



Leach, J., Gibson, G.M., Padgett, M.J. , Esposito, E., McConnell, G., Wright, A.J., and Girkin, J.M. (2006) Generation of achromatic Bessel beams using a compensated spatial light modulator. *Optics Express*, 14 . pp. 5581-5587. ISSN 1094-4087

<http://eprints.gla.ac.uk/29109/>

Deposited on: 18th July 2012

Generation of achromatic Bessel beams using a compensated spatial light modulator

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Abstract: We report the creation of white-light, achromatic Bessel beams using a spatial light modulator and a prism to compensate for the dispersion. Unlike the Bessel beam created by a refractive axicon, this achromatic beam has a radial wavevector and hence an intensity cross-section which is independent of wavelength. The technique also lends itself to the generation of higher order Bessel beams with an on-axis optical vortex and associated orbital angular momentum.

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OCIS codes: (230.6120) Spatial light modulators; (999.9999) Optical vortices; (190.4370) Nonlinear optics, fibers.

References and links

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1. Introduction

Spatial light modulators (SLMs) are now widely being used as diffractive optical components for the generation of exotic beams. They are particularly popular for applications in holographic optical tweezers [1] or studies of optical vortices [2]. When comparing refractive and diffractive optical elements one recognizes that a refractive optic introduces a spatially dependent path delay, $\Delta(x, y)$, whereas a diffractive element introduces a spatially dependent phase delay, $\phi(x, y)$, making it inherently dispersive. For example, the focal power of a lens is set by the dispersion of the glass but the focal length of a Fresnel lens is proportional to the wavelength of the light. However, although an ideal lens is designed to be achromatic in terms of its focal length, and hence $\Delta(x, y)$, this is not necessarily the optimal form for other optical components.

Optical vortices follow the phase singularity along the axis of a beam with helical phase fronts characterized by a phase term $\exp(il\theta)$ that carries an orbital angular momentum of lh per photon [3]. The helical phase fronts can be created by passing a plane wave beam through a spiral phaseplate; a glass disc with a thickness, t , that is a function of azimuthal angle $t(\theta) - t(\theta = 0) = \frac{\theta}{2\pi}(n-1)\lambda$, and such techniques have been used to generate such beams at both optical [4] and mm-wave frequencies [5]. However, when used away from the design wavelength these spiral phaseplates create beams with a non-integer value of l and an extremely intricate vortex topology [6, 7]. Ideally, for generating vortex beams, one would use an optical element that is achromatic in terms of the phase properties $\phi(x, y)$.

Bessel beams [8] are another beam type that are becoming increasingly of interest in areas such as optical tweezers [9] and interferometry [10]. The intensity cross-section of a zero order Bessel beam comprises a central bright spot surrounded by equally spaced rings. Although often termed "diffraction free" these beams are better understood as the circularly symmetric interference patterns formed by a distribution of plane waves directed along a cone in k -space. If the plane waves have an infinite aperture, the interference pattern too is of infinite aperture and retains a fixed form along the beam axis, i.e. is propagation invariant. For a finite radius, R , the interference pattern is only maintained over the region for which the plane waves overlap. This distance Z_{\max} is set by a combination of the cone angle and beam aperture, and approximated by $Z_{\max} \approx R k_0 / k_r$, where k_r is the radial component of the wavevector $k_0 = 2\pi/\lambda$ and equates to a cone half-angle in the k -space distribution of plane waves of $\sin^{-1}(k_r/k_0)$. The spacing between the rings and approximate size of the centre spot is given by $\lambda/2k_r$. These Bessel beams are frequently created using an optical element called an axicon, a circularly symmetric glass cone of refractive index n and exterior-angle α , giving a cone semi-angle for the interfering plane waves of $(n-1)\alpha = k_r/k_0$, i.e. $k_r = \alpha(n-1)k_0$. The refractive axicon therefore produces a Bessel beam where both size of the centre spot and radii of surrounding rings are proportional to wavelength and hence if used with a white-light will produce a beam with wavelength independent Z_{\max} but where the rings in particular are spectrally dispersed [11].

2. Diffractive optical components for beam generation

As an alternative to refractive optics, both spiral phase-plates and axicons are frequently implemented using an SLM configured as diffractive optical components, effectively forming a computer-generated hologram. Although in principle the SLM could be programmed

directly with the required phase profile, $\phi(x, y)$, imperfections in the linearity and pixilation of the device mean that the resulting beam would in effect be the superposition of several different diffraction orders. When used with a white-light source, this problem is further exacerbated by the fact that the phase change is wavelength dependent such that the weighting between different diffraction orders changes with wavelength. These limitations are overcome by the addition of a phase grating which introduces an angular deviation between the diffraction orders. This allows a spatial filter positioned in the Fourier-plane of the SLM to select the first-order diffracted beam. Each wavelength component of this first-order beam has the required phase structure irrespective of any non-linearity in the SLM. Unfortunately, the angular separation of this off-axis design makes the SLM inherently dispersive. Recently, this angular dispersion has been compensated by imaging the plane of the SLM to a secondary dispersive component such as a prism [12], or grating [13].

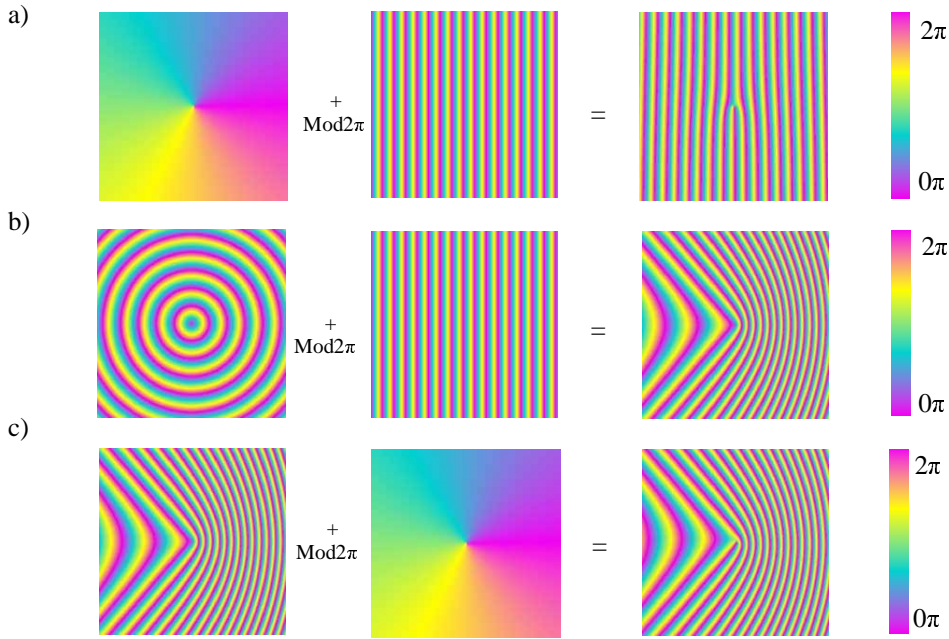


Fig. 1. The form of an off-axis phase hologram is obtained by the modulo 2π addition of the desired phase structure of the beam, $\phi(x, y)$ with that of a phase ramp with period Λ . a) shows the design of a Laguerre-Gaussian hologram where $\phi(\theta) = l\theta$ (in this case $l=1$), b) shows the design for a Bessel beam hologram where $\phi(r) = \beta r$ and c) shows the combination of the two to create a Bessel beam carrying orbital angular momentum.

To generate a Laguerre-Gaussian beam, the ideal phase form for the hologram is $\phi(\theta) = l\theta$. By contrast for a Bessel beam, the hologram is defined as $\phi(r) = \beta r$, where $\beta = k_r$ and hence is related to the exterior-angle of the glass axicon by $(n-1)\alpha \approx \beta/k_0$. Both of these holograms can be transformed into their off-axis equivalent by the modulo 2π of a phase grating of period Λ (Fig. 1), which introduces an angular deviation between the diffraction orders of $\sin^{-1}(\lambda/\Lambda)$. A Bessel beam created in this way is fundamentally different to that created by a refractive axicon. As discussed, for the axicon, the radii of the individual rings are proportional to λ . By contrast, for the diffractive optic, $k_r = \beta$, meaning that the size of the central spot and indeed all the surrounding rings, is independent of λ .

3. Experimental configuration

In this study we use a photonic crystal fibre (PCF) (NL-1.9-745, Crystal Fibre, Denmark) [14] pumped by a 100 fs pulsed Ti:Sapphire laser (Mai Tai, Newport Spectra Physics, USA), repetition rate 80 Hz, operating at 785 nm to generate a spatially coherent white-light supercontinuum source extending from 430-750 nm, see Fig. 2. The fibre is 2 m long, has a core diameter of 2 μm and zero dispersion wavelength of 745 nm. A Faraday isolator of 30 dB is used to minimize feedback to the laser and the laser beam polarization can be adjusted using the half waveplate placed between the Faraday isolator and the fibre.

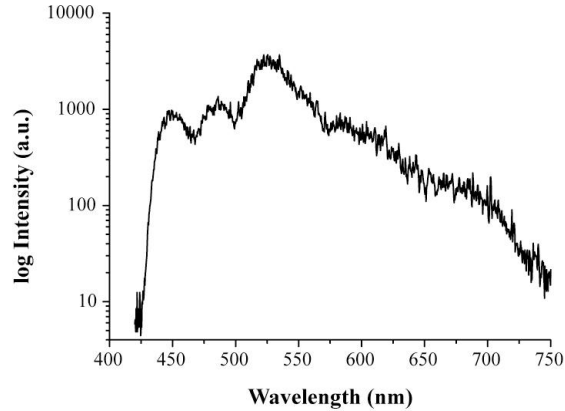


Fig. 2. Spectra of the white-light supercontinuum measured using an Ocean Optics B.V. (Netherlands) spectrometer.

An SLM (LC-R 2500 HoloEye GmbH, Germany) is programmed with an off-axis Bessel beam hologram and this plane is imaged onto a small angle (6°) prism to compensate for the angular separation set by the period, Λ , of the grating component of the Bessel beam hologram. A spatial filter positioned in the Fourier-plane between the SLM and the prism selects the first-order diffracted beams within the 430-750nm window. The combination of the SLM and prism effectively forms a phase-axicon $\phi(x,y)$ in the plane of the prism. See Fig. 3 for a schematic of the experimental setup. The resulting beam patterns were recorded on a colour camera (MicoPublisher 3.3 RTV, QImaging), where the colour images could be saved as three separate red, green and blue images to be analysed.

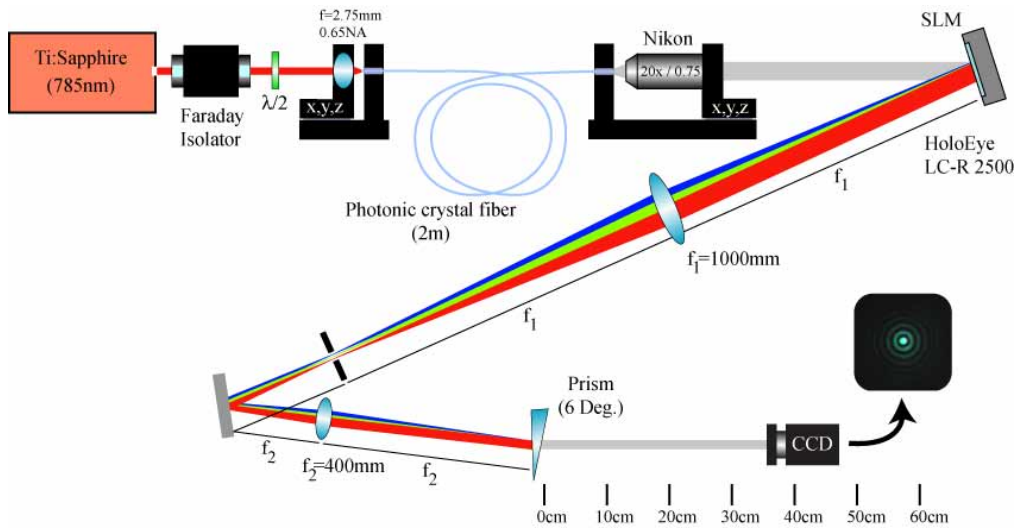


Fig. 3. Schematic of the experimental setup.

4. Generation of white-light achromatic Bessel beam

Figure 4(a) shows a series of cross sections of a white-light achromatic Bessel beam taken at various propagation distances from the prism. Figure 5(a) is an image of the $l=0$ Bessel beam at 20 cm from the prism but with enhanced brightness on the left-hand side to show the extent of the outer rings.

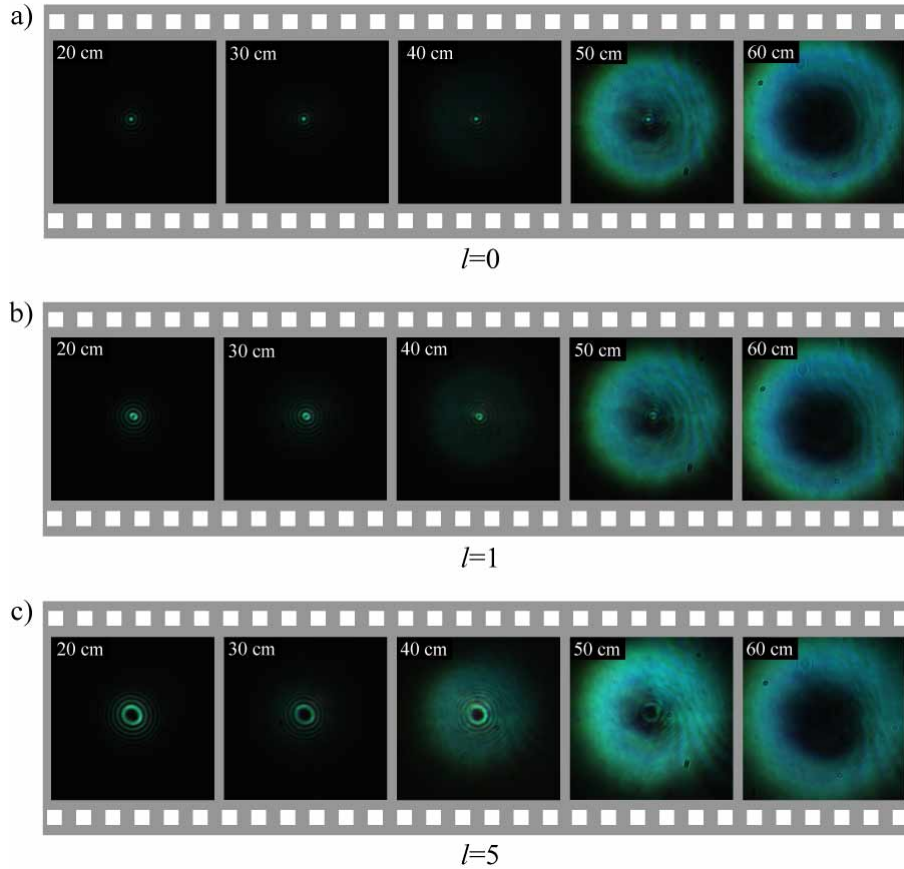


Fig. 4. A series of cross-sections of a white-light achromatic Bessel beam where a) $l=0$, b) $l=1$ and c) $l=5$, taken at various propagation distances from the prism. See accompanying movies, $l=0$.mov (744KB), $l=1$.mov (795KB) and $l=5$.mov (933KB).

As anticipated, the nature of the diffractive axicon means that, $k_r = \beta$ is independent of the wavelength and the resulting Bessel beam is fully achromatic with the various spot and ring spacings also being independent of wavelength. More surprising is the degree to which the pattern is stable with respect to propagation. From the equation $Z_{\max} \approx R k_0 / k_r$, one would anticipate a propagation distance for the green spectral component of the Bessel beam to be of order 0.5 m and that the blue spectral component would remain invariant for longer than the red. However, this geometrical approximation ignores the diffraction and aberrations in collimation of the various wavelength components. In our case we find that the white-light emitted from the PCF is intrinsically not perfectly achromatically collimated, the result being that the red spectral component of the beam diverges more quickly than the blue. Consequently, the effective radius, R , of the red beam exceeds that of the blue and hence has a larger propagation range than would have been anticipated from the geometric limit. Somewhat conveniently we find that this gives a white-light Bessel beam that not only has an intensity distribution that is the same for all wavelengths but also where all wavelengths have a similar maximum range of propagation. Figure 5(a) shows average of several line profiles of the red, green and blue colour channels recorded 20 cm from the prism using the CCD camera, clearly demonstrating that the three wavelength regions overlap.

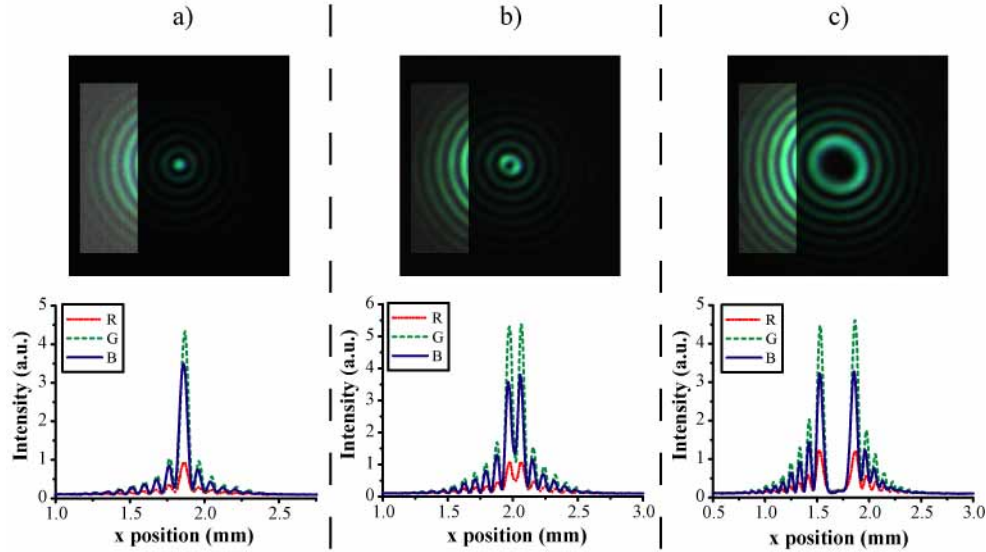


Fig. 5. Images of achromatic white-light Bessel beams taken at 20 cm from the prism (top) and the corresponding averages of several intensity line profiles across the Bessel beam, showing the overlap of the red, blue and green channels recorded on the CCD camera (bottom). a) $l=0$ Bessel beam, b) $l=1$ Bessel beam, and c) $l=5$ Bessel beam. The brightness has been boosted on the left-hand side of the images to show the extent of the outer rings.

5. Generation of white-light achromatic Bessel beam carrying orbital angular momentum

As with Laguerre-Gaussian beams, Bessel beams can possess optical vortices that are also characterized by an $\exp(il\theta)$ phase term. Such higher-order Bessel beams have been created by illuminating a conventional axicon with a Laguerre-Gaussian beam [14], but can also be created directly by adding an azimuthal phase term to the generating hologram. See Figs. 4(b) and 4(c) for examples of an achromatic white-light Bessel beam with $l=1$ and $l=5$ respectively. The resulting beam has no central bright spot but simply comprises of concentric rings, making the achromatic nature of this approach particularly significant if the white-light nature of the beam is to be realised.

Figures 5(b) and 5(c) show images taken 20 cm from the prism with the brightness enhanced on the left-hand side of the image, along with the average of several intensity line profiles for the three different colour channels of the camera, for an $l=1$ and an $l=5$ beam respectively.

6. Discussion and conclusions

Here we have reported a technique for the generation of exotic white-light beams, such as Laguerre-Gaussian or Bessel beams, where the desired aspect of their achromaticity is described in terms of their spatial phase structure, $\phi(x, y)$, rather than a path length $\Delta(x, y)$. The achromatic generation of Bessel beams is particularly relevant for higher-order beams where the desired interaction is with the rings rather than a central spot, since it is only for the achromatic beam where the radii of the rings is independent of wavelength. A further feature of these beams is an understanding of how the degree of collimation of the input beam to the phase axicon influences the extent which the beam remains propagation invariant. In that the red spectral component of a white light beam tends to spread more quickly than the blue, the overall effect is that all the spectral components tend to propagate a comparable distance.

Acknowledgments

This work is supported by the EPSRC, RCUK and the Royal Society of Edinburgh.