Environmentally Stable Ultra-Low Noise Self-Injection Locked Semiconductor Lasers

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Abstract: Self-injection locking (SIL) of semiconductor lasers by means of monolithic optical cavities allow generation of high spectral purity and high stability optical signals under varying environmental conditions. We review recent advances in the field and focus at the SIL by means of monolithic Fabry-Perot resonators. *©2023 California Institute of Technology. Government sponsorship acknowledged.*

1. Introduction

Linewidth is one of basic parameters defining quality of a laser. Fundamentally the linewidth value is restricted by the Shawlow-Townes limit [1]. Linewidth of a semiconductor laser is larger than the fundamental quantum limit because of the nonlinearity of the laser host material [2]. In the both fundamental cases it is assumed that the laser is characterized with the white frequency noise. The value of the linewidth of a realistic laser is not defined well and full spectral analysis of the laser noise is needed to characterize performance of the laser. Phase noise of a realistic laser can be satisfactory described using Leeson model originally developed for microwave oscillators [3]. The model shows that the noise reduces with increase of the laser power as well as quality (Q-) factor of the laser cavity. Various experimental techniques took advantage of this property and lasers characterized with high spectral purity (or low phase noise) were realized. In this presentation we will focus at the self-injection locking technique that attracted a lot of attention recently and allowed realization of compact and environmentally stable semiconductor lasers having spectral purity comparable with the best fiber as well as solid state lasers.

SIL was originally utilized to improve performance of radio-frequency systems [11, 12]. Later it was adapted for laser stabilization [13, 14]. More recent developments resulted in integration of a SIL system on a chip [4] as well as true photonic integrated circuit (PIC) SIL laser realizations [5–10].

Semiconductor SIL lasers are not only characterized with low both amplitude and phase noise [15], but they also have low environmental sensitivity [16]. The main reason for the that is small size of the cavity used for the SIL operation. On one hand, the small size allows better thermal stabilization of the cavity. On the other hand, the small size of the cavity shifts its mechanical modes to higher frequencies, leading to less sensitivity of the cavity to acceleration as well as vibration. For example, it was shown that the acceleration sensitivity of a 2μm semiconductor SIL distributed feedback laser is approximately $5 \times 10{-}11$ g^{-1} in the 1-200 Hz frequency bandwidth and thermal sensitivity is approximately 10 MHz/C. The frequency noise of the SIL laser is below 50 Hz/Hz$^{1/2}$ at 10 Hz frequency offset, reaching 0.4 Hz/Hz$^{1/2}$ at 400 kHz. The instantaneous linewidth of the laser is improved by nearly 4 orders of magnitude compared to the free-running semiconductor laser and is measured to be 50 Hz at 0.1 ms measurement time. The Allan deviation of the laser frequency is on the order of 10^{-9} in the interval of 1–1000 s. All the results were obtained for a laser packaged with a compact electronic controller.

The small size of the cavity used in SIL systems, on the other hand, results in increase of the fundamental thermodynamic fluctuations that limit the performance of the laser. One can increase the cavity size to reduce these fluctuations, but size increase results in increase of the spectral density of the cavity modes. We propose to take advantage of the monolithic Fabry-Perot (FP) cavities, that lend themselves for the better spectral filtering than the ring cavities. It is easier to reduce the mode density impacting SIL in an FP cavity than in a multi-mode ring resonator.

2. Self-injection locking with Fabry-Perot Cavities

A ring cavity is a natural choice for self-injection locking experiments since such a cavity provides resonant feedback to the laser chip exclusively at the frequencies of the cavity modes. An FP cavity usually reflects light at all the frequencies but the resonant ones. While SIL with FP cavities is possible, it calls for certain optimizations of the setup. It is possible to use special cavity configuration and modes [13,17–21]. It is also possible to put the high-finesse FP cavities into the low finesse ring cavities [22–24]. While these methods result in great performance, their implementation is technically hard.

We have developed a technique of SIL of a semiconductor laser to a compact and monolithic cylindrical Fabry-Perot cavity [25, 26]. We propose to couple light to high-order modes of the FP cavity that diverge from the symmetry axis of the FP cavity. We created a system that supports efficient resonant back-reflection that locks the laser to the cavity mode by sending the light backwards along one of the lobes of the cavity far-field emission. The forward emission of the laser, that does not enter the cavity, is efficiently reflected and spatially filtered out from reentering the laser chip. We observed a low noise optical signal in this way.

There are a few advantages of the proposed system if compared with other SIL schemes. Our system can be aligned in a simple way. It also can be packaged rather robustly. It is easier than the alignment and packaging of a laser with a larger ring cavity. Our method works with any mirror configuration of the cavity. The monolithic FP cavity does not need a vacuum enclosure to eliminate gas effects in hollow FP cavities. It also does not need clean optical environment required for the cavities based on the total-internal reflection, because small contaminants, accumulated at the external cavity surfaces, do not degrade the cavity performance. The bulk FP cavity is mechanically and environmentally stable. It has a relatively large volume resulting in reduced fundamental thermodynamic fluctuations. On the other hand, the volume is small enough to ensure high frequency of the mechanical modes of the cylinder, and that reduces vibration sensitivity compared to hollow FP resonators requiring heavier support.

The cavity is created using a the technique published recently [25]. It is made from a fused silica preform of 15 mm diameter and 25.4 mm length. One end-surface of the cavity was polished flat, and the other was shaped to be convex with 1 meter radius of curvature (not the confocal configuration). High reflectivity ion-beam-sputtering coating centered at 1550 nm are deposited on both surfaces.

To lock a semiconductor laser to the cavity we utilize high order modes along with a spatial filter. Because of the technical reasons, the placement of the mirrors is not symmetric. We measured the optical axis of our cavity to be displaced 1.4 mm from the cylinder axis. We were able to accommodate this eventual geometry and implement alignment in the system. The high order modes of the cavity have lobes propagating at the angle with respect of the cavity mirror surface. We have matched the input laser beam with one of such a lobes. The beam both pumps the cavity mode and reflect from the mirror surface. We use spatial filtering to suppress impact of the reflection on the laser. Since the mode of the cavity supports standing optical wave, the light confined in the mode propagates back to the laser via the same optical path. It happens only when the laser frequency coincides with the frequency of the mode. The non-resonant reflection of the light can be filtered out spatially. As the result, the laser locks to the mode by means of the self-injection locked process. Since the locking requires only a few percent of light to be back reflected, we split the laser beam in two parts and use only one of the parts for the cavity interrogation, while the other part is utilized as output.

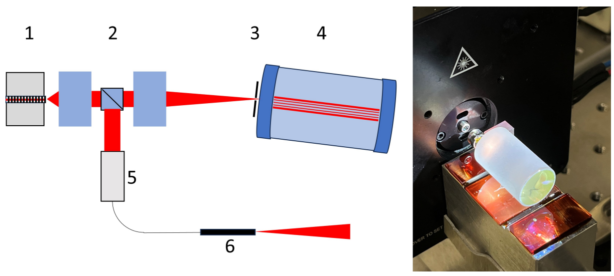

Fig. 1. Left: Schematic of the experimental setup of the SIL semiconductor laser based on a monolithic FP cavity. Light emitted by a laser chip sub-assembly (1) is collimated and split by a beam splitter (2) to separate the light used for the laser locking and the output light. Light leaving one port of the beam splitter is coupled to a Fabry-Perot cavity (4). The resonant optical feedback is achieved with the direct back-reflection aperture filter (3). The collimated output light exiting the other port of the beam splitter is coupled to a fiber using a collimator (5) and released from the fiber using a standard fiber connector (7). Right: A photo of the laser chip in the sub-assembly and the cavity installed on a holder.

3. Conclusion

We have reviewed recent experimental work associated with self-injection locking of semiconductor lasers by means of high-Q optical cavities. The lasers are characterized with low noise as well as low environmental sensitivity. The SIL technique is applicable to laser chips operating at any available wavelength. It is also suitable for stabilizing various semiconductor lasers such as distributed-feedback, distributed Bragg grating, Fabry-Perot, and others. The lasers can be packaged in a small form factor. Overall, the self-injection locked lasers compete with best solid state, fiber and gas lasers available on the market.

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