Absolute frequency measurements of the 532 nm radiation recommended for the realization of the metre.

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Abstract. Absolute frequency measurement at the International Bureau of Weights and Measures of an iodine-stabilized Nd:YAG laser with $\lambda \approx 532$ nm is reported. The reference laser system Nd:YAG-C stabilized to the a_{10} component in the R(56) 32-0 line was measured using an optical femtosecond comb set-up. The frequency found was 563 260 223 510.4 kHz with a standard uncertainty of $u_c = 0.2$ kHz. A simplified scheme was used in which the absolute frequency measurements were made possible while controlling only the repetition rate of the comb; this reduces the control of the frequency comb to a one-dimensional problem.

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Introduction.

In 1983, the present definition of the metre was adopted based on a fixed value of the speed of light [1, 2]. At that time a list of five well-defined frequencies provided by frequency-stabilized laser sources was recommended; this list has subsequently been revised several times and now includes some 20 different radiations [3]. One of these radiations is provided by frequency-doubled iodine-stabilized Nd:YAG lasers at $\lambda \approx$ 532 nm. This type of diode-pumped solid-state laser is an excellent tool for metrology, combining high power, single frequency and low noise.

Excellent results using external modulation techniques at $\lambda \approx$ 532 nm have been demonstrated by Hall and co-workers [4-5] and recently by Robertsson et al. [6]. For some years the International Bureau of Weights and Measures (BIPM) has developed standards at this wavelength, and currently maintains three systems, named Nd:YAG-A, -B and the recently finished -C.

In the last few years direct frequency measurements of optical frequencies have been made possible using femtosecond-laser-based optical combs [7-9]. This has brought about an enormous change to the conditions and possibilities in frequency metrology. The new comb technique has already been applied to a considerable number of absolute frequency measurements. In particular, frequency measurements on Nd:YAG-B were reported in early 2003 [10]. Additional measurements are reported here on the new Nd:YAG-C system.

Experimental and results

The optical comb set-up named BIPM-C1 has been described in detail elsewhere [10]. It is composed of a femtosecond laser of four-mirror ring-type cavity, with a repetition rate f_{r} of about 740 MHz, and is contained in a sealed aluminium box. The photonic crystal fibre and the self-referencing set-up [9], for detection of the carrier-envelope-offset signal f_{CEO}, were mounted on the same optical table but without additional protection. Typically an f_{CEO} signal to noise ratio (S/N) of 45 dB to 55 dB (given for a 300 kHz bandwidth) was obtained. The frequency of each comb line f_N can be expressed as

$$f_N = f_{\mathrm{CEO}} + N \times f_{\mathrm{r}} \ ,$$

where N is an integer number giving the mode order.

The frequency-doubled Nd:YAG laser locked to the a_{10} component in the R(56) 32-0 line was kept on a different table. The laser is frequency stabilized using modulation-transfer saturation spectroscopy [11] with a modulation frequency of 350 kHz and a modulation index of 1.4. A saturation beam with a diameter of 2.7 mm and a power of 4.77 mW was used. The cold finger of the 40 cm long iodine cell (BIPM/NIM 339) was kept at –15.0 °C and radiation at 1064 nm was transferred to the comb table by means of an optical fibre. Some 17 mW of the IR radiation of the Nd:YAG laser was superimposed on the comb light on an InGaAs PIN photo-detector giving a beat, $\delta = \pm(f_{1064} - f_N)$, with a S/N of some 45 dB. The two signals f_{CEO} and δ were after appropriate filtering and amplification fed to a double balanced mixer (see Fig. 1).

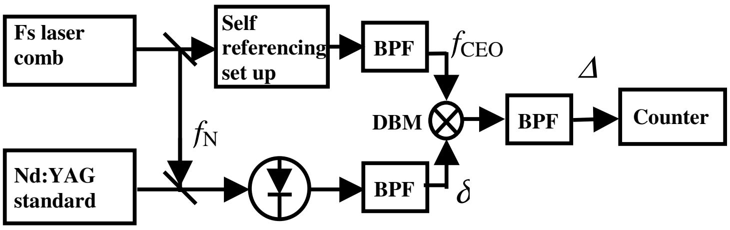

Fig. 1 Experimental arrangement to measure the frequency of a iodine stabilised Nd:YAG laser standard. BPF – Band pass filter. DBM – Double balanced mixer.

The resulting sum or difference signal, $\Delta = \delta \pm f_{\mathrm{CEO}}$, with a typical S/N of 40 dB to 45 dB, can be tuned by changing the f_{r}, to appear within a range of a few megahertz (allowing for relatively narrow band filtering) and counted directly. Fig. 2 shows such a recording of ~560 one second samples. The corresponding relative stability is depicted in Fig. 3. The short-term stability is limited by the noise of the frequency synthesizer used for the phase lock of f_{r}.

The frequency of the laser standard is obtained as

$$f_{1064} = f_N \pm \delta = f_{\mathrm{CEO}} + N \times f_{\mathrm{r}} \pm (\Delta \pm f_{\mathrm{CEO}}) = N \times f_{\mathrm{r}} \pm \Delta) \, .$$

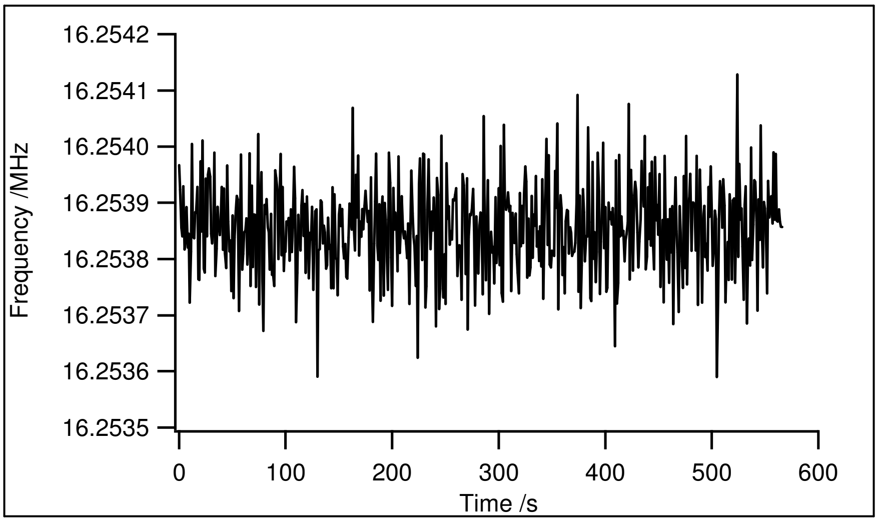

Fig. 2. Recording of the *Δ* beat. A 1 s gate time was used.

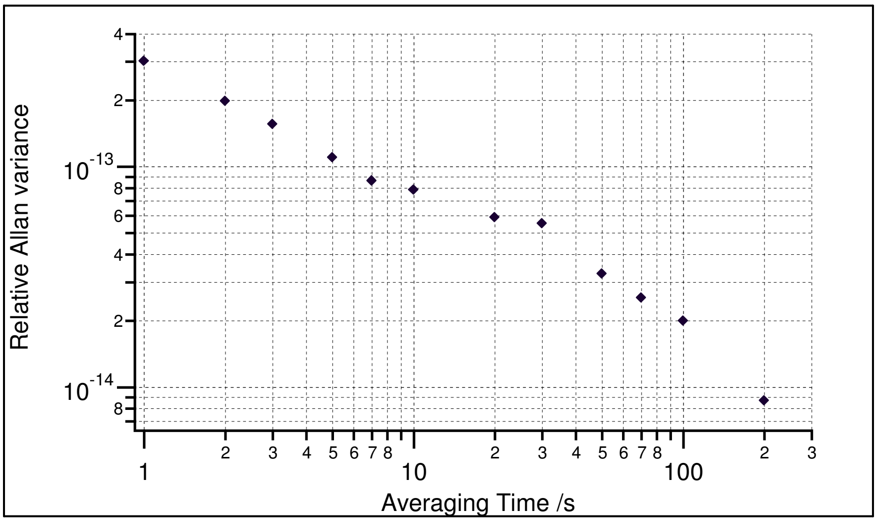

Fig. 3 Relative Allan variance of the recorded beat.

It is seen that the laser standard frequency, f_{1064}, is obtained without knowledge of the f_{CEO}. The f_{r} is known since it is phase-locked to the synthesizer and the Δ is found by counting this frequency. The frequency of the 1064 nm light of the stabilized laser was found to be

$$f_{1064} = 281\ 630\ 111\ 755.2 \text{ kHz}\ ,\quad u_{\mathrm{c}} = 0.1 \text{ kHz}.$$

The frequency for the a_{10} component of the R(56) 32-0 line can then by found as twice this frequency:

$$f(a_{10}) = 563\,260\,223\,510.4 \text{ kHz}, \; u_c = 0.2 \text{ kHz}.$$

This value can be compared to the recommended value [3], which is 563 260 223 513 kHz. The estimated uncertainty budget at the wavelength 532 nm is given in Table 1. The frequency value found for the C-system agrees well with that earlier found for the B-system which is 563 260 223 510.8 kHz , u_c =0.2 kHz [10].

Table 1. Uncertainty budget at 532 nm wavelength.

Parameter	value	uncertainty		Sens coeff.		δf /Hz
alignment	0	0.016*	mrad	Non linear		34*
offset	0	0.15	mV	1100	Hz/mV	165
temperature	-15	0.1	°C			
pressure	0.812	0.0093	Pa	2.8	KHz/Pa	26
modulation	1.4	5	%	5	Hz/%	25
cell wall temp	20	0.4	°C	200	Hz/°C	80
light power	4.8	0.3	mW	100	Hz/mW	30
Comb meas.						42
						195

* Repeatability (one σ)

Conclusion

The normal operating scheme for an optical comb is to phase-lock both the repetition rate, f_r , and the carrier-envelope-offset frequency, f_{CEO} to the reference RF oscillator through two frequency-synthesizers. The actuators on the laser are normally a piezo-ceramic for the control of f_r and an acousto-optic modulator or sometime an electro-optic modulator for the control of f_{CEO}. This thus constitutes a two-dimensional feedback system in which the two channels are non-orthogonal. Here, a technique was used with which absolute frequency measurements using a femtosecond laser comb are possible while controlling only its repetition rate. The f_{CEO} is eliminated in the detected beat and therefore need not be controlled or measured. This scheme resembles measurements made on a f/2f system where the f_{CEO} beat is similarly eliminated [12]. However, the present technique can also be applied to a more general group of standards such as the iodine-stabilized HeNe laser at 633 nm which is the most common laser standard for length applications.

The excellent short-term stability of the Nd:YAG lasers, in combination with their f/2f emission, can be used as a flywheel for the comb - providing a stable RF while the interrogation of an optical clock is taking place. Likewise, by transferring the Nd:YAG laser stability to the comb-lines, an RF source with high short-term stability is generated: this could become a useful tool in time-transfer experiments. This type of diode-pumped solid-state laser has been also shown to be an excellent tool for metrology, combining high power, single frequency and low noise.

Continued study of the characteristics of this type of stabilized laser systems is therefore justified to further improve their performance. The frequency found in this measurement agrees well with that observed in earlier measurements of the Nd:YAG-B system but lies almost 3 kHz below the current recommended value.

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