



Fig. 6. Allan deviation of the out-of-loop performance of the carrier-envelope offset frequency, normalized to the optical carrier, for the unstabilized frequency comb (red) and with the time-domain CEP stabilization (green).

The CEP instability was, however, one order of magnitude worse than that of the repetition rate at 0.1 second and higher than the value expected in the in-loop noise analysis of Section 3. This difference is thought to originate from the out-of-loop drift of the BXCOR signal, and therefore τ , in the current system. Because a relatively long femtosecond pulse of 800 femtosecond ($\sim 240 \mu\text{m}$ in length) was used for this experiment, out-of-loop timing drift less than the BXCOR detection limit (2.5 nm) could not be compensated [23–25,29,30]. The drift level agreed with the saturated relative CEP stability of 1.67×10^{-9} in Fig. 6, which corresponds to the ratio of this 2.5 nm and the unbalanced OPD of 5.80 m. The current performance could be improved by adopting shorter pulses in order to obtain a steeper BXCOR signal as demonstrated in Ref [31], where hundred-fold steeper BXCOR was demonstrated, or by elongating the unbalanced OPD in order to increase the CEP detection sensitivity.

5. Conclusion

In summary, a time-domain CEP stabilization of femtosecond pulses was demonstrated by controlling the pulse envelope and the carrier phase using the BXCOR and IXCOR signals. The proposed CEP stabilization method was confirmed to function with a low pulse energy of ~ 10 pJ without subsequent pulse amplification or spectral broadening. The out-of-loop measurement showed frequency stability of 1.18×10^{-11} at 0.1 second as an Allan deviation. These capabilities could be applied to absolute laser ranging, surface measurements, and real-time CEP tagging.

Acknowledgments

This work was supported by the Global Research Network Program, the National Space Laboratory (NSL) Program, and the National Honor Scientist Program funded by the National Research Foundation of the Republic of Korea.