Unusual techniques for absolute distance measurement

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Abstract. I describe four unusual laser systems for absolute measures of linear distance. All employ the familiar techniques of multiple wavelengths, chirped wavelength, optical feedback and intensity modulation, but in somewhat unfamiliar architectures. These examples serve to illustrate the breadth of solutions to this important problem. [DOI: 10.1117/1.1330702]

Subject terms: interferometry; laser diode; laser radar; distance measurement.

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1 Absolute Distance Measurement

There is clearly a great practical benefit to determining the absolute distance to an object without the fringe ambiguity that often accompanies interferometric measurements of distance. Bosch and Lescure provide a detailed review of absolute distance measurement including evolving solutions such as chirped-frequency optical feedback in laser diodes and picosecond time of flight laser radar.[1] The applications range from precision gauging of manufactured surface to large-scale coordinate measurements.

In this paper, I describe four laser-based techniques for absolute distance measurement using multiple-wavelength interferometry. I have selected example systems that differ from the more common systems that are part of the standard toolbox of solutions to emphasize the breadth of architectures in this rapidly evolving area of research.

2 Multimode Laser Diode Interferometry

The cyclic nature of interference phenomena results in the well-known fringe ambiguity in laser distance measurement. This problem has been solved in the context of precision gauge block measurement by a sequence of wavelengths to determine the absolute fringe order.[2,3] The simplest multiple-wavelength interferometer (MWI) involves only two wavelengths λ_1 and λ_2, for which it is customary to define a synthetic wavelength

$$\Lambda = \frac{1}{\sigma_1 - \sigma_2}, \tag{1}$$

where the wavenumber σ is the reciprocal of the laser wavelength. The synthetic phase Φ is the difference $\phi_1 - \phi_2$ between the interference phases for the two wavelengths taken individually. The synthetic phase evolves with distance much more slowly than the interference phase, making it easier to resolve 2π phase ambiguities:

$$\Phi = 4\pi L/\Lambda. \tag{2}$$

In some cases, combinations of synthetic wavelengths result in even larger, compound synthetic wavelengths.

Modern laser diodes are a natural source[4,5] for MWI, and complement the more established gas lasers for this application.[6] Two or more single-mode lasers locked to a Fabry-Pérot étalon provide high relative wavelength stability for large variations in optical path length.[7,8] An even simpler configuration for short path differences is one or more multimode laser diodes.[9,10] From the composite spectrum of Fig. 1, for example, one can select three or more wavelengths according to the need.

Figure 2 shows a three-wavelength multimode laser diode apparatus based on a fiber-coupled Michelson interferometer with a diffraction grating to separate the individual lasing modes. An array of detectors measures the interference effects as a function of emission line. A piezoelectric transducer (PZT) modulates the path difference and electronic processing employs the usual phase-shift algorithms to determine the synthetic phase Φ. An experimental instrument using IR laser diodes has a 0.5-nm measurement resolution over a 360-μm unambiguous range.[11] Example data in Fig. 3 show point-scanning profilometry of a spherical object performed without the usual (and often problematic) phase unwrapping procedure.

An even simpler configuration is made possible by a single, short external cavity (SXC) laser. Unlike conventional Fabry-Pérot type diodes, the SXC laser incorporates an additional reflecting surface about 100 μm behind the main cavity, resulting in three-walled resonator. Tuning this device away from its normal operating temperature generates emissions in two spectral regions separated by several nanometers, effectively simulating the superposition spectrum of two independent multimode laser diodes. Experiments with a Sharp LTO80 diode show that simultaneous synthetic wavelengths ranging from 356 to 0.16 mm are feasible with a single device.[12]

3 Chirped Synthetic Wavelength

In the previous examples, the multiple source wavelengths separate prior to detection by means of diffraction grating

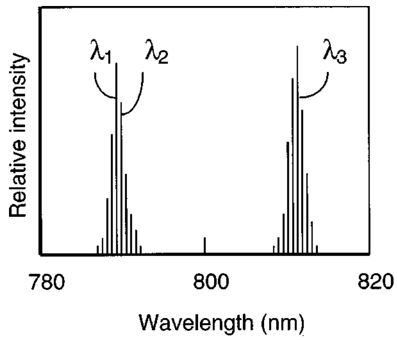

Fig. 1 Selection of emission lines from the combined spectrum of two multimode laser diodes.

(Fig. 2). An alternative approach advanced, e.g., by Dändliker and coworkers does not rely on optical separation of the wavelengths. Instead, heterodyne signals for two wavelengths beat against each other on a common detector, resulting in a *superheterodyne* signal.[13,14]

In the most familiar superheterodyne configuration, acousto-optic modulators and polarization encoding of the reference and measurement beams provide heterodyne optical signals at frequencies f_1 and f_2 corresponding to wavelengths λ_1 and λ_2. The optical signals are allowed to interfere incoherently on a common detector, resulting in an electronic signal of the form

$$I(t)=a_0+a_1\cos(2\pi f_1 t+\phi_1)+a_2\cos(2\pi f_2 t+\phi_2). \quad (3)$$

If the frequencies f_1 and f_2 are equal, the amplitude of the ac signal becomes[15]

$$P_{\mathrm{ac}}=a_1^2+a_2^2+2a_1a_2\cos(\Phi). \quad (4)$$

The phase Φ corresponds to the synthetic wavelength Λ directly, via Eq. (2). If we now vary or chirp the synthetic wavelength, the ac signal P_{ac} modulates and it is possible to perform desensitized phase-shifting interferometry (PSI) to determine Φ and, finally, the absolute distance L.

Note that Eq. (4) is a measure of the interference fringe contrast with a two-wavelength source. This observation is the starting point for a measurement technique called chirped synthetic wavelength interferometry, which relies

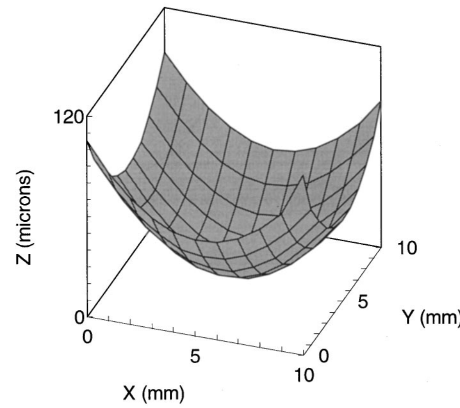

Fig. 3 Unambiguous surface profile data from the apparatus in Fig. 2.

on a continuously varying fringe contrast function by chirping the synthetic wavelength.[16] The resulting signal contains a great deal of information about the object distance.

The two single-mode tunable laser diodes shown in Fig. 4 generate a continuously variable synthetic wavelength via current tuning. The interference signal results from the mixture of light scattered from the object and the natural 4% Fresnel reflection from the end of a single-mode fiber. The 25 μW output beam from the graded index (GRIN) lens is 250 μm in diameter. The PZT generates a signal having essentially the same heterodyne frequency f for both wavelengths. The electronic processing consist of an analog demodulator and digital Fourier analysis of the resulting fringe-contrast signal.

The signal shown in the lower portion of Fig. 4 has two important characteristics, a synthetic phase Φ related to the average wavenumber separation of the lasers and a modulation frequency F related to the chirp rate. Combining the frequency and the phase information in the time-dependent fringe contrast determines absolute distance. The frequency is used to obtain a range estimate $2\pi F/\Lambda$, which is then used to remove the 2π ambiguity in the synthetic phase offset Φ.

Continuous calibration is critical to accurate metrology with laser diodes. Not shown in Fig. 4 is a calibration in-

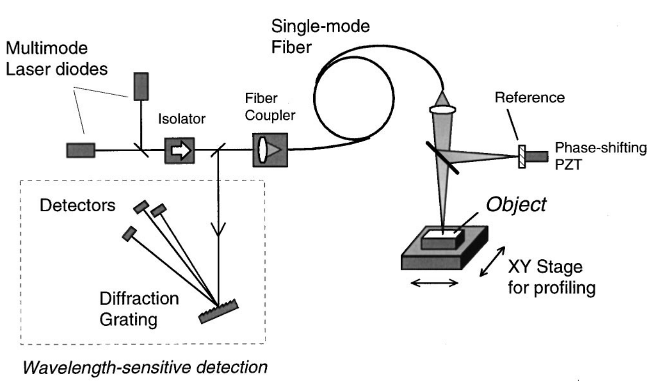

Fig. 2 Three-wavelength profilometer using a combination of two multimode laser diodes.

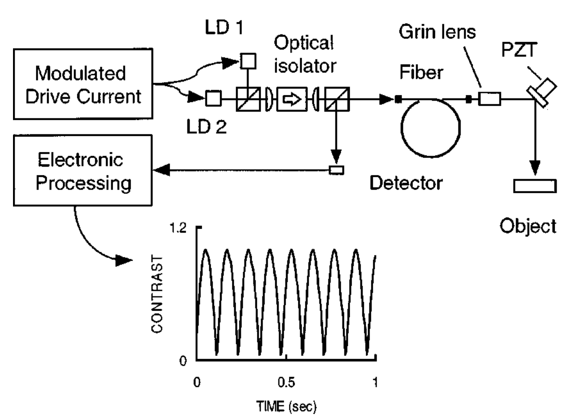

Fig. 4 Chirped synthetic wavelength interferometer and fringe-contrast signal.

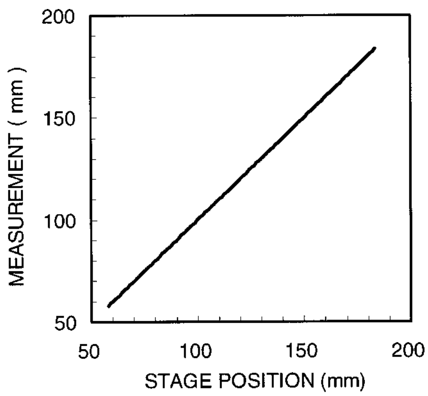

Fig. 5 Absolute distance measurement test using the CSW (chirped synthetic wavelength) apparatus of Fig. 4.

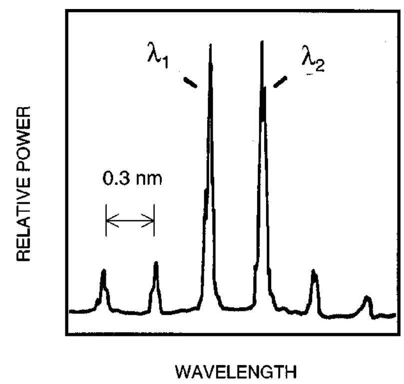

Fig. 7 Emission spectrum of a common inexpensive laser diode.

terferometer comprised of a compact, fiber-coupled Michelson with three parallel optical paths. The three paths provide enough information for unambiguous determination of wavenumber separation for the two lasers as well as the chirp excursion.[16]

The data in Fig. 5 show a sequence of distance measurements to a precision linear stage equipped with an optical encoder. The difference plot of Fig. 6 shows a standard deviation of 3 μm or about 0.002% of the 150-mm operational range. The system is also sensitive enough to measure nonspecular targets such as machined metals and stampings. A special sensor was also designed for measuring the inner diameter of drilled holes.[17]

4 Multimode Optical Feedback

The experimental systems of Figs. 2 and 4 both include an optical isolator. The isolator protects the laser from slight amounts of scattered light that might otherwise accidentally feed back into the laser cavity and disrupt normal operation. This optical feedback effect is especially troublesome in semiconductor laser diodes, because of their very high gain and low facet reflectivity.

Some researchers view the extreme sensitivity of laser diodes to optical feedback as an opportunity rather than a nuisance. A recent review paper by Donati and Merlo summarizes this point of view.[18] For small amounts of feedback (e.g., -40 dB of coupled intensity), the laser diode power and frequency are modulated periodically as a function of object position, very much like a conventional two-beam interferometer but without all of the auxiliary bulk optics.[19] The result is a feedback interferometer of very small size, low cost and easy construction. These characteristics are attractive for industrial applications.[20]

Most often, optical feedback interferometry entails measurement of power fluctuations in a single-mode laser diode. However, an equally interesting effect takes place when working with multimode devices. When a low-cost diode is lasing simultaneously in multiple longitudinal modes, weak feedback strongly influences the emission spectrum. This *mode modulation* phenomenon can be more dramatic than the more familiar forms of optical feedback effects.

The mode modulation for the spectrum in Fig. 7 is characterized by an oscillation of power between the principle lines. The lasing power shifts from one mode to the other when a feedback source moves one-quarter wavelength, just as one might suspect. If we now isolate a spectral line and monitor its power, we observe a very deep modulation of the signal even with very small amounts of optical feedback.

Figure 8 shows a simple apparatus to detect mode modulation induced by optical feedback. Rather than a diffraction grating, this system makes use of a tilted glass plate having a slight amount of wedge. The interference fringe pattern generated by the plate shifts position when the emission spectrum shifts from one mode to the next. A 1-kHz, 1-mA drive current modulation induces a continuous shifting of the fringe pattern, which a small detector picks up and converts to an electronic signal.

Figure 9 shows that the depth of mode modulation is strongly a function of distance. The periodicity is equal to

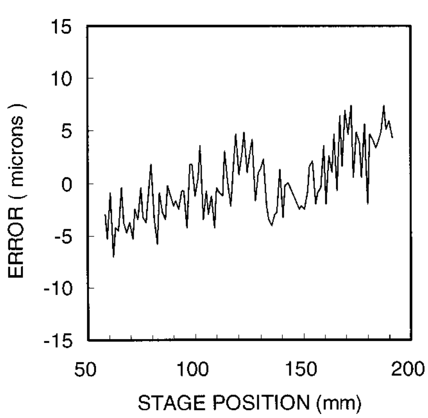

Fig. 6 Difference plot showing CSW measurement error with respect to a linear optical encoder.

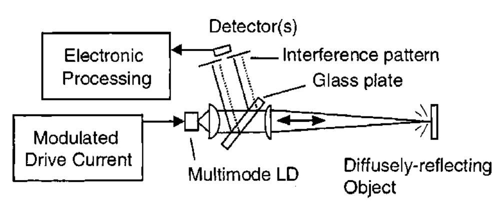

Fig. 8 Optical feedback "mode modulation" experimental apparatus.

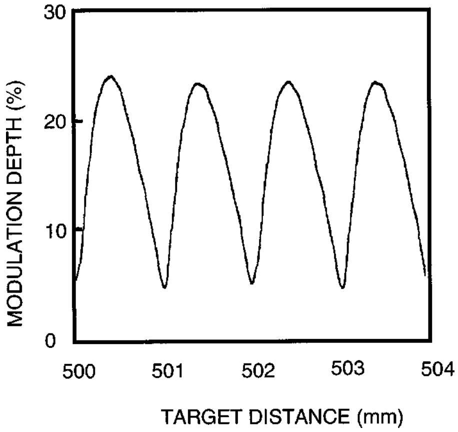

Fig. 9 Modulation depth for signals generated by the apparatus of Fig. 8.

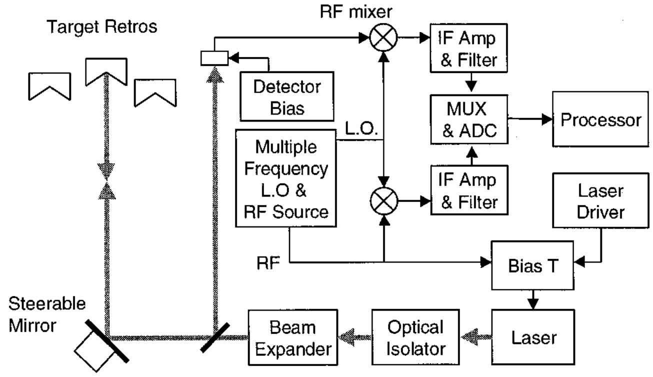

Fig. 10 Multiple frequency intensity modulated laser radar. IF=intermediate frequency, ADC=analog-to-digital converter.

the optical length of the laser cavity, just as one might have guessed. What is all the more remarkable is the actual value of the modulation depth, which at over 20% is two orders of magnitude greater than what is usually observed with optical feedback systems.

I have used the apparatus of Fig. 8 for several lab tasks, including long-term position monitoring, distance measurement and even some simple profiling. However, the instability in the emission spectrum of multimode lasers makes this simple design less suitable for an instrument product than other potential approaches, including the one I describe next.

5 Three-Frequency Intensity Modulated Laser Radar

Those of us who are fond of optical interferometry are occasionally guilty of neglecting more established incoherent techniques for measuring distance. With a short enough pulse width, for example, a traditional time-of-flight approach can have sufficient distance resolution to map surface profiles of coins.[21] Continuous wave intensity modulation is also a very viable approach.[22] Collins et al.[23] and Abbas et al.[24] have shown that a chirped radio frequency intensity modulation can be just as accurate as interferometric chirp laser ranging. Multiple-frequency intensity modulation is also an attractive option.[25]

Coordinate measurement systems based on intensity modulated laser radar are currently in use for high-precision metrology of large-scale structures. I describe one such system for determining absolute x,y,z position of small retroreflective targets for distances from 0 to 12 m by means of a laser radar integrated into a theodolite.[26] The laser radar employs a sequence of high-frequency intensity modulations of a laser diode so as to generate synthetic wavelengths, in much the same way as coherent MWI.

Figure 10 is a block diagram of the original experimental system.[†] A steering mechanism (e.g., theodolite) directs the measurement beam to several target objects in sequence. Three intensity modulation frequencies of 7.0, 7.012 and 7.3 GHz for the 7-mW, 1.3-μm laser provide a base wavelength of 5 cm and synthetic wavelengths of 1 and 25 m. Fourier analysis yields phase data to one thousandth of a cycle, sufficient for absolute distance measurements using a succession of wavelengths to a final accuracy of 25 μm. Atmospheric temperature and pressure are monitored and entered in the processor to correct for variation in the index of refraction.

Direct comparison of laser radar measurements with those of an interferometric displacement gauge over a 0- to 1.2-m range support an accuracy claim of better than 1×10^{-5}, which is competitive with more recent work in coherent synthetic wavelength interferometry. The advantage of intensity modulation for industrial applications is that the coherence properties of the laser are unimportant, and the accuracy burden is shifted to rf electronics. Eliminating the need for optical coherence also reduces speckle effects when ranging to nonspecular surfaces.

[†]R. L. Hagman and coworkers at the Boeing High Technology Center in Bellevue, WA constructed the original experimental laser radar in 1992.

6 Conclusions

The four experimental systems described here illustrate the variety of potential solutions for absolute distance interferometry. With continued research and the increasing availability of advanced light sources, we can expect more examples with higher performance and better adaptation to the needs of high-technology manufacturing and industrial metrology.

Acknowledgments

Portions of this work were completed while the author was at the Boeing High Technology Center in Bellevue, Washington, and at Hughes Danbury Optical Systems in Danbury, Connecticut.

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