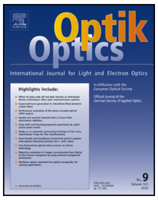
Optik 125 (2014) 4568–4571

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



Optimum beam steering of optical phased arrays using mixed weighting technique

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ARTICLE INFO

Article history:
Received 16 October 2013
Accepted 25 February 2014

Keywords:
Optical phased array
Beam steering
Grating lobes

ABSTRACT

In this paper, we present a novel technique for high precision optical beam steering of optical phased arrays (OPA) using mixed weighting method. Optimal OPA parameters are determined to obtain the best beam directivity by minimizing the main lobe width and eliminating grating lobes of the far field diffraction pattern. The quantitative analysis for a fibre-type optical phased array is given. The calculation results demonstrate that the grating lobe level can be distinctly reduced from 80% to 20% of the main lobe level. Thus, the mixed weighting technique proposed in this paper can substantially improve the beam steering efficiency and the beam quality.

1. Introduction

A non-mechanical beam steering approach is essential to many applications where the optical direction of the instrument changes rapidly to random locations. An optical phased array (OPA) is a device to manipulate the spatial phase distribution of an incident laser beam. It is a revolutionary system with random access pointing, similar to microwave radar phased arrays [1,2]. OPA can provide an elegant means for the inertialess, high-resolution beam steering that is required by numerous applications, including laser ladar, laser communication, and laser projection display [3–5].

There are various types of optical phased arrays such as $LiNbO_3$ or $LiTaO_3$ crystal, PLZT ceramic, optical waveguides, spatial light modulators (SLMs) and liquid crystal [6–8]. The latter got more and more popular since it provides good performance at relatively low prices thanks to their applications in projectors and displays. With the rapid advent of integrated optics, some new steering techniques for wide angle beam steering have been investigated such as holographic glass and birefringent prisms integrated with commonly liquid crystal OPA. The steering angle can steer plus or minus 60° [9,10]. However, one of the major drawbacks is low steering efficiency because of the large number of grating lobes in far-field diffraction pattern. The inter-element spacing d should be less than half wavelength λ, i.e., $d < \lambda/2$ based on Nyquist sampling criterion [11]. For microwave phased arrays, the essential condition can be easily satisfied due to its long wavelength. But half wavelength spacing in the visible or near IR region is currently impossible for these OPA-based devices because the required separation will be less than 1 μ. Grating lobes have a deleterious influence on the OPA performance and should be avoided. If many grating lobes exist, a strong secondary signal appears in the directions other than the steering angle, resulting in spurious and confusing signals. Hence, for their effective use in laser ladar and optical communications, OPA should be designed to perform optimally for specific needs and requirements.

To eliminate the grating lobes while maintaining the $d > \lambda$ condition, different unequally spaced phased array techniques were proposed. Yin et al. [12] developed an unequally spaced phased array technique by destructive interference between the phase shifters. Hosseini et al. [13] present a design methodology for silicon nanomembrane-based phased array structures with unequally spaced elements. It can achieve a steering angle of ±45° and avoid the optical coupling by designing an unequally spaced array composed of sub-arrays with non-overlapping grating lobes. An array structure formed by gradually doubling the inter-element spacing along the array also can suppress side lobes [14]. However, the OPA with irregular and unequally spaced array structures are difficult to fabricate in practical materials. For their effective use in agile beam steering and precise tracking, optical phased arrays are generally designed as regular structures to perform optimally in high efficiency and high beam quality.

In this paper, we propose a novel technique for high precision optical beam steering of optical phased arrays (OPA) using mixed weighting method. Optimal OPA parameters are determined to obtain the best beam directivity by minimizing the main lobe width and eliminating grating lobes of the far field diffraction pattern.

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http://dx.doi.org/10.1016/j.ijleo.2014.02.004
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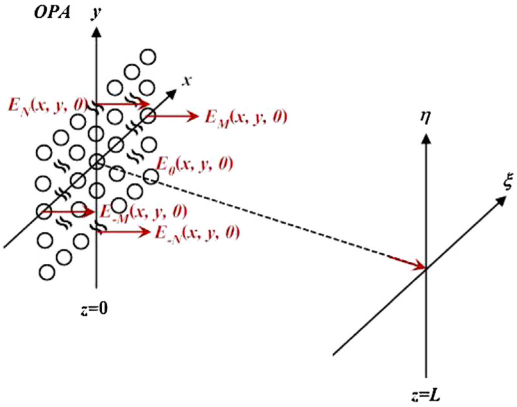

Fig. 1. Definition of coordinate system and geometry parameters for the 2-D optical phased array.

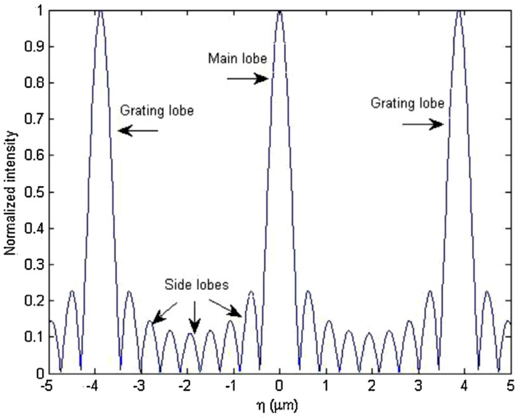

Fig. 2. A typical plot showing the main lobe, side lobes, and grating lobes.

These optimal parameters are achieved by mixed weighting method. For an example, the detailed quantitative analysis of a fibre-type optical phased array is given. The calculation results demonstrate that the grating lobe level can be distinctly reduced from 80% to 20% of the main lobe level. Thus, the mixed weighting technique proposed in this paper can substantially improve the beam steering efficiency and the beam quality. Finally, an optimized scheme of OPA transmitter antenna for optical communications with both high power and good beam directivity is also developed.

2. Optimized optical phased array – theory

2.1. Geometry of matrix array

The general configuration of a 2-D OPA is a rectangular array. A total of $2M+1$ phase elements, each with diameter d, are spaced equally apart by T_x along the x axis. And $2N+1$ phase elements are spaced equally apart by T_y along the y axis. The overall x and y extent of the array is D_x and D_y. When $T_x = T_y$ and $M = N$, the OPA is defined as a square matrix array. The coordinate system is defined in Fig. 1. Consider a paraxial, z-directed beam propagation geometry, where the OPA is placed on the $z = 0$ plane.

We assume that each phase element emits a monochromatic, scalar and paraxial beam with wavelength λ. The electric field of the m–nth element at the transverse coordinate (x, y) on the $z = 0$ plane is given by

$$E_{mn}(x, y, 0) = Ae^{imn\Delta\varphi} W\left(\frac{x - mT_x}{d}, \frac{y - nT_y}{d}\right), \tag{1}$$

here A and $W(x, y)$ describe the constant amplitude and the axial beam profile exited from each emitter aperture and $\Delta\varphi$ is the linear phase increment in each emitter. The fill factor γ in x and y directions is respectively defined as $\gamma_x = d/T_x$, $\gamma_y = d/T_y$. The total light field in the x–y ($z = 0$) plane can be written as

$$E(x, y, 0) = \left[\frac{1}{T_x T_y} \mathrm{comb}\left(\frac{x}{T_x}, \frac{y}{T_y}\right) \otimes E_{mn}\right] \cdot \mathrm{rect}\left(\frac{x}{D_x}, \frac{y}{D_y}\right), \tag{2}$$

The total light field is written as a convolution of a comb function and $E_{mn}(x, y)$, the shape of each element is a circular function of diameter d or a rectangular function, and the OPA is bounded by a rectangle function of dimension D_x and D_y.

In this case, using the Fraunhofer far field approximation, the far field diffraction pattern of the array at $z = L$ can be calculated as

$$F(\xi, \eta, L) = [\mathrm{comb}(l_x\xi, l_y\eta) \cdot \tilde{E}_{mn}] \otimes [D_x D_y \ \sin c(D_x\xi, D_y\eta)] \tag{3}$$

where $\tilde{E}_{mn}$ is the 2-D Fourier transformation of E_{mn}, $\xi = x/\lambda L$ and $\eta = y/\lambda L$ are the space frequency components at the observation plane.

2.2. Grating lobes for the general OPA

Fig. 2 shows the typical plot of the far field pattern of a general OPA, in which the amplitude is the same for all the phase elements ($M = N = 9$), $\lambda = 1.55$ μm and $d = 8$ μm. We can observe that the main lobe is surrounded by many smaller lobes (side lobes) appearing at multiple locations. This means the scanning beam is propagated not only in the steering direction but in the other directions as well and results in energy leakage in the steering direction. If the amplitudes of the side lobes are much smaller than that of the main lobe, the main lobe is sharp and the directivity is good.

There are also grating lobes beside side lobes. Grating lobes have a deleterious influence on the OPA's excellent performance. A strong disturbing signal appears in the other directions and can result in spurious and confusing signals in the detector of laser ladar. Steinberg [11] pointed out that the inter-element spacing d should be less than half the wavelength in order to avoid grating lobes, based on Nyquist sampling criterion. But it is extremely difficult to realize this condition in the general OPA. Therefore, it is desirable to eliminate (or suppress) the grating lobe amplitudes.

To obtain good beam directivity, we develop a mixed weighting optical phased array technique to eliminate grating lobes and sharp the main lobe of the far field diffraction pattern.

2.3. Mixed weighting optical phased array technique

To reduce the grating lobes and side lobes, we modulate the electric field of the OPA at $z = 0$ using a complex (amplitude and phase) plate based on the complex function C_{mn}. The resultant field in the $z = 0$ plane is modified as

$$E(x, y, 0) = \sum_{m=-M}^{M} \sum_{n=-N}^{N} C_{mn} \ e^{imn\Delta\varphi} W\left(\frac{x - mT_x}{d}, \frac{y - nT_y}{d}\right), \tag{4}$$

where $C_{mn} = |C_{mn}| \exp(-i\delta_{mn})$, the amplitude weighted function $a_{mn} = |C_{mn}|$ and the phase weighted function δ_{mn}. We call it the mixed weighting method. We can pre-fabricate a complex plate with the parameters of a_{mn} and δ_{mn} and put the plate next to the OPA, as shown in Fig. 3. The complex plate is very similar with a complex filter. It can modulate the OPA in both amplitude and phase.