Ultra-high Resolution and Compact Spectrometers using Volume Holograms as Dispersive Elements

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Abstract: Compact and efficient spectrometers are of great interest for biological and environmental sensing. In this talk, we describe a class of spectrometers that work based on diffractive properties of spherical beam and cylindrical beam volume holograms. The hologram in these spectrometers acts as a spectral diversity filter (SDF), which maps different input wavelengths into different locations in the output plane. The main properties of these holographic SDFs and the new techniques for removing the ambiguity between incident wavelength (or the input channel) and the incident angle (or the input spatial mode) are discussed, and the performance of the overall holographic spectrometers will be compared with that of the conventional spectrometers. Finally, it is also shown that by combining such volume holograms with a Fabry-Perot interferometer, a true two-dimensional spatial-spectral mapping can be formed which allows for the formation of wideband spectrometers with ultra-high resolution in a very compact slit-less architecture.

Keywords: Volume hologram; Spectrometer
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INTRODUCTION

Compact and sensitive spectrometers are of high utility in biological and environmental sensing applications. Wavelength channels in a conventional spectrometer are separated using gratings, cavities, and interferometers. While conventional devices efficiently separate multiple wavelength channels of a spatially coherent (or collimated) incident beam, their direct application for spatially incoherent beams is not trivial. A spatially incoherent beam has multiple spatial modes, which can be considered as different incident angles, resulting in the spatial overlap of multiple wavelength channels on the output plane of the grating. To suppress this ambiguity in the output spectrum, spatial filters and the lens are used in the conventional spectrometer to limit the incident light to one spatial mode resulting in the detection of only one wavelength channel. The main drawback of this single-mode single-channel scheme is the low optical throughput. For sensing applications where the information-bearing signal is weak, more sensitive schemes must be implemented. Besides, since too many elements (including slits, lenses, a dispersive medium, and a detector) are required, the conventional spectroscopic system is bulky and sensitive to alignment.

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For any application where the portability is the top concern, a more compact spectrometer with less sensitive to alignment also has to be developed.

VOLUME HOLOGRAPHIC SPECTROMETER

In this paper, we present volume hologram-based technologies to develop a new class of compact, sensitive and high resolution spectrometers for diffuse source spectroscopy. The hologram used in these spectrometers acts as a spectral diversity filter (SDF), which maps different input wavelengths into different locations in the output plane. Using a single spherical beam volume hologram (SBVH) recorded by a plane wave and a diverging spherical beam (the recording setup is shown in Figure 1(a)), we successfully demonstrated the spectral diversity output pattern (in the transmission direction) with a unique crescent shape corresponding to a monochromatic reading beam, and the position of the crescent in the dispersive direction (i.e., horizontal direction on the CCD camera) is sensitive to the incident wavelength [1-2]. However, since the position of the crescent is also sensitive to the incident spatial mode, the ambiguity in the output spectrum exists and the SBVH can not be used alone for diffuse source spectroscopy. To eliminate the ambiguity problem, a Fourier transforming lens is added behind the SBVH, and a Fourier transform volume holographic spectrometer [3] is demonstrated for the first time.

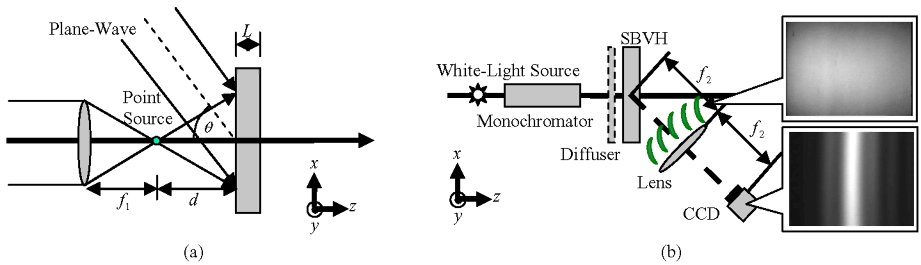


FIGURE 1. The general schematics of (a) recording and (b) reading setups for a spherical beam volume hologram. A rotating diffuser can be added into system to produce a diffuse incident beam as shown in (b).

Figure 1(b) shows the schematics of this holographic spectrometer. As shown in Figure 1(b), when the hologram is read by a monochromatic diffuse source, a diffuse pattern which is consisting of many crescents is diffracted. No spectral diversity is observed in this case because the diffracted pattern is almost uniform and identical for any incident wavelength. However, since all crescents (which correspond to a certain wavelength) propagate along the same direction [4], only one crescent is obtained on the CCD camera at the Fourier plane. Because the position of the crescent at the Fourier plane is only sensitive to the incident wavelength, this holographic spectrometer can be operated well under diffuse source illumination.

To investigate the effect of the incident wavelength on the performance of this holographic spectrometer, we used the experimental setup in Figure 1(b) and scanned the input wavelength from λ = 482 nm toλ = 587 nm with 5 nm spacing using the monochromator with full width at half maximum (FWHM) resolution equal to 8 nm. The output pattern for each incident wavelength is captured by the CCD camera. The normalized output intensity with respect to the location in the horizontal axis on the CCD camera is show in Figure 2(a).

Each curve in Figure 2(a) corresponds to one incident wavelength. Figure 2(a) clearly shows that the output spatial intensity pattern is a function of the incident wavelength under diffuse light illumination. Note that the peak of the normalized intensity is slightly different for different wavelengths because the efficiency of partial Bragg matching from the SBVH depends on the wavelength. By rotating the SBVH slightly, the relative strengths of different wavelength channels can be modified. Figure 2(a) also suggests that this SBVH has a 102 *nm* spectrum analyzing range (which can be controlled by the focal length of the Fourier-transform lens) without rotating the SBVH. However, the spectral bandwidth (as well as resolution) can be modified by changing the design parameters such as material thickness and the divergence angle of the recording spherical wave. A holographic spectrometer (using a single SBVH as dispersive medium) with 300 nm spectral bandwidth and 2 nm resolution has recently been demonstrated.

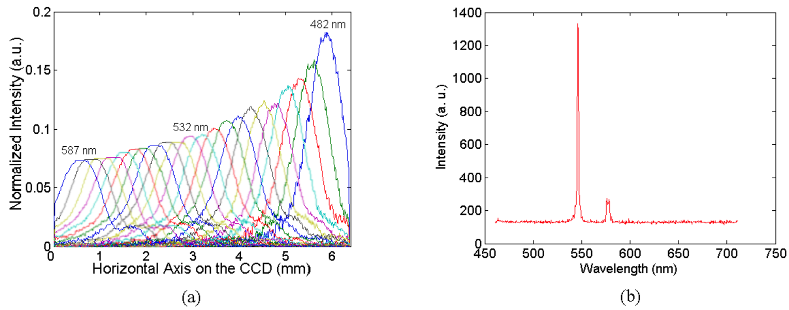


FIGURE 2. (a) Normalized intensity versus the location along the horizontal axis on the CCD in Figure 1(b) for the SBVH described in the text. (b) The spectrum estimation for a Hg-Ar lamp by using the Fourier transform volume holographic spectrometer.

In Figure 2(b), the spectrum estimation for a Hg-Ar lamp is also demonstrated by using the holographic spectrometer. The SBVH used in this experiment is recorded on a 2-mm-thick $LiNbO_3:Fe:Mn$ crystal. Theoretically, the higher resolution can be obtained if a thicker holographic recording material is used. As shown in Figure 2(b), two close peaks of 577 nm and 579 nm can be resolved indicating that the resolution of this spectrometer is better than 2 nm. This holographic spectrometer has several advantages over conventional spectrometers. First, because the collimator (i.e., a slit and a lens) and the grating in the conventional spectrometer are replaced by a hologram, the system is simpler, lighter, and a more compact design. Secondly, since the light source can be placed right in front of the hologram, the system is not sensitive to the input alignment as it works best with diffuse input signals. Furthermore, no moving part (i.e., rotation of the hologram) is required for limited spectral operation bandwidth (a few hundred nanometers).

For SBVH-based holographic spectrometers discussed in previous paragraphs, only the dispersion direction on the output plane is useful to determine the spectral properties of the unknown input light source. In other words, the degenerate direction (i.e., the direction perpendicular to the dispersion direction) on the output plane does not carry any spectral information resulting in waste of the output power. Therefore, as the new design of the hologram for spectroscopic system, we proposed to replace the spherical beam by a cylindrical beam in the holographic recording configuration (shown in Figure 1(a)).

CYLINDRICAL BEAM VOLUME HOLOGRAM

The cylindrical beam volume hologram (CBVH) is recorded by a plane wave and a cylindrical beam as shown in Figure 3(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 = 2.7 cm from the center of the hologram. The interference pattern formed by a diverging cylindrical beam and a plane wave is recorded inside a sample of Aprilis photopolymer with a thickness of L = 400 μm. The angle between the propagation direction of the plane wave and that of the cylindrical beam outside the recording material is 36°. The wavelength of both recording beams is λ = 532 nm.

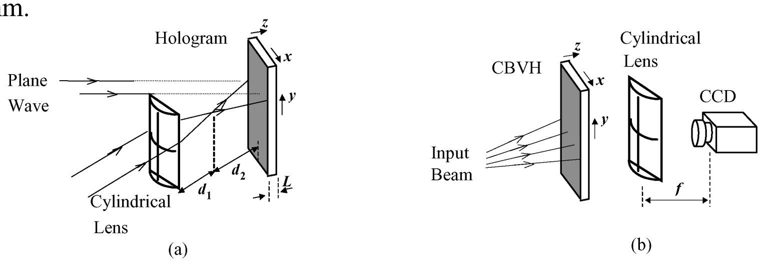
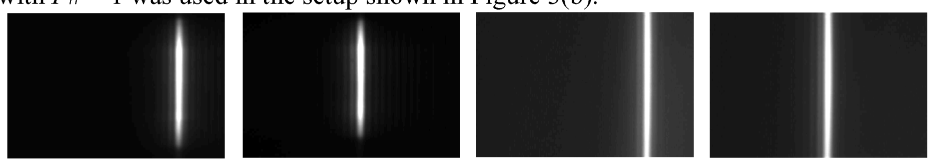


FIGURE 3. (a) Recording geometry for a cylindrical beam volume hologram (CBVH). (b) The arrangement of the spectrometer.

The arrangement for the spectrometer is shown in Figure 3(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 cylindrical lens with a focal length of f. 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 3(b), we illuminated the CBVH with a monochromatic light formed by passing a white light beam through a monochromator. The outputs on the CCD camera corresponding to the monochromatic inputs at wavelengths λ = 482 nm and λ = 532 nm are shown in Figures 4(a) & 4(b), and in Figure 4(c) & 4(d) with diffuse light reading. In these experiments, a cylindrical lens with the focal length of f = 5 cm and with $F\#$ = 1 was used in the setup shown in Figure 3(b).



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

FIGURE 4. The outputs on the CCD in the spectrometer shown in Figure 1(b) corresponding to the inputs at (a) λ = 482 nm and at (b) λ = 532 nm with the input being the light from a monochromator directly coupled to the spectrometer. The outputs corresponding to the diffuse input beams at wavelength λ = 482 nm and λ = 532 nm are shown in (c) and (d), respectively.

Figure 4 shows that the location of the output stripe on the CCD is different in the *x*-direction for different incident wavelengths. Thus, this structure can be used as a spectrometer. On the other hand, in the *y*-direction, the output is not affected by the holographic spectrometer (i.e., the CBVH and the lens) and its dimension is determined by the properties of the incident light source (e.g., the dimension is larger for diffuse incident light source due to the large diverging angle). This independence between the effects on the input beam in the *x*-direction and the *y*-direction is the main advantage of the CBVH-based spectrometers.

Based on the characteristics of the CBVH shown in Figure 4 and the design of the freedom in the degenerate direction, unique applications can be realized by designing more complex holograms. For one of the important applications, a large spectral operation bandwidth spectrometer is demonstrated by using spatially-multiplexed CBVHs [5]. While not shown here, the spatially-multiplexed CBVHs are recorded in adjacent 1-mm wide slices of the recording material in the y-direction (with no overlap between the holograms) by using a 1-mm-wide slit, which can be shifted to record different holograms. Each CBVH is recorded by using a cylindrical beam and different angles of the plane wave for different holograms. For the first demonstration, 2-spatial-angular multiplexed CBVHs are recorded in a 400-μm-thick Aprilis photopolymer. The focal length of the recording cylindrical lens is 2.5 cm. The recording angles between the cylindrical beam and the plane wave for these two holograms are 40° and 35 °, respectively. To avoid any cross-talk in output patterns, a 1-mm-wide buffer layer is used in the y-direction between these two holograms.

The total diffracted beam of the spatially multiplexed CBVHs is a two-dimensional pattern, and the diffracted beam corresponding to each multiplexed hologram has the same spatial frequency in the y-direction. To obtain the Fourier transformation only in the x-direction and avoid the pattern overlapping in the y-direction on the Fourier plane, the design of the reading system of the spatially multiplexed CBVHs is different from that of a single CBVH. Thus, one more cylindrical lens is added in the reading system shown in Figure 3(b). The first cylindrical lens (with the focal length of 2.5 cm) does the imaging (i.e., demagnification) in the y-direction while the second cylindrical lens (with the focal length of 5 cm) does the Fourier transformation in the x-direction separately. Since the imaging lens is located in front of the Fourier transforming lens, the Fourier transformation can be perfectly performed in the x-direction (i.e., the spectral diversity direction) and the size of the two-dimensional output pattern is limited within the range of the CCD camera even under diffuse source illumination.

To evaluate the performance of this multiplexed CBVH, we scan the incident wavelength from 450 nm to 900 nm and the output patterns at different wavelengths are shown in Figure 5. Figures 5(a)-5(d) clearly show that the output pattern is wavelength sensitive and the resolution (i.e., the width of the output pattern) is similar over the entire 450 nm operation bandwidth. The two-dimensional spatial-spectral diversity of this spectrometer is clearly observed from Figure 5. Therefore, by using this multiplexed CBVH, the spectral bandwidth is significantly improved (compared to a single CBVH) without sacrificing the resolution. It is also suggested that the resolution-spectral bandwidth trade-off in conventional spectrometers can be solved in this holographic spectrometer. The spectral bandwidth can be further improved by recording more spatially multiplexed CBVHs or an optimal complex CBVH.

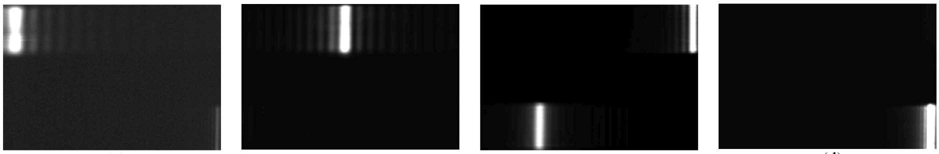


FIGURE 5. The output pattern for a 2-spatially-multiplexed CBVH read by a monochromatic light source at wavelength (a) 900 nm (b) 750 nm (c) 600 nm (d) 450 nm.

FABRY-PEROT-CBVH TANDEM SPECTROMETER

Although the spectral bandwidth is significantly increased by using multiplexed CBVH, the resolution of the spectrometer is still limited by the thickness of the holographic recording material and can not be dramatically improved. Therefore, another important application in CBVH-based spectrometer is to achieve ultra-high resolution by using the design of the freedom in the degenerate direction. Based on this idea, we here present for the first time to integrate the CBVH with a Fabry-Perot etalon which enables us to optimize and control both resolution and spectral bandwidth simultaneously.

Figure 6 shows the schematic of the proposed spectrometer, which is composed of a Fabry-Perot etalon cascaded with a single CBVH. The key advantage of this spectrometer is the combination of the high resolution (but small spectral bandwidth) in interferometers with the large spectral bandwidth (but low resolution) of the volume holographic spectrometers.

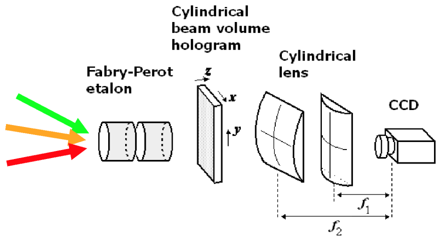


FIGURE 6. Schematic of the tandem Fabry-Perot etalon CBVH spectrometer.

The Fabry-Perot interferometer is composed of two dielectric mirrors with a fixed 50 µm air gap between them. When illuminated by a diffuse light, the output of the Fabry-Perot structure is a circularly symmetric spatial-spectral pattern with very high resolution as shown in Figure 7. However, there are two drawbacks attributed to the spectral response of the Fabry-Perot etalon. First, its spectral operating range is limited to its free spectral range (FSR) which is practically small (about 3 nm for the Fabry-Perot used in these experiments). Second, the circularly symmetric spatial pattern has only one-dimensional (1D) spatial-spectral diversity (i.e., along the radial direction in Figure 7). The scalar nature of the spectrum requires the separation of the wavelength components in only one direction in the spatial domain; however, the two-dimensional (2D) nature of the output of most of the optical detectors can potentially be used to improve the performance of the spectrometer, if the input spectral information is converted into a truly 2D spatial-spectral pattern in the output. For this purpose, the spectrum of the input beam should be mapped independently in the orthogonal directions at the output plane, which is not the case for the simple Fabry-Perot spectrometer shown in Figure 7. In summary, the Fabry-Perot etalon is a high-resolution small-bandwidth spectrometer with a 1D spatial-spectral response.

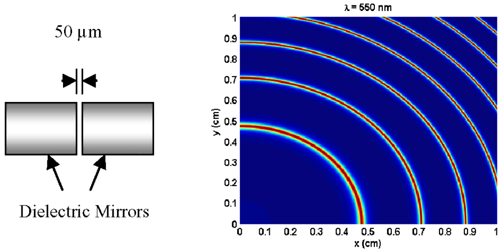
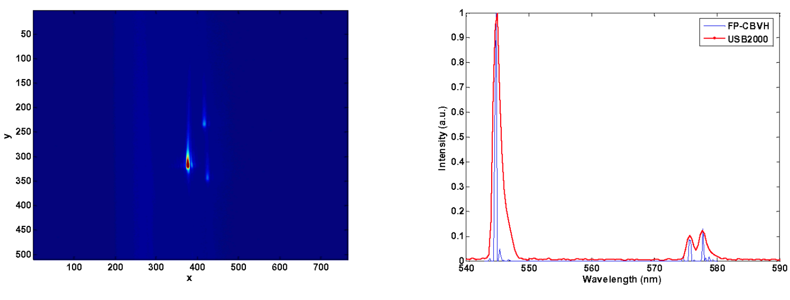


FIGURE 7. Schematic of the Fabry-Perot etalon composed of two dielectric mirrors with a fixed 50 μm air gap between them. The spectral information of the input diffuse beam is mapped into a 2D circularly symmetric spatial pattern on the CCD.

As shown in Figure 4, the CBVH typically separates the wavelength channel in the dispersive direction with lower resolution but large spectral bandwidth. In contrast, as shown in Figure 7, the Fabry-Perot separates the wavelength channel in any radius direction with ultra-high resolution but small spectral bandwidth. Therefore, by combining these two elements, the full spectral operation bandwidth will be coarsely divided into stripes in the dispersive direction by the CBVH, and then finely chopped into spots in the degenerate direction by the Fabry-Perot. As a result, for a tandem spectrometer composed of a CBVH and a Fabry-Perot, the resolution is primarily defined by the Fabry-Perot etalon while the operation bandwidth is primarily defined by the volume holographic spectrometer.



(a) (b)

FIGURE 8. (a) The image formed on the CCD corresponding to an unknown source spectrum. Each spot is a signature of a different wavelength in the source spectrum. (b) The sharper curve is the unknown spectrum measured by the tandem Fabry-Perot etalon CBVH spectrometer and the broader curve is the one measured by USB2000 spectrometer.

Figure 8(a) shows the CCD image of the output light of this tandem spectrometer when illuminated by a diffuse source spectrum including three distinct wavelengths. In this figure, the spectrum of the source is mapped into a 2D spatial-spectral pattern. As far as the resolution of the CBVH is better than the FSR of the Fabry-Perot etalon, there is only a one to one correspondence between spectral and spatial responses. Therefore, the spectrum of the unknown light source can be retrieved after the inverse processing on the output pattern. Figure 8(b) shows the spectrum of the diffuse light source (a Hg-Ar lamp with a diffuser) estimated by the tandem spectrometer (broader curve) compared to that of measured by commercial USB2000 spectrometer (sharper curve). Obviously, the proposed spectrometer estimates the unknown spectrum very accurately with much higher resolution than USB2000 spectrometer does. Besides, by comparing Figure 2(b) to Figure 8(b), one order magnitude of improvement in resolution is obtained by combining the Fabry-Perot interferometer and the volume holographic spectrometer. Currently, a tandem spectrometer with 0.2 nm resolution has been experimentally demonstrated over a large spectral bandwidth, and higher resolution is achievable by using a Fabry-Perot with shorter FSR.

CONCLUSION

In conclusion, we demonstrated for the first time a volume holographic spectrometer based on Fourier-transform technique using a SBVH. We showed that the ambiguity between incident angle and incident wavelength in a holographic spectrometer can be eliminated by taking the Fourier-transform of the diffracted beam. The resulting spectrometer works optimally under diffuse light illumination which is useful for diffuse source spectroscopy, especially in biological and environmental sensing applications. Since all required elements are integrated into a volume hologram, the volume holographic spectrometer is more compact, light weight, low-cost, and insensitive to input alignment compared to conventional spectrometers. Furthermore, we demonstrated a new design of the holographic spectrometer using CBVHs. Based on its characteristics of independent control in dispersive direction and degenerate direction, several unique applications are realized. We showed a large spectral bandwidth spectrometer using spatially-multiplexed CBVH, and an ultra-high resolution tandem spectrometer using the combination of a CBVH and a Fabry-Perot. We also showed that the resolution-spectral bandwidth trade-off in conventional spectrometers is solved by using the CBVH-based spectrometer. Finally, with considerable design flexibility of the volume hologram, any complex hologram with desired properties can be recorded for special purpose spectrometer without adding complexity to the spectroscopy system.

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