Compact slit-less spectrometer using cylindrical beam volume holograms

Chaoray Hsieh, Omid Momtahan, and Ali Adibi

School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332 USA
Phone: (404) 385-3017; Fax: (404) 894-4641
hcj@ece.gatech.edu; omid@ece.gatech.edu; adibi@ece.gatech.edu

Abstract: We present compact slit-less spectrometers using cylindrical beam holograms with several advantages over conventional spectrometers. We demonstrate large spectral range spectrometers using spatially multiplexed cylindrical beam holograms without adding any moving part in spectroscopic systems.

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The principle of conventional grating spectrometers is based on the separation of different wavelength channels of the input beam into different locations in the output plane using a dispersive element (i.e., a grating). The output is then detected using a detector array or a charged coupled device (CCD) chip. Because of the scalar nature of the spectrum, the dispersive elements, such as gratings and prisms, provide the mapping between the wavelength and spatial locations along a line on the detector. Thus, a one dimensional spectral diversity pattern is obtained along the dispersive direction. However, the direction perpendicular to the dispersive direction in the output plane is almost uniform without carrying any spectral information resulting in the loss of the throughput. Therefore, using this second direction to increase the performance of the spectrometer has been extensively studied. For example, using proper coding in different horizontal rows and a CCD chip as the detector results in the Hadamard spectrometer that has better signal to noise ratio compared to the conventional spectrometer [1].

We have recently demonstrated a compact slit-less spectrometer with promising performance for applications in diffuse source spectroscopy based on using spherical beam volume holograms (SBVHs) [2]. In this design, the three elements of the input slit, the input collimating lens, and the dispersive grating of the conventional spectrometers are implemented using a single SBVH. Thus, this slit-less spectrometer is more compact than the conventional spectrometer because only a lens, a hologram, and a CCD chip are required. However, similar to the conventional spectrometers, the dispersive property of the SBVH is observed only in one direction (i.e., x-direction in Figure 1) in the output plane. Since the output beam of this slit-less spectrometer has a crescent shape with a finite curvature and it diverges in the direction perpendicular to the dispersive direction (i.e., y-direction in Figure 1) [2-3], the width of the output pattern is thicker resulting in worse resolution if any imaging is performed in the y-direction. Therefore, it is not possible to use the similar coding method (such as Hadamard coding) introduced in conventional spectrometers to improve the performance of the SBVH-based spectrometer. To solve this problem, we propose to replace the SBVH by a cylindrical beam volume hologram (CBVH) so that the properties of the output pattern can be controlled individually in the x-direction and in the y-direction.

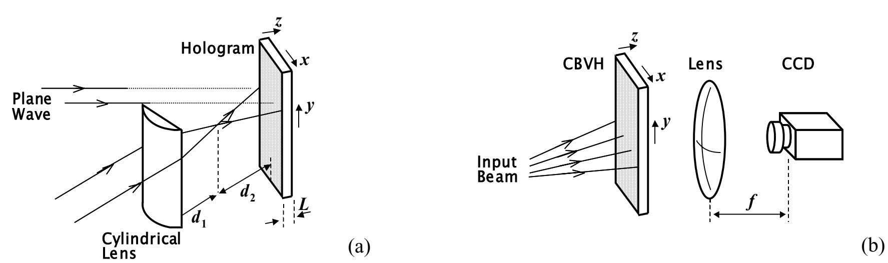
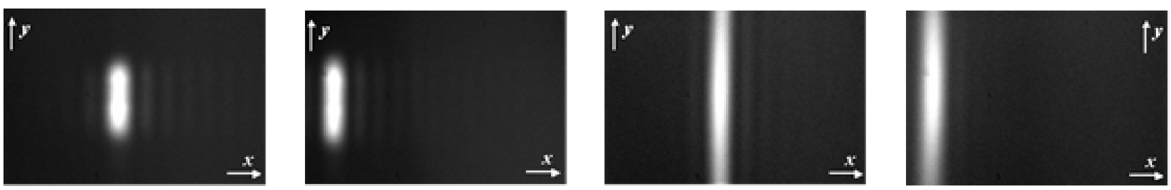


Fig. 1. (a) Recording geometry for a cylindrical beam volume hologram. The hologram is recorded using a plane wave and a beam focused by a cylindrical lens. The focus of the cylindrical beam is at a distance d_1 behind the lens and at a distance d_2 in front of the hologram. The hologram thickness is L. The incident angle of the plane wave and the cylindrical beam can be modified based on the application. (b) The arrangement of the spectrometer in the slit-less spectroscopy implementation. The hologram is a cylindrical beam volume hologram. The lens projects the Fourier transform of the diffracted beam over the CCD located at its focal plane. The focal length of the lens is f.

Different from the SBVH recorded by a plane wave and a spherical beam, the CBVH is recorded by a plane wave and a cylindrical beam as shown in Figure 1(a). A collimated beam is passed through the cylindrical lens and focused in the *x-z* plane at a distance d_1 = 2.5 cm from the lens. The focusing location is at a distance d_2 = 3.5 cm from the center of the hologram. The interference pattern formed by a diverging cylindrical beam and a plane wave is recorded inside the Aprilis photopolymer with a thickness of L = 300 μm. The angle between the propagation direction of the plane wave and that of the cylindrical beam outside the recording material is 35.6°. The wavelength of both recording beams is λ = 532 nm. The arrangement for the spectrometer is shown in Figure 1(b). The input beam illuminates the hologram primarily in the direction of the recording cylindrical beam. The diffracted beam from the hologram is Fourier transformed using a lens with a focal length of f. This lens can be either a spherical lens or a cylindrical lens depending on the application. The output of the system is obtained using a CCD located at the focal plane of the lens. To study the spatial-spectral mapping in the spectrometer in Figure 1(b), we illuminated the CBVH with a monochromatic light formed by passing a white light beam through a monochromator. The outputs on the CCD corresponding to the monochromatic inputs at wavelengths λ = 500 nm and λ = 532 nm are shown in Figures 2(a) and 2(b), respectively. In these experiments, a spherical lens with the focal length of f = 10 cm and with $F\#$ = 3.8 was used in the structure shown in Figure 1(b).



(a) (b) (c) (d)

Fig. 2. The outputs on the CCD in the spectrometer shown in Figure 1(b) corresponding to the inputs at (a) λ = 500 nm and at (b) λ = 532 nm with the input being the light from a monochromator directly coupled to the spectrometer. A spherical lens with f = 10 cm and $F\#$ = 3.8 was used in the spectrometer. To increase the divergence angle of the input, a rotating diffuser was used right before the CBVH. The outputs corresponding to such diffuse input beams at wavelength λ = 500 nm and λ = 532 nm are shown in (c) and (d), respectively.

As expected, Figure 2 shows that the location of the output is changed in the *x*-direction, while in the *y*-direction the output remains similar. In the *x*-direction, the intensity profile of the output shows a sinc-squared behavior similar to what observed in SBVH-based spectrometer [2-3], while the variation in the *y*-direction is totally different from that in the SBVH case. The limited size in the y-direction of the output in Figures 2(a) and 2(b) is because of the limited divergence angle of the input beams in the *y*-direction. To increase the divergence angle of the input, a rotating diffuser is placed right before the CBVH. The outputs corresponding to the diffuse input beams at wavelength λ = 500 nm and λ = 532 nm are shown in Figures 2(c) and 2(d), respectively. In the *x*-direction, the outputs are not changed compared to the previous case (i.e., without the diffuser), but the size of the output in the y-direction is increased by adding the diffuser due to the wider range of the incident angles in the input. From these results, it is clear that the CBVH-based spectrometer performs spectral separation in the *x*-direction for non-diffuse or diffuse input beam, while the hologram itself does not affect the beam in the *y*-direction. In the results shown in Figure 2, the input beam undergoes a Fourier transformation in the *y*-direction imposed by the lens. If a cylindrical lens is used after the CBVH instead of a spherical lens, the input beam would not be changed in the *y*-direction. This independence between the effects on the input beam in the *x*-direction and the *y*-directions is the main advantage of the CBVH-based spectrometers. It should be noted that the dispersion property of the CBVH is very similar to that of the SBVH in the *x*-direction, while a freedom in the design is obtained in the *y*-direction.

Based on the characteristics of the CBVH shown in Figure 2, unique applications can be realized by designing more complex holograms. For example, we can record a set of spatially-multiplexed CBVHs by dividing the hologram in the *y*-direction into several slabs. In each slab, a CBVH is recorded with proper design parameters dedicated to different ranges of wavelength. Thus, the one-dimensional spectral diversity is wrapped into two dimensions over the CCD detector. This can be used to increase the range of the operating wavelength without adding any moving part in the spectroscopic system. The spectrometer with a 550 nm spectral operating range has been demonstrated by using a 3-spatially-multiplexed CBVH. The details of the properties and the structure of this spectrometer will be discussed and the spectrum estimation for an unknown light source will also be demonstrated.

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