Cylindrical Beam Volume Holograms Recorded in Reflection Geometry for Diffuse Source Spectroscopy

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A Thesis Presented to the Academic Faculty
in Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Electrical Engineering with Research Option

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Note Regarding Research Goals Met

This thesis document is the result of the research completed to date and is based on the earlier proposal "Spherical Beam Volume Holograms Recorded in Reflection Geometry for Diffuse Source Spectroscopy." The research completed to date represents the low-level goals presented in the original proposal. Research on this project will not continue beyond the results already obtained; however, work on related areas is progressing steadily by other members of the research group.

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ABSTRACT

Multimodal multiplex spectroscopy (MMS) has been demonstrated to increase the optical throughput of a spectrometer as opposed to that of conventional optical spectrometers [5] and has been implemented using three-dimensional photonic crystals [5] and spherical-beam volume holograms recorded in the transmission geometry [6-7, 9] as spectral diversity filters. While such efforts have resulted in compact and sensitive Fourier-transform holographic spectrometers [8], there still remains much room for performance improvements. Previous studies [6,7,9] have proven the utility of spherical-beam volume holograms recorded in the transmission geometry as spectral diversity filters for spectrometers. The role of the recording geometry in the performance of cylindrical-beam volume holograms as spectral diversity filters is investigated here. The transmission recording geometry is compared to the reflection recording geometry on the basis of the spectral operating range of the resultant spectral diversity filters.

Key Words: spectroscopy, holography, diffuse-source, volume hologram, spectral de-multiplexer, spectral diversity filter, spectral operating range, holographic spectrometer, optical processing

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1 Background and Literature Review

Optical spectroscopy has been an important research field during the past century. The realization of novel spectrally dispersive elements (e.g., gratings, prisms, volume holograms) has been crucial to the development of a variety of spectrometers for various applications and incident-light conditions. Of particular interest is the application of novel spectrally dispersive elements for diffuse-source spectroscopy. The advent of Fourier-transform spectroscopy by Fellgett in 1949 [2] was a key event leading to the adoption of spectroscopic and interferometric techniques for diffuse-source applications (e.g., infrared laboratories, astronomy, environmental sensing, and biological sensing). For diffuse-source spectroscopy, the Fourier-transform spectrometer is advantageous over a more direct method of optical spectroscopy because of the gain in the resultant signal-to-noise ratio described by Fellgett's principle [2]. This property for the Fourier-transform spectrometers has allowed them to gain popularity in many applications despite the bulkiness of the initial devices.

Holography as a method for digital imaging and optical processing is a recent trend and emerged prominently over the last few decades [3,5]. Holograms are recorded by the interference of two polarized beams of coherent light. During the recording process, considerations of geometry, recording time (i.e., schedules), source types, and media types allow for many possibilities in the function of the end result. Applications of holography include data storage, imaging, and most recently, spectroscopy [3,5,6].

Adibi *et al.* performed a detailed comparison of recording schemes of 90-degree geometry and transmission geometry for holography [4]. While not directly related to the spectroscopic application, it is shown that many characteristics (i.e., holographic lifetime, persistency of holographic memory) differ considerably between recording geometries.

Multiplex spectrometers operate by employing a weighted projection of multiple wavelength channels (i.e., differing spatial modes) to retrieve the input signal of the incident light. Such post-processing of the input signal leads to a better spectral characterization and higher signal-to-noise ratio as compared with a more direct method of optical spectroscopy (e.g., grating- or prism-based), especially for diffuse-source spectroscopy [1,5].

Despite the vast progress in research in optical spectroscopy over the past half-century, many challenges remain in the field, and spectrometers for every application need to be tuned to perform optimally under the specific light conditions at hand. Highly sensitive and portable spectrometers are desirable for applications in biological and environmental sensing because the optical sources are diffuse in nature. Conventional spectrometers generally operate by employing gratings for wavelength dispersion and de-multiplexing. The intermediate signal achieved by the grating is then usually retrieved by a photodetector for data collection. Because the overlap of multiple spatial modes in some incident signals (for instance, as occurs with diffuse sources) can result in false output patterns, spatial filtering is necessary and is accomplished in conventional spectrometers by means of a slit-lens collimating setup. Although spatial filtering in such a manner can effectively increase the resolution which can be achieved with a grating-based conventional spectrometer, the slit-lens collimator blocks most of the intensity of the original light source [5].

Because of the resolution-throughput tradeoff caused by spatial filtering, conventional spectrometers are highly limited when used with diffuse, incoherent light sources, such as those often encountered in biological and environmental sensing applications. In 2003, Xu *et al.* [6] demonstrated multimodal multiplex spectroscopy (MMS) as a method particularly useful when dealing with diffuse sources in 2003. In MMS, an input light source is projected onto a spectral diversity filter (SDF), which converts the input spatial-spectral signal into an output spectral diversity pattern. In this way, the SDF acts analogously to a more general wavelength dispersive element (such as a prism or holographic grating) but is readily more flexible and eliminates the resolution-efficiency tradeoff of conventional spectrometers. An MMS system would employ a Fourier-transforming lens and a chargecoupled device for processing and capturing of the intermediate signal achieved by the SDF. Post-processing of the output signal retrieved by the CCD can successfully estimate the spectrum of the input signal [6].

Karbaschi *et al.* [7] demonstrated the feasibility of using a spherical-beam volume hologram as the spectral diversity filter in the Fourier-transforming MMS spectrometer. The MMS spectrometer using the volume hologram within photopolymeric material was shown to have comparable spectrally dispersive and filtering properties similar to the photonic crystal spectral diversity filter.

Hsieh *et al*. [9] demonstrated implementations of compact, Fourier-transform MMS-based spectrometer using the photonic crystals spectral diversity filers and also volume holographic spectral diversity filters. Initial prototypes showed the spectrometers worked with limited success. There were many factors (e.g., poor signal-to-noise ratio, low spectral operating range) that needed to be dealt with in further optimization of the spectroscopic design.

Hsieh *et al.* [8] provided a brief comparison of the performance of two types of volume holograms under different recording geometries. The role of the recording geometry was investigated, and the two types of holograms (i.e., transmission geometry hologram and reflection geometry hologram) were compared on the basis of spectrally dispersive characteristics. The two types of holograms were compared on the basis of performance as spectral diversity filters within an implementation of a compact Fourier-transform spectrometer.

Hsieh *et al*. [11] demonstrated an implementation of the compact Fourier-transform MMS-based spectrometer using only a volume hologram and a CCD detector. The integration of the function of the Fourier-transforming lens into a volume hologram yielded an even more compact and portable spectrometer with comparable performance to the previous designs. In the lensless case, the Fourier-transforming lens is not present, and so the resultant spectrometer is even more compact than it otherwise would be. The efficacy of the reflection geometry holograms in the lensless case has not yet been affirmed.

To date, SDFs have been implemented using three-dimensional photonic crystals [6], spherical-beam volume holograms (SBVHs) [7,8], and cylindrical-beam volume holograms [13]; MMS systems based on all these SDF implementations have been proposed, prototyped, and studied for sensitivity [6,9,10,13]. Recently MMS systems for laboratory settings have entered the marketplace and demonstrate the capabilities and promise of this new technology. Of high interest, however, are compact and inexpensive spectrometers employing spherical-beam volume holograms as SDFs because of their low cost and high robustness when compared to conventional optical spectrometers.

Currently, volume holographic Fourier-transform spectrometers consisting of one of more volume holograms recorded in a piece of photopolymer along with a Fourier-transforming lens and a detector array have been demonstrated [8]. The key operating feature of the holographic spectrometer is the retrieval of the intermediate spatial-spectral signal achieved by the holographic spectral diversity filter (i.e., the diffracted crescent) by the detector array. Such intermediate signal retrieval is necessary for the eventual post-processing of the spatial-spectral signal for retrieval of the spectrum of the original signal.

2 Problem Statement

Optimizing the parameters that define the spectral diversity filter is essential to improving the sensitivity and resolution of holographic spectrometers. Spherical-beam volume holograms have been shown to be usable for spectral diversity filtering [6], and a compact Fourier-transform spectrometer has been demonstrated using a SBVH as the SDF [8].

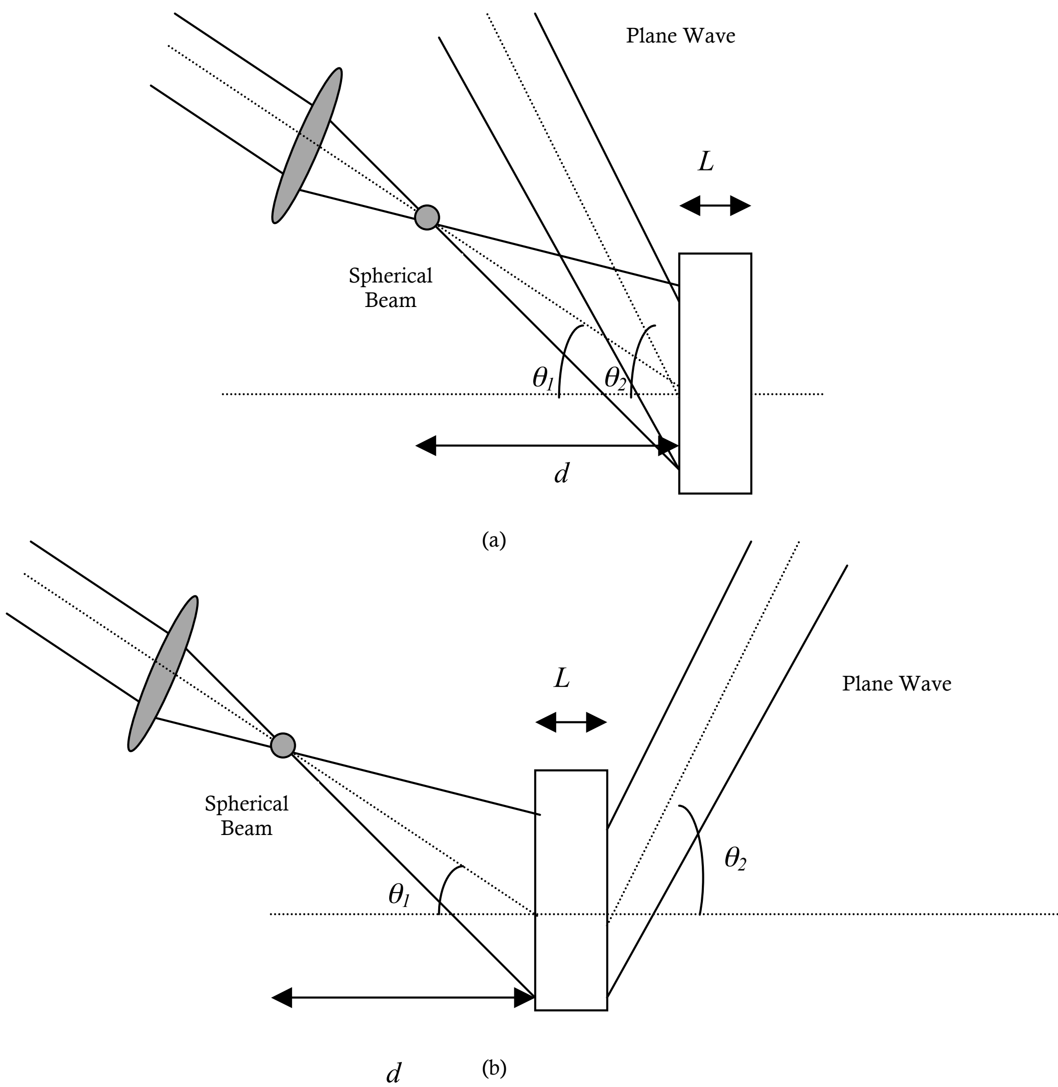

Fig. 1. Recording geometries for spherical beam volume holograms. In transmission geometry (a), the plane wave and the spherical beam enter the hologram from the front face. In reflection geometry, the plane wave and the spherical beam enter the hologram from opposing sides.

Recording geometries for spherical-beam and cylindrical-beam volume holograms are shown in Fig. 1. The recording of a SBVH involves the interference of a plane wave (i.e., the signal beam) and a spherical beam (i.e., the reference beam that results by the passing of a plane wave through a spherical lens) in the plane of the photopolymer being used. For the case of recording a cylindrical-beam volume hologram (CBVH), the spherical lens is replaced by a cylindrical lens. In transmission geometry, the plane wave enters the photopolymer from the same direction as the spherical beam. In reflection geometry, the plane wave and the spherical beam enter the photopolymer from opposing directions. Both recording geometries offer unique transmission and diffraction characteristics for recorded holograms.

It is the goal of the present research to produce parameters that will eventually lead to a viable, robust, and versatile volume holographic spectral diversity filter for inclusion as part of a commercially-viable, compact, efficient, and inexpensive MMS-based holographic spectrometer. Such spectrometers have applications (e.g., in biological and environmental sensing) when dealing with diffuse input light sources and where portability and robustness in a spectrometer is highly desirable.

Previous studies have determined the efficacy of spherical and cylindrical beam volume holograms recorded in transmission geometry as SDFs [7,10,11,13]. A preliminary study has indicated the potential of SBVHs recorded in reflection geometry as SDFs and for implementation in compact Fourier-transform spectrometers [8]. However, while the potential of reflection geometry SBVHs for spectral diversity filtering has been asserted, studies of the performance of reflection geometry holograms in spectral diversity filtering and as the key element for a compact holographic spectrometer have not been conducted.

It is the major goal of the current study to gauge the potential of reflection geometry holograms recorded on photopolymer film for compact, efficient, and sensitive spectrometers when compared to that of transmission geometry holograms. For a baseline comparison, studies of the spectral operating range and resolution of holograms for the spectroscopic application recorded in both geometries will be performed.

3 Methods

Spectral Operating Range

The spectral operating range for a given spectrometer is an important parameter that defines the range of incident wavelengths for which the spectrometer is able to perform most accurately. More specifically, the spectral operating range defines the range of incident wavelengths for which the spectrometer is most sensitive and offers the best resolution and hence the best performance.

The spectral operating range for holographic spectral diversity filters recorded in both transmission geometry and reflection geometry was characterized. Similar recording parameters (e.g., recording time, angle between signal and reference beams, recording beam intensities) were used to record holograms in both geometries on separate pieces of photopolymer. A monochromator was used to provide the incident light source for the reading setup. By varying the incident wavelength of the incident source, the spectral operating range for the holograms was characterized.

In the cases of recording the holograms for measurement of these parameters, the incident light source was a solid-state diode pumped (SSDP) laser operating at $\lambda = 532$ nm. The holograms were recorded according to the recording schemes shown in Fig. 1. The distance d in the cases of both recording geometries was chosen to be an appropriate distance such that the divergent beam was incident on the majority of the exposed face of the photopolymer. That is, the interference of the two beams (i.e., divergent cylindrical-beam and collimated plane wave) exposed an area approximately equal to the entirety of the exposed face of the photopolymer. In all cases, the distance d was greater than the focal length f of the cylindrical lens used.

An appropriate cylindrical lens was used for all recording schemes. Trial-and-error test recordings with the available lenses revealed that a lens with a focal length of $f = 3$ cm yielded the holograms with the best diffraction efficiencies (i.e., strengths).

For the study of the spectral operating range, the two types of holograms were recorded on InPhase *HDS2000* photopolymeric media. The thicknesses of the media used were $t = 0.5$ mm, $t = 1$ mm, and $t = 2$ mm. For each case (i.e., each recording geometry investigated), the incident intensity of each recording beam (i.e., plane wave and cylindrical beam) was set to be 16 mW/cm^2 at the face of the medium.

To measure the strength of the recorded holograms before subjecting them to tests for performance parameters, the diffraction efficiencies of the recorded holograms were measured using a setup consisting of two optical power meters. The strength of the transmitted beam through the face of the hologram (i.e., transmitted beam intensity) at any particular incident laser power was compared to that of the diffracted beam (i.e., diffracted beam intensity). When measuring diffraction efficiency, it is also necessary to measure the strength of the diffracted beam at its highest value along the axis of the face of the hologram. This measurement is accomplished by the use of a translation stage on which the recording stage for the hologram is placed. The diffracted intensity can then be scanned over the length of the hologram. The resulting ratio (i.e., diffraction efficiency) indicates the strength and potential of each recorded hologram for successful implementation as spectrally dispersive elements.

The reading setup is akin to the eventual spectrometer that will result from these research studies. For the purposes of these experiments, the reading setup consisted of a monochromator (to scan through incident wavelengths), collimating optical elements, the recorded hologram, a cylindrical lens (to perform the inverse optical Fourier-transform), and a CCD imager for retrieval of the resultant spatial-spectral signal. The distance between the output face of the hologram and the input face of the CCD is precisely the focal length of the inverse Fourier-transforming cylindrical lens.

For the reading setup, a monochromator was used to shine incident light on the face of each recorded hologram. The wavelength of the monochromator was scanned within a radius of 150 nm from the center recording wavelength (λ = 532 nm). The output pattern was recorded by the CCD imager, and the resultant measurements were used to analyze the spectral analyzing range for the volume holographic spectral diversity filters tested. The spectral operating range is analyzed for the three strongest holograms (as indicated by the diffraction efficiency with regards to photopolymer thickness) and averaged.

In general, the spectral operating range was characterized and compared for both types of recording geometry by observing the range of the output spatial-spectral pattern given otherwise identical reading setups. Additionally, a qualitative comparison of the spatial-spectral output patterns produced was useful in assessing the performance of each hologram as a spectral diversity filter.

4 Results

The diffraction efficiency for each recorded hologram was measured through a dual optical power meter setup. The results are listed in Table 1 below.

Hologram	Recording Geometry	Medium Thickness (μm)	Exposure Time (s)	Diffraction Efficiency (%)
1	Transmission	500	5	24.4
2	Transmission	500	10	32.7
3	Transmission	500	20	34.0
4	Transmission	1000	5	22.8
5	Transmission	1000	10	34.6
6	Transmission	1000	20	31.0
7	Transmission	2000	5	42.1
8	Transmission	2000	10	48.4
9	Transmission	2000	20	46.3
10	Reflection	500	5	17.2
11	Reflection	500	10	35.5
12	Reflection	500	20	38.0
13	Reflection	1000	5	30.5
14	Reflection	1000	10	35.3
15	Reflection	1000	20	28.1
16	Reflection	2000	5	29.7
17	Reflection	2000	10	28.1
18	Reflection	2000	20	29.2

Table 1. Recorded holograms and their properties.

These results indicate the increasing strength of the diffracted beam with increasing photopolymer thickness and marginally increasing strength with increasing exposure time. Plots of the average diffraction efficiency versus exposure time and photopolymer thickness are shown in Fig. 2 and Fig. 3.

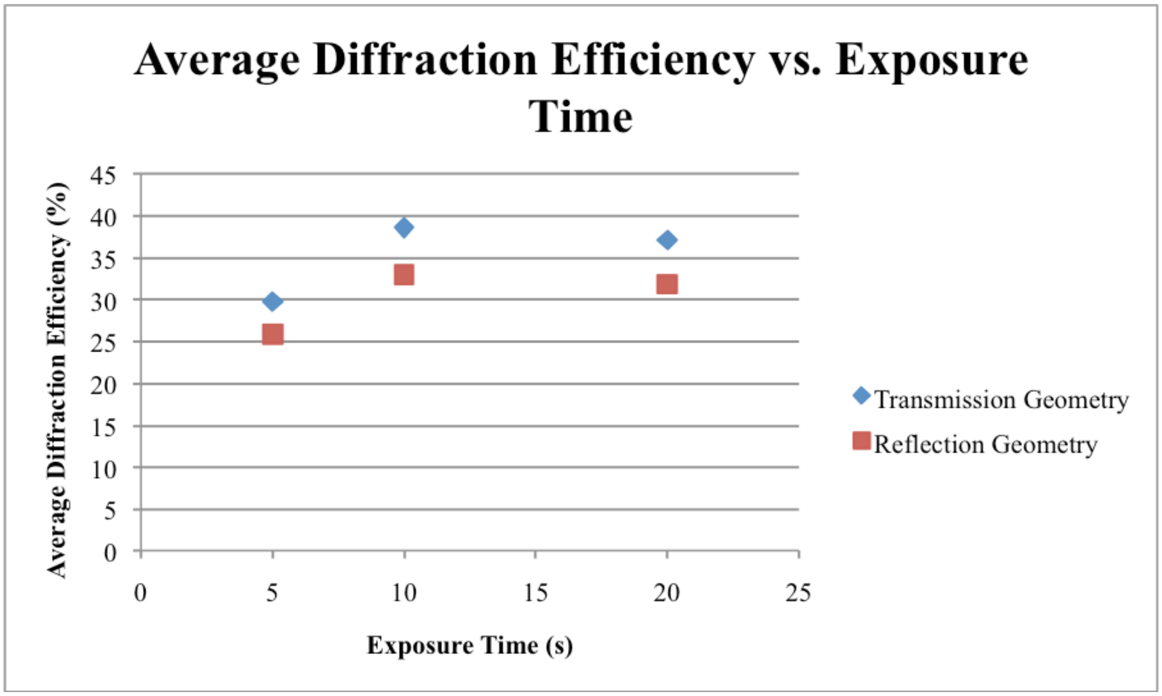

Fig. 2. Plot of average diffraction efficiency versus exposure time for holograms of both geometries.

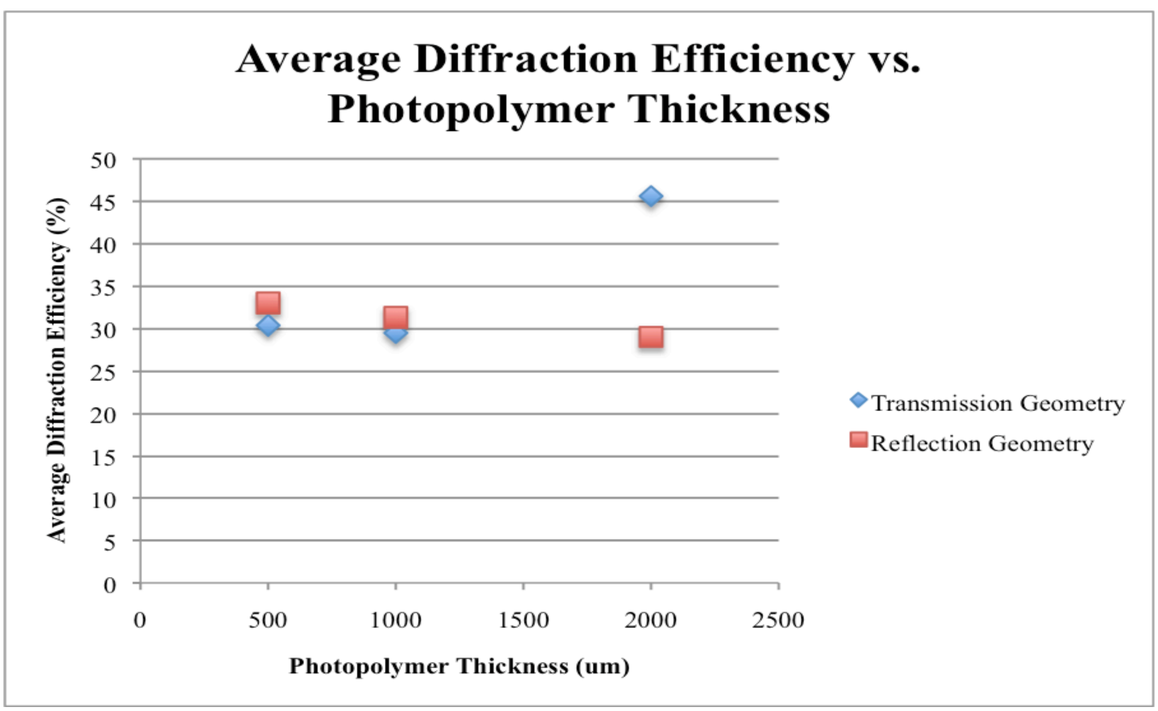

Fig. 3. Plot of average diffraction efficiency versus photopolymer thickness for holograms of both geometries.

The results for the wavelength scan for the transmission geometry volume hologram are shown in Fig. 4 and Table 2. The results for the wavelength scan for the reflection geometry volume hologram are shown in Fig. 5 and Table 3.

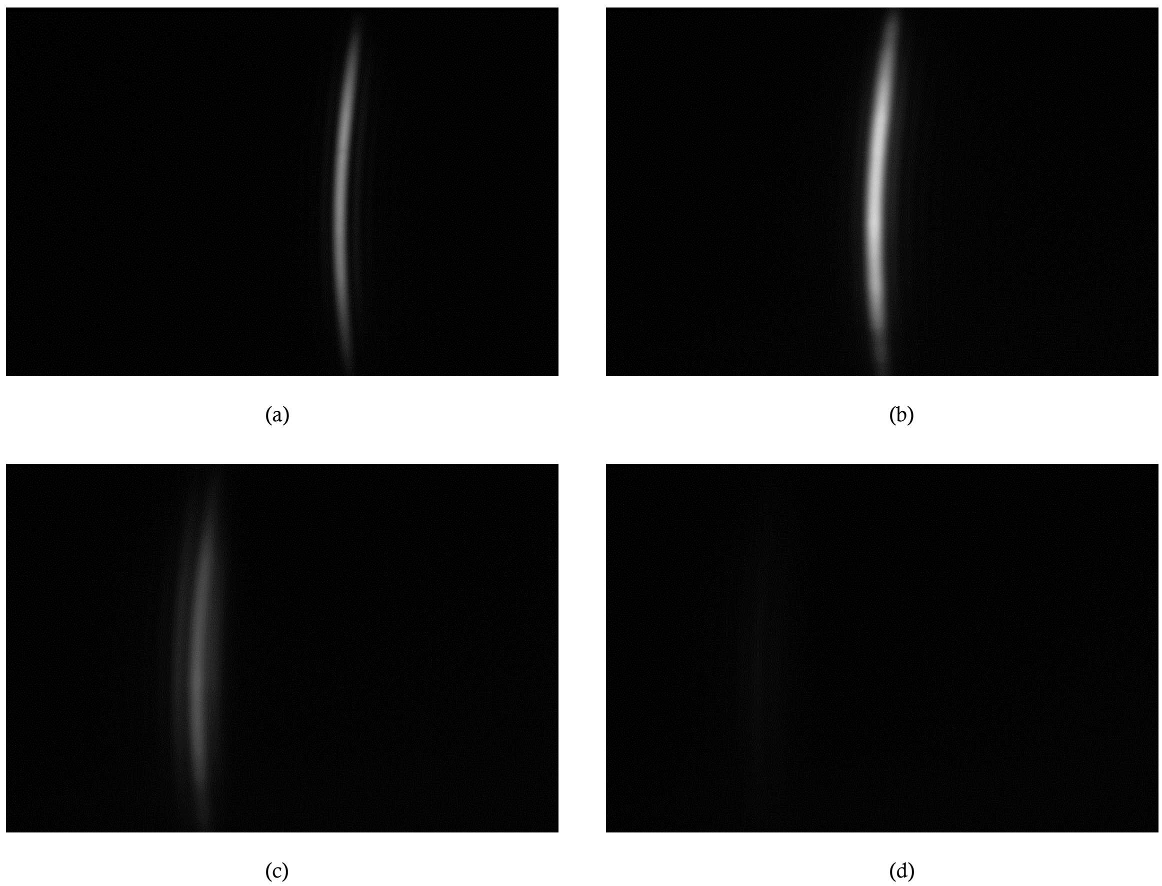

Fig. 4. Sample spatial-spectral patterns scan for transmission geometry spherical beam hologram recorded on t = 1.0 mm InPhase Photopolymer Material with a center wavelength of 532 nm. (a) Pattern at 75 nm below center wavelength, (b) pattern at center wavelength, (c) pattern at 45 nm above center wavelength, (d) pattern at 75 nm above center wavelength

Lower Bound	433 nm
Upper Bound	584 nm
Spectral Response Bandwidth	151 nm

Table 2. Data for spectral operating range for transmission geometry holograms. Bound data is averaged from measurements on holograms #3, #5, and #8 as listed in Table 1.

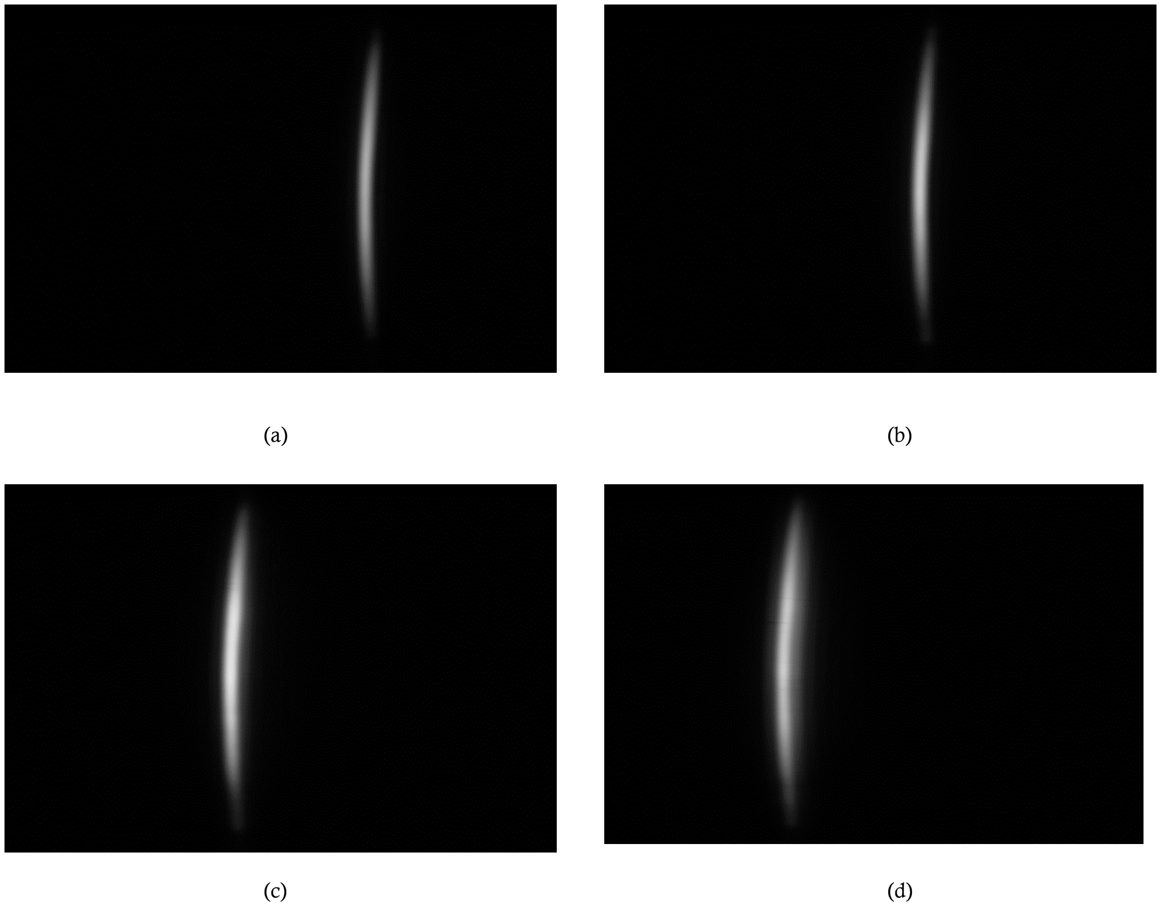

Fig. 5. Sample spatial-spectral patterns scan for spherical beam reflection geometry hologram recorded on t = 1.0 mm InPhase Photopolymer Material with a center wavelength of 532 nm. (a) Pattern at 75 nm below center wavelength, (b) pattern at center wavelength, (c) pattern at 45 nm above center wavelength, (d) pattern at 75 nm above center wavelength

Lower Bound	431 nm
Upper Bound	619 nm
Spectral Response Bandwidth	188 nm

Table 2. Data for spectral operating range for reflection geometry holograms. Bound data is averaged from measurements on holograms #12, #14, and #16 as listed in Table 1.

5 Discussion, Conclusions, and Implications

The goal of this research is to produce parameters that will eventually lead to a viable, robust, and versatile volume holographic spectral diversity filter for inclusion as part of a commercially-viable, compact, efficient, and inexpensive MMS-based holographic spectrometer. Such spectrometers have tremendous applications when dealing with diffuse input light sources and where portability and robustness in a spectrometer is highly desirable.

The successful implementation of a spectral diversity filter using a spherical beam volume hologram recorded in the reflection geometry would invariably be followed up by studies to improve the efficacy of such an SDF by further investigation into, for instance, multiplexing methods for overcoming the resolution tradeoff that occurs when using photopolymers of varying thicknesses for better throughput.

The data collected regarding diffraction efficiencies for both types of recording geometries with differing recording or material parameters are not conclusive in themselves with respect to differences between the two geometries. However, it is important the note the positive effect of increased exposure (i.e., recording) time on the strength (i.e., diffraction efficiency) of the resultant hologram. This point is important because a stronger holographic strength invariably lends itself to better performance in all types of applications, especially the spectrally dispersive one examined here.

Of notable interest are the trends represented in Fig. 3, which seem to indicate an important difference between the two recording geometries. Here it is important to note that the transmission geometry holograms seem to perform much more strongly with thicker recording media than the reflection geometry holograms do under similar recording conditions. Again, this information is not useful in itself for comparing the spectroscopic performance of both recording geometries but lends itself to further consideration and study.

When considering spectral operating range measurements, it is evident that reflection geometry clearly indicates a better operating bandwidth. For transmission geometry, it is seen (Fig. 4) that the transmitted spatial-spectral pattern drops off to zero as the scanning wavelength gets higher and higher. However, this drop off does not occur with using the holograms recorded in the reflection geometry. In this case (Fig. 5), the spatial-spectral signal remains strong through the same wavelength scan. The consistency of the spectral signal over a large range of incident wavelengths indicates a better spectral diversity patterning and better spectrally dispersive characteristics for reflection geometry holograms over transmission geometry holograms.

The quantitative data seem to indicate that, in the course of these experiments, reflection geometry holograms exhibited, on average, a 24.5% increase in spectral operating bandwidth over their transmission geometry counterparts.

The measurements of the spectral operating range for both types of holograms indicate that reflection geometry holograms have better spectrally dispersive characteristics than transmission geometry holograms. However, this alone does not affirm the superiority of reflection geometry holograms over transmission geometry holograms for the spectroscopic (diffractive element) application. There still remain many parameters (e.g., sensitivity, resolution, signal-to-noise ratio, real-world performance) to be tested before such a firm statement can be made regarding either type of hologram.

Despite the fact that further research needs to be conducted in order to affirm the superiority of holograms recorded in reflection geometry over those recorded in the transmission geometry for the spectroscopic application, the research presented here does indicate the tremendous role recording geometry plays in the performance of volume holograms as spectrally dispersive elements. While the proof-of-concept may have been established with the holograms recorded in transmission geometry, the holograms recorded in reflection geometry have strong potential and the reflection geometry may indeed becoming the recording geometry of choice for this application.

The implications of this research towards applications of volume holograms in data storage are not clear. Further research into the role of the recording geometry for volume holograms for such an application needs to be conducted.

6 Future Research

In order to create a marketable spectrometer based on volume holographic diffractive elements, further research into parameter optimization needs to be conducted. While a key feature of any spectrometer is the spectral operating range, many other specifications (e.g., sensitivity, output resolution, precision) are of interest.

These parameters have been measured for spectrometers implementing volume holograms recorded in transmission geometry as spectral diversity filters; however, there have been no studies to date of such parameters for spectrometers implementing volume holograms recorded in reflection geometry. In order to have a more thorough picture of the performance of such a spectrometer employing a volume hologram recorded in reflection geometry, these parameters need to be determined.

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