Ultra-stable laser with hollow-core fibers

Zitong Feng[1,2], Giuseppe Marra[2], Francesco Poletti[1], Radan Slavík[1]

[1] Optoelectronics Research Centre, University of Southampton, Southampton, UK, SO17 1BJ
[2] National Physical Laboratory, Hampton Road, Teddington TW11 0LW, UK

Email: Zitong.Feng@npl.co.uk

Ultra-stable lasers are crucial for precise measurement devices and scientific experiments such as optical atomic clocks and gravitational wave detection. Their state-of-the-art frequency stability is nowadays achieved through phase-locking to ultra-Low Expansion (ULE) cavities that can be up to half-meter long[1] or to cryogenically cooled silicon cavities[2]. These systems, installed in highly controlled metrology lab environments, have reached short-term frequency stabilities at the 10^{-17} level at 1s with long-term drift of less than 10s of mHz/s. Significant efforts have been spent to enhance their portability to enable applications such as astronomy, quantum sensing, and seismic detection. This has been achieved by using small ULE cavities that have demonstrated frequency stability at the level of 10^{-15} to 10^{-16} at 1s with long-term drift from 10s of mHz to 100s of mHz.

Emerging technologies such as micro-resonators and optical fiber delay lines present alternative laser stabilization methods that provide a compact size, easier construction, and lower costs than ULE cavities. Micro-resonators have shown frequency stability levels down to 10^{-13} at 1s[3], and standard single-mode fiber (SMF) delay lines[4] have demonstrated a matched short-term stability with small-size ULE cavities at the level of 10^{-15}. However, one of the main challenges with these new technologies is maintaining long-term stability, which is affected by temperature changes causing frequency drifts, due to the thermo-optic effect. For optical fiber delay lines, measurements over days have demonstrated a residual drift of 16 Hz/s, even after correcting for temperature-induced changes. This is 2-3 orders of magnitude higher than for ULE cavities, which limits diverse applications such as the special relativity tests in space and search into Earth-like exoplanets.

To improve long-term stability of fiber delay lines, we propose the use of hollow-core fibers (HCF), which has significantly lower thermal phase sensitivity than SMF[5]. We will demonstrate a laser stabilized using an HCF delay line with both the short-term frequency stability and the long-term drift performance matching that of a laser stabilized by ULE cavities. We will present the characterization of the frequency drift change of an HCF delay line over three years. Additionally, we will demonstrate significant frequency drift reduction by correcting for temperature effects with thermistor-based measurements of the HCF delay line. These advancements reveal that HCF delay lines offer a simple to construct, cost-effective solution with exceptional frequency stabilities.

---

[1] M. Schioppo et al., "Comparing ultrastable lasers at 7×10^{-17} fractional frequency instability through a 2220 km optical fibre network," Nature communications, vol. 13, p. 212, 2022.

[2] T. Kessler et al., "A sub-40-mHz-linewidth laser based on a silicon single-crystal optical cavity," Nature Photonics, vol. 6, pp. 687-692, 2012.

[3] K. Liu et al., "36 Hz integral linewidth laser based on a photonic integrated 4.0 m coil resonator," Optica, vol. 9, pp. 770-775, 2022.

[4] J. Dong, "Subhertz linewidth laser by locking to a fiber delay line", Applied Optics, vol. 54, pp. 1152-1156, 2024.

[5] R. Slavík et al., "Ultralow thermal sensitivity of phase and propagation delay in hollow core optical fibres," Scientific reports, vol. 5, p. 15447, 2015.