Temperature stabilization for superresolved swept-wavelength interferometry

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Abstract

For superresolved swept-wavelength interferometry measurements to reach theoretical uncertainty limits, the temperature of the trigger interferometer used to linearize the SWI system's sampling rate must tracked and stabilized at the 0.01 – 0.1 °C level.

Introduction

In previous work, we showed that frequency estimation methods can be used to superresolve SWI measurements, allowing 2σ uncertainties as low as 10^{-4} to 10^{-5} of the Fourier transform-limited resolution of the SWI instrument [1]. We further showed that, depending on the choice of frequency estimator, the variance of these measurements can approach the Cramér-Rao lower bound. With signal-to-noise ratios (SNRs) between 70dB to 90dB, measurement standard deviation can approach between $2.5\text{x}10^{-4}$ and $2.5\text{x}10^{-5}$ of the instrument's transform-limited resolution. Our previous results were obtained through numerical simulation, and therefore delineate the theoretical limits of superresolved SWI, both in uncertainty and in precision. As a predictor of precision, our results are in excellent agreement with earlier experimental work [2] in which a series of 50 measurements, having an estimated 90dB of SNR [3], were reported to have a standard deviation of $5\text{x}10^{-5}$ of the SWI instrument's transform-limited resolution.

The accuracy of superresolved SWI is much more difficult to evaluate, however. Both the SWI model used for numerical experiments in [1] and the instrument used for physical experiments in [2] have transform-limited resolutions of approximately 36μm in free space, meaning that superresolved resolution can be on the order of a single nanometer. SWI systems with higher bandwidths have much smaller transform-limited resolutions, as little as 4μm in free space [4], making sub-nanometer measurements a theoretical possibility.

To evaluate the accuracy of any SWI system, the system's measurement of optical path length (OPL) through some reference sample must be compared to the known OPL of that reference. However, even very slight temperature fluctuations will cause the OPL of the reference to change on the nanometer scale, through shifts in both the thickness and group refractive index of the reference, making the accuracy of superresolved SWI extremely difficult to establish. Despite this difficulty, the uncertainty of SWI measurements may nevertheless be deduced.

Trigger interferometer calibration

We showed in [1] that the uncertainty of any superresolved measurement fundamentally depends on uncertainty in sample spacing, i.e. uncertainty in DFT bin size. For the experimental work presented here, we used an SWI system very similar to the numerical model in [1]. In this system, a secondary trigger interferometer is used to ensure equal sample spacing in the primary measurement interferometer [2], and uncertainty in DFT bin size is ultimately limited by the quality of the hydrogen cyanide (HCN) gas cell used to calibrate the trigger interferometer [1].

DFT bin size is equal to the differential delay time τ_t of the trigger interferometer, divided by the total number of samples taken during one laser sweep. This differential trigger delay time is measured by counting the number of fringe periods p emerging from the trigger

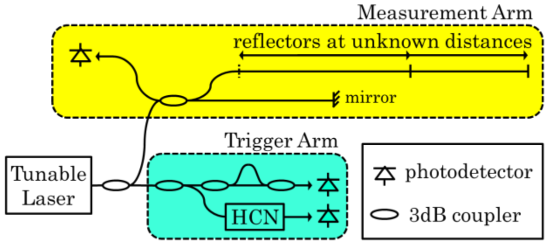

Fig. 1. System diagram of fiber-based SWI. The Michelson geometry of the measurement arm (upper, yellow) enables the measurement of multiple reflective surfaces. The trigger arm (lower, blue) consists of a Mach-Zehnder interferometer and a hydrogen cyanide reference cell.

interferometer within the frequency spacing $\Delta\nu_{HCN}$ between two HCN absorption lines. This spacing is measured by passing a portion of the laser sweep through an HCN gas cell. Thus

$$\tau_t = \frac{p}{\Delta\nu_{HCN}}, \tag{1}$$

and uncertainty in the measurement of trigger delay time $u(\tau_t)$ is given by

$$u(\tau_t) = \frac{\tau_t}{\Delta\nu_{HCN}}\left[\frac{u^2(p)}{\tau_t^2} + u^2(\Delta\nu_{HCN})\right]^{1/2}, \tag{2}$$

where $u(p)$ is uncertainty in the number of fringe periods between two HCN absorption lines, and $u(\Delta\nu_{HCN})$ is uncertainty in frequency spacing between those two absorptions lines.

In Fig. 2a, the measured absorption spectrum of HCN is shown as a function of laser wavelength λ. In Fig. 2b, the Lorentzian fit to the R20 line is shown as a function of fringe period count *p*. The 1σ uncertainty in the fit is less than 0.04 of a fringe period.

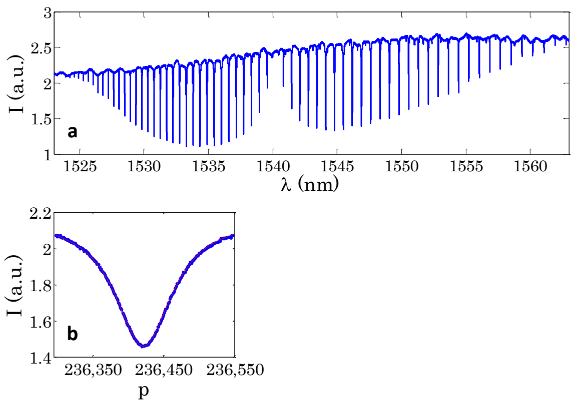

Fig. 2. (a) Measured absorption spectrum from a dBm Optics hydrogen cyanide wavelength reference gas cell. (b) Lorentzian fit to R20 absorption line has an uncertainty of less than 0.04 fringe periods.

Thermal instability of trigger interferometer

If the temperature of the trigger interferometer is constant, uncertainty in trigger delay time is dominated by the uncertainty in frequency spacing $u(\Delta\nu_{HCN})$ between the absorption lines used in the calibration, and the contribution to uncertainty $u(p)$ from the fringe period count is comparatively small [2]. However, the trigger delay time is extremely sensitive to temperature fluctuations in the trigger interferometer. The temperature dependent change Δp in fringe period count is given approximately by

$$\Delta p \approx \tau_t \Delta\nu_{HCN}\Delta T\left(\alpha_L + \frac{1}{n_g}\frac{dn}{dT}\right), \tag{3}$$

where $\alpha_L = 0.52\text{x}10^{-6}$ is the coefficient of thermal expansion for Corning SMF-28 fiber, $n_g = 1.462893$ is the fiber's group index, $dn/dT = 7.97\text{x}10^{-6}$ is the fiber's thermo-optic coefficient, and ΔT is the change in temperature from 25°C.

Temperature change in the trigger interferometer alters the trigger delay time τ_t, and therefore the fringe period count *p* used for calibration. If this temperature-dependent change in trigger delay time is not eliminated or otherwise accounted for, it adds uncertainty to the fringe count *p*. Therefore, total fringe count uncertainty u(p) is given by

$$u(p) = u_f(p) + \Delta p, \tag{4}$$

where $u_f(p)$ is the uncertainty in the Lorentzian fits to HCN absorption lines, and Δp is the temperature-dependent change in the fringe period count, given by (3).

Uncertainty in the measurement of delay time τ_s between two sample reflectors is given by

$$u(\tau_s) = \tau_s \frac{u(\tau_t)}{\tau_t}, \tag{4}$$

where $\delta\tau$ is DFT bin size for the SWI instrument. In Fig. 3, the temperature-dependent change in uncertainty is shown for any sample delay time τ_s. A 0.02°C temperature increase causes a 1% increase in measurement uncertainty, and a 0.1°C increase results in a 10% increase in uncertainty. Consequently, temperature change during any single measurement (i.e. during any one laser sweep) must be minimized in order to minimize overall measurement uncertainty.

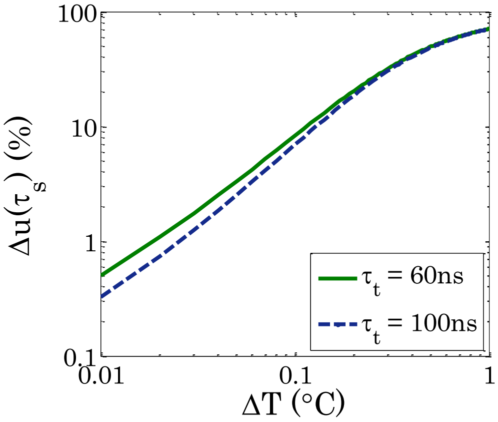

Fig. 3. Temperature change in the differential delay time of the trigger interferometer increases uncertainty in measurements of delay time through a sample. The change in uncertainty varies slightly depending on initial trigger delay time τ_t. Uncertainty in absorption line spacing is derived from the 30fm and 20fm 1σ wavelength uncertainties of the R21 and P9 absorption lines of a NIST-traceable HCN wavelength reference gas cell.

Experimental Results

Fig. 4 shows a series of 4,400 measurements of trigger delay time in our SWI system. During the 4.5hr measurement period, the the temperature of an aluminum block housing the trigger interferometer was monitored and recorded. The aluminum housing was clamped to a hot plate which was stepped in temperature in two 0.5°C increments. Both the temperature of the aluminum block and the trigger delay time rapidly increased when the hot plate temperature was increased.

During the entire series of measurements, the maximum rate of temperature change during a single laser sweep was less than 0.02°C, resulting in a maximum temperature-dependent change in the number of fringe periods of less than 0.02 periods. The maximum fringe period uncertainty u(*p*), from temperature change and line fit uncertainty, is therefore less than 0.06.

The mean rate of temperature change during the series of measurements was 4.3×10^{-5} °C/s. Excluding measurements immediately following a temperature step, 1σ variation in measured trigger delay time was approximately 11.5fs, consistent with the 10fs variation predicted using (2), the average uncertainty of all 8,800 HCN line fits, and the mean fringe period uncertainty due to temperature variation in the trigger interferometer.

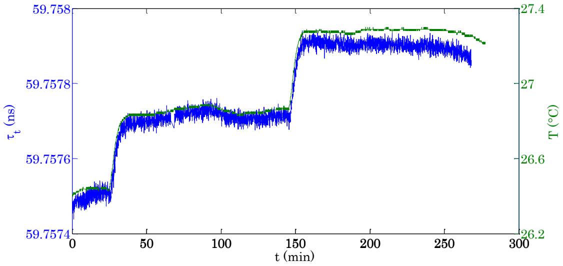

Fig. 4. A series of 4,400 measurements of trigger delay time taken over a 4.5hr period illustrate the strong temperature-dependence of trigger delay time.

Conclusions

Theoretical uncertainty limits for SWI are as low as 10^{-4} to 10^{-5} of the Fourier transform limit. In order to approach these limits, the uncertainty in DFT bin size for the SWI system must be thoroughly characterized. In SWI systems using a trigger interferometer to acquire equally spaced samples, uncertainty in DFT bin size depends primarily on uncertainty in calibration of the trigger interferometer. We have shown that for SWI measurements to reach theoretical uncertainty limits, the temperature of the trigger interferometer must be stabilized at the 0.01 – 0.1 °C level for at least the duration of each measurement.

References

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