Digital holograms for laser mode multiplexing

Thandeka Mhlanga[a, b], Abderrahmen Trichili[c], Angela Dudley[a], Darryl Naidoo[a, b], Mourad Zghal[c] and Andrew Forbes[a, b]

[a]CSIR National Laser Centre, P.O. Box 395, Pretoria 0001, South Africa
[b]School of Physics, University of KwaZulu-Natal, Private Bag X54001, Durban 4000, South Africa
[c]University of Carthage, Engineering School of Communication of Tunis (Sup'Com), GreS'Com Laboratory, Ghazala Technopark, 2083, Ariana, Tunisia.

ABSTRACT

High-capacity data transmission has been implemented using single channel optical systems. This technique is limited and soon it will be unable to fulfill the growing needs for higher bit rate data transmission. Hence multi-mode transmission has been recently given attention as a potential solution to the current problems. In this context, we demonstrate a method of multiplexing laser modes using spatial light modulators (SLMs). In our proposed technique, we use Laguerre Gaussian (LG) modes, which form a complete basis set; hence multi-mode masks can be created by taking a linear combination of the LG modes. Since LG modes are characterised by two degrees of freedom, the azimuthal index ℓ and radial index ρ, this allows for multi-dimensional states. There are however some experimental challenges which include the sensitivity of the setup to misalignment, that leads to mode-coupling. It is also important that the injected modes ha a uniform power spectrum so that are weighted equally. The size of the multi-modes is highly dependent on the resolution of the SLM.

Keywords: spatial modes, multiplex, mode coupling

1. INTRODUCTION

Optical networks form a foundation of modern communications networks since the replacement of copper wires with optical fibres in the 1980's. This fibre technology has been based on single mode fibres (SMF), and due to the increasing demand in data transmission by a factor of approximately 10 every four years[1] as a result of the digital world we live in, the available capacity of the SMF will be limited in the near future. This limit in capacity is based on the Shannon capacity for non-linear fibre channels,[1] where the SMF cannot carry more than 100 Tbits s^{-1} of data. Optical transmission through SMF has been achieved through other optical properties of light, the dimension that has not yet been explored to transmit data is space. Spatial modes such as the Laguerre-Gauss (LG) modes,[2] have been studied as potential solutions to increase the bandwidth for optical communication through the process of mode division multiplexing (MDM),[3–5] which is based on using the LG modes as independent information carriers through SMFs, as they carry orbital angular momentum (OAM)[6] which is an unbounded degree of freedom. This OAM property of light has shown to be useful in various applications from manipulation of micro-particles[2] to successful classical and quantum free-space communication experiments.[6] There are certain limitations in using these modes for optical communication, such as mode coupling, which we look into, to improve the signal detection. It has been show that aberrated wave fronts result in a distorted modal spectrum.[7] We illustrate that by taking this into account, we can successful multiplex and demultiplexed the LG modes of two degrees of freedom in free-space, with minimized mode coupling.

Further author information: (Send correspondence to A. Forbes)
A. Forbes: E-mail:aforbes1@csir.co.za

Laser Beam Shaping XV, edited by Andrew Forbes, Todd E. Lizotte, Proc. of SPIE Vol. 9194, 91941B © 2014 SPIE · CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2062999

2. THEORY

The Laguerre-Gauss beams[2] form a complete basis set as a solution to the Helmholtz wave equation in cylindrical co-ordinates with a field function given by:

$$\begin{aligned} u_{\ell,\rho}(r,\theta,z) &= \frac{1}{\omega(z)}\sqrt{\frac{2\rho}{\pi(|\ell|+\rho)}}(\frac{\sqrt{2}r}{\omega(z)})^{|\ell|}\exp(\frac{-r^2}{\omega(z)})L_{\rho}^{|\ell|}[\frac{2r^2}{\omega^2(z)}] \\ &\times \exp[i\frac{kr^2}{2R(z)}]\exp(i\ell\theta)\exp(i\Phi(\rho,\ell,z)). \end{aligned} \quad (1)$$

These LG modes are characterized by two indices ℓ and ρ corresponding to the azimuthal and radial indices respectively. When ℓ=ρ=0, the mode simplifies to a Gaussian mode having a flat wave front. The wave front of these modes spirals around the beam axis creating a phase singularity,known as an optical vortex, where no energy nor momentum exist around that point. The simplest generation of these modes is through digital holography,[2] where the phase of the incoming Gaussian field is diffracted by a ℓ-fork diffraction grating into a LG mode of order ℓ, where ℓ corresponds to the number of fork dislocations which indicates the amount of OAM carried by these modes as shown in Fig. 1.

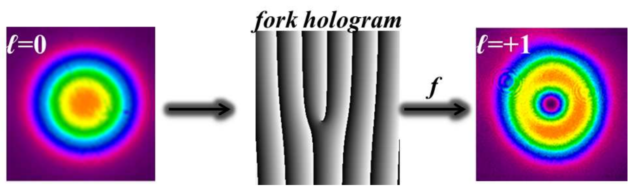

Figure 1. Generation of the LG mode of ℓ=+1 using a fork hologram.

These are not the only spatial modes that carry OAM, Bessel-Gauss (BG) beams also form part of the family of helical modes and they are similar to the LG modes in that they also carry OAM. They do however differ in their ability to reconstruct themselves after encountering an obstacle,[8] and they remain diffraction-free upon propagation for a finite distance.[9] The Bessel-Gaussian (BG) function in polar coordinates, is given by

$$E_{\ell}^{BG}(r,\Phi,z) = \sqrt{\frac{2}{\pi}}J_{\ell}\left(\frac{z_R k_r r}{z_R - iz}\right)\exp(i\ell\Phi - ik_z z)\exp\left(\frac{ik_r^2 z w_0^2 - 2kr^2}{4(z_R - iz)}\right), \quad (2)$$

where ℓ is the azimuthal index (a signed integer), $J_{\ell}(\cdot)$ is the Bessel function of order ℓ; k_r and k_z are the radial and longitudinal wave numbers. The initial radius of the Gaussian profile is w_0 and the Rayleigh range is $z_R = \pi w_0^2/\lambda$. The propagation constant k and the parameters k_r and k_z are related by $k^2 = k_r^2 + k_z^2$. These modes can be generated using a Durnin's ring-slit,[10] which can be implemented digitally[11] by modulating the input beam Fig. 2 (a) with a ring-slit surrounded by a checker board pattern in Fig. 2(b), which is simply an array of alternating sets of pixels that are out of phase by π allowing us to modulate the amplitude and phase of the incident beam to produce the desired mode in Fig. 2 (c).

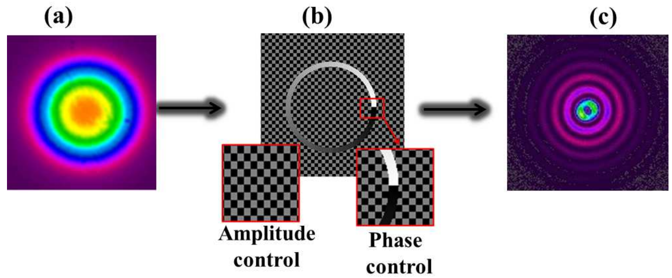

Figure 2. (a) Gaussian beam incident on (b) spiral hologram with inserts of the checker board and the ring-slice of azimuthal variation used to modulate the amplitude and phase of light respectively, generating (c) a BG mode of ℓ=1 at the far-field.

3. EXPERIMENTAL REALISATION

Using the experimental setup in Fig. 3 where a Gaussian beam Fig. 3 (a) was expanded and collimated using lenses L1 (f=35 mm) and L2 (f=750 mm) to approximate a plane wave front in Fig. 3 (b) onto SLM1. At SLM1 LG modes of radial index ρ and azimuthal index ℓ were generated and filtered through the $4f$ imaging system using an aperture and imaged onto SLM2, which we encode with varying azimuthal and radial indices. These indices were detected from the signal obtained at the focal plane of lens L3 (f=250 mm) on the CCD camera. Using the Arrizon *et. al* technique,[12] we generated holograms that modulate the phase and amplitude of the incident Gaussian beam with a flat wave front such that we could generate the superposition of the LG modes in Fig. 4 (a, b, c).

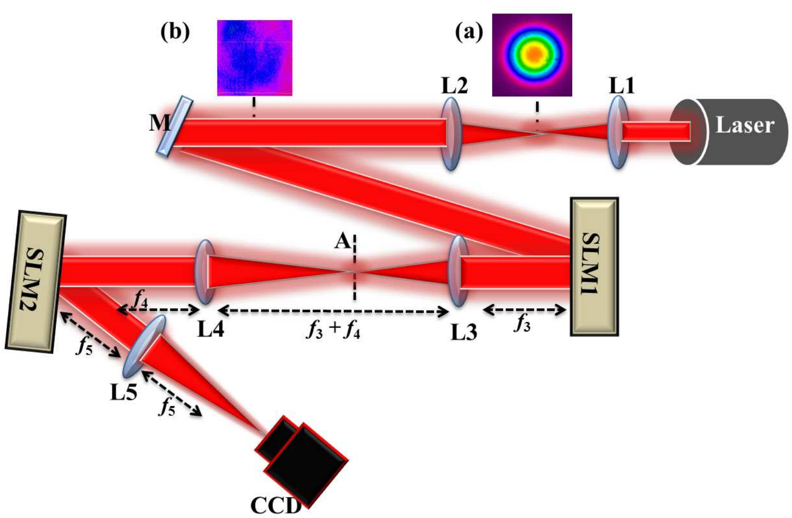

Figure 3. Schematic of the experimental setup where(a) is the Gaussian mode from the laser was expanded by a telescope to approximating a plane wave (b), where L-lens, M-mirror, SLM-spatial light modulator, CCD-camera.

Bessel-Gauss (BG) beams have shown to be useful in manipulation of micro-particles,[8] and in single photon experiments for high-dimensional entangled state,[13] and for reconstruction of quantum entanglement.[14] However the multiplexing of BG modes for optical communication purposes has not been investigated. Holograms encoded with multiple azimuthal phase components at varying radial distances generate superpositions of BG modes and can be implemented in the same experimental setup as in Fig. 3, where SLM1 was encoded with the annular ring holograms with the corresponding petal structures in Fig. 4 (d,e,f).

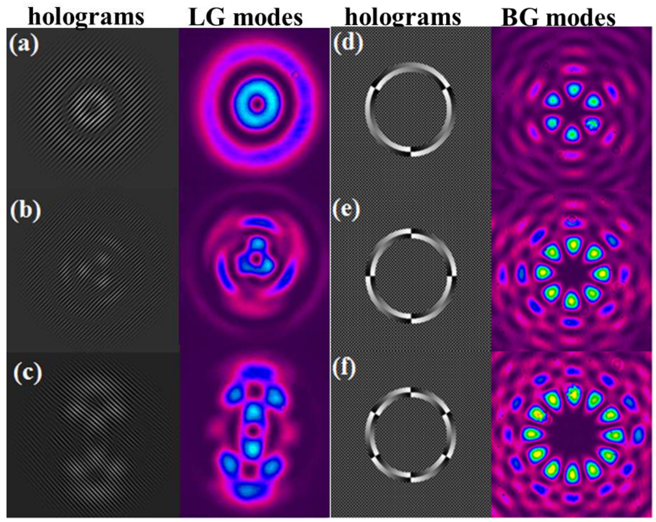

Figure 4. Holograms of ρ, ℓ modes of (a) ρ, ℓ=(1, 1), (b) the superposition of ρ, ℓ=(3, 4) and ρ, ℓ=(1, 1) modes as well as (c) the superposition of ρ, ℓ= (1, 1), (1, 3), (1, 5), (1, 7). BG holograms of (d) the superposition of ℓ=± 3 resulting into 6 petal structures, (e) ℓ= ± 4 resulting into 8 petal, and (f) ℓ=± 6 resulting into 12 petals.

3.1 Detection of the helical modes

Different detection tools have been introduced to extract the azimuthal and radial components of these modes, from the use of dove prisms separating the odd and even azimuthal indices,[2] to the use of refractive optical elements that transforms the azimuthal varying beam into a linear phase variation resulting in spots of light at ℓ dependent positions.[15,16] Similarly to the generation of LG modes using the fork hologram in Fig. 1, when a LG mode of order ℓ is pass through a fork diffraction grating of order $-\ell$, the output mode results in a Gaussian signal in the Fourier plane of a lens as seen in Fig. 5, referred to as the azimuthal decomposition technique.[17] This technique can be used to detect any arbitrary field $u(r, \theta)$ by expanding the field into the angular harmonics, $\exp(i\ell\theta)$:

$$u(r, \theta) = \sum c_\ell(r) \exp(i\ell\theta), \tag{3}$$

where c_ℓ is the r dependent coefficient and ℓ is the azimuthal index. We implemented this detection tool in our experimental setup in Fig. 3, where we generated an ℓ varying beam in Fig. 5(a) on SLM1 and encoded SLM2 with a $-\ell$ hologram Fig. 5(b), to observe a Guassian signal Fig. 5(c) on the CCD camera.

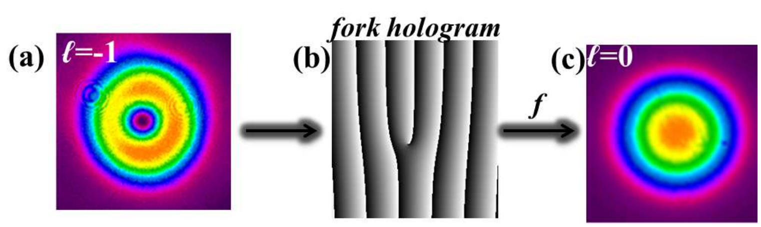

Figure 5. (a)LG mode of ℓ=-1 passing through (b) the azimuthal filter fork hologram with charge of ℓ=+1, (c) resulting in a Gaussian signal of charge ℓ=0.

There are detection limitations associated with these modes such as mode coupling. The contributing factor to this mode coupling is the spherical aberration of the Gaussian envelope which was corrected for, by generating a collimated flat wave front. The uneven power distribution of these modes since their sizes increase by a factor of ℓ, contributes to the uneven modal spectrum. To correct for the uneven power distribution we measured the power spectrum of these modes and normalised the power to the minimum modal power. The normalised coefficients were incorporated in the encoded holograms which modulated the intensity of the modes to be equal as shown in Fig. 6.

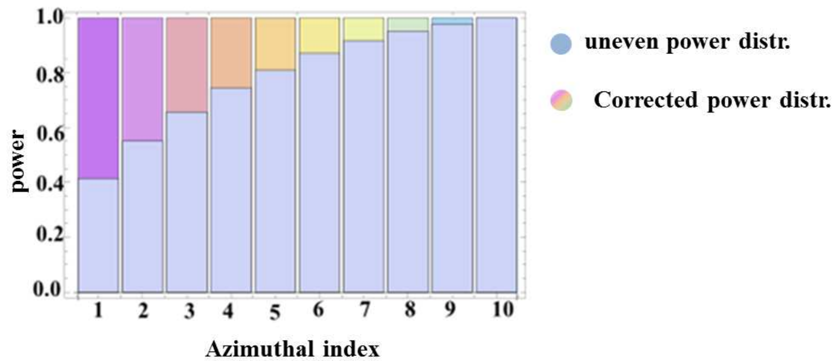

Figure 6. The uneven and corrected power spectrums.

Taking these factors into consideration we show that we can improve the mode coupling between the neighbouring ℓ modes in Fig. 7(a), to a pure spectrum of ℓ, ρ modes in Fig. 7(b), so that they become more efficient for optical communication.

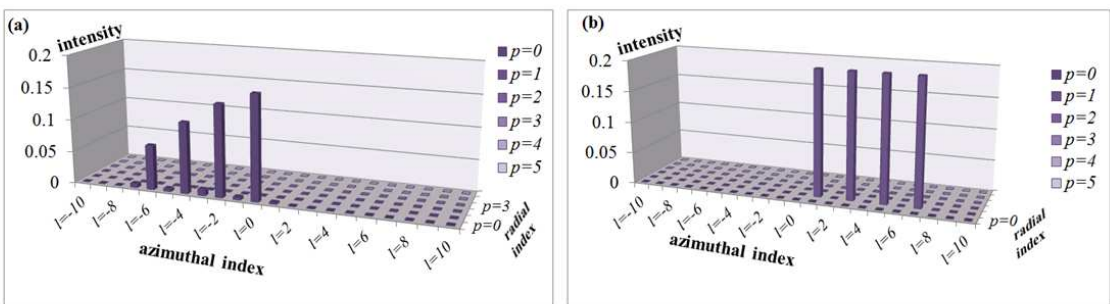

Figure 7. Azimuthal and radial spectrums of the multiplexed modes of (a)ρ=0, ℓ=1,3,5,7 without the power and wave front corrections and (b) ρ=1, ℓ=1,3,5,7 with the power and wave front corrections.

4. CONCLUSION

We have successfully multiplexed spatial modes of two degrees of freedom in free-space and have shown that by correcting the wave front and the uneven power distribution of the modes we can improve the mode coupling of multiplexed modes in free space. The next step will be to propagate these modes through a single mode fibre and incorporate different detection tools to improve our signal processing for optical communication applications.

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