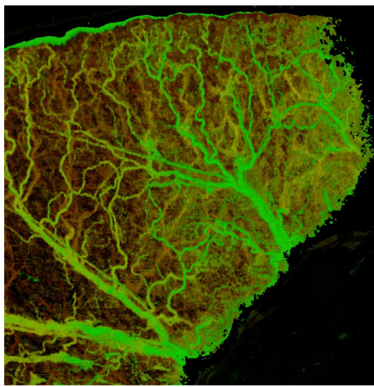


OCT Spectrometer Design

Understanding roll-off to achieve the clearest images

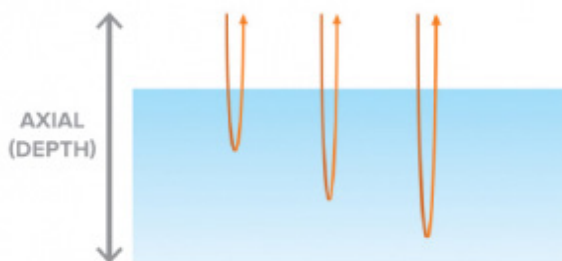
Building a high-performance spectrometer for OCT imaging requires a deep understanding of the finer points of both OCT theory and spectrometer design. In this tech note, we'll show how custom-designed optics can offer a tremendous improvement in signal and image clarity over off-the-shelf optics by enhancing overall signal strength and minimizing roll-off with depth. When optimized optics are augmented with a high-performance camera, even better images can be achieved, as in our Cobra OCT spectrometers.



Ask anyone in optics how a spectrometer works and they can tell you – it separates a beam of light into its constituent colors or wavelengths for qualitative or quantitative analysis of the incoming light's spectral composition. Spectrometers are widely used for identification, characterization and quantification of substances in many fields of research and industry. Ask the same person how optical coherence tomography (OCT) works and the answer may not be as quick. They can probably tell you that it's a widely used optical imaging technique known for its high-sensitivity and speed, now a mainstay in ophthalmic diagnostics. They may even be able to tell you that there are two main approaches to OCT: SS-OCT, which uses a swept wavelength source and a single element detector, and SD-OCT, which uses a broadband source and a spectrometer for detection.

If you ask them to combine the two topics and tell you what kind of spectrometer is best for OCT, you may not get much detail beyond some basic comments on resolution and sensitivity. In truth, it has to do with a number of factors, including resolution, SNR, and a property that seems very mysterious to the typical spectroscopist or optical designer – camera roll-off. To truly understand these factors, let's first take a step back to consider how OCT works.

OCT relies on low-coherence interferometric measurements (learn more about the theory at wasatchphotonics.com/octtutorial/). In the first generation of OCT devices, this was performed by moving the reference mirror arm of an interferometer, placing the sample in the other arm and scanning the reference arm through different time points (depths) within the sample. Interference between the sample & reference arms carries with it information



Spectral domain OCT (SD-OCT) uses low coherence interferometry of infrared light to estimate the time of flight of light scattered from structures within a sample, providing micron-level spatial resolution.

about degree of scattering at different depths, allowing a cross-sectional image of structure to be created as the beam is scanned across the sample. However, researchers soon realized a more effective way to obtain the same information was by analyzing the light at different wavelengths rather than at different time points (i.e., spectral domain interference vs time domain interference). This change in approach offered an exponential increase in speed and sensitivity, but analysis of the different wavelengths required an appropriate spectrometer.

The requirements for a good OCT spectrometer differ from those of a standard spectrometer used for direct spectral

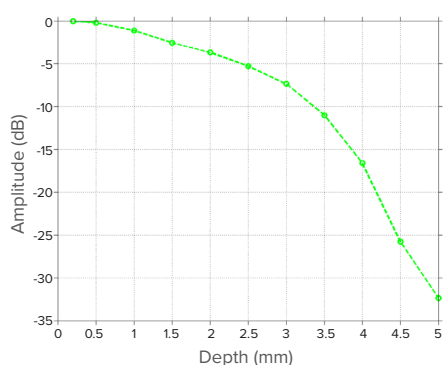
analysis of absorbance, fluorescence, or Raman. OCT spectrometers are required to work at very high speeds compared to standard spectrometers to facilitate the generation of 2D or 3D images in a reasonable amount of time. Light reflected back from an OCT sample can also have different polarization modes, and thus it is also important to maintain as little dependence on polarization as possible. This is challenging for spectrometers which use a reflective grating in their design, as specular reflection from a surface inherently favors s-polarization.

It is also important to realize that an OCT scan is not looking for the location of a spectral peak or the relative or absolute intensity of a spectral band, but instead an interference pattern reported in the spectral domain. This makes the resolution of the spectrometer an extremely important performance parameter. In particular, an OCT spectrometer has very little tolerance for light from one pixel leaking into nearby pixels. If such cross talk occurs, there will be a loss of sensitivity in the image as a function of depth.

ROLL-OFF IN OCT: LOSING SENSITIVITY WITH DEPTH

The loss of sensitivity in OCT as function of depth is called roll-off or fall-off, referring to a gradual decay in sensitivity as a function of depth. Roll-off is essentially a result of loss of fidelity of the interference pattern. Each

individual pixel detecting light in the spectrometer corresponds not just to one exact wavelength, but a small range of wavelengths. A perfect interference effect, however, requires measurement of a single, infinitely narrow wavelength. The figure at left shows a typical example of loss in sensitivity vs the depth of measurement.



In an OCT spectrometer, signal strength decreases with depth, impacting image quality as you probe deeper into the sample. This phenomenon is called roll-off.

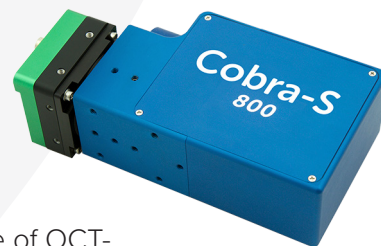
The problem is further worsened by the spread of wavelengths to neighboring pixels due to the finite resolution of the spectrometer. While the first issue is fundamental, the second one can be controlled via careful design of the spectrometer optics. Cross talk between the camera (detector) pixels, a property of the camera itself, also adds to the roll-off in a spectrometer. Therefore, choice of an appropriate camera (detector) becomes of paramount importance in spectrometers used for OCT applications.

APPLYING SPECTROMETER DESIGN KNOW-HOW TO OCT ADVANTAGE

Over a decade ago, the Wasatch Photonics optical engineering team began applying their considerable expertise in spectroscopy to the design of the ultimate OCT spectrometer. The result was the Cobra spectrometer, well-known for its image clarity and depth resolution in OCT applications. These spectrometers have several features that make them ideal for OCT imaging:

- High-efficiency diffraction gratings with low-polarization dependent loss
- Integration with high-speed and high sensitivity cameras (we've found the best!)
- Compact and robust design for OEM integration & tight spaces

While these features are critical, the need for excellent roll-off reigns supreme when it comes to selection of an OCT spectrometer. We mitigate this need through the use of OCT-specific features like single-mode fiber input and tall-pixel cameras, and proprietary focusing optics that are near diffraction-limited.

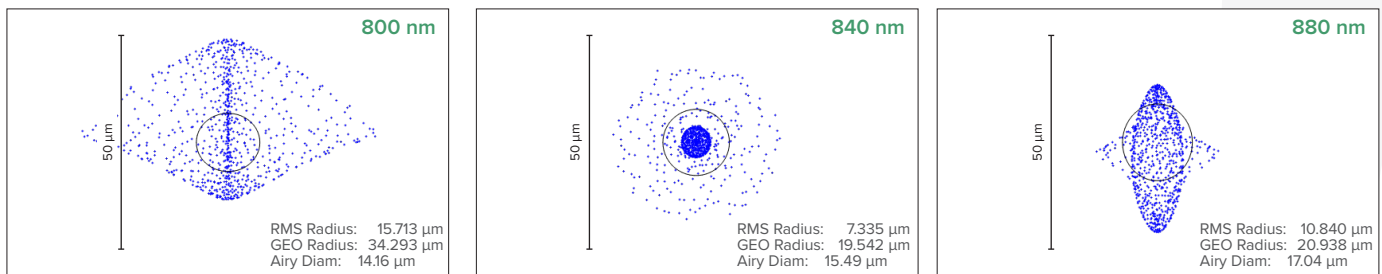


Off-the-shelf optics often fail to deliver high clarity OCT images because the optical constraints to obtain good roll-off are so stringent. The spot size on the pixel should theoretically be small. In addition, near diffraction limited performance is required across a long array of pixels and a wide range of wavelengths. These optical design constraints require spectrometer optics optimized specifically for the needs of OCT, and corrected for chromatic, spherical, and higher order aberrations in that particular optical layout.

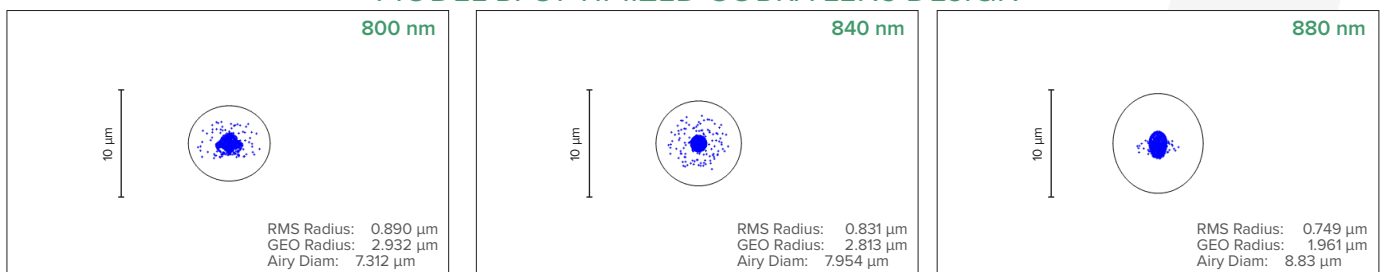
COBRA SPECTROMETER vs OFF-THE-SHELF OPTICS

To quantify the importance of these optimizations, we compared models of spot size and MTF (modulation transfer function) for the same diffractive OCT spectrometer design, but with two different lens sets. In both cases, the OCT spectrometer design spanned 800-880 nm, and used a transmissive VPH (volume phase holographic) grating for dispersion. Model A employed the best available off-the-shelf commercial lenses capable of minimizing spot size and aberrations across the camera image plane, while Model B used the proprietary custom-designed lenses developed for use in our Cobra OCT spectrometers.

MODEL A: OFF-THE-SHELF LENS DESIGN



MODEL B: OPTIMIZED COBRA LENS DESIGN

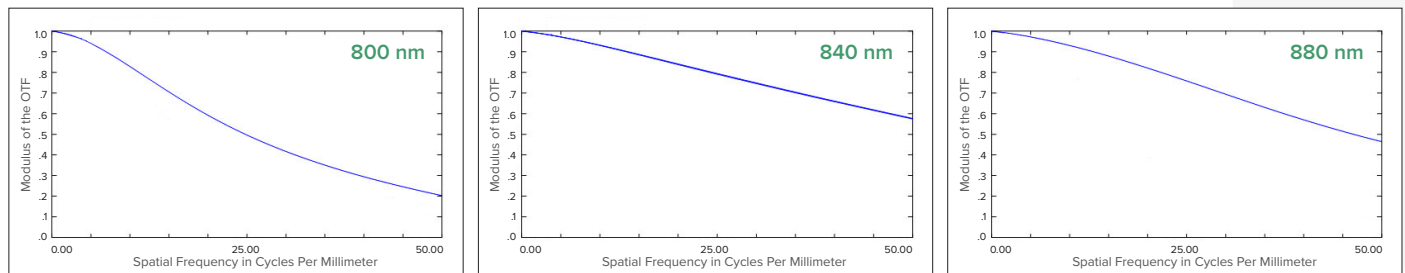


Comparison of spot size at the image plane for a diffractive OCT spectrometer as simulated with best available off-the-shelf lenses (model A) and fully optimized, customdesigned lenses used in our Cobra spectrometers (model B). Note that the scale of the Cobra spot diagram has been expanded by >2.5x to show the detail of its much smaller spot size and inclusion of all rays within the Airy disk.

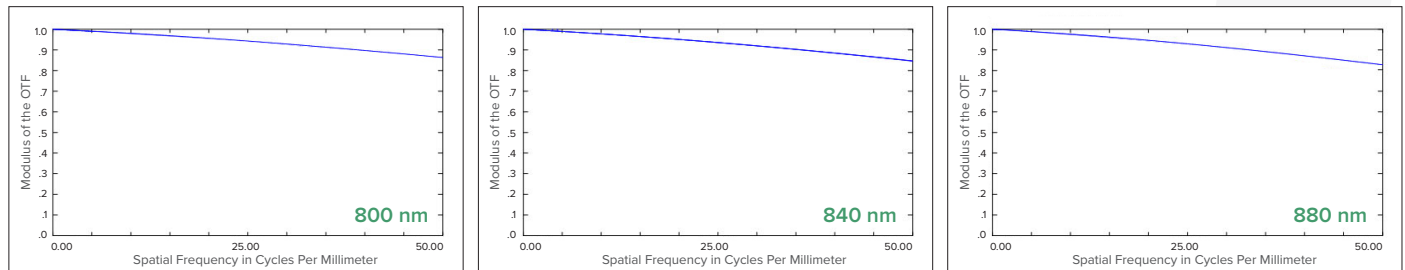
First, spot diagrams for both models were created using simulated chief ray tracing of the image plane in Zemax, with each spot representing a possible path of light through the spectrometer. The off-the-shelf lenses used in Model A yielded relatively well-focused light at the center of the camera (840 nm), but the off-the-shelf lenses were not able to maintain the same quality of focus at the camera extremes (800 & 880 nm). The wide distribution of spots represent uncorrected aberrations, and result in poor roll-off performance because not all components of the Fourier transform have equal signal. Model B using the Cobra optimized lens design, in contrast, showed much tighter, uniform focusing at all points along the camera, from 800-880 nm. Both the RMS and geometric radii were considerably smaller for the Cobra design vs off-the-shelf lenses. Falling well within the Airy disk, they indicate diffraction-limited performance. Note also that the Cobra results are displayed on a much finer scale of 10 µm.

Second, we calculated the modulation transfer function (MTF) for each model at the center and extremes of the camera (and thus wavelength). MTF is a measurement of an optical system's ability to transfer contrast from the sample to the image plane (camera) at a specific resolution. MTF is important in OCT to ensure accurate data resampling for reconstruction of the image from spectral data via Fourier transform. In this case, the goal is to achieve a high MTF at a spatial frequency of 50 mm^{-1} , which corresponds to the Nyquist frequency for the spectrometer's $10 \text{ }\mu\text{m}$ pixel width. Calculation of MTF for the best available off-the-shelf lenses (Model A) ranged from ~60% for the central region of the camera (840 nm), but degraded to 20%-45% for the extremes (800 & 880 nm). Performing the same MTF for the optimized Cobra spectrometer delivered significantly better results, with MTF values better than 80% across the camera (800-880 nm).

MODEL A: OFF-THE-SHELF LENS DESIGN



MODEL B: OPTIMIZED COBRA LENS DESIGN



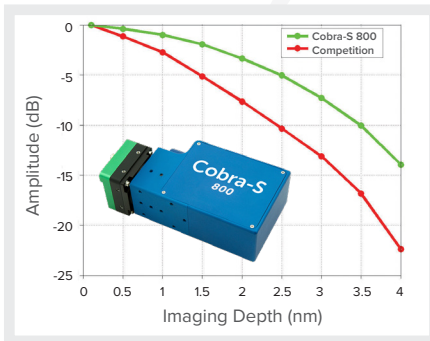
Comparison of the polychromatic diffraction modulation transfer function (MTF) for a diffractive OCT spectrometer as simulated with best available off-the-shelf lenses (model A) and fully optimized, custom-designed lenses used in our Cobra spectrometers (model B). MTF calculations are shown for the short, center, and long wavelength ends of the camera array (800, 840, and 880 nm, respectively).

Comparing the spot diagram and MTF for the Cobra OCT spectrometer design against the same spectrometer built with off-the-shelf lenses demonstrates the importance and benefits of using custom-designed lenses in an OCT spectrometer. Despite optimizing the combination of off-the-shelf lenses to reduce aberrations as much as possible, both spot size and MTF degraded at the camera (and wavelength) extremes. The Cobra spectrometer design, however, was able to deliver diffraction-limited spots and excellent MTF across the entire field. When used for OCT, this superior performance at the wavelength extremes translates into more signal, less roll-off, and greater clarity at depth for the optimized Cobra spectrometer design.

That said, design and development of a custom lens set can be prohibitive for the individual researcher, not to mention intimidating. By leveraging the design expertise, OCT experience, and volume manufacturing benefits available to us at Wasatch Photonics, we are able to deliver the performance of custom-designed optics in a fully optimized spectrometer design at a cost-effective price through our Cobra spectrometer products.

COBRA-S: THE NEXT GENERATION IN SD-OCT

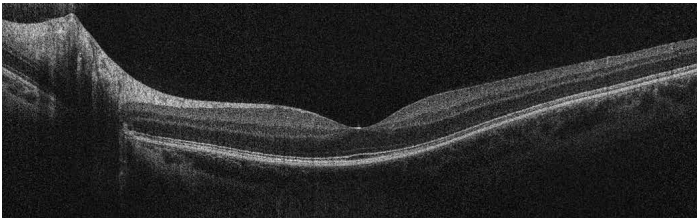
While careful optical design optimized specifically for OCT can help to significantly reduce the degree of roll-off in an OCT system, crosstalk between camera pixels also limits the performance that can be achieved. That's why we work closely with the best camera providers in the industry to integrate innovative, new cameras into our Cobra product family. The Cobra-S uses one such sensor, designed specifically for OCT applications.



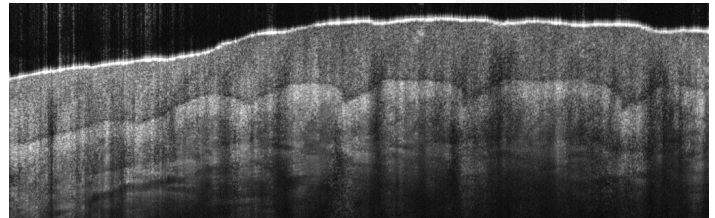
The high sensitivity & low crosstalk of the Cobra-S camera further enhances the design optimization of the Cobra-S, giving it >40% better roll-off and greater clarity than any other commercially-available OCT spectrometer. It also allows the Cobra-S to scan at an unprecedented 250 lines/second, an improvement of 2-3x in speed over any other off-the-shelf spectrometer. Delivering unprecedented scan rates and < 6 dB roll-off for 2.5 mm imaging depths, the Cobra-S is a major challenger to swept source systems, as it approaches the roll-off and speed of SS-OCT while still delivering the cost and resolution advantages of SD-OCT.

SEE MORE OF WHAT'S IMPORTANT TO YOU

The low roll-off offered by an optimized spectrometer design and industry-leading camera results in several application-friendly benefits. Clearer images are obtained, allowing more detailed structure can be seen. Greater depths can also be probed with high resolution, yielding a more complete picture of the sample under study. Last but not least, the rapid scan speed of the Cobra-S spectrometer greatly reduces motion artefacts during scanning without compromising resolution, allowing larger volume images to be captured with higher quality.



The combined speed and image quality of the Cobra-S allows wide-field OCT images to be acquired while minimizing motion artefacts.



Dermal layers and detailed structure are visible with high resolution to depths of up to 4 mm with the Cobra-S.

OCT + SPECTROSCOPY = BETTER TOGETHER

While an expert in spectroscopy may not understand OCT and vice versa, working with a company that understands the intricacies of theory and design in both fields can dramatically reduce your system design & build time, while significantly improving performance. At Wasatch Photonics, we combine our optimized OCT spectrometer optical designs with the newest and highest quality cameras on the market to offer you the best in OCT spectrometers, like the Cobra-S.

Contact us at info@wasatchphotonics.com to discuss your needs.

