Coherence-based three-dimensional imaging spectrometry

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ABSTRACT

A brief review is presented for recent progress in a fully interferometric technique to obtain a set of spectral components of three-dimensional images for usual polychromatic objects. The review includes a principle of method and experimental demonstrations in which the measured object is regarded as spatially incoherent in each spectral component. We also suggest that some alternative ways to realize the same results having different characteristics based on modified synthetic aperture techniques.

Keywords: Low coherence holography, Coherence imaging, Three-dimensional imaging, Computational imaging, Fourier transforms, Spectroscopy, Imaging spectrometry, Synthetic aperture technique

1. INTRODUCTION

Possibility to obtain both three-dimensional (3-D) spatial information and spectral information of spatially incoherent, polychromatic objects by a fully passive interferometric technique has extensively studied for the past decade of years[1, 2]. For this purpose, we have proposed a method which uses a two-wave front folding interferometer to obtain a suitably arranged 3-D spatial coherence function. This spatial coherence function is computed from originally measured 5-D interference data-set [2]. Recently, we have reported experimental results to retrieve 3-D position and spectrum of a monochromatic point source [3], a pair of monochromatic point sources that have different frequencies [4] and a polychromatic object composed of planar light sources, located at different 3-D positions, having different continuous spectra and shapes [5].

We call this method the digital holographic 3-D imaging spectrometry. This paper presents a review of recent progress in this method. The review includes a description and principle of the method and typical experimental demonstrations. In addition, alternative ways to realize the same results having different characteristics based on modified synthetic aperture technique [6,7] are suggested.

2. PRINCIPLE

A basic idea of the method is a combination of the principles of Fourier transform spectrometry and incoherent holography. In the usual Fourier transform spectrometry, 1-D interferogram along the optical axis is measured and Fourier transformed. The result gives a set of spectral densities for incident light.

In our method, we compute 3-D volume interferogram from an originally measured 5-D interference data set. Taking Fourier transform along the optical axis gives a set of cross-spectral densities, each of which is equivalent to a complex hologram for spectral component of polychromatic object. Thus, 3-D images at different spectra may be obtained simultaneously.

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Fig.1 Principle of method.

3. DESCRIPTION OF METHOD

Figure 2 shows schematic of the two-wave front folding interferometer that is used in our method. It is one of interferometers to measure 5-D interferogram. A free propagating light wave, which is emitted from a polychromatic light source, placed on the x - y stage, is incident upon the interferometer. Each wave front, split by the beam splitter BS, is reversed left to right or up to down by the right-angle prism, P or P', and superposed again on the BS. A revealed interference pattern, called the elementally interference pattern, is detected by CCD and, then, recorded. This measurement process is repeated while moving x - y stage and z stage (PZT) stepwise. The 5-D interferogram measured with this interferometer records the 5-D spatial coherence function of the form: $\Gamma(-\xi + \hat{x}, \eta + \hat{y}, z_0; \xi + \hat{x}, -\eta + \hat{y}, z_0 + Z)$. Here, Z denotes the path difference along the optical axis that is introduced by translation of z stage, $(\hat{x}, \hat{y})$ indicates the position of the cross point of apexes of the right-angle prisms P and P' that are set orthogonally, (ξ, η) stands for the coordinate system taken over the observation plane. The relationship between the coordinate system (ξ, η) and (x, y) components of the original Cartesian coordinate system that is fixed on the x - y stage are written as $\xi = x - \hat{x}$ and $\eta = y - \hat{y}$. Since each elementally interference pattern is parametrized by $\hat{x}$, $\hat{y}$, and Z , one may imagine the whole 5-D interferogram as a set of 2-D elementally interference patterns, namely (ξ, η) , arranged in the 3-D $(\hat{x}, \hat{y}, Z)$ space.

Fig.2 Schematic of the experimental system

To retrieve a set of spectral components of the object images, we begin by applying the synthetic aperture technique to the 5-D interferogram to compute a volume interferogram that is suitable for our purpose. This procedure is performed by choosing one pixel value in each elementally interference pattern and, then, rearranging in a new 3-D space. For synthesis an interferogram which we call spherical-type volume interferogram, the selection rule is written as $\xi = \hat{x}, \eta = -\hat{y}$ and the rearrangement rule as $X = 2\hat{x}, Y = 2\hat{y}$. The resultant volume interferogram contains the 3-D spatial coherence function of the form $\Gamma(\mathbf{R}_0, \mathbf{R}_0 + \mathbf{p})$, with $\mathbf{R}_0 = (0, 0, z_0)$ indicating the position of the observation plane $z = z_0$, and $\mathbf{p} = (X, Y, Z)$ being 3-D shear. For paraxial regime, this spatial coherence function is related to the cross-spectral density W by the following relationship:

$$\Gamma(\mathbf{R}_0, \mathbf{R}_0 + \mathbf{p}) = \int_0^\infty W(\mathbf{R}_0, \mathbf{R}_0 + \mathbf{p}_\perp; \omega) e^{ikZ} d\omega, \quad (1)$$

where $\mathbf{p}_\perp = (X, Y)$, $\omega = ck$ is the angular frequency and c is the speed of light. Then, similar to the Fourier transform spectrometry, one may obtain a set of the cross-spectral densities $W(\mathbf{R}_0, \mathbf{R}_0 + \mathbf{p}_\perp; \omega)$ from the reduced volume interferogram by taking Fourier transform with respect to Z . Since each cross-spectral density is proportional to a spectral component of the complex amplitude $U(\mathbf{R}_0 + \mathbf{p}_\perp, \omega)$, W is regarded as an incoherent complex hologram of frequency ω . It is then possible to retrieve a spectral component of 3-D image of the light source by a usual back propagation technique.

4. EXPERIMENTAL DEMONSTRATION

We now demonstrate the performance of the digital holographic 3-D imaging spectrometry, in which the measured object is composed of many planar light sources of different shapes, each having different continuous spectrum, located at different depth. We used three different color LEDs as primary light sources.

Table 1. Specification of planar light sources.

Light source	Wavelength (nm)	Depth (mm)	Shape of planar light source
S1	630 (Red)	50	Rectangle
S2	504 (Green)	61	Left-side triangle
S3	458 (Blue)	70	Right-side triangle

These light sources are attached to the ends of acrylic rods. The cross sections on the other ends of the three rods are shaped as a rectangle and two different triangles. In this way, three planar light sources are created. These planar light sources are set up on the x - y stage of the two-wavefront folding interferometer. The x - y stage is moved along the x and y axes at $12.9\mu\text{m}$ in every step. The prism P, placed on the piezo translator (PZT), is also moved $0.08\mu\text{m}$ in every step as well. The total steps of experiment, i.e., the number of acquired elementary interference pattern is $64 \times 64 \times 64$. The specification of the planar light sources is summarized in Table 1.

Fig.3 Continuous spectral profile of each light source: S1, S2 and S3

Fig.4 Phase distributions of the cross-spectral density for S1 (left), S2 (middle) and S3 (right).

The object under measurement is composed of these planar light sources. The peak wavelengths of the light sources are 458 nm, 504 nm and 630 nm. The optical depths of these light sources from the observation plane are 70 mm, 61 mm and 51 mm, respectively. Figure 3 shows the continuous spectral profile of the object measured over the observation plane. This spectral profile is acquired from the volume interferogram obtained in our experiment. Three spectral peaks around 458 nm, 504 nm and 630 nm are clearly seen. The phase distributions of the cross-spectral density at the three spectral peaks are shown in Fig.4. Each phase distribution is essentially equivalent to that of incoherent hologram of the corresponding spectral component.

Fig.5 In-focus spectral images of the three planar light sources, located at different depths, for many spectral bands.

Finally, Fig. 5 partly shows a whole set of the retrieved in-focus images for many spectral bands. Variation of intensity across the images agree well with the retrieved spectral profile shown in Fig 2. We also find that the size of these images agree well with the actual size of the original light sources. As a result, a set of spectral components of 3-D images of three planar light sources with different shapes of cross section are successfully retrieved by our method.

5. CONCLUDING REMARKS

We have shown that both 3-D spatial information and spectral information of spatially incoherent polychromatic light sources with different continuous spectra, located at different positions, can be obtained by the digital holographic three-dimensional imaging spectrometry.

Our final remark is that it in fact exists a set of alternative ways to realize almost the same results shown above. An important fact is that some of them have their unique merits, i.e., improved imaging characteristics or novel benefit to enable heterodyne detection of the spatial coherence function. These new methods may be realized by modifying synthetic aperture processing so as to produce a hyperbolic-type volume interferogram [6] or a rotated-hyperbolic-type volume interferogram [7]. One may find some reports for them elsewhere in literature. More detailed reports will be planned to publish in future.

6. ACKNOWLEDGMENTS

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