Optical Design for OCT

Z. Hu and A.M. Rollins

This chapter aims to provide insights and tools to design high-quality optical subsystems for OCT. First, we discuss the various optical subsystems common to OCT and relevant optical design criteria. Second, we review several fundamental optical design principles important for OCT designs. Finally, we discuss a number of examples of designed optical systems for OCT.

To simplify the discussion, the following schematics of OCT in the time domain and spectral domain (or Fourier domain) are shown in Fig. 12.1. The major subsystems are labeled by Roman numerals. Illumination sources and sample scanners are labeled by I and II, respectively, in both schematics in Fig. 12.1. Numeral III refers to a scanning optical delay line (ODL), while numeral IV refers to a fixed-pathlength ODL. Numeral V refers to a single-point detector, and numeral VI refers to an array-based spectrometer (for spectrometer-based Fourier-domain OCT). This notation will refer to these subsystems throughout the chapter.

12.1 Optical Design Considerations for OCT

12.1.1 Unique Optical Design Needs for OCT

OCT presents unique design needs different than, for example, microscopy or photography or laser scanning. Therefore, custom optical subsystems are typically designed especially for OCT and often for a specific application. For example, OCT sample scanning optics (II) are typically confocal systems that scan 0.05–0.1 NA beams over a range of several millimeters. Time-domain OCT (TD-OCT) systems typically use fast-scanning, reflective ODLs (III). In spectrometer-based Fourier domain OCT (FD-OCT) systems, the interfering spectra are collected by a linear array spectrometer (VI). The following six design considerations will be discussed:

1. Clear sample spot profile
2. Uniform chromatic coupling and high coupling efficiency
3. Spectral response  
4. Depth of focus vs. lateral resolution (numerical aperture)  
5. Frequency resolution  
6. Spectrometer spot size and fall-off  

Items 1–3 are critical for the ODL design (III or IV), 1–4 are important for scanner optics (II), and 1–3, 5–6 are key for the spectrometer designs (VI). The next three subsections will discuss these items in more detail. As a general principle, telecentric and achromatic optics will be used in the system designs to help achieve the design goals.

12.1.2 Sample Scanners  

Clear Spot Profile  

To achieve a high resolution, high contrast OCT image, a clean probe beam spot profile is necessary. Ideally, the clean spot profile will be maintained over the entire range of the scan, not merely on the optical axis. OCT makes 2-dimensional or 3-dimensional images by using spot scanning optics. The spot profile of the paraxial beam is usually closer to Gaussian than the skew beams or the beam significantly off the optical axis because of spherical and chromatic aberrations of the optical components. Sometimes, commercially available lenses with a small aperture are used to build scanners with a large lateral scanning range that degrades the spot profile toward the edge the lenses because of significant spherical and chromatic aberrations.

The use of certain lens types and design principles can be used to reduce design time, construction difficulties, and alignment issues. To minimize difficult design considerations, achromatic and aspheric lenses and a telecentric configuration is suggested in the sample arm scanner (II) design. Design
software such as Zemax is usually a suitable tool for optimizing the spot profiles over the entire scanning range, while a beam analyzer is useful for measuring the real spot profile to optimize the assembled design [1]. Use of these tools will help to ensure a minimum amount of work and maximum results when designing OCT optical systems.

**Uniform and High Coupling Efficiency**

Coupling efficiency refers to any point where the light enters and or exits the OCT system. The efficiency refers to both the amount of power lost during transitions from, for example, air to fiber or fiber to air, and the chromatic efficiency of the transitions. Proper consideration of these parameters will ensure that optimal use of the light source occurs, and maximum axial resolution is maintained throughout the length of the scan.

The sample scanner of an OCT system typically delivers the light to the sample and collects the scattered light back from the sample through the same optics, as shown in Fig. 12.1. The higher the coupling efficiency, the lower the source power that is needed to achieve the same image quality. Besides the neutral attenuation due to optical surfaces, both the spherical and the chromatic aberrations of the lenses affect the coupling efficiency. In most sample designs, the light is delivered by an optical fiber to the scanner (II). The wavefront of the back-reflected (scattered) beam is changed because of spherical and chromatic aberrations. These changes result in both misalignment and mode mismatch between the fiber and the back-reflected beam, which lead to some loss of the coupling efficiency. Coupling efficiency may also vary as a function of the lateral scan position.

A telecentric optical configuration can minimize misalignment, while achromatic and aspheric lenses can minimize spherical and chromatic aberrations. Optical design software can help the designer create an optimum arrangement of the components to build a scanner with a uniform and high coupling efficiency.

**Spectral Response**

The spectral response of an OCT sub-system affects the axial resolution of the images, the system’s sensitivity to dispersion, and the degree to which optical corrections have to be made. Appropriate design, taking into account the spectral response, can ensure that image quality remains high even in conditions such as imaging through large volumes of water. Designing for an appropriate spectral response profile will result in optimal use of the bandwidth of the light source and the highest quality images.

The variation of the coupling efficiency as a function of wavelengths filters the spectrum of the light. The center wavelength, bandwidth, and amplitude are all altered by the optics and the sample between the light source and the detector. These variations may not be identical in the sample arm scanner.
(II) and the ODL (III or IV). In general, this filter function generated by the non-constant spectral response of the optics affects the signal amplitude and the axial resolution of the OCT image [2]. Since the coupling efficiency may be different at different transversal positions, the spectral response will be different as well.

**Depth of Focus vs. Resolution**

To obtain high lateral resolution and large depth of focus are always the goals in an OCT scanner design. Unfortunately, the depth of focus and the lateral resolution are inversely proportional so that increasing the depth of focus typically reduces the lateral resolution. An optical designer must consider the trade-off between the two parameters. The intended application must be carefully considered when designing these parameters.

Assuming the OCT beam is Gaussian, the depth of focus is defined as twice the Rayleigh range [3],

\[ 2z_0 = \frac{2\pi W_0^2}{\lambda}, \quad (12.1) \]

where \( W_0 \) and \( \lambda \) are the radius of the beam waist at focus and the wavelength, respectively. The Rayleigh range \( z_0 \) is measured from the waist to the spot size \( \sqrt{2} \) times of the waist. For instance, if the wavelength \( \lambda = 1.3 \, \mu\text{m} \) and the radius of waist \( W_0 = 5 \, \mu\text{m} \), the depth of focus will be 121 \( \mu\text{m} \). The dependence of the beam radius on \( z \) is expressed as

\[ W(z) = \left[ W_0^2 + \left( \frac{\lambda}{\pi W_0} \right)^2 z^2 \right]^{1/2}, \quad (12.2) \]

where the beam divergence \( \theta_0 = W_0/z_0 \), and the distance variable \( z \) is measured from the point of waist. The value of \( \sin(\theta_0) \) is defined as the numeric aperture (NA). Equation 12.2 indicates that the spot size is smaller for a higher NA and that the higher the lateral resolution, the shorter the depth of focus.

**12.1.3 Scanning ODLs**

Uniform Coupling Efficiency

In OCT, the function of the ODL (III or IV) is to produce the optical path or the phase match with the sample arm (II). Numerous scanning ODL designs have been demonstrated [4]. Although only a small amount of reference light is needed, the coupling efficiency can affect system sensitivity. More importantly, the reference ODL should have a uniform coupling efficiency. The coupling pattern of the rapid scanning ODL (RSOD) is described in the Sect. 12.3.
Spectral Response

The spectral response requirement in the reference arm or the ODL is of the same importance as discussed previously for the sample arm scanner design. Although the optics of the ODL are usually simpler than that of the sample scanner, they still normally create a nonuniform coupling efficiency over the spectrum. This creates a curved spectral response filter that operates on the spectrum of the light source. This spectral response is normally different from the spectral filter of the scanner, which results in a degradation of the amplitude and the axial resolution of OCT signal [2].

12.1.4 Spectrometers

Resolution

In spectrometer-based FD-OCT, three parameters influence the quality of the spectrometer and hence the OCT image quality: the frequency resolution, spectral response, and the spot size of the beam. These determine the fall-off characteristic and the axial resolution of the image.

A spectrometer based on a linear detector array samples the spectrum illuminating the array, resulting in a discrete signal. The integral area or the frequency interval of each pixel in the dispersive direction of the spectrum determines the un-aliased imaging range of FD-OCT according to the sampling theorem. The higher the frequency resolution, the larger the image range of the FD-OCT. Because the pixel number of the detector array is finite, the trade-off between the imaging range and the axial resolution should be considered in the spectrometer design.

Spectral Response

The spectral response of the spectrometer is important in the same way as discussed previously for both scanner and delay line designs. Besides going through the reference and sample arms, the light travels through the optics of the spectrometer before it is collected by the detector array. A nonuniform spectral response filters the interfering spectra, which changes the axial resolution and the contrast of the OCT image.

One of the design goals is to minimize the difference between the coherence spectra and the spectrum of the light source in order to achieve an optimum image quality. The design example of a spectrometer in Sect. 12.5.1 presents an example of a case where there is a trade-off between the flatness of the spectral response and the throughput of the spectrometer.

Spot Size and Fall-Off

The penetration depth of spectrometer-based FD-OCT is also limited by the signal fall-off due to the interference fringe washout due to the window in
frequency space. In other words, the fall-off is mostly determined by the spot size of a single wavelength component of the beam illuminating the array and the pixel size of the detector in the spectral dispersion direction \[5\] such that the smaller the spot size or the pixel size, the better the fall-off.

12.2 Some Key Optical Design Principles for OCT

12.2.1 Telecentric Optics

Telecentric optical systems are characterized by a flat imaging plane and are important to the design of OCT systems because they increase the coupling efficiency. The flat imaging plane decreases the amount of postimage processing needed to display geometrically correct images and increases the coupling efficiency because the back-reflected light goes in close to the same incident path.

The definition of a telecentric optical system is a system in which all of the chief rays on the image side are parallel to the local optical axis and perpendicular to the planar image plane. Telecentric optics generally reduce image artifacts caused by off-axis optical aberrations. This leads to several advantages for an OCT scanner, including constant magnification, constant spot size both on and off axis, and a planar imaging plane. Figure 12.2 shows the ray trace of three examples of approximately telecentric lens systems (modeled by Zemax) in which the stop is located at the front focus. Three collimated incident beams at different angles go through the optical system and are focused on the almost-flat image plane at the back focus. All of the chief rays on the image side are parallel to the optical axis. This feature results in a maximum reflection or scattering from the sample at and around the focus and back through the same optics.

In Fig. 12.2a–c, the foci of off-axis beams were closer to the lens than the paraxial focus by 0.36 mm, 3.15 mm, and 0.012 mm, respectively, for the three simulated configurations. Figure 12.2a is sometimes the most economical configuration, since a singlet is much cheaper than a second achromatic doublet (c), yet the performance is much superior to a doublet alone (b). For a telecentric design, the scanning mirrors of an OCT scanner (or their image) should be placed at the front focus of the optics, which results in a more consistent image quality over a wide lateral scanning range. It should be noted that telecentric optics do not necessarily need an achromatic doublet, but the achromatic doublet provides better performance.

12.2.2 Aspheric Optics

The use of aspheric optics in an OCT system provides several distinct advantages. First, it reduces the effects of spherical aberrations in the system.
Second, because of this reduction, imaging spot profiles are more clean. Third, a clean spot profile results in an increased coupling efficiency.

The curvature of an aspheric surface varies with the height of the incident ray [6]. Aspheric surfaces are usually used to collimate a beam with a large numerical aperture. Spherical aberration is defined as the variation of the focus with the aperture, which is because a spherical surface is only an approximation of an ideal focusing surface. Figure 12.3 is a somewhat exaggerated sketch of a simple lens, forming an “image” of an axial object point a great distance away. The ray close to the optical axis comes to a focus (intersects the axis) very near the paraxial focus position. The higher the ray height at the lens, the farther the position of the ray intersection with the optical axis moving from the paraxial focus. The distance between the paraxial focus and the axial intersection of the ray is also called the longitudinal spherical aberration.

The spherical aberration can be improved by correctly orienting the lens. For instance, the aberration of the optics in Fig. 12.3a was improved by just flipping this lens to Fig. 12.3b. It is always a preferred set up that the more curved surface faces the collimated beam and the less curved surface faces the focused beam. To achieve high-order removal of the spherical aberration, an aspheric lens should be used as shown in Fig. 12.3c.
Fig. 12.3. A simple converging lens with under corrected spherical aberration. (a) The rays farther from the axis are brought to a focus nearer the lens, (b) a correctly oriented spherical lens, (c) an aspheric collimator

12.2.3 Achromatic Optics

The use of achromatic optics in an OCT system has several advantages. They preserve axial resolution, reduce the dispersion effects of the optical system, improve coupling efficiency, and produce a clean spot profile. For these reasons, it is advantageous to use achromatic optics when designing an OCT system. Again, achromatic optics is more expensive but the result is typically worthwhile.

Chromatic aberration is the longitudinal variation of focus (or image position) with wavelength. The refractive index of the glass varies as a function of the wavelength of light, which results in the focal length of the lens as a
function of the wavelength. For most optical materials, the longer the wavelength, the lower the refractive index. This index feature of the material causes the short wavelengths to be more strongly refracted than the long wavelengths at the surface. For example, the blue light rays (shorter wavelengths) going through a simple positive lens are brought to a focus closer to the lens than the red rays (longer wavelengths) as shown in Fig. 12.4a (detailed later). The distance along the axis between the two focus points is the longitudinal axial chromatic aberration [7].

To clearly demonstrate chromatic aberration, we virtually “dissected” an achromatic doublet lens (Edmund Optics 45805), shown in Fig. 12.4. The lens materials are respectively LAKN22 (index: 1.6536@550nm; 1.6333@1350nm) for the AB layer and SFL6 (index: 1.8118@550nm; 1.7665@1350nm) for the BC layer. The radii of curvature of surfaces A, B, and C are, respectively, 43.96 mm, −43.96 mm, and −321.46 mm. The center thicknesses are 6 mm for AB and 4 mm for BC. After the removal of the BC layer, Fig. 12.4a shows the significant chromatic aberration of a simple positive element. In Fig. 12.4a, the short (550nm) and long (1350nm) wavelength rays incident at point A on the first surface of the lens were separated by the dispersion of the glass shown in the zoom-in window at point B of the second surface. The zoom-in window at focus indicates an aberration of 1.12 mm for a beam with height of 12 mm, and that the focal length of the long wavelength is longer than that of the short wavelength.

Compared to the first piece AB, the second piece BC is made of a glass with different dispersion and polished to lower power (curvature). Figure 12.4b shows that an achromatic doublet lens is made by bonding pieces AB and BC together using an index matching epoxy. Observe that the positions of long and short wavelengths are swapped during propagation from surface B to C, and the longitudinal aberration at the focus is reduced to 0.005 mm from 1.12 mm for the wavelengths of 550 nm and 1,350 nm.

OCT optics must support broad optical bandwidths in order to achieve high-quality, high-resolution imaging.

12.3 Scanning ODL Design Example

All OCT systems require an ODL to provide a reference field to interfere with the sample field. A FD-OCT system used a fixer-path ODL, but a TD-OCT system requires a high-speed scanning ODL for real-time imaging. The most commonly used ODL for real-time TD-OCT in the Fourier-domain rapid-scanning ODL (RSOD) [8–11].

In this section, we will review the optical design and the performance analysis of the RSOD, and demonstrate how to address the design requirements 2–3 in Sect. 12.1.1 and the use of telecentric and achromatic optics in Sects. 12.2.1 and 12.2.3. The coupling efficiency and the spectral response will be addressed by simulations using a Zemax model of a previously
Fig. 12.4. Schematic diagram of chromatic aberration and correction by use of an achromatic doublet. The lens is simulated by Zemax. (a) A simple double convex positive lens and part of the doublet of (b) and (b) the achromatic doublet lens. Green and Red represent the short and long wavelengths, respectively reported [11]. Figure 12.5a shows a schematic drawing of the RSOD, [11] while Fig. 12.5b,c are the Zemax models at two different scanning angles showing the ray propagation step by step on which we will discuss the design procedure.
Fig. 12.5. (a) Schematic of the Fourier domain optical delay line (view from above) [11]. (b and c) Zemax modeling at two different scanning angles. Round trip by going through the fiber - collimator - A - B - C - D(D') - E(E') - F(F') - D(D') - C - B - A - collimator - fiber. The incident and output rays at the lower parts of the grating and the objective in (a) and (b). The folded part of the travel are scanning in horizontal lines from D to D', E to E', and F to F' on upper part of the objective, grating, and folding mirror, respectively.

Figures 12.5b, c show that the collimated broadband light is dispersed by a diffraction grating at point A. The dispersed beam goes through the lower part of the objective at point B before it is imaged onto a resonant scanning mirror at point C (other designs have galvanometric scanning mirrors). The objective collimates the spectrum and images or focuses every wavelength on the scanning mirror. The resonant scanning mirror vibrates on a vertical axis reflecting the dispersed beam back to the upper part of the objective from D to D'. Then, the objective collimates each single wavelength and reconverges the spectrum to point E (through E' when the resonant mirror scans) on the diffraction grating that recombines the dispersed spectrum into a single collimated beam and directs the collimated beam toward the folding mirror at point F (through F' when the resonant mirror scans). To the folding mirror, one half of the round trip is completed. The next propagation is identical to the first series but opposite in order. In summary, the ray finishes a round trip by going through the following steps: the fiber - collimator - A - B - C - D (D') - E(E') - F (F') - E (E') - D (D') - C - B - A - collimator - fiber.

The group delay resulting from the tilting of the resonant scanning mirror can be expressed as,

$$\Delta l_g = 4\sigma \eta \left( x - \frac{f\lambda}{p} \right),$$  \hspace{1cm} (12.3b)
where, the $x$ is the offset distance between the mirror pivot and the center wavelength, $\sigma$ is the tilting angle in radians of the resonance mirror, $\eta$ is the duty cycle during which the data is taken, $l_f$ is the effective focal length (not the back focal length) of the objective, $\lambda$ is the center wavelength of the light source, and $p$ is the pitch of the diffractive grating [11]. Our design goal is to achieve a large scanning range and fast scanning speed without significantly distorting the spectrum. The first step is to determine the required axial scanning range. For this design example, we select the axial scanning range to be about 4 mm, which is reasonable considering that the penetration depth of 1310 nm OCT is no more than 3 mm for most biological tissue. The second step is to begin selecting components based on design equations and commercial availability. For example, for this design, we choose a commercially available 2 kHz resonant scanner, a 600 lines/mm (pitch = 1.667 μm) diffraction grating optimized for 1310 nm light, and a 77 mm focal-length achromatic doublet for the objective lens. We also choose a duty cycle of $\eta = 0.86$ because the resonant scanner motion is a sinusoidal function of time.

The maximum axial scanning range $\Delta l_g = 4$ mm can be calculated by substituting the above parameters and the tilting angle $\sigma = \pm 0.5$ degrees into (12.3). A telecentric configuration shown in Fig. 12.5a is advantageous because this objective lens is used to collimate the spectrum and focus the beam on the scanning mirror (although for purposes of dispersion compensation, the grating-lens distance is often adjusted after the delay line is aligned). Therefore, the grating should be at the front focus, while the scanning mirror should be at the back focus of the lens. The grating is modeled as normal to the diffracted forward ray. The exact alignment of the components is optimized using optical design software (Zemax).

Three characteristics of the delay line will be evaluated at two opposite tilting angles using the Zemax model: the group delay, the coupling efficiency, and the spectrum as a function of the tilting angle.

First, the group delay is evaluated by comparing the calculation using (12.3) and the simulation using Zemax, as shown in Fig. 12.6. The delay versus the tilting angle is very linear. The delay produced by this Zemax RSOD mode agrees closely with the calculation of (12.3), in which the effective focal length is used.

Second, a uniform coupling efficiency is important for preserving image quality across an image. The coupling efficiency varies with the tilting angle of the resonance mirror and this variance changes significantly with slight changes in the alignment of the optical components. The objective is to minimize this variance. The achromatic lens combination as shown in Fig. 12.2a was used in this design in order to minimize the chromatic dispersion, improving uniformity of coupling efficiency. The coupling efficiencies for three wavelengths versus the tilting angle are shown in Fig. 12.7. The upper three curves are the coupling efficiencies at three different wavelengths, while the lower three are the relative variations versus the scanning angle corresponding to each wavelength. It indicates that the maximum relative tolerance is less
Third, the spectral response versus tilting angle is another critical parameter of the RSOD because a filtered spectrum will affect the axial resolution and the amplitude of the interference signal [2]. To obtain the spectral response of the optical system using optical design software, we calculate the coupling efficiency as a function of wavelength. The spectral responses are obtained at the

than 5/10,000 in the scanning range −0.5, 0.0, +0.5 degrees and that the coupling efficiency is quite stable in the scanning range.
angles \(-0.5, 0, \text{ and } +0.5\) degrees and are shown in Fig. 12.8. The upper three curves represents the coupling efficiencies at the three different tilting angles, \(-0.5, 0, \text{ and } +0.5\) degrees respectively, while the lower one represents averaged relative variation of the scanning at each wavelength. Results indicate that the spectrum of the light source is just very slightly filtered by the optics; about 1\% at shorter wavelengths, and that the relative variation of the spectra is less than \(6/10,000\).

In summary of this section, we designed and analyzed an RSOD using optical design software and making use of telecentric and achromatic optics. The simulated group delay agrees to the theoretical predication, and the coupling
efficiency varies only slightly with the tilting angle of the scanning mirror and
with wavelength. An achromatic lens is necessary for the objective because
the incident light has a broad bandwidth spectrum. A telecentric design is
also required because the lens should collimate the spectrum and focus the
beam for every single wavelength. Notable lessons from this design example
are that the recoupling as a function of tilt angle and wavelength are much
worse without use of achromatic and telecentric optics, and that the distance
between the lens and the scanning mirror is much more critical than the
distance between the lens and the grating.

12.4 OCT Scanner Design Examples

12.4.1 Overview of OCT Scanners

The OCT sample scanner (II) is one arm of the two beam OCT interferometer
and is used to deliver and focus the probe light into the tissue and to collect
the scattered light back to the interferometer to generate the image signal by
interference of the sample light with the reference light back from the ODL.

Many types of scanners have been demonstrated for a variety of applica-
tions [4]. Recent developments include high resolution devices involving
adaptive optics [12, 13] and high numerical aperture systems [14, 15], high
scanning speed using micromotors [16, 17], and three-dimensional imaging
[18, 19].

In the rest of this section, we will discuss two design examples of OCT
sample arm (II) design. For sample arm design, as with reference arm design,
coupling efficiency and spectral response are important. In addition, the spot
profile and the scanning range are critical parameters.

12.4.2 Design Example: Bench-Top Scanner

The purpose of this design example is to demonstrate how to address the
design requirements 1–4 in Sect. 12.1.1 by making use of telecentric and achor-
matic optics (Sects. 12.2.1–12.2.3). The example that will be used in the design
discussion is a bench-top OCT scanner described previously [1]. The goal
of this design was to develop an OCT scanner with high lateral resolution,
long working distance (the distance between the final optical component and
the sample), and large lateral scanning range. In addition, we attempted to
achieve a uniform spot size and image quality over the entire lateral scan
range. Another design goal was to provide a view-port for a microscope to
visualize the sample simultaneously while OCT imaging. The primary pur-
pose of this scanner is for use with an OCT system intended for bench-top
studies of biomedical samples under the guidance of a microscope [1].

Figure 12.9 shows the optical design of the scanner [1]. The illuminating
light delivered via optical fiber is collimated by an aspheric lens AL (see
Sect. 12.2.2) into a diameter of 2.2 mm and then deflected by a commercially available, small and compact $x$-$y$ galvanometric scan head. The $x$-$y$ scan head (Cambridge Technology, Cambridge, MA) used in our design provides high scanning speed and has a distance ($d$) of 5.4 mm between $x$ and $y$ mirrors, which leads to a small deviation from telecentric optics. The relay optics consists of two pairs of achromatic lenses, LP$_{1a}$ and LP$_{2}$, which magnify the OCT beam by a factor of two. To minimize spherical aberration in a large angle scan, LP$_{1a}$ and LP$_{2}$ are pairs of identical achromatic lenses face to face (see Fig. 12.2c). The focal lengths of LP$_{1a}$ and LP$_{2}$ are $f_1 = 62$ mm and $f_2 = 124$ mm, respectively, and they are separated by $f_1 + f_2$. Folding mirrors M1 and M2 are used to make the scanner compact. A dichroic mirror DM at 45 degrees incident angle is employed to deflect infrared light and transmit visible light and is located at the back focus $f_2$ of LP$_{2}$ and the front focus $f_3 = 20$ mm of the objective OB$_{1}$. DM deflects the OCT beam through the objective lens OB$_{1}$, which then focuses the beam onto the sample. OB$_{1}$ is a combination of singlet and achromatic lenses, which is a simplified method of minimizing spherical aberration similar to LP$_{1a}$ or LP$_{2}$. The OCT signal reflected or scattered from the sample placed at the back focus $f_4$ of OB$_{1}$ is collected back through the same path to the OCT detector, while visible light passes through OB$_{1}$, DM, and OB$_{2}$ to the microscope and CCD camera. OB$_{2}$ is identical to OB$_{1}$, so that they constitute a finite conjugate system to provide a 1:1 image of the sample at conjugate plane IS and allows the microscope to indirectly image the sample at IS. All optical components used in the design are commercially available and the alignment was optimized using optical design software (Zemax).
Spot analysis and characterization: Figure 12.10a–c shows the spot profiles on the flat image plane simulated by Zemax in physical optics propagation (POP) mode, while Figure 12.10d–f shows the same spot profiles measured by a beam analyzer placed at the image plane 16.5 mm away from last surface of the objective lens. The $1/e^2$ diameter of the simulated central spot was 14.9 $\mu$m, while the diameter of the 2.2 mm $y$-offset spot was 15.4 $\mu$m, and the diameter of the 2.2 mm $x$-offset spot was 15.3 $\mu$m. This achieves our design goal of not exceeding 17 $\mu$m spot diameter. The maximum fractional spot size deviation is 2.3% over the full lateral scan range of 4.4 mm, which is better than our tolerance criterion of 5%. The average ellipticity of $x$- and $y$-scans is 3.2%, which also meets our tolerance criterion of 5%. The measured $1/e^2$ diameter of the central beam was 14.8 $\mu$m, while the diameters of the 2.2 mm $y$-offset beam and 2.2 mm $x$-offset beam were 16.1 $\mu$m. This corresponds well to above simulated spot profiles. The spot size remained below our design goal of 17 $\mu$m over the full scan range, and the maximum fractional spot size deviation of 4.4% meets our tolerance criterion. The average measured ellipticity of $x$- and $y$-scans in Fig. 12.10 is 1%, which is better than our tolerance criterion of 5%.

Comparing Fig. 12.10a–c with d–f, we note that except for the central beam, the spot size measured by the beam analyzer is slightly larger than the one simulated by Zemax. One possible explanation is that we assumed the core diameter of the SMF-28 optical fiber to be 9 $\mu$m, but the diameter of the actual fiber may vary by $\pm 0.4 \mu$m. Another possible explanation is that the beam analyzer might not be precisely aligned with the image plane. The off-axis spot profiles are slightly elliptical, which is a typical problem for a system with slight spherical aberration. The further the spots are from the
optical axis, the more elliptical they become. Another important property shown in Fig. 12.10 is the purity of the spot profile. There are no side lobes, which could decrease the image contrast.

To investigate the effects of varying the degree of quasi-telecentricity, we varied the distance between the two scanning mirrors in our Zemax model while keeping both the front focal length of LP1 constant and the focus of LP1 at the middle distance between the two mirrors (see Fig. 12.9). The quasi-telecentricity parameter value of zero in Fig. 12.11 represents a telecentric system. We varied the distance \( d \) up to 10 mm, which varies the quasi-telecentricity parameter up to approximately 8%. In Fig. 12.11, we plotted the variation of the two spot parameters at the maximum of the lateral scan range as a function of the quasi-telecentricity parameter: the spot size variation and spot ellipticity. The average values for the \( x \)- and \( y \)-spots are plotted.

The results shown in Fig. 12.11 indicate that the relative spot size increases slowly until the QTP reaches approximately 5% and then increases more rapidly. The ellipticity generally decreases slowly with QTP. We observe an oscillation in ellipticity with QTP, but have no explanation for this observation at this time. The arrow in Fig. 12.11 represents the QTP of our implemented system, 4.4%. At this value, as discussed above, both spot size variation and ellipticity are well below our tolerance criteria.

**Coupling efficiency**: As discussed in Sect. 12.4.2, the coupling efficiency directly relates the signal amplitude and affects the axial resolution, since it filters the spectrum of the light source. Evaluating the coupling efficiency of this scanner via the Zemax model requires ray-tracing the light propagating

![Fig. 12.11. Simulations showing variation of the relative off-axis spot profile with QTP. Diamond and square represent spot size variation and ellipticity, respectively](image-url)
through the optical components from the optical fiber to the sample (the end mirror in Zemax model), and reflected through the same optical path back to the optical fiber. The model should be built as a round trip, and both the emission and receiving fibers should have the same NA at the given wavelength before evaluating the coupling efficiency. For instance, the numerical aperture of SMF-28 fiber is 0.14 at 1550 nm wavelength, but is 0.118 at 1310 nm wavelength. Steering the optical beam by tilting the scanning mirror from the center to the edge of the field of view, we obtained the coupling efficiencies as a function of wavelength at different transversal positions, as shown in Figure 12.12. The incident spectrum in the simulation was normalized to unity in the calculation range. Figure 12.12 shows that the spectral bandwidth will be slightly narrowed by the filtering effect of the wavelength-dependent coupling efficiency and that the peak of the function shifts toward the longer wavelengths as the tilting angle increases from 0 to 4 degrees or the beam is moved toward the edge of the scanning range. For a typical OCT light source, this filter function will not significantly affect the spectrum. In the case of a light source with ultra-broad bandwidth, for instance 200 nm, this effect could be significant and require more careful design. To achieve a flat spectral dependence of the coupling efficiency, telecentric optics for the last objective and careful compensation of chromatic dispersion are essential.

12.4.3 Design Example: Catheter Probe

In this section, we examine the design of a relatively high numerical aperture (NA) and long working distance catheter probe (II). Catheter probes with high NA require a beam with a large diameter to produce a sufficiently small spot size that leads to a high-resolution image. A probe with a long working distance requires an even larger beam in order to maintain a small spot size. This requirement of a large beam makes careful optical design important in order to meet design specifications. A GRIN lens is typically used in catheter
probe designs in order to achieve a small probe diameter. Here, we choose conventional refractive lenses with around 2 mm diameter to achieve a high NA and a long working distance probe because of improved off-axis performance. The astigmatism due the probe sheath also needs to be compensated in the design of high NA probe.

Figure 12.13 shows the Zemax model of a catheter probe using conventional lenses. The light out of the fiber is focused by a spherical lens pair, reflected by an angle prism and adjusted by two orthogonal cylindrical lenses as well as the compensator and the protective sheath. The working distance between the outside surface of the sheath and the focus is about 2.6 mm. The outer diameter of the sheath is 3 mm. Figures 12.14–12.16 compares the spot profiles of the probe design with and without astigmatism compensation. The spot achieved with the compensation lens, shown in Fig. 12.14 shows a clear profile with a high relative irradiance and a Strehl ratio of 0.73. The spot

![Fig. 12.13. Zemax model of a high NA, long working distance catheter probe design using refractive lenses and a cylindrical lens for the compensation of the astigmatism due to the protective sheath](image)

![Fig. 12.14. Spot profile of the design with astigmatism compensation. Image window is 32 × 32 μm](image)
achieved without the compensation, shown in Fig. 12.15, shows some fuzzy or star pattern with a lower relative irradiance of 0.423. The “star pattern” spreads the energy from the peak of the spot, which reduces the contrast and the resolution of the image. Figure 12.16 shows the cross section of the spot profiles achieved with and without astigmatism compensation, and are normalized to the spot with compensation. The curves represent the cross sections through the center of the spot images orthogonally in two directions. The $1/e^2$ diameter of the spots are 13 and 20 μm, respectively, for the designs with and without the compensator. The profile of spot with the compensation lens is symmetric around the center, while the profile without the compensation lens is not symmetric.

As a summary of this subsection, to accommodate the relatively large beam necessary for a higher NA and longer working distance catheter probe,
Fig. 12.17. Zemax model of spectrometer for FDOCT at 1,310 nm. Pixel number of detector array, 512; Pixel size, 50 μm; average wavelength spacing, 0.2 nm

refractive optics may be advantageous and correction for the astigmatism caused by the curved catheter probe sheath is important.

12.5 FD-OCT Spectrometer Design Example

The spectrometer (VI) is a critical component of array-based FD-OCT. The typical components of a fiber-coupled spectrometer include the collimator, diffractive grating, objective lens and linear detector array as shown in Fig. 12.17. The spectral coverage of the spectrometer determines the axial resolution of the FD-OCT system together with the bandwidth of the light source. The spectral range integrated by each pixel, together with the optical resolution of the spectrometer, determines the axial signal fall-off, which is a result of fringe visibility washout. The spectral spacing between pixels determines the unambiguous imaging range (limited by aliasing). To design a high-quality spectrometer, the chromatic aberration, optical resolution, and the detector array resolution should be taken into account. Chromatic aberration could be avoided by using all reflective optics, i.e. curved mirrors, but the optical resolution (the spot profile) would be more difficult to control than if refractive lenses were used. The following two subsections will describe a refractive-lens-based spectrometer design and the performance analysis.

12.5.1 Achromatic Spectral Response

In this section, we discuss correction of chromatic aberration due to the dispersion of the glass of the lenses and analyze the spectral response in this design. Figure 12.17 is the Zemax model of a refractive-lens-based spectrometer. The specifications of this spectrometer are the following: The wavelength coverage is 102 nm and the center wavelength of the spectrum, located at the center of the letter array, is 1310.6 nm. The detector array contains 512 pixels and are 50 μm wide. The orientation of the grating is fixed at the optimum incident
angle at the center wavelength for the expected light source spectrum, which makes the design relatively simple. The broad bandwidth coverage requires good achromatic optics. According to the principles discussed in Sect. 12.2, we used one achromatic lens to collimate the beam before the grating and three lenses for the objective. This consideration provided acceptable spot profiles through the entire spectrum of the light source as shown in Fig. 12.18. Figure 12.18 shows that the spot sizes at wavelength 1257 nm and 1359 nm are slightly broader in the dispersive direction than the spot at the center wavelength, 1310 nm, which is optimized in this design. They are all significantly smaller than the pixel width of 50 μm. The optimized optical design gives a flat throughput, covering the entire spectrum of this spectrometer (data not shown).

12.5.2 Optical Resolution and Detector Array Resolution

Both optical resolution and detector array resolution affect the axial image range of the spectrometer-based FD-OCT. According to the Nyquist theorem, the maximum axial imaging range \( \Delta D \) is limited by the following equation:

\[
\Delta D = \frac{\lambda^2}{4 \Delta \lambda N},
\]

where \( \lambda_c \), \( \Delta \lambda \), and \( N \) are the center wavelength, spectral range covered by the spectrometer, and the pixel number of the detector array. For \( \lambda_c = 1307.8 \text{ nm} \), \( \Delta \lambda = 102 \text{ nm} \) and \( N = 512 \), the maximum imaging range \( \Delta D \) is 2.142 mm. This distance can be thought of as the “folding range,” or the maximum range that image signal can be collected from without aliasing. The imaging range will be doubled to 4.284 mm if the pixel number \( N \) is increased by a factor of 2 or the spectral coverage is decreased by the same factor. The smaller the wavelength or frequency spacing, the longer the folding range will be. Therefore, for a given number of pixels available, there is a design trade-off between axial resolution and axial range.

In addition, the spectral resolution of the spectrometer determines the fall-off of the FD-OCT. The signal amplitude \( I(x_j) \) at pixel number \( j \) can be expressed as [5].
Coordinate function $x(k)$ varies with wave number $k$ and is defined by the optical design of the spectrometer. Erf, $\Delta y$, $\Delta x$, and $x_j$ are, respectively, the error function, the pixel height, the pixel width of the detector array and the position of the center of pixel $j$. The spot diameter $a$ is defined as the FWHM of the beam focused on the detector, and is assumed to be constant. The variable in the error function $k = 2\pi/\lambda$ is the wave number of the illuminating light. The spectral densities of reference and sample fields $r_{\text{ref}}$ and $r_{\text{sam}}$ are not necessarily the same. In (12.5), the quantum efficiency is assumed to be constant and the system attenuation factor was normalized. The pixel height $\Delta y$ in (12.5) comes out of the integral and does not affect the spectral interference or the fall-off of the FD-OCT signal, but it affects the amplitude when it is not large enough when compared to the spot size $a$. The pixel width $\Delta x$ of the detector and the spot diameter $a$ determine the fall-off of FD-OCT.

In the extreme condition, when the spot diameter $a$ goes to infinitely small, the sum of the two error functions under integral in (12.5) degrades into three special expressions: a step function either 2 in the pixel area or 0 outside the pixel if $\Delta x$ has a finite and nonzero size ($\Delta x > a$), a Delta function with a maximum value of 1.68 if $\Delta x$ goes to infinite small ($\Delta x = a$), and zero if $\Delta x = 0$. Therefore, (12.5) degrades correspondingly into the following expressions:

\[ I(x_j) = \frac{1}{4} \text{Erf} \left( \frac{\Delta y \sqrt{\ln 2}}{a} \right) \times \int_0^\infty \left[ \text{Erf} \left( \frac{(\Delta x - 2x(k) + 2x_j)\sqrt{\ln 2}}{a} \right) + \text{Erf} \left( \frac{(\Delta x + 2x(k) - 2x_j)\sqrt{\ln 2}}{a} \right) \right] \times \left[ r_{\text{ref}}(k) + r_{\text{sam}}(k) + 2 \sqrt{r_{\text{ref}}(k)r_{\text{sam}}(k)} \cos(2k\Delta D) \right] dk \] (12.5)

\[ I(x_j) = S_{\text{ref}}(k_j) + S_{\text{sam}}(k_j) + \sqrt{S_{\text{ref}}(k_j)S_{\text{sam}}(k_j)} \times \cos(2\Delta Dk_j) \left( \frac{\sin(\Delta D\Delta k_j)}{\Delta D\Delta k_j} \right) (\Delta x > a), \] (12.6)

\[ I(x_j) = S_{\text{ref}}(k_j) + S_{\text{sam}}(k_j) + \sqrt{S_{\text{ref}}(k_j)S_{\text{sam}}(k_j)} \times \cos(2\Delta Dk_j)(\Delta x = a) \] (12.7)

where $k_j$ is the wave number at position $x_j$ and $\Delta k_j$ is the segment of wave number around $k_j$ covered by the $j$th pixel. Equation (12.6) shows a clear sinc fall-off when $\Delta k_j$ is a constant over the spectrum, representing the case where the spectral resolution is dominated by the pixel size. Equation (12.7) is the familiar formula describing OCT interference, representing the case of infinitesimal spectral resolution and negligible fall-off.
As an example, we evaluate the fall-off versus different spot sizes for a spectrometer at center wavelength 1307.8 nm with bandwidth coverage of 102 nm. The design layout of this spectrometer is similar to the one in Fig. 12.17 except the grating is aligned for the center of the spectrum to be 1307.8 nm. After integrating (12.5) over $k$ space and Fourier transforming, the fall-off curves at different ratios of the spot size to pixel size (pixel width: $50 \mu m$), $0, 0.002, 0.25, 0.5, 0.75, 1.0, 1.5$ from top to bottom, are shown in Fig. 12.19. As expected,

![Graph](image)

**Fig. 12.19.** Fall-off curves at 8 different spot sizes ratios, fall-offs for $0, 0.002, \text{and } 0.25$ are very close. The higher the curve, the smaller the spot size. Pixel size = $50 \mu m$; center wavelength = 1307.8 nm; wavelength coverage = 102 nm

![Graph](image)

**Fig. 12.20.** $-3\text{dB}$ and $-10\text{dB}$ fall-off distances as a function of the ratio of spot size to pixel size. The fall-off is near optimum when the ratio is less than 0.25
the calculations show that the smaller spot size leads to a better fall-off. In the cases of the ratio $<0.25$, the fall-off is close to a sinc function, dominated by the pixel width. To easily compare the image attenuation versus the spot size ratio, we evaluated the image attenuation at $-3\text{dB}$ and $-10\text{dB}$ as a function of the spot size ratio (Fig. 12.20). This plot indicates that as long as the spot size ratio is less than 0.25, the fall-off is near optimum.

References
