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Graphic processing unit accelerated real-time partially coherent beam generator

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ABSTRACT

A method of using liquid-crystals (LCs) to generate a partially coherent beam in real-time is described. An expression for generating a partially coherent beam is given and calculated using a graphic processing unit (GPU), i.e., the GeForce GTX 680. A liquid-crystal on silicon (LCOS) with 256 × 256 pixels is used as the partially coherent beam generator (PCBG). An optimizing method with partition convolution is used to improve the generating speed of our LC PCBG. The total time needed to generate a random phase map with a coherence width range from 0.015 mm to 1.5 mm is less than 2.4 ms for calculation and readout with the GPU; adding the time needed for the CPU to read and send to LCOS with the response time of the LC PCBG, the real-time partially coherent beam (PCB) generation frequency of our LC PCBG is up to 312 Hz. To our knowledge, it is the first real-time partially coherent beam generator. A series of experiments based on double pinhole interference are performed. The result shows that to generate a laser beam with a coherence width of 0.9 mm and 1.5 mm, with a mean error of approximately 1%, the RMS values needed 0.021306 and 0.020883 and the PV values required 0.073576 and 0.072998, respectively.

1. Introduction

Since the 1970s and the late 1980s, PCBs have been extensively investigated and widely applied in many fields, such as free-space optical (FSO) communications, material thermal processing via a laser beam, laser scanning and inertial confinement fusion via a laser, nonlinear optics and imaging applications [1–4]. Many types of partially coherent beam generators (PCBGs) are available [5,6]. One of the most important types of PCBG is the LC PCBG, which generates PCBs with liquid-crystal spatial light modulators (LC SLM). LC SLM has many merits, such as its high resolution, programmability, low cost, low power consumption and light weight, and has been widely applied in many fields [7–13]. However, the large number of pixels and the slow rate of response seriously constrain the application of LC SLM. The general procedure used to generate the PCB using a LC SLM is as follows: first, one must calculate gray map pictures according to a specific coherence width before experimentally generating the PCB. Then, the pictures should loaded into the buffer of the LC PCBG electric board, the pictures are displayed to generate a PCB by modulating the incident light. However, if you want to change the coherence width of the laser beam, you will have to regenerate a series of gray maps. Obviously, this is very inconvenient [14,15]. In recent decades, the graphics processing unit (GPU) architecture, a scheme based on multi-threading, has been widely used to enhance the computing capability in many applications. Because of its highly parallel architecture, GPU is rapidly gaining maturity as a powerful engine for computationally demanding applications, such as liquid-crystals, which have numerous pixels that must be controlled independently. Ref. [16] proposed a method to reduce the computation time of a liquid-crystal atmosphere turbulence simulator (LC ATS) by using a GPU, which makes it possible to generate a turbulence phase in real time.

For the same purpose, in this paper, we implemented the GPU-accelerated real-time calculation method to generate PCBs for our LC PCBG and demonstrated that the PCB generation frequency can be up to 312 Hz. Compared with the LC ATS mentioned in Ref. [16], the idea of computation time reduction using a GPU happens to coincide, but the application area is completely different. Moreover, for LC ATS, the basic generation algorithm is matrix multiplication, while it is matrix convolution for our LC PCBG, which is much more complicated than LC ATS. Moreover, the coherence width determines the size of the convolution kernel, presenting a large challenge for parallel optimization.

Our work is divided in the following way: first, we describe the principles of generating the PCB, and then the generation algorithm is given. Second, we present an improved PCB generation

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method and use a graphic processing unit (GPU) to accelerate the calculation of generation. Moreover, partition convolution and parallel sequential optimization are used to improve the generating speed of our LC PCBG. Then, we demonstrate the functionality of LC PCBG by analyzing the experiment results of generation beams for different coherence widths. Finally, conclusions are given.

2. Generation algorithm

There are two major ways to generate a partially coherent beam, by transmission of a laser beam through a rotating ground glass plate [17] or by using a LC SLM, which acts as a phase modulator (phase screen) [18]. Fig. 1(a) shows the generation system with a rotating ground glass plate. We assume that the laser beam source generated by the He–Ne laser is a Gaussian beam. Then the laser beam passes through a thin lens and illuminates a rotating ground glass disk (RGGD); the transmitted light can be approximately considered as a PCB, which can be characterized by the mutual coherence function (MCF), expressed as

$$\Gamma(r_1,r_2)=\exp\left[-\frac{r_1^2+r_2^2}{\omega_0^2}-\frac{(r_1-r_2)^2}{2\sigma_g^2}\right]. \quad (1)$$

Here, $r_i\equiv(x_i,y_i)$ is the position vector in the source plane, ω_0 is the transverse beam width, and σ_g is the coherence width of the GSM beam. The plate should be rotated continuously, the thin lens is used to control the beam size illuminated on the RGGD, which is large with respect to the ground glass in homogeneities. We can vary the coherence of the partially coherent laser beam by controlling the size of the focused beam spot on the ground-glass disk and the rotating characteristic scale of the ground-glass disk. Therefore, one ground-glass disk corresponds to one fixed coherence width, relative coherence length can also be varied by controlling the size of the beam spot on the ground-glass disk. Obviously, this method cannot generate a partially coherent beam in real time and it is not convenient and economical.

Fig. 1(b) shows the generation system with a LC SLM. The laser beam generated by a He–Ne laser is considered as a coherent light source. The laser beam passes through a polarizer to change the polarization state meeting the requirements of the liquid-crystal. Then, we can obtain PCB at the output plane by modulating the phase of the laser beam using the LC SLM. Most of the LC SLM are controlled by an electric signal. The phase associated with each pixel of LCOS is typically proportional to the intensity of the control signal applied to the pixel of the LCOS. Therefore, to generate a PCB, the major work is to calculate the random phases map [18,19]; if you want to change the coherence width of the laser beam, a series of grey maps should be regenerated, which involves a long computation time and is impossible to achieve in real- time. Moreover, the calculation process is not suitable for GPU because of the limited functions available for mathematic calculation in the software development kit (SDK) of the Compute Unified Device Architecture (CUDA) supplied by NVidia Corp. Therefore, it is necessary to modify and optimize the algorithm into basic expressions and suitable for parallel computation. The basic method for generating a random phase will be introduced in the following section.

First, we summarize the elementary method to calculate the random phases map. Assume that the random phase function $\varphi(\vec{\rho},\omega)$ obeys the zero mean Gaussian distribution, whose second-order correlations are given by the expression [18]

$$<\varphi(\vec{\rho}_1,\omega)\varphi(\vec{\rho}_2,\omega)> =\varphi_0^2\exp\left[-\left|\vec{\rho}_1-\vec{\rho}_2\right|^2/(2\delta_\varphi^2)\right], \quad (2)$$

where

$$\phi_0=\sqrt{\langle\left|\phi\left(\vec{\rho},\omega\right)\right|^2\rangle}. \quad (3)$$

Here, δ_ϕ is the phase coherence width. Then the cross-spectral density function of the electric field at the exit plane $z=z_0$ of the LCOS is given by the expression

$$\begin{aligned}W(\vec{\rho}_1,\vec{\rho}_2,z_0)&=S_0\mu(\vec{\rho}_1,z_0)\mu^*(\vec{\rho}_2,z_0)\\&\quad\times<\exp i[\phi(\vec{\rho}_2,\omega)-\phi(\vec{\rho}_1,\omega)]>\\&\approx S_0\mu(\vec{\rho}_1,z_0)\mu^*(\vec{\rho}_2,z_0)\times\exp[-\left|\vec{\rho}_1-\vec{\rho}_2\right|^2/(2\delta_\phi^2)].\end{aligned} \quad (4)$$

Here, $S_0=S_0(\omega)$ is the spectral density of the initial plane wave, $\mu(\vec{\rho},z_0)$ denotes the partially coherent electromagnetic field at frequency ω, and $\vec{\rho}_1$ and $\vec{\rho}_2$ are the two-dimensional position vectors in the plane $z=z_0$.

Therefore, if the spatial light modulator (SLM) is loaded with an appropriate random phase $\phi(\vec{\rho},\omega)$, a PCB is generated with a certain coherence width.

As the first step, a two-dimensional real-valued random function $R_\phi(\vec{\rho})$ which obeys Gaussian statistics with zero mean is generated. Because the components of the array are independent and Gaussian distributed, they are also uncorrelated.

$$R_\phi\left(\vec{\rho}_1\right)R_\phi\left(\vec{\rho}_2\right)=\delta^{(2)}\left(\vec{\rho}_1-\vec{\rho}_2\right). \quad (5)$$

Here, $\delta^{(2)}\left(\vec{\rho}\right)$ is the two-dimensional Dirac delta function. Then, a Gaussian-correlated random function $g_\phi\left(\vec{\rho}\right)$ is produced by performing a convolution integral of random function $R_\phi(\vec{\rho})$.

$$g_\phi(\vec{\rho})=f_\phi(\vec{\rho})*R_\phi(\vec{\rho}), \quad (6)$$

where the window function is given by

$$f_\phi\left(\vec{\rho}\right)=\exp\left(-\frac{\vec{\rho}^2}{\gamma_\phi^2}\right). \quad (7)$$

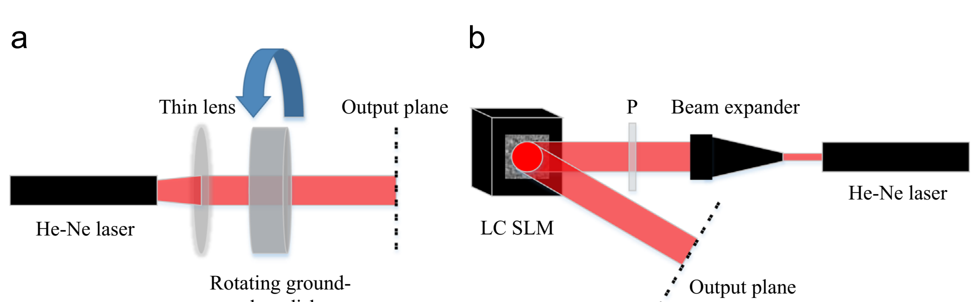

Fig. 1. Typical PCB generation system. (a) Rotating ground glass plate, (b) LC SLM.