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Two-Dimensional Coherent Detection Imaging in Multiple Scattering Media Based on the Directional Resolution Capability of the Optical Heterodyne Method

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Abstract. This paper describes a new application of optical heterodyne detection using a laser beam for two-dimensional imaging of the internal structure of strongly scattering media in which the structure is completely obstructed from normal visual observation. The directional resolution capability for image formation due to the excellent antenna properties of the heterodyne technique is verified experimentally using a ground glass to cause strong scattering of the signal beam. Successful image detection of a test target placed in a highly scattering absorptive medium, with spatial resolution better than 400 μm in the case of our experiments, demonstrates that this Coherent Detection Imaging (CDI) method can overcome the diffuse nature of images in media such as those of biomedical interest and others to achieve scanning and tomographic imaging.

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The fundamental advantages and virtues of the optical heterodyne method are fairly well recognized and its use has been extended to fields such as optical fiber communications, laser radar, scientific and industrial measurements and so on. An optical heterodyne system is understood to be, in essence, both a receiver and an antenna [1, 2]. In this scheme, a coincidence between phase fronts of a signal beam and a local oscillator (reference) beam is required at the surface of the detector operated as an optical frequency mixer, whose size is much larger than the wavelength concerned. Thus, the antenna properties can provide not only high spatial resolution for detection and ranging of various objects and their image formation [3] but also excellent directionality.

This paper proposes and reports a new application of the optical heterodyne method for imaging within highly scattering absorptive media whose internal structure is completely hidden from normal visual observation or conventional direct detection by widely spread multiple scattering of light. It should be stressed that this heterodyne method offers a practical and feasible means for imaging in highly scattering absorptive media such as biological tissues, systems and substances, as well as various objects and environments obscured by smoke, fog, clouds or other materials. To the best of our knowledge, no explicit proposal or experimental investigations regarding application of the advantageous features of the optical heterodyne method to overcome the diffuse nature of image quality have been reported so far. From this standpoint, this Coherent Detection Imaging (CDI) method is currently being studied in our project for image detection and processing in highly scattering absorptive media, with the aim of establishing optical computed tomography (OCT) or laser sensing tomography (LST) for non-invasive and non-contact biomedical measurements [4–8].

The present paper describes the basic concept and reports experimental results of evaluations of the directional resolution capability and the first image detection of a test sample in highly scattering media, based on the antenna properties of the optical heterodyne technique [7].

Experiments and Discussion

Figure 1 shows schematically the experimental setup. The optical beam from a single-wavelength He–Ne laser at 632.8 nm with a few mW output power is divided into two different paths by a beam splitter. One passes through an acousto-optic modulator to give a frequency shift of 80 MHz and this signal beam is then collimated to the sample by a lens system. The second beam, serving as a local oscillator, passes through another acousto-optic modulator which introduces a frequency shift of 81 MHz.

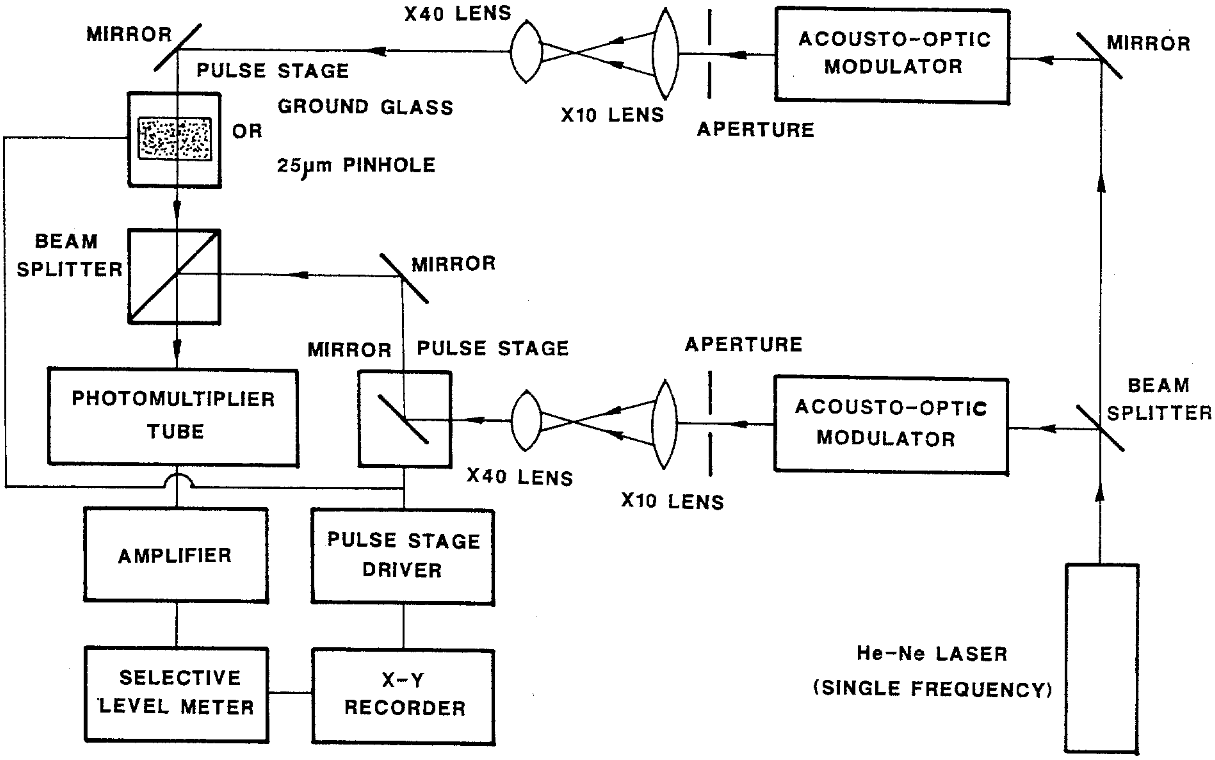

Fig. 1. Block diagram of the experimental arrangement for evaluation of the directional resolution capability of the optical heterodyne detection method in highly scattering media

The two wavefronts of these optical beams are then effectively superimposed by a beam splitter before an optical frequency mixer employing a photomultiplier tube. An IF output signal from the photomultiplier tube is amplified and filtered electronically with a selective level meter, and then recorded on an X–Y recorder as a function of the shifted position of the local oscillator beam with respect to the beam axis. To distort the wavefront of the signal beam, a ground glass is placed in the signal beam path. In this experimental setup, a dynamic range of about 100 dB with a minimum detectable optical input power of approximately 10^{-13} W was achieved using a local oscillator beam of 10 μW at the photomultiplier tube and a detection bandwidth of 10 kHz.

Figure 2 displays results of measurement using this optical heterodyne detection method, which were used to evaluate the spatial resolution in comparison with the conventional direct detection techniques. Figure 2a indicates the intensity distribution of the IF output without the ground glass, and is normalized to the peak IF output power, when both the signal beam and local oscillator beam powers are 10 μW at the photomultiplier tube. Figure 2b shows the intensity distribution of the IF output normalized to its peak power employing the signal laser beam power of 200 μW with the ground glass. This peak IF output power is measured to be −21.4 dB relative to that without the ground glass as explained in Fig. 2a. In the case of direct detection, only the signal beam with output power of 200 μW that is intensity-modulated by the acousto-optic modulator was employed and a pinhole of diameter 25 μm was installed in the back of the ground glass. Figure 2c shows the intensity distribution as a function of shift in pinhole position with respect to the beam axis measured by the direct detection method without the ground glass; it is normalized to the signal peak power of approximately 35 nW which was incident on the photomultiplier tube after passing through the pinhole. Figure 2d is the result employing the signal laser beam power of 200 μW with the ground glass; it is normalized to the maximum transmitted power of about 1.1 nW in this case.

In both the cases shown in Fig. 2a, b the FWHM was measured to be approximately 400 μm and is equal to the theoretical value in this heterodyning scheme. On the other hand, the FWHM for the intensity profile of Fig. 2c was about 400 μm, which is about the same as the value for the optical signal beam. However, no signal was detected by the direct detection technique when the ground glass had been placed in the beam, as seen in Fig. 2d. These results demonstrate clearly that the optical heterodyne technique achieves the desirable capability of distinguishing the original signal beam in the presence of strong scattering or migration inside the medium. In other words, the antenna properties can provide high spatial resolution for image detection in highly scattering materials and the potential for removing scattered light from the imaging along with an inherent capability for improving signal-to-noise ratio.

Consequently, we carried out an image detection experiment utilizing a setup similar to the arrangement shown in Fig. 1, except for the scanning and image display operations. The sample used for the imaging experiment was a NBS 1963A test target which consists of vertical and horizontal five bar patterns with 1.0 cycles per mm

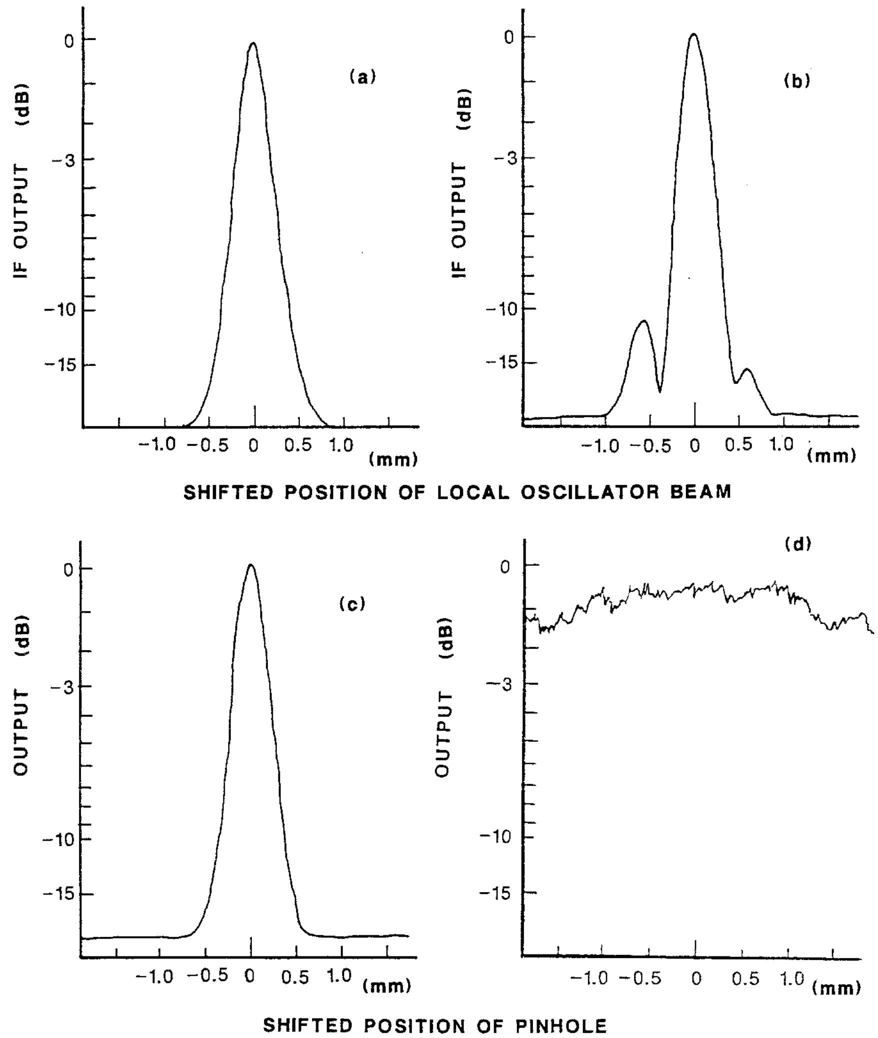

Fig. 2a–d. Relative intensity distribution of IF output with optical heterodyne detection as a function of the shifted position of the local oscillator beam with respect to the optical axis of the signal beam, compared with the result obtained by conventional direct detection. (**a**) and (**b**) show results without and with the ground glass in the signal beam path, respectively, while (**c**) and (**d**) show the relative intensity distribution of the signal beam measured by the direct detection technique without and with the ground glass in front of the pinhole, respectively

(Fig. 3a). Both the bar width and the bar spacing are 500 μm and the bar length is 12 mm. This test target was immersed in a glass cell filled with a curdled milk–gelatine mixture with 1 mm thickness both in front and behind the target. This milk–gelatine solution was prepared by melting 30 g gelatine in 200 cm^3 of a 25% milk–water solution at 70° C. After placing the test target in the glass cell, the cell was filled with the 25% milk–gelatine solution and then cooled in a refrigerator to 4° C. This sample transmitting the collimated laser beam was scanned two-dimensionally over an area of $20 \times 18\,mm^2$ using a two-axis pulse stage. In this imaging experiment, the signal laser beam power of 25 μW irradiated the sample cell without a curdled milk–gelatine mixture, while the signal beam power of 0.5 mW irradiated the sample cell with the mixture. We stored the image data measured at all scanning points (400 × 360 dots) in the memory of a personal computer via a GP-IB. All measured data were sorted into 16 levels spanning the signal maximum and minimum. The image was then displayed on the CRT of the personal computer with 16 tones.

The results of two-dimensional image detection are shown in Fig. 3. Figure 3a shows an original photograph of the test target, while (b) is a photograph of the target in the milk–gelatine curdling cell as it appears to the eye illuminated with white light, where absolutely nothing of the target is visible. In Fig. 3c, the image detected by the optical heterodyne method without the milk–gelatine curdling in the cell is shown for comparison. In this experiment, average transmitted laser power away from the patterns was estimated to be about 10^{-5} W at the photomultiplier tube. On contrast Fig. 3d shows the image detected by the same method with the curdling in the glass cell. The average transmitted laser power away from the patterns with the milk–gelatine curdling was estimated by the measurement to be approximately 3×10^{-10} W. We can see that successful image formation is achieved in Fig. 3d by the optical heterodyning technique by virtue of its ability to detect only the directly transmitted beam in spite of the presence of strong scattering in the medium. Because our heterodyne detection system has a spatial resolution of nearly 400 μm, as seen in Fig. 2, the vertical and horizontal five bar patterns are well resolved in the optical heterodyne image Fig. 3d.

The spatial resolution was further confirmed by image detection of another NBS 1963A test target made up of vertical and horizontal five bar patterns with 1.25 cycles per mm, as shown in Fig. 4. It is seen that since this target has bar widths and distances of 400 μm, the optical heterodyne image is barely resolved, as expected.

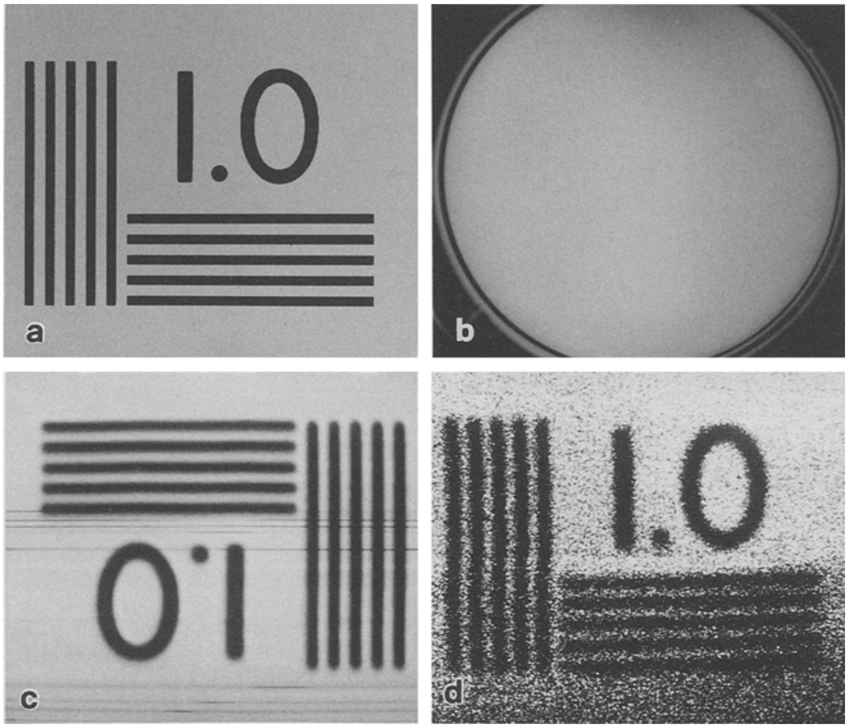

Fig. 3a–d. Comparison of detected images of a NBS 1963A test target composed of vertical and horizontal five bar patterns with 1.0 cycles per mm, obtained with the optical heterodyne scanning method and the conventional direct detection technique. (**a**) original photograph of the target, (**b**) photograph of the target in the milk–gelatine curdling cell, and (**c**) and (**d**) optical heterodyne images without and with the milk–gelatine curdling in the glass cell, respectively

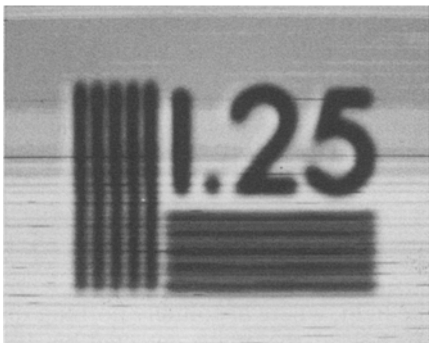

Fig. 4. Detected image of a NBS 1963A test target made up of vertical and horizontal five bar patterns with 1.25 cycles per mm by means of the optical heterodyne scanning method

Conclusion

Experimental verification of the directional resolution capability for image detection in highly scattering media was made employing the optical heterodyne method and compared with the conventional direct detection technique, which prevents complete imaging of the object due to light scattering. The formation of images of the test target by the optical heterodyne scanning scheme demonstrates successfully, and we believe for the first time, that this method can overcome the diffuse nature of images inside the medium accompanying strong scattering and even attenuation. This technology should be applicable not only in the transmission mode of image detection but also in reflection, employing either a cw laser or an optical pulse technique, even with ultrashort pulses, in so far as the heterodyne detection configuration is well aligned and operated. Further development of scanning and tomographic imaging applications of this Coherent Detection Imaging (CDI) method will now involve further simulations using various biomedical samples together with objects of differing sizes in a variety of highly scattering absorptive media.

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