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The Correction Method for Wavefront Aberration Caused by Spectrum-Splitting Filters in Multi-Modal Optical Imaging System

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Abstract: In current biomedical and environmental detection, multi-modal optical imaging technology is playing an increasingly important role. By utilizing information from dimensions such as spectra and polarization, it reflects the detailed characteristics and material properties of the targets. However, as detection system performance becomes more complex, issues such as aberrations introduced by multilayered lenses, signal attenuation, decreased polarization sensitivity, and latency can no longer be ignored. These factors directly affect the assessment of image details, influencing subsequent analyses. In this paper, we propose a method for designing and optimizing spectrum-splitting filters that considers the wavefront aberration and transmittance of the multi-modal optical imaging system. The method of optimizing coating phases to minimize scalar phase aberrations while maximizing system transmission leads to substantially improved imaging performance. Simulation and experimental results demonstrate that the method can improve the imaging performance. The proposed approach has potential applications in fields such as biomedical field, multi-spectral, remote sensing and microscopy.

Keywords: coating; spectrum splitting filter; polarization aberrations; Jones pupil; wavefront aberration; lens design; dichroic beamsplitters

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1. Introduction

In recent years, multi-modal optical imaging and detection technologies have seen widespread applications across various fields, gradually playing an important role in the biomedical diagnosis and the environmental detection [1–3]. The efficient application of these technologies in feature extraction, clinical diagnosis, and image digitization is closely tied to advancements in optical imaging technology. However, current multi-modal optical technologies mainly focus on the back-end analysis and recognition of digital images. The front-end imaging systems often rely on commercial systems and lack targeted system design optimization.

In optical and spectroscopic imaging systems, the application of technologies such as dichroic coatings directly affects the chromatic aberration of the imaging system and, to some extent, influences both amplitude and phase. These factors directly impact the subsequent analysis of detection results. As the complexity and scope of information required in detection scenarios continue to increase, the use of these coatings and dichroic technologies becomes unavoidable. Therefore, it is necessary to conduct in-depth research on the effects of optical filter coatings and develop targeted optimization control schemes.

Amplitude and phase are critical pieces of information obtained through optical detection. Coatings modify both the amplitude and phase of the optical wavefront. The effects on amplitude are well understood and are utilized to alter surface reflectance and spectral performance. Moreover, multilayer coatings introduce phase shifts to the reflected or transmitted radiation, which directly influence aberrations and consequently affect image quality. Traditionally, coating design and lens design have been treated as separate tasks, which is largely because the wavefront aberrations induced by coatings were considered negligible in multi-modal systems. However, for optical systems with hyper-numerical aperture, complex multilayer coatings, and stringent image quality requirements, the analysis and assessment of coating-induced aberrations cannot be overlooked during the design phase [4–6].

The impact of multilayer coatings on optical system performance has been extensively investigated in various studies. These papers have demonstrated how coatings affect performance criteria such as diattenuation, polarization sensitivity, and retardance [7–11]. As early as 1992, Reiley and Chipman explored the effects of coatings on image quality, noting that reflective coatings can dominate geometrical wavefront aberrations (scalar phase) in systems like Cassegrain telescopes when assessed with single-ray methodologies [12]. The influence of coated surfaces has been represented using Jones calculus [13].

Commercial optical design software has simulated the impact of antireflection and reflective coatings on polarization point-spread [11], yet previous research has not deeply extracted and analyzed wavefront errors caused by coatings. Consequently, the mechanisms and direct causes remain insufficiently specified, leading to unclear reverse requirements for coating design. In multi-modal optical imaging systems, dichroic beam splitters commonly use dichroic coatings, where the primary requirement is often reflectance and transmittance characteristics within specific spectral ranges. However, factors such as phase shifts and their effects on image quality are frequently overlooked during the design stage. Comprehensive and systematic studies examining the effects of filter coatings on image quality, along with inverse control methods during the design phase, are notably scarce.

In this paper, we propose a method for designing and optimizing spectrum-splitting filters which considers the wavefront aberration and transmittance of the multi-modal optical imaging system. The method through optimizing coating phases to minimize scalar phase aberrations while maximizing system transmission leads to substantially improved imaging performance. Firstly, based on the existing polarization aberration theory, the wavefront aberration introduced by the spectrum-splitting filters is analyzed. Then, through the analysis results, the design and optimization method of the spectrum-splitting filters are improved. Finally, the validity of the design results is verified by simulation and experiment. Results show that the proposed scheme shows significant effectiveness in reducing the aberration caused by spectrum-splitting filters. The proposed method can be applied in a wide range of imaging scenarios, including the biomedical field, multi-spectral, remote sensing and microscopy.

2. Theory and Analysis Model

Polarization aberration (PA) is the more comprehensive representation of the aberration of optical systems which consists of the phase aberration, apodization, diattenuation and retardation aberration [1,14]. The apodization and phase aberrations are scalar aberrations, and diattenuation and retardation aberrations are vector aberrations. To analyze the effect of coating for the optical imaging performance, the polarization aberration analysis model with the phase shift of coating was established. In the polarization aberration analysis model, the traditional ray tracing is performed between the optical surface interfaces and at each surface interface; thin film matrix calculations are performed to compute the changes in the amplitude, phase, and polarization state of each feature ray. Based on the polarization aberration analysis model, the polarization aberration of optical systems at the exit pupil can be expressed as many modes, such as the Jones pupil, physical pupil, Mueller pupil and Pauli pupil. In this paper, the Jones pupil is used to describe the effect of the polarization aberration for the optical system [15]. To better describe the polarization characteristics of the system. Geh et al. decomposed the Jones matrix into several optical elements through the polar decomposition method [16]. They supposed that the optical system could be decomposed into a filter, a phase plate, a partial polarizer $\mathbf{J}_{\mathrm{pol}}$, a rotator

$\mathbf{J}_{rot}$ and a retarder $\mathbf{J}_{ret}$. Jones matrix for a single ray propagating through an optical system, which could be decomposed as

$$\mathbf{J} \approx t \cdot e^{i\Phi}\mathbf{J}_{pol}\mathbf{J}_{rot}\mathbf{J}_{ret} \tag{1}$$

in which t is the total amplitude transmissivity of a filter, and the scalar phase Φ is the phase shift of a filter. The transmissivity and the phase shift can describe the aberration of most polarization-insensitive measurement systems. The aberrations can either be considered separately or integrated into the Jones pupil and physical pupil according to the research purpose. If the total PA needs to be analyzed, the phase aberrations can be integrated into scalar phase pupils conveniently.

3. Design and Control Method

3.1. The Performance of Ideal Imaging System without Dichroic Coating

As shown in Figure 1, the correction method is demonstrated by a two-channel system. Channel 1 (C1) is a high-resolution imaging system within the visible band, and Channel 2 (C2) is an infrared system whose wavelength is 1064 nm. The optical system consists of two mirrors and some corrective lens. The spectrum of different wavelengths is separated on the first surface of the dichroic beamsplitter. In this system, C2 is applied in scenarios requiring the transmission of infrared laser energy, such as laser surgical excision. Thus, our study mainly focuses on Channel 1, whose imaging performance is mainly affected by the coating variations.

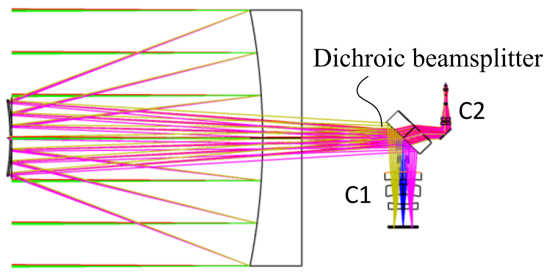

Figure 1. The configurations of the two-channel system with splitting filter film.

The imaging performance specifications for an ideal system of C1 are listed in Table 1. The mean value of modulation transfer function (MTF) for all sample fields of view is 0.465 at 68 lp/mm. The composite wavefront error is below 0.031 λ. Furthermore, the MTF of C1 is shown in Figure 2, which shows that the image quality is close to the diffraction limitation.

The wavefront error at the exit pupil for on-axis and off-axis field of views are shown in Figure 3. The central obscuration of the optical system that caused the exit pupil is a ring. The system is a good starting point for the dichroic coating design.

Table 1. Specifications of the high-resolution imaging system.

Parameter	Specification
Wavelength [nm]	450~900
Field of views [°]	1.4
Focal length [mm]	100
F/#	6.5
Composite Wavefront error [λ]	0.031
Mean value of MTF@68 lp/mm	0.465
Distortion [%]	0.6

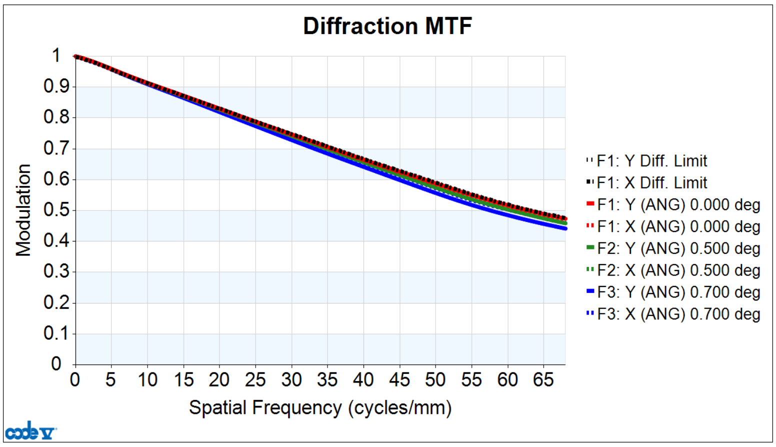

Figure 2. MTF of the high-resolution imaging system without dichroic coating.

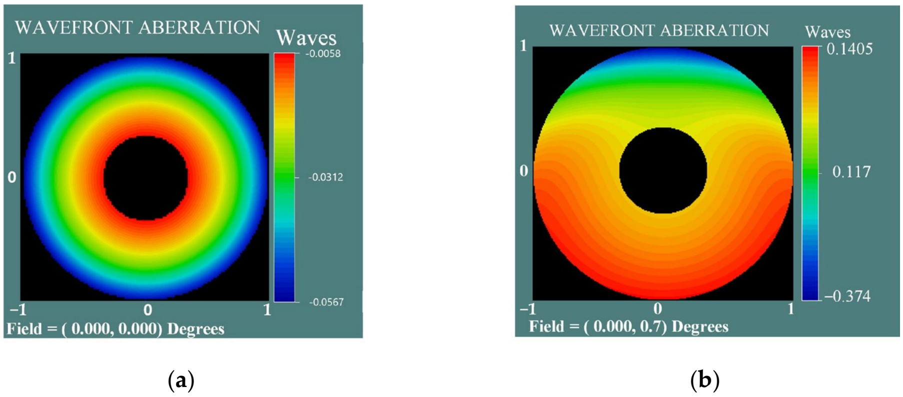

Figure 3. Wavefront error of on-axis (**a**) and off-axis (**b**) for imaging system without dichroic coating.

In the high-resolution imaging system, the front surface of a dichroic beamsplitter is coated by a dichroic coating. The influence of the dichroic coating can be characterized by the reflectivity and transmission, which can be represented as a function of wavelength, polarization and angle of incidence (AOI). The distribution characteristic of an incident angle on a dichroic beam splitter is the critical information for dichroic coating design, especially the phase design and control. As shown in Figure 4, the range of the incidence angle on the dichroic coating is 40.7–49.3°, and the incidence angle is only changed in the Y direction. The design requirements of the dichroic coating are that the reflectance is greater than 90% in the wavelength range of 450 to 900 nm, and the transmittance is more than 80% in the wavelength range of 1054 to 1074 nm.

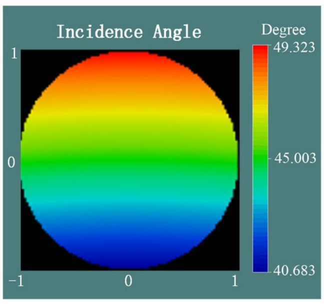

Figure 4. The incident angle distribution on dichroic beamsplitter.

3.2. The Mechanism of Wavefront Error Introduced by Dichroic Film

The conventional dichroic coating Dichroic-I consisted of alternately coated Ta_2O_5, and SiO_2 was designed through the traditional coating design method. In this design process, the coating design and lens design have been treated as separate tasks. To meet the design requirements for reflectance and transmittance, the number of layers and thickness of the coating layer are chosen as optimization variables in a traditional coating design method. The reflectance of Dichroic-I is shown in Figure 5, which was composed of 117 layers. In the wavelength range of 450 to 900 nm, Dichroic-I achieves an average reflectance of over 98%. Additionally, it can achieve a high transmittance of 98% at the 1064 nm wavelength.

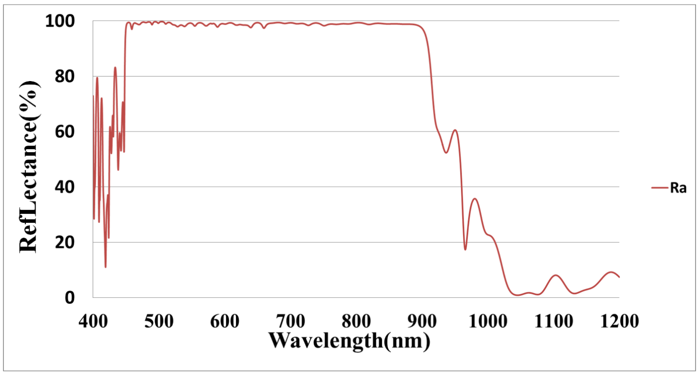

Figure 5. The reflectance of Dichroic-I.

The performance of the high-resolution imaging system with Dichroic-I was simulated with optical design software CODE V 10.4. Through the polarization ray tracing, the MTF of C1 is shown in Figure 6. Compared with the ideal imaging system, the mean value of the MTF in the whole field of view is sharply declined by 0.2. The dichroic coating seriously influences the imaging quality of the imaging system, which cannot be accepted. Therefore, it is necessary to research the mechanism and correction method of aberration introduced by spectrum-splitting filters in a multi-channel imaging system.

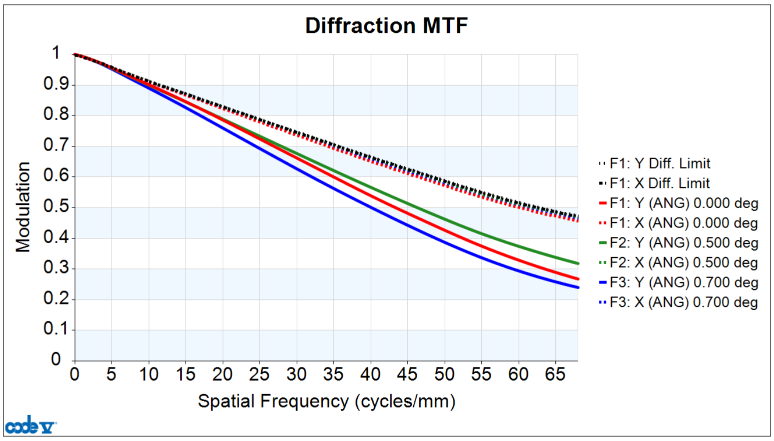

Figure 6. The MTF of C1 with Dichroic-I.

With the method described in Section 2, the total polarization aberration of the imaging system with Dichroic-I was calculated. Through the polar decomposition method, the polarization aberration was represented by the physical pupils. As shown in Figure 7, the subset aberrations of polarization aberration for an on-axis field of view contain a scalar phase (wavefront error), apodization (scalar transmission), diattenuation and retardation aberrations. Based on the data quantitatively analyzed in the physical pupil, the polarization aberration of C1 is mainly related to the scalar phase aberration. The phase changes contain the phase aberration caused by the coatings and the conventional phase aberration caused by the optical path difference (OPD). In Figure 7, the phase is expressed in units of wavelength, and pupil dimensions are relative coordinates. The peak-valley value of the scalar phase induced by Dichroic-I is 0.5 λ, which is much larger than the phase aberration caused by OPD (0.06 λ), as shown in Figure 3a. The exotic distribution of the pupil map for the scalar phase shows that the wavefront error is periodical fluctuation in the Y direction of the pupil. According to the polar decomposition method, the scalar phase induced by the coating is the average of the phase shifts of s and p light of the coating, which varies with the incidence angle. As shown in Figure 4, the incidence angle is only changed in the Y direction of the pupil, which causes the wavefront error to only be changed in the Y direction of the pupil, and the MTF in Figure 6 is sharply declined in the meridional direction.

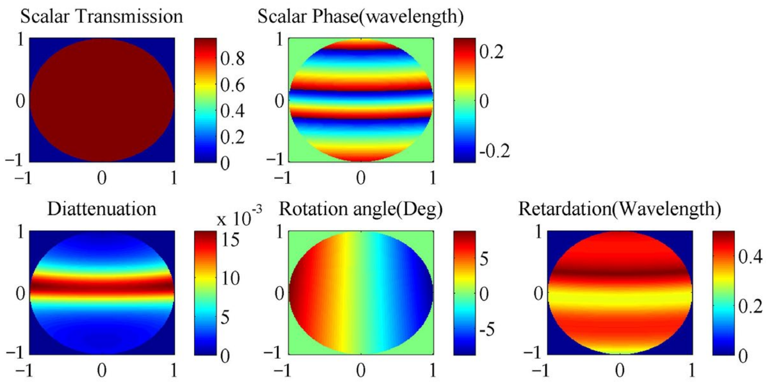

Figure 7. Physical pupil of on-axis filed at wavelength of 632 nm.

As shown in Figure 8, the phase shift includes periodical fluctuation as the incidence angle increases, which is similar to the scalar phase in Figure 7. The deviation for the average of the coating phase shifts at the incident angle on a dichroic beamsplitter and the phase shift periodically will cause wavefront aberration in the imaging system with a spectrum-splitting filter. Thus, the additional wavefront aberrations caused by the phase characteristics of multilayer coatings must be considered in both optical design and coating design processes.

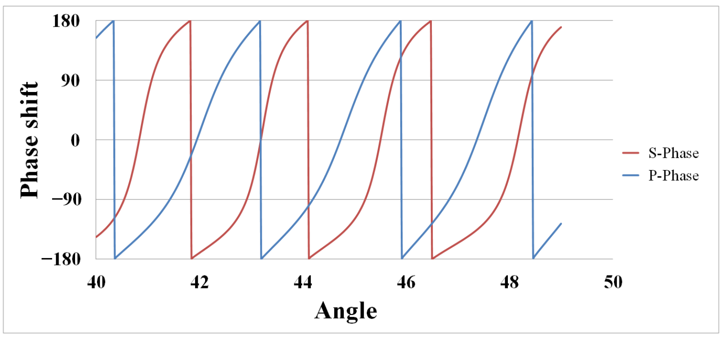

Figure 8. Phase characteristics of Dichroic-I at the incidence angles from 41° to 49°.

3.3. The Correction Method for Wavefront Aberration Caused by Spectrum-Splitting Filters

Based on the analysis in Section 3.2, the phase characteristics of multilayer coatings are an important factor in inducing additional wavefront aberrations in the imaging system. To control the wavefront aberration caused by spectrum-splitting filters in a multi-modal optical imaging system, we propose a method for designing and optimizing spectrum-splitting filters considering the wavefront aberration and transmittance in the multi-modal optical imaging system. In the design process of the dichroic coatings, it is imperative to not only achieve the reflectance/transmittance requirements within specific spectral bands but also to control the phase variation of the coatings across the range of incident angles.

This will ensure that the wavefront aberrations introduced by the coatings are within a reasonable limit. The merit value of this multilayer coatings in the design process is

$$\mathbf{MF} = \sum_{j=1}^{m}\sum_{i=1}^{n} w_R \left|\boldsymbol{R}_{ij} - \boldsymbol{R}_{tag}\right| + w_{PS}\left|\boldsymbol{PS}_{ij} - \boldsymbol{PS}_{tag}\right| + \sum_{h=1}^{p}\sum_{k=1}^{q} w_T \left|\mathbf{T}_{kh} - \mathbf{T}_{tag}\right| \quad (2)$$

in which $\boldsymbol{R}_{ij}$ is the reflectance of the current multilayer coating at the ith sampling incidence angle and jth sampling wavelength; $\boldsymbol{R}_{tag}$ is the design requirement of the reflectance for coating; and w_R is the weight of the reflectance for coating. $\boldsymbol{PS}_{ij}$ is the average of the phase shifts of s and p light of the current coating at the ith sampling incidence angle and jth sampling wavelength; $\boldsymbol{PS}_{tag}$ is the design requirement of the phase shift caused by the coating; w_{PS} is the weight of the phase shift caused by the coating; $\boldsymbol{T}_{kh}$ is the transmittance of the current multilayer coating at the kth sampling incidence angle and hth sampling wavelength; $\boldsymbol{T}_{tag}$ is the design requirement of the transmittance for coating; m and p are the total number of sampling wavelengths; n and q are the total number of sampling incidence angles.

The flow diagram of the design process for spectrum-splitting filters is shown in Figure 9. Firstly, the initial structure for the multilayer coating will be established as the starting point. Then, we evaluated the thickness of each coating layer to minimize the value of the merit function. With the method described in Section 2, the total polarization aberration of the imaging system with the current coating will be calculated. If the phase shift is periodical fluctuation, the number of current coating layers will be adjusted. The thickness of the system is re-optimized, and the polarization aberration of the imaging system will be evaluated until the design requirements are met. In addition, the reflectance/transmittance of the current coating will also be calculated when the phase shift is not periodical fluctuation. If the reflectance/transmittance does not meet the design requirement, the number of current coating layers will be adjusted. The thickness of the system is re-optimized, and the polarization aberration of the imaging system will be evaluated until the coating meets all of the design requirements.

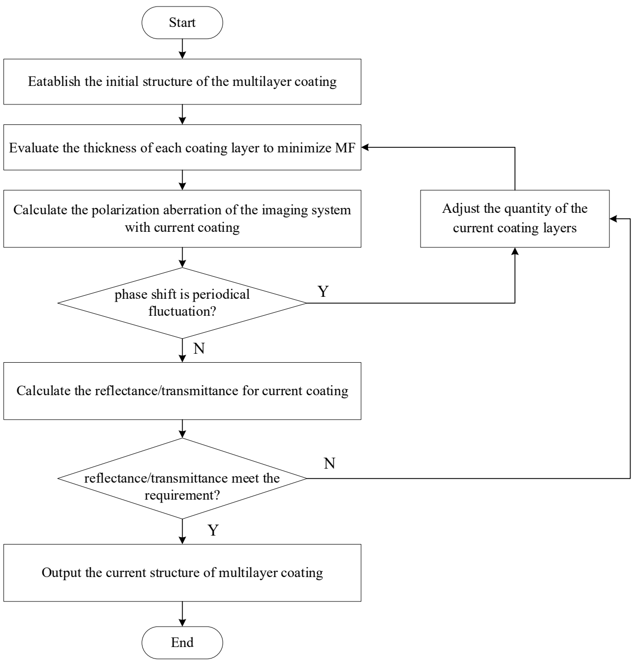

Figure 9. Flow diagram of the correction method for wavefront aberration caused by spectrum-splitting filters.

4. Simulation and Experimental Verification

4.1. Optimization and Performance

Dichroic-I described in Section 3.2 is chosen as the starting point for optimization to obtain a new dichroic coating. To further reduce the additional wavefront aberrations caused by Dichroic-I, the number of layers and thickness of the coating layer will be optimized through the method described in Section 3.3. The new dichroic coating Dichroic-II is composed of 73 layers. As shown in Figure 10a, the average reflectance of Dichroic-II is greater than 95% in the wavelength range of 450 to 900 nm, and the transmittance of Dichroic-II is greater than 98% in the wavelength range of 1054 to 1074 nm. As shown in Figure 10b, as the incidence angle increases, the phase shift almost remains unchanged. This ensures the imaging performance in the visible wavelength range and the transmission of infrared laser energy.

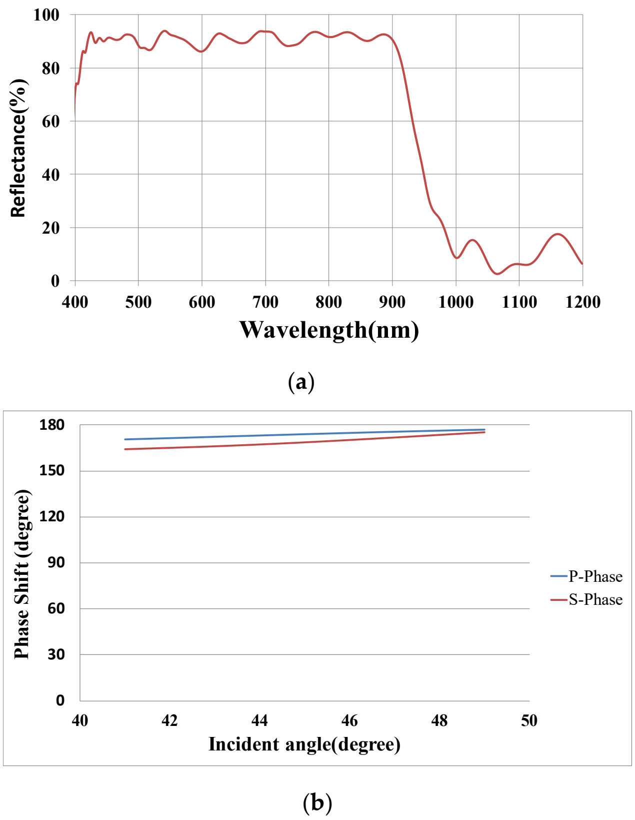

Figure 10. The reflectance (**a**) and phase shift at the incidence angle of 41–49° of Dichroic-II (**b**).

The performance of the high-resolution imaging system with Dichroic-II was simulated with optical design software CODE V. As shown in Figure 11, through the polarization aberration analysis model, the wavefront aberrations of the imaging system with Dichroic-II were calculated. The aberrations caused by Dichroic-II are low-order and high-order coma (Z8, Z15, Z24 and Z35) and spherical aberrations (Z9, Z25 and Z36).

The modulation transfer function is shown in Figure 12, and it shows that the image quality is close to the diffraction limitation. Comparing with the imaging system with Dichroic-I, the mean value of the MTF in the whole field of view is decreased by 0.12. All the optical characteristics of this optical system show that the effects of the dichroic coating have been effectively corrected.

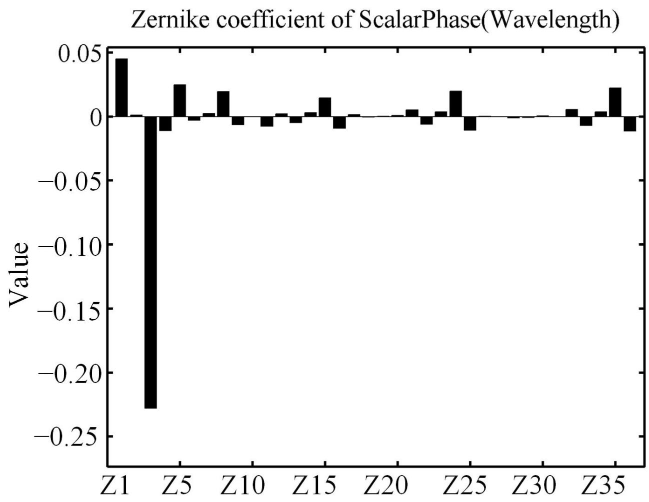

Figure 11. Wavefront aberration analysis of the system after incorporating Dichroic II with fringe Zernike coefficients.

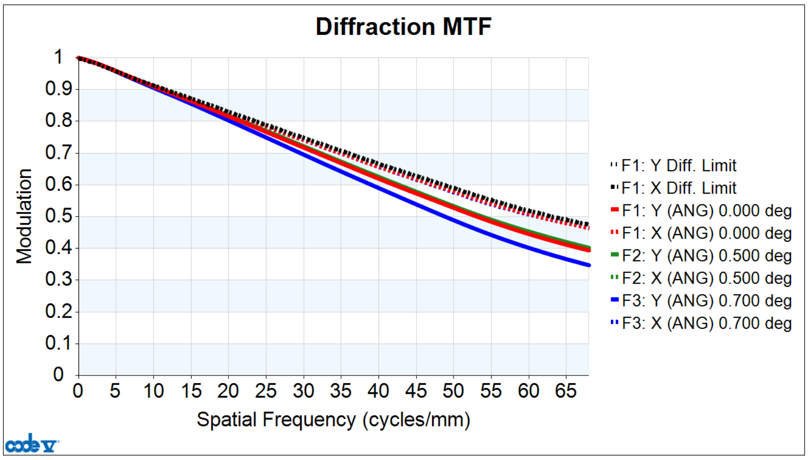

Figure 12. MTF of the optical system with Dichroic-II.

4.2. Experimental Verification

The beamsplitters with Dichroic-I and Dichroic-II are manufactured. The substrate material of the beamsplitter is silica. The reflection and transmission of different dichroics are measured. The results show that the reflectance of Dichroic-I is greater than 98% in the wavelength range of 450 to 900 nm and the transmission is greater than 90% in the wavelength range of 1054 to 1074 nm. The reflectance of Dichroic-II is greater than 90% in the wavelength range of 450 to 900 nm, and the transmission is greater than 80% in the wavelength range of 1054 to 1074 nm. The measured results are basically the same as the design simulation results.

As shown in Table 2, the mean value of the MTF for all sample fields of view at 68 lp/mm was also measured through the interferometer and classical interference method. The mean value of the MTF at the Nyquist frequency, including the modulation transfer function of the detector, will reduce the design value by 50~60%. Apparently, the meridional MTF of the system with Dichroic-I is lower than the sagittal MTF, which is the same trend as the simulation result in Section 3.3. Meanwhile, the meridional MTF of the system with Dichroic-II is the same as the sagittal MTF, which is also the same as the simulation result in Section 4.1. The difference between the meridional MTF value and sagittal MTF value remarkably reduce from 0.087 to 0.025. The experimental results demonstrate the effectiveness of the proposed method in Section 3.

Table 2. The measured results for MTF of C1 with different spectrum splitting filter.

	Meridional MTF	Sagittal MTF
Dichroic I system	0.09	0.177
Dichroic II system	0.153	0.177

5. Conclusions

We have investigated the impact of spectrum-splitting filters on the optical performance of a multi-modal optical system which has potential applications in biomedical diagnosis and environmental detection. Our study reveals that wavefront aberrations induced by coatings can significantly dominate within such optical systems. These aberrations were evaluated numerically using the physical pupil method, focusing on phase shifts averaged between s and p polarizations of dichroic coatings over a range of incident angles. To address these findings, we propose a method for designing and optimizing spectrum-splitting filters. The simulation and experimental results demonstrate that optimizing coating phases to minimize periodic scalar phase aberrations while maximizing system transmission leads to substantially improved imaging performance. Our study emphasizes the necessity of integrating coating design and optical system design into a unified task, particularly when dealing with complex multilayer stacks. In the design of dichroic coatings, achieving optimal characteristics involves balancing not only transmittance or reflectance but also the averaged phase shifts of s and p polarizations. By implementing tailored design solutions, we can effectively restore spectral and polarization information from targets, enhancing the comprehensive characterization of biological and environmental features. Moreover, in our design process, the tilt angle of the spectrum-splitting filters will also influence the aberration caused by the coating. In our future work, the tilt angle of the spectrum-splitting filters will be added in our correction to improve the imaging performance.

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