

Photonicallly Generated 10 GHz Microwaves with Close-to-Carrier Phase Noise < -100 dBc/Hz

T.M. Fortier, M. S. Kirchner, F. Quinlan, J.A. Taylor, N. Lemke, A. Ludlow, Y. Jiang, T. Rosenband, J. C. Bergquist, C.W. Oates and S.A. Diddams

Time and Frequency Division, National Institute of Standards and Technology
325 Broadway, MS 847 Boulder CO, 80305
fortier@boulder.nist.gov

Abstract—We demonstrate a 10 GHz photonic oscillator based on optical frequency division of a high-stability optical reference with a modelocked fs laser. Characterization with a second independent photonic oscillator reveals a close-to-carrier phase noise that is < 100 dBc/Hz, reducing to a shot noise floor of -156 dBc/Hz at a 1MHz offset.

I. INTRODUCTION

A photonic approach to microwave generation that uses high quality factor ($Q \sim 10^{11}$) optical cavities and optical frequency division can enable high-stability and low timing-jitter signals without requiring cryogenic temperatures [1-3]. Stabilization of the light from a continuous wave (CW) laser to a high-finesse, passive optical cavity can yield a fractional frequency instability of $\Delta f/f \leq 1 \times 10^{-15}$ for short averaging times [4, 5]. Ideally, transfer of this stability to the microwave domain with a modelocked fs laser preserves the frequency stability of the reference while reducing the optical phase noise by the division factor squared. Using this technique, we demonstrate a 10 GHz microwave signal with a fractional frequency instability $< 1 \times 10^{-15}$ and with a phase noise that is < 100 dBc/Hz at a 1 Hz offset. The integrated timing jitter of the phase noise spectrum from 1 Hz to 1 MHz is < 1 fs.

II. GENERATION OF 10 GHz MICROWAVE SIGNALS VIA OPTICAL FREQUENCY DIVISION

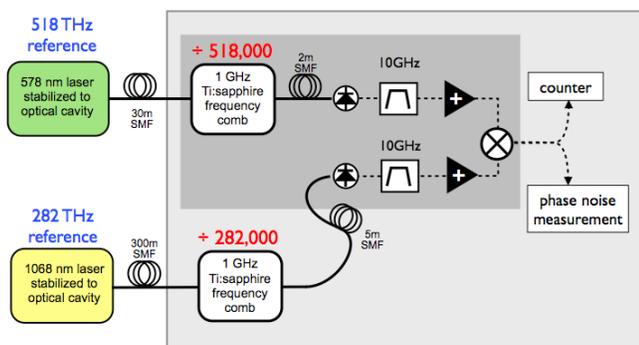


Figure 1. Generation and characterization of 10 GHz signals via optical frequency division. SMF denotes single mode fiber.

We generate 10 GHz microwave signals via photodetection and of the tenth harmonic of the repetition rate, f_r , of a 1 GHz Kerr-lens modelocked Ti:Sapphire laser [6] that is phase-locked to an high- Q optical reference [4, 5]. Stabilization of an optical frequency comb divider (OFCD) to an optical reference transfers the stability of that reference to a timing stability in the OFCD laser pulse train. Photodetection of this pulse train produces photocurrent that yields a microwave spectrum of harmonics of f_r up to the photodetector (PD) cut-off bandwidth. A spectrally pure 10 GHz microwave signal is extracted via electronic filtering and amplification of the photocurrent signal. As seen in Figure 1, a second similar but fully independent photonic oscillator is used to characterize the frequency stability and phase noise of the generated 10 GHz microwave signals. Details of the measurement methods can be found in [1].

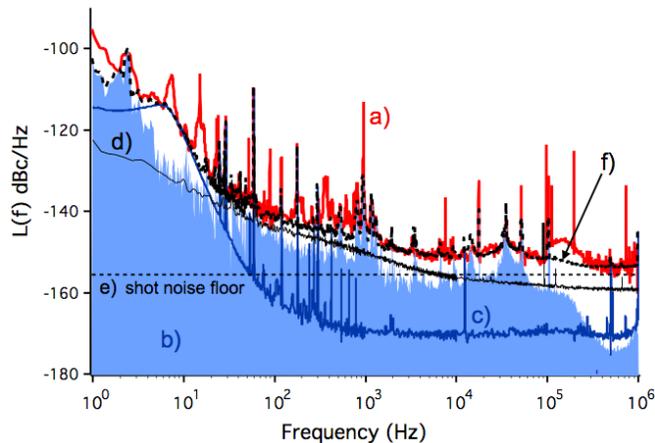


Figure 2. Single sideband phase noise on a 10 GHz carrier contributed by two oscillators. a) red solid trace – phase noise resulting from the comparison of two independent photonic oscillators. b) blue filled trace - phase noise contribution, scaled to 10 GHz, of the optical references, and the optical frequency comb dividers. c) blue solid trace – phase noise of the digital phase noise measurement system. d) black solid trace – phase noise contributed by the electronic amplifiers. e) Shot noise floor from two photonics oscillators. f) black dashed line – sum of the noise contributions from b), c), d) and e)

Figure 2 shows the phase noise on a 10 GHz carrier that is generated via comparison of two photonic oscillators. Also shown is the optical phase noise, scaled to 10 GHz, which is contributed by the optical references and the residual noise of

the OFCDs. Fig 2b represents the microwave phase noise that would be possible ignoring the noise that is contributed by the measurement electronics and photodetection of the laser repetition rate. Figure 2c is the calculated noise that results from contributions of the electronic amplifiers, the phase noise measurement system, the shot noise floor, the optical references and the residual noise of the OFCD. The good agreement between the calculated and the measured phase noise demonstrates that we have properly identified the current limitations to the purity in the 10 GHz microwave signal.

In conclusion, we have produced 10 GHz microwaves with sub-femtosecond timing jitter. The demonstrated phase noise produced is comparable to, or better than those achieved with cryogenic dielectric oscillators [7-9]. Future work will aim at reducing the phase noise contributions of the electronics and photodetection. At frequencies > 10 kHz photodetector nonlinearities result in a saturation of the photocurrent at -8 dBm for 12 mW of incident optical power [10]. In the future, the shot noise limited floor can be decreased with more optical power provided the high-speed photodetector remains linear. Additionally saturation effects in the PD can be mitigated by repetition rate filtering with a Fabry-Perot cavity [Kirchner]. A still lower noise floor would require photodetectors with increased power handling or an alternative hybrid approach with a dielectric sapphire oscillator locked to our photonic oscillator.

The fundamental limits to the achievable phase noise of our photonic approach are given by thermally-excited noise in the glass spacer, mirror substrates and optical coatings of the FP reference cavity [Numata], as well as the photodetector shot noise mentioned above. The lowest reported thermal noise for a FP reference cavity corresponds to approximately $L(f) = -117$ dBc/Hz at 1 Hz offset when converted to a 10 GHz carrier.

III. ACKNOWLEDGMENT

We thank A. Hati, L. Hollberg, D. Howe, C. Nelson, N. Newbury, and S. Papp for their contributions and comments on this manuscript, and A. Joshi and S. Datta of Discovery

Semiconductor for providing the 10 GHz InGaAs photodiodes. This work was supported by NIST. It is a contribution of an agency of the US government and is not subject to copyright in the US.

REFERENCES

- [1] Fortier T.M. et al., "Generation of Ultrastable Microwaves via Optical Frequency Division," *Nature Photonics*, in press.
- [2] Bartels, A. et al., "Femtosecond-laser-based synthesis of ultrastable microwave signals from optical frequency references," *Opt. Lett.* **30**, 2005, pp. 570-572.
- [3] Millo J. et al., "Ultralow noise microwave generation with fiber-based optical frequency comb and application to atomic fountain clock," *Appl. Phys. Lett.* **94**, 2009, pp.141105-141103.
- [4] Jiang Y.Y. et al. "Making optical atomic clocks more stable with 10-16-level laser stabilization," *Nature Photonics* **5**, 2011, pp.158-161.
- [5] Young B.C. et al., "Visible Lasers with Subhertz Linewidths," *Physical Review Letters* **82**, 1999, pp. 3799-3802.
- [6] Fortier T.M., Bartels A. and Diddams S.A., "Octave-spanning Ti:sapphire laser with a repetition rate of 1 GHz for optical frequency measurements and comparisons," *Opt. Lett.* **31**, 2006, pp. 1011-1013.
- [7] Mann, A. G., Sheng, C. & Luiten, A. N. Cryogenic Sapphire Oscillator with Exceptionally High Frequency Stability. *IEEE Trans. Inst. Meas.* **50**, 519-521 (2001).
- [8] Locke, C.R., Ivanov, E.N., Hartnett, J.G., Stanwix, P.L. & Tobar, M.E. Invited Article: Design techniques and noise properties of ultrastable cryogenically cooled sapphire-dielectric resonator oscillators. *Review of Scientific Instruments* **79**, 051301-051312 (2008).
- [9] Grop, S. et al. ELISA: A cryocooled 10 GHz oscillator with 10^{-15} frequency stability. *Review of Scientific Instruments* **81**, 025102-025102-025107 (2010).
- [10] Taylor J.A. et al. "Characterization of Power-to-Phase Conversion in High-Speed P-I-N Photodiodes," *IEEE Photonics Journal*, 2011, pp. 140-151.
- [11] Diddams et al. "Improved signal-to-noise ratio of 10 GHz microwave signals generated with a mode-filtered femtosecond laser frequency comb," *Opt. Exp.* **17**, 2009, pp. 3331-3340.
- [12] Numata, K., Kemery, A. & Camp, J. Thermal Noise Limit in Frequency Stabilization of Lasers with Rigid Cavities. *Phys. Rev. Lett.* **93**, 250602 (2004).