Effect of mechanical jitter on higher-order incoherent beam combination system

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***Abstract*—The spot size variation due to mechanical jitter is calculated for the Hermite Gaussian (HG) incoherent beam combination system. It is observed that the spot size increases with an increase in mechanical jitter and higher modes HG beams experience less mechanical jitter effect compared to lower mode HG beams.**

***Index Terms*—Hermite Gaussian, Thermal blooming, Optimum power, Incoherent beam combination.**

I. Introduction

High-energy lasers are utilized in various directed energy applications that require high-intensity beams [1]. Achieving higher power requires combining multiple laser beams in turbulent atmospheres. Higher-order Gaussian beams, such as Hermite Gaussian and Laguerre Gaussian, provide better efficiency in incoherent beam combination systems [2]. As these beams propagate through the atmosphere, they encounter various atmospheric effects. Additionally, mechanical instabilities in the laser system can also induce small, rapid, and random movements of the beam, collectively known as mechanical jitter. This phenomenon can cause the beam to deviate from its original path, leading to spot and intensity variations. Consequently, it is essential to investigate the effects of mechanical jitter on spot size and intensity variations. The mean irradiance profile of a Gaussian beam under random jitter is described in [3]. The effect of residual mechanical jitter has been analyzed on the Gaussian incoherent beam combination through various atmospheric turbulence in [4]. This paper examines mechanical jitter effects on spot size variations in different modes of Hermite Gaussian beams and intensity variations under varying mechanical jitter for incoherent beam combination systems.

II. Methodology and Results

A Hermite Gaussian beam is a type of higher-order Gaussian beam characterized by its rectangular symmetry and mode patterns described by Hermite polynomials. The intensity of Hermite Gaussian beam is given as [2]

$$I_{l,m} = I_0 \left[\frac{W_0^2}{W_x W_y}\right] H_m^2 \left[\frac{\sqrt{2}x}{W_x}\right] H_n^2 \left[\frac{\sqrt{2}y}{W_y}\right] \times exp\left[\frac{-2x^2}{W_x^2} - \frac{2y^2}{W_y^2}\right] \quad (1)$$

Where I_0 is the initial intensity of the HG beam, W_0 is the initial spot size, W_x and W_y is the spot size at the target along x and y axis. The spot size is defined by the second-order moments of the variance $\sigma_s^2(L)$ in the spatial domain given by [5]

$$\sigma_s^2(L) = \frac{2\int\int_{-\infty}^{\infty} s^2 I(x,y,L)dxdy}{\int\int_{-\infty}^{\infty} I(x,y,L)dxdy} \quad (2)$$

The spot size variation due to the diffraction of HG can be obtained by substituting the Eq. (1) into the Eq. (2) given by

$$\begin{aligned} W_x^2 &= W_0^2(2l+1)\left[1+\left(\frac{\lambda L}{2\pi W_0}\right)^2\right] \\ W_y^2 &= W_0^2(2m+1)\left[1+\left(\frac{\lambda L}{2\pi W_0}\right)^2\right] \end{aligned} \quad (3)$$

Where l and m are the azimuths and radial indices called beam modes along the x and y axis, λ is the wavelength, and L is the propagation distance. The mechanical jitter is a random fluctuation leading to small changes in the beam propagation direction and angle. It is the product of the deviation angle and propagation distance, which also follows a zero-mean Gaussian distribution for both the horizontal and vertical axes as follows [6]

$$\begin{aligned} f(r_x) &= \frac{1}{\sqrt{2\pi}\sigma_r} exp\left(\frac{-r_x^2}{2\sigma_r^2}\right), \\ f(r_y) &= \frac{1}{\sqrt{2\pi}\sigma_r} exp\left(\frac{-r_y^2}{2\sigma_r^2}\right) \end{aligned} \quad (4)$$

Where $r_x = \theta_x L$ and $r_y = \theta_y L$ denote displacements along the horizontal and vertical axes respectively. θ_x and θ_y represent the deviation angles along the horizontal and vertical directions respectively. Correspondingly, $\sigma_r = \sigma_\theta L$ denotes the standard variance of r_x and r_y and σ_θ represents the standard variance of θ_x and θ_y. The statistical averaging results for HG beams at different positions can be expressed as follows

$$\langle I_{l,m}(x,y,L)\rangle_{jitter} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I_{l,m}(x-r_x, y-r_y, L) f(r_x) f(r_y) dr_x dr_y \quad (5)$$

By substituting Eq. (1) and (4) into (5), the intensity of the HG beam including jitter is obtained. Similarly, the spot size under mechanical jitter can be calculated using (2), (4) and (5) given by

$$\begin{aligned} W_{x_{jitter}}^2 &= W_0^2(2l+1) + 4\sigma_r^2 \\ W_{y_{jitter}}^2 &= W_0^2(2m+1) + 4\sigma_r^2 \end{aligned} \quad (6)$$

To observe the effect of the Hermite Gaussian beam on incoherent beam combinations 19 HG beams and a collimated

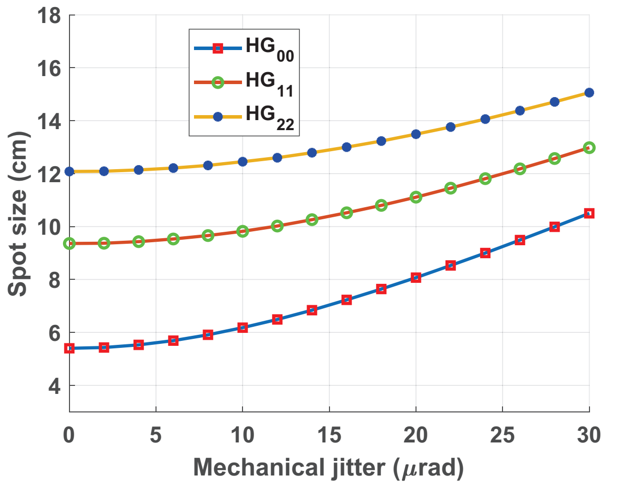

Fig. 1: Spot size of various HG modes with mechanical jitter

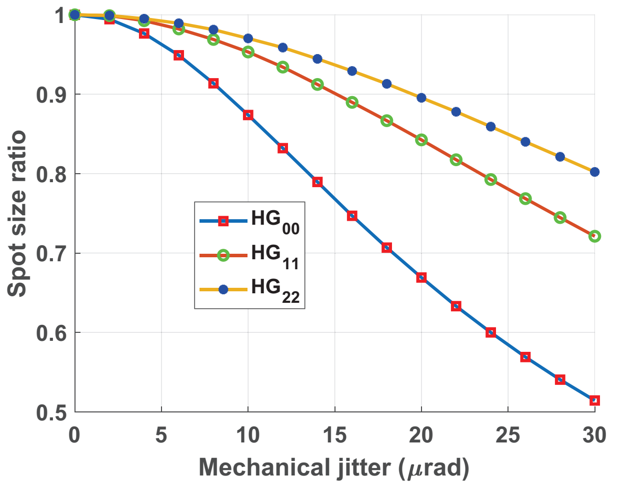

Fig. 2: Spot size ratio of various HG modes with mechanical jitter

beam directing mechanism are utilized [2]. The combined intensity including the jitter effect is given by

$$I_{com} = \sum_{i=1}^{19} I_{l,m}(x, y, L)_{jitter} \quad (7)$$

To calculate the spot variation due to jitter and the combined intensity of the Hermite Gaussian beam at the target an HG beam with an initial width $W_0 = 5\ cm$ and a propagation distance $z = 3\ km$ is considered. To determine the intensity at the target, a grid matrix (241×241) was formed with a step size of 0.5 cm by varying the x and y dimensions from -60 cm to 60 cm.

The spot size variations of different modes of Hermite Gaussian beams are shown in Fig. 1. As mechanical jitter increases, there is a corresponding increase in spot size across all modes of HG beams. This effect is further elucidated by examining the spot size ratio, as shown in Fig. 2, which denotes the ratio of spot size with and without the inclusion of mechanical jitter. Interestingly, it is observed that the spot size ratio decreases less rapidly in higher modes of the HG beam compared to lower modes. This suggests that the higher modes of HG beams are less affected by mechanical jitter, indicating that they experience less broadening under jitter compared to their lower mode counterparts. This phenomenon can be attributed to the distribution of higher modes across multiple lobes, where the individual shifting of lobes has a comparatively lesser impact on the effective spot size of the HG beam. The combined intensity variation of the HG beam in different modes due to jitter, as depicted in Fig. 3, it becomes evident that the intensity of the combined beam deteriorates with higher levels of mechanical jitter across all modes of the Hermite Gaussian beam.

III. Conclusions

In this paper, the effect of mechanical jitter on various modes of the Hermite Gaussian beam is thoroughly analyzed. Spot size and intensity variations of the 19-beam incoherent beam combination system are calculated in response to mechanical jitter. It is found that spots become larger with an increase in jitter, and intensity values decrease accordingly. Additionally, It observed that higher modes of the Hermite

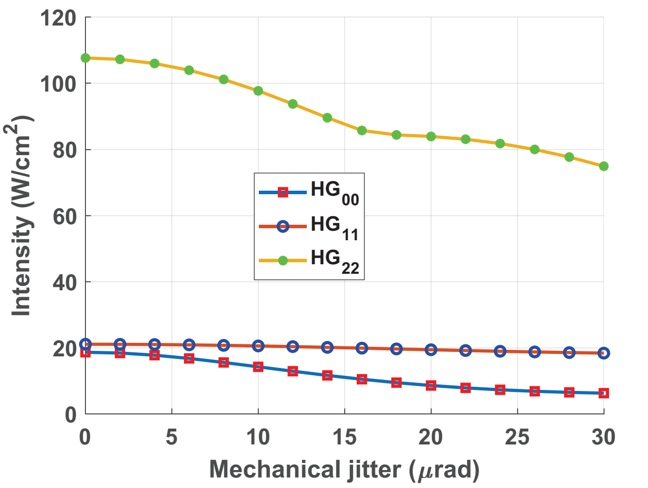

Fig. 3: Combined intensity variation of various modes of the HG beam

Gaussian beam exhibit lower sensitivity to mechanical jitter compared to lower modes. This insight underscores the importance of understanding the effects of mechanical jitter on beam characteristics of HG beam, particularly in complex beam combination systems involving multiple modes and beams.

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