Phase shifting optical coherence tomography

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ABSTRACT

We demonstrate the use of phase-shifting interferometry in OCT to determine the optical phase and fringe visibility within the coherence envelope. Phase-shifting algorithms provide both the optical phase and visibility from a series of intensity measurements corresponding to controlled phase shifts. In addition to providing phase information which supplements the visibility or envelope data which is traditionally obtained in OCT, this technique will provide an independent, highly sensitive measurement of the coherence envelope which may be used for a precise determination of the source power spectrum.

2. INTRODUCTION

The algorithms employed in phase shifting interferometry have been designed to determine the phase (optical path length) rapidly and with high precision.[1] In addition to offering much higher precision than fringe counting methods (in certain cases, a precision of $\lambda/1000$ can be achieved), the application of these algorithms offers many advantages including insensitivity to intensity variations and good results for low contrast fringes.[1] Because the success of these algorithms is predicated on the visibility remaining constant as the phase shifts are introduced, previous authors have assumed that these algorithms are not valid when a broadband source is used for illumination. For applications with white light sources, approximate methods have been developed which assume that the fringe visibility is locally linear.[2,3] In OCT, however, the spectral wavelength bandwidth of a source is typically much more narrow (70 nm at 1.3 μm).[4] Therefore, we show that the standard phase shifting algorithms may be applied to recover the phase (optical path length) and visibility and that it is straight forward to characterize the small errors introduced by this approach.

3. PHASE SHIFTING INTERFEROMETRY APPLIED TO OCT

When phase shifting techniques are applied to a two beam interferometer illuminated by a monochromatic source, the measured intensity may be modeled by Eq. 1:[5]

$$I(m, \phi, \alpha) = I_0 (1 + m \mathrm{Cos}[\phi + \alpha]) \tag{1}$$

where m is the visibility of the fringes, ϕ is the phase, I_o is the dc intensity and α is an experimentally controlled phase shift. Using an over-determined set of measurements, it is possible to solve for the unknowns in Eq. 1.[1] For example, if the phase shift angles are $\alpha = 0, \pi/2, \pi, 3\pi/2$ the four intensity measurements become:

$$\begin{aligned} I_1 &= I_0 (1 + m \mathrm{Cos}[\phi]) \\ I_2 &= I_0 (1 - m \mathrm{Sin}[\phi]) \\ I_3 &= I_0 (1 - m \mathrm{Cos}[\phi]) \\ I_4 &= I_0 (1 + m \mathrm{Sin}[\phi]) \end{aligned} \tag{2}$$

The phase may be determined from the four measurements according to Eq. 3:

$$\tan(\phi) = \frac{I_4 - I_2}{I_1 - I_3} \qquad (3)$$

A different combination of the four intensity measurements (Eq. 4) will yield the visibility:

$$m = \frac{2\sqrt{(I_2 - I_4)^2 + (I_1 - I_3)^2}}{(I_1 + I_2 + I_3 + I_4)} \qquad (4)$$

Equations 3 and 4 show that the phase and visibility can be determined independently of each other and independently from the dc intensity I_o. The combination of intensity measurements represents one algorithm that can be used to determine the phase and visibility. An analysis of several phase shifting algorithms as well as the methods for experimentally introducing the phase changes has been described in several publications.[5] It is worth noting that it is possible to use an algorithm, called the Carré algorithm, which does not require a specific phase shift angle. Therefore, this algorithm is not affected by linear errors in the phase shifting device.

A commonly used algorithm, called the Hariharan algorithm, which has several advantages compared with other algorithms uses five discrete phase shifts, $\alpha = -\pi, \pi/2, 0, \pi/2, \pi$.[1] Once the phase step has been introduced, the intensity, I, is measured at the corresponding phase shift. The five phase shifted measurements are combined and the phase and visibility may be determined from Eqs. 5 and 6:[1]

$$\tan(\phi) = \frac{2(I_2 - I_4)}{2 I_3 - (I_1 + I_5)} \qquad (5)$$

$$m = \frac{3\sqrt{(2(I_2 - I_4))^2 + (2 I_3 - I_5 - I_1)^2}}{2(I_1 + I_2 + 2 I_3 + I_4 + I_5)} \qquad (6)$$

For a polychromatic source, however, Eq. 1 is no longer valid. Instead, we must account for the effect of the power spectral density (PSD) of the broadband source. Therefore, we examine the form of the interference term in Eq. 1 when a broadband source is used. We assume that the PSD may be modeled by a single Gaussian with a full-width half-maximum (FWHM) spectral bandwidth Δk and a center wavenumber k_o:

$$S[k\_, \Delta k\_] = \frac{1}{\sqrt{2\pi}\,\Delta k}\, e^{-\left(\frac{k-k_o}{\sqrt{2}\,\Delta k}\right)^2} \qquad (7)$$

The spectral bandwidth in Eq. 7 is related to the central wavelength, λ_o, by $\Delta k = 2\pi\Delta\lambda/\lambda_o^2$. Because of the broad spectrum, the interference term of the measured intensity now contains both a dependence on OPL, δ, and the wavelength (Eq. 8):

$$I = I_o \left(1 + m \int_{-\infty}^{\infty} S[k, \Delta k]\, \mathrm{Cos}[2 k \delta]\, dk\right) \qquad (8)$$

Performing the integration in Eq. 8 we get:[5,6]

$$I(m, \delta) = I_o \left(1 + m\, e^{-2\Delta k^2 \delta^2}\, \mathrm{Cos}[2 k_o \delta]\right) \qquad (9)$$

It is essential to note that the effect of the broadband source is to modify the visibility so that it is now dependent upon the optical path length δ. Therefore, when phase shifting algorithms are applied to Eq. 9, the Gaussian spectrum results in a phase shift dependent visibility. Applying the Hariharan algorithm to Eq. 9, the combination of the intensity measurements in Eq. 5 yields:

$$\frac{2\,(I_2 - I_4)}{2\,I_3 - (I_1 + I_5)} = \frac{2\,e^{\frac{\pi\,(3\,\pi+8\,k_0\,\delta)\,\Delta k^2}{8\,k_0^2}}\left(1 + e^{\frac{2\,\pi\,\delta\,\Delta k^2}{k_0}}\right)}{1 + e^{\frac{4\,\pi\,\delta\,\Delta k^2}{k_0}} + 2\,e^{\frac{\pi\,(\pi+4\,k_0\,\delta)\,\Delta k^2}{2\,k_0^2}}}\tan(2\,k_0\,\delta) \tag{10}$$

A series expansion of Eq. 10 to $O(\Delta k/k_o)^6$ yields (with $\Delta k/k_o = \Delta\lambda/\lambda_o$) Eq. 11:

$$\frac{2\,(I_2 - I_4)}{2\,I_3 - (I_1 + I_5)} = \left(1 + \frac{\pi^2\,\Delta\lambda^2}{8\,\lambda_0^2} - \frac{\pi^4\,\Delta\lambda^4}{\lambda_0^4}\left(\frac{3}{128} + \frac{2\,\delta^2}{\lambda_0^2}\right)\right)\tan\left(\frac{4\,\pi}{\lambda_o}\,\delta\right) \tag{11}$$

Similarly, the combination of intensity measurements in Eq. 6 no longer precisely yields the visibility, m. Although we have determined the exact resulting expression, the algebra is lengthy. A series expansion of the expression for m to order $(\Delta k)^3$, but expressed in terms of λ is given in Eq. 12:

$$\frac{3\sqrt{(2\,(I_2 - I_4))^2 + (2\,I_3 - I_5 - I_1)^2}}{2\,(I_1 + I_2 + 2\,I_3 + I_4 + I_5)} =$$

$$m\left(1 - \pi^2\,\frac{\Delta\lambda^2}{\lambda_0^2}\left(\frac{3}{16} + \frac{8\,\delta^2}{\lambda_0^2} + \frac{\mathrm{Cos}\left[\frac{8\,\pi\,\delta}{\lambda_0}\right]}{16}\right)\right) - m^2\,\pi^2\,\frac{\Delta\lambda^2}{\lambda_0^2}\left(\frac{\mathrm{Cos}\left[\frac{4\,\pi\,\delta}{\lambda_0}\right]}{6} + \frac{2\,\delta\,\mathrm{Sin}\left[\frac{4\,\pi\,\delta}{\lambda_0}\right]}{3\,\lambda_0}\right) \tag{12}$$

The magnitude of the systematic error in the optical path length and visibility will be presented in Section 5 for parameters specifically used in our experimental verification of the method.

4. METHODS

We have applied the phase shifting methodology to a fiber coupled Michelson interferometer with a broadband source (AFC Technologies, BBS1310ER1P); the specifications supplied with the source stated a center wavelength λ_o = 1318 nm and a full width half maximum wavelength bandwidth $FWHM_\lambda$ = 69 nm. The discrete phase shifts are introduced with a piezoelectric transducer (PZT) (Burleigh, PZT91) mounted on a dc stepper motor (Newport, UT100-150); both devices were controlled by a PC. At each phase shift, the photodetector signal (New Focus, 1617) was digitized with a 100kHz, 16 bit A/D board on a PC bus (Keithley, DAS 1800 HR); this board was also used to send voltage steps to a summing operational amplifier (New Focus, 3211) to move the PZT. This summing amplifier could also be used to add another voltage signal to the control voltage for the phase shifts. Mirrors were used in both the sample and reference arm.

5. RESULTS

Figure 1 shows that for small differential changes (of order λ_o) in the optical path between the two arms of the interferometer, the ideal fringe visibility which would be obtained with our polychromatic source does not differ significantly from the fringe visibility which would be obtained with a monochromatic source. Qualitatively, therefore, we anticipate that the systematic errors will be small when the phase shifts employed in the phase shifting algorithms are of order λ_o. Because we have an analytic expression for the phase and visibility (Eqs. 10-12), however, it is possible to determine the systematic error exactly. Figure 2 shows that the error in the OPL (a) and visibility (b) is indeed quite small even for differential path length changes as large as 10 λ_o.

Figure 3 shows the OPL and visibility, both as a function of time, when a slowly varying ramp voltage was applied to the PZT with the dc motor held fixed. In this instance, the PZT was used for both phase shifting and to introduce an "unknown" change in OPL.

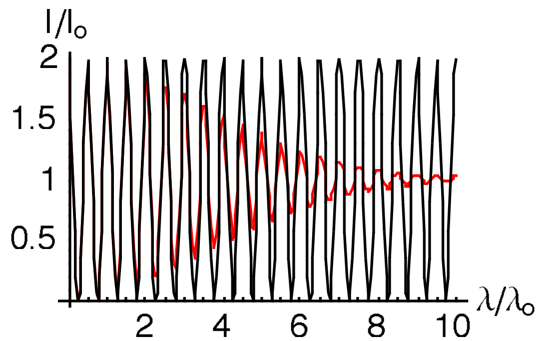

Figure 1. Fringes formed with monochromatic and polychromatic sources when the differential OPL changes by 10 λ_o.

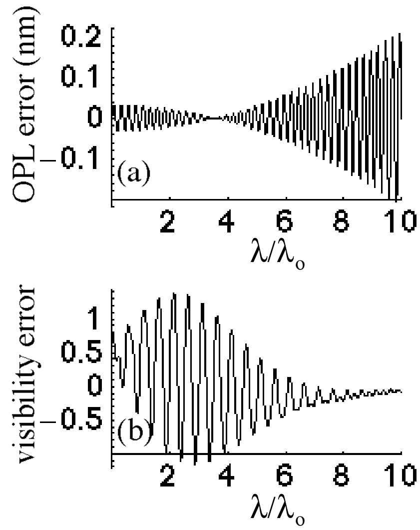

Figure 2. Resulting systematic errors when the phase shifting algorithms (Eqs. 5 and 6) are employed with a polychromatic source. Error in optical path length (a) and visibility (b) as a function of the change in OPL.

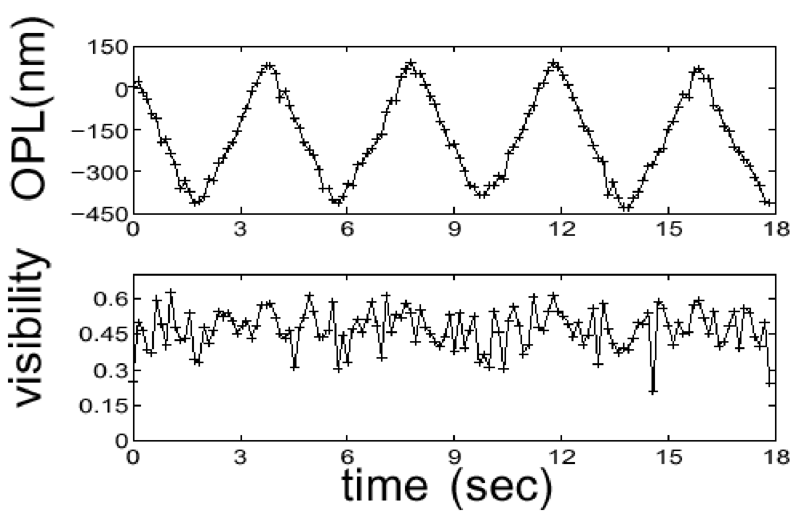

Figure 3. Linear OPL change caused by a voltage ramp to the PZT (top). The visibility (bottom) is approximately constant.

6. DISCUSSION and CONCLUSIONS

When phase shifting algorithms are applied with the sources typically used for OCT, the phase and visibility are recovered with only a small error systematic error. Therefore, as in other applications of phase shifting interferometry, this is a simple and fast method for determining both the phase and visibility. As in other forms of PSI, there are a plethora of methods for introducing the phase shift. As indicated by the data in Fig. 3, the method may be used to measure changes of order nanometers or it can be combined with phase unwrapping techniques to measure large changes in OPL.[7] This measurement technique is important for OCT both for determining structural phase variations within the coherence envelope as well as high resolution reflectance information.

7. REFERENCES

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ACKNOWLEDGEMENTS

The authors wish to acknowledge Drs. J. A. Izatt and A. M. Rollins, Case Western Reserve University for guidance in choosing the equipment for the OCT setup. This research is supported by the Biotechnology Program, Microgravity Research Division, NASA under grant NAG3-2504.