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Multiple polarized beam interferometers for array generation with improved efficiency

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A highly efficient multiple polarized beam interferometer for the generation of hexagonal array is reported. An expression for the intensity distribution is worked out using Jones' calculus and computed pattern is compared with the experimental results. The array pattern could be scanned over large longitudinal distances without loss of distortion. Fringe visibility of interferograms has been studied as a function of relative state of polarization of the interfering beams. Some of the potential applications of such arrays are also proposed.

Keywords: hexagonal array, interferometry, polarization.

1. Introduction

Tiny light spots in the hexagonal array structures have been commonly used in image processing [1], fiber couplers [2], atom lithography [3] and wave front sensing [4], *etc*. Hexagonal tiny arrays of equal illuminating light spots have been reported using a direct three beam interferometer [3], a three wave lateral shearing interferometer [5, 6], as well as using eight randomly polarized beams from the three interferometers in tandem [7]. The interference pattern and hence the arrays are highly localized in direct three beam interferometer [3]. In the lateral shearing interferometer [5, 6], the array pattern is independent of the plane of observation along the longitudinal direction but the scope of on line control on the dimensions and the geometry are limited. An N beam interferometer is reported [8] for generation of various array patterns but it requires the designing of special aperture/grating making the on line control on array geometry limited. The eight beam randomly polarized interferometer [7] offers the advantage of on line control on the array geometry and pattern can be scanned over large longitudinal distances making it delocalized in longitudinal direction. The efficiency of such configuration [9] is only around 0.09. The reason for poor efficiency is the repeated splitting of the beams at the beam splitters after reflection from mirrors of the Michelson interferometers used. This efficiency can be improved by using the polarized beam and polarizing beam splitters along with quarter wave plate's (QWP) and polarizer placed at appropriate locations in the configuration similar to Michelson interferometer. One such configuration was reported theoretically [10] for the formation of square array. Recently, we reported experimentally such configuration [11] for the generation of square arrays using polarized beams having light coupling efficiency of 44.3% which is about twice the efficiency of randomly polarized setup [7]. In the present paper, we report the hexagonal arrays of small light spots by using the interference of eight polarized beams coming out from the three interferometers in tandem. The light coupling efficiency of such system is four times higher than that of randomly polarized setup [9]. The resultant intensities at the output plane are worked out using Jones' calculus for the polarized light and computed patterns are compared with the experimental observations. Several possible applications of this array have been proposed and discussed.

2. Experimental set-up

The experimental set-up is shown in Fig. 1**a**. A collimated beam was passed through a polarizer P1 and launched into an interferometric setup consisting of three interferometers in tandem as shown in the figure. The polarizer P1 (03FPG003 – Melles Griot) was aligned at 45° to ensure 50-50 splitting of light from polarizing cube beam splitter PBS1 (03PBB005 – Melles Griot). The reflected beam from PBS1 (only *s*-polarized light) was passed through quarter-wave plate Q1 (02WRM015 – Melles Griot), and converted into left circularly polarized light (l.c.p.) for Q1 oriented at 45° (fixed throughout the experiment). The l.c.p. beam was reflected from mirror M1 and changed into right circularly polarized (r.c.p.) and again passed through Q1. It was turned into *p*-polarized light and completely transmitted through PBS1 in the output of the first stage of the interferometer. The transmitted beam (only *p*-polarized light) from PBS1 was passed through quarter-wave plate Q2 and changed into r.c.p. light for Q2 oriented at 45°. The r.c.p. beam was reflected from mirror M2 and converted into l.c.p. and again passed through Q2. It turned into *s*-polarization and reflected from PBS1. Thus, the two orthogonally linear polarized beams came out from PBS1. After passing through the quarter-wave plate Q3 these two orthogonally polarized beams converted into l.c.p. and r.c.p. The two beams were launched into another similar setup with one polarizing beam splitter (PBS2), two quarter-wave plates (Q4 and Q5) and two mirrors (M3 and M4). The output of the second stage consists of two pairs of orthogonally polarized beams. These four beams were passed through a quarter-wave plate Q6 and subjected into another similar interferometric setup comprising one polarizing beam splitter (PBS3), two quarter-wave plates (Q7 and Q8) and two mirrors (M5 and M6). The four pairs of orthogonally polarized beams (total of eight polarized

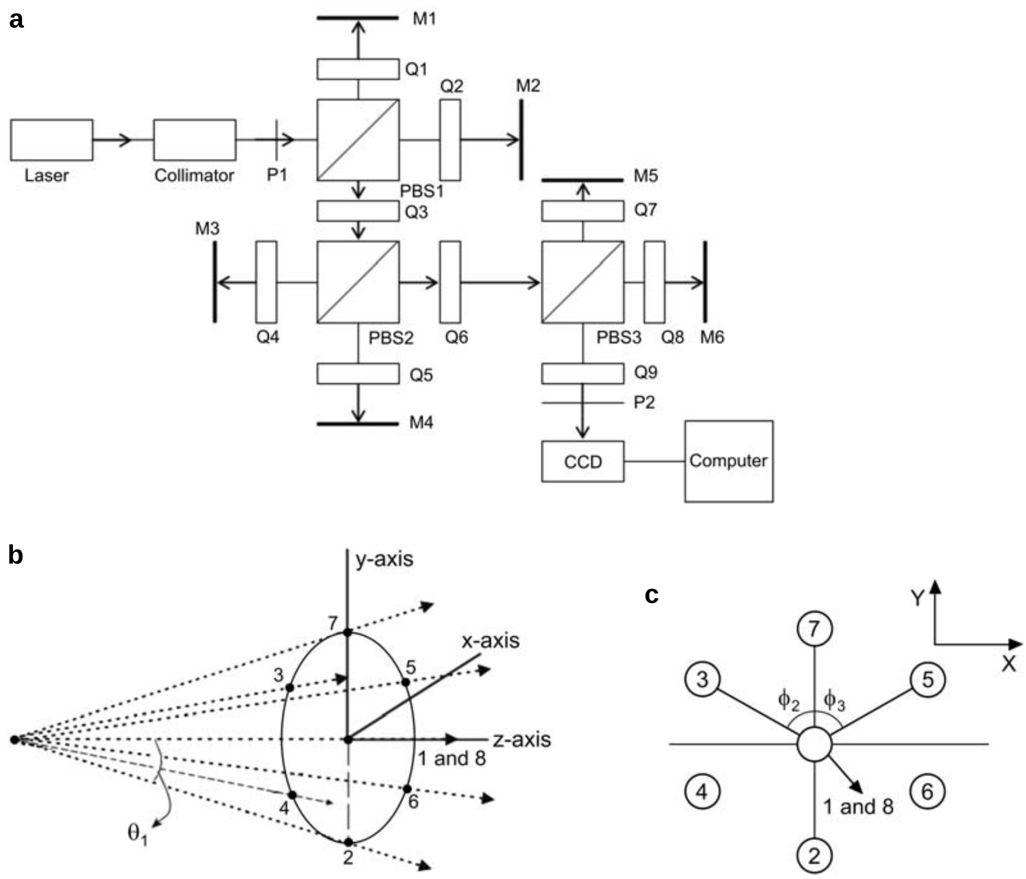

Fig. 1. Experimental setup for generation of hexagonal arrays, P – polarizers, PBS – polarizing cube beam splitters, Q – quarter-wave plates, CCD – charged coupled device – **a**; Schematic of the path of all eight beams – **b**; Location of the center of eight beams in the transverse plane, defining ϕ_p – **c**.

beams) came out from the final stage. These polarized beams after passing through the quarter-wave plate Q9 became circularly polarized and produced non-observable fringes. The fringes were observed using a polarizer P2 at the output plane. The Q1–Q9 and P2 were oriented in such a way that the optic axis of each made 45° with respect to the plane of polarization of the wave. Mirrors M1, M3 and M5 were kept for normal incidence and mirrors M2, M4 and M6 were adjusted by giving tilt for the interference pattern of individual stages. To generate the regular hexagonal pattern mirrors M2, M4 and M6 were given the tilt such that the interferograms from each stage were oriented 60° with each other and had same spatial frequencies. The use of polarized beam splitter does not bring about the problem of repeated splitting of the beams in any arm and hence the Michelson like geometry has the advantage as it requires less number of optical components compared to the Mach–Zehnder configuration.

The complex field distribution of the entire set of eight beams at the output plane is given by:

$$u_1 = \frac{a}{16}[1+i]\begin{bmatrix}1\\1\end{bmatrix} \tag{1}$$

$$u_2 = \frac{a}{16}[1+i]\begin{bmatrix}1\\1\end{bmatrix}\exp(-i\mu_1 y) \tag{2}$$

$$u_3 = \frac{a}{16}[1+i]\begin{bmatrix}1\\1\end{bmatrix}\exp\left[-i(\mu_2 y + \nu_2 x)\right] \tag{3}$$

$$u_4 = \frac{a}{16}[1+i]\begin{bmatrix}1\\1\end{bmatrix}\exp\left[-i(\mu_1 y + \mu_2 y + \nu_2 x)\right] \tag{4}$$

$$u_5 = \frac{a}{16}[1+i]\begin{bmatrix}1\\1\end{bmatrix}\exp\left[-i(\mu_3 y - \nu_3 x)\right] \tag{5}$$

$$u_6 = \frac{a}{16}[1+i]\begin{bmatrix}1\\1\end{bmatrix}\exp\left[-i(\mu_1 y + \mu_3 y - \nu_3 x)\right] \tag{6}$$

$$u_7 = \frac{a}{16}[1+i]\begin{bmatrix}1\\1\end{bmatrix}\exp\left[-i(\mu_2 y + \mu_3 y + \nu_2 x - \nu_3 x)\right] \tag{7}$$

$$u_8 = \frac{a}{16}[1+i]\begin{bmatrix}1\\1\end{bmatrix}\exp\left[-i(\mu_1 y + \mu_2 y + \mu_3 y + \nu_2 x - \nu_3 x)\right] \tag{8}$$

The resultant intensity of the eight beams is given by

$$I = \left|\sum_{i=1}^{8} U_i\right|^2 \tag{9}$$

where $\mu_1 = 2\pi\sin(\theta_1)/\lambda$, $\mu_2 = 2\pi\sin(\theta_2\cos(\phi_2))/\lambda$, $\mu_3 = 2\pi\sin(\theta_3\cos(\phi_3))/\lambda$, $\nu_2 =$ $= 2\pi\sin(\theta_2\sin(\phi_2))/\lambda$, $\nu_3 = 2\pi\sin(\theta_3\cos(\phi_3))/\lambda$, a^2 is the intensity of the incident beam, with θ_p ($p = 1, 2, 3$) being an angle between the two beams of the p-th stage interferometer (Fig. 1**b**), and ϕ_p ($p = 2, 3$) an angle between the y-axis and the line joining two beams of the p-th stage (Fig. 1**c**).

3. Results and discussion

The output, at any interferometric stage in the present experiment, *i.e.*, after Q3, Q6 or Q9 shows non-observable fringes. The fringes can be observed by placing a polarizer after Q3, Q6 or Q9. When patterns from individual stages were oriented with respect to each other at 60° and were of exactly the same frequency, then only the resultant interference pattern was of regular hexagonal geometry. The near field hexagonal pattern of regular geometry recorded onto CCD is shown in Fig. 2**a**. The measured values of the angle between the beams were $\theta_1 = \theta_2 = \theta_3 = 1.1$ mrad and angle

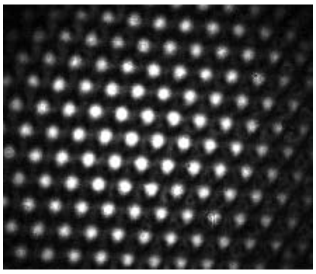

Fig. 2. Hexagonal array pattern at the out put of third stage of interferometer (**a**) recorded onto CCD, (**b**) computed pattern.

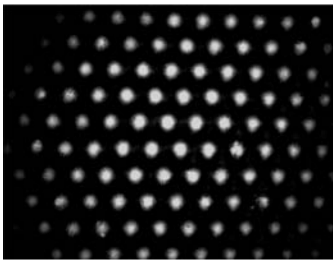

Fig. 3. Hexagonal array pattern at a distance of 2.5 m.

between the *y*-axis and the line joining two beams is $\phi_2 = \phi_3 = 60°$. The corresponding computed hexagonal array pattern from Eq. (9) is shown in Fig. 2**b**. It is in good agreement with the experimental results. The appearance of faint spurious peaks in Fig. 2**a** can be attributed to the front surface reflections from various optical components. The arrays were scanned to a distance of 2.5 meter without observing any significant loss of distortion and loss of contrast. The array pattern recorded at a distance of 2.5 m is shown in Fig. 3.

The variation of fringe visibility as a function of quarter-wave plate Q9 is shown in Fig. 4, where one can see that fringe visibility is sensitive in the range of orientation of Q9 from 0° to 20° and from 70° to 90°.

The efficiency of interferometric configuration was estimated by comparing the output power in the plane of observation after P2 and the input power to

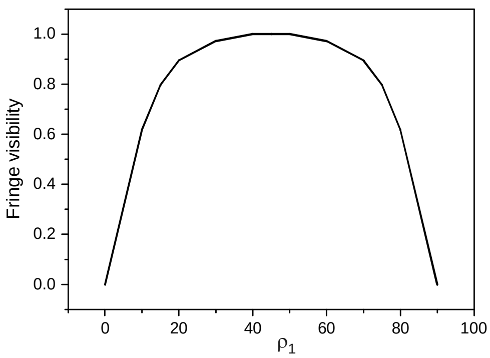

Fig. 4. Fringe visibility curve for the orientation of the quarter-wave plate Q9.

the interferometers after P1. The ratio of the output power to the input power was 0.384. In comparison with the eight-beam interferometers [9] of randomly polarized setup the efficiency of polarized setup is ~ 4 times better.

4. Several possible applications

There are widespread applications of the arrays. Some of the possible applications of these arrays are discussed here.

The interferometric array illuminators have non-uniform light intensity distribution within each spot, the spot densities and width of which can be varied in real time, which allows some possible applications in modifying the trajectories of the atoms. An atom placed in such a non-uniform optical field experiences the dipole force [12, 13]. Due to the interaction of induced dipole moment in the presence of field with non-uniform light distribution the dipole force is generated [12]. The magnitude of this force depends on the intensity gradient and the amount of detuning from the atomic resonance frequency. This dipole force can modify the trajectories of atoms and by carefully choosing the parameters it can lead to the focused spots of atoms of the order of tens of nanometers [14], with periodicity down to $\lambda/8$ [15]. The interference fringes can also be used as optical tweezers for the alignment and manipulation of low-index spheres [16]. Optical tweezer techniques found widespread application in biological research as well.

The delocalized arrays reported in the present paper can be assumed to be traveling in the form of optical channel. There is an intensity variation in any transverse plane of the interferometric arrays. If a nonlinear medium with an intensity dependent non-linear refractive index is placed in the path of the arrays, an array of light channels will be established in the medium. These optical channels in the medium will behave like a light induced graded-index polarization dependent optical planar waveguide. The state of polarization within the spots of arrays can be changed from linearly polarized light to circularly polarized light or elliptical polarized light. Hence, this set up may find applications in light induced graded index optical channel [17], atomic beam channels [4] and polarization optical switching. The polarized arrays can find application in measuring the properties of birefringent media [18].

The interference of the polarized beams can also be used to generate the periodic microstructures. Thus, an array illuminator can be used to write down the three--dimensional photonic crystal [19]. By controlling the relative polarization of eight interfering beams and their angular separations, the periodicity and the geometry of the arrays can be controlled on line. Therefore, the band gap of such engineered materials can be controlled. By changing the geometry and spatial frequencies of arrays, periodic multiple structures can also be generated which allows further fine tuning on to the band gap. These photonic band gap materials have promising application in fabricating optical waveguide, high capacity data storage devices, digital optical computing [20], and in other related areas. The dependence of fringe visibility on the orientation of the quater-wave plate Q9, can be used in on line optical testing.

5. Conclusions

We have demonstrated the formation of regular hexagonal arrays of tiny light spots with good contrast using interference of eight polarized beams. The efficiency of the polarized setup is four times more than that of the randomly polarized setup. The interference patterns were observed without any significant loss of quality to distances of 2.5 m, confirming the formation of delocalized arrays. The computed pattern shows good agreement with experimental results. Hence, using computer controlled motorized optomechanical mounts, an array pattern can be obtained in the predetermined geometry or can be controlled on line in a programmable way. In the present set-up, we reported the improved efficiency compared to randomly polarized set-up but the efficiency is low compared to some of the diffraction based techniques. However, this technique has the major advantage in terms of on line control of the array geometry, no requirement of specialized aperture/grating, and the pattern can be scanned in the longitudinal direction. In the present paper, the analysis was focused on the bright spot or, in other words, on the intensity distribution, a simple recordable parameter for the interference where the phase information is embedded in the interference field. There have also been reports on alternative approach of optical vortices seeded in the dark spot of the interference field for the analysis of phase singularity [21, 22]. Some of the potential applications are also listed in the article.

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