Phase-only SLM Generating Variable Patterns Applied in Optical Connection

B H Liu, L Y Wu and J Zhang
P.O. Box 718, Harbin Institute of Technology, Harbin, 150001, China
E-mail: hit_bohanliu@yahoo.com.cn

Abstract. An adaptive optical communication system is proposed. The system sends spatial information by emitting multiple variable laser beams generated from a programmable diffractive optical element (DOE): phase-only liquid crystal Spatial Light Modulator (SLM). Laser beams carrying signals are programmable by an optimal algorithm based on an iterative Fourier transformation algorithm. The system has the advantage in redundancy of signal by the means of broadcast. It can adaptively seek position and transmit information in parallel.

1. Introduction
The free-space optical communications including the inter-connections possess the advantages of massive parallelism, high space bandwidth product, low power consumption, low cross talk, and low time skew as compared to electronic interconnections [1]. Dynamically reconfigurable phase-only Computer Generated Holograms (CGH) have important applications in the areas of agile optical emitting and receiving. Attention has been given in various optical techniques, such as diffraction optics, holographic optics and optical tweezers. An electrically addressed liquid crystal Spatial Light Modulator (SLM) is a programmable Diffractive Optical Element (DOE), which can dynamically transfer information from the electronic domain to the optical domain [2]. Desired optical diffractive pattern (information), such as the multi-spot pattern, can be easily obtained with CGH technology. The light beams carrying information can be steered into multiple beams pointing to different desired directions, and the information can be transferred into multiple destinations simultaneously. There is enough redundancy in the transmitted signal to overcome obstacles in the transmit path. Further, multiple spots allow for the possibility of recipients at different locations obtaining the same information—“broadcast”, which provides multi-coverage with less risk of interception. If the multi-spot generator is also a modulator, then recipients at different locations could receive different messages simultaneously. So it is a key technology in the laser multiple links communications between space, air, ground and sea. In the view of real-time it can also been adopted as multiple target objects tracking and defense [3].

1.1. Adaptive System Design
Based on agile multiple spots beam steering, an adaptive optical communication system is designed as Figure 1. Firstly, the information to be transmitted, an image for example, is inputted to the computer. According to certain algorithm, the information is encoded into DOE controlled by certain computer program. Then, the incident laser light is steered into multiple beams pointing to different designed positions where information receivers exist. The system can adaptively select the position and transmit
the information in parallel. It is of great value in optical parallel connections. The key technology is to beam steering arbitrarily. One way to get the aim is to generate arbitrary pattern by controlling variable DOE and Liquid Crystal SLM (LCSLM) is one of such elements.

![Figure 1. Schematic graph of the adaptive system.](image)

1.2. Principle of Beam Steering with an LCSLM

LCSLM is a programmable DOE with the merit of light and without mechanical inertia. The nematic liquid crystal is widely adopted because it can realize the phase only modulate and has a large phase modulation (for example $2\pi$) [4].

![Figure 2. Liquid crystal index controlled by the external voltage.](image)

In Figure 2, it shows the schematic diagram of liquid crystal index controlled by electrical field. For the uniaxial molecules liquid crystal, the two refractive indices are called ordinary, $n_0$ and extraordinary, $n_e$. The effective refractive index can be written as

$$n_{\text{eff}} = \frac{n_0 n_e}{\sqrt{n_0^2 \sin^2 \beta + n_e^2 \cos^2 \beta}},$$  \hspace{1cm} (1)

where $\beta$ is the angle between molecule long axis and x axis. When the light with wave length $\lambda$ propagating through the LC layer with the thickness of $d$, a phase delay $\phi$ can be described by

$$\phi = \frac{2\pi}{\lambda} \int_0^d [n_{\text{eff}}(\beta) - n_0] \, dy.$$  \hspace{1cm} (2)

Figure 3 shows the phase profile composed of several periodic quantified ramps composed of repeating structures from Figure 2. The m:th order diffraction angle is given by the grating equation as

$$\theta_m = \sin^{-1}\left(\frac{m \lambda}{\Lambda}\right),$$  \hspace{1cm} (3)

Where $\lambda$ is the wavelength, $\Lambda$ is the period of the (variable) “grating”.

![Figure 3. Phase profile composed of several periodic quantified ramps.](image)
2. Arbitrary Pattern Generation

In Figure 4, an incident monochromatic plan wave with its initial phase zero, passes through the SLM with transmittance of \( t(\xi, \eta) \).

\[
t(\xi, \eta) = r(\xi, \eta) \exp[i\varphi(\xi, \eta)]
\]

(4)

Where \( \varphi \) is the phase delay of the SLM. When the amplitude of \( t \) is unit, \( t \) can be written as \( t(\xi, \eta) = \exp[i\varphi(\xi, \eta)] \). In general, the relation between output function \( g(\xi, \eta) \) and \( t(\xi, \eta) \) is:

\[
g(x, y) = H(x, y, \xi, \eta) t(\xi, \eta),
\]

(5)

where \( H(x, y, \xi, \eta) \) is the transfer function. Assuming \( A(m, n) \) is the complex amplitude of 2-D diffractive order it can be written by the Fourier Transformation of the unit function of \( t \) as the following:

\[
A(m, n) = \int \exp\{j\varphi(\xi, \eta)\} \exp\{-j2\pi(m\xi + n\eta)\} d\xi d\eta,
\]

(6)

Where \( \varphi(\xi, \eta) \) is a periodic function with the expression of \( \varphi(\xi + T_\xi, \eta + T_\eta) = \varphi(\xi, \eta) \), \( T_\xi \) and \( T_\eta \) is the period in the direction of \( \xi \) axis and \( \eta \) axis respectively. The phase of each periodic pixel \( [\xi_i, \xi_{i+1}, \eta_k, \eta_{k+1}] \) of the pixel is constant: \( \varphi(\xi_i, \eta_k) = \varphi_{i,k}, \varphi_{i,k} \in [0, 2\pi] \). Then,

\[
g_{m,n} = \text{DFT}\{\Gamma(\varphi(\xi_i, \eta_k))\},
\]

(7)

\( g_{m,n} \) is the quantified expression of \( g(x, y) \) from \( A(m, n) \), \( \Gamma \) is a quantified function of phases with stepping levels. As we know, the far field diffractive pattern (Frauhofer diffractive pattern) is the Fourier transformation of the complex with phase of \( \varphi_{i,k} \). Then the far field pattern is only depended on the phase distribution. It is an optimal process to find the proper phase distribution whose pattern intensity is approaching to the expected pattern intensity:

\[
|I - \overline{I}| = \varepsilon,
\]

where \( \varepsilon \) is a real permitted threshold, \( I \) is the intensity and \( \overline{I} \) is the expected intensity. It is a phase retrieval process and the phase can be obtained by the optimal algorithm.

![Figure 4](image-url)

**Figure 4.** System schematic diagram of phases design.

Using a phase only SLM to generate the expected intensity patterns is a problem of phase retrieval. There are many algorithms such as iterative Fourier, simulated annealing and genetic annealing algorithm etc. Simulated annealing algorithm and genetic annealing algorithm are both optimization
algorithms that can generate satisfying “phase mask”, but they are closely depend on optimal objective function and need much time of computing. These methods are fit for off-line designs and not fit for the rapid time respond conditions such as fast beam steering. Here, we adopt the Iterative Fourier Transformation Algorithm (IFTA) which are also named G-S algorithm [5]. IFTA has good convergence at its several iterations and its program is not complex. In order to speed up the convergence and avoid the stagnation of the G-S algorithm, here we adopt an improved algorithm which initialized the GS algorithm with pseudorandom encoding phases not zero phases. Figure 5 is algorithm schematic diagram.

![Figure 5](image)

**Figure 5.** Flow chart of G-S algorithm blending with pseudo-random phase encoding initialization.

To compare with the G-S algorithm without phase encoding we have the two algorithms iterated the same times. In Figure 6 (c), the results of the modified algorithm has an improved image effect than Figure 6 (b). The bright noises on the background of the modified one are less and the letters on the image are finer than the unmodified one. The two algorithms consume with nearly the same time, but the improved algorithm has the better convergence. Many similar experiments also have been performed and the modified algorithm gives better results.

![Figure 6](image)

**Figure 6.** (a) Expect intensity pattern; (b) G-S algorithm without the pseudorandom phase encoding, iteration=5 (c) G-S algorithm with the pseudorandom phase encoding, iteration=5 (d) phase bitmap of the third condition (the black is 0 and white is 2π). All the pictures are only central 64×32 pixels of the 256 ×256 pixels.

3. Experimental

In order to test our adaptive optical connection system an experimental setup is constructed as shown in Figure 7. The SLM investigated in this study is a Zero-Twist nematic liquid crystal SLM purchased from BNS(Boulder Nonlinear System, Inc.) with 256×256 pixels. A laser source operating at 633 nm wavelength, polarizers, a beamsplitter, a conventional optical components and a 10-bits 1300×1030 pixels CCD camera was used in the set-up. The camera was placed one focal length (70cm) behind the achromatic lens to produce a far field pattern on the CCD.

![Figure 7](image)

**Figure 7.** Phase only LCSLM generating diffractive patterns set-up.
3.1. Results and Analysis

Since the orientation of the extraordinary axis of the LC-pixels is approximately known, the SLM can be mounted in such a way that the extraordinary axis is aligned with the optical axes of the polarizers. Such a set-up will produce pure phase modulation. The camera was placed one focal length behind the achromatic lens to produce a far field diffractive pattern on the CCD. The focus length of the lens is 70cm. Our expected optical connection sample is like the right image (25 bright points) in Figure 8.

![Image](image_url)

(a) (b)

Figure 8. The result of transmitting pattern of “HIT” with the adaptive system set-up. (a) the original image, (b) the result.

According to the Figure 8, we can see that the received image is exactly similar to the original image with little distortion. The bright cross point in the bottom-right of the result image is the zero order diffraction. The distortion can be eliminated by the methods of image processing. Then, the processed image can be received by the receiver and transformed into the information of positions and shape information. The cost time of generating a phase image is about 300 ms running under Windows 2000 operating system with 2.4 GHz Pentium IV processor and 1GB of memory.

4. Conclusion

In this paper, an optical communication system is proposed with a LCSLM to steer laser beams arbitrarily. The system can adaptively select the position and transmit the information in parallel by adopting the phase optical design method based on the G-S algorithm. An experimental set-up is built to test the effect of transmitting a digital image projected by multiple laser beams. This system has the advantages in redundancy of signals by the means of broadcast and it is of great value in the international optical connection and the laser radar.

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