



# Spatial Generation of Gauss Beam Array for Photonic Applications

*Fotonik Uygulamalar için Gauss Işın Dizisinin Mekansal Üretimi*

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## Abstract

In this paper, an alternative experimental method has been proposed in relevant to the generation of Gauss beam array. For this purpose, the light beams have been modeled based on the diffraction of a plane wave by an array of Gaussian apertures and implemented accordingly. Spatial generation of the Gauss beam array has experimentally been performed by the use of Spatial Light Modulator (SLM). The produced light beams have been recorded by a Charge Couple Device (CCD) detector with a large field of view and the profile evaluations of monitored beams are done. Moreover, theoretical calculations have been verified with empirical observations. With this proposed new beam shaping method, it can make it possible to generate and control the Gauss beam array in real-time for many high throughput photonic applications such as optical communications and biophotonics.

**Keywords:** Beam shaping, Gauss beam array, Optoelectronics, Photonics

## Öz

Bu makalede, Gauss hüzmeye dizisinin üretimi için alternatif deneysel bir yöntem önerilmiştir. Bu amaç doğrultusunda, ışık hüzmeleri düzlem dalgalanının Gaussian açıklık dizisinden kırılımına göre modellenmiş ve buna göre elde edilmiştir. Gauss hüzmeye dizisinin uzaysal üretimi Uzaysal Işık Modülatörü (SLM) kullanılarak deneysel olarak gerçekleştirilmiştir. Üretilen ışık hüzmeleri geniş görüş açılı bir CCD dedektörü tarafından kayıt edilmiş ve gözlemlenen hüzmelerin profil değerlendirmesi yapılmıştır. Buna ek olarak teorik hesaplamalar deneysel gözlemlerle doğrulanmıştır. Önerilen bu yeni hüzmeye şekil üretme yöntemi ile Gauss hüzmeye dizisinin üretilmesi ve gerçek zamanlı kontrolü, optik haberleşme ve biyofotonik gibi yüksek kazançlı fotonik uygulamaları için mümkün hale gelebilir.

**Anahtar Kelimeler:** Hüzmeye şekillendirme, Gauss hüzmeye dizisi, Optoelektronik, Fotonik

## 1. Introduction

In order to modify field patterns of light sources by use of beam shaping techniques have become a fast increasing trend in the last decade (Dickey and Holswade 2000). The acquired new type of light beams become a key technology in various fields ranging from the communication sector to the health sector. For instance, new types of light beam, such as Bessel light beam in intense and scattering media (blood, atmosphere, water), are more resistive and increase system performance, which is shown in the microscopy field (Fahrbach and Rohrbach 2012) (cell evaluation) and also free-space optical communication (increase of link efficiency) (Chen and Pu 2009). For the reconfiguration of the waves transmitted by a light source, different opto-mechanic methods have been proposed by O'Shea et al. (2003). Usually,

according to the requirements of these methods, the new types of the lens such as axicons are required to be designed and manufactured. However, this brings some restrictions in terms of resiliency and progression of application, e.g. for each application, redesign of optical components and renewal of opto-mechanical components are necessary. With the development of the modulators which controls the light electrically or magnetically as spatial, light modulation becomes resilience and easily executable (Neff 1990). These types of modulators provide flexible, changeable and real-time control possibility to users in many optic applications from diffraction to polarization. Due to these advantages in photonic applications, special attention appears to use SLM for beam generation (Chattrapiban et al. 2003, Ma et al. 2010, Wang 2013 et al., Eriksen et al. 2002). In terms of easy and low-cost production capabilities, most relevant beams used in industry (Silvennoinen 2013) are Gaussian beams which may be produced by light sources such as lasers and light-emitting diodes. A Gaussian beam

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is a mode of spherical mirror resonator and the method used for experimental generation of a Gauss light type is generally dependent on the determination of the light intensity of a laser, such as a He-Ne (operating at TEM<sub>00</sub> mode) output. The irradiance distribution of this emission is expressed by the Gaussian profile. The generation of Gauss beam array is generally realized by spatial filtering or by the use of diffractive micro-optical elements and by the systems that contain other optic components (Reynolds et al. 1989, Fruendt et al. 2008). These methods depend on the fabrication techniques and an optical design which may also bring some restrictions to end-users. Recently, the multi-spot array beam steering method has been proposed based on a diffractive optical design by SLM (Xiaodong et al. 2004). Furthermore, independent manipulation of Gauss beam array to trap micro-sized particles was suggested for biophotonics workstation by Ulriksen et al. (2008). Here we propose an alternative new method to implement multi Gauss beam array based on the diffraction of a plane wave by an array of Gaussian apertures. Light beams, generated by the testing apparatus that was set up with the help of SLM, were recorded by a CCD, and profile evaluations of the monitored beams were conducted. This beam multiplexing technique provides an efficient and high throughput illumination scheme to cover a wide field of the area (i.e. 9 cm<sup>2</sup>). With the proposal of this method, in the many photonics applications particularly in microscopy, it is possible to generate and control an array of Gauss light beams in real-time.

## 2. Material and Methods

In this section, we explain the proposed diffraction model for the generation of Gauss beam array by use of SLM. The gaussian light beam could be implemented on the diffraction of a plane wave by a Gaussian aperture. To realize this, transparency like material in the form of Gaussian distribution has to be employed. In this work, a special modulation mask was developed to acquire Gaussian aperture by changing SLM's pixels transmittance gradually. For the generation of light beams with this platform, all the active area of the SLM (~1920 × 1080 pixels, with a pixel pitch of 8 μm) is divided into small regions to produce individual Gaussian spots. For each Gauss light beam, a 37×37 array is used from the SLM pixels. The Gauss aperture function  $p(x, y) = \exp[-(x^2 + y^2)/w_0^2]$  is assigned to this area as a transparent modulation mask where x and y show the spatial coordinates on the SLM plane.  $w_0$  defines the  $1/e^2$  beamwidth of the function. By this method, with

all the pixels formed in the SLM, it is possible to generate a total array of 52×29 different Gauss beams. Diffraction patterns formed behind the SLM can be modeled based on the Fresnel diffraction of the plane wave by a Gaussian aperture. Within this approach, the incident plane wave is multiplied by the aperture function and propagates according to the Fresnel approach. If the aperture function is taken as a Gaussian function, the complex amplitude of the diffracted field can be evaluated by the convolution of the aperture function with an impulse response of free space, namely  $h(x, y) \approx \frac{j}{\lambda d} \exp(-jkd) \exp -jk \frac{x^2 + y^2}{2d}$ . After propagation a distance d in free space, the intensity pattern at detector plane can be found as the squared magnitude of the complex amplitude as,

$$I(x', y') = \frac{I_i}{(\lambda d)^2} \left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} p(x, y) \exp\left(\frac{-j\pi(x' - x)^2 + (y' - y)^2}{\lambda d}\right) dx dy \right|^2, \quad (1)$$

where  $I_i$  shows the intensity of plane wave travelling towards the SLM plane,  $k = 2\pi/\lambda$  is the wave number,  $\lambda$  is the wavelength,  $x'$  and  $y'$  defines transverse coordinates at the detector plane. By substituting the aperture function  $p(x, y)$  into Eq. (1) and rearranging, we obtain

$$I(x', y') = \frac{I_i}{(\lambda d)^2} \left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{\exp\left(\frac{-(x)^2}{w_0^2} - \frac{j\pi x^2 + 2j\pi x'x}{\lambda d}\right)}{\exp\left(\frac{-(y)^2}{w_0^2} - \frac{j\pi y^2 + 2j\pi y'y}{\lambda d}\right)} dx dy \right|^2. \quad (2)$$

Performing the integration by using the following rule (Gradstein et al. 2015)

$$\int_{-\infty}^{\infty} \exp(-p^2 x^2 \pm q(x)) dx = \exp\left(\frac{q^2}{4p^2}\right) \frac{\sqrt{\pi}}{p}, \quad (3)$$

Eq. (2) turns into

$$I(x', y') = \frac{I_i}{(\lambda d)^2} \left| \frac{\exp\left(\frac{2j\pi x'^2}{\lambda d}\right)}{\frac{4(\lambda d + j\pi w_0^2)}{\lambda d w_0^2}} \frac{\sqrt{\pi}}{\sqrt{\frac{\lambda d + j\pi w_0^2}{\lambda d w_0^2}}} \right| \left| \frac{\exp\left(\frac{2j\pi y'^2}{\lambda d}\right)}{\frac{4(\lambda d + j\pi w_0^2)}{\lambda d w_0^2}} \frac{\sqrt{\pi}}{\sqrt{\frac{\lambda d + j\pi w_0^2}{\lambda d w_0^2}}} \right|. \quad (4)$$

Using the property of  $e^a = |e(a + bj)|$  and rearranging Eq. (4), the intensity pattern is found as

$$I(x', y') = I_i \frac{w_0^4 \pi^2 (\lambda^2 d^2 + \pi^2 w_0^4)}{(\lambda^2 d^2 + \pi^2 w_0^4)^2} \exp\left(\frac{-2((x')^2 + (y')^2) \lambda d \pi^2 w_0^2}{\lambda d (\lambda^2 d^2 + \pi^2 w_0^4)}\right). \quad (5)$$

To make Eq. (5) more clear, we introduce a new formula  $w^2(d) = w_0^2 + \theta_0^2 d^2$ . In this equation  $w(d)$  defines the  $1/e^2$  half-beam width at detector plane,  $\theta_0$  refers to beam divergence angle and is given as  $\theta_0 = \frac{\lambda}{\pi w_0}$ . By this approach, Eq. (5) is simplified as

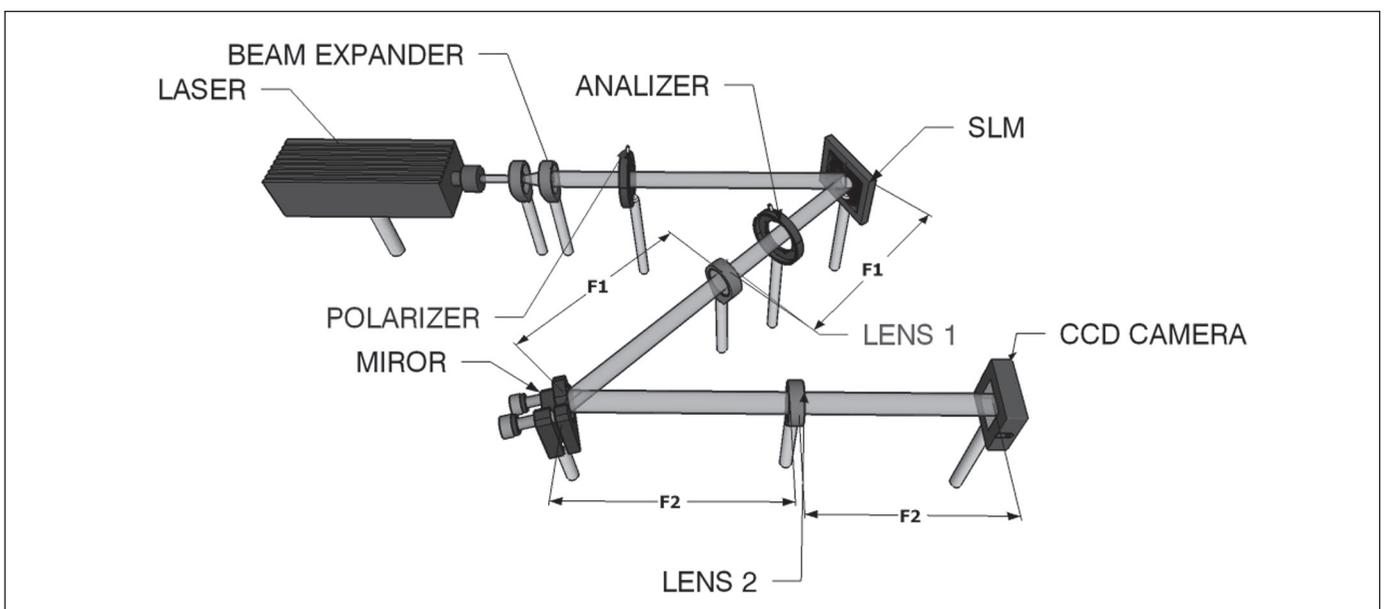
$$I(x', y') = I_i \frac{w_0^2}{w^2(d)} \exp\left[\frac{-2((x')^2 + (y')^2)}{w^2(d)}\right]. \quad (6)$$

It is seen from Eq. (6) that the diffraction pattern at the detector plane is a Gauss beam with beam size  $w(d)$ . For small  $d$ ,  $w(d) \approx w_0$ . This approximation is valid only in the Fresnel region. To determine the validity range of the Fresnel region, we can use the parameter known as the Fresnel number  $FN = (\pi/2)w_0^2/\lambda d$ . If  $FN > 1$ , then the Fresnel approximation is valid for selected detector distances. In our configuration, the detector (CCD) was placed very close to the back focal plane of the coupled lens system to provide  $FN > 1$ . The light intensity profile at this range is shaped as a Gauss beam. The aperture function  $p(x, y)$  made for a two dimensional single Gauss modulation mask was multiplexed as  $52 \times 29$  arrays to cover the whole surface of the SLM with the help of the LABVIEW program, and the result Gauss beam array mask was obtained. This mask was then loaded to SLM by an electronic circuit controlled computer and the experiment was performed.

### 3. Experimental Setup

The proposed system for the experimental generation of Gauss beam array with SLM is illustrated in Figure 1. SLM is a device that can be electrically controlled and the optical wavefront can be modulated according to amplitude and/or phase. In this experiment, an SLM which is the Holoeye PLUTO 6001 model was used. A light beam generated by a laser diode of 473 nm wavelength and 113 mW was expanded by a  $30 \times$  expansion capacity telescopic lens system.

The aim of this system was to illuminate the active area of the SLM with equal and uniform light intensity. Then the obtained plane wave was directed towards the SLM. In order to control the phase or amplitude modulation of the incoming wavefront, before and after the SLM a polarizer and analyzer were involved in the system, respectively. In order to increase the modulation efficiency of SLM, the angle between the light coming towards the SLM plane and the reflecting light after modulation is decreased as much as possible, down to  $8^\circ$ . One of the aims of this experiment was to generate Gauss beam array covering a wide area; thus, a large detector was selected for the evaluation of the generated beams and the active area of approximately  $9 \text{ cm}^2$ . The detector used was the KAI-29050 interline model CCD that is composed of multi-dimensional array sensors. In order to transfer the modulated light signal to the detector and increase the illuminated area of the projected light, a coupled lens system after the SLM was used. The proportion of the focal distances of these coupled imaging



**Figure 1.** Test apparatus for experimental generation of gauss beam array.

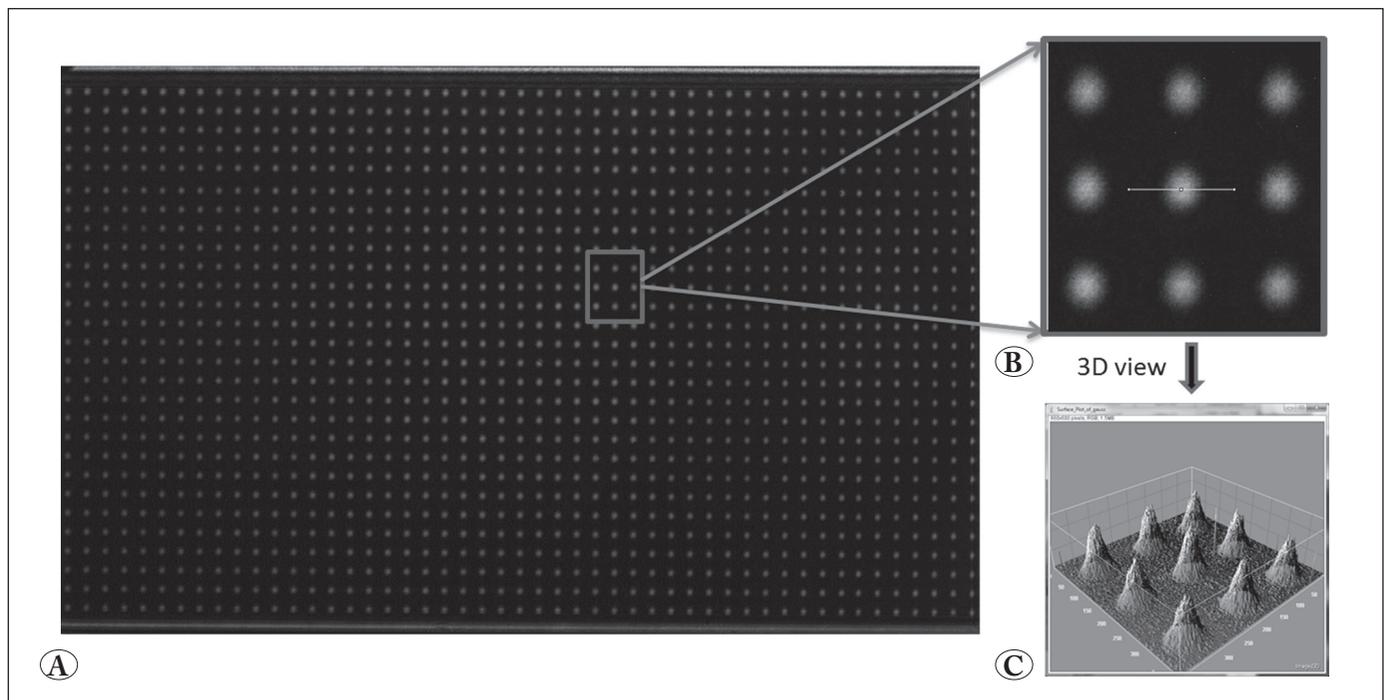
lenses was selected to reflect the SLM plane to the CCD plane at a maximum coverage rate ( $F2/F1=2.5\times$ ), thereby effectively using 90% of the active area of the detector plane. Finally, the light signals from the coupled lens system were transferred to the CCD by planar mirrors.

#### 4. Results

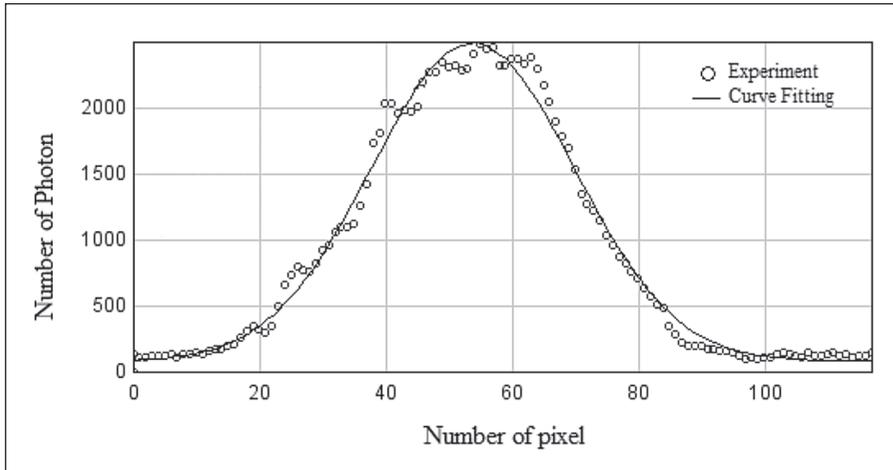
Figure 2 illustrates the intensity patterns of the Gauss beam array obtained by a wide field of view CCD. In this recorded image, Gauss light beams are patterned as an array. The generated light image reached the detector in transposition due to the reflection of the coupled lens system and the effect of the projection. The light intensity of the Gauss beams recorded onto the CCD plane seems quite good in terms of uniformity and even distribution. Since the SLM is a programmable device, it is possible to control each Gauss spot independently. The projected light pattern, with the assistance of the coupled lens system, constituted an enlargement of all active SLM areas with the ratio of  $2.5\times$  and thus, a rather wide illuminated area was provided to the CCD plane ( $9\text{ cm}^2$ ). The value of a single mask produced at the SLM plane was  $101\mu\text{m}$ . The diffracted light intensity after a  $2.5\times$  enlargement ratio of the coupled lens system can be calculated by Eq. (6), so beam size of a single Gaussian beam at the CCD plane is found to be  $w(d) = 252.5\mu\text{m}$ .

The experimental measurement of the Gaussian beam size at the CCD plane was  $w_e(d) = 250\mu\text{m}$ . Since the mechanical alignment of the CCD was done by a manual XYZ translation stage, the small difference between theory and experiment is acceptable and it can easily be eliminated by using a motorized piezo stage. Based on these results, we can conclude that this experimental observation complies with the theoretical calculations. The enlarged group of the nine images of the Gauss beam array and 3D intensity views can be seen in Figure 2B and C, respectively. Subsequently, a side profile light intensity distribution of the selected Gauss beam array from this group is illustrated in Figure 3. These images were recorded by an interface written with the LABVIEW program with the aid of a CCD. The integration time of the CCD is selected as 55 ms.

As discovered from the light intensity profile which is clearly seen from Figure 3, and from the maximum and minimum values of the distribution point of view, with curve fitting method, the shape is rather close to the Gauss profile. This trend is an approximate shape for the other beams as well. It is possible to increase the number of Gauss light beams to be generated by using the SLM pixel number effectively. In this case, different optimization techniques, such as spatial filtering, would be necessary to overcome some SLM based challenges (interpixel cross-talks, etc.). However, this is a subject of another experiment and study.



**Figure 2.** A) Recorded CCD image showing array of Gauss beam array B) with an enlarged view of selected Gauss light beam from this group and C) 3D intensity distributions.



**Figure 3.** Profile view of a Gauss light beam with curve fitting method.

## 5. Conclusion

In this article, an alternative new method of experimental generation of Gauss beam array with the aid of SLM was mentioned. The generated Gauss light beams were recorded with the help of a detector (CCD) and the monitored beams profiles were evaluated. The spots, generated by designed lens system modified to cover an area of 9 cm<sup>2</sup> and wide illumination area was provided. System was modeled based on diffraction of light by an array of Gaussian apertures and the experiment was implemented accordingly. Experimental observation complies with theoretical calculations. In the recorded images, the Gauss beam profile fits the Gaussian function, which also keeps its shape along the SLM plane in different directions. With this proposed method, it is possible to generate high throughput real-time controllable Gauss beam array which has potential applications particularly in biophotonics and free space optic communications.

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