Overall characterization of assembled optical storage devices with a heterodyne microscope: a qualitative comparison with a confocal microscope

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We present local profile measurements of inner mirrorlike and external front-end polycarbonate surfaces at the same spot of assembled optical storage devices, a CD and a DVD, performed with a heterodyne scanning interferometer that uses Gaussian beams. We show that the heterodyne interferometer can reproduce the profiles of both surfaces with accurate precision. We describe a procedure for calibrating the instrument based on the measurement of reflecting calibrated gratings. To show the advantages that the heterodyne interferometer represents as a valuable tool for the characterization of optical disks, we include a comparison of experimental results obtained with a confocal microscope under similar working conditions. © 2009 Optical Society of America

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1. Introduction

As the storage capacity of optical disks increases, it is important to improve the surface quality of both the inner mirrorlike surface, where the data are stored, as well as the external polycarbonate layer that covers the front end of these devices. These demanding requirements, in turn, make more precise methods necessary for surface profiling, especially if we take into consideration that the front surface of optical devices exhibits low reflectivity and, at the same time, high surface quality, making difficult the task of profiling this surface with far-field optical techniques. An overall measure of a finished assembled optical storage device should include the measurement or the profile of both surfaces: the external polycarbonate layer and the inner mirrorlike surface where the digital information is recorded inside a finished assembled disk. The results of measuring both profiles are relevant since the combination of both surfaces affects the performance of the finished optical devices.

To measure the external polycarbonate layer, one could consider different options that are commercially available. Nevertheless, if one also wishes to measure the inner mirrorlike surface with the same setup, a reasonable option would be to use a confocal microscope because of its inherent high depth of field discrimination [1–8]. However, a confocal microscope is unable to measure the profile of the front-end polycarbonate surface because this surface presents low reflectivity and, at the same time, low roughness of less than 4 nm [9,10]. These two characteristics combined would require a narrow pinhole detector in the confocal microscope, thus attaining a low intensity beam at the photodetector and producing a signal that would be immersed in the noise. One must, therefore, look for other options.

To overcome the limitation just described, we show that it is possible to measure both profiles with the same instrument: the inner mirrorlike surface as well as the front-end polycarbonate layer. This task can be performed easily since the only requirement is

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to adjust a screw to slightly change the position of a focusing lens. This instrument is a heterodyne scanning interferometer with two Gaussian beams and has been recently reported [11]. To better clarify the advantage of using the heterodyne interferometer in this application, we present comparisons of the measurements with those obtained with a confocal microscope working under similar conditions. Our results show that both instruments can be used to record the profile of an inner mirrorlike surface with reasonable accuracy. However, the heterodyne interferometer gives cleaner profiles and registers accurately the profile of the external polycarbonate surface, whereas the confocal system is unable to record any roughness of the polycarbonate layer. As indicated, this is due to the low reflectivity and low roughness of this layer. Thus, if one wishes to use a confocal microscope to characterize optical storage devices, the profile of the inner surface is not well defined, and it would be necessary to use a second measuring device such as an atomic force microscope (AFM) for complete characterization of the storage device.

In Section 2 we present a brief description of the heterodyne interferometer as well as its use and calibration. In Section 3 we present our experimental results and give our conclusions in Section 4.

2. Heterodyne and Confocal Microscopes with Gaussian Beams

Here we provide a brief description of the optical systems, the spatially filtered confocal microscope, and the heterodyne scanning interferometer, depicted in Figs. 1(a) and 1(b), respectively. For the interested reader, a detailed description of each optical system can also be found in [11,12]. In both systems the illuminating light is obtained from a He–Ne laser ($\lambda = 632.8$ nm), with a Gaussian intensity profile and a semiwidth $(1/e^2) \approx 0.6$ mm. The probe beam consists in focusing the laser at the surface under test by means of a 100X microscope objective with a focal length of approximately 2 mm. For easy placement of the components, the optical path length between the laser and the focusing lens is approximately 2 m. With these conditions, the narrowest semiwidth of the focusing spot, or optimal probe beam, is obtained at a distance of 1 μm from the back focal plane of the focusing lens, resulting in a semiwidth of approximately 0.65 μm; this semiwidth will be seen to be an important parameter as described below. For all practical proposes, both optical systems work with unclipped Gaussian beams, allowing us to use the Fresnel diffraction integral as described in Refs. [11,12].

A. Description of the Optical Scanning Systems

The confocal microscope makes use of a spatial filter, a pinhole placed in front of a photodiode [Fig. 1(a)]. The size of the pinhole represents one of the most critical parameters of the confocal microscope since it determines sensitivity, vertical and lateral resolutions, and depth of field. Because of the presence of the polycarbonate layer in front of the inner mirrorlike surface of the disk, to measure the profile of this inner surface it is necessary to select an appropriate pinhole size to attain the required depth of field discrimination. However, as indicated, the pinhole size selected will in turn affect the lateral resolution and the sensitivity of the system [12].

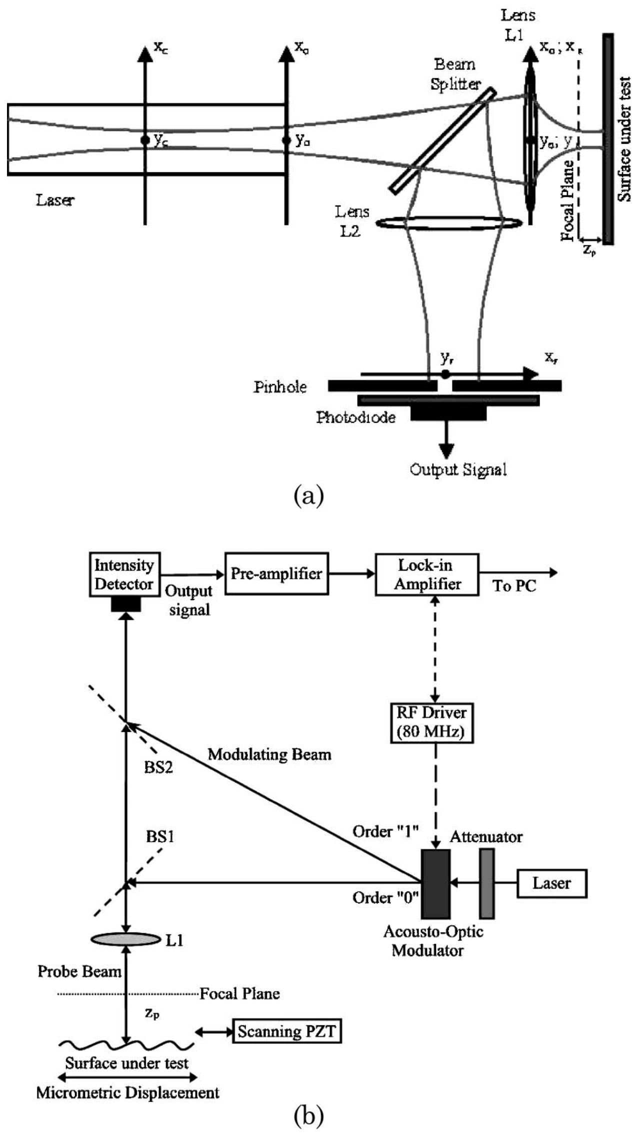

Fig. 1. (a) Spatially filtered confocal microscope and (b) heterodyne microscope. BS1 and BS2, 50:50 beam splitters; L1, focusing lens. The distance between the focal plane and the plane of the surface under test has been exaggerated.

In the heterodyne interferometer [Fig. 1(b)], the photodiode integrates the overall power of the two interfering beams as it uses a photodiode with a sensitive area larger than the size of the beams under detection. Thus, depth of field discrimination does not affect sensitivity. In this interferometer, one of the beams, the reference beam, also called the modulating beam, is obtained from first-order diffraction at the output of a Bragg cell [an acousto-optic medium of tellurium dioxide (TeO_2) excited at 80 MHz]. The second beam is obtained from the zero-order beam at the output of the Bragg cell and is directed by means of beam splitter BS1 to lens L1 and focused at a short distance z_p from the back focal plane of lens L1 at the surface under test. This beam is called the probe beam. Distance z_p needs to be adjusted accurately to obtain a linear response as a function of the height variations of the sample under measurement, as described in Subsection 2.B. After being reflected by the surface under test, the probe beam is modulated in its phase by the local surface irregularities and travels back, transmitted again through lens L1 and directed to the photodetector.

The modulating beam is guided toward the photodetector by beam splitter BS2. The temporal frequency of this beam corresponds to the sum of the frequencies of the light and the frequency of excitation of the acousto-optic cell. As depicted in Fig. 1(b), both beams are superimposed and coherently added at the plane of the photodetector. The electrical signal at the output of the photodiode consists of a temporal sinusoidal signal whose frequency is equal to the excitation signal of the acousto-optic cell. When the system is appropriately adjusted, the system exhibits a linear response, and the amplitude of the sinusoidal signal results proportional to the local vertical height under measure. This is analytically shown in Ref. [11].

B. Selection of Appropriate Working Conditions for Both Optical Systems

As indicated, in the analytical formulation given in Ref. [11] it is shown that the signal at the output of the photodiode for the heterodyne interferometer consists of a DC term P_{DC} plus a time-varying signal ($P_{AC}\cos(\omega_s t + \varphi)$), where $\omega_s = 2\pi$ times the excitation frequency and φ is a constant phase. The AC signal is recorded by means of a narrowband or lock-in amplifier, which measures the P_{AC} value. As shown in Ref. [11], amplitude P_{AC} results as a function of distance z_p. Figure 2 shows (solid curve) that power amplitude P_{AC} as a function of z_p. The following parameters were chosen: 100X focusing lens, 2 mm focal length, and an illuminating Gaussian beam with a semiwidth intensity $(1/e^2)$ of 0.6 mm. In Fig. 2 point $z_p = 0$ corresponds to the condition of placing the surface under test precisely at the back focal plane of lens L1. As is shown in Ref. [11], this is not the place of best focusing.

In Fig. 2 one can see that, to obtain a linear response, the system must be adjusted to work in a small region where the curve shows constant slope. Additionally, the slope should be as high as possible. It is also necessary to take into account the value of the depth of field that one wishes to attain. Thus, from Fig. 2, one can see that there are two possible working conditions: one in a zone located around the left of the back focal plane and a second zone at the right. The second zone corresponds to the situation of placing the sample a distance away from the back focal plane of the lens. We chose the second zone (around 1 μm away from the back focal plane), since this zone presents the higher slope, or equivalently, higher sensitivity. Additionally, selecting the zone with a higher slope results in a narrower probe beam and higher lateral resolution. This zone can be considered to be linear because very small vertical variations, less than 200 nm, are measured when we take experimental measurements. As indicated above, under these working conditions the probe beam will have a semiwidth $(1/e^2)$ of approximately 0.65 μm.

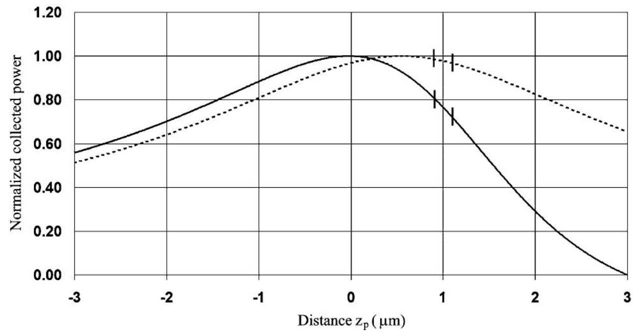

Fig. 2. Normalized collected power for both microscopes: solid curve, the heterodyne interferometer; dotted curve, the confocal microscope. The operating point is selected around the value $z_p = 1\,\mu$m, within the range marked by the short segments on the graph; this range corresponds to vertical amplitude variations of less than 200 nm. We used a 2 mm focusing lens, an illuminating Gaussian beam with an intensity semiwidth $(1/e^2)$ of 0.6 mm, and a 1 μm pinhole.

According to the above description, the heterodyne interferometer has characteristics that are similar to a confocal microscope in terms of depth of field and linear response, with the additional advantage that the heterodyne microscope shows a higher slope or higher sensitivity. Additionally, as the heterodyne system collects the overall beams under detection, the sensitivity is highly improved, making it suitable to profile the inner surface as well as the external low-reflecting surface of an optical storage device.

3. Calibration

For illustrative purposes, a simple calibration method was performed for both optical systems. The method consists of using two calibrated reflective gratings, commercially available, with pitches of 600 and 1200 lines/mm, with an average peak-to-peak amplitude of approximately 120 nm. The calibration of the gratings was checked with an AFM. The measurements of the gratings with both optical techniques are shown in Figs. 3(a), 3(b), 4(a), and 4(b). Only two gratings were used to calibrate the optical systems because linear response was assumed. As indicated, this was made only for illustrative purposes. If more precision is desired, more gratings and thus, more measurements can be taken. It can

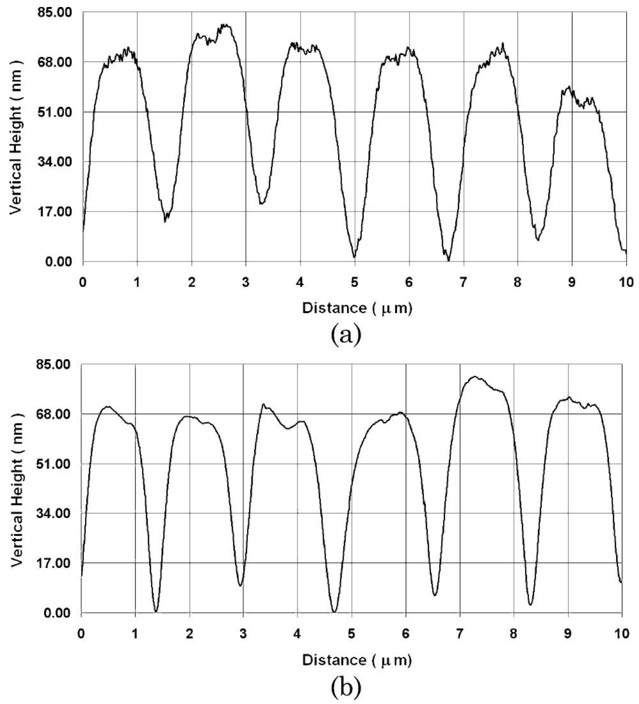

Fig. 3. Measurements of a 600 lines/nm reflective grating taken with (a) a spatially filtered confocal microscope and (b) a heterodyne microscope.

be noted that the measurements taken with the heterodyne microscope are better defined and cleaner because of its higher sensitivity and overall beam power collection.

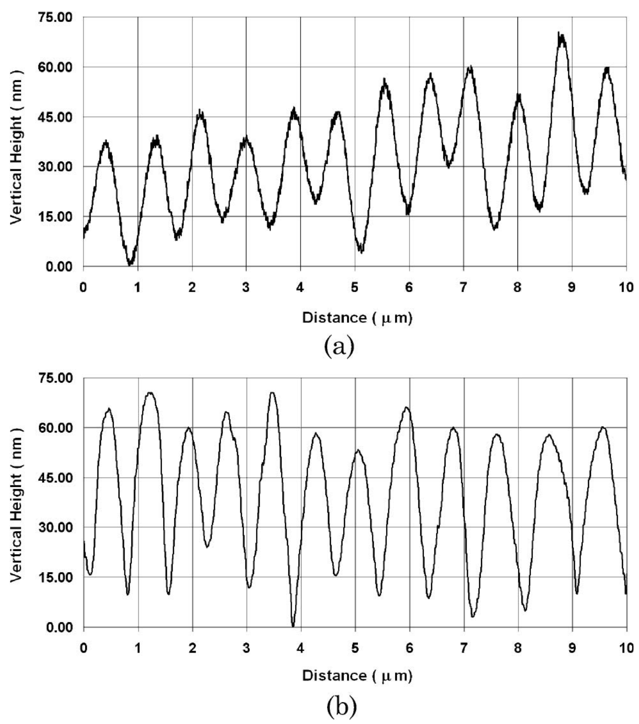

Fig. 4. Measurements of a 1200 lines/nm reflective grating taken with (a) a spatially filtered confocal microscope and (b) a heterodyne microscope.

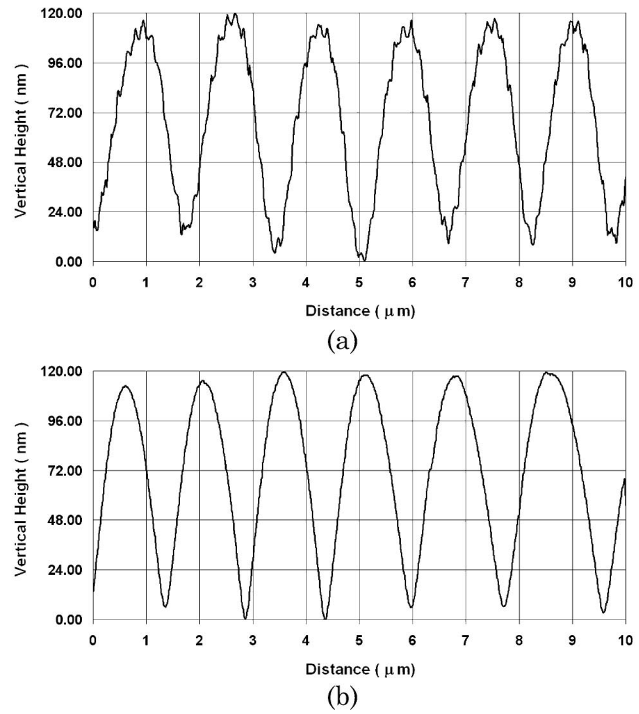

Fig. 5. CD optical data storage measurements taken with (a) a spatially filtered confocal microscope and (b) a heterodyne microscope.

A. Optical Storage Devices Measurements

Next, measurements of two commercially available optical data storage devices, a CD and a DVD, both without data marks, were taken across the polycarbonate layer with both optical systems. The

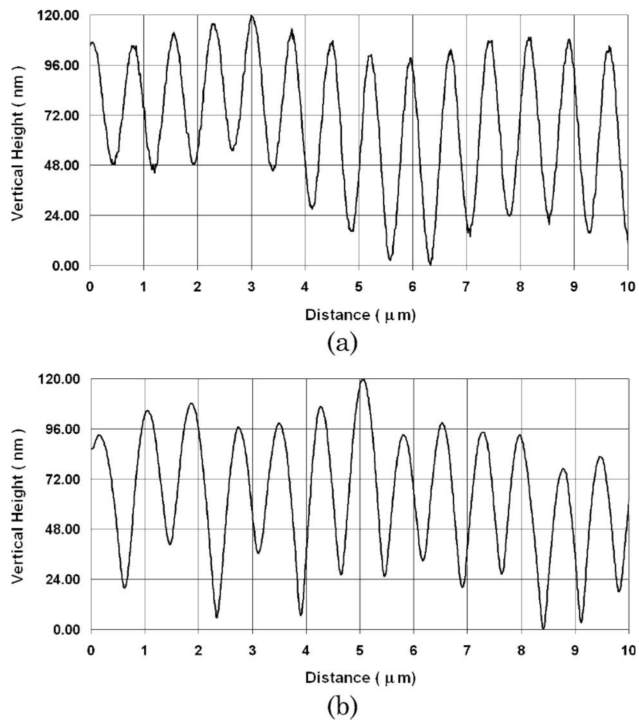

Fig. 6. DVD optical data storage measurements taken with (a) a spatially filtered confocal microscope and (b) a heterodyne microscope.

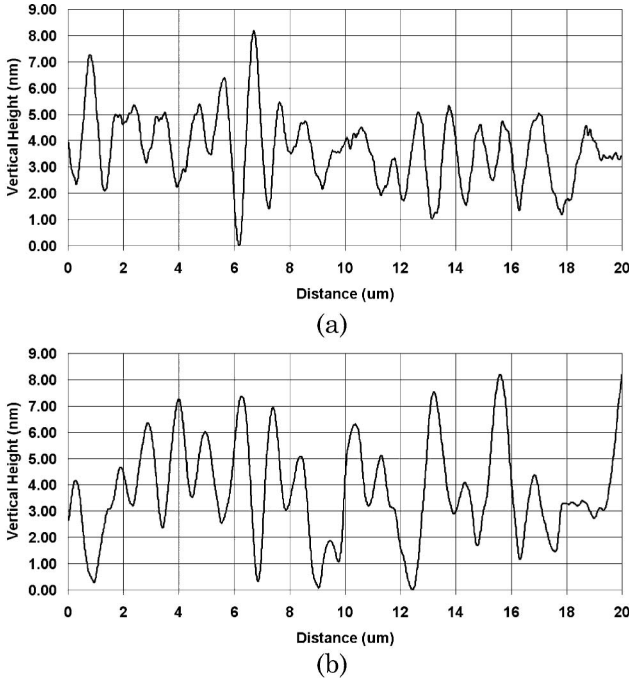

Fig. 7. Profiles of the (a) CD polycarbonate layer and (b) DVD polycarbonate layer; the standard deviation was approximately 0.11 nm.

resulting profiles are shown in Figs. 5(a), 5(b), 6(a), and 6(b). Again, it can be observed that the measurements taken with the heterodyne interferometer are better defined.

Finally, we show measurements of the profile of the external polycarbonate layer of the optical storage devices taken with the heterodyne interferometer. To perform these measurements it is only necessary to focus the probe beam at the front surface of the disk. As indicated above this requires only the adjustment of a screw, showing the functionality of the heterodyne system.

Figures 7(a) and 7(b) show the resulting profiles taken with the heterodyne microscope. As indicated, the spatially filtered confocal microscope was not able to show the profiles of these surfaces, as indicated, mainly because of the low reflectivity and low roughness of the polycarbonate surfaces. The maximum peak-to-peak amplitude for both storage devices can be seen to be approximately 8.5 nm, in good agreement with measurements previously reported [9,10]. To show the repeatability of the measurements we took ten measurements at the same spot of the polycarbonate layers for the CD and DVD. Only one measurement is shown in the graphs, as tracing more than one measurement in the same graph would only result in a thickened plot losing visibility of the resultant amplitude distribution. Instead, we indicate in the graph the standard deviation of the measurements. Additionally, the lateral resolution is limited by diffraction by the illuminating wavelength and was estimated in approximately 0.7 μm. For comparative purposes we measured an equivalent zone with an AFM and obtained similar results.

We must also point out that the well-known fact that a heterodyne system has better resolution and sensitivity than a baseband system [7,8] has been widely fulfilled with the additional feature of maintaining a high depth of field discrimination, thus proving to be a powerful, versatile, and functional tool for the characterization of both layers of interest in the same region of an assembled optical storage device.

4. Conclusions

We have shown that the scanning two-Gaussian beam heterodyne interferometer represents an excellent tool to accurately measure the profiles of both the inner mirrorlike reflecting surface as well as the external polycarbonate layer at the same region of commercially available finished optical storage devices. This represents an overall characterization of the optical storage devices, since the quality of both surfaces affects the performance of these devices. We have presented profile measurements of two finished optical disks, a CD and a DVD, taken with a heterodyne interferometer. We have shown experimentally that the heterodyne interferometer can be used to record the profiles of both accurately, the inner mirrorlike surface inside the optical storage devices, as well as the outer polycarbonate layer, due to the high depth of field discrimination and high sensitivity of the instrument. We presented comparisons of the measurements with a spatially filtered confocal microscope and showed experimentally that, as the confocal microscope has low sensitivity in comparison with the heterodyne interferometer, it was not able to measure the polycarbonate layers, mainly because of the combination of low reflectivity and low vertical amplitudes of this layer. Since the heterodyne microscope can be used to perform both measurements accurately in the same region, it provides the possibility to be used as a standard tool for quality control in the manufacture of optical storage devices.

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