Multifunctional and compact spectrometers based on cylindrical beam volume holograms

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We propose a new class of slitless spectrometers using cylindrical beam volume holograms. These holograms disperse an input beam in one direction in an output plane while they do not affect the beam in the perpendicular direction. We show that the spectral mapping of the input beam can be obtained in one direction and the beam can be independently modified in the perpendicular direction. Using this unique property, we demonstrate a spectral wrapping technique to considerably increase the operation spectral range of the slitless spectrometers, without sacrificing their resolution. © 2007 Optical Society of America

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In principle, a spectrometer maps different wavelength channels of the input beam into different locations in the output plane (i.e., a detector) by using a dispersive element. Because of the scalar nature of the spectrum, the dispersive elements, such as gratings and prisms, provide the mapping between the wavelength components of the input beam and the output spatial locations along a line. For example, for the case of a simple sinusoidal grating, the dispersion is obtained on a line in the direction parallel to the grating vector. Therefore, in the direction perpendicular to the dispersion direction, the light distribution at the output is similar to that at the input without carrying any additional information. Recent advances in detector technology have made two-dimensional arrays of detectors (for example, CCD chips) widely available. Thus, by proper modification of the beam in the direction normal to the dispersion direction, further information can be obtained on the detector at the output. For example, different horizontal rows can be used to map different wavelength ranges and provide spectral wrapping at the output. As another example, using proper coding in different horizontal rows results in a Hadamard spectrometer that has better signal-to-noise ratio than a conventional spectrometer [1,2].

We have recently proposed a slitless spectrometer based on spherical beam volume holograms (SBVHs), which are more compact, less sensitive to alignment, and less expensive than conventional spectrometers [3,4]. In these slitless spectrometers, the three input elements (i.e., the input slit, the collimating lens, and the dispersive grating) of the conventional spectrometers are implemented by a single SBVH, which is recorded using a spherical beam and a plane wave. In the spectrometer setup, the hologram is illuminated mainly in the direction of the recording spherical beam. The partial Bragg matching of the SBVH during diffraction causes the output beam to have a crescent shape [4,5] with the location of the output crescent being only a function of the input wavelength. Similar to conventional spectrometers, the dispersive property of the volume hologram is observed in only one direction at the output plane. The other direction is the direction of the degeneracy of the Bragg condition of the SBVH and does not provide any spectral information. Therefore, in a SBVH spectrometer, a linear (1-D) detector array can be used to provide all the available information for the spectroscopy. The rest of the output crescent does not provide further information for the spectrum estimation.

In this Letter, we demonstrate a new design for the slitless spectrometer using cylindrical beam volume holograms (CBVHs). The CBVH spectrometers have the same properties as those of the SBVH spectrometers in the dispersion direction, while in a direction normal to that they can implement independent functionalities. The recording geometry of a CBVH is shown in Fig. 1(a). The hologram is recorded by interfering one plane wave and one cylindrical beam inside the recording medium. The cylindrical beam is formed by passing a plane wave through a cylindrical lens. The cylindrical lens focuses the beam in the x-direction, but it does not affect the beam in the y-direction. The resulting cylindrical beam has almost the same properties as a spherical beam in the $x-z$ plane. Therefore, the dispersion properties of the CBVH are the same as those of the SBVH in the $x-z$

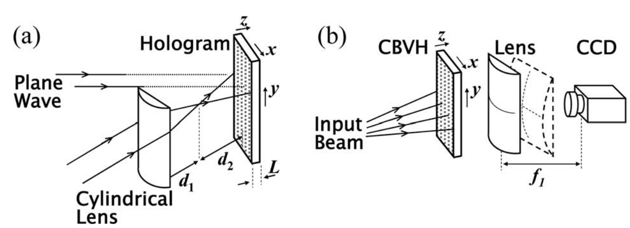

Fig. 1. (a) Recording geometry for the cylindrical beam volume hologram. The hologram is recorded in a holographic material with thickness L using a plane wave and a beam focused by a cylindrical lens. The focus of the cylindrical beam is at distance d_1 and d_2 from the lens and the hologram, respectively. (b) Arrangement of the slitless spectrometer based on a CBVH. A cylindrical lens with focal length of f_1 obtains the Fourier transform in the x-direction. In the y-direction the beam can be modified independently (e.g., imaged) using another cylindrical lens with a focal length of f_2, shown by the dashed lines.

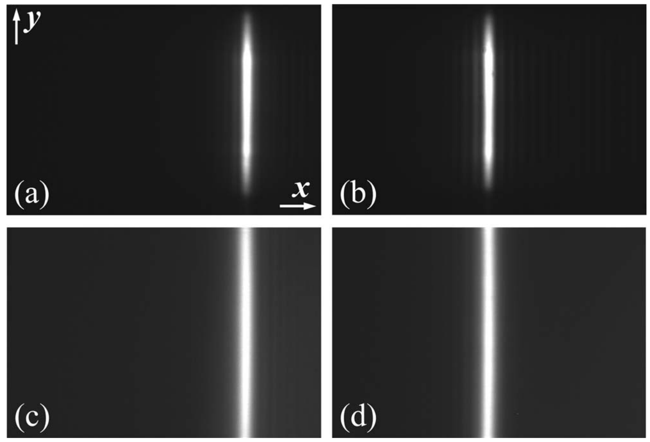

Fig. 2. Outputs on the CCD for the spectrometer shown in Fig. 1(b) corresponding to the inputs at (a) wavelength $\lambda = 482$ nm and at (b) wavelength $\lambda = 532$ nm, with the input being the light from a monochromator directly coupled to the spectrometer. A cylindrical lens with the focal length of $f_1 = 5$ cm is used in the spectrometer. The outputs corresponding to such diffuse input beams at wavelength $\lambda = 482$ nm and $\lambda = 532$ nm are shown in (c) and (d), respectively.

plane. Furthermore, the CBVH recorded in the arrangement of Fig. 1(a) does not have any grating component in the y-direction and does not affect the input beam in that direction.

To demonstrate the properties of the CBVH, we recorded different holograms inside an $L = 400$ μm sample of Aprilis photopolymer [6] using the arrangement shown in Fig. 1(a) with $d_1 = 2.5$ cm and $d_2 = 2.7$ cm. The angle of incidence of the plane wave in the air is 36°, and the cylindrical beam propagates normal to the hologram. The wavelength of both recording beams is $\lambda = 532$ nm. The performance of the recorded SBVH for spectroscopy is tested using the spectrometer setup shown in Fig. 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_1. In general, this lens can be either a spherical lens or a cylindrical lens depending on the application. In the experiments reported in this Letter, we used a cylindrical lens with $f_1 = 5$ cm to perform Fourier transformation in the x-direction (while keeping the beam intact in the y-direction). A white-light beam is passed through a monochromator and is used as the input to the spectrometer. The output of the system is measured using a CCD camera located at the focal plane of the lens. The outputs on the CCD corresponding to the inputs at wavelengths $\lambda = 482$ nm and $\lambda = 532$ nm are shown in Fig. 2(a) and 2(b), respectively. Figure 2 shows that the output pattern of the CBVH spectrometer at each wavelength (within the operating range) has a strip shape (in contrast with the crescent shape obtained in SBVH spectrometers [4]). This is consistent with our expectation described earlier that the CBVH does not affect the input beam in the y-direction. Furthermore, the locations of the output strips change in the x-direction as the wavelength changes (spectral–spatial mapping).

The limited size in the y-direction of the output in Figs. 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 (corresponding to an incoherent input beam), a rotating diffuser is used after the monochromator and located right before the CBVH. The diffuser is perpendicular to and its rotating axis is parallel to the beam from the monochromator. The outputs corresponding to the diffuse input beams at wavelengths $\lambda = 482$ nm and $\lambda = 532$ nm are shown in Figs. 2(c) and 2(d), respectively. In the x-direction, the intensity profile is not changed considerably compared with the previous case (without the diffuser), but the size of the output in the y-direction is increased corresponding to the wider range of the incident angles of the input beam. From these results, it is clear that the CBVH-based spectrometer performs spectral separation in the x-direction for a nondiffuse or diffuse input beam, while the hologram itself does not affect the beam in the y-direction. This is an important observation and shows the capability of the CBVH spectrometer for diffuse source spectroscopy without requiring collimation optics (e.g., an input slit and a collimating lens).

The independence between the effects on the input beam in the x- and y-directions is an advantage of the CBVH spectrometers over the SBVH spectrometers for which no design freedom in the y-direction exists. As an example, by adding a second cylindrical lens to the experimental setup of Fig. 1(b) (this lens is shown by dots) perpendicular to the Fourier transforming lens, we can modify the beam in the y-direction independently. This lens can be used to provide the tight focusing of the beam in the y-direction to collect more light onto the detection area. Note that the increase in the intensity by tightly collecting the light in the y-direction is limited by the Lagrange invariant of the system or in general by the constant radiance theorem [7]. However, using the arrangement in Fig. 1(b) we can achieve the maximum output intensity for partially incoherent sources, which are the most practical sources of interest.

Using the design flexibility of the CBVH spectrometer in the y-direction (reported here for what is to our knowledge the first time), we can extend its operating spectral range without sacrificing the resolution. For this purpose, we use the second cylindrical lens (shown by dots) in the setup of Fig. 1(b) to image the hologram onto the CCD in the y-direction. In this case, the combination of the CBVH and the two cylindrical lenses provides the spectral diversity in the x-direction while it maps the hologram over the CCD in the y-direction. For example, we can divide the hologram in the y-direction into several segments and record different CBVHs in different segments. A CBVH in each segment is properly designed to map a certain range of wavelength onto its corresponding spatial range on the CCD. Thus, the operating spectral range of the spectrometer is considerably increased as it is wrapped into two dimensions in the output (i.e., two-dimensional spectral–spatial mapping). However, since the thickness of each diffracted strip in the x-direction on the CCD (see Fig. 2) is not affected by the design in the y-direction, the resolution of the spectrometer remains unchanged.

To experimentally demonstrate this idea, we divide the hologram in Fig. 1(a) into three equal segments in the y-direction. The middle segment is used as a buffer, and two holograms are recorded in the top and bottom segments. During the recording of each hologram, the other regions of the material are covered to prevent recording unwanted holograms. The incident angles of the recording plane wave are 36° and 41° for the top and bottom holograms, respectively, and are designed for the corresponding ranges of the spectrum. The cylindrical recording beam is the same for both holograms. All other parameters are the same as those used in the previous experiment. The hologram is then put in the spectrometer setup of Fig. 1(b) with $f_1=5$ cm, and the focal length of the other cylindrical lens (shown by dots) is $f_2=2.5$ cm. The output beam on the CCD for a diffuse monochromatic beam at 620 nm wavelength is shown in Fig. 3(a). In this figure the top and bottom portion of the CCD receives the diffraction from the bottom and top holograms, respectively. In other words, we have realized two spectrometers with similar resolution operating in two separate ranges of wavelength in the same arrangement of Fig. 1(b). Note that the number of spectrometers that can be integrated using this method can be more than two and is limited only by the size of the CCD and the $f/\#$ of the second cylindrical lens.

The normalized output intensity profiles on the CCD at different wavelengths corresponding to the bottom and top holograms are shown in the top and the bottom plots of Fig. 3(b), respectively. Each curve in the figure shows the output at one wavelength. For each measurement, we use a diffuse monochromatic light obtained by passing the white light through a monochromator and a diffuser. The wavelength of the monochromator output is changed in the range from 450 to 800 nm with steps of 10 nm. The output intensity measured on the CCD is normalized to the intensity of the monochromatic input beam for each measurement. The large spectral range feature of this CBVH spectrometer is evident from Fig. 3(b). The spectral mapping obtained by the two spatially multiplexed holograms is the main source for this feature.

The results of this Letter clearly show the advantages of using CBVH for spectroscopy. It is important to note that the use of the design flexibility in the y-direction is not limited to the cases reported here. One can use the spectral wrapping technique in conjunction with thicker recording material to improve both resolution and spectral range. While there is some trade-off between the ultimate resolution and operating spectral range in every spectrometer, the optimal use of the spectral wrapping property of the CBVH spectrometer can minimize this trade-off. Note also that the segmented hologram can be easily recorded in one step (for example, by incorporating a spatial light modulator or a mask in the recording setup) or in sequential steps depending on the recording setup. Furthermore, since the holograms are recorded in different regions of the recording material, the full dynamic range of the material can be used for recording each hologram to obtain high diffraction efficiency. This configuration is not possible for a spectrometer based on the SBVH.

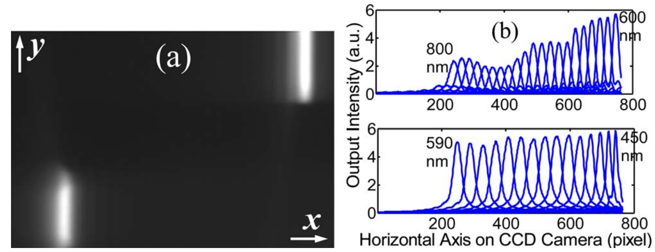

Fig. 3. (Color online) (a) Output on the CCD for a diffuse monochromatic beam at 620 nm wavelength in the spectrometer of Fig. 1(b) with a spatially multiplexed CBVH. (b) Normalized intensity profile in the x-direction on the CCD for the operating range of wavelengths from 450 to 800 nm with steps of 10 nm. The top and bottom plots correspond to the top and bottom regions of the CCD, respectively.

In conclusion, we demonstrated a new platform for designing slitless holographic spectrometers with considerable design flexibility using CBVHs. We showed that the spectral contents of an arbitrary beam (collimated or diffuse) can be successfully mapped into different spatial locations along one direction using a CBVH. The CBVH can provide the spectral diversity in one direction without affecting the beam in the normal direction. Thus, independent functionalities can be added to the CBVH spectrometer by designing the system to manipulate the beam in the second direction. For example, we showed the operating spectral range of the spectrometer can be increased by a factor of 2 using two spatially multiplexed CBVHs. Depending on the pixel size of the CCD, the total number of the pixels, and the $f/\#$ of the lens focusing in the y-direction, more CBVHs can be multiplexed to obtain larger spectral ranges.

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