Spatial phase filtering with a porphyrin derivative as phase filter in an optical image processor

Kaladevi Sendhil, C. Vijayan *, M.P. Kothiyal

Department of Physics, Indian Institute of Technology, Chennai 600036, India

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Abstract

A robust, self-aligned, polarization independent, pure phase filter was obtained using the intensity dependent refractive index (IDRI) medium, zinc tetraphenyl porphyrin (ZnTPP), a metalloporphyrin. An optical image processor with ZnTPP as the phase filter was designed so that both weak and strong phase objects can be tested with no appreciable design modification. A good phase contrast image with negligible amplitude reduction of the input beam was achieved and the porphyrin as phase filter was found to have several specific advantages over other IDRI media.

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1. Introduction

Imaging and visualization of thin transparent phase objects such as liquid flows, biological samples, thin films, etc. are areas of considerable interest and invite extensive research. Also, the study of the phase aberrations and discontinuities in transparent optical components is important in the field of applied optics. Conventional imaging of these objects does not provide the thickness profile or the phase information since they are transparent in the visible wavelength regime. In such cases, methods like optical interferometry, wave-front sensing, phase contrast methods, etc. are employed where the intensity distribution of the image depends on the phase of the object. Of all the techniques, the phase contrast method, originally developed by Zernike [1], is a highly successful and robust method to image thin transparent phase objects. This technique involves the introduction of a phase step equivalent to $\pi/2$ in the Fourier plane of the image-forming system to
introduce a phase shift between the zero order and higher order spatial frequencies in the Fourier plane to obtain a highly phase contrasted image in the output plane. This technique forms the basis for the phase contrast microscopy which is widely used in the visualization and imaging of biological samples such as living cells, etc.

Design and fabrication of the phase step equivalent to $\pi/2$ and the alignment of the phase step exactly at the zero-order spatial frequency region involves considerable difficulty in the operation of the phase contrast microscope. To overcome these difficulties, a robust phase filtering method using an intensity dependent refractive index (IDRI) material has been proposed, where the IDRI medium is used as the phase filter [2–5]. In this method, the zero order of the Fourier spectrum possessing a higher intensity than the higher orders induces an IDRI and in consequence modifies the phase of the zero-order spectrum. Since only the zero order induces a phase shift and not the higher orders, the filter is automatically aligned to the zero order as is required by the Zernike phase filtering condition. Such a self-alignment is a major advantage in phase filtering where the main difficulty is the alignment of the phase step in the frequency plane. Since the phase shift introduced is intensity dependent, any desired phase step can be achieved by changing the intensity of the input beam. Certain nonlinear media, which exhibit an IDRI like liquid crystals, bacteriorhodopsin and photorefractive crystals, have been successfully used in spatial phase filtering of thin transparent phase objects [2–5]. Also, a similar technique using the IDRI medium in the 4-f image forming system, a commonly used processor configuration, where the input plane and the output plane are separated by four times the focal length $f$ of the Fourier transform lens [6] has been proposed for the determination of the nonlinear refractive index of the such media [7].

In this paper, we propose a phase filtering method based on the nonlinear material, a metalloporphyrin, placed in the 4-f imaging configuration for the phase contrast imaging of both thin and thick phase objects. In the conventional techniques of phase filtering, to image thin phase objects ($<\pi/3$), Zernike phase contrast condition is adopted and for thick phase objects ($\sim 2\pi$) the Zernike phase contrast condition is modified to the generalized phase contrast condition [8]. The generalized phase contrast method differs from the Zernike phase contrast method in that the contribution from the higher order terms in the phase distribution is taken into account. In the case of a significant modulation of the input phase, the contribution from the spatially varying higher order terms results in an attenuation of the focal spot amplitude, which may lead to design and fabrication complications of the phase filter. We show here that with porphyrin as the IDRI medium, the required phase filter ($\pi/2$ for thin phase objects and $>\pi/2$ for thick phase objects) is obtained by just varying the input intensity and the fill factor of the illuminating beam without involving any design modification of the phase filter as is required by the conventional techniques. The fill factor has a major influence on the contrast of the image in the Zernike type phase contrast filtering [9].

The metalloporphyrin used as the intensity dependent phase filter is zinc tetraphenyl porphyrin (ZnTPP). Porphyrins are known to exhibit a nonlinear refractive index value of $\sim 10^{-18}$ cm$^2$/W when probed with a continuous wave (CW) low power laser source [10,11] and are physically and chemically stable. The major advantage of using ZnTPP is that the nonlinearity exhibited by ZnTPP is polarization independent in the CW regime and has a thermo-optic origin that can manifest itself at low powers. It also shows a very low linear absorption at the probing wavelength and exhibits a nonlinear refractive index which is not very high as is exhibited by some liquid crystals ($\sim 10^{-6}$ cm$^2$/W) or very low ($<10^{-12}$ cm$^2$/W) under low power sources. This makes it ideally suitable to be a phase filter since one of the requirements of the nonlinear optical medium to perform the function of a phase filter is that no phase shift should be introduced by the higher orders of the spatial frequencies.

The nonlinear refractive index and linear optical absorption coefficient of ZnTPP are separately determined using the Z-scan technique [12] and a HITACHI U-3400 spectrophotometer, respectively.
2. Description

The experimental set-up of the 4-f phase filtering system for obtaining the phase mapping of transparent objects is shown in Fig. 1(a). A thin lens of 25-mm aperture and focal length of 100 mm was used to achieve the object’s Fourier transform. The IDRI medium, ZnTPP in toluene solvent, was taken in a glass cuvette of 1-mm thickness and placed in the focal plane (FP) of the lens. A linearly polarized He–Ne laser beam of Gaussian output and maximum power 20 mW was used as the input source. The input intensity was varied with a polarizer placed before the input plane (IP) of the imaging system. The phase objects, both thin and thick, are placed in the input plane and image is obtained in the output plane (OP) of the imaging system and subsequently captured by a CCD camera. Image of phase objects without any phase contrast operation are also obtained for comparison purposes.

For thin transparent phase objects that fulfill the condition of Zernike phase contrast method (phase $\phi < \pi/3$), the intensity distribution of the image is given by

$$I(x) = 1 + 2\phi(x),$$

where the small scale phase approximation

$$\exp(i\phi) = 1 + i\phi$$

has been employed.

For imaging such thin phase objects, the fill factor (the ratio of the area of the object to the area of the illuminating beam) of the illuminating beam is maintained at 1 and the intensity of the incident radiation is varied until best possible phase contrasted image is obtained in the output plane. But in the case of thick phase objects, the higher orders in the Taylor expansion of the input phase given by

$$\exp(i\phi) = 1 + i\phi - 1/2\phi^2 - 1/6i\phi^3 + \cdots$$

have to be taken into account leading to the generalized phase contrast method.

The intensity distribution in the image plane in such cases has been studied in detail by Glückstad and Mogensen [13]. They present a complete description of the design and optimization of 4-f optical systems based on common path interferometer and derive optimal conditions for the fringe accuracy, peak irradiance and visibility of the fringes in the image plane. They further show that for thick phase objects (>3$\pi/2$) the fringe visibility and peak irradiance cannot be maximized simultaneously and visibility is rendered maximum at an expense of reduced peak irradiance when large input phase is involved. They also suggest extensions to the linearity of the phase-to-intensity mapping, for example, up to a phase of $2\pi$, by introducing two common path interferometers in parallel.

As can be deduced from the above-mentioned considerations, the zero-order intensity now will have a contribution from higher orders as well, altering the ratio of the intensities between the zero order and the higher orders. While using conventional techniques to image such thick phase objects, the phase filter used for the purpose has to undergo design and fabrication changes to take into account the higher order contribution to the zero-order intensity in the Fourier plane. But in the phase contrast method with an IDRI phase fil-

Fig. 1. (a) 4-f Imaging set-up for phase contrast filtering with ZnTPP as the phase filter. (b) The difference in the area of the illuminating beam for imaging thin and thick phase objects.
ter, the task is made easier by just varying the fill factor of the illumination beam in order to obtain the required intensity in the zero-order frequency spectrum and thus altering the ratio between the zero and higher orders. The fill factor is an important factor in the imaging of thick phase objects since it results in a higher intensity in the zero order which is required to obtain a higher phase shift than earlier (as in the case of thin phase objects). Both the fill factor and the incident intensity were varied to obtain a satisfactory phase contrasted image in the output plane. The fill factor differences in the imaging of thin and thick phase objects have been depicted in Fig. 1(b).

The phase shift introduced by the nonlinear medium, ZnTPP was mapped with respect to the incident intensity in a separate experiment where the phase shift dependence on the intensity of the incident beam induced in a nonlinear optical medium is given by the expression

\[ \phi = \left( \frac{2\pi dn_2 I_0}{\lambda} \right), \]

(4)

where \( d \) is the thickness of the medium, \( n_2 \) the nonlinear refractive index of the medium, \( I_0 \) the intensity of the incident beam and \( \lambda \) the wavelength of the incident light. This gives an approximate idea of the incident intensity to obtain the required phase step, e.g., \( \pi/2 \) or \( \pi \) as the case may be.

3. Results and discussion

The linear and nonlinear optical properties of ZnTPP at the probing wavelength were determined. The linear absorption coefficient of the ZnTPP in toluene solution taken with the help of HITACHI U-3400 spectrophotometer at the probing wavelength of 632.8 nm was found to be 0.2/cm. The value of the nonlinear refractive index \( (n_2) \) of ZnTPP in toluene solvent as determined by the well-known Z-scan technique was found to be \(-1.4 \times 10^{-7}\) cm²/W. The phase shift with different intensity using ZnTPP separately obtained using the phase shifting techniques based on Mach-Zehnder interferometer is shown in Fig. 2. We can see from the graph that the phase shift introduced by the ZnTPP is linearly dependent on the intensity making it easier to set the required intensity to obtain the desired phase shift in the zero order of the frequency spectrum. The low value of the linear absorption coefficient and the adjustable phase shift makes the IDRI medium an ideal phase filter that does not modify the amplitude but alters only the phase of the incident beam.

3.1. Thin transparent phase objects

For the phase contrast imaging of thin phase objects using ZnTPP as the phase filter, two thin phase objects, which satisfy the Zernike condition, have been chosen i.e. a candle flame and a thin film of polymer polymethyl methacrylate (PMMA). A \( \pi/2 \) phase shift is induced in the zero order by setting the input beam power at \(-6\) mW (equal to intensity \( 4.3 \) MW/m²) so that the Zernike condition is satisfied and a high phase-contrasted image of the thin phase objects placed in the input plane is obtained.

Figs. 3(a) and (b) show the images of the candle flame without phase contrast and with the application of the phase contrast technique with ZnTPP as phase filter, respectively. The airflow around a candle flame is clearly visible after phase filtering whereas in the image without phase contrast, only the wick of the candle can be made out. Similarly for another thin phase object, the transparent thin film of PMMA, the phase-contrasted image is shown in Fig. 4(b) and compared with the original image in Fig. 4(a). In this case a slight depth profile is visible in the unfiltered image which is enhanced.
considerably and phase mapping of the rest of the surface is brought out clearly with the application of phase contrast technique.

3.2. Thick phase objects

A parallel glass plate and a glass sphere have been chosen as thick phase objects to demonstrate the phase contrast imaging using ZnTPP as the phase filter. The values of the fill factor and the power of the incident beam for a satisfactory phase contrast image to be obtained in the output plane for the glass plate were found to be $\sim 0.12$ and $8\,\text{mW}$ (equal to intensity $5.7\,\text{MW/m}^2$), respectively. The corresponding values of the fill factor and power for the glass sphere were $\sim 0.10$ and $6\,\text{mW}$ (intensity $4.3\,\text{MW/m}^2$), respectively.

Figs. 3(a) and (b) show the image of the glass plate without and with the application of phase contrast technique using ZnTPP as phase filter. The parallel fringes with equal spacing are obtained in the phase contrast image for the glass plate hiding a small wedge. Similarly, Figs. 6(a) and (b) show the images of the glass sphere with a tubular glass fibre stem. Circular fringes of varying thickness have been obtained which is characteristic of the phase distribution of any spherical optical component. Fringes are visible even in the stem area bringing out the tubular nature of the glass fibre stem.
4. Conclusion

A simple, robust and self-aligned phase contrast method using an IDRI refractive index as phase filter in the Fourier plane of the 4-f imaging configuration was developed with the ZnTPP as the IDRI medium. Phase contrast imaging of thin and thick transparent phase objects was obtained using the same experimental set-up, by varying the incident intensity and the fill factor of the illuminating beam. The low absorption coefficient of the material and a linear dependence of the phase shift on the intensity render ZnTPP an ideal material for phase filtering techniques. Since the nonlinearity of porphyrins is not polarization dependent it has an added advantage with respect to phase filtering over other materials like liquid crystals and photorefractive crystals.

References