Qualitative demonstration of spectral diversity filtering using spherical beam volume holograms

Arash Karbaschi, Chaoray Hsieh, Omid Momtahan, Ali Adibi

Department of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
arash@ece.gatech.edu , hcj@ece.gatech.edu , omid@ece.gatech.edu , adibi@ece.gatech.edu

Michael E. Sullivan, David J. Brady

Fitzpatrick Center for Photonics and Communication Systems, Duke University, Durham, NC 27708, USA
sullivan@ee.duke.edu , dbrady@duke.edu

Abstract: We investigate the feasibility of designing spectral diversity filters using spherical beam volume holograms. Our experimental results qualitatively show the separation of the information of different incident wavelength channels using spherical beam volume holograms. The major trade-off in using these holograms is between the degree of spatial spectral diversity and the number of allowed spatial modes (or the divergence angle) of the incident beam.

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1. Introduction

Recently, there has been a lot of interest in designing compact and sensitive spectrometers essentially for bio and environmental sensing. The key element of every spectrometer is a wavelength sensitive (or dispersive) device that allows for separation of different wavelength channels for detection. Holograms (or gratings) are well-known candidates for this task due to their wavelength selectivity [1], which results in non-uniform diffraction of different wavelength channels of a collimated optical beam. Most of the optical spectrometers built based on this phenomenon exploit surface relief or thin film gratings which primarily have single grating vectors. However, these spectroscopy techniques are not efficient for spatially incoherent light sources. The reason is that for an incoherent source with uniform spectrum in the input plane of such spectrometers, the output will be an ambiguous pattern with

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contributions from different wavelength channels overlapping each other. The problem has been solved in conventional spectrometers by limiting the angular range of the incident beam by using spatial filtering. Unfortunately, spatial filtering drastically reduces the photon throughput for diffuse source spectroscopy. While such inefficiency might be tolerated in absorption spectroscopy (where a strong incoherent source can be used), it is a major limitation for weak diffuse sources, such as those generated in Raman spectroscopy. In such cases, the signal from the desired molecules is very weak and successful sensing requires a sensitive and efficient spectrometer.

In order to design more sensitive spectrometers, multimode multiplex spectroscopy (MMS) was recently proposed based on using a weighted projection of multiple wavelength channels (i.e., multimode) of the incident signal [2]. In contrast to conventional spectrometers, the output signal in MMS is composed of multiple wavelength channels, and the information of each channel is separated by post processing of the detected signal. The key element in MMS is a spectral diversity filter (SDF) that inverts an incident optical signal with uniform spectrum over the input plane to an output pattern with non-uniform spatial-spectral information. By measuring the output light intensity over the output plane by a detector array (for example a CCD camera) and performing an inverse filtering (as outlined in Ref. [2]), we can approximate the input spectrum.

A spectral diversity filter maps a homogeneous but diffuse spectral source onto a spatially encoded pattern. Inversion of the spectral-spatial mapping enables spectral estimation. Construction of spectral diversity filters is constrained by the constant radiance theorem [3]. According to the constant radiance theorem it is not possible to produce spatial patterns from a diffuse source without increasing the mode volume or reducing the photon throughput. In contrast with conventional spectroscopy, however, throughput losses using spectral diversity filters may be independent of spectral resolution. Spectral diversity filters have been demonstrated using an inhomogeneous three-dimensional (3D) photonic crystal [2]. Under the photonic crystal approach, the input-output mode volume is fixed but a spatially structured fraction of diffuse incident light is reflected. While 3D photonic crystals are very attractive as super-dispersive elements, they are hard to fabricate based on an arbitrary design. Thus, other (more designable and manufacturable) schemes for the development of SDFs are needed.

This paper considers the feasibility of making SDFs using spherical beam volume holograms (SBVHs). The holograms are recorded by the interference pattern between a plane wave and a spherical wave inside a photopolymer. We will qualitatively show that during readout of these holograms with a white light source, the information of different wavelength channels of the incident beam have different spatial distribution in the output plane. The details of our experiments are presented in section 2. Experimental results are presented in section 3 and further discussed in section 4. Final conclusions are made in section 5.

2. Experiments

For demonstrating the spectral diversity of SBVHs, we have recorded a few holograms using the interference of a spherical beam and a planar beam to obtain a range of grating vectors (in contrast to a plane wave hologram that only has one grating vector). We have read these holograms with monochromatic beams with different degrees of collimation (from a collimated beam to a completely diffuse beam) illuminating the hologram in the direction of the spherical recording beam.

Figure 1 shows the basic schematic of the experimental setup for recording the SBVHs. In all experiments reported in this paper our recording material was the Aprilis photopolymer [4] with L = 200μm thickness. It is a photopolymer recording medium which uses the cationic ring-opening mechanism [5]. Our recording light source was a solid state laser operating at λ = 532nm. We passed a plane wave through a lens with f = 2.5cm to make a spherical beam. The distance of the focus of the spherical beam to the center of the hologram was d = 16mm. When measured in air, the angles of the spherical beam axis and the plane wave with respect to the normal axis were $\theta_1 = 10°$, $\theta_2 = 46°$, respectively, as shown in Fig. 1. Both beams were TE polarized (E vector perpendicular to the plane of the figure). The size of the hologram is

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8mm by 8mm. In some experiments, we changed the distance of the lens with respect to the recorded hologram to change the numerical aperture of the spherical beam. Also we have varied the angle of the plane wave using a 4-f system (not shown in Fig. 1).

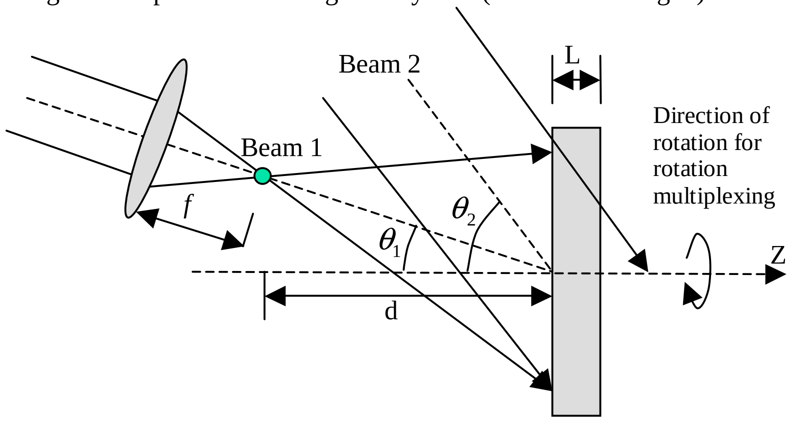

Fig. 1. Basic schematic of the recoding geometry of the SBVH. d = 16 mm, f = 2.5cm, L = 200µm, θ_1 = 10°, θ_2 = 46°, λ = 532 nm. The angles are measured in air. The size of the hologram is 8mm by 8mm. For rotation multiplexing, the recording medium is rotated about the z-axis.

We recorded both single holograms and multiplexed holograms in each spot of the recording material to investigate the effect of the complexity of the hologram on its spectral diversity. In the multiplexed hologram case, we have used rotation multiplexing. This technique is implemented by means of rotating the sample with respect to the plane containing the center of the spherical beam, the center of the recording spot, and a line parallel to the recording plane wave (i.e., rotating the hologram about z-axis in Fig. 1).

The hologram was probed using an approximately monochromatic signal generated by passing the light from a regular 50W light bulb through a monochromator (Fig. 2). The full width half maximum (FWHM) bandwidth of the output light from the monochromator was 8nm. The hologram was far enough (d ≈ 70cm) from the output slit of the monochromator to approximate a collimated reading beam at the hologram. A CCD camera with an imaging lens system was put behind the hologram to capture the image of the transmitted light through the hologram right on the back face of it. We also changed the transmission wavelength of the monochromator and grabbed the image of the transmitted light for different wavelengths to observe the spatial-spectral diversity.

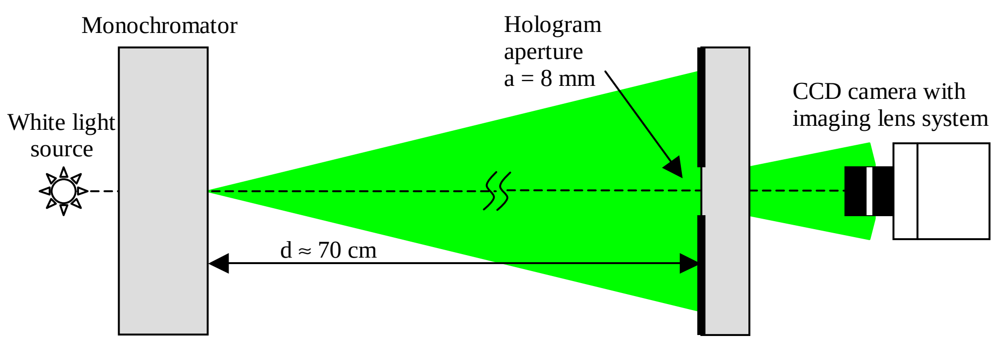

Fig. 2. Reading SBVHs with a monochromatic collimated beam and imaging the back face of the hologram. The light source is far enough from the hologram aperture to approximate a collimated reading beam.

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We also investigated the diffracted light from the hologram, as it was illuminated by a collimated white light beam normal to the hologram face. The diffracted beam hit a white screen at distance about 2cm and the picture of the screen was taken by a digital camera as shown in Fig. 3. The diffracted beam was focused at some point on the screen and the location of the focus varied with wavelength resulting in a colorful picture on the screen.

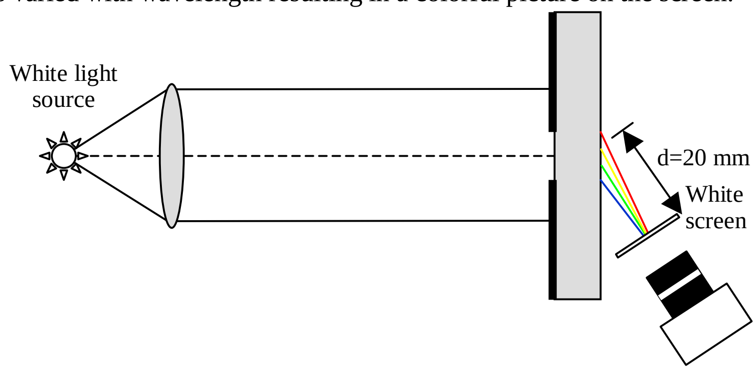

Fig. 3. Reading SBVHs with a collimated white light source. The diffracted light focuses on a white screen and a digital camera takes its picture.

3. Spectral diversity of SBVHs

When reading the SBVHs in the direction of the recording spherical beam using the experimental setup shown in Fig. 2, we observed a dark crescent in the middle of a uniform bright background in the output plane as shown in Fig. 4. Figure 4 (which is a movie) shows the output pattern as the reading wavelength is continuously scanned from 600nm to 900nm. It is clearly seen from the movie that the dark crescent moves as the reading wavelength changes. This change in the output pattern corresponds to the spectral diversity that is required for MMS.

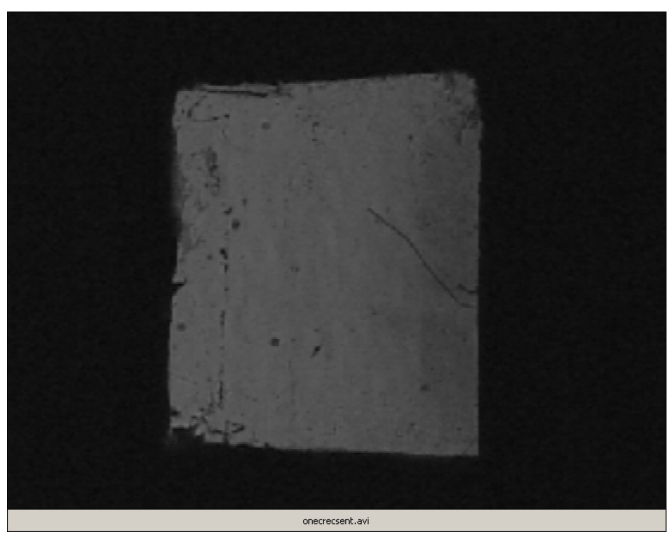

Fig. 4. (862 KB movie) Output pattern of a single SBVH illuminated by a collimated monochromatic beam as the wavelength of the incident beam is continuously scanned from 600nm to 910nm. The dark crescent moves as the wavelength is scanned.

Both the presence of the crescent and its displacement with wavelength are due to the partial Bragg matching of the SBVH by the reading beam. It is known that when a hologram

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with multiple grating vectors (for example recorded by plane wave and a modulated beam formed by passing a plane wave through a spatial light modulator) is read by a reading beam that is not exactly the same as one of the recording beams, only a portion of the hologram (i.e., a subset of grating vectors) is Bragg matched resulting in the reconstruction of only a portion of the other recording beam [6-8]. When the SBVH is read by the collimated beam from the monochromator in Fig. 2 (i.e., by approximately a plane wave) instead of the spherical beam) only a portion of the SBVH is Bragg matched, which corresponds to a diffracted beam that has a crescent shape. Reading with a different reading wavelength results in Bragg matching another subset of grating vectors of the hologram and thus another crescent diffracts. In other words, by scanning the reading wavelength, the position of the dark crescent in the output plane in Fig. 2 shifts as shown in Fig. 4.

In order to observe the effect of the reading wavelength on the partial Bragg matching, we also captured the diffracted light from the hologram using the setup in Fig. 3 when the hologram was illuminated with a collimated white light source in the direction of the recording spherical beam. The resulting image is shown in Fig. 5. One can observe that the SBVH diffracts the entire visible spectrum although it is a thick hologram. The range is in fact broader than just the visible range. This is due to the partial Bragg matching of different potions of the SBVH by different incident wavelengths as explained above. This is not the case for a plane wave volume hologram (PWVH) that is used in conventional spectrometers. A PWVH either diffracts the entire collimated reading beam (and not a crescent) or does not diffract it at all because the hologram has only one grating vector, which is either Bragg matched or mismatched by the reading beam.

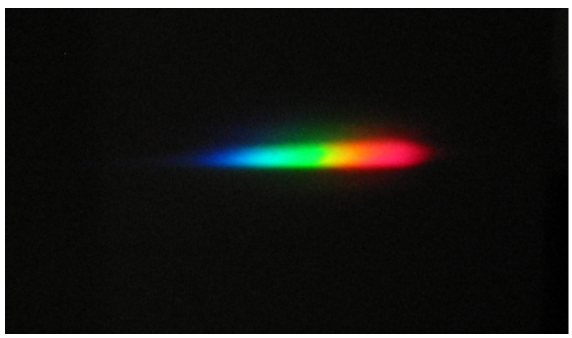

Fig. 5. Diffracted beam from a SBVH illuminated by a collimated white light source measured using the experimental setup in Fig. 3.

To make the output patterns even more diverse, several SBVHs can be multiplexed by rotation multiplexing explained in section 2. Figure 6 (which is a movie) illustrates the output pattern of an 8 rotation-multiplexed SBVH set in the reading setup of Fig. 2, when the incident wavelength (controlled by the monochromator) is continuously scanned from 644nm to 878nm. In performing rotation multiplexing, the rotation angle of the recording material between two successive recordings is 45°. It is clear from Fig. 6 that the output pattern (composed of 8 crescents each corresponding to diffraction from one SBVH) has different spatial distributions for different wavelengths. Thus, the spectral diversity here is better than that for a single SBVH. Note that the dynamic range parameter (or the M/# [9]) of the recording material limits the number of holograms that can be multiplexed. To obtain dark crescent, large diffraction efficiency for all holograms is required. This diffraction efficiency is given by $\eta = (M\# / M)^2$, with M being the number of multiplexed holograms [9,10]. The material used in our experiment has M/# = 5. That is why we used a maximum of M = 8 holograms in these experiments to have η close to 50%.

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4. Discussion

The results presented in section 3 demonstrate the potential of SBVHs for designing SDFs. However, all these results were obtained with collimated incident beams. In other words, we have demonstrated that these holograms might be used to separate the information of different wavelength channels of a collimated incident beam. For practical applications, we would like this diversity to be present for a spatially incoherent beam (or at least a beam with reasonably large divergence angle).

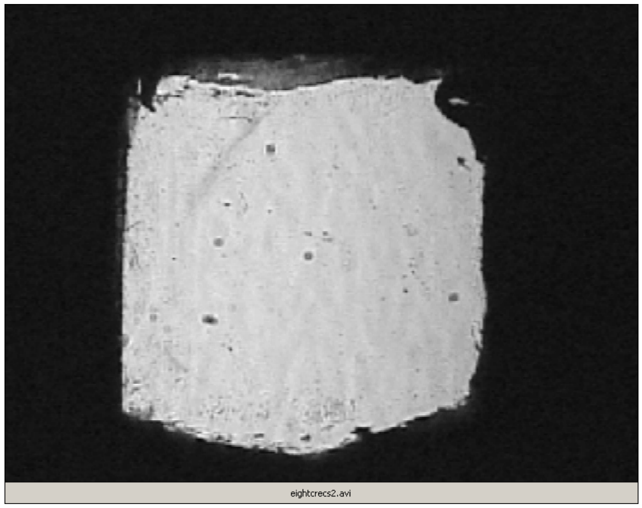

Fig. 6. (707 KB movie) Output pattern of a complex volume hologram (formed by rotation multiplexing of 8 SBVHs) illuminated by a collimated monochromatic beam as the wavelength of the incident beam is scanned from 644nm to 878nm. The output multi-crescent pattern changes as the wavelength is scanned.

For evaluating the spectral diversity of SBVHs for non-collimated reading beams, we have read them both with spherical (i.e., non-collimated with finite divergence angle) and diffuse beams. For the spherical beam case, the reading experiments were performed using the experimental setup shown in Fig. 2 with an additional lens placed in front of the hologram to generate a spherical beam. The results for a collimated beam (with no additional lens) and a beam with reasonable divergence angle (full angle $\theta = 20°$ measured in air) are shown in Figs. 7(a) and 7(b). It is clear that the dark crescent becomes wider and brighter as the divergence angle increases.

To study more extreme cases, we put a diffuser in the reading setup shown in Fig. 2, in front of the hologram. Figures 7(c) and 7(d) show the output of the CCD camera when the distance between the diffuser and the hologram is 27.5cm and 2.5cm, respectively. The latter implements the worst case by approximating a fully incoherent source. The smaller the distance between the hologram and the diffuser, the larger the divergence angle of the reading beam and the lower the spectral diversity in the output plane will be.

Figure 7 clearly demonstrates the trade-off between the spectral diversity and the divergence angle of the incident beam (or the number of spatial modes that are included in the spectrometer). We expect that limiting the divergence angle of the incident beam to $\theta = 40°$ would allow for a reasonable diversity in the output plane. Furthermore, by recording more complex holograms (For example between a plane wave and a modulated beam through a spatial light modulator) better diversity for a given divergence angle can be obtained. Note that the first demonstration of MMS using a 3D photonic crystal was done using an incident beam with $\theta = 20°$ divergence angle.

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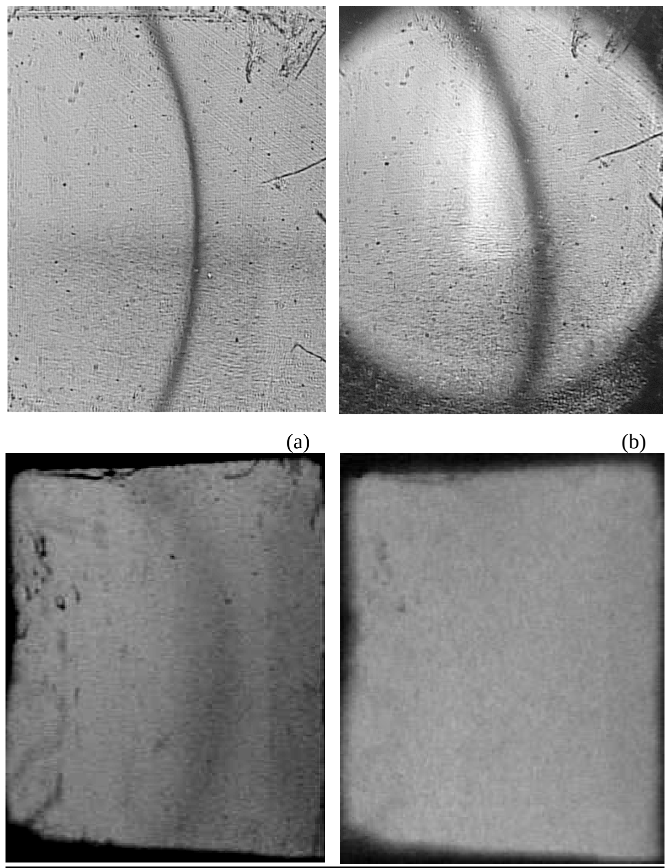
5. Conclusion

We demonstrated qualitatively that a SBVH formed by the interference pattern of a plane wave and a spherical beam can act as a spherical diversity filter. We also showed that by multiplexing several spherical beam holograms using rotation multiplexing, we can obtain better output spectral diversity. There is a trade-off between the spectral diversity and the number of spatial modes (or the divergence angle or the power) of the input beam that is allowed to pass through the hologram. The more collimated beam results in a better spectral diversity.



(a) (b)

(c) (d)

Fig. 7. Effect of the divergence angle of the reading beam on the spectral diversity of the SBVHs. A single SBVH is read at λ = 532nm with (a) a collimated monochromatic beam , (b) spherical beam with divergence angle of 20° (full angle in air), (c) diffuse light where the diffuser is 27.5cm far from the hologram in the setup of Fig. 2, (d) diffuse light where the diffuser is 2.5cm far from the hologram in the setup of Fig. 2.

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