White-light interference microscopy: effects of multiple reflections within a surface film

Maitreyee Roy[*], Ian Cooper[*], Peter Moore[*], Colin J. R. Sheppard[†] and Parameswaran Hariharan[*]

[*]*Physical Optics Laboratory, School of Physics A28, University of Sydney, NSW 2006, Australia.*
[†]*Division of Bioengineering and Department of Diagnostic Radiology, National University of Singapore, Singapore 117576*
mroy@physics.usyd.edu.au

Abstract: The effects of the presence of a transparent thin film on a test surface in white-light interferometric surface profiling are investigated. An expression is obtained for the output intensity variations in a Michelson interferometer which includes the effect of multiple reflections within the thin film. The number of reflections that need to be considered to obtain good convergence to the correct solution is discussed.

OCIS codes: (180.3170) Interference microscopy; (180.6900) Three-dimensional microscopy; (120.3180) Interferometry; (150.3040) Industrial inspection.

References and links

1. M. Davidson, K. Kaufman, I. Mazor and F. Cohen, "An application of interference microscopy to integrated circuit inspection and metrology," in Integrated Circuit, Metrology, Inspection and Process Control, K. M. Monahan, ed., Proc. SPIE **775**, 233-247 (1987).
2. M. Roy, C.J.R. Sheppard and P. Hariharan, "Low-coherence interference microscopy using a ferro-electric liquid crystal phase-shifter," Optics Express, **12**, 2512-2516 (2004), http://www.opticsexpress.org/abstract.cfm?URI=OPEX-12-11-2512.
3. P. Hariharan and M. Roy, "Interferometric surface profiling with white-light: effects of surface films," J. Mod. Opt., **43**, 1797-1800 (1996).
4. S-W. Kim and G.H. Kim, "Thickness profile measurement of transparent thin-film layers by white-light scanning interferometry," Appl. Opt. **38**, 5968-5973 (1999).
5. P. de Groot and X. C. de Lega, "Signal modeling for low-coherence height-scanning interferometric microscopy," Appl. Opt., **43**, 4821-4830 (2004).
6. P. Hariharan, *Optical Interferometry* (Academic, San Diego, 2003).
7. G. W. C. Kaye and T. H. Laby, *Tables of Constants in Physics and Chemistry* (Longmans, Green & Co Ltd, London, 1959).
8. L. J. Fried and H. A. Froot, "Thickness measurements of silicon dioxide films over small geometries," J. Appl. Phys. **39**, 5732-5735 (1968).

---

1. Introduction

White-light interferometry (WLI) is a recent development in noncontact optical profiling which has many advantages over conventional (monochromatic) interferometric techniques [1]. The most promising property of WLI is that it can overcome the ambiguity problems encountered at steps and discontinuities with monochromatic interferometric systems. WLI systems have a virtually unlimited ambiguity-free range, so that surfaces can be measured without using phase unwrapping techniques. Another important characteristic of WLI is its optical sectioning property. This is due to the short coherence length of the light, so that the interference term is appreciable only over a very limited range of depths; as a result, an optical section is extracted, allowing three-dimensional images to be formed.

#5754 - $15.00 US Received 17 November 2004; revised 20 December 2004; accepted 23 December 2004

In WLI, images are produced by scanning the object in height and calculating the degree of coherence (the fringe-visibility) between corresponding pixels in the object and reference image planes. The variations in intensity at each point in the image are processed to find the peak of the fringe-visibility curve. The location of this peak along the scanning *z*- axis then corresponds to the height of the surface at this point.

A major area of application of white-light interference microscopy [2] is in investigations of micromachined devices and integrated structures in the semiconductor device and photonics industries. However, such surfaces are sometimes covered with thin films of transparent materials such as oxides, sulfides or nitrides which can significantly change the spectral reflectance of the surface. An earlier study [3] considered the effect of a single reflection in such a film on measurement of the intensity variations and the fringe visibility. However, in practice, the effects of multiple reflections must be considered, since they result in a nonlinear variation of the phase of the reflected beam with wave number [4]. In this paper, we present a detailed study of effects of thin film on a test surface which includes the effects of multiple reflections. These results are then applied to the practical case of a dielectric film on a metallic substrate. A particular case of an oxidized silicon surface is discussed. We show that the effects of multiple reflections are particularly significant for a high film/substrate reflectance ratio.

For simplicity, we have neglected the effects of the variation of the angle of incidence over the aperture with high NA-value objectives [5]. We have also assumed that, over the illumination bandwidth, the dispersion and absorption of the dielectric film, as well as any variations in the reflectance of the substrate can be neglected.

2. Effects of multiple reflections on visibility measurements

We consider a Michelson interferometer in which one of the mirrors M_1 is covered with a transparent dielectric film (thickness *d*, refractive index *n*). Assume the amplitude reflectance at M_2 to be *b*, and at the surfaces of M_1 to be r_1 and r_2. Note that $r_1(<1)$ and $r_2(<1)$ are real quantities corresponding to the fractional amplitudes of the fields reflected from the upper surface of the film and the surface of the mirror, respectively.

If we represent the incident field by the frequency dependent ensemble $U_{in}(\omega)$, the reflected fields $U_1(\omega)$ and $U_2(\omega)$, from each of the two arms can be written, to a first approximation as

$$U_1(\omega) = U_{in}(\omega)A(\omega) \tag{1}$$

and

$$U_2(\omega) = U_{in}(\omega)be^{i\omega\tau}, \tag{2}$$

where τ is the time delay between the two arms of the interferometer. In equation (1), $A(\omega)$ is the amplitude reflectance at M_1 and is given by

$$A(\omega) = r_1 + r_2(1-r_1^2)\sum_{k=0}^{\infty}(-r_1r_2)^k e^{i(k+1)\omega\Delta\tau} \tag{3}$$

where $\Delta\tau = 2nd/c$ is the time delay between the reflected fields introduced by the extra optical path in the film [6]. Each term is related to successive reflections within the film. If we assume a lossless 50:50 beam splitter, the resultant output field is

Received 17 November 2004; revised 20 December 2004; accepted 23 December 2004

$$U_{out}(\omega) = U_1(\omega) + U_2(\omega)$$
$$= U_{in}(\omega)\left[be^{i\omega\tau} + r_1 + r_2(1-r_1^2)\sum_{k=0}^{\infty}(-r_1 r_2)^k e^{i(k+1)\omega\Delta\tau} \right]. \tag{4}$$

The spectrum of the output field $S_{out}(\omega)$ is then given by the relation

$$S_{out}(\omega) = \langle U^*_{out}(\omega)\, U_{out}(\omega) \rangle \,, \tag{5}$$

where the asterisk denotes the complex conjugate and the angle brackets denote the ensemble average. Accordingly,

$$S_{out}(\omega) = S_{in}(\omega)\left\{ \left[be^{-i\omega\tau} + r_1 + r_2(1-r_1^2)\sum_{k=0}^{\infty}(-r_1 r_2)^k e^{-i(k+1)\omega\Delta\tau} \right] \right.$$
$$\left. \times \left[be^{i\omega\tau} + r_1 + r_2(1-r_1^2)\sum_{k=0}^{\infty}(-r_1 r_2)^k e^{i(k+1)\omega\Delta\tau} \right] \right\}. \tag{6}$$

where $S_{in}(\omega)$ is the spectrum of the input field, yielding the result

$$S_{out}(\omega) = S_{in}(\omega)$$
$$\times \left[b^2 + r_1^2 + 2r_1 b cos\omega\tau + 2r_2 b(1-r_1^2)\sum_{k=0}^{\infty}(-r_1 r_2)^k cos[(k+1)\omega\Delta\tau - \omega\tau] \right.$$
$$+ 2r_1 r_2(1-r_1^2)\sum_{k=0}^{\infty}(-r_1 r_2)^k cos[(k+1)\omega\Delta\tau] \tag{7}$$
$$\left. + r_2^2(1-r_1^2)^2 + \sum_{k=0}^{\infty}\sum_{j=0}^{\infty}(-r_1 r_2)^{k+j} e^{i\omega\Delta\tau(k-j)} \right).$$

Typical curves presented in Fig. 1. for $r_1 = 0.4$ and $r_2 = 0.8$, show the incident spectrum (see curve for $2nd/\lambda_0 = 0$) and the changes in the spectrum of the reflected field with increasing optical thickness of the film on the mirror and for different numbers of reflections. The shape of the reflected spectrum is dependent on film thickness. The amplitude of the spectrum initially decreases as the film thickness increases up to $\lambda_0/2$, and then increases again. Note that the peak of the spectrum is also shifted. For a given thickness of a film, the shape of the spectrum changes for a small number of reflections, but when the number of reflections is greater than about 5, there is very little change in the shape as shown by the red and green lines for 5 and 7 reflections in Fig. 1 being superimposed upon each other.

In Eq. (7), the interference term is

$$2b\left[r_1 cos\omega\tau + r_2(1-r_1^2)\sum_{k=0}^{\infty}(-r_1 r_2)^k cos[(k+1)\omega\Delta\tau - \omega\tau] \right]. \tag{8}$$

Accordingly, the variation of the output intensity with the delay is given by the relation

#5754 - $15.00 US Received 17 November 2004; revised 20 December 2004; accepted 23 December 2004

$$I(\tau)=\int_{-\infty}^{\infty}S_{out}(\omega)d\omega \tag{9}$$

and, from Eq. (8),

$$\begin{aligned}I(\tau)&=\int_{-\infty}^{\infty}S_{in}(\omega)\left[2b\{[r_1 cos\omega\tau+r_2(1-r_1^2)\sum_{k=0}^{\infty}(-r_1r_2)^k cos[(k+1)\omega\Delta\tau-\omega\tau]\}\right]d\omega\\&=Re\left[2b\{r_1F(\tau)+r_2(1-r_1^2)\sum_{k=0}^{\infty}F[(k+1)\Delta\tau-\tau]\}\right],\end{aligned} \tag{10}$$

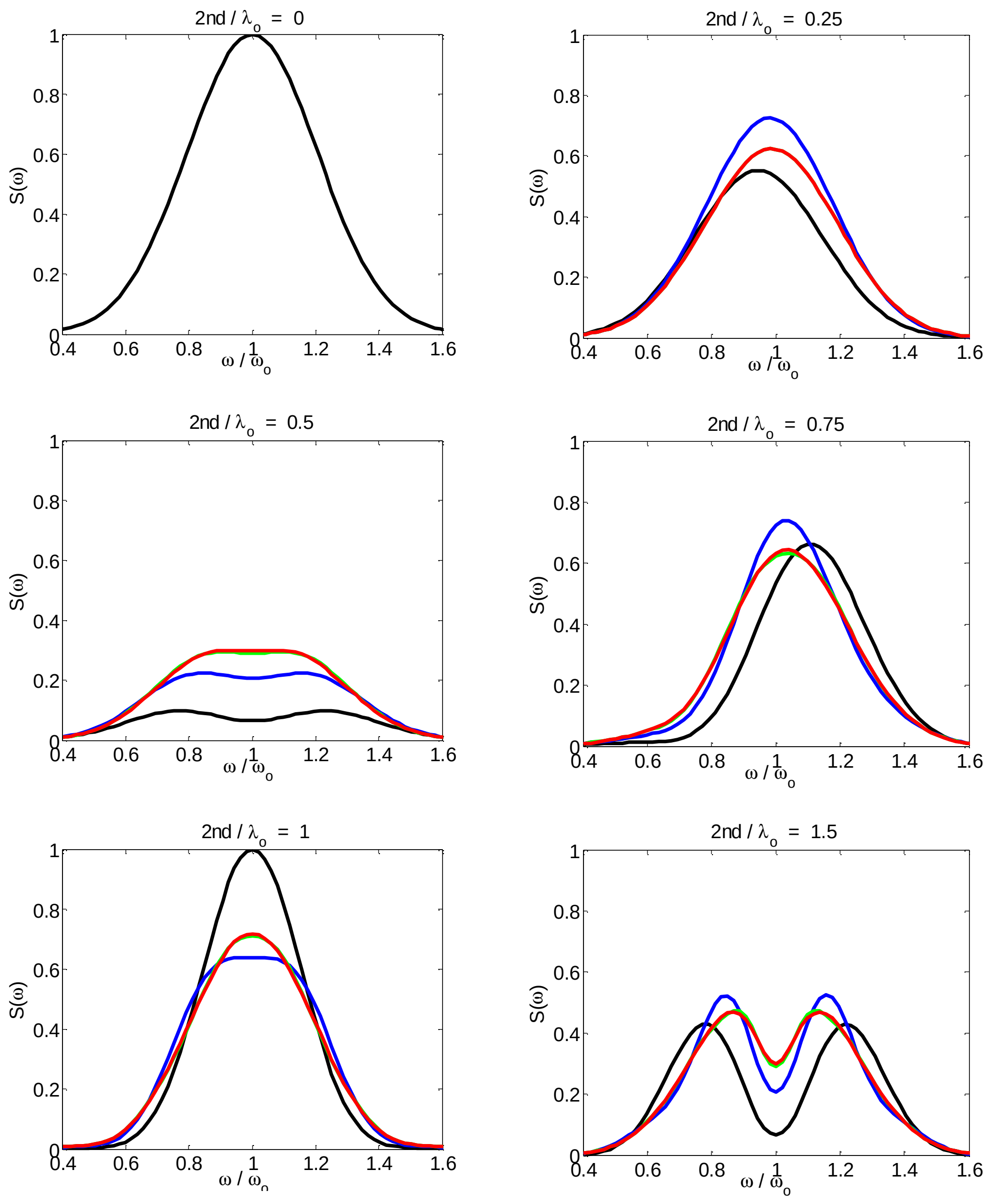

Fig. 1. Spectrum of the reflected field from the surface of a mirror coated with various thicknesses of a dielectric film from $2nd = 0$ to 2nd = 1.5 λ_o for multiple reflections (black- 1 reflection, blue- 3 reflections, green- 5 reflections and red- 7 reflections).

#5754 - $15.00 US Received 17 November 2004; revised 20 December 2004; accepted 23 December 2004

where $F(\tau)$ is the Fourier transform of the input spectrum $S_{in}(\omega)$, given by

$$F(\tau) = \int_{-\infty}^{\infty} S_{in}(\omega) e^{i\omega\tau} d\omega \,. \tag{11}$$

If we assume a Gaussian input spectrum of the form

$$S_{in}(\omega) = \frac{1}{N} \exp\left[-\left(\frac{\omega - \omega_0}{\omega_1} \right)^2 \right], \tag{12}$$

where N is a normalizing constant, then the Fourier transform

$$F(\tau) = \exp(i\omega_0\tau)\exp[-(1/4)\omega_1^2\tau^2], \tag{13}$$

and the variation of the output intensity with the delay τ is given by the relation

$$I(\tau) = Re\left[2b\sum_{k=0}^{\infty}(-r_1r_2)^k \left[r_1 e^{i\omega_0(k\Delta\tau-\tau)} e^{-(1/4)\omega_1^2(k\Delta\tau-\tau)^2} + r_2 e^{i\omega_0((k+1)\Delta\tau-\tau)} e^{-(1/4)\omega_1^2[(k+1)\Delta\tau-\tau]^2} \right] \right]. \tag{14}$$

3. Dielectric film on a metal substrate

In this case, the refractive index of the substrate is a complex quantity, and the spectrum of the output field is given by the relation

$$S_{out}(\omega) = S_{in}(\omega)\left\{ \left[be^{i\omega\tau} + r_1 + r_2(1-r_1^2)\sum_{k=0}^{\infty}(-r_1r_2)^k e^{i(k+1)\omega\Delta\tau} \right] \times \left[be^{-i\omega\tau} + r_1 + r_2^*(1-r_1^2)\sum_{k=0}^{\infty}(-r_1r_2^*)^k e^{-i(k+1)\omega\Delta\tau} \right] \right\}. \tag{15}$$

where r_2 is the complex reflectance of the film/substrate interface given by the relation

$$r_2 = \frac{(n_1/n_2) - 1 - ik_2}{(n_1/n_2) + 1 + ik_2}. \tag{16}$$

In this relation, n_1 is the refractive index of the dielectric film and n_2 and k_2 are the refractive index and absorption index of the metal surface. The corresponding reflectance for the air-film interface is

$$r_1 = \frac{n_0 - n_1}{n_0 + n_1}, \tag{17}$$

where n_0 is the refractive index of the external medium (for air $n_0 \approx 1.0$). Hence, the variation of the intensity with the delay is

$$I(\tau) = Re\left[b\left\{ r_1F(\tau) + r_2(1-r_1^2)\sum_{k=0}^{\infty}(-r_1r_2)^k F[(k+1)\Delta\tau - \tau] + r_1F(\tau) + r_2^*(1-r_1^2)\sum_{k=0}^{\infty}(-r_1r_2^*)^k F[(k+1)\Delta\tau - \tau] \right\} \right]. \tag{18}$$

Received 17 November 2004; revised 20 December 2004; accepted 23 December 2004

For the particular case of a silica film on silicon ($n_1 = 1.46$, $n_2 = 4.05$ and $k = 0.03$) [7], the visibility curves for various thicknesses of the film are shown in Fig. 2.

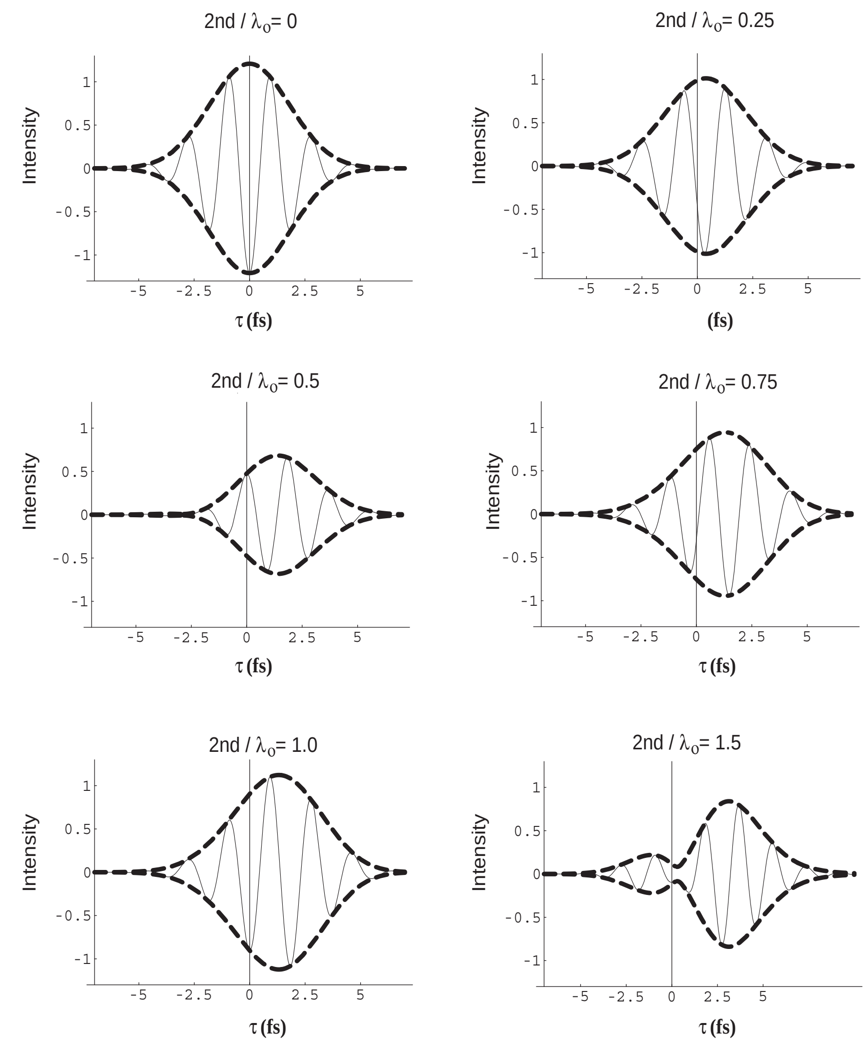

Fig. 2. Visibility curves, including the effect of multiple reflections, for various thicknesses of a silica film on silicon ($n_1 = 1.46$, $n_2 = 4.05$ and $k = 0.03$).

3. Shifts in the position of the fringe-visibility maximum with multiple reflections

In practice, when attempting to determine the actual height of a substrate with a thin transparent film deposited on it, a shift in the position of the visibility maximum occurs due to multiple reflections; this shift results in an error in the surface height. However, if one knows the approximate thickness of the film, say, from ellipsometric measurements [8], one can determine the magnitude of the expected shift and correct for it. In order to evaluate the shift accurately, we must take into account contributions from a sufficient number of reflections within the thin film. The magnitude of the error in determining the shift, as a function of the number of reflections considered, for different film/substrate reflectances: (i) $r_1 = 0.2$, $r_2 = 0.8$ (ii) $r_1 = 0.4$, $r_2 = 0.8$ (iii) $r_1 = 0.8$, $r_2 = 0.8$ (iv) $r_1 = 0.4$, $r_2 = 0.6$, and film thicknesses is shown in Fig. 3.

#5754 - $15.00 US Received 17 November 2004; revised 20 December 2004; accepted 23 December 2004

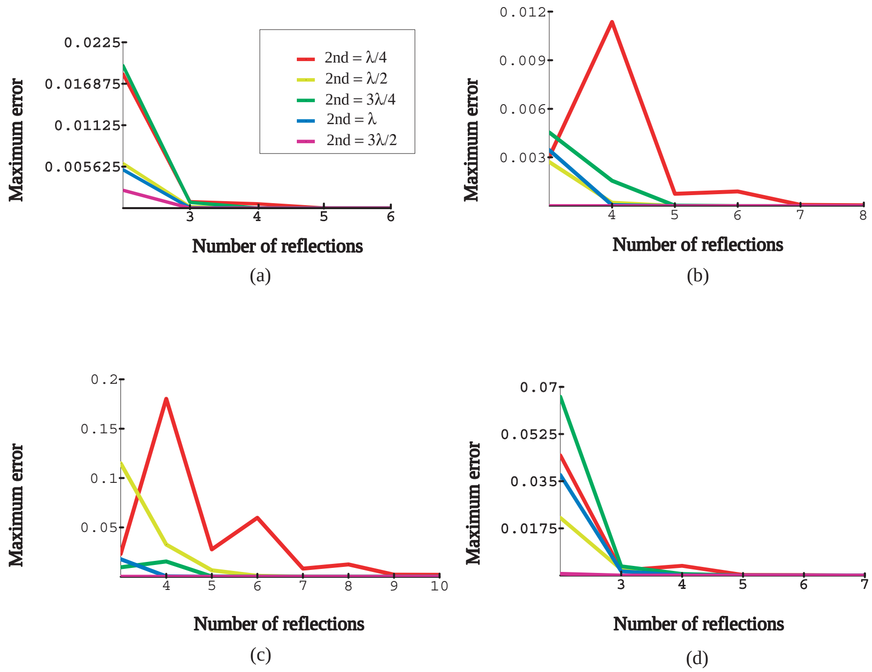

Fig. 3. Convergence of the error in the location of the visibility maximum, with the number of multiple reflections, for different film/substrate reflectances: (a) $r_1 = 0.2, r_2 = 0.8$ (b) $r_1 = 0.4, r_2 = 0.8$ (c) $r_1 = 0.8, r_2 = 0.8$ and (d) $r_1 = 0.4, r_2 = 0.6$.

4. Conclusions

We can summarize our results as follows:

(a) For a low reflectance film on a high reflectance substrate ($r_1 = 0.2$, $r_2 = 0.8$), after 3 reflections there is little effect on the position of the visibility maximum at any film thickness.

(b) For a higher film/substrate reflectance ratio, more reflections are needed for good convergence.

(c) For all film thicknesses and film/substrate reflectances, about 7 reflections are the maximum necessary to achieve good convergence to the correct solution.

(d) Significant errors in the location of the visibility maximum are observed beyond the first few reflections only for certain critical film thicknesses. A film with $2nd = \lambda/4$ seems to produce the largest errors.

(e) If the film/substrate reflectances and the approximate thickness of the film are known, the data presented above can be used to determine the minimum number of reflections that must be taken into account in evaluating the shift in the position of the visibility maximum.

#5754 - $15.00 US Received 17 November 2004; revised 20 December 2004; accepted 23 December 2004