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Ultra-low phase noise all-optical microwave generation setup based on commercial devices

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In this article, we present a very simple design based on commercial devices for the all-optical generation of ultra-low phase noise microwave signals. A commercial, fibered femtosecond laser is locked to a laser that is stabilized to a commercial ultra-low expansion Fabry–Perot cavity. The 10 GHz microwave signal extracted from the femtosecond laser output exhibits a single sideband phase noise $\mathcal{L}(f) = -104$ dBc/Hz at 1 Hz Fourier frequency, at the level of the best value obtained with such "microwave photonics" laboratory experiments [Nat. Photonics 5, 425–429 (2011)]. Close-to-the-carrier ultra-low phase noise microwave signals will now be available in laboratories outside the frequency metrology field, opening up new possibilities in various domains.

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1. INTRODUCTION

Ultra-low phase noise microwave signals are being used in a growing number of fields. Industrial applications include telecommunication networks, deep-space navigation, high-speed sampling [1], and radar systems [2]. Fundamental physics tests and research experiments also benefit from ultrastable microwave signals, as in atomic fountain clock setups [3], Lorentz invariance tests [4], or very long baseline interferometry [5].

Such signals are usually generated in three different ways: from a quartz resonator, included in a frequency synthesis [6,7]; from a sapphire oscillator [8], often cooled down to cryogenic temperatures [9,10]; or from the optical domain, using an optoelectronic oscillator [11] or a cavity-stabilized laser and an optical frequency comb [12,13]. In the latter case, a laser is locked to an ultrastable Fabry–Perot (FP) cavity, thus providing an ultra-low phase noise optical signal and a short-term relative frequency instability below 10^{-15}. This signal is used to phase lock the repetition rate of an optical frequency comb, which allows for dividing the signal frequency down from the optical to the microwave domain with minimal degradation [14]. Progress in the past ten years has allowed extremely low levels of relative frequency stability to be reached for FP cavity laser stabilization setups, both by improving the design [15–17] and materials [18,19] of the cavities. On the other hand, compact and portable FP cavities have been developed for field operation [20,21], and such setups are now commercially available. Fiber-based optical frequency combs have followed the same path and are becoming an essential tool in various experimental physics laboratories.

Cryogenic sapphire oscillators (CSOs) and optically generated microwave signals now reach a similar level of phase noise for Fourier frequencies between 0.1 Hz and 10 MHz. The phase noise floor of optically generated microwave signals can even be reduced by 10–20 dBs as compared to CSOs, using dedicated photodetection techniques [22]. CSOs offer the advantage of very low frequency drifts, offering relative frequency instabilities lower than 10^{-15} for $\tau = 1$ to 10^4 s [23]. The main practical advantage of optical generation is the absence of a cryostat or a cryocooler, thus considerably reducing the energy consumption. Moreover, the integration of an all-optical setup might be easier in a laboratory working in an optics-related domain where people might not be familiar with high frequency electronics. Finally, the microwave signal is readily carried at an optical frequency at the output of the femtosecond laser, making it easy to distribute at the scale of a laboratory.

In this article, we present a setup for all-optical microwave generation based on both a commercial FP cavity and a commercial fibered optical frequency comb. We use this setup to generate an ultrastable reference signal at 10 GHz, which will later be distributed through the laboratory for future phase noise characterizations of other oscillators based on sapphire, quartz, or optical resonators. It will also be complementary to an optical reference signal distributed to French time and frequency laboratories through the REFIMEVE+ network [24]. In the following sections, we outline the 10 GHz signal generation scheme and analyze the measured signal phase noise and frequency stability.

2. ALL-OPTICAL MICROWAVE GENERATION SETUP

Our setup for all-optical microwave signal generation is described in Fig. 1. A commercial continuous-wave (CW) laser at 1542 nm [25] is locked to a FP cavity using the Pound–Drever–Hall (PDH) technique. The ultrastable cavity is a 5 cm long commercial spherical cavity [26] based on a design by the National Institute of Standards and Technology (NIST) [20]. The spherical spacer is held at an optimized angle for minimizing vibration sensitivity [20]. Fused silica mirror substrates are optically contacted to a spherical ultra-low expansion (ULE) spacer; ULE rings are placed on the SiO_2 substrates to adjust the cavity inversion temperature [27]. The inversion temperature of our cavity was determined to be 10.5°C and we measured a finesse of about 400,000 for the fundamental TEM_{00} mode.

We estimate that the thermal noise floor of our cavity will limit the stabilized laser phase noise to $\mathcal{L}(f) = -106$ dBc/Hz at 1 Hz with a $1/f^3$ slope, corresponding to a relative frequency flicker $\sigma_y \approx 8 \times 10^{-16}$.

The cavity is pumped to ultra-high vacuum using a 2.5 l/s ion pump. The vacuum chamber and the free space PDH optical setup are placed on a commercial active vibration isolation platform and inside a thermal insulation box with a total volume of about 0.25 m^3. We use homemade electronics for the loop filter, as those are on hand in our laboratory and are usually lower-priced, but similar systems are commercially available. An electro-optical modulator (EOM) modulates the laser phase at 22.5 MHz to provide the PDH error signal. The fast corrections are applied to an acousto-optical modulator (AOM) through a proportional integrator (PI) controller with a bandwidth higher than 100 kHz, while the slow corrections are applied to the laser's piezoelectric transducer (PZT) through a second integrator controller, with a bandwidth of a few tens of Hz. This setup has proven to be very robust and the laser can stay locked to the FP cavity for weeks without any external intervention.

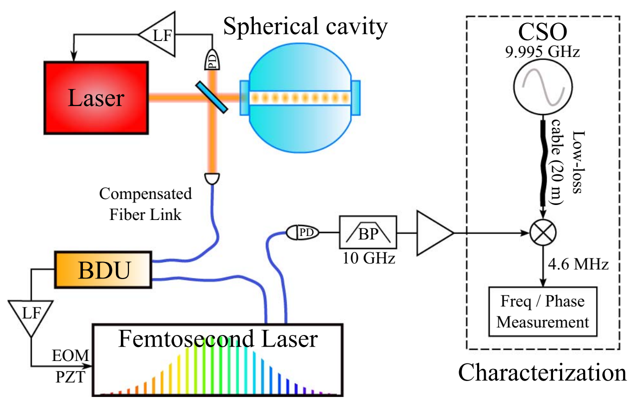

Fig. 1. All-optical microwave signal generation and characterization setup. *Generation*: a 1.5 μm laser is stabilized to a commercial ULE spherical cavity by the PDH technique. The stabilized output of the laser is used to optically lock a commercial femtosecond laser. The output of the stabilized femtosecond laser is detected by a fibered fast photodiode and filtered and amplified at 10 GHz. *Characterization*: the signal is electronically mixed with the output of a CSO at 9.995 GHz. The resulting beat note at 4.6 MHz is monitored using a frequency counter referenced to a hydrogen maser. BDU, beat detection unit; LF, loop filter; PD, photodiode; BP, bandpass filter.

We optically mix the stabilized laser output with an optical frequency comb produced by a commercial femtosecond laser [28] using the so-called "beat detection unit" provided by the manufacturer. This allows for locking the femtosecond laser repetition rate at 250 MHz. A fibered interferometer is readily aligned to detect the beat note between the optical comb and the reference laser on a high sensitivity photodetector. The output voltage is then processed to generate a lock signal and fed back to an EOM and a PZT placed inside the femtosecond laser cavity to stabilize its repetition rate. The fast corrections to the EOM are generated through an analog PI control loop with a bandwidth higher than 100 kHz, and the slow corrections are generated through a second integrator controller. The comb carrier envelope offset is stabilized to a radio frequency reference using the so-called $f - 2f$ technique [29]. This is all done using the electronics provided by the manufacturer. Our only addition is a small RF circuit that allows for the substraction of the CEO to the optical beat note signal, following Ref. [14]. We obtained similar results with and without this substraction scheme.

We detect the 40th harmonic of the repetition rate, near 10 GHz, using a fibered fast InGaAS PIN photodiode [30]. Such photodiodes have been well characterized in microwave photonics applications, including the effect of AM/PM conversion when detecting microwave signals [31]. Pulse-interleaving setups have also been developed to increase the power of a given harmonic, therefore decreasing the shot noise floor of the microwave detection [22]. In our setup, no particular optimization of the microwave detection has been performed. With an optical power of about 3 mW, we obtain about −30 dBm microwave power at 10 GHz. This signal is bandpass filtered at 10 GHz and amplified using two low phase noise microwave amplifiers [32]. The residual phase noise added by such optical division schemes has been measured to be about −111 dBc/Hz at 1 Hz with an earlier version of the optical frequency comb [33]. In principle, this value can even be lowered to −120 dBc/Hz at 1 Hz using additional noise reduction techniques [14].

The optical fiber link between the ultrastable laser and the optical frequency comb is actively stabilized using a fiber- noise compensation scheme [34]. A fibered AOM is used to correct for optical path fluctuations through a PI loop, with a bandwidth of a few tens of kHz. This can be avoided by placing the FP cavity right next to the femtosecond laser and using a short optical fiber.

The whole microwave generation setup has stayed locked for periods of up to 5 days without intervention, even through fairly high temperature fluctuations due to a temporary failure of our air conditioning system. The PDH and the

Doppler-cancellation locks have proven to be the most robust, confirming the low acceleration sensitivity of the cavity (characterization of a similar system shows a sensitivity below $3.1\times10^{-10}/\mathrm{g}$ [20]) as well as its low temperature sensitivity (we measure a slope of about $2.1\times10^{-9}/\mathrm{K}$ at $T = 10.5°\mathrm{C}$). All in all, the system is robust enough to continuously provide a 10 GHz ultrastable reference signal.

3. MEASUREMENTS

The characterization setup of the optically generated microwave signal is illustrated in Fig. 1. The output of a fast photodiode is filtered at 10 GHz, amplified, and then mixed with a 9.995 GHz signal generated by one of the CSOs of the laboratory. The resulting 4.6 MHz beat note is then sent to a frequency counter referenced to a hydrogen maser (with a stability $\sigma_y(1s) = 7.7\times10^{-14}$ at 100 MHz) [35]. The CSO has been fully characterized and presents a relative frequency instability below 8×10^{-16} for integration times between 1 and 1000 s [23]. The sapphire whispering gallery mode resonator is held at cryogenic temperature near its inversion point at 6 K, and is integrated in a Pound–Galani oscillator loop. The ultrastable output is transferred to the "microwave photonics" room through a 20 m low-loss coaxial cable without any noise compensation. We have checked on a separate setup that a similar 10 m-long cable did not degrade the CSO signal phase noise.

We measure a relative phase noise $\mathcal{L}(1\ \mathrm{Hz}) = -102$ dBc/Hz for the beat note, competitive with state-of-the-art optically generated ultrastable microwave signals [13,23]. Figure 2 presents the phase noise spectrum. The noise floor is close to the photodetection DC shot noise limit at −137 dBc/Hz (dashed line). For ultrashort pulses, the actual shot noise level can be orders of magnitude lower than for a CW laser [36]; however, other phenomena, such as AM/PM conversion by the photodetector or carrier scattering, might explain our observed noise floor [37]. The spurious peaks between 1 and 100 Hz belong to the CSO phase noise. In particular, resonances at 1.4 Hz and its harmonics are related to the vibrations of the cryocooler [9]. We plot the phase noise spectrum of the beat note between two nearly identical CSOs for reference (dashed red line; the CSOs are placed in the same room, the 20 m long cable was not used here). It is worth noting that the two measurements do not differ by more than 3 dB between 0.1 and 100 Hz, meaning that the optically generated microwave signal phase noise is very close to the CSO signal phase noise in this frequency range.

Between 0.2 and 0.7 Hz, the spectrum fits the f^{-3} law (frequency flicker) with a value of −103 dBc/Hz at 1 Hz (black line). This would translate to a relative frequency stability floor of 1.2×10^{-15} for the beat note. The spectrum shows excess phase noise at frequencies below 0.2 Hz. Temperature monitoring of the PDH optical bench indicates that this is linked to temperature fluctuations that most likely cause polarization rotations within the PDH optical setup. These rotations induce power fluctuations of the CW laser that couple to the FP cavity resonance frequency.

The phase noise of the CSO we use has been measured to be $\mathcal{L}_{\mathrm{CSO}}(1\ \mathrm{Hz}) = -106$ dBc/Hz. By subtracting this value from the beat note phase noise, we obtain $\mathcal{L}_{\mathrm{opt}}(1\ \mathrm{Hz}) = -104$ dBc/Hz for the optically generated 10 GHz signal. This is very close to the expected thermal noise floor of the ultrastable cavity $\mathcal{L}_{\mathrm{cav}}(1\ \mathrm{Hz}) = -106$ dBc/Hz.

Figure 3 presents the relative frequency stability of the optically generated microwave signal versus the CSO. We recall that the CSO relative frequency stability (not shown here) is below 8×10^{-16} from 1 to 1000 s [23]. We obtain $\sigma_y(1s) = 1.9\times10^{-15}$ for the beat note, higher than the flicker frequency floor (1.2×10^{-15}). This is mostly due to excess frequency noise at low frequencies. In particular, a parasitic modulation of the beat note around 26 mHz degrades the signal relative frequency stability between 1 and 20 s. We find a similar modulation when plotting the Allan deviation of the PDH optical bench temperature. We have numerically extracted the relative

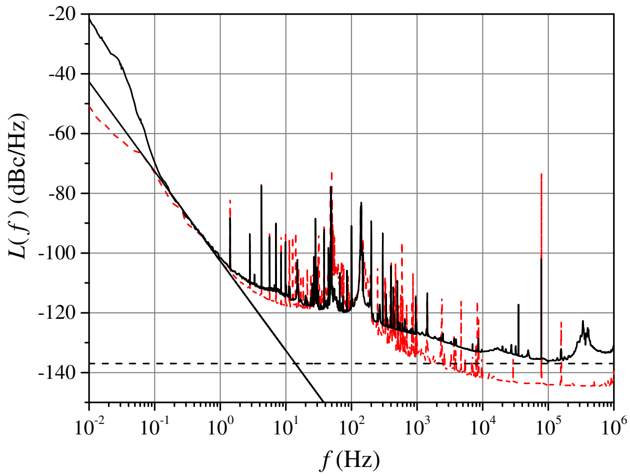

Fig. 2. Phase noise of the all-optical microwave signal compared to a CSO signal. *Black curve:* phase noise spectrum of the beat note between the CSO and the cavity signals. *Black line:* f^{-3} fit of the spectrum between 0.2 and 0.7 Hz. *Red dashed curve:* phase noise spectrum of the beat note between two identical CSOs. *Dashed line:* photodetection shot noise limit.

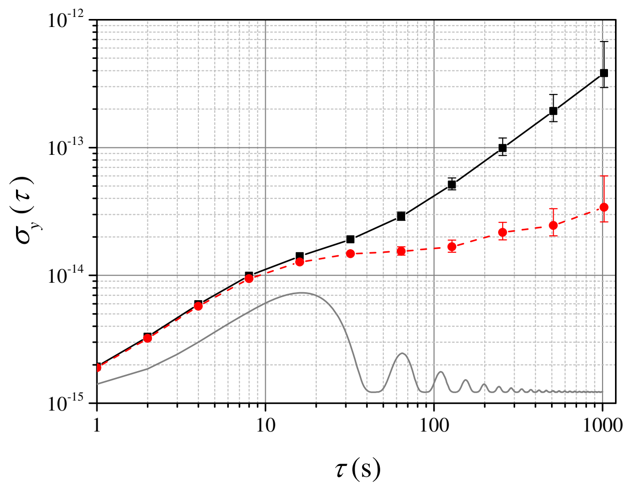

Fig. 3. Allan deviation of the all-optical microwave signal compared to a CSO signal. *Red dashed curve:* relative frequency stability with linear drift removed. *Light gray curve:* estimated contribution of the 26 mHz modulation to the Allan deviation.

frequency power spectral density S_y at this frequency from the drift-removed temporal dataset. We plot the relative frequency stability obtained with a purely sinusoidal modulation added to the flicker floor at 1.2×10^{-15} for reference (gray line—see [38] for details). The initial slope and frequency stability qualitatively agrees with our measurement; the quantitative discrepancy as well as the broad excess noise found on the phase noise spectrum indicate a broad frequency modulation range rather than a purely sinusoidal modulation.

The linear drift of the frequency leads to a $3.8 \times 10^{-16}\tau$ stability for an integration time longer than 200 s. Potential improvements of the short-term relative frequency stability include the better rejection of the room-temperature fluctuations as well as a refined measurement of the inversion temperature of the cavity.

4. CONCLUSION

In summary, we have presented the first all-optical setup for microwave signal generation based on commercially available instruments. This setup shows a phase noise spectrum competitive with the best reported values both for all-optical setups [13] and cryogenic sapphire oscillators [9].

To this day such "microwave photonics" setups are still found mostly in metrology institutes, as they used to require the design of an ultrastable FP cavity and/or optical frequency comb. The setup that we present in this article should allow the spreading of optical microwave generation outside of frequency metrology labs, thanks to the availability and technological readiness of the key devices and the relative simplicity of the setup. This will pave the way to tantalizing new developments in fields such as high-resolution spectroscopy, atomic physics, and very-long baseline interferometry.

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