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Path length stabilization in optical fibers using a superheterodyne receiver architecture

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Many applications in high precision optical frequency metrology require the stable transfer of light through optical fibers. To correct for frequency deviations caused by optical path length fluctuations with an acousto-optic modulator (AOM), it is common practice to reflect part of the transferred light and overlap it with light from a short reference arm of a very asymmetric Michelson interferometer on a photodiode (PD). The signal produced by this heterodyne detection is usually mixed with a reference signal at the nominal beat frequency. The resulting DC signal is used as the error signal of a control loop steering the frequency of the AOM. Recently, a realization of such a phase locked loop has been realized by directly sampling the beat signal detected at the photodiode with an analog-digital converter (ADC) and implementing a digital control loop after digital down-conversion [1].

In contrast we employ a superheterodyne receiver architecture [2]. The PD signal is mixed with a variable reference frequency to obtain a signal at a fixed intermediate frequency. Our design utilizes the STEMlab (originally Red Pitaya) platform and a purposefully developed analog front-end. Further processing of the signal at the intermediate frequency is carried out in the digital domain employing a field programmable gate array (FGPA). These processing steps include digital down-conversion, a CORDIC arctan algorithm and a digital loop filter. The output of the digital loop filter steers the phase offset of a direct digital synthesizer (DDS) whose output is fed to the AOM.

We characterize the device using an ideal radiofrequency source instead of the PD signal and find limiting phase flicker noise of less than 1 mrad for averaging times from 10^{-5} s to 10^{3} s. For the transfer of an optical signal at 344 THz, this translates to a fractional frequency instability of 2×10^{-19} at one second. For most of the intended applications, we find that the signal-to-noise ratio of the optical beat signal determines the instability of the frequency transfer [3]. In addition, we have investigated the effect of variations of the optical power on the measured phase difference. This conversion of an amplitude modulation to a phase modulation (AM to PM conversion) is determined for the different parts of our analog front-end. Based on these results, we determine potential uncertainties and will explain how to correct for AM to PM conversion errors in our system.

In cases when the stabilized optical signal transported over the fiber must be interrupted temporarily, e.g., between Ramsey spectroscopy pulses, and no relevant phase information can be obtained, unwanted excursions of the control loop output need to be avoided. We explain how this is realized for our system with a hold functionality. Detailed investigations of the transient response after reactivation of the control loop permit a prediction of potential errors for different applications.

References

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