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A modified fractal zone plate with extended depth of focus in spectral domain optical coherence tomography

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Abstract

In optical coherence tomography (OCT) systems, there is a trade-off between the depth of focus (DOF) and lateral resolution when conventional lenses are used. We propose a new method that employs a modified fractal generalized zone plate (MFraGZP) combined with a conventional lens to improve the trade-off effect, with an extended DOF of about 2.5 mm (14 times larger) while the lateral resolution is maintained at $\sim 9.5 \mu\text{m}$. As an example, images of the calibration microspheres are obtained and demonstrated with the extended DOF in a spectral domain OCT system.

Keywords

optical coherence tomography; depth of focus; fractal zone plate

Optical coherence tomography (OCT) is a new technology that provides high-resolution internal microstructural images of a tissue in a noninvasive manner [1]. In conventional optical imaging systems, axial and lateral resolutions are correlated; hence one cannot achieve high performance on both in the same system. In OCT systems, however, the axial and lateral resolutions are independent of each other; they are determined by the coherence length of the light source and the numerical aperture (NA) of the objective lens, respectively. Using a broadband light source one can improve the axial resolution while the lateral resolution can be improved by increasing the NA. However, there is a trade-off between the lateral resolution and the depth of focus (DOF) when conventional focusing lenses are used. Namely, high lateral resolution imaging requires a large NA whereas a large DOF prefers a small NA. To overcome this limitation, a few methods have been proposed and reported in the literature, including wavefront coding [2], hybrid refractive-diffractive optical elements [3] and diffractive optical elements [4] to extend the DOF by beam shaping techniques. In OCT, dynamic focusing compensation and diffractive optical elements are commonly used to overcome the limitation. The former as reported in [5–7] is limited to low speed OCT systems such as low-frame-rate OCT. In addition, the dynamic focusing lenses are bulky and they cannot be used when physical space is a limitation, such as in an endoscopic OCT. The latter employs an axicon or a microaxicon lens in the sample arm of

an OCT to produce a zero-order Bessel beam for high lateral resolution and large DOF simultaneously [8–10]. However, the Bessel beam requires a large number of concentric rings to maintain its non-diffraction property in propagation. This encounters some difficulties in terms of optical elements and their aperture sizes in diffraction-limited systems in practice. The binary-phase spatial filter proposed by [11] has a great possibility to extend the DOF in an OCT system. However, the method used to design filters is exhaustive searching, which is complicated and time-consuming in the process of finding the optimal pupil radius.

In this paper, we propose a new method to extend the DOF in an OCT system, which incorporates a modified fractal generalized zone plate (MFraGZP) into the sample arm to achieve the large DOF without involving the Bessel beams and which is easy to design. A fractal zone plate (FZP) as introduced in [12] is a micro-optical imaging element that produces fractal structures at foci, where irradiance along the optical axis produced by the FZPs gives a self-similar profile. An imaging FZP was demonstrated in [13] with the advantages of an extended depth of field and reduced chromatic aberration under white-light illumination. In 2004, [14] gave a variable of lacunarity (opaque part) to study the effects on axial response by changing the lacunarity value. Based on the variable, a fractal generalized zone plate (FraGZP) was introduced in [15]. It is modified by controlling the ratio ε between the period and the transparent portion in a period to modify the number of foci. But the ratio ε must be adopted as a positive integer and this requirement more or less restricted the design parameters for some optimized intensity distribution cases. In order to improve the intensity distributions among foci, we introduce a new parameter ω as the ratio between the transparent and opaque parts (lacunarity) in the design of FraGZP. The parameter ω is positive which is different from ε . The optimized model is referred to as modified FraGZP (MFraGZP). Using the multiple foci technique aforementioned, we employ the MFraGZP combined with a focusing lens under a broadband light source illumination to achieve an extended DOF in our spectral domain OCT (SDOCT). It is noted that FZPs can be built up by the same method used for conventional Fresnel zone plates. It is well known that a Fresnel zone plate consists of alternately transparent and opaque zones whose radii are proportional to the square root of natural numbers [12]. Fresnel zone plates can be generated by starting with a 1D compact-supported periodic function $p(r_0)$, followed by a change of coordinates $\zeta = (r_0/a)^2 - 0.5$, where a is the maximum extent of the pupil function and r_0 is the radius. The function $q(\zeta)$, which is a Ronchi-type periodic binary function with period p , can be written as [12]

$$q(\zeta) = \text{rect}(\zeta) \text{rect}\{\text{mod}[\zeta + (p-1)/2, p]/p\} \quad (1)$$

where the function $\text{mod}(x, y)$ gives the remainder on division of x by y .

In the same way, an FZP can be constructed by replacing the periodic function $p(r_0)$ by $q(\zeta)$ with a fractal profile. We use the regular Cantor fractal to produce the FZP. The procedures are summarized as follows: the initial segments are divided into an odd number of concentric ring areas, $2N - 1$, and areas at even positions are removed. For the remaining N segments in the first stage this slicing-and-removing process is repeated in the second stage, and so on [12]. In mathematical terms, the FZP transmittance function, developed up to a certain growing stage S , can be expressed as the product of the periodic functions $q(\zeta)$ as [12]

$$q(\zeta) = q_{\text{FZP}}(\zeta, N, S) = \prod_{i=0}^S q_{\text{ZP}}[\zeta, p(N, S)]. \quad (2)$$

It is instructive to note that the FZP can be understood as an associated Fresnel zone plate $q_{\text{ZP}}[\zeta, p(N, S)]$, with a period $p(N, S)$, but with some missing clear zones. After calculation, the period $p(N, S)$ of the MFraGZP used in our case is

$$p(N, S) = \left(\frac{w}{Nw + (N-1)} \right)^S \left(1 + \frac{1}{w} \right) \quad (3)$$

where N determines the fractal segments, S is the fractal stage and w is the ratio between the transparent and opaque parts. The irradiances along the optical axis provided by the MFraGZP can be calculated by using the Fresnel approximation [12]:

$$I_0(u) = 4\pi^2 u^2 \left| \int_{-0.5}^{0.5} q(\zeta) \exp(-i2\pi u \zeta) d\zeta \right|^2 \quad (4)$$

$$u = a^2 / 2\lambda R \quad (5)$$

where u is the normalized axial coordinate; R is the axis distance from the pupil plane and λ is the wavelength of the light. We manufacture the MFraGZP with parameters of $N = 2$, $S = 2$ and $w = 2$ by UV photolithography. Figure 1 shows the cross section and schematic diagrams of the binary structures of the MFraGZP in (a) and (b) and a microscopic photograph of the fabricated MFraGZP in (c). The MFraGZP was fabricated in a chemically amplified photoresist (AR-N 4340) by a UV laser direct writing technique (DWL66, Heidelberg Instruments). It is a binary phase-only surface relief micro-optical element with a depth of about 833 nm for π phase shift when the refractive index is given as 1.51. The triadic Cantor set presents four gaps limited by the following positions inside the unit length along the radial direction: $[0, 4/25]$, $[6/25, 10/25]$, $[15/25, 19/25]$, $[21/25, 1]$.

In our paper, we combine the MFraGZP with a conventional lens to obtain the OCT images. Intensity distributions along the propagating axis of the combination are calculated by the Rayleigh–Sommerfeld diffraction formula and the results are given in figure 2(a), where lines in different colors represent different wavelengths of a bandwidth light source of 40 nm with the center wavelength at 850 nm. Through calculation we found that the MFraGZP has a main focus and several secondary foci. The main focus plays the main important part in extending the DOF of the system. However, the secondary foci also play important roles in extending the DOF. As mentioned above, the MFraGZP is obtained from the FZP, whose focal length is related to the wavelengths, so the focal length of the MFraGZP also changes with the wavelengths. This makes it that different wavelengths can make contributions to extending the DOF too. In our case, the DOF can be achieved as about 2.5 mm according to simulation. The point spread function (PSF) in the focal plane is described in figure 2(c). The transversal spot sizes given in (c) are in the main focus of the MFraGZP and the focus of the conventional lens. Comparing with a conventional lens, we give the longitudinal and transverse intensity distributions of the same imaging lens without the hybrid MFraGZP lens in figures 2(b) and (c), respectively. The focal length of the conventional lens is 35 mm. To give a visual effect, we give the distribution of the PSF in the $x-z$ plane with a wavelength of 850 nm in figure 2(d). The transverse spot sizes of the MFraGZP with different distances in the main focus can be maintained, while in the area of the secondary foci the spot size is smaller than in the main focus, which means a higher resolution. Because of the character of

a fractal, the longitudinal intensity distributions are nonuniform at different foci and zero-intensity points exist. However, the main role in extending the DOF of MFraGZPs is provided by the main focus, so the zero-intensity points have little effect on the image. But we can use a broader light source to make the foci of different wavelengths overlapping with each other, so it can reduce the zero-intensity points and the Dammann grating can also be added to the MFraGZP to give a uniform distributions [16]. It is seen in the figures that the DOF is extended by using the MFraGZP while the PSF is well maintained.

To verify our theory of the invariable lateral resolution in the large DOF, the lateral resolution along the DOF was measured using a binary grating fabricated by the UV laser direct writing technique. The density of the grating to be imaged was 53 lines mm^{-1} , which corresponds to a spatial resolution of $\sim 9.5 \text{ }\mu\text{m}$. The grating was put on the sample arm of the SDOCT system in figure 3. Light from a supercontinuum source (Fianum-SC450-FC, 450–1800 nm) is split by a 50:50 fiber coupler into separate paths for the reference and sample arms. Two filters are used in the reference and sample arms respectively, to get a spectral bandwidth of 40 nm with the center wavelength at 850 nm. In the reference arm the collimated beam from the single-mode fiber passes the filter onto the reference mirror and reflects in the same way. In the sample arm, light from the single-mode fiber is collimated with a fiber collimator to produce the parallel illumination on the MFraGZP and the focusing lens ($f = 35 \text{ mm}$) and then is focused on the sample. The interference signals are detected by an in-house developed spectrometer, including a fiber collimator, a diffraction grating ($1200 \text{ lines mm}^{-1}$), an achromatic lens and a line scanning CCD (e2v AViiVA SM2 CL, $4096 \times 1, 10 \text{ }\mu\text{m}$) in the detection arm and transferred into the computer to implement a fast Fourier transform by the camera link of the CCD.

Figure 4 shows the OCT images and their corresponding cross-sectional profiles for the grating located at different axial positions relative to the focus of the hybrid MFraGZP lens over a depth of 2.5 mm in the region of focus. These results confirm a focusing depth range of about 2.5 mm with a lateral resolution of $\sim 9.5 \text{ }\mu\text{m}$. However, in the conventional condition, the Rayleigh range for a Gaussian beam with a waist of $\sim 9.5 \text{ }\mu\text{m}$ at a wavelength of 850 nm was less than 0.2 mm. The DOF is about 14 times greater in comparison with the conventional condition.

To confirm the idea of extending the DOF experimentally by the MFraGZP, we obtained OCT sample images of calibration microspheres (Bands Laboratories, Inc.) with a mean diameter of $9.5 \text{ }\mu\text{m}$ embedded in agarose using the hybrid MFraGZP lens in the sample arm. Based on geometrical optics, the focal length of the imaging system can be calculated by

$$f = \frac{f_{\text{MFraGZP}} \times f_{\text{lens}}}{f_{\text{MFraGZP}} + f_{\text{lens}}} \quad (6)$$

The lateral resolution of the FDOCT system is determined by [17]

$$\Delta x = \frac{4\lambda f}{\pi d} \quad (7)$$

where d is the diameter of the collimated incident spot on the hybrid MFraGZP lens. Under the broadband light source illumination, the foci produced by the hybrid MFraGZP lens are distributed about 2.5 mm along the axis. The lateral resolution is $\sim 9.5 \text{ }\mu\text{m}$ and it can be maintained within the long focal depth, although the intensity has been reduced due to the loss of the binary pupil of the MFraGZP.

In addition, in our experiment, we localized the zero-phase delay line on the sample to separate the mirror image and the real image, and use the method proposed by [18] to eliminate autocorrelation artifacts. Figures 5(a) and (b) are the images of the calibration microspheres obtained by a conventional lens and the MFraGZP combined with the focusing lens, respectively. The focal point was settled at the position of $\sim 100\ \mu\text{m}$ in figure 5. From figure 5(a), we find that the particles settled in the focal area are clear; outside the focal depth the particles are blurred. However, in figure 5(b) the particles are distinct in an area of about 2.1 mm because of using the hybrid MFraGZP lens. This is a little different from the theory. The inconsistency is due to the mold of the microspheres and agarose is not perfect. We will improve this in the following study. In addition, optimizing other new parameters of the FZPs, a greater DOF can be achieved with a more evenly distributed intensity at the foci.

In conclusion, we give a new parameter ω to improve the intensity distributions of FZPs for OCT systems. Experimental results have verified the imaging performance with an extended DOF in our SDOCT system. Comparing with non-diffraction beams such as Bessel beams and the binary-phase spatial filter, the proposed method has a unique advantage in terms of maintaining the beams without concentric rings and is easy to design. It gives rise to a possible extension to microscopic OCT when an objective lens is applied in the sample arm. In addition, the MFraGZP can easily be incorporated into an existing OCT system with minimum modification.

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Figure 1. (a) Schematic cross section of the binary structure of MFraGZP. (b) Schematic diagram of the MFraGZP. (c) Microscopic photograph of the fabricated MFraGZP.

Figure 2.

(a) and (b) are the longitudinal intensity distributions at foci of the hybrid MFraGZP lens and the conventional lens illuminated by a bandwidth of 40 nm with center wavelength at 850 nm, respectively. (c) is the transverse intensity distributions of the point spread function (PSF) at the main foci, the conventional lens (solid red line) and the hybrid MFraGZP lens (dashed black line). (d) is the distribution of the PSF in the x - z plane with the central wavelength of 850 nm. The axial direction in (a), (b) and (d) represents a dimensionless unit.

Figure 3.
Schematic diagram of the SDOCT system.

Figure 4.

OCT images and their cross-sectional profiles of the testing grating. Images are successive from top to bottom and show the grating located at different axial positions relative to the focus of the hybrid MFraGZP lens over a depth of 2.5 mm in the region of focus. The image at the top is the image in focus.

Figure 5.
SDOCT images of $9.5\ \mu\text{m}$ calibration microspheres obtained by (a) the conventional lens and (b) the hybrid MFraGZP lens.