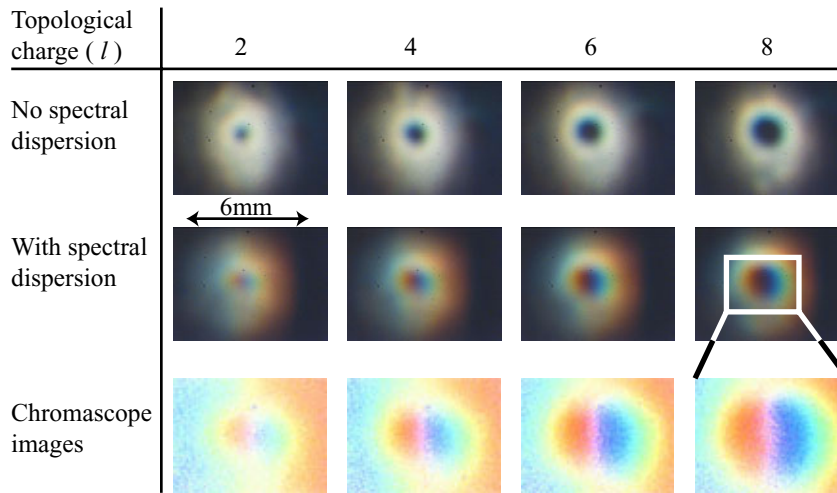


**Figure 4.** Image cross-section of the white-light vortex beam, where the various spectral components are no longer collinear. (a) Image as recorded by the camera, (b) the same image after the chromascope has been applied and (c) the RGB components of the image. The coloured dots in (b) mark the position of the red, green and blue vortices.

Figure 4(a) shows observed beam cross-section in the vicinity of a dispersed white-light vortex, and figure 4(b) the same image after applying the chromascope. We see that, rather than a characteristic intensity minimum, the vortex position is marked by a distinct chromatic pattern. As predicted by Berry we see a red–blue transition across the vortex separated by a narrow area of purple; specifically, there is no green. Figure 4(c) shows the corresponding images of the colour planes enabling the degree of spectral dispersion to be measured; the positions of the vortices are marked in figure 4(b) by the appropriately coloured dots.

#### 4. Discussion

Although the detailed form of these patterns have been modelled, the underlying principles which give rise to these chromatic effects can easily be understood. For any given wavelength component, the intensity at the vortex axis is zero but increases radially with  $r^{2|l|}$ . At larger radii, the beam intensity reaches a maximum, giving the characteristic doughnut intensity pattern. For a spectral dispersion small compared to the beam diameter, the high-intensity regions for the components are similarly positioned giving the appearance of a white-light doughnut. Close to the beam axis, the local intensity zeros in each spectral component mean that the ratio becomes spatially dependent, giving strong chromatic effects. Moving along the



**Figure 5.** Image cross-sections of the white-light beam with different value of topological charge, recorded in a plane where the uncompensated spectral separation of the red and blue vortices is 1.2 mm.

line joining the dispersed vortices, at every position, a particular wavelength component has zero intensity. At the extremes, the absence of blue or red light gives a red or blue bias to the perceived colour. In the centre, the absence of green light gives the characteristic purple line originally predicted. The absence of any green region over the entire beam cross-section is simply explained since it would require the red and blue vortices to be coincident, which they are not. By contrast, the complementary colours of cyan, magenta (purple) and yellow are seen at regions throughout the image. Moving away from the vortices and their associated intensity zeros means that the saturation of the perceived colours becomes less and the white-light appearance is restored. We note that although these chromatic effects do result from optical vortices, they are not a direct consequence of the angular momentum, but rather a result of the localized null intensity.

As discussed above, the exact form of the chromatic image depends on many factors, the most obvious being the colour balance of the white-light source itself. The main source of chromatic imbalance arises from the diffraction efficiency of the spatial light modulator. The modulator imparts a delay in the optical path rather than the phase itself, and consequently, the diffraction efficiency cannot be optimized simultaneously for all wavelengths. To counterbalance the red bias of the light source, we optimize the path delay in the modulator for the blue-end of the spectrum ensuring a resulting colour balance in the plane of the displaced vortices nearer to that of white light.

Figure 5 shows images of the white-light source with and without spectral dispersion for differing values of topological charge ( $l$ ). Again differing in detail, the images share the same universal characteristic, specifically a purple area in the middle and no green.

## 5. Conclusions

In this paper, we have shown how a diffractive optical element may be combined with a dispersion compensator such as a prism to form a white-light vortex with co-axial spectral

components, carrying an orbital angular momentum of  $l\hbar$  per photon. This optical arrangement performs an analogous transformation for orbital angular momentum as an achromatic quarter-wave plate does for spin angular momentum. By adjusting the dispersion compensation so that each wavelength component is no longer co-axial, the corresponding vortices are displaced. This allows us to observe and confirm the recently predicted chromatic effects that occur in the dark regions of the image.

### Acknowledgment

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