Optical data manipulation technologies increasingly employ densely aperiodic optical 3D phase elements. Refinement of such technologies will require the capability to quantitatively characterize the volumetric dielectric modulation of an optical sample to a high level of precision and spatial resolution. We present a scanning transmission microscopy system that uses a position-sensitive detector to impart sensitivity to both the phase and absorption components. We describe the layout of the instrument and then derive its phase and absorption transfer functions. Simulations and experiments are presented to validate the analysis. For phase detection, the instrument possesses depth-sectioning properties similar to those of a confocal microscope without the use of a pinhole, enabling full 3D object reconstruction. © 2006 Optical Society of America

1. Introduction

New 3D manufacturing technologies are renewing interest in volumetric phase structures for engineering applications such as holographic data storage and optical device integration using direct-write waveguides in photopolymer or fused silica. Transmission mode data holograms and point-written waveguides both occupy spatial frequency bands that are amenable to detection with a microscope in a transmission geometry.

Volumetric imaging has long been of interest to engineers, physicists, and biologists, and microscopists have provided many solutions to the problem. Traditional bright-field microscopy is not phase sensitive, nonquantitative, and does not provide 3D information. The optical depth sectioning property of the confocal reflection microscope allows a desired 2D image plane within a 3D sample to be effectively isolated from other image planes. Investigators have further developed the theory of volumetric imaging to include the development of 3D transfer functions for microscopy.

Refractive index is not straightforward to measure in transmission since detectors are not generally sensitive to optical phase. Instruments such as the phase-contrast microscope and the differential interference contrast (DIC) microscope use white light to produce images indicative of phase effects at an image plane within a volume, but are typically unsuitable for obtaining quantitative 3D measurements. Diffraction tomography is quantitative in three dimensions, but complex to implement. Confocal microscopy is also quantitative in three dimensions but is generally practical only in reflection, which limits its applicability to high spatial frequency features with specific orientations.

Another method with particular relevance to this discussion was described by Kawata et al. that utilizes the differential signal from a split detector to provide phase sensitivity. This method is phase sensitive only for grating components that are Bragg matched by coupled waves that straddle the detector elements, leading to voids in the transfer function passband. The split-detector differential phase contrast microscope does, however, demonstrate the use of detector position information for phase sensitivity in a manner basically similar to the position-sensitive detector (PSD).

The present device is a coherently illuminated transmissive scanning microscope that employs a position sensing detector such as a lateral effect photodiode, rather than an ordinary photodiode or split detector. We show that the extra information provided by the PSD can be used to calculate the complex...
3D dielectric distribution, i.e., the volumetric distribution of both refractive index and absorption, of a weakly diffracting optical sample. The instrument is noteworthy for phase-depth-sectioning properties that do not depend on a confocal pinhole, and for the fact that its phase-transfer function is relatively flat throughout the region of support, reducing the problem of noise enhancement during reconstruction. Since high frequencies within the passband are enhanced by the differentiating transfer function, the practically achievable resolution may in some cases be higher than that of a nondifferentiating microscope of the same numerical aperture.

We will describe the operation of the instrument, derive its transfer functions, and verify them with numerical simulations. We will also predict and verify the depth-sectioning properties. Finally, some images scanned by the prototype instrument are presented.

2. System Overview

A schematic of the instrument constructed for the experimental demonstrations is shown in Fig. 1. A diode laser at 635 nm is used to provide a nominally coherent probe beam for the system (the temporal coherence requirements are quite undemanding). After collimation, the probe beam is passed through a polarizing beam splitter (PBS) and a quarter-wave plate (QWP) so that the sample is probed with circularly polarized light, which diffracts isotropically. The objective lens is a LightPath 350340 aspheric microscope objective (N.A. = 0.62), which is corrected for a focal depth of 1.2 mm. Typically, the objective beam is apertured to N.A. = 0.3 to permit a total scanning depth range of approximately 1 mm without active spherical aberration correction.

Figure 1 also shows a confocal reflection path consisting of a condenser lens, a pinhole, and a conventional photodetector (PD). Fresnel reflections of the probe beam by the sample are detected here, thereby implementing a conventional confocal reflection microscope. The reflection channel is not further considered in this paper, but it provides a complementary spectral passband of dielectric sensitivity, and is also useful for alignment purposes (such as locating the sample surface).

The light transmitted through the sample is collected by a 4 F camera lens relay, and then apertured down to the angular extent of the original (undeviated) probe beam. The relay allows a large working distance on the exit side of the sample despite the small 4.0 mm size of the ON-TRAK model PSM2-4 PSD. The PSD detects the x and y centroids of the optical power distribution upon the detector (i.e., beam position), as well as the total optical power. The PSM2-4 is a lateral effect photodiode, which is a monolithic analog PSD that can be operated at moderately high bandwidths.

Scanning is accomplished by mounting the sample on a high-precision x, y, z translation platform incorporating Newport PM500 linear stages. A 3D image is collected by translating the probe focus through each point in a 3D grid that samples the volume of interest. At each sampling position, the controller computer digitizes and records the x centroid, the y centroid, and the total optical power. The reflection channel signal is also collected. Speed is maximized by taking data while the stage is in motion; care is taken to ensure that all electrical signal bandwidths exceed the scan sampling rate.

Once collected, the scan data are postprocessed by using a dielectric computation algorithm. The algorithm calculates a volumetric map of the complex dielectric of the sample by linear deconvolution in accordance with the instrument’s theoretical transfer function, as derived in Section 3.

3. System Analysis

An analysis of the instrument’s response begins by noting that the probe beam may be decomposed into pairwise plane-wave components, each pair representing coupled modes interacting with a specific dielectric grating component that satisfies the Bragg condition

\[ \hat{k}_d = \hat{k}_p + \hat{k}_g, \]

where \( \hat{k}_d \) and \( \hat{k}_p \) are the wave vectors of the interacting coupled modes, and \( \hat{k}_g \) is the grating vector. Figure 2 illustrates the relationships between the grating and the coupled components in real and reciprocal space (\( \hat{k} \) space).

For propagating monochromatic light, we have

\[ |\hat{k}_d| = |\hat{k}_p| = \frac{2\pi n_0}{\lambda} = k_n, \]

where \( n_0 \) is the homogeneous (nonspatially varying) refractive index of the sample.

![Fig. 2. (a) Coupled plane-wave probe components interact with a Bragg-matched grating within the sample and are detected at points \( p \) and \( d \) on the detector in the far field. (b) \( \hat{k} \) space representation of the grating and wave vectors.](image)

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The complex dielectric modulation of the grating component dictates both the amplitude and the phase of the diffracted light.⁴ We shall make the assumption that the object is weakly diffracting and absorbing, so that the diffracted field is small and linear with the inhomogeneous dielectric modulation, the probe is effectively undepleted, and the rediffracted fields are negligible (i.e., Born regime diffraction). The diffracted light mixes coherently with the undepleted probe producing an irradiance modulation that can be detected at a specific point on the detector in the far field. This mixing has the effect of providing coherent gain to the diffracted portion of the light, offering the possibility of extremely high sensitivity.

The absorptive and index grating components give detectably different responses, and thus can be simultaneously and independently measured. In the case of an imaginary (absorptive) dielectric grating component, the two probe components are intensity modulated in tandem as the probe scans. In this case, the grating component will be detected as a modulation of the total optical power seen by the PSD.

In the case of a real dielectric grating (phase grating), the two probe components are intensity modulated 180° out of phase. As a phase grating is scanned, diffracted light swaps back and forth between the two coupled components with no net change in intensity. A conventional photodiode does not detect this situation, but a PSD does. The grating is manifested as a cyclic modulation of the irradiance centroid position striking the PSD.

A. Single Sideband Detection
To develop this characterization analytically, we first consider the one-way diffraction of an \( E_p \) probe mode into an \( E_d \) diffracted mode, as illustrated by the \( E_p \) to point \( d \) path in Fig. 2. In the weakly diffraction regime, the complex amplitude of the diffracted beam is proportional to the product of the probe beam and the dielectric

\[
E_d(\mathbf{k}_d) = j\kappa \varepsilon(\mathbf{k}_s) E_p(\mathbf{k}_d - \mathbf{k}_s),
\]

where \( E_p(\mathbf{k}) \) and \( E_d(\mathbf{k}) \) represent the complex amplitudes of the undiffracted and diffracted light, respectively; \( \varepsilon(\mathbf{k}) \) is the inhomogeneous part of the dielectric distribution; \( \mathbf{k} \) is the spatial frequency vector; and \( \kappa \) is the coupling factor, which is approximately constant for a small N.A.

We then apply this relationship to write eigen-decompositions of the three individual Fourier components of Eq. (3) in real space:

\[
\varepsilon(r) = \varepsilon(\mathbf{k}_s) \exp[-j\mathbf{k}_s \cdot (r - r_s)],
\]

\[
E_p(r) = E_p(\mathbf{k}_d) \exp(-j\mathbf{k}_d \cdot r),
\]

\[
E_d(r) = j\kappa \varepsilon(\mathbf{k}_s) \exp[-j\mathbf{k}_s \cdot (r - r_s)] E_p(\mathbf{k}_d - \mathbf{k}_s) \exp[-j(\mathbf{k}_d - \mathbf{k}_s) \cdot \mathbf{r}],
\]

where \( r \) is the spatial coordinate vector and \( r_s \) is the spatial scanning coordinate vector (i.e., the relative displacement of the sample with respect to the probe beam). The non-Bragg-matched conjugate sideband of the dielectric distribution is neglected here, and will be considered in Subsection 3.B. The irradiance at point \( d \) is determined by the coherent summation of the original and diffracted components:

\[
I(\mathbf{r}_d) = |E_p(\mathbf{r}) + E_d(\mathbf{r})|^2
= [E_p(\mathbf{k}_d) \exp[-j\mathbf{k}_d \cdot \mathbf{r}] + j\kappa \varepsilon(\mathbf{k}_s) E_p(\mathbf{k}_d - \mathbf{k}_s) \exp[-j(\mathbf{k}_d - \mathbf{k}_s) \cdot \mathbf{r}] |^2
\]

\[
= [E_p(\mathbf{k}_d)]^2 + |\kappa \varepsilon(\mathbf{k}_s) E_p(\mathbf{k}_d - \mathbf{k}_s)|^2
+ E_p(\mathbf{k}_d)(-j\kappa \varepsilon(\mathbf{k}_s) E_p(\mathbf{k}_d - \mathbf{k}_s) \exp[-j(\mathbf{k}_d - \mathbf{k}_s) \cdot \mathbf{r}])
+ E_p^*(\mathbf{k}_d) j\kappa \varepsilon(\mathbf{k}_s) E_p(\mathbf{k}_d - \mathbf{k}_s) \exp[j(\mathbf{k}_d - \mathbf{k}_s) \cdot \mathbf{r}].
\]

In the last form, the first term represents the intensity of the undiffracted probe, which is not modulated with the scanning position (no \( r_s \) dependency). Given the assumption that we are operating in the low-diffraction regime, the probe is undepleted, and we may drop this constant background term by subtracting the dc component of the detected irradiance. Similarly, the second pure diffraction term is not modulated with \( r_s \) and is very small compared to the coherently amplified third and forth terms, and thus may also be neglected leaving

\[
I(r_s) \equiv E_p(\mathbf{k}_d)(-j\kappa \varepsilon^*(\mathbf{k}_s) E_p^*(\mathbf{k}_d - \mathbf{k}_s) \exp[-j(\mathbf{k}_d - \mathbf{k}_s) \cdot \mathbf{r}_s])
+ \exp(-j\mathbf{k}_s \cdot r_s) + \text{c.c.},
\]

where c.c. is used to denote the complex conjugate of the preceding term. The detected power of this signal is integrated over the angular acceptance aperture of the detector:

\[
P_0(\mathbf{r}_s) = \int \mathbf{d} \mathbf{k}_d A(\mathbf{k}_d) I(\mathbf{r}_d)
\]

\[
= -j\kappa \varepsilon^*(\mathbf{k}_s) \exp(-j\mathbf{k}_s \cdot \mathbf{r}) \int \mathbf{d} \mathbf{k}_d A(\mathbf{k}_d) E_p(\mathbf{k}_d)
\]

\[
\times E_p^*(\mathbf{k}_d - \mathbf{k}_s) + \text{c.c.},
\]

where

\[
A(\mathbf{k}) = \begin{cases} 1, & \mathbf{k} \text{ strikes the detector} \\ 0, & \text{otherwise.} \end{cases}
\]

Applying the definition for cross correlation,

\[
F(\mathbf{k}) \otimes G(\mathbf{k}) = F^*(-\mathbf{k}) \ast G(\mathbf{k}),
\]

where the binary operator \( \ast \) denotes convolution and the unary operator \( \ast \) denotes complex conjugation, Eq. (7) becomes
\[ P(\vec{r}) = -jke^*(\vec{k}) \exp(-j\vec{k} \cdot \vec{r}) E_p(\vec{k}) \times [A(\vec{k}) E_p(\vec{k})] + \text{c.c.} \] (8)

We define a manifold function that expresses the cross-correlation term as

\[ M^s(\vec{k}) = E_p(\vec{k}) \times [A(\vec{k}) E_p(\vec{k})]. \] (9)

Taking the Fourier transform of Eq. (8) with respect to the scanning coordinate gives us the 3D spatial spectrum of the detected data:

\[ P(\vec{k}) = jk [e(\vec{k}) M(\vec{k}) \delta(\vec{k} - \vec{k}_s) - e^*(\vec{k}) M^s(\vec{k})] \times \delta(\vec{k} + \vec{k}_s). \] (10)

The \( \delta \) function sifts \( \vec{k}_s = +\vec{k}_s \) and \( \vec{k}_s = -\vec{k}_s \), giving

\[ P(\vec{k}) = -jke^*(\vec{k}) M(\vec{k}), \] (11a)

\[ P(\vec{k}) = +jke(\vec{k}) M(\vec{k}), \] (11b)
equations representing the conjugate sidebands of the real detector signal individually. Therefore we can equate the detected data Fourier transform to the sample dielectric Fourier transform and define

\[ H_{SS}(\vec{k}) = \frac{P(\vec{k})}{e(\vec{k})} = j2\kappa M(\vec{k}), \] (12)

which is the transfer function relating the sample dielectric to the detected power for the single grating sideband (in this simplified unidirectional coupling case).

The preceding discussion shows how the single grating sideband, \( e(\vec{k}) \), is mapped onto both sidebands of the detected power signal, \( P(\pm \vec{k}) \). Such a situation would be physically realized for some angular components if the detector aperture, \( A(\vec{k}) \), is of smaller angular extent than the probe beam, \( E_p(\vec{k}) \), so as to collect only one sideband. However, no information has been conveyed about the other sideband of the grazing vector, and thus the absorptive and phase components of gratings so detected cannot be distinguished. We will henceforth restrict our discussion to the case in which the detector aperture has been selected to match the angular extent of the probe beam, and both sidebands are detected.

B. Coupled Sideband Detection

As a preface to our discussion of coupled sideband detection, let us review the symmetry properties of the sample dielectric. In real space, the complex sample dielectric may be expressed as the sum of real and imaginary parts as \( e(\vec{r}) = e_p(\vec{r}) + je_a(\vec{r}) \), where \( e_p(\vec{r}) \) is the real part describing the phase delay of the medium, and \( je_a(\vec{r}) \) is the imaginary part that accounts for absorption (or emission). Accordingly, in \( \vec{k} \) space, the dielectric transform may be expanded into real and imaginary parts of the phase and absorptive components with the following symmetries:

\[ e(\vec{k}) = e_p(\vec{k}) + je_a(\vec{k}), \] (13)

where real phase, \( e_p(\vec{k}) \), is even, imaginary phase, \( e_a(\vec{k}) \), is odd, real absorption, \( e_a(\vec{k}) \), is even. Returning to Fig. 2, we now consider both diffraction paths, \( E_p \to d \) and \( E_p \to p \). Coupled-mode detection may be represented as the summation of single sideband detection of both of the involved modes. From Eq. (11), we can write the optical power in the \( d \) mode as

\[ P_d(\vec{k}) = +jke^*(\vec{k}) M(\vec{k}), \] (14)

where we have added the \( d \) subscript to distinguish these terms from the power in the coupled \( p \) mode. The latter may be written by inspection from symmetry:

\[ P_p(\vec{k}) = -jke^*(\vec{k}) M(\vec{k}). \] (15)

The \( d \) and \( p \) modes are spatially incoherent, so we may sum powers:

\[ P(\vec{k}) = P_d(\vec{k}) + P_p(\vec{k}) = jk M(\vec{k})[e^*(\vec{k}) - e^*(\vec{k})], \] (16)

incorporating also the fact that for our choice of even probe, \( M(-\vec{k}) = M(\vec{k}) \). Expanding the dielectric into phase and absorption parts with Eq. (13), we find that the phase parts cancel and the detected power becomes

\[ P(\vec{k}) = j2\kappa M(\vec{k}) e_a(\vec{k}), \] (17)

leading to the transfer function relating the absorptive dielectric to the detected power in the coupled sideband case:

\[ H_{CS}(\vec{k}) = \frac{P(\vec{k})}{e_a(\vec{k})} = j2\kappa M(\vec{k}). \] (18)

The fact that the phase component of the dielectric has disappeared is consistent with our earlier observation that a phase grating can swap power only between the coupled modes with no net power change.

Figure 3 shows a \( k_x - k_z \) cross section of the imaginary part of the transfer function for a 0.5 N.A. focusing probe beam with uniform angular illumination. The strong attenuation of the high-frequency components and the overall butterfly shape of the region of support are characteristics shared by other types of transmission microscopes.14
C. Detection with a Position Sensitive Detector

An ideal 2D PSD outputs signals that are proportional to the $x$ and $y$ centroids of the irradiance distribution falling upon the active area of the detector. Proceeding in a manner analogous to the preceding development, recall the expression for the intensity of a single diffracted sideband (Eq. 6):

$$I_d(\vec{r}_s) = E_p(\vec{k}_d)(-j\kappa e^*(\vec{k}_d)E_p^*(\vec{k}_d - \vec{k}_s)) \times \exp(-j\vec{k}_s \cdot \vec{r}_s) + c.c.,$$

and note that for our choice of even probe beam, $S_r(\vec{k})$ is real so that $S_r^*(\vec{k}) = S_r(\vec{k})$. The Fourier transform with respect to the scanning variable is then

$$C_{dx}^*(\vec{k}_s) = j2\kappa S_r(\vec{k}_s)e(\vec{k}_s),$$

or

$$C_{dx}^*(\vec{k}_s) = j2\kappa S_r(\vec{k}_s)e^*(-\vec{k}_s).$$

Comparing Eq. (22) with Eq. (8), we see that the effect of using a PSD instead of an ordinary power detector is to include a $k_x$ factor in the cross correlation constituting the manifold function. We define this single sideband PSD manifold:

$$S_r(\vec{k}) = E_p(\vec{k}) \otimes [\kappa A(\vec{k}) E_p(\vec{k})],$$

and by symmetry the coupled mode becomes

$$C_{dx}^*(\vec{k}_s) = j2\kappa S_r(\vec{k}_s)e^*(-\vec{k}_s).$$

The overall centroid is the mean of the $d$ and $p$ mode centroids:

$$C_x(\vec{k}) = \frac{1}{2} [C_{dx}(\vec{k}) + C_{px}(\vec{k})] = j\kappa [S_r(\vec{k})e(\vec{k}) - S_r^*(-\vec{k})e^*(-\vec{k})].$$

Expanding the dielectric by using Eq. (13) and canceling terms,

$$C_x(\vec{k}) = j\kappa [S_r(\vec{k}) - S_r^*(-\vec{k})]e(\vec{k}) + [S_r(\vec{k}) + S_r^*(-\vec{k})]e_a(\vec{k}).$$

If the absorptive dielectric, $e_a(\vec{k})$, is known (e.g., from applying Eq. (18) to the sum channel of the PSD), then the phase dielectric may be computed as
further simplified by noting that lower magnitude regions of the transfer function.

The problem of noise amplification when inverting the amplitude transfer function of Fig. 3 (a). This reduces throughout the region of support in comparison to the phase dielectric transform are calculated according to the transform of the unsquared probe intensity pattern. An estimate of the inhomogeneous volumetric index modulation, may be determined from the raw data by applying the \( \xi \) microscope, whereas the PSD-phase response of Eq. (30) falls into neither category.

D. Evaluation of the Transfer Functions

The specific form of the PSD transfer function depends on the 3D pupil function of the probe, \( E_p(\mathbf{k}) \). Closed-form expressions for the autocorrelation of spherical shells have been derived by investigators seeking the transfer functions for high-aperture microscopy systems. For the case in which the probe consists of uniform angular illumination and both the probe and the detector are circular with numerical aperture \( \sin \alpha \), the autocorrelation can be expressed as

\[
M(\mathbf{k}) = \frac{4}{\pi k_n} \cos^{-1} \left[ \frac{k_x |k_z|}{2 \sqrt{(k_x^2 + k_y^2)(1 - \frac{1}{4} k_n^2)}} \left( \frac{2 \cos \alpha}{|k_z|} + 1 \right) \right].
\]

(32)

Combining Eqs. (30), (31), and (32), we arrive at the PSD-phase transfer function

\[
H_{\text{PSD}}(\mathbf{k}) = \frac{j \beta k_n}{\pi k_n} \cos^{-1} \left[ \frac{k_x |k_z|}{2 \sqrt{(k_x^2 + k_y^2)(1 - (1/4)k_n^2)}} \right] \times \left( \frac{2 \cos \alpha}{|k_z|} + 1 \right).
\]

(33)

An analogous expression holds for \( H_{\text{PSD}}(\mathbf{k}) \). These closed-form transfer function expressions are incorporated into the instrument controller and are used to transform the raw PSD-phase function data into the measured sample dielectric distribution.

E. Applying the Transfer Functions

An estimate of the inhomogeneous volumetric index modulation, \( \hat{n}(\mathbf{r}) \), may be determined from the raw data by applying the \( H_{\text{PSD}}(\mathbf{k}) \) and \( H_{\text{PSD}}(\mathbf{k}) \) transfer functions as follows. First, two separate estimates of the phase dielectric transform are calculated accord-

\[
\varepsilon_p(\mathbf{k}) = \frac{C_\alpha(\mathbf{k}) + \kappa [S_\alpha(\mathbf{k}) + S_\alpha(-\mathbf{k})]}{j \kappa [S_\alpha(\mathbf{k}) - S_\alpha(-\mathbf{k})]}.
\]

(29)

Alternatively, for a weakly absorbing object, the absorptive dielectric may be ignored, and the phase dielectric transfer function may be written,

\[
H_{\text{PSD}}(\mathbf{k}) = \frac{C_\alpha(\mathbf{k})}{\varepsilon_p(\mathbf{k})} = j \kappa [S_\alpha(\mathbf{k}) - S_\alpha(-\mathbf{k})] = 2 \kappa D_\alpha(\mathbf{k}).
\]

(30)

This transfer function is illustrated in Fig. 4, showing the noteworthy uniformity of frequency response throughout the region of support in comparison to the amplitude transfer function of Fig. 3 (a). This reduces the problem of noise amplification when inverting the lower magnitude regions of the transfer function.

The double sideband PSD transfer function can be further simplified by noting that

\[
D_\alpha(\mathbf{k}) = j k_x \{ E_p(\mathbf{k}) \otimes [A(\mathbf{k}) E_p(\mathbf{k})]\} = j k_x M(\mathbf{k}).
\]

(31)

In the typical case where the aperture function \( A(\mathbf{k}) \) matches the angular extent of the probe beam, the manifold function may be simplified to \( M(\mathbf{k}) = E_p(\mathbf{k}) \otimes E_p(\mathbf{k}) = I(\mathbf{k}) \), i.e., the manifold function is simply the Fourier transform of the probe beam’s 3D intensity distribution. Similarly, the differential manifold \( D(\mathbf{k}) \) is simply the Fourier transform of the probe beam’s intensity pattern differentiated with respect to \( x \). By comparison, the transfer function manifold of an ideal confocal microscope is the transform of the probe beam’s intensity pattern squared. The confocal microscope has been designated a type 2 microscope to distinguish it from a conventional type 1 microscope, which has a transfer function proportional to the transform of the unsquared probe intensity pattern. Evidently, the absorptive response for the present instrument [Eq. (18)] constitutes a type 1 microscope, whereas the PSD-phase response of Eq. (30) falls into neither category.

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The refractive index modulation may usually be determined from the relation $n_i(r) = \varepsilon_p(r)/2n_o$, where the homogeneous refractive index, $n_o$, must be established by other means. (Note that throughout we have been concerned only with the inhomogeneous dielectric—the homogeneous component is not directly detectable owing to the null at D.C. in the differentiating transfer function.)

F. Optical Depth-Sectioning Properties

For 3D imaging, it is desirable to limit rather than enhance the depth of field in a microscope. A pinhole placed in an image plane of the probe focus limits the depth of field in a scanning confocal reflection microscope. However, in a transmission microscope, sample aberrations or wedging may create a poor or nonstationary image of the probe focus, making a transmissive confocal microscope very difficult to implement.\textsuperscript{16}

As the 3D point spread function for the type 1 microscope has the form of the probe beam intensity pattern, the conservation of power has ramifications for depth sectioning. The total signal contribution from all focal planes must remain equal, and only the frequency response may change. Adapting a depth-of-field metric from Sheppard and Wilson,\textsuperscript{17} we define the integrated point spread function

$$psf_{int}(z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} |psf(r)| \, dx \, dy,$$

where the integrated point spread function, $psf_{int}$, is used in lieu of the less general integrated intensity, $I_{int}$. We note that the point spread function for the PSD-phase response [shown in Fig. 4(b) and given by the Fourier transform of Eq. (30)] is not an intensity and thus is not physically constrained to conserve depthwise power (nor is the response of the type 2 microscope). Figure 5 shows the numerically integrated $psf_{int}$ of both the power-absorption response and the PSD-phase response for the probe beam of Eq. (32), as well as $psf_{int}$ for the type 2 microscope of Ref. 17. We likewise follow the focal depth normal-ization convention of Born and Wolf\textsuperscript{18} given by

$$u = k_n \tan^2 \alpha. \quad (37)$$

4. Simulation Results

A computer code was created to validate the analysis results. The code simulates the propagation of a probe with the form of Eq. (32) and an external N.A. of 0.3 through a small 3D volume grating. The simulation was performed by split-step propagation, wherein for each of 128 depth slices, the sampled complex amplitude of the probe beam was advanced incrementally by applying the free-space transfer function in the Fourier domain and then applying the grating phase delay in real space. The exiting beam was analyzed in the far field to determine the detected value of the $x$ and $y$ centroids and the total power. The entire process was repeated at a plurality of probe $x$ positions in order to simulate scanning in the $x$ direction.

The absolute value of the transfer function was sampled along the positive $k_x$ axis by simulating scans on a series of unslanted gratings with varying $k_x$ grating frequency values. Figure 6 shows the resulting response of the PSD $x$ centroid channel to weak phase gratings compared to the curve predicted by Eq. (33). Also shown is the response of the total power channel to weak absorption gratings compared to Eq. (32). These curves confirm the theoretical transfer
functions by showing good agreement with purely numerical simulations.

Additionally, the computer code was used to test the depth selectivity of both channels. The null at D.C. makes this task slightly more complicated for the PSD-phase channel than for a type 1 or type 2 microscope where one would simply scan a thin reflective (or transmissive) object depthwise. Instead, the simulated probe was scanned past a thin phase object with a unit step phase profile in the \(x\) direction at various depths relative to the probe waist. The peak-to-valley difference of the resulting simulated PSD \(x\) centroid waveform was defined as the response. The absorption channel was similarly tested on a thin unit step absorptive object. These results are shown in Fig. 7, and are in substantial agreement with the predicted curves of Fig. 5. Hence numerical simulations confirm the predicted depth selectivity as well as the predicted transfer functions for both the absorption and the phase channels.

5. Laboratory Images

The scanning microscope is being used to characterize volumetric index structures in thick photopolymer. Holographic data storage makes use of photopolymer media to record densely multiplexed volume holograms of data images composed of pixels representing individual data bits. These holograms are typically recorded with a Fourier plane of the object beam located in the middle of the recording layer to minimize the hologram size. The structural features of the hologram may be detected with the PSD phase channel of the microscope. Figure 8 shows a phase image of the Fourier plane of a holographic object beam recorded in photopolymer at a depth of 0.75 mm. The square shape represents the image of the polytopic aperture used to band limit the object beam, and the fan of striations emanating from the center are low-frequency fringes created by interference among components of the object beam. Note that these terms are never Bragg matched directly by the reference beam during the normal operation of the storage device, hence motivating the use of 3D phase metrology to quantify their effects.

Figure 9 shows a waveguide written from the tip of a single-mode telecommunications fiber embedded in photopolymer. The waveguide was written by scanning the focus of a beam along the desired path of the waveguide, thereby exposing the photopolymer to create a local high-index guiding channel. The instrument’s sensitivity is demonstrated by the clear contrast between the fiber and the nearly index-matched photopolymer. The \(3\) \(\mu\)m fiber core, which has an index contrast of only \(\Delta n = 5 \times 10^{-4}\) versus the cladding \((\sim 2 \times 10^{-2}\) waves of delay), is also visible.
6. Conclusions
A scanning transmission microscope using a PSD has been shown to exhibit phase sensitivity and optical depth sectioning without the use of a confocal pinhole. In the weak diffraction regime, the phase impulse responses have the form of the probe beam intensity pattern differentiated in the transverse (x and y) directions. The absorption impulse response has the form of the probe beam itself. These transfer functions, as well as depth-selectivity properties, were derived and confirmed by numerical simulation.

References