# Wavelength References for Optical Interferometry

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Applications that demand high-accuracy dimensional metrology often utilize optical interferometers with frequency-stabilized laser sources. Many configurations are possible, each measuring in terms of a known wavelength of light. In vacuum, the wavelength uncertainty of a typical commercial frequency-stabilized HeNe laser is approximately $\Delta\lambda/\lambda \sim \pm 2 \times 10^{-8}$, and becomes an issue only during the measurement of longer optical path differences or if very high accuracy is required. However in air the wavelength uncertainty is greatly increased by uncertainty of the air's refractive index. To reduce the uncertainty, sensors that measure atmospheric pressure, temperature and humidity are used in conjunction with refractive index models to estimate the laser wavelength. Achieving measurement performance even to the $\Delta L/L = \Delta\lambda/\lambda \sim \pm 2 \times 10^{-7}$ level in air requires great care and calibrated sensors, neither of which are always employed. Reducing the uncertainty $\Delta\lambda/\lambda$ in air would enable better positioning in semiconductor and nanotechnology post-processing steps.

An approach to stabilizing the interferometer's laser source that promises to provide reduced wavelength uncertainty is to lock a tunable laser to a specific mode of a stable optical cavity.[1,2] A previous measurement of the mode using optical frequency metrology allows the wavelength to be known more accurately than $\Delta\lambda/\lambda < 10^{-7}$. In addition, this technique also enables absolute interferometry, since multiple wavelengths can be supplied to the user. The cavity must be open to air and positioned near the interferometer so that the air characteristics in the cavity are the same as in the interferometer path. Locking a tunable laser to a particular mode will stabilize the wavelength as the servo changes the laser frequency to remain aligned with the cavity resonance. Using $L$ for the cavity round-trip path-length we write

$$\lambda_m = \frac{L}{m + \dfrac{\varphi(\lambda) + \psi_G}{2\pi}} ,$$

where $\lambda_m$ is the wavelength of the $m^{th}$ longitudinal ($TEM_{00}$) mode, $\varphi(\lambda)$ is the cumulative phase shift upon reflection over a cavity round-trip, and $\psi_G$ is the Gouy phase shift in one round-trip. Note that the cavity medium's refractive index does not explicitly appear in this equation. The mode index $m$ is a number on the order of $4 \times 10^5$ for the 25 cm long ring cavities we are considering. The stability of $\lambda_m$ is for the most part dependent upon the stability of the cavity length $L$. That conclusion is based on observing that changes in the denominator terms $\varphi(\lambda)/2\pi$ and $\psi_G/2\pi$ (both on the order of one) as large as 0.1% would cause a wavelength uncertainty of only a few parts in $10^9$. The cavity length $L$ is dependent on temperature, hydrostatic atmospheric compression, material aging and mirror contamination. In practice, a measurement of a mode resonant wavelength versus temperature includes both the temperature change of the cavity spacer and the temperature dependence of the mirror phase-shift.

An implicit assumption is that the tunable laser wavelength can be easily returned to the same mode, and a simple means to accomplish that using a small secondary cavity has been demonstrated.[2] At 633 nm, to return to the same longitudinal mode over normal atmospheric conditions would require a laser tunable over about ±5 GHz.

The resonant wavelength in air may be determined in a calibration step by measuring the frequency of a laser locked to the cavity resonance frequency in vacuum and applying a correction unrelated to the air's refractive index. We have been measuring the mode frequencies in vacuum by way of a femtosecond laser optical frequency comb. The primary contribution to the final wavelength uncertainty appears to be the residual uncertainty after correcting for the hydrostatic compression of the cavity due to atmospheric pressure. A potential source of uncertainty we have identified is the error in determining the effective temperature of the cavity, fabricated from very low thermal conductivity glass. Another potential source of wavelength uncertainty is mirror contamination. We have recently investigated cleaning the mirrors (hard ion-beam sputtered dielectric coatings) using a wipe of anhydrous methanol, and monitoring the mode frequency before and after. The results on our prototype cavity indicate that any disturbance of the cavity resonant wavelength from the mirror cleaning process is significantly less than $\Delta\lambda/\lambda \sim 10^{-8}$.



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[1] M. L. Eickhoff and J. L. Hall, Applied Opt. **36**(6) 1223 (1997).
[2] S. Topçu, Y. Alayli, J.-P. Wallerand, and P. Juncar, Eur. Phys. J. Appl. Phys. **24**, 85 (2003).

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