Sub-1 K Spectral Hole Burning for Ultra-stable lasers

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We report the latest developments on the ultra-stable laser referenced on spectral hole patterns in Eu^{3+}:Y_2SiO_5. By cooling the crystal down to about 300 mK[1] using a custom fit dilution stage in our pulse-tube cryocooler, and interrogating simultaneously a specific three-spectral-hole pattern using our multi-heterodyne interferometry[2] to servo lock the frequency of a laser, we demonstrate a fractional frequency instability of $4(1).10^{-16}$ at 1 s. Further improvements are expected by compensating the phase noise induced by the vibration of the cryocooler, and by further increasing the number of spectral hole used in interrogation. Our current instability represents a factor 2 improvement compared to the best previously reported results in a similar system implemented at NIST[3], and demonstrates the potential of rare-earth ion reference ultra-stable lasers as a relevant tool in optical frequency metrology.

[1] X. Lin, *et al.*, "Anomalous sub-kelvin thermal frequency shifts of ultra narrow-linewidth solid state emitters", under review at Physical Review Letters, 2023.

[2] X. Lin, *et al.*, "Multi-mode heterodyne laser interferometry realized via software defined radio", Optics Express vol. 31, p. 38475–38493, 2023.

[3] M. J. Thorpe, *et al.*, "Shifts of optical frequency references based on spectral-hole burning in Eu^{3+}: Y_2SiO_5", New Journal of Physics, vol. 15, p. 033006, 2013.