

# Frequency-comb-referenced two-wavelength source for absolute distance measurement

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We propose a new tunable laser source concept for multiple-wavelength interferometry, offering an unprecedented large choice of synthetic wavelengths with a relative uncertainty better than  $10^{-11}$  in vacuum. Two lasers are frequency stabilized over a wide range of frequency intervals defined by the frequency comb generated by a mode-locked fiber laser. In addition, we present experimental results demonstrating the generation of a  $90\ \mu\text{m}$  synthetic wavelength calibrated with an accuracy better than 0.2 parts in  $10^6$ . With this synthetic wavelength we can resolve one optical wavelength, which opens the way to absolute distance measurement with nanometer accuracy.

Two-wavelength interferometry allows absolute distance measurements<sup>1,2</sup> over a range defined by the synthetic wavelength<sup>1</sup>  $\Lambda = \lambda_1 \lambda_2 / (\lambda_1 - \lambda_2) = c / \Delta\nu$ , where  $\lambda_1$  and  $\lambda_2$  are the individual wavelengths. Starting from a long synthetic wavelength (e.g., 1 m), a nanometer-level accuracy can be ultimately achieved by gradually decreasing  $\Lambda$  until single-wavelength interferometry is performed. This requires the capability to resolve an optical wavelength; thus the accuracy obtained with the smallest synthetic wavelength must be better than  $\lambda/4$ . The measurement accuracy at large distances may be limited by the instability and uncertainty of the synthetic and optical wavelengths. We propose a new concept of a tunable two-wavelength laser source stabilized with high accuracy and over large frequency ranges that replaces the previously used frequency comb of a Fabry–Perot resonator<sup>3</sup> with the highly accurate frequency comb of a femtosecond (fs) laser. The use of an optical frequency comb has been recently proposed for gauge block length calibration.<sup>4</sup> However, the reported detection technique is based on consecutive measurements at different wavelengths and therefore requires high mechanical stability during the measurement time. We present in this Letter a tunable two-wavelength source with which dynamic distance measurements with nanometer accuracy can be achieved by means of superheterodyne interferometry.<sup>4</sup>

An active frequency comb is based on a fs mode-locked laser,<sup>5</sup> whose repetition rate,  $f_{\text{rep}}$ , defines exactly the frequency separation between two adjacent modes of its frequency spectrum. Several cw lasers can be locked to different modes of the comb by beat frequency measurements and electronic phase locked loops. The stability of the laser frequency separation is determined entirely by the relative stability of the frequency reference used to control the repetition rate of the fs laser. To cancel the frequency drift of the comb, either the comb can be self-referenced<sup>6</sup> or one of the lasers can be locked onto a molecular transition and the comb locked to that laser through control of the comb offset.

The tunable two-wavelength source (Fig. 1) consists of a Nd:YAG laser ( $\lambda_1 = 1.319\ \mu\text{m}$ , Lightwave Model 125), an external cavity laser diode (ECLD,  $\lambda_2 \sim 1.3\ \mu\text{m}$ , Thorlabs INTUN 1300), and finally a mode-locked fiber laser (Menlo Systems TC-1500). A 10 MHz frequency reference with a relative uncertainty of  $<10^{-11}$  is provided to the comb by a radio-controlled master clock synchronized to the carrier frequency of the Swiss time signal (HBG), which is derived from an atomic clock. This reference is used by the TC-1500 to generate two subreferences (100 and 20 MHz) with the same relative uncertainty. The concept of the mutual stabilization (Fig. 2) of the lasers is as follows: one comb mode of the mode-locked fiber laser is locked to the master Nd:YAG laser, and

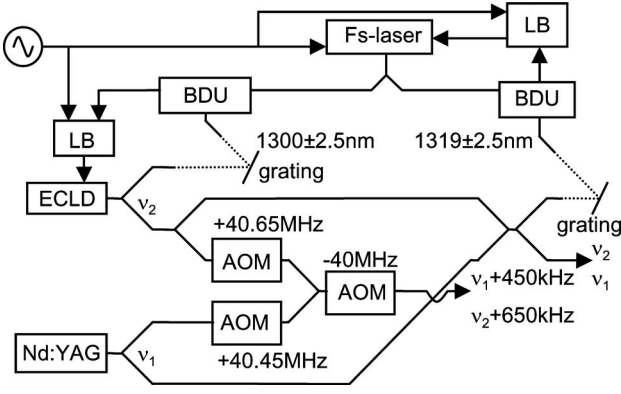


Fig. 1. Schematic of the frequency-comb-referenced light source. The beat detection unit (BDU) generates the beat signal between two lasers and feeds the lock box (LB), which contains a phase sensor and a proportional–integral regulator. The two pairs of optical frequencies,  $(\nu_1, \nu_1 + 450 \text{ kHz})$  and  $(\nu_2, \nu_2 + 650 \text{ kHz})$ , are generated by means of acousto-optic modulators (AOMs).

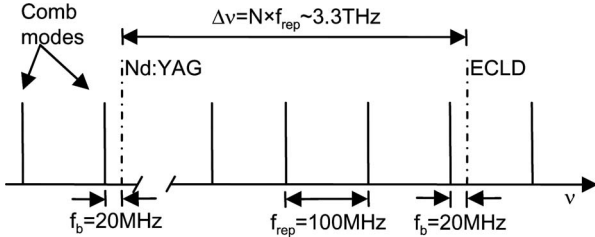


Fig. 2. Simplified sketch of the optical spectrum of the comb combined with the Nd:YAG and the ECLD. The repetition rate of the pulsed laser is  $f_{\text{rep}} = 100 \text{ MHz}$ ;  $f_b = 20 \text{ MHz}$  is the reference frequency used by the phase-locked loop.

the ECLD is locked in turn to another comb mode. In practice, the repetition rate is phase locked to the 100 MHz reference signal by changing the pump power of the fs laser. For each cw laser, the beat signal  $f_b$  with the closest mode of the frequency comb is detected and phase locked to the 20 MHz signal. The frequency comb is stabilized on the Nd:YAG laser by controlling the length of its cavity. The ECLD is locked to the comb by tuning its injection current.

The beat frequency fluctuations of the Nd:YAG and of the ECLD with their closest frequency comb mode were measured by a frequency counter (HP53131A) with a gate time of 1 s. We measured fluctuations below 1 Hz for both cw lasers. In vacuum, the synthetic wavelength is given by the light velocity,  $c$ , divided by the frequency difference between the two lasers,  $\Delta\nu$  (Fig. 2):

$$\Lambda = \frac{c}{\Delta\nu} = \frac{c}{(Nf_{\text{rep}})}, \quad (1)$$

where  $N$  is the number of modes between the two cw lasers. When  $N$  is known, the uncertainty of the synthetic wavelength in vacuum is limited mainly by the uncertainty of the master clock.

An experiment based on superheterodyne interferometry<sup>2</sup> (Fig. 3) was set up to calibrate the synthetic wavelength in air and to prove the feasibility

of resolving an optical wavelength. For that purpose, we directly operated with a small synthetic wavelength  $\Lambda \approx 90 \mu\text{m}$  ( $\Delta\nu \approx 3.3 \text{ THz}$ ). For each laser, acousto-optic modulators generate two orthogonal polarizations of slightly different frequencies. These heterodyne frequencies are  $f_1 = 450 \text{ kHz}$  for the Nd:YAG and  $f_2 = 650 \text{ kHz}$  for the ECLD. These two orthogonal polarizations propagate in a polarizing Michelson-type interferometer. Two photodetectors produce reference and interferometer signals of the form

$$I(t) = A_1 \cos(2\pi f_1 t + \phi_1) + A_2 \cos(2\pi f_2 t + \phi_2), \quad (2)$$

which is the sum of the two heterodyne signals for the wavelengths  $\lambda_1$  and  $\lambda_2$ , with the corresponding interferometric phases  $\phi_1 = 4\pi n_1 L / \lambda_1$  and  $\phi_2 = 4\pi n_2 L / \lambda_2$ ;  $n_1$  and  $n_2$  are the index of refraction at  $\lambda_1$  and  $\lambda_2$ , respectively. After amplitude demodulation, one obtains a signal of frequency  $f_2 - f_1$  and phase  $\Phi = \phi_2 - \phi_1$ . In air, the phase is

$$\Phi = \frac{4\pi}{\lambda_2} n_2 L - \frac{4\pi}{\lambda_1} n_1 L = \frac{4\pi}{\Lambda_c} n_2 L, \quad (3)$$

with

$$\Lambda_c = \frac{c}{\Delta\nu + [(n_2 - n_1)/n_2]\nu_1}, \quad (4)$$

where  $\nu_1 = c/\lambda_1$ . We note that this new definition of the synthetic wavelength differs from Eq. (1) because of the air dispersion between  $\lambda_1$  and  $\lambda_2$ . The phase  $\Phi$  is measured by a digital phasemeter (resolution of  $2\pi/1024$ ) with the ability to count the number of  $2\pi$  cycles.

The performance of our prototype is verified by comparison with a HP 5529A interferometer [ $\lambda_{\text{HP}} = 633 \text{ nm}$ , accuracy  $\pm 0.02$  parts in  $10^6$  (ppm)], as shown in Fig. 3. The beam of the HP laser is superimposed on the two-wavelength source with an accuracy of  $\pm 3 \text{ mm}$  over 6 m, reducing the cosine error to 0.13 ppm. The length of the interferometer target arm was scanned over 90 cm in steps of 50 mm. After each step, the phase  $\Phi$  and the optical path difference at 633 nm are measured by means of the digital phasemeter and the HP interferometer, respectively.

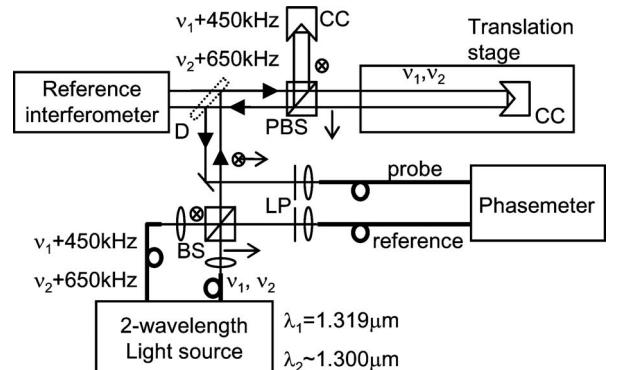


Fig. 3. Setup for the calibration of the synthetic wavelength. (P)BS, (polarizing) beam splitter; CCs, corner cubes; LP, linear polarizer; D, dichroic plate.

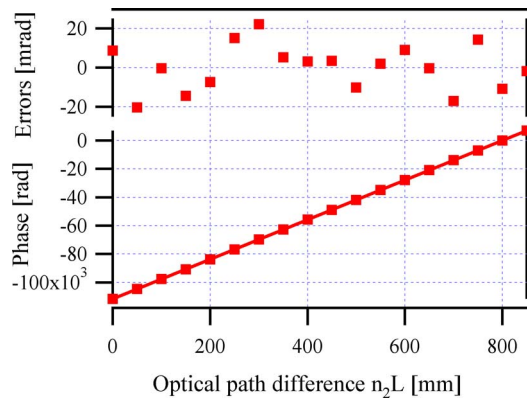


Fig. 4. Experimental results of the phase measurement as a function of the optical path difference.

The optical path difference  $n_2L$  at  $1.3 \mu\text{m}$  is calculated by taking the air dispersion into account. The integration time of the phasemeter was 2 ms. Results are shown in Fig. 4. The linear regression gives a slope  $m = 139.541582 \text{ rad/mm}$  with a standard deviation  $\sigma_m = 11 \mu\text{rad/mm}$ , yielding a synthetic wavelength in air of  $\Lambda = 90.054666 \mu\text{m}$ . The residual errors are lower than  $\delta\Phi = 22 \text{ mrad}$ . Therefore the distance accuracy is  $\delta\Lambda = \Lambda \delta\Phi / 4\pi \approx 160 \text{ nm} < \lambda_1/4$ , thus enabling the gap to be bridged with interferometric measurements at  $\lambda$  to reach a nanometer accuracy. The frequency difference can be calculated by using Eqs. (3) and (4):

$$\Delta\nu = \frac{c}{4\pi}m - [(n_2 - n_1)/n_2]\nu_1. \quad (5)$$

The correction term  $[(n_2 - n_1)/n_2]\nu_1$  is estimated from the updated Edlen equations.<sup>7</sup> For  $\lambda_1 = 1319 \text{ nm}$  and  $\lambda_2 = 1300 \text{ nm}$ , we found a correction of about 5.77 MHz. The uncertainty of  $\Delta\nu$  is caused mainly by the uncertainty of  $m$  and the cosine error. We estimated a frequency difference  $\Delta\nu = (3.32899949 \pm 0.00000067) \text{ THz}$  at a confidence level of 95%. The relative accuracy of this calibration is better than 0.2 ppm. Within this uncertainty range, we see that the frequency difference corresponds to  $N = 33,290$  modes of the comb.

In conclusion, we have proposed a novel concept of highly stable multiple-wavelength light sources in which an optical frequency comb is used to stabilize cw lasers with frequency differences as large as several terahertz. Applied to two-wavelength interferometry, this technique permits the generation of synthetic wavelengths from tens of micrometers to several meters. Assuming that the number of modes between the two lasers is known, the accuracy of the frequency difference and of the vacuum synthetic wavelength is limited only by the relative uncertainty of the radio frequency reference signal feeding the comb. In air, it is limited by the dispersion. We have verified experimentally that the two-wavelength source can generate synthetic wavelengths as small as  $90 \mu\text{m}$  with an accuracy better than 0.2 ppm. With a phase accuracy better than  $2\pi/200$ , this synthetic wavelength allows us to resolve the optical wavelength and to reach a nanometer accuracy. With the frequency tuning capacity of the ECLD, the two-wavelength source should permit long-distance measurements with very high accuracy by using a chain of highly accurate synthetic wavelengths.

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