Higher order Laguerre Gaussian, Hermite Gaussian and custom designed spatial intensity beam profiles are generated. These beams are further propagated through a confocal microscope for manipulation of submicron size particles. The same has been studied numerically to predict and verify the nature of higher order Gaussian modes when propagating through series of lens and other optical components.

I. INTRODUCTION

Generation of higher order modes are interesting because of the phase singularity and the characteristic intensity distribution. In particular, the dark region is very useful to manipulate particles in single beam optical traps [1]. Large number of vortices available in higher order modes could be appropriately controlled to manipulate sub-micron sized particles.

On the other hand propagation of such beams through a confocal microscope leads to lots of spatial and temporal changes to the beam. Hence, it needs to be understood while using such higher order Gaussian beams. It has been thought that Gaussian beam propagating through an ideal thin lens or a mirror with small curvature undergoes a change in parameters of the beam itself and the emergent field is related to the incident field by means of the transmission function of the lens. However, for highly divergent beams such assumption with Gaussian beam propagation breaks down. The reason is that the theory is based on paraxial approximation, which does not hold well in case of highly divergent beams [2].

The effect of introduction of a system of lenses is well understood using ABCD matrix approach, where the contribution of each component of the lens system is described as the cascaded operation. The calculations suggest that the higher modes of Hermite Gaussian (HG) and Laguerre Gaussian (LG) beams, irrespective of the order, converge to a single point and the spatial profile is lost, when focused tightly, at the focal plane.

The aim of the present work is two fold, viz., first to generate standard and custom designed spatial intensity profiles and second to propagate these profiles through set of lens system such that the same may be utilized for trapping submicron sized particles. We use Holoeye LC2002 spatial light modulator and program code written using MathCAD and LabVIEW to generate and propagate spatial profiles.

II. HERMITE AND LAGUERRE GAUSSIAN BEAM

Hermite-Gaussian beams are a family of structurally stable laser modes which have rectangular symmetry along the axis of propagation [3]. The equation for complex electric field distribution is defined as the product of a Gaussian function and a Hermite polynomial along with the phase term is given by [4]

\[
E_H(r, z) = E_{H0} \frac{w_0}{w(z)} H_p \left( \frac{\sqrt{2}r}{w(z)} \right) H_l \left( \frac{\sqrt{2}y}{w(z)} \right) 
\times e^{-\left(\frac{r^2}{w(z)^2}\right)} e^{-jkz-j\frac{kz^2}{2w(z)^2}-j\theta}
\]

(1)

Laguerre-Gaussian modes have circular symmetry along the propagation axis and carry an intrinsic rotational orbital angular momentum per photon. Due to this a refractive object placed along the propagation axis will experience a torque. This property makes it useful in the field of optical trapping and for driving micromachined elements with the help of light. The equation of amplitude for a Laguerre-Gaussian beam is given as
the depth of focus, spot size laser beams.

These images are addressed to a SLM to manipulate generated using software written using MathCAD and equation 2. These of the modes is determined by the values of Hermite Gaussian function of order \( p \) \( l \). The Hermite-Gaussian beam is a newer kind of beam that can be used to describe higher-order modes. It also allows analytical study of propagation and transformation of certain complex laser beams [5]. The higher order beams have larger widths than those of the lower order beams. The width of the beam is proportional to \( \omega(z) \) so that as \( z \) increases the intensity pattern is magnified by the factor \( \omega(z) / \omega_0 \) but otherwise maintains its profile.

\[
E_L(r, z) = E_0 \frac{w_0}{w(z)} \rho(z)^l L_p^l[\rho(z)^2] \cos(\theta)
\]

where, \( \rho(z) = \sqrt{2r/w(z)} \), \( r^2 = x^2 + y^2 \), \( R(z) = z + iz_R \) is the radius of curvature with \( z_R = \pi w_0^2 / \lambda \) being the depth of focus, spot size \( \omega(z) = w_0 \sqrt{1 + z/z_R} \) and \( p, l \) \( (= 0, 1, 2 ... \) \) are integers defining laser modes. \( H_p^l \) is Hermite Gaussian function of order \( p \) \( l \). The order of the modes are characterized by two integer numbers \( p \) and \( l \) called the indices. The shape of the beam profile is determined by the values of \( p \) and \( l \) in the \( x \) and \( y \) directions respectively. Hermite-Gaussian beam is a newer kind of beam that can be used to describe higher-order modes. It also allows analytical study of propagation and transformation of certain complex laser beams [5]. The higher order beams have larger widths than those of the lower order beams. The width of the beam is proportional to \( \omega(z) \) so that as \( z \) increases the intensity pattern is magnified by the factor \( \omega(z) / \omega_0 \) but otherwise maintains its profile.

IV. EXPERIMENTAL SETUP

We used a Spatial Light Modulator (SLM) to generate higher order modes. Appropriate angle of polariser, analyser and waveplates combinations produces required beam profiles. Output beam of a He-Ne laser (TEM\(_{00}\)) is expanded and allowed to fall on the SLM. Using conventional equations of LG and HG beams generalised spatial profiles of required beams are generated. These spatial profiles are addressed to SLM to generate the higher order Gaussian beam. These profiles are further collimated using telescope assembly.

Using the above setup different spatial profiles may be obtained. As of now we have obtained different higher order modes of Hermite and Laguerre Gaussian beams. The camera is moved along the propagation direction to get the profile at different distances from the lens L\(_5\). The SLM had been characterized with the laser, polarizer and analyzer before recording different modes.

It is interesting to note that the theoretical and experimental measurements agree very nicely for both HG\(_{00}\) and LG\(_{22}\) modes. Similar measurements are made for LG\(_{00}\) and LG\(_{22}\) modes. These results also agree well with the theoretical calculations. It should be noted here that the poor quality images are attributed to dark noise of the CCD and background noise in the laboratory. This could be avoided by taking appropriate precautionary measures.

After successful demonstration of generalized beam profiles, we proceed to obtain custom designed beam profiles. Few custom patterns like “A”, “Λ” and “star” as shown in the first row of Figure 6 are used. Two sets of images are obtained by controlling the polarizer angles. Second and third rows show the images obtained with 45° phase difference.

III. GENERATION OF HIGHER ORDER MODES

Using equation (1), we calculate the spatial profiles of Hermite-Gaussian beam for modes \( m = n = 0,1,2 \cdots 8 \) in Figure 1. The rectangular spatial profile of HG beams can easily be verified from the figures.

The higher order spatial profiles of Laguerre-Gaussian beams are generated by using equation (2) and demonstrated in Figure 2. The theoretically expected Laguerre-Gaussian beam profiles are - The circular symmetric nature of the profiles are evident from the figures.
V. CONCLUSIONS

The paper aims at developing a theoretical understanding of propagation of higher order Gaussian modes through a system of lenses using Q matrix calculation. A setup has been developed using SLM that generates desired profiles for higher order modes and the experimental results are in good agreement with the proposed theoretical results. Custom designed laser beam profiles are generated for use in various experiments. It is quite reasonable to believe that, these modes may be used as a tool for attaining objectives in experiments involving micron and submicron sized particle manipulation using optical tweezers.

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Figure 5: Using the experimental setup developed at SGSITS, Indore, Laguerre Gaussian modes are generated. The profiles obtained using equation (2) and the images shown in Fig. 2, are used. The generated profiles are recorded using CCD (magnified views are shown in some images for clarity).

Figure 6: Custom designed spatial beam profiles generated using the setup. The first row shows three templates. Second and third rows show the images recorded corresponding to a phase difference of 45°.