Published in final edited form as:

Appl Opt. 2010 October 1; 49(28): 5399–5406.

Hyperspectral Shack–Hartmann test

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Abstract

A hyperspectral Shack–Hartmann test bed has been developed to characterize the performance of miniature optics across a wide spectral range, a necessary first step in developing broadband achromatized all-polymer endomicroscopes. The Shack–Hartmann test bed was used to measure the chromatic focal shift (CFS) of a glass singlet lens and a glass achromatic lens, i.e., lenses representing the extrema of CFS magnitude in polymer elements to be found in endomicroscope systems. The lenses were tested from 500 to 700 nm in 5 and 10 nm steps, respectively. In both cases, we found close agreement between test results obtained from a ZEMAX model of the test bed and test lens and those obtained by experiment (maximum error of 12 μm for the singlet lens and 5 μm for the achromatic triplet lens). Future applications of the hyperspectral Shack–Hartmann test include measurements of aberrations as a function of wavelength, characterization of manufactured plastic endomicroscope elements and systems, and reverse optimization.

1. Introduction

Endomicroscope systems are important for rapid disease diagnosis. Diseases can be readily identified through the presence of endogenous fluorophores, dyes, or other optical characteristics. Our larger goal is to design endomicroscope systems capable of operating over many modalities. By moving toward multimodality systems, we offer the diagnostician multiple sets of data with which to diagnose a patient.

When designing multimodality systems, the optical engineer is challenged by the chromatic correction necessary for diffraction limited performance between the extreme wavelengths used in the system. Typically, this problem is easily corrected using different glass types with large differences in Abbe number. However, all-glass endoscopes and endomicroscopes are very expensive. Our solution is to move toward all-polymer optical systems that are corrected for chromatic aberration over a large spectral band (>300 nm). All-polymer endomicroscopes offer compelling advantages in the spheres of mass manufacturing through injection molding and inexpensive material cost compared to that of optical glasses. All-polymer injection molded systems also offer assembly advantages due to concurrent molding of both the optics and optomechanical components of a lens.

Polymer optics for endomicroscopy applications or miniaturized objectives, such as those used in array-microscopy configurations, are typically designed as three-singlet or four-singlet forms [1]. The reason is that a relatively simple fabrication process can be used to make the specified lens elements (e.g., diamond turning or injection molding) [2]. A

characteristic of this type of lens design is a correction of chromatic aberrations over a 50–75 nm spectral range [3]. In some cases, this is not a disadvantage, e.g., monochromatic reflectance confocal laser scanning microscopy (CLSM) [4] or sequential narrow-band imaging with intermediate refocusing using LEDs for illumination (a sort of dynamic correction of chromatic aberrations). However, there remain a significant number of endomicroscopy modalities in which an achromatic or an apochromatic endomicroscope objective (e.g., a 164 nm spectral range) would be preferred while retaining the benefits of using plastic optics that are inexpensive to fabricate [5]. In at least one instance, chromatic aberration is used for position encoding in endoscopy [6–8]. However, even in that case, control and characterization of the chromatic aberration is desirable. Figure 1 presents an overview of imaging-modality examples and typical associated wavelength ranges.

For applications such as *in vivo* optical biopsies, information from multiple modalities is beneficial. Designing a system to operate over multiple modalities generally requires spectrally corrected performance over a wide spectral band. The high cost of glass endoscopic and endomicroscopic systems has pushed us to explore the realm of polymer optics with broadband performance.

2. Shack–Hartmann Test

Shack–Hartmann wavefront sensors provide a non-interferometric technique to retrieve wavefront data from a test lens or test system. These sensors have become well-established in the metrology of astronomical systems [9], medical applications such as human-eye aberrometry [10,11], and adaptive optics systems [12,13], as well as many other fields. The Shack–Hartmann test works by piecewise sampling the exit pupil wavefront using a lenslet array. If a perfect wavefront is incident upon a lenslet, the focal spot will fall on the local optical axis of the lenslet. However, when an aberrated wavefront is incident upon the lenslet array, the focal spot of each lenslet will be displaced by the product of the focal length of the lenslet and the average slope of the incident wavefront. The Shack–Hartmann test offers compelling advantages compared to other metrological tests due to the ease of testing aspheric elements, asymmetrical, and nonsymmetrical systems, as well use of commercial off-the-shelf parts to construct the test [14,15]. These advantages are discussed later in this article.

3. Doublet Designs

An achromatized optical polymer lens system requires two optical polymers with high and low dispersion. To develop a hyperspectral Shack–Hartmann test that was capable of measuring extremely small shifts in focal length as a function of wavelength, we designed an achromatized plastic doublet. An extensive study was performed on the doublet design to choose the very best plastics that would give minimal CFS, and consequently require the greatest precision of the hyperspectral Shack–Hartmann test. As a start, we designed an achromatic doublet using poly(methyl methacrylate) (PMMA) and optical grade polystyrene (PS). This material combination was chosen based upon an extensive analysis of 10 polymers' optical, mechanical, and manufacturing characteristics. The PMMA/PS doublet design will be presented, as well as the mechanical and optical properties of PMMA and PS.

A. Doublet Design

Designing an achromatic lens system requires the use of two different materials with a large difference in Abbe number. This is challenging due to the limited variety of optical polymers available to the designer. In order to demonstrate that an achromatic doublet could be made from optical polymers, we performed a design study using the following materials: (crowns) acrylic, low styrene, PMMA, Topas, and Zeonex E48R; and (flints) CTE-

Richardson, NAS-21 Novacore, polycarbonate, polystyrene, and styrene acrylonitrile. Detailed parameters for these materials can be found in the work of I. D. Nikolov and C. D. Ivanov [16]. This detailed design process was done such that the best achromatic doublet material combination could be found while constraining our design to a lens similar to those found within endomicroscopes. Consequently, the following design is representative of the smallest and therefore the most challenging to measure CFS that one would expect to encounter using the hyperspectral Shack–Hartmann to test an achromatized endomicroscope.

The terms “crown” and “flint” are associated with optical materials of low and high dispersive power, respectively [17]. The final doublet design, seen in Fig. 2, was chosen so that its design was similar to elements inside past endomicroscopic systems that we have developed [18–20]. Selected parameters of the doublet lens include a numerical aperture of $NA = 0.336$, a clear aperture diameter of 3 mm, and an effective focal length of 4.7 mm. The prescription of this lens can be found in Table 1. The design study exhaustively evaluated 90 candidate crown–flint pairings. In selecting the material pairs, we also considered each material’s manufacturing properties, cost, environmental properties (e.g., hydrophilic), and availability.

Each material pair was then optimized in ZEMAX to evaluate the final criterion: maximum achievable image quality as a function of wavelength. This was achieved through evaluating on-axis performance of the doublet with the ZEMAX default merit function, modified to include achromatized performance across the entire spectral band. Given the parameters of the design study, we found that a pair of PMMA and polystyrene satisfied best all criteria (see Fig. 3). Important optical and mechanical parameters for PMMA and polystyrene are presented in Table 2.

4. Multispectral Shack–Hartmann Test Bed

The Shack–Hartmann test was chosen to measure the axial chromatic focal shift of miniature lenses due to its flexibility, inexpensive components, and the simple modifications necessary to create a hyperspectral test. Previous projects have shown the usefulness of the monochromatic Shack–Hartmann test when testing miniature optical systems, and as a tool to characterize the point spread function of a well-corrected microscope [21].

A. Verification Tool Comparison

There are multiple methods of measuring the presence of aberrations in optical systems. One can divide verification methods into two broad categories based upon their measurement: systems that measure the aberration coefficients directly, and systems that measure performance metrics, such as modulation transfer function (MTF), which are a function of the present aberrations. When measuring the axial chromatic aberration of a system, we require a verification tool capable of directly measuring the W_{020} aberration, commonly known as defocus.

Table 3 provides an overview of three candidate techniques for measuring spectral aberrations of miniature optical systems and optical elements. Interferometers are excellent tools for measuring the aberrations of an optical system at a discrete wavelength, but are limited by the difficulty of testing systems, such as optical elements with surfaces that depart significantly from a sphere, nonrotationally symmetric systems, and divided-aperture systems. This is compounded by the high cost of interferometers and the null optics or computer generated holograms that may be necessary to test nonspherical surfaces. The chromatic focal shift behavior of a system cannot be measured across a wide spectrum using an interferometer due to the single wavelength at which interferometers test.

Image-evaluation techniques for measuring spectral aberrations of an optical system or element consist of imaging a test object onto a camera and adjusting the camera until the best focus is achieved [22,23]. The wavelength is then altered and the image is refocused by adjusting the camera conjugates. The difference between the best-focus positions for a non-reference wavelength and the best-focus position of an arbitrary reference wavelength is the axial chromatic aberration value. This technique is limited when measuring small changes in wavelength (<10 nm) using image quality alone, especially for achromatized systems that have extremely small axial chromatic aberration values across the entire spectral band. Finally, these systems are not readily capable of extracting aberration coefficients beyond spectral defocus.

B. Principles of Shack–Hartmann Test

The hyperspectral Shack–Hartmann test offers an inexpensive solution to measuring aberration coefficients of an optical element, or an entire optical system, as a function of wavelength. In our configuration, the Shack–Hartmann test requires a plane wave incident on the lens under test. The test lens focuses the incident light, which is then recollimated by a suitable lens (Thor Labs LB1092). This recollimated light is incident on a lenslet array (Wavefront Sciences OPT-MLA-FS-103), the key element of the Shack–Hartmann test setup (see Fig. 4). The recollimating lens also images the pupil of the lens under test onto the lenslet array. Each lenslet in the array spans only a small portion of the incident wavefront. Each lenslet averages the local wavefront bounded by its aperture (rectangular in our case, measuring 250 μm on a side), essentially seeing a tilted wavefront. Each local wavefront tilt results in a shift in the x and y coordinates of each lenslet's focal spot (see inset of Fig. 4). Determining the aberration content of the test lens requires software analysis of the focal-spot images produced by the Shack–Hartmann test [21,24].

Conceptually, we can view the Shack–Hartmann test as a device that converts angular wavefront shape into an precisely measurable quantity, i.e., lenslet focal-spot displacement. Unlike interferometers, image-evaluation techniques, [23] and edge spread function methods, [25] the Shack–Hartmann test is very flexible and able to test a wide variety of optics, including nonrotationally symmetric systems, [26] divided-aperture systems, and a host of other nontraditional configurations [27].

The wavefront from the test lens is modeled with a weighted sum of defocus and third-order spherical aberration. The centroid data collected with the Shack–Hartmann test are then fitted with this model, revealing estimates of the defocus (W_{020}) and spherical aberration (W_{040}) coefficients. The aberration fitting can be seen by Eq. (1):

$$\begin{pmatrix} W_{020} \\ W_{040} \end{pmatrix} = (B^T B)^{-1} B^T \Delta, \quad (1)$$

where the W_{020} and W_{040} coefficients represent the estimated defocus and spherical aberration, and B is a matrix that contains the wavefront gradients modeled across each lenslet aperture. The Δ vector contains the x direction and y direction difference of each centroid data set from an arbitrary zeroed reference set. The B matrix is a $2M \times 2$ matrix, and Δ is a $2M \times 1$ matrix, where M is the number of Shack–Hartmann spots used in the analysis. For the data presented below, 169 (13×13 grid) Shack–Hartmann spots were used in software analysis. The product yields the least-squares fit estimates of the W_{020} and W_{040} coefficients [21]. Detailed descriptions of the computational steps in the Shack–Hartmann test are well-described in the literature [21]. In the next section, we describe the major modifications necessary to create a hyperspectral Shack–Hartmann test for metrological purposes.

C. Monochromatic Shack–Hartmann Test Versus Hyperspectral Shack–Hartmann Test

Literature on the hyperspectral Shack–Hartmann test is sparse and mostly related to the field of human-eye aberrometry [28–30]. In these systems, a Shack–Hartmann test is used to measure aberration coefficients at a few discrete wavelengths across a spectral band. Typically, xenon arc lamps with filters or tunable lasers are used as illumination sources in these systems, and results are taken over a finite set of wavelengths, generally fewer than 10 [31]. In contrast, the hyperspectral Shack–Hartmann test, which we describe next, collects aberrations data across 20 or more contiguous, narrow spectral bands.

There are three necessary modifications to the monochromatic Shack–Hartmann test to create a fully functioning and precise hyperspectral Shack–Hartmann test capable of testing a wide range of optical systems: (i) the use of a monochromator as a hyperspectral illumination source, (ii) determination of an axial scale factor, and (iii) video image capture to improve the precision of the test.

D. Hyperspectral Illumination

To test the axial chromatic focal shift properties of miniature achromatized lenses and systems for biomedical applications, the Shack–Hartmann test must operate over a broad range of wavelengths, from the ultraviolet to the near-infrared (see Fig. 1). To achieve this requirement, a monochromator is used as the illumination source of the system. Illumination from a monochromator allows for precise selection of the wavelength the system will operate over, allowing the experiment to collect images at discrete wavelengths that can then be analyzed and compared through software analysis. Such an instrument also allows for easy automation of the experiment. In our setup, a microscope objective was used to focus the output light of the monochromator into an optical fiber. This allowed for the fiber to become an easily movable source in the test setup, as well as removed the spatial structure in the output of the monochromator due to the filament light source.

E. Axial Scale Factor

Typical Shack–Hartmann tests measure the centroid displacements of an image compared to the centroid locations of an image while a pinhole is inserted at the common focal point of the test lens and the recollimating optic. The analysis of these displacements can determine the defocus present in the system when the pinhole is removed. Many issues complicate the use of a pinhole when performing the hyperspectral Shack–Hartmann test on miniature optical components. When using optics with an extremely short focal length, mechanical insertion of the pinhole becomes prohibitive. Compounding this, chromatic focal shift measurements are inherently challenging to make accurately, since every optical element in the Shack–Hartmann test is refractive. The chromatic focal shift of the lenslets, for example, can incorrectly contribute to the measured chromatic focal shift of the test lens or test system. Finally, fixed parameters inside the aberration coefficient analysis software, such as test lens exit pupil diameter, lenslet aperture size, lenslet focal length, and other properties, such as camera pixel dimension, could either be unknown if testing whole systems or vary from the manufacturer's specifications. Variations in these factors all lead the image-analysis software to report aberration coefficients that are not scaled properly. To counter these effects, we developed an experimental procedure that accounts for all scale factors in the data analysis using calibration measurements with the Shack–Hartmann test.

First, the monochromator was set to a wavelength within the spectral range of interest for the CFS test. Next, high-precision digital micrometers (Heidenhain MT2500) attached to the test lens were zeroed at an arbitrary axial position where the test lens produced an in-focus image of the lenslet array on the camera. The test lens was then physically moved axially by small steps (approximately 25 μm) to either side of this arbitrary zero location. Shack–

Hartmann test images were recorded at each physically defocused test-lens position. This stack of images was then analyzed within our image-analysis software to determine the W_{020} corresponding to a physically defocused test lens. The arbitrary zero position image centroids were used as the reference centroid data set for all subsequent centroid data. The analysis result is a set of W_{020} coefficients that correspond to a set of physically defocused test-lens positions. If no axial scale factor were present, a plot of the W_{020} coefficient as a function of physically defocused test-lens position would have a slope of unity. However, a scale factor is generally present, as explained above, and is determined through the linear least-squares fit slope of this plot. The scale factor absolute value for this system is generally two to six, depending upon the positioning of each optical element, especially the relay lens. An important point to note is that this axial scale factor is wavelength-dependent, due to the optical power in all system component lenses varying as a function of wavelength. Therefore, this procedure is repeated at multiple wavelengths distributed within the spectral region of interest for the CFS test. For the data presented later in this document, nine different wavelengths distributed uniformly across the spectral band of interest were used to determine axial scale factors. Interpolation between data points was used to determine the correct scale factor at every wavelength used within the entire axial chromatic focal shift test.

Figure 5 shows the measured axial scale factors for the defocus tests presented later in this work. Using this technique, a simple system level corrective factor is found. This enables the large number of variables in this setup to be reduced to a single measured factor that can be applied to the defocus test output. Without this calibration method, factors such as extremely precise element separation, relay magnification as a function of wavelength, degree of input collimation as a function of wavelength, and many other factors, would be required before any useful data could be determined from the Shack–Hartmann test.

F. Video Image Capture and Precision

The purpose of the hyperspectral Shack–Hartmann test is to accurately measure minute changes in the focal length of a test lens or test system as a function of wavelength. The magnitude of such shifts across a spectral range, such as the visible spectrum for well-corrected optics, is generally in the tens of micrometers. For example, the 18 mm focal length triplet achromatic lens test results presented later in this paper have a maximum change in focal position of about $23\ \mu\text{m}$ across the 500 to 700 nm band. Ten-nanometer steps in wavelength for this test lens result in predicted focal length changes ranging from $17\ \mu\text{m}$ down to $0.28\ \mu\text{m}$. The $0.28\ \mu\text{m}$ axial shift translates to an expected change in centroid position on the camera of 1/55th of a pixel. Measurements of such small centroid shifts is well below the precision of the Shack–Hartmann test setup (see Fig. 6). To resolve such small centroid shifts, video sequences were recorded at each wavelength in the chromatic focal shift test. The centroids of each lenslet's focal spot in each video frame were calculated and then averaged together for a single wavelength video file. Up to 1000 frames were processed for each wavelength being tested. This approach ultimately resulted in approximately 3.5 million centroids being averaged down to a set of 21 “super centroid” results, which were subsequently analyzed using the Shack–Hartmann analysis software and wavefront model.

5. Results

Two lenses were tested in the hyperspectral Shack–Hartmann test bed; a singlet composed of NBK7 (Edmund Optics 45863), and a triplet with achromatic behavior composed of BASF1 and NBK7 (Edmund Optics 45399). The processed Shack–Hartmann test defocus data as well as the predicted ZEMAX defocus data are compared for both cases (see Fig. 7).

A. Singlet and Achromatic Triplet

The glass singlet (NBK7) was chosen so that the total magnitude of chromatic focal shift would be comparable to that of a single-material plastic endomicroscope, on the order of hundreds of micrometers for a bandwidth of 500 to 700 nm. Similarly, the glass achromatic triplet (BASF1 and NBK7) was chosen so that the magnitude of chromatic focal shift over the same spectral range would be comparable to the predicted focal shift of the plastic achromat presented earlier in this work.

Figure 7 shows the comparisons of the chromatic focal shift modeling and measurement results for the singlet lens and the triplet lens. The singlet data set measured defocus with a maximum error of 14 μm and an average error for all data points of 5 μm , compared to the ZEMAX predicted defocus. The achromatic triplet data set measured that maximum error was 5 μm and an average error of all data points is 0.2 μm . The large decrease in average error for the achromatic triplet is due to achieving higher precision through capturing sequential image stacks. Larger image stacks would help reduce the larger errors of the singlet data, but due to the much larger magnitude of the total shift, they would give a minimal performance increase.

The results of the predicted defocus values and measured defocus values from the hyperspectral Shack–Hartmann test match closely.

B. Future Work

The plastic achromatic doublet presented will be fabricated and tested next using the hyperspectral Shack–Hartmann test setup to determine its axial chromatic focal shift and compare that experimental result to the design prediction. The hyperspectral Shack–Hartmann test will be modified to measure even smaller chromatic focal shifts of highly corrected achromats and apochromats (see Fig. 8). This can be achieved through using a lenslet array with a longer focal length than implemented in this effort and further improving the environmental isolation of the setup.

The dependence of the spherical aberration coefficient on wavelength and analysis of higher order aberrations' spectral dependence, as well as other aberration expansions (e.g., Zernike polynomials), will be the subject of future work. Software modifications can be made to the Shack–Hartmann analysis software to accommodate these models. It is important to note that no test-bed changes need be made to estimate these terms. Ultimately, we plan to use the hyperspectral Shack–Hartmann test for through-the-lens testing of complete plastic endomicroscope optical systems and combine such testing with reverse optimization [32–36] of the corresponding optical design so as to determine fabrication errors in the assembled system.

6. Conclusion

The long-term purpose of this project is to build inexpensive endomicroscope systems from optical plastics that operate over a wide spectral range. To demonstrate the feasibility of such a development effort, we have reported on a design study of a plastic achromatic doublet and found that using PMMA and optical grade polystyrene represents a minimum level of chromatic aberration. Consequently, the PMMA and polystyrene doublet is representative of the most challenging measurement the hyperspectral Shack–Hartmann test would encounter. The fabrication of such optical elements and systems is feasible using methods, such as single point diamond turning (SPDT) or diamond milling [2].

The need for a hyperspectral Shack–Hartmann test originates in the desire to measure the chromatic behavior of aberrations for lenses and entire optical systems without using

interferometric techniques, which are too expensive and generally give limited spectral information. The hyperspectral Shack–Hartmann test was constructed from off-the-shelf lenses, operates from 400 to 1000 nm, used an experimental method to properly calibrate the system when new lenses are placed under test, and uses stacks of image to increase the precision of the instrument. The singlet lens and triplet achromatic lens were chosen so that their chromatic performance was similar to a single-material endomicroscope and the achromatized doublet presented earlier in this work, respectively. The singlet lens and triplet achromatic lens were tested with the hyperspectral Shack–Hartmann test. The experimental measurements were found to agree very closely with simulated data predicted from each lens model inside the ZEMAX optical design software.

Acknowledgments

This work is supported by National Cancer Institute (NCI) grant R01 CA124319.

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Fig. 1.

(Color online) Spectrum of applications and the associated wavelength ranges. Blue bars denote the approximate excitation waveband, and gray bars denote the approximate emission waveband. Acronyms: CLSM, confocal laser scanning microscopy [4]; (SHG), second harmonic generation [37]; LED, light emitting diode; STED, stimulated emission depletion [38]; 2PEF, two-photon excited fluorescence.

Fig. 2.
(Color online) PMMA and polystyrene doublet. See text for details.

Fig. 3. (Color online) Best-performing achromatic doublet designed using optical-polymer materials (PMMA and PS). The lens diameter is 3 mm and the total lens thickness is 4.1 mm. A.S., aperture stop. Part (b) shows the chromatic focal shift for the doublet design of (a). See text for details.

Fig. 4.
(Color online) Schematic representation of the hyperspectral Shack–Hartmann test bed. The inset illustrates how wavefront deformations in the exit pupil of the lens (or system) under test are converted to lenslet focal-spot displacements.

Fig. 5.
(Color online) Axial scale factors measured for singlet (a) and doublet (b) test lenses. The axial scale factor is determined in 25 nm increments of wavelength.

Fig. 6.

(Color online) Black box representing the size of a single pixel ($5.2 \mu\text{m} \times 5.2 \mu\text{m}$) in our camera. Blue crosses represent the focal-spot centroids calculated for a series of 200 sequential measurements from a single lenslet at a fixed test-lens position and fixed wavelength. Noise in the system contributes to reduced precision of the centroid calculation. These centroids are averaged together to produce a single centroid location for this lenslet at this wavelength, which will then be processed with the Shack–Hartmann analysis software.

Fig. 7. (Color online) Predicted and measured hyperspectral Shack–Hartmann test results. Part (a) compares the predicted spectral change in focal length for a singlet lens to experimental measurements with the hyperspectral Shack–Hartmann test. Part (b) compares the predicted spectral change in focal length for a triplet achromatic lens to experimental measurements with the hyperspectral Shack–Hartmann test. Note the change in the ordinate-axis scale between Parts (a) and (b). See text for details.

Fig. 8.
(Color online) ZEMAX predicted axial chromatic focal shift for PMMA/polystyrene achromatized doublet. Blue regions denote shifts in focal length that are larger than the smallest focal length shift experimentally detected in the triplet achromat below 20% relative error. Yellow regions denote shifts in focal length that are smaller than the smallest focal length shift experimentally detected from the triplet achromat above 20% relative error.

Table 1

Design Parameters for the PMMA and Polystyrene (PS) Doublet (See Text for Details)

Surface number	Radius of curvature [mm]	Thickness [mm]	Material	Semidiameter [mm]	Conic
1	2.67	1.1	PMMA	1.5	-0.12
2	-2.10	3.0	PS	1.5	
3	-5.18				6.63

Table 2

Optical and Mechanical Properties of PMMA and Polystyrene Used to Create the Achromatized Doublet^a

	<i>n</i> (435.8 nm)	<i>n</i> (587.6 nm)	<i>n</i> (703 nm)	Abbe Number	Coefficient of Thermal Expansion	Water Absorption
Polystyrene (Rexoliate 1422)	1.617	1.592	1.582	30.5	$7.0 \cdot 10^{-5}/^{\circ}\text{C}$	0.08% Max
PMMA	1.502	1.491	1.486	59.2	$5-10 \cdot 10^{-5}/^{\circ}\text{C}$	0.1–0.5%

^aThe water absorption column specifies a percent increase in the weight of the plastic after a time and amount of water specified by the ASTM D570 test. This factor is important in endomicroscopy, since an optical element might be exposed to aqueous environments when inserted into the body.

Table 3

Overview of Verification Method Trade-Offs (See Text for Details)

	Interferometry	Image Evaluation	Shack–Hartmann Test
Hyperspectral		•	•
Able to test nonspherical object without null surface		•	•
Can measure multiple aberrations	•		•
Commercial off-the-shelf equipment and minimal setup labor		•	•
Highly sensitive	•		•