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Multi-beam steering with low grating lobes using optimized unequally spaced phased array

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ABSTRACT

We propose a multi-beam steering technique with low grating lobes using unequally spaced phased array. The multi-beam steering is achieved using Array Division Multiplexing (ADM) technique. The unequal spacing distribution in ADM is optimized by the algorithm of particle swarm optimization (PSO) to minimize the grating lobes levels. The results show that the grating lobe level can be effectively reduced from 37.96% to 4.99% of the main lobe power using the proposed technique within the whole scanning range of the two steered beams.

1. Introduction

Beam steering [1,2] is widely applied in optical microscopy, communications [3,4] and laser processing. A variety of beam steering techniques have been proposed such as mechanical beam steering [5,6], electro-optical beam steering [7] and optical phased arrays [8–11]. Mechanical beam steering is a relatively mature technology but suffering from some limitations such as slow scanning speed, low robustness, high sensitivity to environment vibrations [12]. Electro-optical beam steering technique can offer relatively high scanning speed but with relatively small scanning angle range. Optical phased array (OPA) [13] which originates from phased antenna array enables accurate and rapid beam steering without the inertia of mechanical motion and shows great potentials in practical applications such as laser radar, optical communication [14], etc. However, OPA suffers from a significant limitation of severe grating lobes, which are consequence of undesired frequency mixing in beam steering technology owing to the large ratio between the element size d and the optical wavelength of the incident light λ for the currently commercial spatial light modulators. They are the result of the periodicity of the phase elements and the existence of the grating lobes can disperse the energy of the emergent beam and degrade the diffraction efficiency. Consequently, severe grating lobes level poses great challenge for the OPA technology. For the single beam steering, some studies suggested that aperiodic configuration of phased array elements enabled the suppression of grating lobes [15–21]. In these techniques, the spacing between adjacent pixels was no longer uniform. By doing this, the energy on the far field of the incident beam was able to be rearranged and the grating lobe was significantly diminished. Besides, some optimizations like PSO [16] or genetic algorithm (GA) [19] is introduced to design sparse aperiodic arrays to further reduce the grating lobes level. The techniques were all brought up in the single beam case while have not been investigated in the multi-beam steering situation. A typical multi-beam steering technique using OPA was to use Array Division Multiplexing (ADM) [22]. This technique divided the OPA into several groups that formed multiple beams where adjacent pixels from arbitrary group had equal intervals. However, due to the fact that the size of the equivalent pixel is multiplied, grating lobes are more serious and dramatically affect the quality of the scanning point and thus, this technique alone with high level grating lobes cannot bring the desired high resolution scanning effect.

In this paper, we propose an ADM approach with unequally element spacing to reduce the grating lobes in multi-beam steering while maintaining the merits of high speed and multi-target detection in multi-beam steering. The unequal spacing distribution in the ADM is optimized by the algorithm of particle swarm optimization (PSO) to minimize the grating lobes levels. Results prove the validity of the proposed idea and related discussion is also provided.

2. Principle

Fig. 1 gives schematic diagram of a typical uniform OPA for single-beam steering. To achieve a deflection angle of θ_0 between the incident and emergent beam, the phase difference between adjacent elements is given by [18]:

$$\Delta\varphi = \frac{2\pi}{\lambda} d_0 \sin\theta_0 \tag{1}$$

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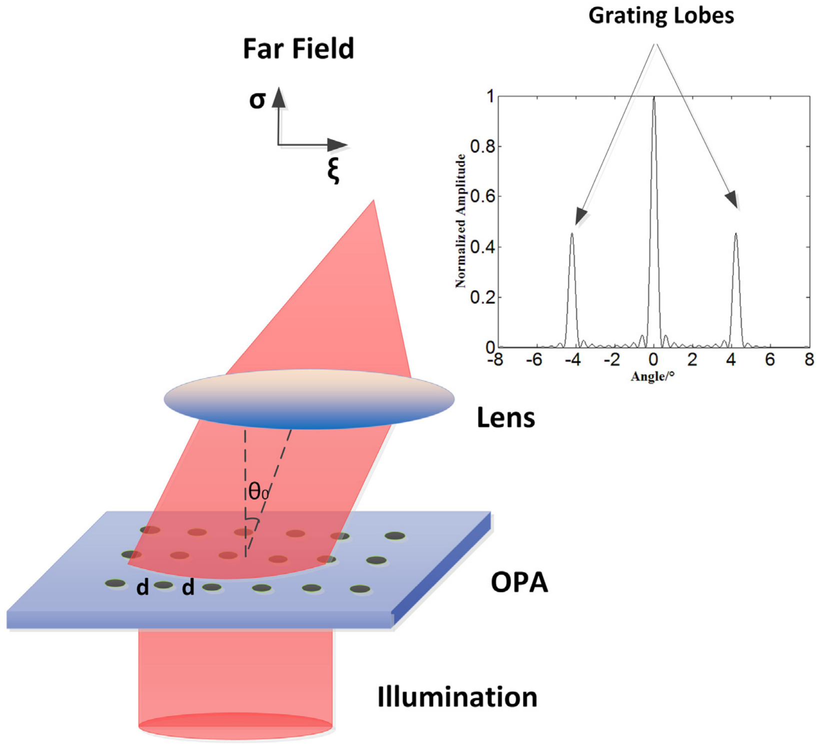

Fig. 1. Schematic diagram of a typical OPA with equal spacing and its far-field distribution in single beam steering.

where d_0 is the distance between adjacent elements and λ is the wavelength of the incident beam. The far-field amplitude along an arbitrary direction θ is:

$$E(\theta) = \sum_{n=1}^{N} A_n e^{j[\frac{2\pi n}{\lambda} d_0(\sin\theta - \sin\theta_0)]} = \frac{\sin[\frac{\pi N d_0}{\lambda}(\sin\theta - \sin\theta_0)]}{\sin[\frac{\pi d_0}{\lambda}(\sin\theta - \sin\theta_0)]}. \quad (2)$$

In this paper, we assume a uniform illumination and $A_n = 1$. The locations of grating lobes in single beam steering are determined by [19]:

$$\frac{\pi d(\sin\theta - \sin\theta_0)}{\lambda} = \pm\pi, \pm 2\pi, \ldots \quad (3)$$

where m denotes the order of grating lobes. The upper right curve in Fig. 1 gives the far-field amplitude of OPA with equal inter-element spacing. One can see the obvious grating lobes.

Now we consider the multi-beam steering case. We use the ADM technique to generate multi-beams. The principle is shown in Fig. 2(a) in which the elements are represented with circles. Elements that have the same color point to the same direction and form a beam. In this case, the electric field in an arbitrary direction θ in multi-beam steering is expressed as [22]:

$$\begin{aligned} E_{ADM}(\theta) &= \sum_{n=1}^{N} e^{jnd_0 \frac{2\pi}{\lambda}(\sin\theta - \sin\theta_i)} \\ &= \sum_{n=1}^{K} e^{jnMd_0 \frac{\pi}{\lambda}(\sin\theta - \sin\theta_1)} + \sum_{n=1}^{K} e^{jnMd_0 \frac{\pi}{\lambda}(\sin\theta - \sin\theta_2)} + \cdots \\ &\quad + \sum_{n=1}^{K} e^{jnMd_0 \frac{\pi}{\lambda}(\sin\theta - \sin\theta_M)} \end{aligned} \quad (4)$$

where M is the multi-beam number, K is the element number within each group to form a beam and θ_i $(i = 1, 2, \ldots, M)$ is the main lobe of the ith beam. Compared with the single-beam steering, the equivalent element spacing of each beam in the multi-beam steering is Md_0, which is M times larger than the original element spacing and thus is vulnerable to generate grating lobes in multi-beam steering. This paper aims to address the problem of grating lobes in multi-beam steering. We use the proposed unequally spaced technique as shown in Fig. 2(b) to suppress the grating lobes level.

Now we calculate the far-field electric field distribution. Assume that there are N elements in total and all elements are located in the x–y plane. The coordinate of the nth element is (x_n, y_n). We apply the Fraunhofer far-field approximation and calculate the far-field diffraction pattern observed in plane $\sigma - \xi$ using [18]:

$$\begin{aligned} E(\sigma,\xi) &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \sum_{n=1}^{N} A_n \exp(j\phi_n) \times \exp[-j\frac{2\pi}{\lambda L}(x\sigma + y\xi)]dxdy \\ &= \sum_{n=1}^{N} A_n \exp(j\phi_n)\exp[-j\frac{2\pi}{\lambda L}(x_n\sigma + y_n\xi)] \end{aligned} \quad (5)$$

where A_n is the amplitude of the nth element, ϕ_n is the phase of the nth element, L is the distance between the x–y plane and the $\sigma - \xi$ plane and ω_0 is the waist width of the incident beam. To simplify the explanation, we use the one-dimensional phased element distribution as an example to illustrate the principle. We assume $x_1 = x_2 = \ldots x_n$ and define the spacing as $d_i = y_{i+1} - y_i$ $(i = 1, 2, \ldots, N-1)$. For the equally spaced case, d_i equals to the original element spacing d_0. For the unequally spaced case as shown in Fig. 2(b), the phase elements are distributed non-uniformly and the grating lobes can be suppressed by selecting a proper set of element spacing d_i.

To find the minimum of the grating lobes value, we apply the optimization algorithm of PSO to search for a proper set of unequal element distribution for the multi-beam steering. The flowchart of the optimization process is shown in Fig. 3. The implementing of the PSO consists of initialization, fitness evaluation, local & global solution updating, and positions & velocities updating and termination. We originally assume a set of equal inter-element spacing with $d_i = d_0$ $(i = 1, 2, \ldots, N)$. A set of inter-element spacing differences $X(t) = (\delta_1, \delta_2 \ldots \delta_N)$ is defined as a particle. By adding $X(t)$ to the equal spacing, we generate a set of unequal inter-element spacing $d_i' = d_0 + \delta_i, (i = 1, 2, \ldots, N)$. Two linearly phase shifting patterns are loaded to the odd and even elements of the unequal inter-element spacing d_i' respectively. The corresponding far-field distribution can be calculated using Eq. (5). We define the peak