Techniques of Noninvasive Optical Tomographic Imaging

Joseph Rosen*, David Abookasis and Mark Gokhler
Ben-Gurion University of the Negev
Department of Electrical and Computer Engineering
P. O. Box 653, Beer-Sheva 84105, Israel

ABSTRACT

Recently invented methods of optical tomographic imaging through scattering and absorbing media are presented. In one method, the three-dimensional structure of an object hidden between two biological tissues is recovered from many noisy speckle pictures obtained on the output of a multi-channeled optical imaging system. Objects are recovered from many speckled images observed by a digital camera through two stereoscopic microlens arrays. Each microlens in each array generates a speckle image of the object buried between the layers. In the computer each image is Fourier transformed jointly with an image of the speckled point-like source captured under the same conditions. A set of the squared magnitudes of the Fourier-transformed pictures is accumulated to form a single average picture. This final picture is again Fourier transformed, resulting in the three-dimensional reconstruction of the hidden object. In the other method, the effect of spatial longitudinal coherence is used for imaging through an absorbing layer with different thickness, or different index of refraction, along the layer. The technique is based on synthesis of multiple peak spatial degree of coherence. This degree of coherence enables us to scan simultaneously different sample points on different altitudes, and thus decreases the acquisition time. The same multi peak degree of coherence is also used for imaging through the absorbing layer. Our entire experiments are performed with a quasi-monochromatic light source. Therefore problems of dispersion and inhomogeneous absorption are avoided.

Keywords: Medical and biological imaging, Coherence imaging, Speckle, Low coherence interferometer, Optical coherence tomography

1. INTRODUCTION

Illuminating an object embedded in a scattering biological medium leads to a seemingly random speckle pattern. Being able to image objects such as bone or being able to spot tumors through tissue would allow noninvasive medical diagnostics. In recent years much effort has been devoted to research in the optical imaging of objects embedded in a scattering medium. This topic has many potential applications in medical diagnostics since it is safe, noninvasive, and relatively inexpensive compared with other often-used tomography techniques. Different optical imaging techniques have been proposed,[1] each of which has advantages and weaknesses. In this paper we survey several recently proposed schemes[2-5] for imaging through a scattering medium.

2. NONINVASIVE OPTICAL IMAGING BY SPECKLE ENSEMBLE

The Earth's atmosphere is well-investigated scattering medium. Stellar speckle interferometry, a method of imaging through the atmosphere, was invented more than 30 years ago by Labeyrie.[6] In this method, after many short-exposure photographs are collected the square magnitude of the Fourier transform of each image is computed and accumulated to a single average power spectrum. However, the square magnitude lacks phase information, and in the end one can obtain only the average autocorrelation of the object function rather than its true shape.

This scheme, inspired by stellar speckle interferometry, is termed noninvasive optical imaging by speckle ensemble (NOISE). It is based on a simple optical imaging system containing a microlens array that images a hidden object through different parts of a scattering medium. By superposing multiple images from many imaging channels, one can see general objects hidden behind scattering layers. We note that there is a space–time analogy between the temporal situation of Labeyrie's speckle interferometry and spatial NOISE. In the former, different speckled images are collected over time, with the atmospheric turbulence changing from one frame to another. On the other hand, in the case of NOISE the

ICO20: Optical Information Processing, edited by Yunlong Sheng, Songlin Zhuang, Yimo Zhang,
Proc. of SPIE Vol. 6027, 602708, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.667705

scattering medium is static. To collect different blurred images of the object through different scattering layers, the object should be observed from unrelated spatial parts of the same scattering medium. This goal is achieved by use of the microlens array, with each lens in the array imaging from the same object through a different part of the scattering layer. However, unlike in the case of astronomical observation, we illuminate the embedded object from outside the medium with coherent light. Moreover, in our experiment we process the speckled patterns in the image plane rather than in the Fourier plane. Therefore the output result is an image of the object itself and not its autocorrelation. In this last sense, our method is closer to another speckle interferometry technique termed the shift-and-add algorithm.[7]

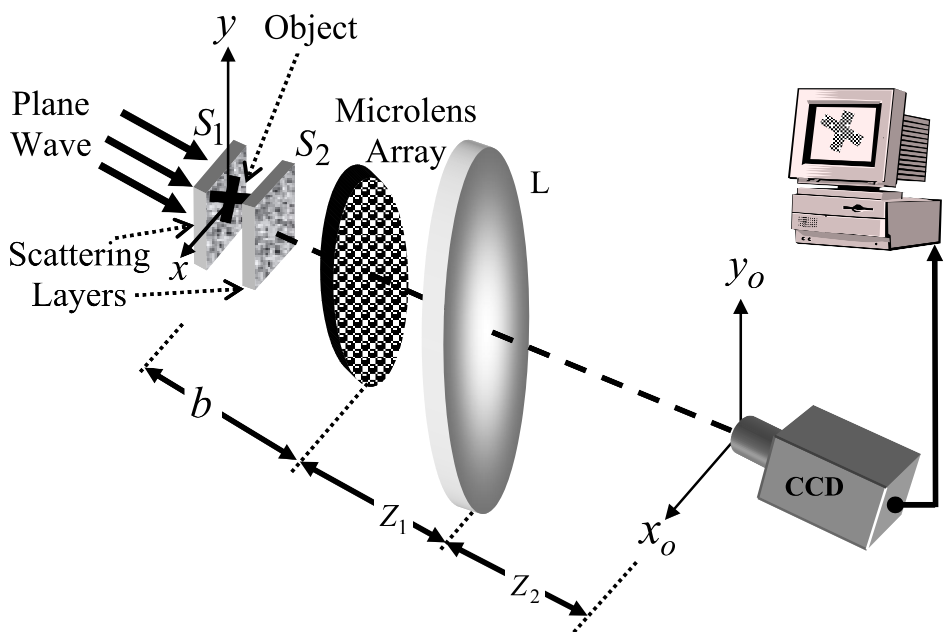


Figure 1: Setup of the NOISE system.

In our demonstration of imaging system, shown in Fig. 1, we placed chicken bone between two slabs of chicken breast. We then illuminated the rear slab, which was three millimeters thick, with the light of a 35mW HeNe laser at 632nm wavelength. Coherent illumination will yield a relatively narrow point spread function if no scattering medium is present. Therefore, without the scattering medium the object will be clearly seen with a reasonable resolution. In our experiment, the light traveled through the chicken breast, past the embedded bone, and through the next slab of tissue, which was eight millimeters thick. The highly randomized light propagated through a 11 by 12 hexagonal refractive element microlens array. Then the resulting array of images was collected using a second ordinary lens and the output was captured using a digital camera.

Examining data from any individual microlens, we found a random speckle pattern. This changed when we used an algorithm to center and combine the sub-images from multiple microlens elements. As this superposition took in more and more elements, what emerged was a clearer and clearer picture of the original bone, as shown in Fig. 2. In a 132 element array, different tests indicated that the most improvement happened between the first and tenth superposition and there was little gained by combining more than 70 images.

3. SYNTHESIS OF SPATIAL DEGREE OFCOHERENCE FOR IMAGING THROUGH ABSORBING MEDIA

The longitudinal spatial degree of coherence is determined by the radial intensity distribution of a quasi-monochromatic incoherent light source according to a particular interpretation of the van Cittert–Zernike theorem.[8] In the present study we suggest synthesizing the intensity distribution of the light source to generate a multipeak spatial degree of coherence.

A key element of the method is an electrically addressed spatial light modulator (SLM) that can spatially modulate the intensity distribution of the light. Using the SLM, one can get complete control of the amplitude and the phase of the degree of coherence in the system without moving any component in the profilometer.[9] Compared with the corresponding temporal method, using a quasi-monochromatic light source eliminates the effects of dispersion that might otherwise limit the use of optical coherence tomography systems. The multipeak degree of coherence can also be used for imaging through a scattering and absorbing medium of variable thickness.

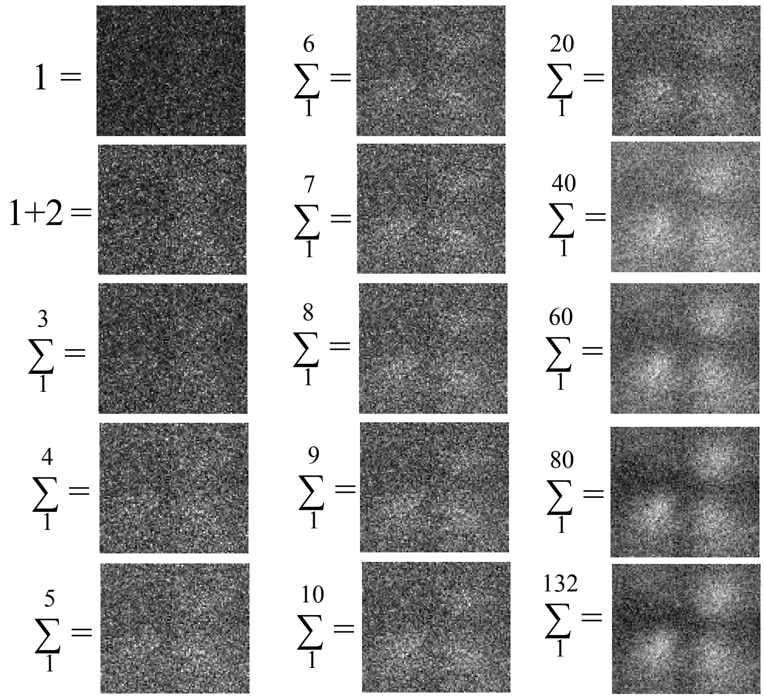


Figure 2: The process of recovering the hidden object by adding more and more pictures from the array of 132 sub-images.

In the present study we describe an experiment of imaging through an absorbing medium of variable thickness by use of a variable gating technique. By shaping the longitudinal spatial degrees of coherence to a multipeak function we can observe various parts of the object through the medium even when they are covered with a layer of different thicknesses or different indices of refraction. In addition, by sculpturing the degree of coherence, this method enables us to see through the medium without moving any part of the interferometer. We believe that applying our method with more-sensitive equipment will enable us to see through the scattering medium as well.

A schematic illustration of the profilometer is shown in Fig. 3. A laser beam illuminates the SLM and images the SLM pattern through lens L_0 onto a rotated diffuser, thus creating a quasi-monochromatic incoherent source with an arbitrary shape. Light from this source propagates through lens L_1 and is split into two beams by a beam splitter. One beam is reflected from the sample mirror, and the other is reflected from the reference mirror. The two reflected beams are combined and recorded by a CCD camera after they pass through lens L_2. Lens L_2 images the sample plane onto the CCD. To achieve a longitudinal degree of coherence with multiple peaks, we display on the SLM a compound Fresnel zone plate (FZP). The compound FZP comprises several angular segments, each of which has a different number of cycles. Using multiple peaks, one can use a longitudinal degree of coherence to observe a pattern hidden behind a dielectric layer with nonuniform thickness or with different indices of refraction. Each part of the layer shifts its degree of coherence differently, according to its thickness (or its index of refraction). If one adjusts distance Δz such that the coherence between the two arms is always on one of the coherence function peaks but a different peak for a different thickness (or for different indices of refraction), then the high fringe visibility is maintained along all the layer area. Thus the pattern behind the layer is revealed, although the optical path is different above different parts of the pattern. An example of such a situation is demonstrated below.

The next experiments demonstrate our method of imaging through absorbing media. Using other coherence orders rather than only the zero order can yield the same results without the shifting of any mirror. Moreover, by using a compound FZP, one can simultaneously reveal several letters. The letters are exposed because of coherence matching with higher-than-zero coherence orders, as demonstrated next. A compound FZP shown in Fig. 4(a) of four segments with two cycle values is used here as the incoherent source. The FZPs create first-order peaks on different distances from both sides of the zero order. Two Perspex slabs with thicknesses of 5 and 10 cm, and a 2-mm-thick NDF that transmits 25% of light intensity, were used in this experiment. Three configurations with three FZPs shown in Fig. 4(a) were tested. In each experiment FZPs with phases 0 and π were used for recording two holograms and subtraction techniques was used for creating more-efficient holograms. Reconstruction of the holograms was made by digital filtering of the information carried on the holographic grating. Positions of high-coherence-order peaks relative to the sample mirror in each experiment are shown schematically in Fig. 4(b). Finally, the images reconstructed from the holograms obtained in the three experiments are shown in Fig. 4(c). This experiment emphasizes the flexibility of using high coherence orders. By tuning only the cycle numbers of the FZP, one can observe different parts of the image, as demonstrated in the middle and bottom parts of Fig. 4. By using the compound FZP one can observe more parts of the image simultaneously, as demonstrated at the top of Fig. 4.

4. CONCLUSIONS

In conclusion, optical tomographic systems for imaging through scattering and absorbing media have been presented. In one method, the three-dimensional structure of an object hidden between two biological tissues has been recovered from many noisy speckle pictures obtained on the output of a multi-channeled optical imaging system. The advantages of the method are relative simplicity, low cost, fast operation and the need of low power CW laser illumination. Because of all these advantages NOISE might be applied to many imaging applications, especially in the medical diagnostic.

In the other system, a new method of imaging through absorbing media without any mechanical movement has been presented. This method is flexible in the sense that different parts of the sample can be viewed separately or simultaneously according to the chosen shape of the coherence function and the thickness profile (or the index of refraction) of the layer covering the sample. The method can potentially be used for imaging through turbid media. All these benefits come with the advantage of working with quasi-monochromatic light such that dispersion effects are inherently avoided.

ACKNOWLEDGMENTS: This research was supported by Israel Science Foundation grant 119/03.

REFERENCES

1. J. C. Hebden, S. R. Arridge and D. T. Delpy, "Optical imaging in medicine: I. Experimental techniques," *Phys. Med. Biol.* **42**, pp. 825-840, 1997.
2. J. Rosen and D. Abookasis, "Seeing through biological tissues using the fly eye principle," *Opt. Exp.* **11**, pp. 3605-3611, 2003.
3. J. Rosen and D. Abookasis, "Noninvasive optical Imaging by speckle ensemble," *Opt. Lett.* **29**, pp. 253-255, 2004.
4. D. Abookasis and J. Rosen, "NOISE 2 imaging system: seeing through scattering tissue with a reference point," *Opt. Lett.* **29**, pp. 956-958, 2004.
5. M. Gokhler and J. Rosen, "Synthesis of a multiple-peak spatial degree of coherence for imaging through absorbing media" To be published in *Appl. Opt.* (5/2005).
6. A. Labeyrie, "Attainment of diffraction-limited resolution in large telescopes by Fourier-analyzing speckle patterns in star images," *Astron. Astrophys.* **6**, pp. 85-87, 1970.
7. R. H. T. Bates and F. M. Cady, "Towards true imaging by wideband speckle interferometry," *Opt. Commun.* **32,** pp. 365-369, 1980.
8. J. Rosen and A. Yariv, "General theorem of spatial coherence application: to three-dimensional imaging," *J. Opt. Soc. Am. A* **13**, pp. 2091-2095, 1996.
9. M. Gokhler, Z. Duan, J. Rosen, and M. Takeda, "Spatial coherence radar applied for tilted surface profilometry" *Opt. Eng.* **42**, pp. 830-836, 2003.

*rosen@ee.bgu.ac.il; phone 972-8-6477150; fax 972-8-6472949;

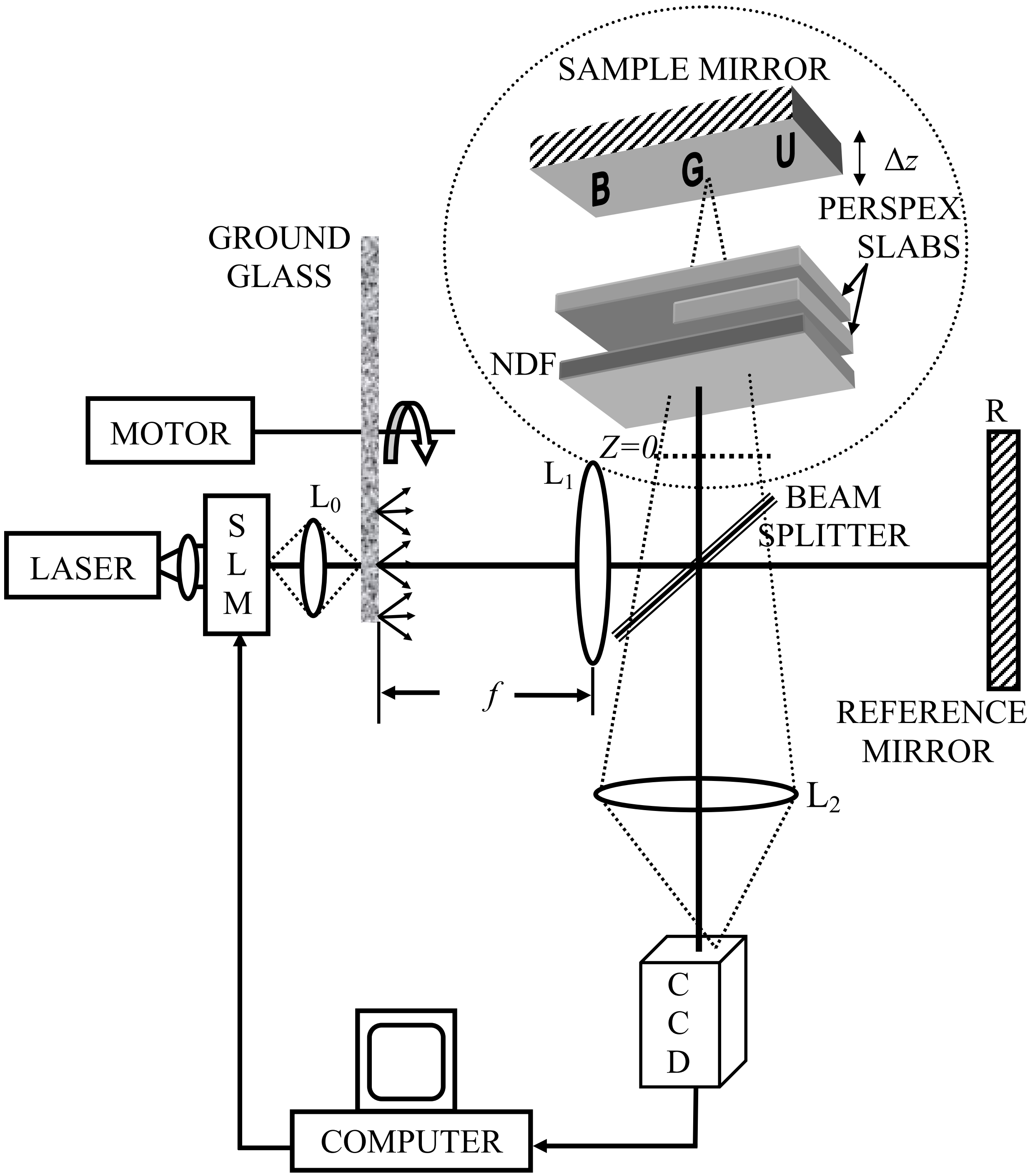
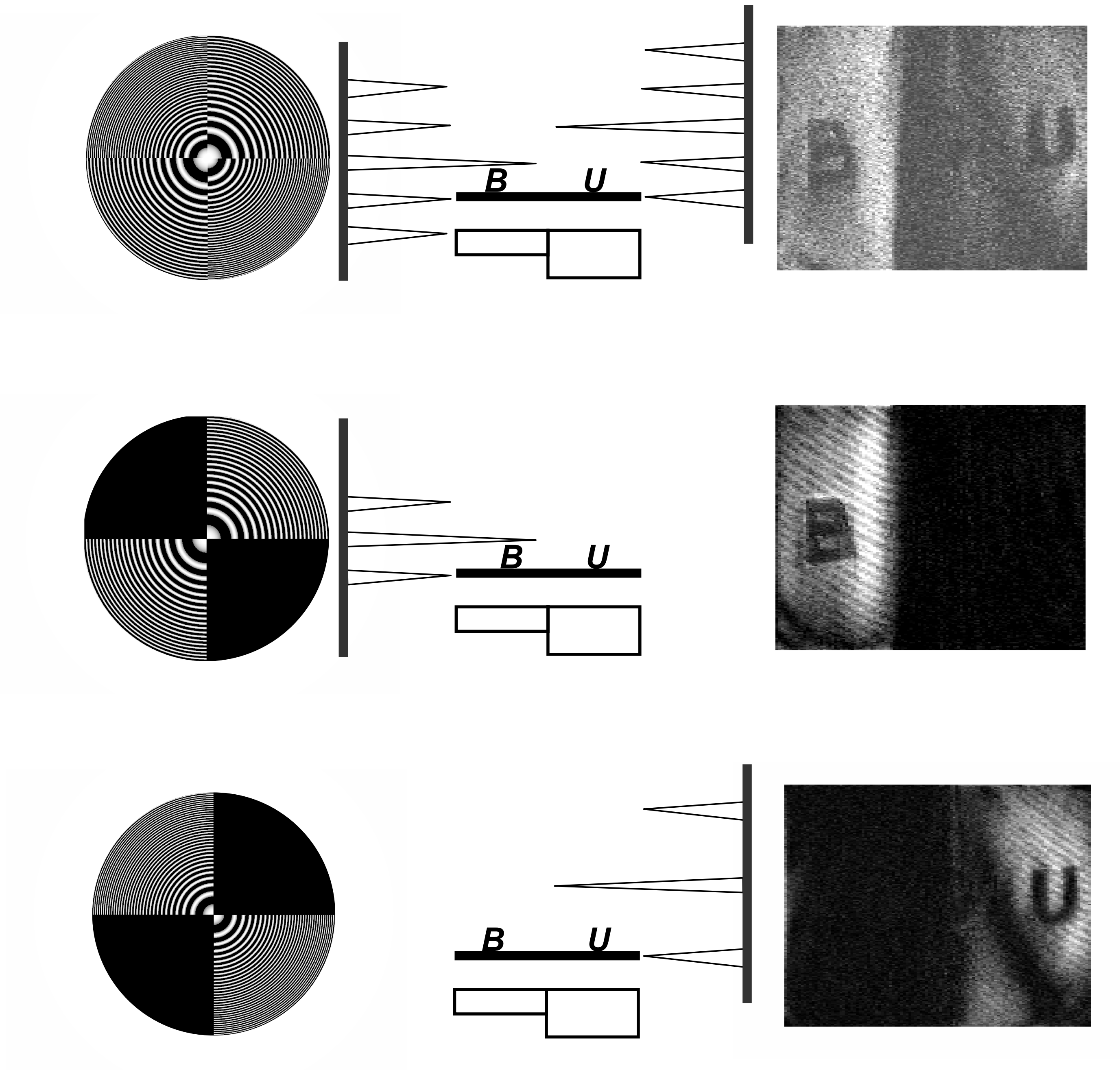


Figure 3: Schematic of the interferometric system used for imaging through the absorbing media by the optical spatial coherence effect.



(a) (b) (c)

Figure 4: (a) Set of FZP's with different cycles values for different angular segments. (b) Schematics of the complex degree of coherence in relation to the structure of the sample mirror covered by absorbing media. (c) Images reconstructed digitally from the holograms recorded by the CCD when the interferometer was illuminated by the FZPs shown in (a).