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Two-to-Four Coherent Beams Interference Patterns of Non-Orthogonal Planes

Aliekber AKTAĞ
Department of Physics, Abant Izzet Baysal University, 14280, Bolu-TURKEY
e-mail: aktag_a@ibu.edu.tr

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Abstract

In this paper, we present an analysis of intensity distribution of interference pattern of two-to-four linearly polarized plane waves at their intersection in a plane surface. A configuration in which the four plane waves intersect at different angles along four non-orthogonal planes is considered. We show that the shape and the intensity distribution of the interference pattern is strong function of the angles of planes, kinds of polarizations, beam incidence angles. A variety of two-dimensional intensity distribution arrays have been formed by two-to-four beams with differing plane angles, angles of beam incidence and beam polarizations, which may potentially be useful in forming arrays of submicron structures in thin films. We also give a few experimental examples in Co-Pt and Co/SiO_x multilayer thin films.

Key Words: Lasers, interference patterning, arrays, multilayers, thin films.

1. Introduction

Recent progresses in fabrication of submicron periodic structures on magnetic and non-magnetic materials have made the optical interference lithography particularly attractive for both scientific and technological explorations [1–2]. Interference lithographic techniques benefit from the availability of highly coherent and powerful light which is the potential source demanded for many applications in the visible and UV ranges [3–6].

The several interference patterns between beams have been studied by others [7–10]. In this paper, we describe the pattern formed by two or more counter, non-orthogonally propagating linearly polarized beams. Interference of four linearly *p*-polarized and *s*-polarized light beams was derived and results of calculations are presented for a few experimental situations.

We describe light as an electromagnetic wave with oscillating electric and magnetic field vectors transverse to the propagation direction. As a consequence of wave properties, light exhibits interference effects. Light waves that are in phase with each other undergo constructive interference. Light waves that are exactly out of phase with each other undergo destructive interference and their displacements (electric fields) cancel. In intermediate cases, the total displacement is given by the vector resultant, and the intensity is proportional to the square of resultant displacement amplitude.

Linearly polarized light moving in a plane may be described by its electric vector **E**,

$$\mathbf{E} = \boldsymbol{\varepsilon} E_0 e^{i\phi}$$

where $\boldsymbol{\varepsilon}$ is the unit polarization vector, E_0 is the amplitude, $\phi = \mathbf{k} \cdot \mathbf{r} - \omega t$ is the phase angle at time t and position $\mathbf{r}$ along the direction of propagation vector $\mathbf{k}$, and ω is angular frequency. The plane wave is a wave with its electric field vector always in the direction $\boldsymbol{\varepsilon}$. Such a wave is said to be linearly polarized with polarization vector $\boldsymbol{\varepsilon}$.

2. System Geometry for Calculation

Figure 1 shows the system of four linearly polarized beams incident on a surface which lies in the (xy) plane ($z = 0$). We assume the geometry of the system is arranged such that optical paths are equal for all beams, all beams have the same frequency ω and they intersect at the (xy) plane. Beams with wave vector $\mathbf{k}_i$ propagate in the β_i planes with electric field vectors $\mathbf{E}_i$. The plane angles ($0 \leq \beta_i < 2\pi$, $i = 1...4$) are measured from the positive x axis and the corresponding angles of incidence ($0 \leq \theta_j < \pi/2$, $j = 1...4$) are measured from the normal z-axis.

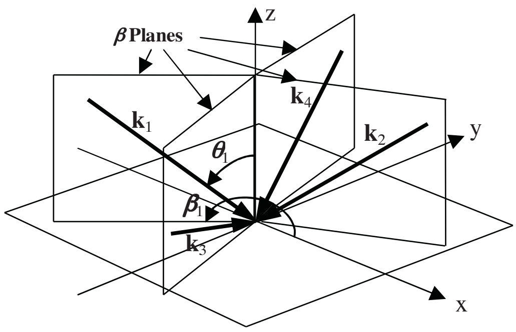

Figure 1. Schematic representation of four linearly polarized beams interfering on the (xy)-plane.

2.1. Interference of four *p*-polarized beams

For all p-polarized systems, the polarization vectors, the propagation vectors and the phase angles in the (xy) plane ($z = 0$) may be written as follows:

$$\boldsymbol{\varepsilon}_{p,n} = \cos\theta_n(\cos\beta_n\hat{x} + \sin\beta_n\hat{y}) + \sin\theta_n\hat{z}, \tag{1}$$

$$\mathbf{k}_n = k(\sin\theta_n(\cos\beta_n\hat{x} + \sin\beta_n\hat{y}) - \cos\theta_n)\hat{z}, \tag{2}$$

$$\phi_n = k\sin\theta_n(x\cos\beta_n + y\sin\beta_n), \tag{3}$$

where $n = 1 \ldots 4$.

Since ω is the same for all beams, the term $e^{-i\omega t}$can be dropped without consequence. Then the resultant electric field of all four p-polarized beams at the intersection may be written as

$$\mathbf{E}_p = \sum_n^4 E_n(\cos\theta_n(\cos\beta_n\hat{x} + \sin\beta_n\hat{y}) + \sin\theta_n\hat{z})\, e^{ik\sin\theta_n(x\cos\beta_n + y\sin\beta_n)}. \tag{4}$$

The intensity of light, I, depends on its electric vector $\mathbf{E}$, at a given instant and position and is proportional to $Re(\mathbf{E} \cdot \tilde{\mathbf{E}})$ where $\tilde{\mathbf{E}}$ is complex conjugate of $\mathbf{E}$. Hence, the intensity for p-polarized beams, I_p may be written as

$$\begin{aligned} I_p \;=\; & \sum_n^4\sum_m^4 E_nE_m(\cos(\beta_n - \beta_m)\cos\theta_n\cos\theta_m + \sin\theta_n\sin\theta_m)[\cos k\,(x(\sin\theta_n\cos\beta_n - \sin\theta_m\cos\beta_m) \\ & + y(\sin\theta_n\sin\beta_n - \sin\theta_m\sin\beta_m))] \end{aligned} \tag{5}$$

2.2. Interference of four s-polarized beams

For s-polarized beam system taking the same propagation vectors as (2), and the phase angles equation (3), the polarization vectors for s-polarization can be expressed as

$$\boldsymbol{\varepsilon}_{s,n} = \sin\beta_n \hat{x} - \cos\beta_n \hat{y}, n = 1...4. \tag{6}$$

Consequently, the resultant electric vector of all four s-polarized beams at the intersection sums to

$$\mathbf{E}_s = \sum_n^4 E_n(\sin\beta_n\hat{x} - \cos\beta_n\hat{y})e^{ik\sin\theta_n(x\cos\beta_n + y\sin\beta_n)}. \tag{7}$$

Then, the intensity for s-polarized beams, I_s can be found as

$$I_s = \sum_n^4\sum_m^4 E_nE_m\cos(\beta_n-\beta_m)\ [\cos k(x(\sin\theta_n\cos\beta_n - \sin\theta_m\cos\beta_m) + y(\sin\theta_n\sin\beta_n - \sin\theta_m\sin\beta_m))]. \tag{8}$$

3. Discussion

We have evaluated expressions (5) and (8) numerically using the symbolic algebra program Maple for a few situations. In our calculations, we have taken all beam electric field strengths to be equal ($E_1 = E_2 = E_3 = E_4 = E_0$), and a wavelength of 532 nm was assumed. In Figures 2 and 4 dark corresponds to low light intensity, while white corresponds to high light intensity.

As it can be seen from Figure 2, β plane orientation have significant role in interference pattern and intensity distributions in addition to E, θ, and $|\mathbf{k}|$. Intensity for both p- and s-polarizations (equations (5) and (7)) is function of the plane angle β and therefore phase.

Figures 2(a) and (b) display the calculated intensity distribution ($\theta_1 = \theta_2 = \theta_3 = \theta_4 = 60°$) for four p- and s-polarized beams for several β planes. In Figure 3, we show how the intensity and "background" intensity vary with the incident angles of p-polarized beams when they interfere in orthogonal four planes. Although it is not shown here, the magnitude of intensity and background intensity for s-polarization did not change with the incident angle.

In Figures 4 and 5, we report some direct laser interference patterning applications in magnetic multilayer thin films: Co/SiO$_x$ and Co-Pt. In Figure 4 atomic force microscope (AFM) image reveals the topographic changes on Co/SiO$_x$ film. In Figure 5 we see no topographic change in AFM, while we see a magnetic pattern or "lattice" in magnetic force microscope (MFM) image clearly.

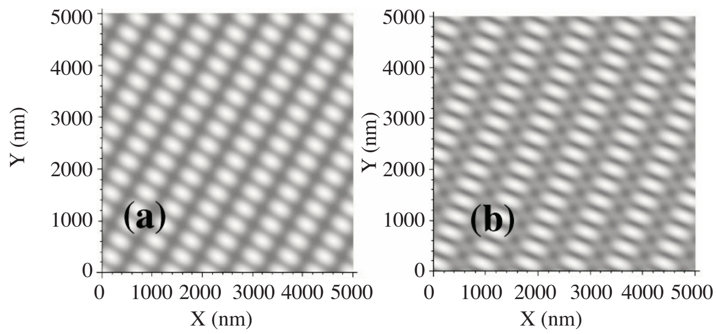

Figure 2. Calculated intensity distribution of four non- coplanar planes at incident angles of $\theta_1 = \theta_2 = \theta_3 = \theta_4 = 60°$. (a) shows p-polarized beams planes at $\beta_1 = 120°$, $\beta_2 = 30°$, $\beta_3 = 270°$, $\beta_4 = 90°$; and (b) shows s-polarized beams in planes at $\beta_1 = 135°$, $\beta_2 = 45°$, $\beta_3 = 270°$, $\beta_4 = 90°$.

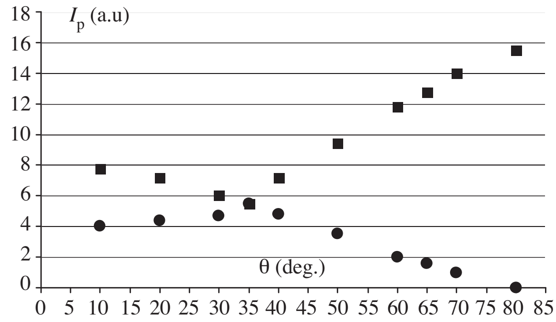

Figure 3. Variation of the intensity (in arbitrary units) (■) and "background" intensity (●) with the incidence angle p-polarized beams.

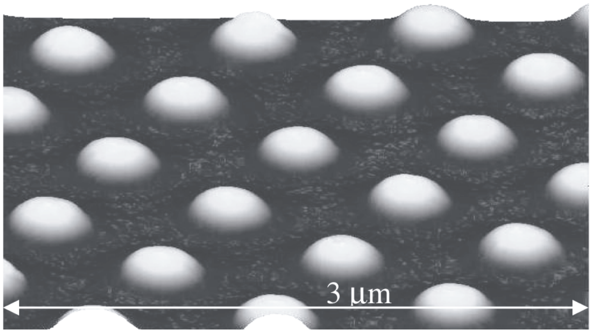

Figure 4. AFM image of Co/SiOx multilayer film.

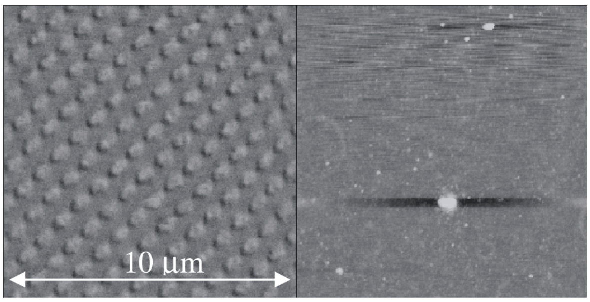

Figure 5. MFM (left), AFM (right) image of Co-Pt multilayer thin film.

4. Conclusion

We have shown that the intensity distribution of interfering non-orthogonal plane beams can produce interesting patterns and applications in thin films. And we also show that the intensity distribution is a strong function of E, θ, k, type of the polarization of the used beam and the plane angle β.

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