Low-coherent optical diffraction tomography by angle-scanning illumination

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1 | INTRODUCTION

Quantitative phase imaging (QPI) is an emerging bio-imaging technique [1–3]. The advantage of QPI is its ability to provide two- and three-dimensional (3-D) structural and functional information in a label-free fashion, which enables observation of biological samples in their optimal conditions. Therefore, QPI has been utilized for long-term behavioral observation of biological samples and rapid quantitative analysis of biological specimens [4, 5]. QPI measures the intact complex amplitude of the scattered optical field, which is an important base unit for advanced modalities such as light scattering analysis [6–8], scattering parameters retrieval [9, 10], Jones matrix measurement [11, 12], synthetic aperture imaging [13–15] and optical diffraction tomography (ODT) [16–18]. The versatile character of QPI has enriched its usability.

Among the QPI modalities, ODT provides the 3-D refractive index (RI) distribution of a sample from the measured optical field at various illumination angles [19–23], at different sample orientation [24–27], or both [28]. Again, owing to its label-free nature, ODT enables visualizing 3-D cellular morphology as well as dynamics of intracellular organelles without any constraints. ODT has been actively
utilized for various applications, including biophysics [29, 30], hematology [31], immunology [32], pharmacology [33], developmental biology [34] and nanotechnology [35].

Since the QPI is an interferometric microscopy technique, the majority of early QPI methods utilized coherent light sources (i.e., lasers) [36–39]. However, it soon turned out that high coherence disturbs the robust reconstruction of optical fields due to inevitable multiple scattering, called “coherent noise.” Even for ideal optical setups, for instance, the sample coverslip interface always induces multiple scattering, and the parasitic fringes would be found in the interferograms. Though several methods have been suggested to remove such noise [40–46], they frequently fail due to time-varying noise originating from sources such as system vibration, sample stage translation, objective lens drift, and light source frequency shifting.

Incoherent QPI techniques have been introduced to fundamentally address the issue. One obvious and general solution involves matching the optical path length (OPL) of the sample and the reference arms in typical interferometric setups [47–49]. Once the interference is maintained, the reconstruction sequences become identical to their coherent counterparts. Later, several “common-path” setups have been proposed to reduce the complexity of the interferometric setup and increase stability [50–52]. However, common-path techniques usually sacrifice generality by introducing assumptions or approximations regarding the sample or incident light, which may induce imaging artifacts [53, 54].

Unlike incoherent QPI, performing incoherent ODT is not a simple task. The main difficulty here is the loss of coherence when a sample is illuminated at oblique angles [55]. Since the ODT requires optical field measurements at multiple angles, such decoherence is inevitable in common Mach-Zehnder (MZ) interferometer-based ODT setups. Although some incoherent ODT methods have been presented based on common-path geometries [22, 56–58], a more general incoherent ODT technique is still in demand.

Here, we report an incoherent angle-scanning ODT setup based on a classical MZ setup. We maintain interference in oblique angles by diffractive modulation of incident light using a digital micromirror device (DMD). We also discuss the principles of incoherent ODT reconstruction in detail based on previous literature [56, 57, 59]. Using the proposed setup and principles, we experimentally perform low-coherent ODT imaging of various samples.

2 | EXPERIMENTAL SETUP

The optical setup is shown in Figure 1. We used a commercial microscope body (IX71, Olympus Inc., Tokyo, Japan) with objective (UPLSAPO 60XW, 60×, NA_{obj} = 1.2, Olympus Inc.) and condenser lenses (UPLSAPO 60XW, 60×,

![FIGURE 1](image_url) Proposed optical setup. A, Temporal illumination spectrum. The minimum and maximum wavelengths, \( \lambda_{\text{min}} = 580 \text{ nm} \) and \( \lambda_{\text{max}} = 597 \text{ nm} \) are defined by the \( 1/e^2 \) bandwidth around the peak wavelength, \( \lambda_c = 588 \text{ nm} \). B, Light illumination unit composed of two DMDs. C, Diffractive modulation based on off-axis scheme. The black arrows denote the sample conjugated planes with corresponding magnification factors. The denoted focal lengths of the lenses are in millimeters. The definitions of the abbreviations are as follows: SS, supercontinuum source; BPF, band-pass filter; BS, beam splitter; trans., translation stage; cond., condenser lens; obj., objective lens; and pol., polarizer.
\( \text{NA}_{\text{cond}} = 1.2, \) Olympus Inc.), where \( \text{NA}_{\text{obj}} \) and \( \text{NA}_{\text{cond}} \) are the numerical apertures of the objective and condenser lenses, respectively. Here, one should notice that spatial coherence is important when specifying a single illumination angle. In this work, a supercontinuum source (EXR-4, NKT Photonics Inc., Birkerød, Denmark) was used as the spatially coherent broadband light source. An additional bandpass filter was used to minimize several issues that arise as the source bandwidth increases (see Section 4.1 for details) (Figure 1A). The OPLs of the two arms were matched with a translation stage in the reference arm. For image acquisition, we used a commercial monochromatic camera (MD120MU-SY, XIMEA GmbH, Münster, Germany) synchronized with the illumination unit. To maintain interference at every oblique illumination angle, major alterations were applied to the conventional MZ interference portion.

### 2.1 Reference beam

In many QPI techniques, off-axis (or spatial modulation) schemes are widely used to obtain the optical field information in a single wide-field acquisition [37, 60]. For ODT techniques that require multiple optical fields, such utility becomes important for preventing motion of the sample during the entire series of measurements. However, as shown in ref. [55], the off-axis configuration with incoherent light usually causes significant coherence loss. This is due to the dispersive nature of mirror-based spatial modulation, \( 2\pi \sin \theta / \lambda \), where \( \lambda \) is the wavelength of light (Figure 2A) and \( \theta \) is the tilted angle of mirror. The dephasing between phasors \( \exp(i 2\pi \sin \theta / \lambda) \) of different wavelengths becomes severe as the lateral position \( x \) increases. Eventually, interference is diminished for \( x \sin \theta > l_c \), where \( l_c \) is the coherence length.

To prevent such decoherence, we introduce a diffraction grating (GT13-03, Thorlabs Inc., Newton, New Jersey) in the reference arm (Figure 1C). Since the diffraction orders originate from the periodic structure of the grating, the \( m \)-th order diffraction peak exhibits identical spatial frequency regardless of wavelength, \( 2\pi N / \Lambda \), where \( \Lambda \) is the period of the grating. For instance, the phasor becomes wavelength-independent when \( N = 1 \) is selected. Therefore, clear interference at any lateral position \( x \) could be observed, as in coherent situations (Figure 2B). We define such wavelength-independent spatial modulation method as “diffractive modulation,” which should be distinguished from conventional “reflective modulation” based on a mirror. Notice that introducing a diffraction grating in the reference beam generation is not a new concept [48, 49, 51, 61].

### 2.2 Illumination unit

We extend the diffractive modulation concept to illumination with incoherent light. Similar to the reference arm, reflection-based angle scanning (eg, galvo mirrors) is no longer suitable in the sample arm of the proposed incoherent ODT (see Supporting Information, Figure S1). Rather, we require use of controllable diffractive elements such as spatial light modulators (SLMs). However, common liquid crystal on silicon (LCoS)-based SLMs usually has rather slow modulation speed and is not an ideal choice for ODT applications [58, 62]. Taking the modulation speed into account, we opted to use a DMD (DLP LightCrafter 6500, Texas Instruments Inc., Dallas, Texas) for the illumination unit.

Despite the advantage of modulation speed, the DMD has not been a good option for broadband light because its intrinsic echelle grating geometry, which induces significant chromatic dispersion [63]. For a blazed grating with \( \theta_b \) blaze angle, the brightest diffraction order \( (N_i) \) is a function of wavelength,

\[
N_i = \text{nint} \left( \frac{\sin 2\theta_b}{\lambda} p_i \right),
\]

where \( p_i = 5.346 \ \mu m \) is the spatial period of the DMD parallel to the blaze direction (45° or diagonal), and \( \text{nint}(x) \) presents the integer nearest to \( x \). Unlike transmission gratings that typically have small \( \theta_b \); the large blaze angle of the DMD \( (\theta_b = 12^\circ) \) induces \( N_i \) variation as a function of wavelength. According to Equation 1, we find \( N_i = 4 \) for the DMD at a center wavelength \( \lambda_c = 588 \text{ nm} \).

In coherent systems, the DMD blaze angle has commonly been compensated by corresponding oblique angle illumination [64, 65]. In incoherent systems, unfortunately, such reflective modulation is not permitted, as discussed above. In this report, we compensate such higher order diffraction and dispersive effects by introducing an identical

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**FIGURE 2** Incoherent interference patterns in (A) reflective modulation and (B) diffractive modulation. Red, greed and blue colors denotes \( \lambda_{\text{max}}, \lambda_c \) and \( \lambda_{\text{min}} \), respectively. Severe decoherence is observed with reflective modulation due to the uneven periods of each phasor.
DMD of idle state (DMD1, Figure 1B). Since the configuration is symmetric to the light propagation direction, diffractions from the DMDs are completely undone with respect to the reciprocity of the setup. Therefore, the composite illumination unit becomes a binary amplitude (0 and 1) modulator without a blaze angle and is the desired nondispersive diffractive modulator.

Based on our previous study using DMD, we used structured illumination with time multiplexing [65]. The four-bit structured illumination was constructed by numerically compounding four measured interferograms from binary patterns with the power of two factors. Notice there is no pixel or resolution loss during the numerical compounding process. In order to decompose the three plane waves in a cosine pattern, we take four identical cosine patterns with different relative phases $\phi = 0, 1\pi/4, 2\pi/4$ and $3\pi/4$. Since we used 15 circular scanning cosine patterns (ie, 30 oblique angle illuminations) and 1 normal illumination, binary illumination was applied a total of 241 (=15 x 4 x 4 + 1) times.

We adjusted the illumination NA, $NA^{(0)} \approx 1.06$ at $\lambda_c$, but please notice that $NA^{(0)}$ is actually the function of wavelength (see Section 3.4 for detail). The entire series of binary patterns could be uploaded onto the DMD boards, which enables the DMD to be operated at maximum modulation speed (9523 Hz). Unfortunately, the maximum speed could not be realized in this report due to the relatively slow acquisition speed of the camera.

3 | ODT RECONSTRUCTION FROM THE INCOHERENT QPI

The principle of ODT is well established from the general electromagnetic wave equations [66, 67]. In coherent systems, ODT reconstruction is the simple realization of the formulas from diffraction theory [17]. However, in incoherent cases, several fundamental and practical issues arise.

3.1 | Incoherent field measurement

The incoherent system can be considered as a linear combination of coherent systems with different wavelengths. Therefore, the optical field retrieved from the incoherent interferogram can be described as

$$U(x, y) = U^{(i)}(x, y) + \int U_s^{(i)}(x, y) \frac{\partial P}{\partial \lambda} d\lambda,$$  \hspace{1cm} (2)

where $U^{(i)}(x, y)$ is the incident plane wave $exp[i(k(x, y)) y]$, which is independent of wavelength in the diffractional modulation geometry; $U_s^{(i)}(x, y)$ is the scattered field as a function of wavelength $\lambda$; $\partial P/\partial \lambda$ is the normalized power spectral density of the light source, $\int \partial P d\lambda = 1$ (Figure 1A).

At this point, the conventional coherent ODT reconstruction theorem could be applied to connect the monochromatic scattered field $\tilde{U}_s^{(i)}(k_x, k_z)$ with unitless scattering potential $\chi_s(x, y, z) = [n_s(x, y, z/m_d)]^2 - 1$ as

$$\tilde{U}_s^{(i)}(k_x, k_z) = \frac{ik^2}{2k_c} \tilde{\chi}_s(\mathbf{k} - \mathbf{k}^{(i)}).$$  \hspace{1cm} (3)

where $n_s(x, y, z)$ is the 3-D RI distribution of a sample, $m_d$ is the RI of a surrounding medium, $k = 2\pi m_d/\lambda$ is the wavenumber of light, and $\mathbf{k}^{(i)} = (k_x^{(i)}, k_y^{(i)}, k_z^{(i)})$ and $\mathbf{k} = (k_x, k_y, k_z)$ are the wavevectors of the incident and scattered field, respectively, that satisfy $k = |\mathbf{k}| = |\mathbf{k}^{(i)}| [66, 67]$. By substituting Equation 3 into Equation 2, we can now associate incoherent QPI measurements with the sample scattering potential,

$$\tilde{U}^{(i)}(k_x, k_z) = \tilde{U}(k_x, k_z) - \tilde{U}_s^{(i)}(k_x, k_z)$$

$$= \int \frac{ik^2}{2k_c} \tilde{\chi}_s(\mathbf{k} - \mathbf{k}^{(i)}) \frac{\partial P}{\partial k} dk.$$  \hspace{1cm} (4)

However, because each wavelength has its own equation (Equation 3), and no general relation holds between different $\tilde{U}_s^{(i)}(k_x, k_z)$ or $\tilde{\chi}_s(\mathbf{k} - \mathbf{k}^{(i)})$, Equation 4 is an ill-posed problem with the infinite number of possible solutions for a single measurement of $\tilde{U}^{(i)}$. Therefore, to reconstruct an ODT from incoherent field measurements, it is indispensable that we introduce proper assumptions to specify each $\tilde{U}_s^{(i)}$. Here, similar to ref. [56], we introduce the nondispersive assumption for the sample and medium, which is generally valid in colorless transparent materials. This assumption forces the scattering potential $\chi(x, y, z)$ to be wavelength-independent.

3.2 | Volumetric k-space and axial resolution

Since each wavelength yields different $k = |\mathbf{k}| = |\mathbf{k}^{(i)}|$, the corresponding value of $\tilde{\chi}_s(\mathbf{k} - \mathbf{k}^{(i)})$ in Equation 4 represents spherical shells with different radii in 3-D k-space (Figure 3) [68]. Therefore, unlike in monochromatic cases, the associated $\tilde{\chi}_s(k_x, k_y, k_z)$ exhibits a certain axial thickness $\Delta k_z$ in k-space that governs finite axial image resolution [56, 57]. Such an incoherence-based axial sectioning ability (ie, coherence gating) also forms the basis of optical coherence tomography (OCT), which shares the fundamental physics with ODT, namely coherent diffraction of light [69].

In general, the k-space volume cannot be acquired in a single measurement. Therefore, the axial-scanning method has been a common solution, as in previous investigations into incoherent ODT [56, 57] or in time-domain OCT setups [69]. However, unlike in reflective geometries [70, 71], transmission geometry exhibits far thinner axial thickness $\Delta k_z$ even for highly incoherent illuminations, which directly presents the far poorer axial resolution and sectioning abilities (Figure 3). Furthermore, $\Delta k_z$ rapidly diminishes as the
lateral frequency $k_\perp = \sqrt{k^2 - k_z^2}$ decreases, and eventually becomes zero for $k_\perp = 0$ (Figure 3). This issue is similar to the missing cone problem in ODT [72] but far more severe; and is especially critical for weakly scattering samples such as biological cells, where the scattering information is mostly distributed near the origin. Therefore, for the majority of biological applications, we find incoherence-induced $\Delta k_z$ barely provides more than two distinguishable points along the $z$-axis. This is identical to assuming uniform $\tilde{\chi}(k - k^{(i)})$ along the $k_z$ axis in Equation 4 and Figure 3.

Notice that the decoherence effect originating from the sample-induced OPL is not related to the axial resolution of the system. For example, a thick dielectric slab would induce the decoherence regardless of its axial position, which directly shows the axial indistinguishability of the system.

### 3.3 Weight function

According to the discussions in the previous subsections, $\tilde{\chi}(k - k^{(i)})$ could be assumed to be independent to $k_z$, and Equation 4 can be simplified as

$$\tilde{U}^{(i)}(k_x, k_y) = \frac{i}{2} w(k_\perp; P) \tilde{\chi}(k - k^{(i)}), \quad (5)$$

where

$$w(k_\perp; P) = \int_{k_\perp}^{\infty} \frac{k^2}{k^2 - k^2_\perp} \frac{\partial P}{\partial k} dk \quad (6)$$

is a weight function related to the lateral frequency $k_\perp$ and the normalized power spectral density $\partial P/\partial k$, and $k_\perp = (m/\text{NA}_{\text{obj}})k_z$ is the minimum transferrable $k$ for a given $k_\perp$ value and NA of the objective lens (Figure 4). Therefore, the sample scattering potential $\tilde{\chi}(k - k^{(i)})$ could be reconstructed from a single incoherent measurement $\tilde{U}^{(i)}(k_x, k_y)$ by calculating $w(k_\perp; P)$.

As shown in Figure 4, $w(k_\perp; P)$ for monochromatic cases increases with $k_\perp$. This is the inverse cosine factor originating from the curvature of a spherical shell. The $w(k_\perp; P)$ exhibits similar trend for incoherent cases in low $k_\perp$ values. However, $w(k_\perp; P)$ rapidly decreases as $k_\perp$ excludes the lower $k$ (i.e., longer $\lambda$) portion of given spectrum. In fact, this feature significantly lowers the signal-to-noise ratio for higher $k_\perp$ values.

In practical situations, we need to remove the residuals from the spectrum to prevent noise amplification when dividing by $w(k_\perp; P) \approx 0$. Therefore, we set the $1/e$ of the maximum weight as the maximum attainable $k_\perp$ value (Figure 4B). Similarly, we bound the valid spectral domain to define the achievable solid volume of $\tilde{\chi}(k - k^{(i)})$ (Figure 5), where $k_{\min} = 2\pi m/\lambda_{\min}$ and $k_{\max} = 2\pi m/\lambda_{\max}$ are the wavenumbers at a factor $1/e^2$ of the peak spectral density (Figure 4B).

### 3.4 Angle-scanning illumination

Although we use the term “angle scanning” to prevent confusion, it is not the exact description because we utilize DMD-based diffractive modulation that conserves the scanning lateral frequency $k^{(i)}_{\perp} = \sqrt{k_x^{(i)} + k_y^{(i)}} = k \sin \theta^{(i)}$ rather than varying the scanning angle $\theta^{(i)}$. In other words, each wavelength is incident at a different angle, $\theta^{(i)} = \sin^{-1} (k^{(i)}_{\perp}/k)$ during a single illumination (Figure 2B).

Therefore, longer wavelengths would be filtered out by the condenser lens as the lateral scanning frequency $k^{(i)}_{\perp}$ increases, which should be avoided to prevent intensity loss and interference visibility. Therefore, the maximum lateral...
scanning frequency $k_{\perp}^{(i)}$ should be limited by $(\text{NA}_{\text{cond}}/m)k_{\min}$ (Figure 5B). Accordingly, the effective illumination NA becomes a function of wavelength $N_{\lambda} = \text{NA}_{\text{cond}}(k_{\min}/k)$, which is always smaller than the given NA of the condenser.

We compare $k$-space volumetric coverage of incoherent angle scanning with monochromatic scanning with the same $\lambda_c$ value in identical optical setups (Figure 5). We set $\text{NA}_{\text{obj}} = \text{NA}_{\text{cond}}$ in this comparison for simplicity. We find incoherent illumination in the circular scanning case has a significant advantage. The decreased illumination angle at shorter wavelengths effectively covers the $\chi_{kz} < 0$ region, which cannot be acquired in monochromatic circular scanning with maximum scanning radius (Figure 5C). Furthermore, its volumetric coverage is already very close to that of
full aperture scanning (Figure 5D). However, we find such an advantage relatively fades for real-valued \( \chi(x, y, z) \) (i.e., phase objects) due to the Hermitian symmetry of its Fourier transform, \( \tilde{\chi}^*(k) = \tilde{\chi}(-k) \) [73]. In other words, the measurement of \( \tilde{\chi}(k_z > 0) \) region is especially beneficial to the absorptive samples, which have complex-valued \( \chi(x, y, z) \).

It is noteworthy that similar \( k \)-space volume information could be acquired with spatially incoherent illumination and axial scanning [48, 56, 57], because it could be regarded as an incoherent summation of different plane waves. Indeed, a proper weight function should be accompanied to quantify \( \tilde{\chi}(k_x, k_y, k_z) \) from measurements.

4 | RESULTS AND DISCUSSIONS

4.1 | On the proper degree of incoherency

According to the theoretical analysis in Section 3, we find the illumination bandwidth should be chosen carefully. Unlike our expectation in Section 1, too broad bandwidth also raises fundamental disadvantages such as sample dispersion effect (Section 3.1) and illumination angle limitation (Section 3.4). Further issues could also arise in practical situations. For example, group delay dispersion matching could be crucial to maintaining the interference of broadband light passing through different optical elements [48].

Meanwhile, the optical sectioning ability is not as significant as in reflection geometries. Therefore, we find that the minimum degree of incoherence is preferred in order to achieve interference suppression induced by unwanted beam paths. In many ODT setups, for instance, the coverslip induces multiple reflections that exhibit minimum additional OPL, which is on the order of 100 \( \mu m \). In such cases, a coherence length of \( l_c \sim 10 \mu m \) could safely meet the noise suppression goal, which corresponds to \(~10 nm \) spectral bandwidth in the visible range. It is commonly referred as low-coherent regime separated from the incoherent regime having \(~100 nm \) spectral bandwidth.

Therefore, as a conclusion, we decided to use the low-coherent light in our experiments. We would like to emphasize, however, this decision is based on the comprehensive theoretical analysis of general broadband illumination for ODT in previous sections (Section 3), which includes both low-coherent and incoherent illuminations.

We obtain a low-coherent source by reducing the spectral bandwidth of supercontinuum to 17 nm (Figure 1A). The corresponding weight function is shown in Figure 6C, which has a similar shape as the previous expectation (Figure 4B), but steeper slope due to far narrower bandwidth. As a low-priced alternative, we suggest a superluminescent diodes, which provides low-coherent light of \(~10 nm \) spectral bandwidth with good spatial coherency.

4.2 | ODT results

Thanks to the diffractive modulation, full-field interference of incoherent illumination is steadily maintained during the
entire scanning procedure (Figure 6A). The optical field \( U(x, y) \) could be retrieved with a conventional off-axis modulation scheme from the acquired interferograms (Figure 6B). As discussed in Section 3.3, the sampling area radius in the plane is set as a factor \( 1/e \) of the maximum weight (Figure 6C). The incident field \( U^0(x, y) \) is measured using an identical procedure without the sample, and the scattered field \( U^s(x, y) \) can be calculated from Equation 2 (Figure 6D,F). Notice, we utilize the first Rytov approximation rather than using Equation 2 directly (ie, the first Born approximation) to achieve more reliable results in micro-sized samples [66, 67]. Substituting \( \tilde{U}(k_x, k_y) \) and \( \chi(k_x, k_y) \) into Equation 5, we obtain \( \chi(k_x, k_y) \), which is directly related to the 3-D RI distribution \( n(x, y, z) \) (Figure 6G). In order to manage the inevitable missing cone issue in ODT with transmission geometry, we applied edge-preserving regularization as discussed in ref. [72]. As demonstrated in previous works [20, 74, 75], the 3-D absorption distribution (imaginary part of RI) of a sample is always retrieved together with the conventional (real part) RI results. However, in this work, we do not find a significant absorptive signal from the samples (see Figure S2) due to the phase-dominant feature of used biological samples, and the low absorption sensitivity of circular angle-scanning strategy. Please see Appendices S1 and S2 for more details.

To test the versatility of the proposed method, we measured the 3-D RI distribution of various samples (Figure 7). Polystyrene microspheres with 10 \( \mu m \) diameter were prepared using proper RI matching by using \( m = 1.561 \) immersion oil (Figure 7A). Red blood cells donated from a healthy donor were prepared using Alservier's solution as a diluent (A3551, Sigma-Aldrich Inc., St. Louis, Missouri) (Figure 7B,C). Rat pheochromocytoma (PC-12) cells were cultured in an incubator for 24 hours at 37\(^\circ\)C and 5% CO\(_2\) concentration (Figure 7D,E). Despite the use of low-coherent light, we find subtle diffraction noise coupled with the sample information. For example, the concentric fringe observed in Figure 7A could originate from a stain on the coverslips. Notice that such low-angle diffraction cannot be decoupled via incoherent illumination due to the poor axial resolution in transmission geometry (see Section 3.2). For the cultured cells, the inhomogeneous background is mainly originated from the unwanted cell debris or microorganisms (Figure 7E).

5 | CONCLUSION

In this article, we present a general off-axis angle-scanning incoherent ODT technique based on the use of an MZ interferometer. Diffraction tilting was used to maintain interference during the scanning procedure. As a controllable diffractive unit, a DMD was used to maximize the acquisition speed. Chromatic dispersion induced from the blaze angle of the DMD pixels is compensated by an identical DMD in the idle state. We also review the principle of incoherent ODT reconstruction and clarify its difference from conventional coherent cases by introducing spectrum-based weight functions. Several assumptions were introduced and discussed during the reconstruction procedure. In addition to such inevitable assumptions, we find several fundamental and practical limitations of incoherent illumination that effectively reduce the ODT volumetric sampling capacity, which dilutes the advantages of incoherent illumination. Taking such disadvantages into account, we discuss and suggest the proper degree of incoherency for the maximum quality of ODT. Based on the proposed setup and reconstruction principle, we successfully
performed low-coherent ODT reconstruction in various samples.

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CONFLICTS OF INTEREST

Dr. K.L., Mr. S.S. and Prof. Y.P. have financial interests in Tomcube Inc., a company that commercializes ODT instruments and is one of the sponsors of the work.

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Please see Supporting Information online.

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SUPPORTING INFORMATION
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