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Chapter 1

IMAGERY OF DIFFUSING MEDIA BY HETERODYNE HOLOGRAPHY

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1. HETERODYNE HOLOGRAPHY

Demonstrated by Gabor [1] in the early 50's, the purpose of holography is to record on a 2D detector the phase and the amplitude of

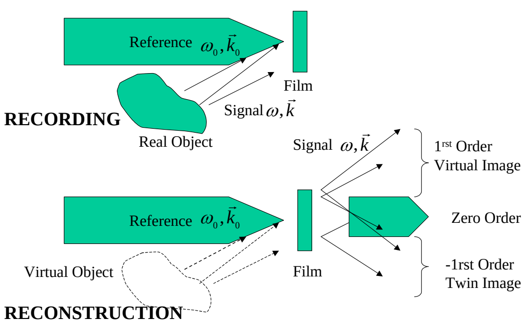

Figure 1.1 Thin film off-axis Holography: $\omega = \omega_0$, $k \neq k_0$

the light coming from an object under coherent illumination. Thin film holography (see Fig.1.1) does not provide a direct access to the recorded data. Numerical holography [2] replaces the holographic film by a 2D electronic detector allowing quantitative numerical analysis. This simple idea needed the recent development of computer and video technology to be experimentally demonstrated [3]. In both thin film and numerical holography the system records only one interference phase state, that allows to calculate only one quadrature of the complex field. This incomplete measurement yields to a virtual image ($order = 1$) of the object that is superposed [4] with a ghost twin image ($order = -1$) and with the remaining part of the reference field ($order = 0$). A solution to this problem (see Fig.1.1) is to tilt the reference beam in respect to the signal beam [5] in order to separate physically the three images and to select the wanted image. This off-axis method reduces the useful angular field of view and restricts measurement to the far field region where the 3 images are spatially separated.

In order to avoid these problems it is necessary to get more information by recording more than one phase state of the interference holographic pattern . A possible method is to record several holograms while shifting the phase of the reference beam with a PZT mirror [6]. We have developed an alternate technique that we call Heterodyne Holography [7] where we record on a CCD camera the interference of the signal field with a reference field, which is frequency shifted by δf. Each pixel of the CCD camera performs thus heterodyne detection of the signal field. To make the demodulation procedure easier the heterodyne frequency $\delta f = 2\pi(\omega_0 - \omega) = 6.25Hz$ is chosen equal to 1/4 of the $25Hz$ video frame rate. If the reference is a plane wave, the complex signal field E_s is proportional to $(I0 - I2) + i.(I3 - I4)$ where $I0$, $I1$, $I2$, $I3$ are four successive video images.

Our heterodyne holography experimental setup is shown in Fig. 1.2. Although we consider here a transmission setup, most of the following remain valid in a reflection configuration. The coherent source is an Helium Neon laser L. The two accousto-optic modulators AOM1 and AOM2, which are working at $80MHz$ and $80MHz{+}6.25Hz$ respectively, provide the frequency shift of the reference beam. The reference and signal beam are expanded by 2 beam expanders BE1 and BE2. The 2 beams are combined by the beam splitter BS and the interference pattern is recorded by the CCD camera. A frame grabber transfers the information to the computer PC. Since the CCD pixel spacing is finite (typically $10\mu m$), the CCD camera performs a spatial sampling of the field. The sampling theorem limits thus the field of view angle θ for valid measurements to:

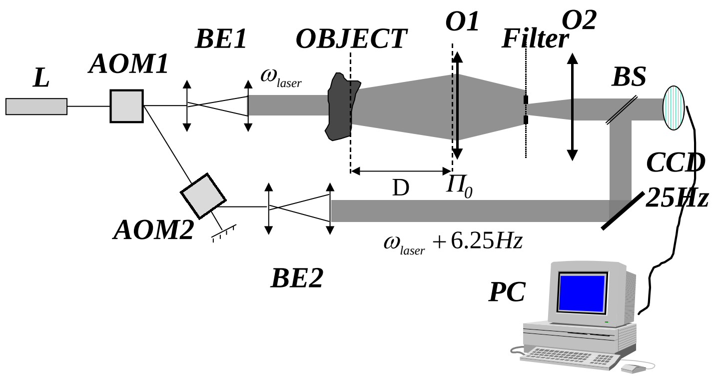

Figure 1.2 Heterodyne Holography Setup: L HeNe laser, AOM1 and AOM2 acousto-optic modulator, BE1 and BE2 beam expanders, O1 and O2 confocal objectives, BS beam splitter and CCD detector.

$$|\theta| \leq \theta_{\max} = \lambda/(2d_{pixel}) \tag{1.1}$$

where d_{pixel} is the CCD pixel spacing. One can notice that this sampling condition is common to both on and off-axis digital holography. In order to fulfill Eq.1.1 we have selected, in our experimental setup, the near axis photons by a spatial filter system ($O1$, $O2$, $Filter$ on Fig.1.2).

Detailed tests and discussions on our system for holography are given in [7]. We show that heterodyne holography performs within the spatial filter selected region, a complete measurement of the signal field without information loss. Since the technique is sensitive to the field amplitude (heterodyne detection), one photon detection is possible. The dynamic range is limited by the number $n \approx 3.10^5$ of electrons that can be stored on each CCD pixel, and corresponds for each pixel to about $n/\sqrt{n} \approx 5.10^2$, i.e to 9 bit data, or to 54 dB. Another important point is information. Our system grabs in one second 12.10^6 words with 16 bit, and extracts 6.25 complex field images with 5.10^5 pixels.

2. APPLICATION TO DIFFUSING MEDIA

In tissues, diffusion of the light is mainly related to the small (≈ 5 to 10%) change of the refractive index within each cell. As these changes occur over distances larger than the wavelength, scattering is highly directive [8] in the forward direction and the 2 lengths l_s and l'_s that govern scattering are very different . $l_s \simeq 50\ \mu m$ is the scattering length, i.e. the length beyond which the light phase is lost, and $l'_s \simeq 1\ mm$ is the

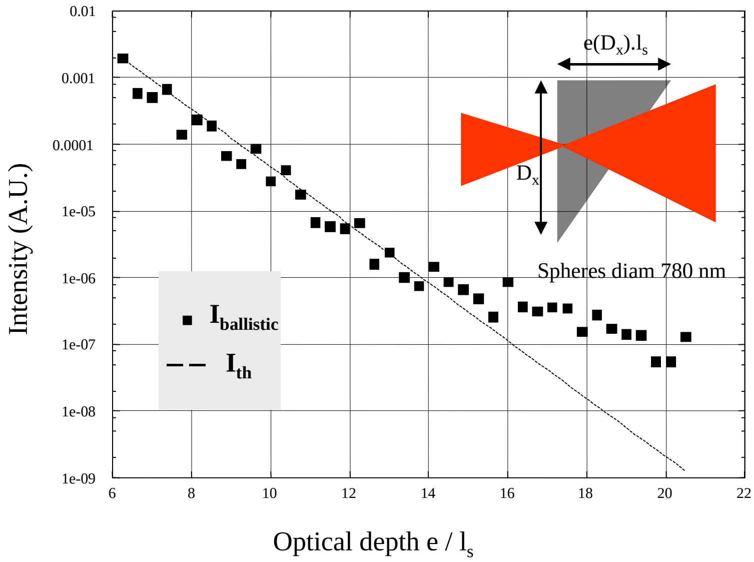

Figure 1.3 Ballistic photons in gel.

light transport mean free path, i.e. the length for loosing the propagation direction.

In this context, heterodyne detection has been used to select the photons transmitted through a diffusing media, which remains coherent. Using this technique Inaba [9] gets quite nice images when scanning a mono pixel detector (photodiode). Here we go further and perform heterodyne detection on 2D detectors by using our heterodyne holography technique. Contrarily to Inaba we record holograms where the pixel to pixel relative phase remains meaningful. Our idea is to acquire a maximum amount of information on a diffusing object, in order to extract later useful pertinent results.

To illustrate this, we have performed an heterodyne holography experiment on latex sphere solutions in gelinxxlatex sphere,in gel and liquidlatex sphere,in liquid, and we have selected in the transmitted signal field, the ballistic component that correspond to the photons, which have passed through the solution without interacting. In gel, the concentration of the 780 nm sphere solution is kept constant while the light is focused on the surface of the prism shaped solution cell. Translating the cell in the transverse direction changes the medium effective depth (see Fig. 1.3). In liquid the cell that contains the 480 nm sphere solution is rectangular. The cell is illuminated by plane light beam and the ef-

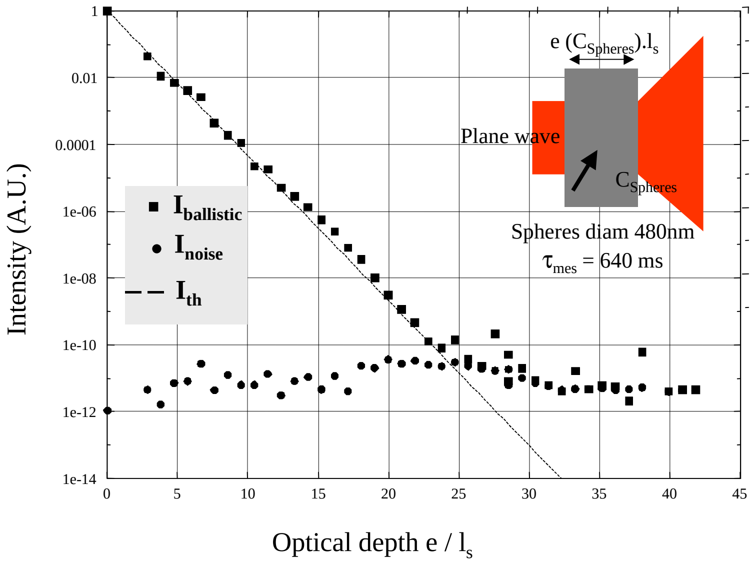

Figure 1.4 Ballistic photons in liquid.

fective depth of the medium is altered by changing the concentration of the solution (see Fig. 1.4).

The diffusing medium transmitted field is first measured. The weight of the ballistic photons components is then determined by calculating the correlation of the measured field, which is the sum of a ballistic and a diffused component, with the pure ballistic reference field, that corresponds to the field measured without scatters. In Fig.1.3 and 1.4 the relative (with respect to the incident field) weight of the ballistic component (black squares) is plotted in log scale (y-axis), as a function of the depth of the medium in scattering length unit l_s (x-axis). As expected, for both liquid and gel, the ballistic component decreases exponentially with a length parameter l_s (dotted line in Fig.1.3 and Fig.1.4). The noise floor is about 70 dB (10^{-7}) and 110 dB (10^{-11}) below the incident field for gel and liquid respectively. This correspond to an effective depth of about 16 l_s and 25 l_s respectively. These results can be compared favorably with [10], who perform the equivalent experiment with pinhole selection of the ballistic photons.

Our results can be understood quite easily. As the diffusing depth is large, most of the incident photons are back reflected, and the small transmitted component is spread over a large solid angle. A small part p of the incident photon ($p \approx 10^{-2}$ to 10^{-3}) passes thus through the Fig.1.2

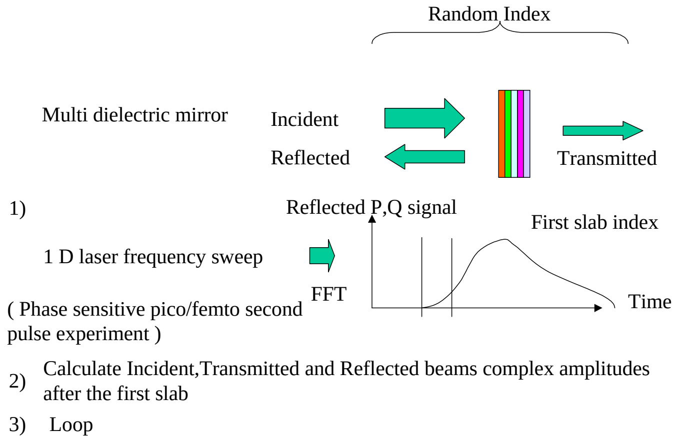

Figure 1.5 Solving the 1D diffusion inverse problem)

spatial filter (that corresponds to Eq.1.1 sampling condition), reaches the CCD, and is detected. By Fourier transform, we have calculated the decomposition of the detected signal over the k-modes. The diffused component is randomly spread with equal weight over all the k-modes, while the ballistic component remains in the k-mode that correspond to the incident field. As the number of k-modes N is simply equal to the number of pixels (5.10^5), the noise floor, which corresponds to the weight of the diffused component within the ballistic k-mode (or any k-mode), is expected to be simply $p/N \approx 2.10^{-7}$ to 2.10^{-8}. This result is in good agreement with the gel experiment.

In liquids, the experiment overcomes this limit, because the Brownian motion of the scatters shifts the frequency of the scattered light. As our heterodyne system has an extremely narrow detection bandwidth (that is equal to the inverse of the measurement time: 640 ms), most of the diffused photons are not detected. We have plotted (black circle on Fig.1.4), for liquid, the average value of the noise per mode. As expected, the ballistic noise floor corresponds to this one mode noise.

Heterodyne holography may also be used in a more ambitious way. The idea is to perform many measurements on a diffusing object in order to solve the inverse diffusion problem. Let's discuss this point on the simpler 1D "gedanken" experiment . Let's perform heterodyne holography on a 1D diffusing object as, for example, a random index flat multi-layer mirror (see Fig.1.5). The 2D detector becomes here a zero D mono pixel detector. To calculate the refractive index for the M slabs of the mirror, one needs M independent measurements (or more) and a mono detector measurement is not sufficient. It is thus required to add one dimension (1D) in the measurement process. Let's sweep, for example, the source wavelength while measuring, as a Network Analyzer does, the response to light (i.e attenuation and phase change) of the mirror DUT (Device Under Test). Making a frequency to time Fourier transform allows to determine the time response of the DUT to ultra short pulses. This sweeping technique is expected to be more sensitive (one photon sensitivity), more precise (phase sensitive) and must work with a higher dynamic range (since it detects an amplitude and not an intensity) than the short laser pulse technique [11]. Solving the 1D diffusion problem is then possible. Let's consider the reflection configuration. The first reflected signal allows to determine the refractive index of the first slab. One can thus calculate the second slab incident field at any time by accounting of the first slab reflection. Calculation of the successive slabs index can thus be done by iteration of this stripping process.

This 1D "gedanken" experiment illustrate the advantage of Heterodyne Holography in performing a complete measurement of the field that allows a further powerful data analysis. It also shows that sweeping the coherent source wavelength is an essential ingredient to go further. We must notice that in the gel experiment (Fig.1.3), the observed noise floor is related to speckle. Speckle comes from the multi scattered photons, which remain coherent in time (because our Helium Neon source have a long coherent length), and which are detected efficiently by our heterodyne system. OCT and short laser pulse experiments [11] use low time coherent source to filter off in time the multi scattered photons. We intend to include time filtering in Herodyne Holography to suppress most of the diffused photons . This can be done either by sweeping the source wavelength, as mentioned above, or by using a OCT low coherent source. With this trick, Heterodyne Holography, which is already a interesting tool, is expected to be very powerful in studying diffusing media.

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