Optical frequency metrology based on photon counting

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Low power can be a concern for traditional calibration of frequency-stabilized laser sources against a reference using the heterodyne beating technique. Here, the relative difference between standard and test sources is obtained at few-photon level from correlated photon counts in a Hong-Ou-Mandel interferometer. Uncertainty is computed and results are validated against traditional heterodyne measurement system.

INTRODUCTION

Practical realization of the meter is based on standard frequencies recommended by the International Committee for Weights and Measures – CIPM [1], including stabilized laser sources (for example, a He-Ne laser referenced to a hyperfine transition $^{127}I_2$ molecule). A secondary laser is calibrated against this reference standard by heterodyne beating of optical frequencies. This well-known technique translates optical frequencies into their difference, f_{beat}, as $I(t) \propto \sqrt{I_1 I_2}\cos(2\pi f_{beat} t)$, where $I_{1,2}$ are optical intensities. The resulting signal is measurable in the RF range, provided the frequency difference, $f_{beat} = |\nu_1 - \nu_2|$, is within the bandwidth of the detection instrumentation. However, low intensity limitation is a practical concern that can jeopardize the measurement capability.

Two-photon interference in a Hong-Ou-Mandel (HOM) interferometer is also a well-known phenomenon [2]: two photons entering a symmetric beam splitter (BS) through different ports tend to bunch together at a random output whenever they are fundamentally indistinguishable. Thus, scanning the relative output temporal modes while monitoring the coincidences between single-photon detectors (SPDs) results in the HOM dip. Furthermore, frequency displacement between photons may result in an oscillatory pattern within the dip [3], even for weak coherent states, as in the case of faint laser sources. This feature is explored in the few-photon heterodyne spectroscopy (FPHS) technique [4,5].

Here, the FPHS technique is used as a tool for calibration of the frequency difference between a test laser and a reference laser traced to CIPM standard radiation. Two frequency-stabilized He-Ne lasers are attenuated and their frequency difference is measured from the interferogram obtained with photon counting. Uncertainty is computed and the method is validated against traditional heterodyne system.

EXPERIMENTAL SETUP

Experimental setup for the measurement system is depicted in Fig. 1. Two independent laser sources (633 nm) couple into optical fibers and feed the HOM interferometer. Single-mode optical fibers ensure spatial modes overlap. The Si avalanche photodiode-based SPDs operate in free-running Geiger mode and are connected to the *start* and *stop* ports of the high-resolution TIC. Time intervals are arranged in a histogram of coincidences per time interval, later converted into an interferogram over relative temporal mode. A delay line at *stop* channel displaces the matched times 3.4 ns from zero. States of polarization (SOP) are made parallel using the auxiliary setting setup and additional quarter- (QWP) and half-wave plates (HWP). Intensities are tuned down to few-photon level and matched by tilting the lenses (L) used to couple laser into fiber.

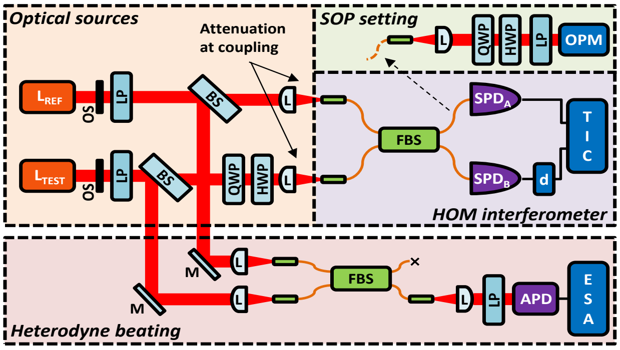

Figure 1. Experimental setup.

Samples of each beam (before attenuation) are also superposed in a photodiode and the heterodyne beating signal is observed in an ESA for validation.

RESULTS

After warm-up of the lasers, time intervals between the SPDs are collected during an one-hour period (~250k samples) into a histogram (Fig. 2a.1). Exponential decay of data (due to Poisson statistics of the photon flux [6]) is corrected and the interferogram is obtained, as depicted in Fig. 2a. The envelope of the interferogram is associated to the mutual coherence of the laser sources, whilst the oscilatory pattern (zoom in shown in Fig. 2a.2) depends on the beat frequency.

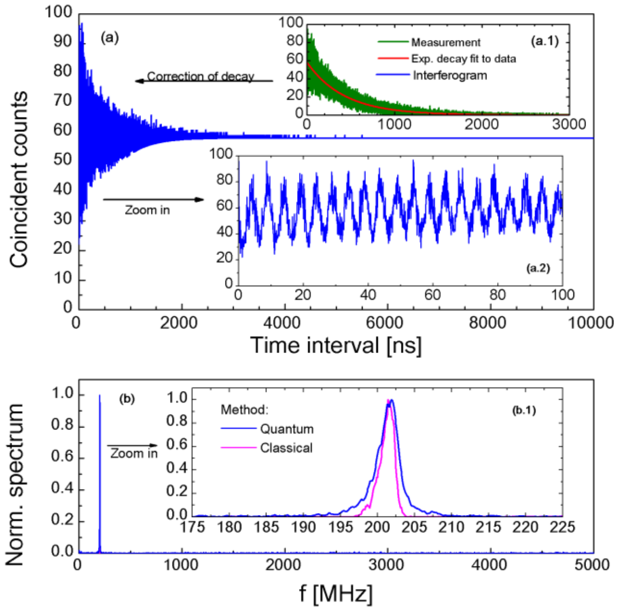

Figure 2. Experimental results: (a) interferogram obtained from histogram (see inset a.1), with first 100 ns in the detail of inset a.2; (b) Power spectrum of the FFT of the interferogram and comparison to results with higher power levels (inset b.1).

Fourier transform of the interferogram results in the convolution of the spectral lines [5]. Figure 2b show the power spectrum obtained with an FFT over the interferogram. The oscilatory pattern at ~200 MHz results in the evident peak at this frequency. Result is compared in Fig. 2b.1 to the heterodyne beating observed in the ESA through classical method. Central frequencies are obtained by computing the first moment of the distribution, $f_{beat} = \sum f(i)P(i)/\sum P(i)$. Evaluation range is taken as full-width at 0.1 of maximum. Uncertainty of centroid, u_{f0}, is computed using $u_f(i)$ and $u_P(i)$ through uncertainty propagation techniques over the first moment and combined to the RMS variance of distribution (second moment).

Histogram is computed up to 10 µs with bin width of 0.1 ns, resulting in sample period $t_s = 0.1$ ns and $N = 10^5$ points. Single-sample resolution of TIC is computed as u_{TIC}=45.1 ps, including timing jitter of the SPDs (characterized using [7]). Combining $\Delta f/(2\sqrt{3})$ and $u_{TIC}/\sqrt{C}$, where C is average number of coincident counts, results in u_{ts}=0.041 ns. Frequency step of the FFT is $\Delta f = (t_s N)^{-1} = 0.100$ MHz, thus $u_f(i)$=0.041 MHz. $u_P(i)$ is taken as square root of the number of events in the (amplitude) spectrum.

ESA was previously verified using a frequency synthesizer driven by a calibrated quartz clock traced to national standards as input, and frequency offset is within instrument resolution bandwidth (10 kHz). Spectral span is sampled at 0.100 MHz, thus $u_f(i)$=0.041 MHz. $u_P(i)$ is computed from the standard deviation over ~2000 traces.

Results are shown in Table 1. The difference of 0.02 MHz, much smaller than uncertainty values, indicates agreement between methods. Note that the ambiguity in absolute frequency, which also appears in the classical case ($\nu_{Test} = \nu_{Ref} \pm f_{\text{beat}}$), could be resolved by a second measuremend using a frequency shifter or a second reference laser.

Table 1. Results for frequency difference using quantum and classical methods. All values in [MHz].

	f_{beat}	u_{f0}	σ_f	$u_c{}^*$
FFT	201.27	0.00067	1.48	1.48
ESA	201.25	0.00076	0.88	0.88

CONCLUSIONS

Relative frequency of a faint stabilized laser sources is determined based on photon counting and validated through conventional heterodyne beating. The method constitutes a practical solution for low power frequency metrology.

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