# Two-wavelength interferometer based on a two-color laser-diode array and the second-order correlation technique

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A novel two-wavelength interferometer is demonstrated that uses a tunable two-color laser-diode array as the light source. The synthetic wavelength can be easily tuned from 2 to 0.043 mm by variation of the spectral separation between the two wavelengths of the laser output. By using the second-order correlation technique we can directly retrieve the phase change at the synthetic wavelength with no need for sophisticated electronic signal processing.

Two-wavelength interferometry is attractive for optical path-length and surface profile measurements because the measurement sensitivity can be increased and the range of unambiguity can be extended by use of a longer synthetic wavelength.[1] A number of techniques have been developed for determination of the interferometric phase at the synthetic wavelength. For example, two-wavelength phase-shifting interferometry is based on changing the phase difference between the two interfering beams either by the introduction of a piezoelectric transducer for modulation in one of the two arms[2] or by independent alteration of the drive currents of the two laser diodes.[3] The interference signal at the synthetic wavelength has also been determined by use of the heterodyne[4] or the superheterodyne detection[5] schemes; however, these techniques require rather sophisticated electronic postdetection signal processing. Numerical methods utilizing phase data at each wavelength have also been demonstrated.[2]

Experimentally, two-wavelength interferometry often requires precision alignment of two frequency-stabilized lasers. It would be a significant advantage if the two required wavelengths could be generated from a single laser diode. Simultaneous emission in two spectral regions from a multimode short-external-cavity laser diode operating near threshold was recently reported,[6] and a two-color light-emitting-diode array was also shown to provide relatively intense, stable illumination at two wavelengths.[7] The synthetic wavelength, however, could not be easily tuned with either method. The side-mode suppression ratios of these light sources were also quite poor.

In this Letter we report a novel design for two-wavelength interferometry. By use of the second-order correlation technique the interference phase at the synthetic wavelength can be directly extracted without postdetection signal processing. In addition, we use a tunable two-wavelength laser-diode array[8] (TWLDA) as the light source, simplifying both the optical system and the alignment.

Optical path-length measurement is usually performed by detection of the intensity variation of the interference fringes that results from the phase difference of light returning from the two arms of a Michelson interferometer. The output of the interferometer can be written as

$$|E_1(r_1)|^2 + |E_2(r_2)|^2 + 2\,\mathrm{Re}[E_1(r_1)E_2(r_2)^*], \quad (1)$$

where $E_1$ and $E_2$ are the optical-field amplitudes from the two arms of the interferometer. The last term of Eq. (1) is just the first-order correlation function, $G^{(1)}(r_1, r_2) = \langle E_1(r_1)E_2(r_2)^*\rangle$, where the angle brackets denote the time average.[9] Now consider a two-wavelength interferometer. If the intensity of each wavelength is equal to $I_0$, the interference fringe intensity is given by

$$I(L) = 2I_0 + 2I_0 \cos(2\pi L/\Lambda)\cos(2\pi L/\Gamma), \quad (2)$$

where $L$ is the single-pass optical path difference, $\Lambda = \lambda_1\lambda_2/|\lambda_1 - \lambda_2|$ is the synthetic wavelength, and $\Gamma = \lambda_1\lambda_2/(\lambda_1 + \lambda_2)$ is the average wavelength.

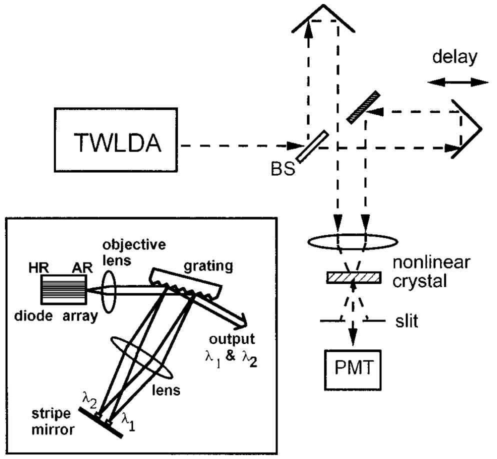

Fig. 1. Schematic of the two-wavelength second-order correlation interferometer. BS, beam splitter; PMT, photomultiplier tube; HR, highly reflective; AR, antireflective. The inset shows the configuration of the TWLDA.

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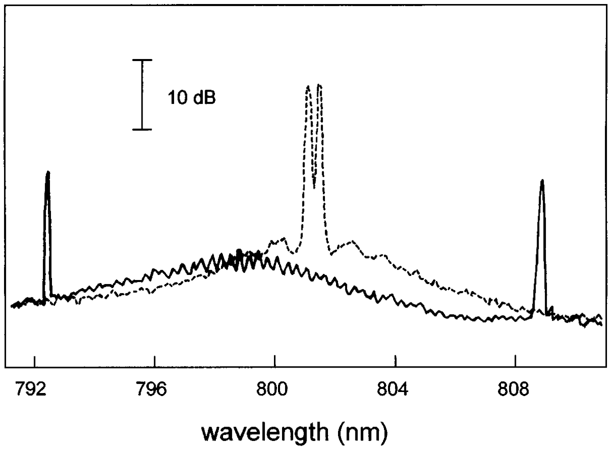

Fig. 2. Laser output spectra at the maximum and minimum spectral separation for $\Delta\lambda = 0.32$ nm (solid curve) and $\Delta\lambda = 17$ nm (dashed curve).

In the second-order correlation technique the configuration of the interferometer is the same as that of a noncollinear second-harmonic autocorrelator for optical pulse measurement[9] (see Fig. 1). The frequency-doubled output of the interferometer is just the second-order correlation function $G^{(2)}(L)$:

$$G^{(2)}(L) = (I_1 + I_2)^2 + 2I_1I_2 \cos(2\pi L/\Lambda), \tag{3}$$

where $I_1$ and $I_2$ are the intensities of the laser at $\lambda_1$ and $\lambda_2$. The phase at the synthetic wavelength as well as the optical path-length difference $L$ can be directly determined from the observed $G^{(2)}(L)$ since $\cos(2\pi L/\Lambda) = \{[2G^{(2)}(L) - G^{(2)}_{\text{max}} - G^{(2)}_{\text{min}}]/[G^{(2)}_{\text{max}} - G^{(2)}_{\text{min}}]\}$. This approach differs from the first-order correlation technique in that light intensities rather than amplitudes are compared.[9]

Figure 1 shows the experimental configuration. The inset shows the light source, a novel TWLDA.[8] The two-wavelength output is coaxial and of the same polarization. The wavelength separation is determined by the separation of the V-shaped double-stripe mirrors, which are used as spectral filters to select the two lasing wavelengths simultaneously. By moving the stripe mirrors vertically out or into the plane of the inset of Fig. 1 we can tune the spectral separation from 0.32 to 15 nm with a side-mode suppression ratio better than 20 dB (see Fig. 2). This corresponds to the generation of the synthetic wavelength from 2 to 0.043 mm. The total output power of the laser at minimum and maximum spectral separation was ~10 and 1 mW, respectively, when the diode was biased at 300 ± 1 mA and 20 ± 0.1 °C. The threshold current of the laser was 260 mA, and the coaxial output of the TWLDA was sent into an interferometer. A 2-mm-long beta-barium metaborate crystal was used to generate the second-harmonic signal that is detected by a photomultiplier tube and fed to a lock-in amplifier synchronized with the frequency of a mechanical chopper and plotter for readout.

Figure 3 shows the measured optical path difference as a function of actual displacement of the retroreflector at a synthetic wavelength of 0.112 nm. The corresponding spectral separation between the two wavelengths from the TWLDA is 5.7 nm. The accuracy of the distance measurement was limited by the sensitivity of detecting the second-harmonic signal. The frequency fluctuation of the TWLDA output and the mechanical stability of the chopper also contributed to the noise level. Since the phase measurement error was approximately $5 \times 10^{-2}$ rad, we estimated that the range resolution of the present system was ~1 $\mu$m at this synthetic wavelength. We could improve the accuracy by using a thicker second-harmonic crystal to enhance the signal and by replacing the mechanical chopper, which provides the reference signal to the lock-in amplifier, with an acousto-optic modulator.

By tuning the TWLDA to the minimum spectral separation of 0.32 nm we see that the synthetic wavelength $\Lambda$ is equal to 2 mm and the range of phase unambiguity is as large as 0.5 mm, as shown in Fig. 4. Since the phase measurement error remains the same while the synthetic wavelength is longer than in the previous case, the accuracy of the measured optical path difference deteriorates to ~10 $\mu$m.

If the synthetic wavelength is tuned from $\Lambda_1$ to $\Lambda_2$ while $L$ remains the same, the phase change can be expressed as $\Delta\phi = 2\pi L \Delta\Lambda/\Lambda^2$, where $\Delta\Lambda = |\Lambda_1 - \Lambda_2|$ is the difference between the two synthetic wavelengths $\Lambda_1$ and $\Lambda_2$. The absolute optical path difference $L$ can thus be determined by measurement of the phase change while the synthetic wavelength

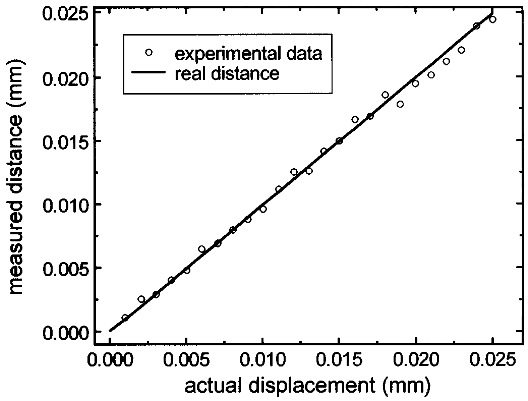

Fig. 3. Measured distance as a function of the actual displacement. The synthetic wavelength is 0.112 mm.

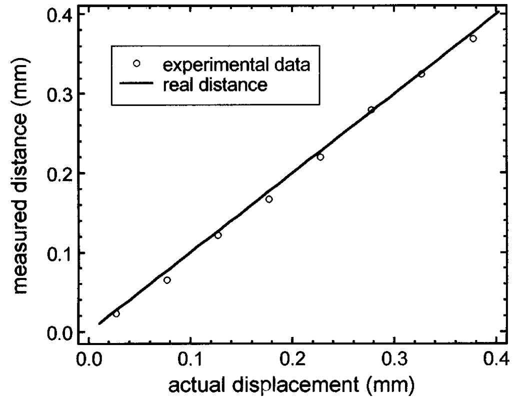

Fig. 4. Measured distance as a function of the actual displacement. The synthetic wavelength is 2 mm.

is tuned from $\Lambda_1$ to $\Lambda_2$. An additional advantage is that the range of unambiguity can be increased to a much longer distance than the synthetic wavelength since phase information at $\Lambda_1$ and $\Lambda_2$ is available.

In conclusion, we have proposed and demonstrated a novel two-wavelength interferometer. The synthetic wavelength is generated directly from the output of a two-wavelength laser-diode array and can be easily tuned from 2 to 0.043 mm. We can directly read out the phase change at the synthetic wavelength by using the second-order correlation function, and we can easily calibrate the absolute optical path difference by tuning the spectral separation of the two-wavelength laser output. The range resolution for the distance measurement was ~1 $\mu$m at a synthetic wavelength of 0.112 mm.

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