National Aeronautics and Space Administration

Superior optical cavity stabilization for compact spaceborne instruments

Principal Investigator: Vladimir Iltchenko (335); Co-Investigators: Andrey Matsko (335), Wei Zhang (335)

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Objectives

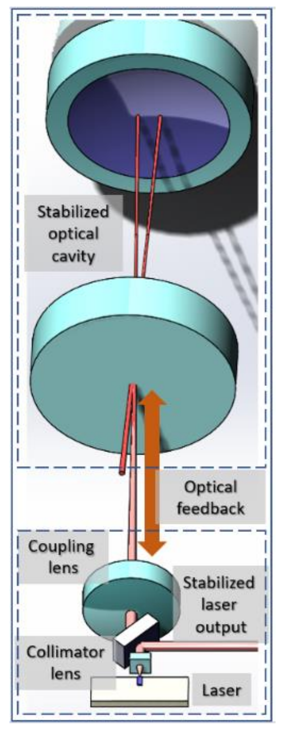
The objectives of this project included i) a trade study of modal and spectral parameters of off-axis high finesse Fabry-Perot (FP) resonators, in their near-confocal, semi-confocal, and ring configuration, and identification of the best suitable modes and layout of the cavity for optical self-injection locking; ii) optimization of a FP resonator configuration with largest FSR, based on commercially available mirrors, and design of a micro-optical train for injection locking of semiconductor laser chips with optical feedback from selected modes; evaluation of the required investment and identification of the necessary test equipment as well as industrial partners/vendors, and preparation of the follow on proposal intended for demonstration of laser modules suitable for space clocks and photonic RF oscillators.

Background

Ultra-high coherence lasers enable optical and RF space instrumentation including coherent satellite communication, high-resolution radars and LiDARs, molecular and atomic clocks. Commercially available high performers like Non-Planar Ring Oscillator lasers have limited scalability and operational wavelengths (1064 and 1319nm). Emerging space clocks and quantum sensors call for broader range of operational wavelengths (from UV to mid-IR). Semiconductor lasers do not provide good enough spectral purity. Laser stabilization with standard hollow and monolithic cavities is not suitable for space applications. Monolithic cavities are highly nonlinear and radiation sensitive. Existing schemes using vacuum Fabry-Perot (FP) cavities are heavy, environmentally unstable, and power hungry. We propose to solve the problem with a miniature vacuum microcavity and optical train configuration with optical resonance feedback. Ultimately, the system will be characterized with 1)ultranarrow linewidth (low phase noise at the level <-120dBc/Hz at 10kHz); and 2)optical frequency stability at the level < 10-12 at 1s. Due to low dispersion and equidistant spectrum, and using directly modulated planarly integrated diode laser chips, cavity will also support mode-locked operation for generation of spectrally pure microwave signals. We propose ultracompact FP cavities and injection-locked laser modules, as disruptive solution for RF and optical instruments on space constraint platforms, e.g. SmallSats and CubeSats.

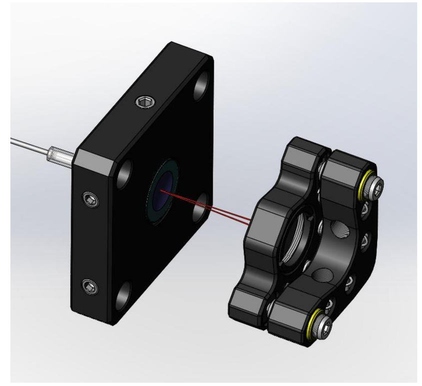
Approach

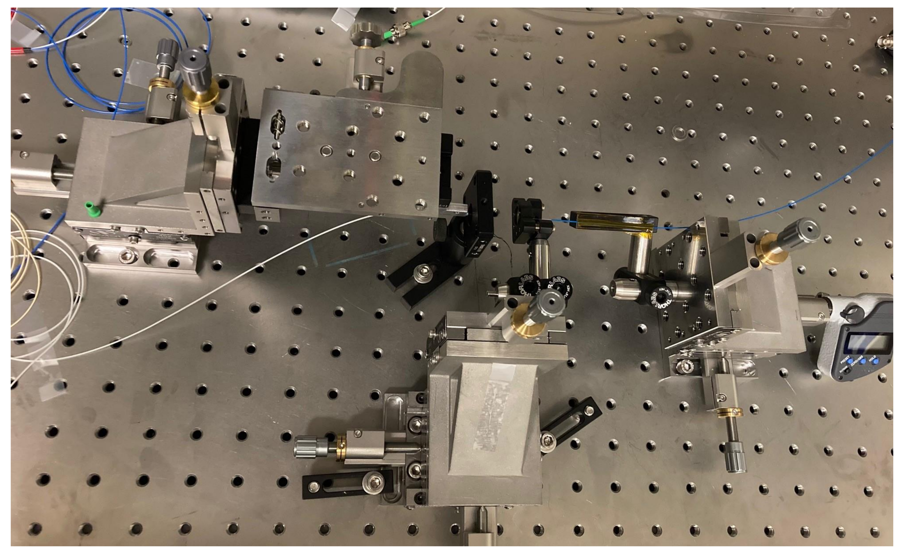
Frequency locking of semiconductor lasers with optical feedback from large Fabry-Perot cavities has been demonstrated in early papers [1], but never developed into compact (~10in^3) packaged devices like those with monolithic resonators [2]. Robust operation of self injection locking requires that 1)frequency spectrum of modes providing optical feedback does not contain variety of competing modes except the TEM_{00} modes separated by free spectral range (FSR) which is in turn determined by the mirror separation L; FSR=c/2L where C is the speed of light; 2)free spectral range is no less than few GHz, i.e. the cavity should be small L=1-2cm; 3)finesse of the mirrors and hence quality-factor of the cavity is high enough to support strong suppression of laser frequency fluctuations and drift; practically Q=0.5-2x10^8, finesse 500-5000 for the chosen length, cavity bandwidth 1-5MHz at wavelength 1550nm; and 4)resonance reflection coefficient from the cavity via optical train to the laser is 0.2-2% to achieve optimized external cavity operation for telecom band DFB laser chips. Fabry-Perot cavities have been extensively analyzed and studied experimentally in axial configuration while injection locking requires off-axis operation in so called V-modes.



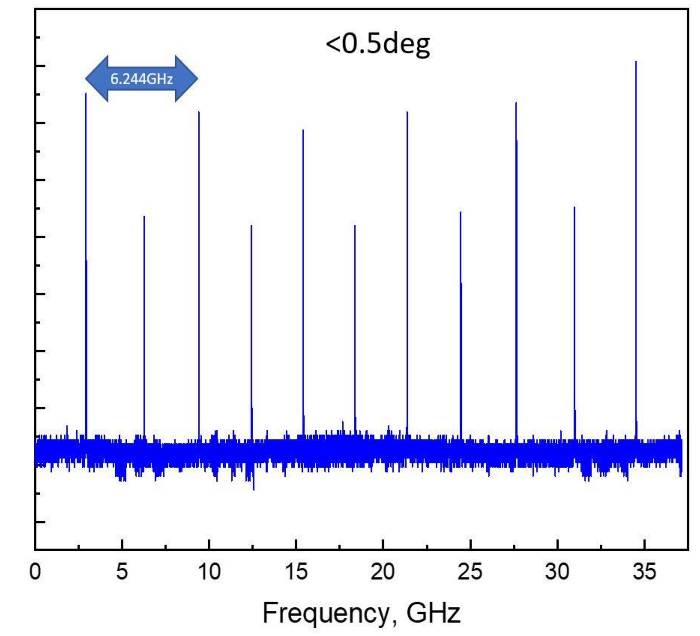
Results

1. We have created **experimental setup with confocal FP cavity with R=24mm** and mode matched model optical fiber coupler with GRIN lens. Setup equipped with 5-axis translation stages and micrometer drives is illustrated in figures below

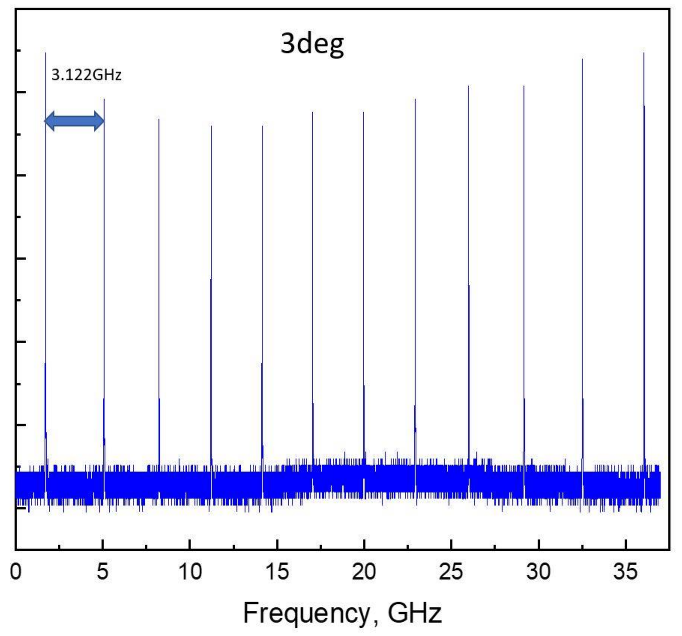




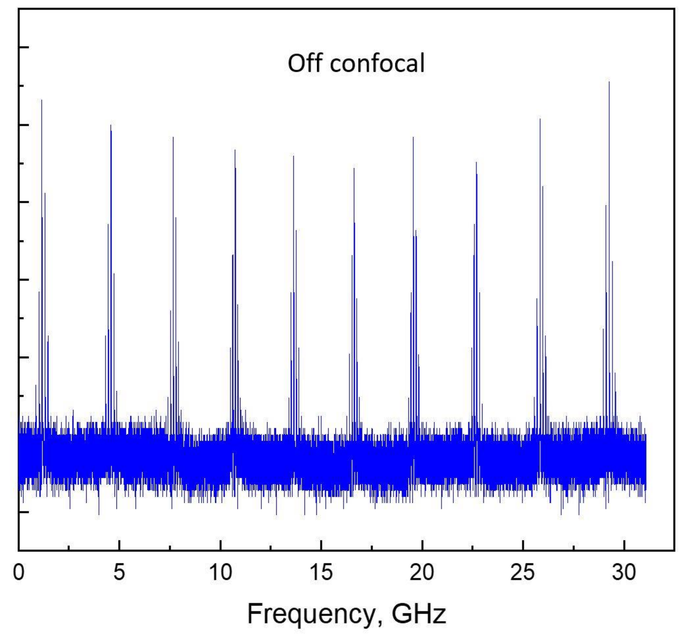
2. Optical alignment procedures were developed and **optical transmission spectra** taken at various alignments obtained



Spectrum in near axial excitation. Prominent FSR = c/2L



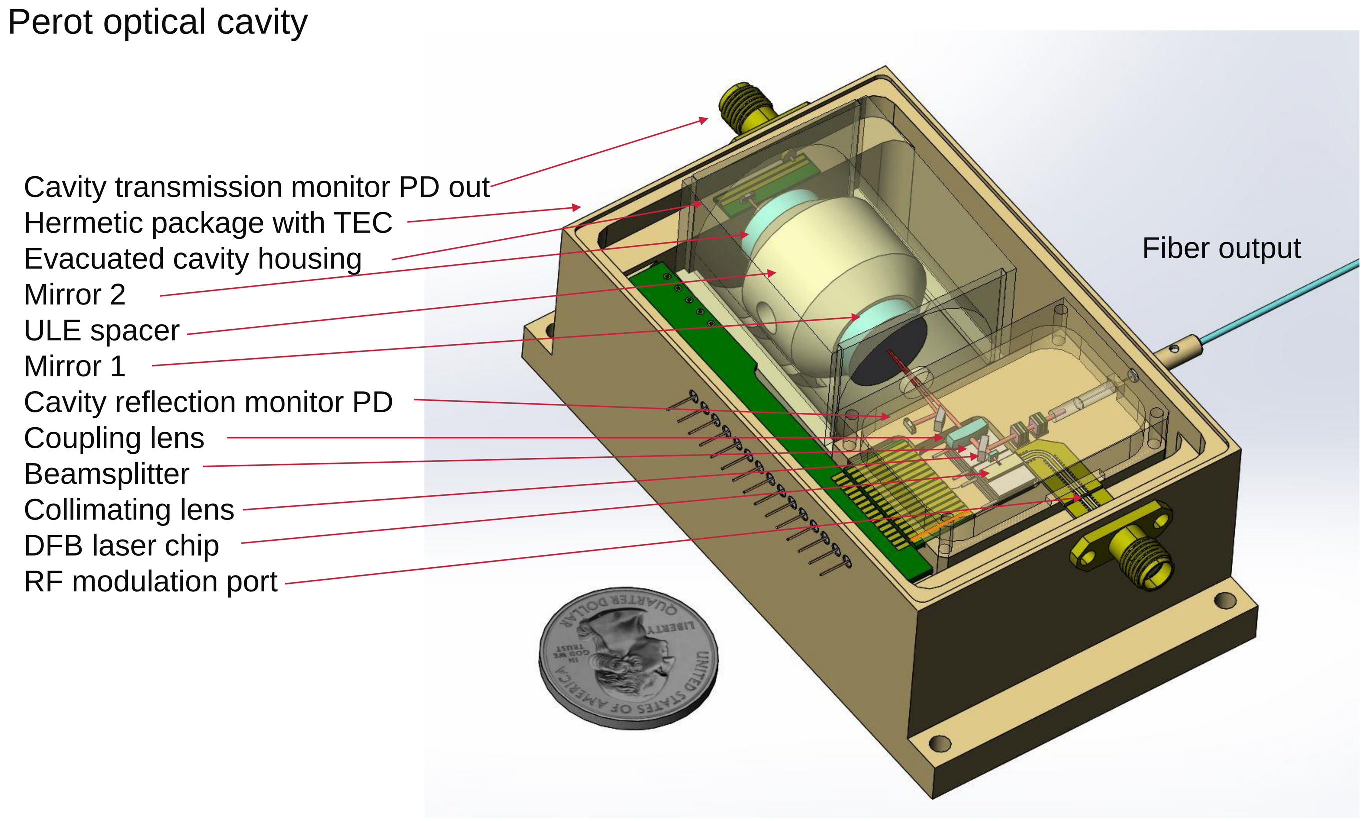
Off-axis V-modes have FSR=c/4L



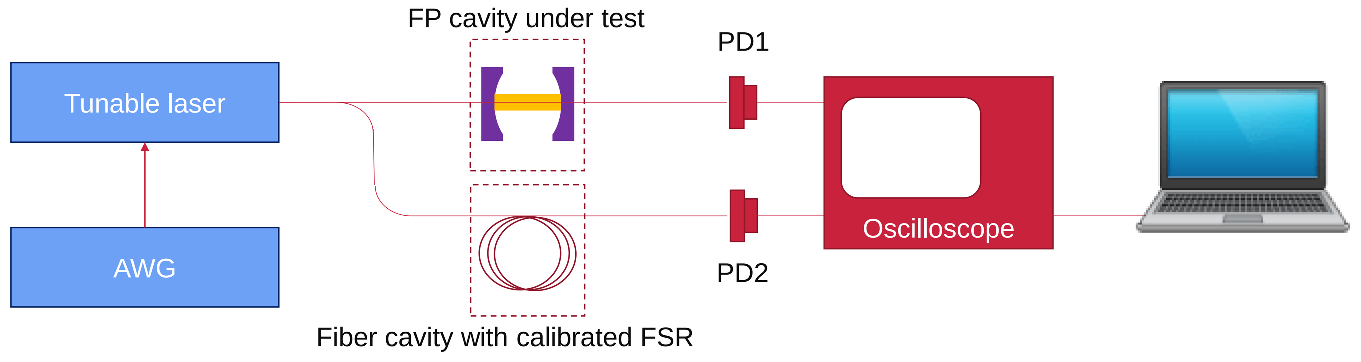
Spectrum with 200um offset from confocality

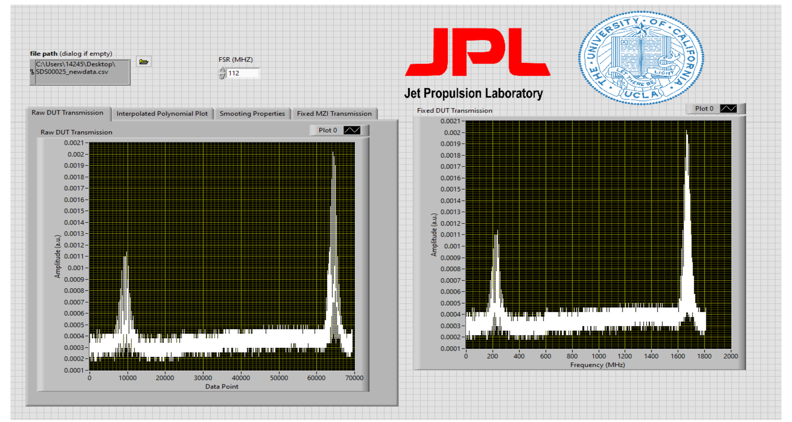
3. Single longitudinal mode operation has been **achieved in V-modes** and tolerance established for alignment precision of the confocal cavity at the manufacturable level of 10um**. Clean single mode spectrum demonstrated with finesse 600 and no parasitic modes within free spectral range detected beyond sensitivity level -20dB.V-mode suitability for optical self-injection locking of DFB lasers confirmed.** Experimental demonstration of injection locking was prevented by high transmission loss (95%) of the inexpensive commercial mirrors used.

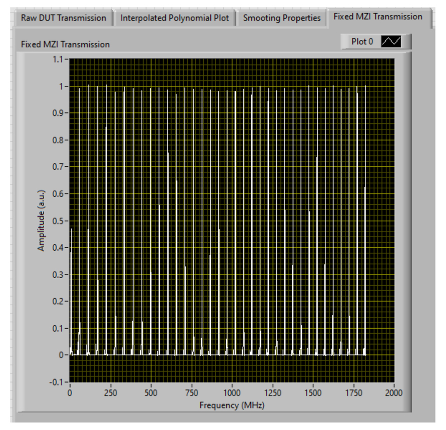
4. Conceptual SolidWork design has been developed for the hermetically packaged injection locked laser oscillator utilizing the V-modes in evacuated Fabry-Perot optical cavity



5. As byproduct in **measurement technique, a method of sweep linearization, and software** has been developed to facilitate high fidelity spectral study of optical cavities using frequency tunable lasers







Significance/Benefits to JPL and NASA

High coherence lasers and oscillators based on optical self injection locking from miniature off axis Fabry-Perot resonators will facilitate creation of a class of low SWaP optical and radio-frequency instruments benefitting from low phase noise in addition to high frequency stability, to operate on space constraint platforms, e.g. SmallSats and CubeSats. Absence of parasitic transverse modes, as well as optimized finesse~10^3 will ensure optically robust operation without mode hopping. Established alignment tolerance in the range of ~10um while not being relaxed, is fully compatible with manufacturing processes of low expansion materials used for cavity spacer, and hermetic packaging technology for space applications. With modest additional RTD funding, optimized custom mirrors can be procured with FiveNine Optics, Boulder CO, and low expansion precision spacer with Perkins Precision Developments, Longmont, CO. The presented design of integrated laser with injection locking form FP can be converted into fully simulated engineering model for TRL 6 prototype. Packaged design can be expanded into that of high frequency microwave oscillator, such as one suitable for pace borne W-band earth radar.

References

1. L.Hollberg, M.Ohtsu, "Modulatable narrow linewidth semiconductor lasers", Appl. Phys. Lett.,**53**, 944-946

2. W. Liang, V. S. Ilchenko, A. A. Savchenkov, A. B. Matsko, D. Seidel, and L. Maleki, “Whispering-gallery-mode-resonator-based ultranarrow linewidth external-cavity semiconductor laser,” Opt. Lett. **35**, 2822–2824 (2010)

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

PI/Task Mgr Contact
Email: Vladimir.S.Iltchenko@jpl.nasa.gov

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