

Very-high-resolution tandem Fabry–Perot etalon cylindrical beam volume hologram spectrometer for diffuse source spectroscopy

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We demonstrate a compact and slitless spectrometer with high resolution formed by cascading a Fabry–Perot etalon (FPE) and a cylindrical beam volume hologram (CBVH). The most significant advantage of this combined spectrometer is that we can independently encode spectral information of a diffuse beam in a 2D plane. Also, we show that in this slitless configuration we can simultaneously benefit from the advantages of both elements: the high resolution of the FPE and the large spectral range of the CBVH. Here, we report on the experimental demonstration of a spectrometer with better than 0.2 nm resolution. © 2007 Optical Society of America

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Recent increasing demand for high-performance handheld sensors for biological and environmental sensing has inspired a lot of research for the development of low-cost spectrometers with high resolution and large operation bandwidth. The use of conventional spectrometers, especially for diffuse source spectroscopy [1] (which is the case of interest in many biological and environmental sensing applications) has a few major drawbacks. First, it requires a collimation subsystem (typically a slit and a lens). This adds to the bulkiness and also requires good alignment of different elements in the system [2]. Second, to improve the resolution and at the same time to increase the bandwidth of operation, one must enlarge the size of the detector array along the dispersion axis, which makes the overall system larger and more expensive [3]. This is caused by the 1D nature of the spatial–spectral coding in these spectrometers and is referred to as the trade-off between the resolution and the operation bandwidth throughout this paper.

The basic property of a spectrometer is to map different wavelength channels of the input beam into different spatial patterns in the output plane using an interferometric and/or a dispersive element. The simplest form of this mapping (which is usually done in conventional spectrometers) is to map each wavelength channel to a distinct spatial location (for example, along a line) in the output plane. The intensity distribution of the output is then detected by a detector array or a charged-coupled device (CCD). By calibration of the spectrometer and inversion of the detected data, we can estimate the spectrum of an unknown input source [4]. For spectrometers with 1D spatial–spectral mapping, spectral information is encoded in only one spatial dimension and the measurement capabilities of the other dimension are not utilized.

We have recently reported a new class of volume holographic spectrometers [2] that do not require any collimation optics. These spectrometers rely on the unique Bragg selectivity and diffractive properties of a spherical beam volume hologram (SBVH) [2,5] or a cylindrical beam volume hologram (CBVH) [6] to measure the spectrum of an unknown source. While the resulting spectrometers are very compact, alignment insensitive, inexpensive, and flexible for design, they still work based on the 1D spatial mapping of the spectral information. Among different holographic spectrometers, the ones using CBVH have shown better flexibility for designing new classes of spectrometers as they do not affect the input light in one direction and perform the spatial–spectral mapping in the other direction [6].

In this Letter, we report for the first time, to the best of our knowledge, the design of a new class of slitless spectrometers with actual 2D spatial–spectral mapping formed by cascading a CBVH with a Fabry–Perot etalon (FPE). We show that by using this two combination a true 2D spatial–spectral mapping is achieved, which provides high resolution over a large operating bandwidth.

The schematic of the tandem FPE-CBVH spectrometer that we investigate in this Letter is shown in Fig. 1(a). The FPE is composed of two dielectric mirrors with the fixed air gap (which is 50 μm wide) between them. The reflectivity of each mirror at the wavelength range used in this paper ($530 \text{ nm} < \lambda < 600 \text{ nm}$) is close to 96%. The CBVH is recorded using a plane wave and a cylindrical beam obtained by focusing a separate plane wave using a cylindrical lens in the arrangement shown in Fig. 1(b) with $d_1 = 2.5 \text{ cm}$ and $d_2 = 2.7 \text{ cm}$. The angle of incident of the plane wave in the air is 36° and the cylindrical beam propagates normal to the hologram. The recording

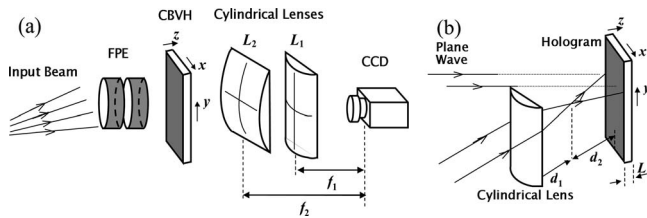


Fig. 1. (a) Schematic of the tandem FPE-CBVH spectrometer. (b) Recording geometry for a cylindrical beam volume hologram.

material is a 2 mm thick $\text{LiNbO}_3:\text{Fe}:\text{Mn}$ crystal and the recording wavelength is $\lambda=532$ nm. During the recording the crystal is sensitized using a beam at $\lambda=404$ nm from a diode laser. The CCD is placed in the simultaneous focal planes of the two cylindrical lenses L_1 (with focal length $f_1=2.5$ cm) and L_2 (with focal length $f_2=5.1$ cm) as seen in Fig. 1(a). The lenses L_1 and L_2 perform the spatial Fourier transformation on the output beam of the CBVH in the x and y directions, respectively.

For a better understanding of the operation of this spectrometer, we first study the role of each major component (i.e., FPE and CBVH). Figure 2(a) shows the CCD pattern calculated using the transfer matrix method for the FPE spectrometer composed of a FPE with the parameters as described earlier and a spherical lens with the focal length of $f=2.5$ cm, where the CCD is in the focal plane of the lens. The reading is performed by a monochromatic diffuse light at $\lambda=550$ nm. It is clear that the FPE maps the diffuse light at $\lambda=550$ nm into a series of concentric circles in the output plane. When λ is changed, the locations of these circles also change. This effect is shown in Fig. 2(b), which depicts the CCD output along a radial direction (in this case the x direction) in Fig. 2(a) at different wavelengths. It is clear from Fig. 2(b) that the FPE is a high-resolution spectrometer as excellent separation of wavelength channels in the output plane is obtained for signals with only 1 nm wavelength difference. The main drawback of this spectrometer is its very limited operation bandwidth. This bandwidth is usually equal to the free spectral range (FSR) of the FPE, which in our case is only 3 nm. This problem is evident from Fig. 2(b) as the outputs at $\lambda=550$ and 553 nm completely overlap and thus cannot be distinguished. It is also impor-

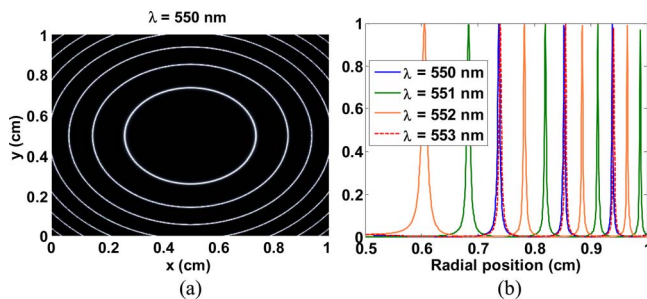


Fig. 2. (Color online) (a) Circularly symmetric fringes formed at the Fourier plane of the spherical lens on the CCD as a result of diffuse light illumination of the FPE spectrometer. (b) Periodic spectral transmission response of an FPE with FSR=3 nm along the radial direction.

tant to note that although the output spatial-spectral pattern of the FPE spectrometer looks 2D [see Fig. 2(a)], the degeneracy in the azimuth direction results in a 1D mapping (along the radial direction). Thus, similar issues for spectrometers with 1D spatial-spectral mapping exist here as well.

The performance of the spectrometer based on only a CBVH can be found similar to what is outlined in [6]. The output pattern on the CCD corresponding to each wavelength is a bright stripe in the y direction [as shown in Fig. 3(a)], where its width depends principally on the thickness of the CBVH. The location of this stripe changes in the x direction as λ changes [as shown in Fig. 3(b)]. It should be noted that the CBVH spectrometer works well for diffuse light [6]. However, in contrast to the FPE spectrometer, the CBVH spectrometer has lower resolution (close to 3 nm for our CBVH) but larger operation bandwidth (more than 100 nm for our CBVH). The spatial-spectral mapping obtained by the CBVH is also 1D.

The main rationale for forming the tandem spectrometer is to combine the unique features of these two dispersive elements (FPE and CBVH) and at the same time cover each one's deficiency by the other one's capability. Furthermore, since both elements work well under diffuse light illumination, a simple and compact slitless design can be implemented to combine the two elements. In this formation, we use the CBVH to separate the input spectrum into horizontal regions (i.e., stripes), each smaller or equal in bandwidth to the FSR of the FPE. Then, the FPE divides the operation range of each stripe into very small regions with very small wavelength differences (i.e., very high resolution) in the vertical direction. Figure 4(a) shows the spatial-spectral pattern of the tandem spectrometer on the CCD for three different wavelengths. As clearly seen in this figure, by changing the input wavelength the spatial pattern on the CCD moves in both x and y directions. Thus, the overall spectrometer performs a true 2D spatial-spectral mapping of the input spectrum. The key aspect of this design is to have the right relation between the FSR of the FPE and the resolution of the CBVH. It is noteworthy to mention that combination of interferometric and diffractive elements has been demonstrated previously [7]; however, the tandem

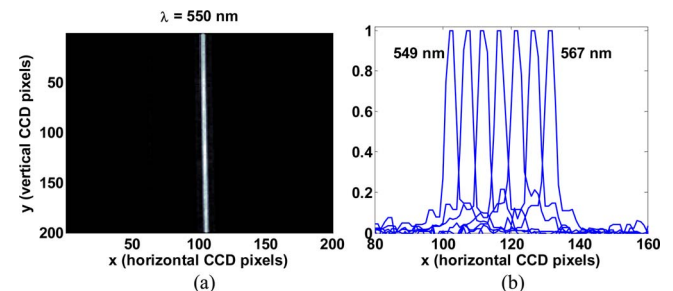


Fig. 3. (Color online) (a) Diffraction pattern of the CBVH formed on the CCD at the Fourier plane of the cylindrical lens with $f=2.5$ cm for diffuse light illumination at $\lambda=550$ nm. (b) Spatial-spectral responses of the CBVH along the x direction in (a) for different incident wavelengths from $\lambda=549$ to 567 nm with 3 nm steps.

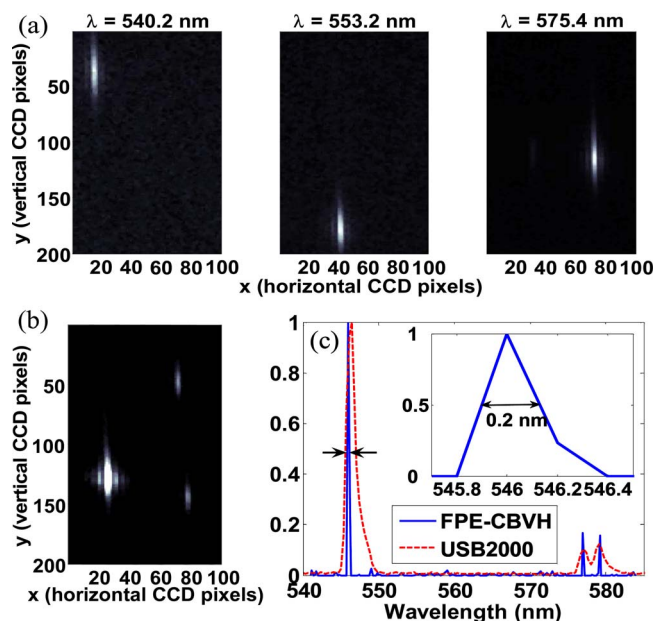


Fig. 4. (Color online) (a) Spatial-spectral pattern of the tandem spectrometer on the CCD for three different input wavelengths. (b) The image formed on the CCD in Fig. 1(a) corresponding to the diffuse light from an Hg-Ar lamp. (c) The spectrum of the Hg-Ar lamp measured by the tandem FPE-CBVH spectrometer and a USB2000 spectrometer.

spectrometer suitable for diffuse source spectroscopy is presented here for the first time.

Figure 4(b) shows the output pattern of the CCD when the input to the tandem spectrometer in Fig. 1(a) is diffuse light from a Hg-Ar lamp with three distinct sharp peaks at 546, 577, and 579 nm. The 2D spatial-spectral mapping is evident from Fig. 4(b). It is interesting to note that the 546 nm line is separated horizontally (i.e., by the CBVH) from the other two lines as its wavelength difference with those two is larger than the resolution of the CBVH. However, the two lines at 577 and 579 nm are separated vertically (by the FPE) in the output as they fall within the same stripe by the CBVH.

To use the tandem spectrometer [Fig. 1(a)] for spectrum estimation, we measure the output corresponding to each monochromatic input formed by passing white light through a monochromator with full width at half-maximum (FWHM) of 0.2 nm in the entire operation bandwidth. This training data defines the system transfer function and is used to estimate the spectrum of an unknown source through a least square optimization process [4].

Figure 4(c) shows the results of the spectrum estimation for the Hg-Ar lamp using our tandem spectrometer. We have also shown the spectrum measured using an Ocean Optics USB2000 spectrometer

for comparison. The results of our estimation agree very well with the lamp data sheet. It is clear from the inset figure that our spectrometer is capable of measuring the fine features of the input light with FWHM of 0.2 nm. Since the resolution of our monochromator is 0.2 nm, we can conclude from this data that the resolution of our tandem FPE-CBVH spectrometer is better than 0.2 nm. The measurement of the exact resolution requires a more sophisticated monochromator and is still underway.

A key feature of the proposed spectrometer is its 2D spatial-spectral mapping, which breaks the conventional trade-off between the resolution and the operation bandwidth. Our initial results demonstrate resolution of better than 0.2 nm with operation bandwidth of better than 100 nm using off-the-shelf optics and CCD. Improvement of the operation bandwidth is possible by using the recently proposed spatial multiplexing of a few CBVH along the y direction in Fig. 1(a) [6]. It is also worth mentioning that although we obtained high resolution over a considerable bandwidth using the proposed tandem spectrometer, the throughput issue is still present (each wavelength corresponds to a small output region). Nevertheless, it is possible to improve the throughput by using unique properties of volume holograms, especially their multiplexing [8] that allows more sophisticated 2D spatial-spectral mapping to obtain better throughput.

In conclusion, we demonstrated here a new class of spectrometers based on cascading a FPE with a CBVH. The resulting spectrometer uses a true 2D spatial-spectral mapping and, thus, does not suffer from the trade-off between resolution and operation bandwidth in contrast to conventional spectrometers. Using this spectrometer, it is possible to achieve high resolution (better than 0.2 nm) over a large operation bandwidth (a few hundred nanometers).

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