A transportable optical frequency comb based on a mode-locked fibre laser

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Abstract

A new transportable frequency comb has been developed at the National Physical Laboratory. The transportable frequency comb is based around a MenloSystems FC1500 Optical Frequency Synthesizer, which is capable of measuring any frequency between 0.5 and 2.1 μm. Measurements made by the comb are referenced to the SI second via a GPS-disciplined Rapco 2804AR rubidium oscillator. All components of the system are mounted on a mobile aluminium frame. This paper describes measurements of a high-stability narrow-band optical source using this system, with either the GPS-disciplined oscillator or a hydrogen maser as a reference. Some of these measurements were made simultaneously with a hydrogen maser-referenced Ti:Sapphire-based comb. It was found that the GPS-referenced transportable comb had an accuracy of approximately 9.0×10^{-13} (averaged over several hours) when compared to the maser-referenced Ti:Sapphire comb, and a stability of 1.0×10^{-12} at 10 seconds.

Introduction

Femtosecond optical frequency combs enable the measurement of the frequency of any optical signal through the direct down-conversion into RF-frequency signals, which can then be counted using conventional electronics. The frequency of an optical signal may therefore be measured relative to RF standards such as the hyperfine 9.2 GHz ^{133}Cs transition that currently defines the second, or relative to any other optical frequency [1].

The frequency comb is therefore a vital component in the optical metrology toolkit. However, often one of the main obstacles to measuring the frequency of an optical signal is that light must be brought from the source of the signal to the comb. It will often be the case that a laboratory will not have its own frequency comb; a transportable frequency comb would therefore be extremely useful in those cases where the source apparatus is too bulky or heavy to be moved.

This paper discusses a transportable frequency comb that has been developed at the National Physical Laboratory.

Femtosecond optical frequency combs

The femtosecond comb is based on a mode-locked laser, which produces a train of regularly timed pulses. The spectrum of such a laser consists of a number of coherent modes spaced in frequency by the repetition rate of the pulses, f_{rep} (figure 1). The frequency of the nth mode of the comb is $f_n = n f_{\mathrm{rep}} + f_0$ where f_0 is an offset frequency due to the difference between the phase and group velocity of light in the laser cavity: $f_0 = \Delta\phi f_{\mathrm{rep}} / 2\pi$ ($\Delta\phi$ is the phase shift between successive pulses). If f_{rep} and f_0 are known then the absolute frequency of an unknown signal f_s may be found by beating it with one of the comb modes, as $f_s = n f_{\mathrm{rep}} \pm f_0 \pm f_{\mathrm{beat}}$, where f_{beat} is the frequency of the beat between the unknown signal and the comb mode.

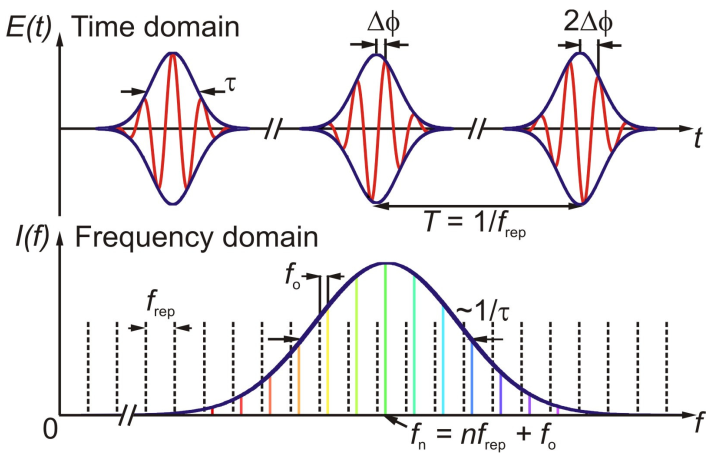

Figure 1: Pulses from a mode-locked laser in the time domain and in the frequency domain.

The offset frequency f_0 may be determined if the comb spectrum extends over a full octave. A portion of the long-wavelength end of the spectrum may then be frequency-doubled and recombined with the short-wavelength end. The beats between the comb modes $f_n = n f_{rep} + f_0$ and the frequency-doubled modes $2f_m = 2m f_{rep} + 2f_0$ with $n = 2m$ will all have the frequency f_0.

The MenloSystems Optical Frequency Synthesizer

The NPL transportable frequency comb is based around a MenloSystems FC1500 Optical Frequency Synthesizer [2]. This has a mode-locked erbium-doped fibre laser operating at 1.5 µm, the output of which is split into three branches (figure 2). Each branch is coupled into an erbium-doped fibre amplifier (EDFA). Light from the first branch is sent through a length of microstructured optical fibre, which broadens the spectrum to an octave by self-phase modulation. A nonlinear (f:2f) interferometer is then used to derive and stabilize the offset frequency f_0.

The beam in the second branch is frequency-doubled and then spectrally broadened, giving an output range of 530 – 1000 nm (40 mW). In the third branch the fundamental light is spectrally broadened, giving approximately 170 mW between 1000 and 2100 nm.

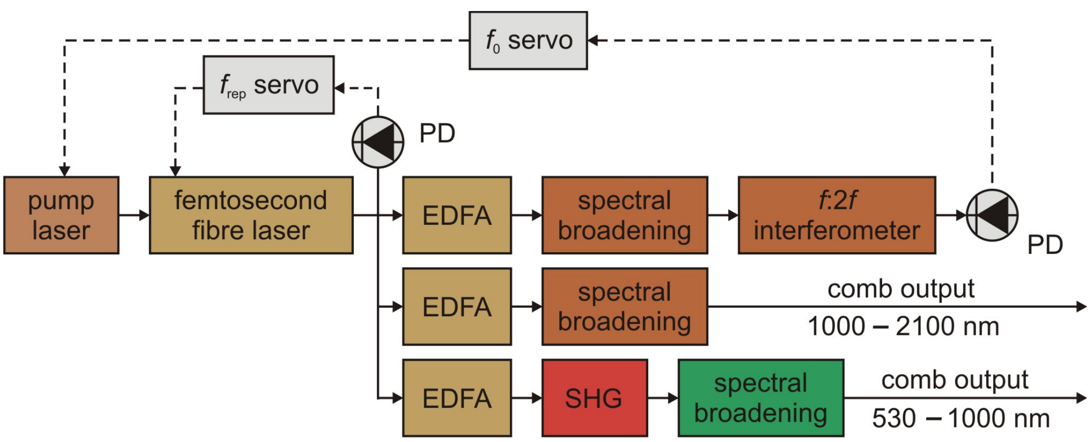

Figure 2: Layout of the MenloSystems FC1500 Optical Frequency Synthesizer.

The GPS-disciplined reference signal

The frequency comb requires a reference signal to relate the measured frequency of the source to the SI second. A highly accurate and stable signal is required for this, and the NPL transportable comb uses the 10 MHz output from a Rapco 2804AR master clock, which contains a rubidium reference oscillator. This oscillator is disciplined by an antenna link to the GPS network [3]. In turn, the 2804AR unit disciplines a separate Rapco 803M quartz oscillator, which gives superior stability at short time-scales. Figure 3 shows the stability of the signal from the quartz oscillator (while locked to the GPS-disciplined Rb oscillator) compared to the 10 MHz output from a hydrogen maser, as measured using a phase comparator with another hydrogen maser as a reference. A back-up power supply is provided so that power to the 2804AR unit is not interrupted during transit, as several days are required for the signal to attain maximum stability after turn-on.

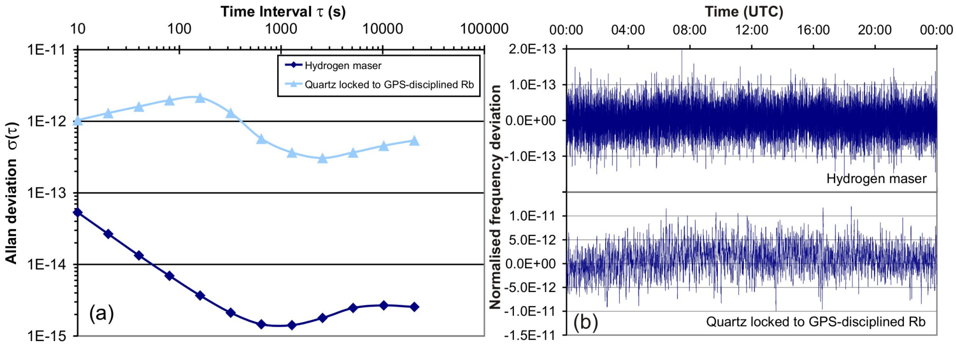

Figure 3: (a) The Allan deviation of 10 MHz signals from the quartz oscillator locked to the GPS-disciplined rubidium oscillator and hydrogen maser compared with another hydrogen maser. (b) The frequency deviation of these two signals averaged over 10 s. These measurements were taken on a different day to the comb measurements shown in figure 4.

Mounting arrangement

All components of the MenloSystems FC1500 (laser, amplifiers, opto-mechanics and rack electronics) and the Rapco timing system are mounted on a wheeled aluminium frame. The entire system has dimensions 1.21 m (height), 0.95 m (width) and 1.72 m (length).

Frequency measurements of high-stability optical signals

Measurements were performed of the frequency of a 934 nm Ti:Sapphire laser stabilised to a high-finesse Fabry-Pérot cavity [4] using the transportable comb. A simultaneous measurement of this frequency was undertaken using another comb based on a femtosecond Ti:Sapphire laser [5]. This comb was referenced to a hydrogen maser, while the transportable comb was referenced to the maser at the beginning and end of the measurement period and to the GPS-disciplined unit otherwise (figure 4).

The Allan deviations of these measurements at 10 seconds were 1.0×10^{-12} and 2.4×10^{-13} (GPS- and maser-referenced transportable comb respectively) and 1.8×10^{-13} (maser-referenced Ti:Sapphire comb). The mean of the GPS-referenced transportable comb measurements relative to that of the maser-referenced Ti:Sapphire comb was +286 Hz, which as a fraction of the laser frequency is $+9.0 \times 10^{-13}$. This gives a measure of the accuracy of the GPS-referenced transportable comb, and agrees well with measurements of the accuracy of the GPS signal, which can deviate from the maser signal frequency by up to 3 parts in 10^{12} for averaging times of a few hours.

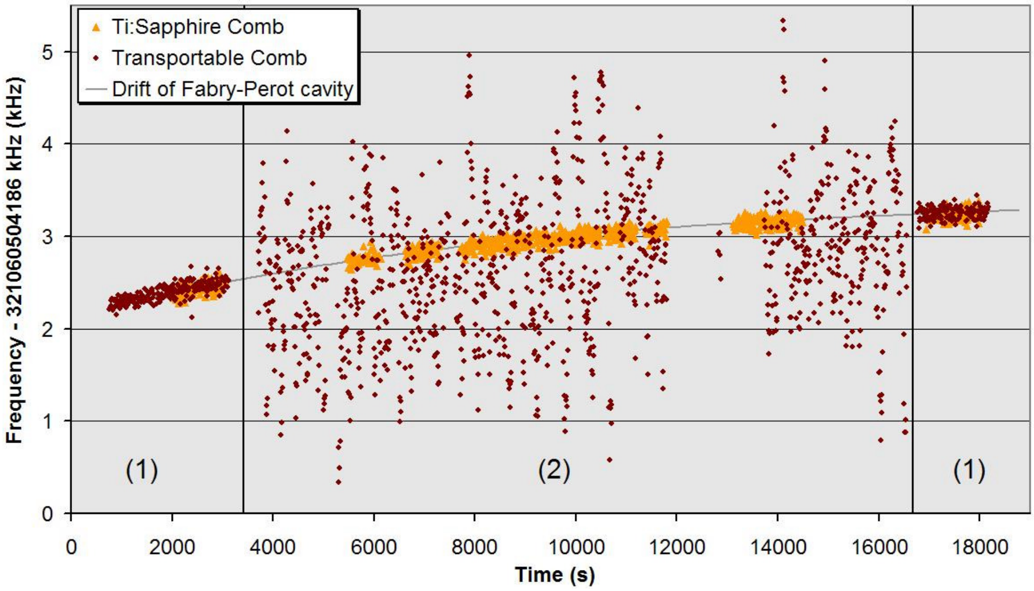

Figure 4: Frequency measurements of a high-finesse cavity stabilised Ti:Sapphire laser. During the periods marked (1) the transportable comb was referenced to a hydrogen maser; in the period (2) it was referenced using the GPS unit.

Conclusions

A transportable frequency comb has been developed at NPL and a comparison has been performed between this comb and a hydrogen-maser referenced Ti:Sapphire comb. It has been shown that the transportable comb has a similar stability and accuracy to the Ti:Sapphire comb when the same RF reference is used. When a GPS-disciplined oscillator is used as a reference, the transportable comb has an accuracy of approximately 10^{-12} over several hours and a stability of about 10^{-12} over 10 seconds.

Acknowledgments

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References

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