Stability Characterization of Optical Injection Phase Locked Loop for Amplification in Optical Frequency Transfer

Joonyoung Kim[1], David S. Wu[1], Giuseppe Marra[2], David J. Richardson[1], and Radan Slavík[1]
1.Optoelectronics Research Centre, University of Southampton, Southampton, U.K
2. National Physics Laboratory, Teddington, UK.
Email: j.kim@soton.ac.uk

Abstract: We suggest using optical injection phase locked loop (OIPLL) as an amplifier for precise frequency transfer via optical fibers. Feasibility of this approach is studied via evaluation of the phase noise and Allan deviation.
OCIS codes: (120.0120) Instrumentation, measurement, and metrology; (140.3520) Lasers, injection-locked

1. Introduction

The dissemination of ultra-stable optical frequencies over long (>100 km) distances through the existing telecommunication fiber links is essentially required for a future redefinition of the SI second and for various tests in fundamental physics [1]. In the transfer of precise optical frequencies over long distances, the optical carrier needs to be eventually amplified without introducing much additional noise. Unlike in standard telecommunications, where fibers are always used uni-directionally, in optical frequency transfer, the signal is propagated bi-directionally over a single optical fiber to allow compensation of the additional noise caused by the optical fiber, e.g., due to temperature variations and vibrations [1]. To allow the bi-directional transfer, bi-directional Erbium Doped Fiber Amplifiers (EDFA) [2], Fiber Brillouin Amplifiers (FBA) [2,3], and Raman Optical-fiber Amplifiers (ROA) [4] were proposed and demonstrated.

In this paper, we propose an application of the optical injection phase locked loop (OIPLL) for a regenerative amplification of signals used in precise frequency transfer. As the optical signal to noise ratio (OSNR) is not affected by the injection power, the optical injection locking (OIL) can provide very high gain, enabling less in-line amplifiers to be used. Also, the OIL amplifies signals only over very narrow bandwidth, suppressesing noise at high frequencies and thus can reduce interference in bi-directional transmission. However, for optimum performance and long term operation (>24 hours), it has to be combined with an electronic feedback loop forming the OIPLL. We characterize the performance of the OIPLL through measuring the short-term (phase noise) and long-term stability (Allan deviation), which are critical for transfer of precise frequencies over optical networks.

2. Experimental set-up and results

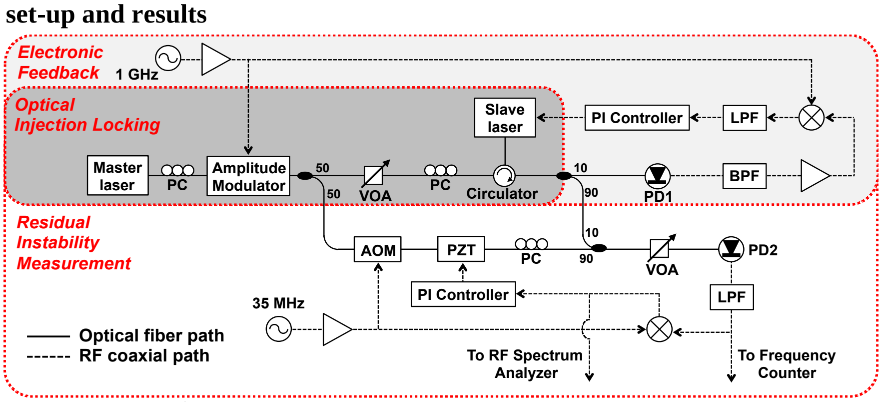

Fig. 1. Experimental set-up for implementing OIPLL (Optical Injection Phase Locked Loop) and its characterization.

Fig. 1 shows the experimental set-up for the implementation of the OIPLL (grey box) and its characterization. The master is a free-running fiber-based laser that generates CW light at 1555.7 nm (< 10 kHz linewidth, Rock from NP Photonics). The output of the master laser is weakly dithered (1% modulation depth) at 1 GHz, and split into two arms (OIL arm and reference arm). In the OIL arm, the master signal is injected into the slave laser through the optical circulator. The slave laser is a discrete mode semiconductor laser (200 kHz linewidth, Eblana Photonics) with an output power of 9 dBm. At its output, a 1 GHz beat signal between the carrier and sidebands is obtained via a 10 % tap and a photo-detector-1 (PD1). The beat signal is compared to the 1 GHz reference in an RF-mixer. In all our experiments, the OIL bandwidth is below 1 GHz and thus OIL is not affected by the pilot tone. As explained in [5], this enables to use the 1 GHz RF-mixer output as an error signal for a slow electronics feedback loop assisting the OIL and in fact forming the OIPLL. In the feedback loop, we used 1 kHz filter (limiting the maximum feedback speed to be <1 kHz) and a proportional-integral (PI) controller, New Focus LB1005. To ensure our locking range is smaller than the pilot tone frequency (1 GHz), we measured the locking range (by changing the slave laser free-running frequency and observing when it gets (un)locked. For the fiber-to-fiber (F-t-F) injection ratio (IR, defined as the master power injected into the slave laser / slave output power) of -39 dB and -50 dB that we used in the experiments, we measured the locking range of 430 MHz and 120 MHz, respectively. In our set-up, Fig. 1, the reference arm is used for the measurement of phase noise and Allan deviation, and consists of an acousto-optic modulator (AOM) providing 35 MHz frequency shift and a piezoelectric fiber phase shifter used to keep the beat signal in quadrature with the reference signal (35 MHz) at the RF-mixer (phase detector). The feedback for the optical phase shifter used slow bandwidth of < 100 Hz. The frequency shifted master signal was recombined with the slave output to be detected by the PD2.

The single sideband (SSB) phase noise from 100 Hz to 17.5 MHz offset is shown in Fig. 2(a) for the F-t-F IR of -50 and -39 dB. The best performance in terms of phase noise was obtained with feedback gain and PI corner set to 3 dB and 100 Hz, respectively. The phase detector sensitivity was measured to be 0.3 V/rad when the beat signal to the phase detector was 4.5 dBm. When the IR was -39 dB, the phase noise reached -122 dBc/Hz at 1 MHz offset. As compared to previously-published results, our phase noise at 1 kHz and 1 MHz were 22 dB and 10 dB lower than that reported by [6], although we used about 10 dB lower IR (-50 dB). We believe this is due to lower linewidth of our slave and master lasers as compared to [6]. The phase error variance (σ^2), calculated by integrating the phase noise from 100 Hz to 17.5 MHz, was reduced with increasing the IR. This is because the amount of the master-slave phase shift as a function of frequency detuning is inversely proportional to the locking range (detailed explanation and analysis is in [5]). We also measured the Allan deviation for the characterization of the long-term stability, Fig. 2(b). At short averaging time (1s), the frequency stability is slightly degraded with decreasing the IR, being expected from the phase noise measurement, Fig. 2(a). However, at long averaging time (1000s), the Allan deviation reached the floor of our measurement set up (measured by removing the slave laser and its circulator, entitled as 'interferometer floor' in Fig. 2(b)) of 1×10^{-19} for both cases (-39 and -50 dB).

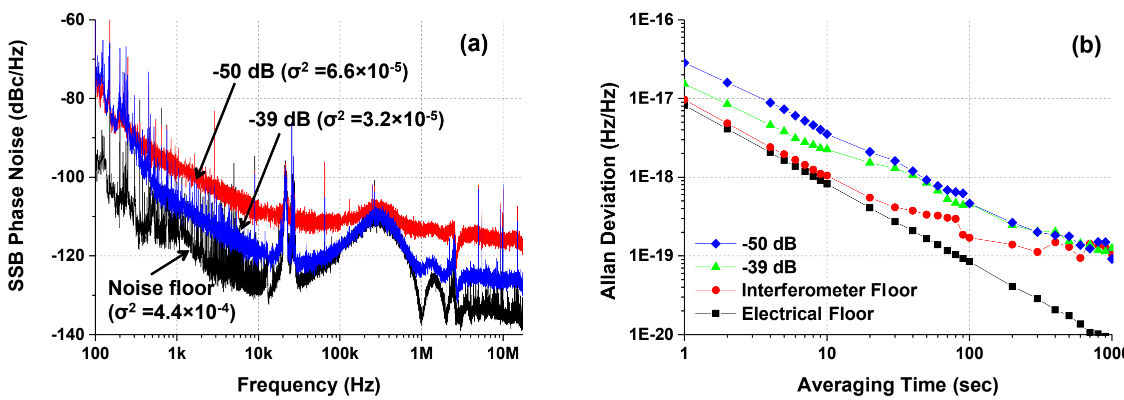

Fig. 2. Measured (a) single sideband (SSB) phase noise and (b) Allan deviation of 35 MHz beat signal

3. Conclusion

We investigated the suitability of the OIPLL for the regenerative amplification in the precise frequency transfer. The phase noise reached -122 dBc/Hz at 1 MHz offset for the IR of -39 dB. In addition, the Allan deviation reached the floor of 1×10^{-19} at 1000 s averaging time for the IR down to -50 dB. These results suggest this method should be well suited for amplification of signals in the applications dealing with optical frequency transfer.

This work was supported by the European Metrological Research Programme EMRP under SIB-02 NEAT-FT and IND 014. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

4. References

[1] N.R. Newbury et al., "Coherent transfer of optical carrier over 251 km," Opt. Lett. **32**, 3056-3058, (2007).
[2] K. Predehl et al., "A 920-Kilometer Optical Fiber Link for Frequency Metrology at the 19th Decimal Place," Science **336**, 441-444, (2012).
[3] S. Droste et al., "Optical-Frequency Transfer over a Single-Span 1840 km Fiber Link," Phys. Rev. Lett. **111**, 11081, (2013).
[4] C. Clivati et al., "Distributed Raman Optical Amplification in Phase Coherent Transfer of Optical Frequencies," IEEE Photon. Technol. Lett. **25**, 1711-1714, (2013).
[5] D.S. Wu et al., "Direct Selection and Amplification of Individual Narrowly Spaced Optical Comb Modes Via Injection Locking : Design and Characterization," IEEE J. Lightwave Technol. **31**, 2287-2295, (2013).
[6] L.A. Johansson et al., "Millimeter-Wave Modulated Optical Signal Generation with High Spectral Purity and Wide-Locking Bandwidth Using a Fiber-Integrated Optical Injection Phase-Lock Loop," IEEE Photon. Technol. Lett. **12**, 690-692, (2000).