Low phase noise microwave generation with fiber-based femtosecond lasers and applications

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Abstract

When a femtosecond laser is servoed onto an ultra-stable cw laser, its repetition rate acquire an extreme spectral purity. By photodetecting the pulses, we are able to generate ultra-low phase noise microwave signals and use it for cutting edge metrology experiments. We present our past and present work to generate microwave signal with very low degradation from the limit imposed by the reference oscillator, using a highly reliable fiber-based system. The latest developments involve employing an intra-cavity electro-optic modulator (for increased servo bandwidth), reduced relative intensity noise of the laser, and studies of the photodetector amplitude to-phase conversion.

1. Introduction

Low-phase-noise and stable microwave signals are of prime importance in a variety of scientific and technological fields, such as radar, telecommunication, deep space navigation and very long baseline interferometry, high-precision timing distribution and synchronisation [1], development of local oscillators for accurate fountain atomic frequency [2,3]. Although low noise microwave sources based on cryogenic sapphire oscillators (CSO) are available in a few laboratories worldwide, they remain difficult to operate high maintenance cost devices unlikely to be used outside dedicated laboratories. The combination of ultra-stable lasers and low noise optical frequency division by use a femtosecond laser presents nowadays a reliable alternative way to realize extremely low phase noise microwave source. In recent years, frequency-stabilized lasers based on highly stable and vibration-immune cavities show a fractional frequency stability about 1×10^{-15} from 0.1 s to 100 s or better [4-6]. Meanwhile, femtosecond laser frequency com, especially fiber based system, have become a mature and reliable technology which allow coherent transfer from the optical domain to the microwave, thereby allowing microwave signal generation with extreme spectral purity.

We will first present our work on low-phase noise microwave generation and its application to the LNE-SYRTE cutting-edge atomic fountain clock primary standards. Careful development have led us to generate microwave signals from optical source with excess phase noise levels at -120 dBc/Hz at 1 Hz from a 11.55 GHz carrier, and white phase noise plateau below -140 dBc/Hz [7,8]. We will proceed by presenting the new strategies we are currently developing to improve further the performance and reliability of our system. The first of these strategies involves using a intra-cavity electro-optic modulator (EOM) in the fiber-based optical frequency comb. This allows higher control bandwidth and reduced inloop residual noise. Independently, careful design of the oscillator's pump current supply allowed us to reduce dramatically the relative intensity noise of the laser. Furthermore, we have extensively studied the amplitude-phase conversion process of the fast InGaAs pin photodiodes used to photo-generate the microwave signal. Our study leads to reduced amplitude noise induced phase noise. The remaining limitation is due to shot-noise and Johnson noise.

2. Low phase noise microwave generation, application to atomic fountain clocks

In the line of previous work at NIST and PTB, we present first our previously reported results on microwave extraction with fiber-based optical frequency combs. Two separate femto-second fiber lasers are optically-mixed with the same ultra-stable optical reference cw laser at 1.55µm to provide beatnotes (f_b). The carrier envelop offsets (f_0) of the two lasers are independently measured using a standard f-2f technique. By mixing f_0 and f_b and mixing with a RF

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reference, we derive error signals for each laser which are retro-acted on the pump powers. This effectively locks the femtosecond lasers on the cw reference. The two pulsed lasers therefore exhibit ultra-stable repetition rates (down-converted versions of the cw-reference's optical frequency) which can be chosen to be identical and therefore easily compared. The repetition rates harmonics near 11.55 GHz are isolated, amplified and phase compared using a standard mixer-based demodulation technique, or, alternatively for low flicker-noise limit measurements (close to the carrier) a carrier suppression scheme. The resulting phase noise, is as low as -120 dBc/Hz at 1Hz from the 11.55 GHz carrier (for a single system) and -135 dBc/Hz above 1 kHz from the carrier. The long term Allan deviation of the microwave extraction is about $1.1\text{x}10^{-16}\ \tau^{-1}$ up to at least 1000 s, which corresponds to a timing stability substantially below 100 as. We also emphasize the reliability and robustness of our fiber-based system, which allows continuous operation over several days without interruption.

The previous results where characterizing the microwave extraction process and were obtained with a single (common-mode) ultra-stable cw optical reference. We separately characterized the *absolute* microwave generation, by comparing our system to both a CSO and a Titanium:Sapphire femtosecond laser system locked to an independent cw reference. Both these systems were, however standing in different rooms and high quality microwave links were used to transfer the signals in between the rooms. Note that these links are a strong limitation on the comparisons and the results obtained are only upper limits of the real performance achieved.

Both comparisons exhibit a phase noise about $10^{-9}/f^{2}$ [rad^2/Hz] (at 9.2 GHz carrier) for Fourier frequencies f in the 0.1Hz-10Hz range and an Allan deviation about 3×10^{-15} at 1 s integration time. These performances, among the very best for microwave sources, along with the reliability and robustness of the fiber-based system qualifies it as an excellent microwave source for long-term operation of atomic fountain clocks.

In a last experiment, we used our fiber-based system to generate a microwave signal at 11.932 GHz, directly suitable to drive the frequency chain of the LNE-SYRTE's FO2 atomic fountain clock (which lies in the same room as the CSO). The 9.2 GHz signal produced by the frequency chain was used to perform Ramsey spectroscopy on Cesium atoms in the FO2 fountain and locked to the atomic signal. The resulting primary standard was characterized by comparison with the CSO and exhibits a stability of $3.5\times10^{-14}\tau^{-1/2}$, limited by the quantum projection noise limit. These performances are identical to the usual operation, which uses the CSO as the local oscillator. Comparable results were obtained simultaneously in the group at PTB [2].

This demonstrates the usability of our fiber-based microwave generation system for operational-level tasks in time and frequency metrology, and in particular, as a future replacement for the CSO in the LNE-SYRTE's primary standards clock systems.

3. Fiber-based frequency comb with intra-cavity electro-optic modulator

In ref 4,5, the bandwidth of the control loop for phase-locked ultrastable laser and frequency comb is limited around 100kHz due to the pump-current modulation. To reduce the residual phase noise in optical-to-microwave division, a new control loop with larger bandwidth is necessary. One possible way for that is to employ intra-cavity electro-optic modulator (EOM) which changes the effective cavity length and then provides high-speed control of laser pulse repetition rate [9,10]. The commercial fiber-based frequency comb system described in Ref 4,5 has been modified by inserting a 2mm-thick EOM in the free space of laser cavity to obtain a large control bandwidth for repletion rate. With careful optimisation of the residual delays in the servo-loop, the servo bandwidth is extended about 700 kHz (see Fig.1). The residual in-loop error, integrated from 100Hz to 10MHz, is about 13 mrad.

The unavoidable cross-talk between EOM based repetition rate control and laser amplitude modulation is measured to be small enough not to be a limitation for any reasonable amplitude-phase conversion of the photodetection process (see fig. 2): the calculated excess phase noise due to EOM amplitude cross talk is calculated to be below -175 dBc/Hz at 10 GHz carrier for realistic conditions.

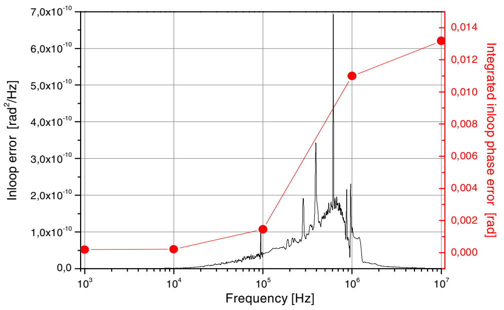

Fig. 1 Inloop error (black line) and integrated error (red line) when EOM is employed for phase lock loop.

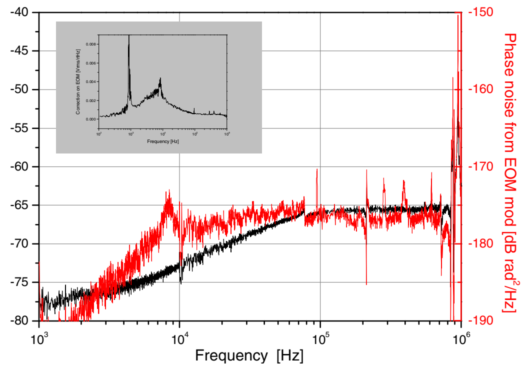

Fig. 2 Inset, EOM correction signal for phase lock comb on ultrastable laser. Black line, transfer function from EOM control to an amplitude monitoring photodiode. Redline, calculated excess phase noise induced by the unavoidable amplitude modulation cross-talk, when the EOM is servoing the repetition rate.

4. Laser relative intensity noise impact reduction

The laser relative intensity noise (RIN) has been significantly improvement by employing a home-made low-noise laser diode power supplier. As shown in Fig. 3, comparing to the result from commercial power supplier, then we have improved the RIN by at least 30dB at 10Hz Fourier frequency. To investigate the relationship between laser RIN and phase noise, we then measure the amplitude-to-phase (AM-to-PM) conversion coefficient in the fast photodiode (see Fig. 4). We have tested three fast photodiodes commonly used for those applications. One is high linearity photodiode (HLPD) from Discovery Semiconductors and the other two are DSC40s (PDA and PDB, respectively, also from Discovery Semiconductors), illuminated by laser pulses with 250MHz repetition rate. Above saturation of the photodiodes (which happens at lower optical power for the DSC40S than for the HLPD as the later is a specially designed highly linear device), we observe alternative positive and negative AM-to-PM coefficients, with special powers were the coefficient vanishes (see fig. 4 where only the absolute value of the coefficient is plotted).

To minimize the phase noise induced by the RIN of the laser, it's particularly convenient to operate the photodiode close to such vanishing point Fig. 4. One practical issue with these special points is that we have observed their exact position to be dependent on temperature, and slightly drifting over time. That being said, it seems feasible to maintain passively the operating conditions in the vicinity of the vanishing AM-to-PM points such that the AM-to-PM coefficient remains lower than 0.1 rad per relative amplitude change. Active stabilization by a method yet to develop may provide even better annihilation of AM-to-PM coefficient.

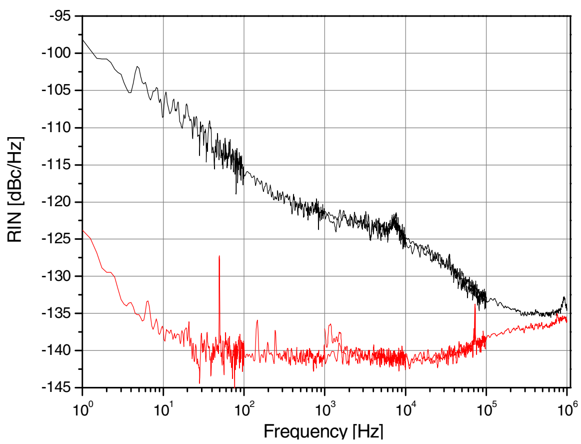

Fig. 3 Femtosecond laser comb relative intensity noise (RIN) obtained with the commercial diode laser power supply (black line), and with a home-made low noise power supply exhibiting about 3nA/rtHz white noise floor (red line).

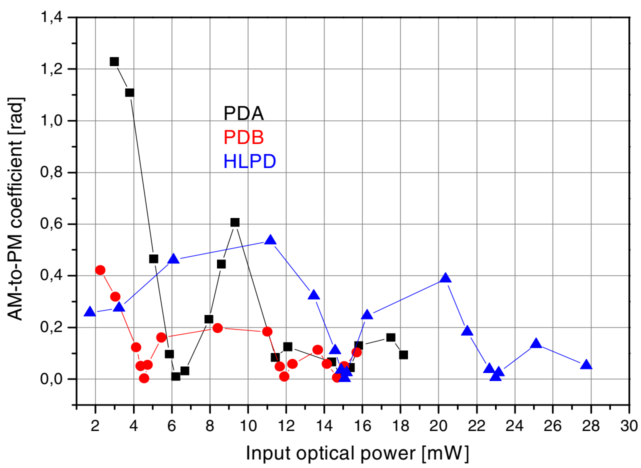

Fig. 4 AM-to-PM conversion coefficients for two DSC40s (PDA black line and PDB red line), and HLPD (blue line) from Discovery Semiconductors.

5. Conclusion

With significant improvement for servo bandwidth of 700 kHz by EOM employing, laser RIN reduced to about -135dBc/Hz, and optimum use of photodiode to decrease AM-PM conversion factor to lower than 0.1 rad per relative amplitude change, it should be possible to achieve microwave generation with excess phase noise below -150 dBc/Hz at high Fourier frequencies (ie near 1MHz). At this level, the shot noise and Johnson noise become the predominant limiting factors and we would need to increase the generated microwave signal level to reach such extremely high spectral purity. Pulse rate multiplication via cavity filtering [11] is one possibility to achieve this prospect which seems feasible with our current setup, and further study is being pursued.

6. References

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