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High spectral purity lasers stabilized on mini Fabry-Perot fiber resonators

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Abstract—Low phase noise and narrow linewidth lasers are realized through locking of semiconductor DFB lasers on compact fiber Fabry Perot resonators. Two locking scheme are used: electronic (PDH) and optical. The results are compared versus the offset from carrier on which the frequency stability has to be improved.

Keywords—laser, optical resonator, fiber optics, quality factor, injection-lock, frequency noise, linewidth

I. INTRODUCTION

Compact low phase noise and narrow linewidth lasers are key devices in many applications such as precision measurements, clock interrogation and optical frequency synthesis. Various types of optical resonators may be used to frequency stabilize semiconductor lasers and get narrow linewidth and reduced frequency or phase noise. However, resonators featuring simultaneously high Q factor, compact size and an easy control of their coupling factor to the optical system are difficult to find.

These last years, we have developed a resonator technology based on the deposition of high quality dielectric mirrors on both ends of a piece of optical fiber, with an approach close to [1-3]. The size of these fiber Fabry-Perot (FFP) resonators goes from 1 cm to 7 cm and their free spectral range is between 10 GHz and 1.5 GHz. The Q factor is in the range of 10^8 , but can exceed largely 10^9 depending on the fiber type and size.

In this communication, we present the stabilization of two different semiconductor lasers on 2 cm length FFP resonators. The locked lasers performance is discussed in terms of frequency noise and potential improvement of this parameter depending on the offset frequency.

II. RESONATORS REALIZATION AND TEST

The resonators are realized from a piece of optical fiber which is carefully polished and on which thin film dielectric mirrors (Bragg mirrors) are deposited. The resonators are embedded in a zirconium ferule before mirrors deposition, which allows an easy coupling of the resonator to input and output optical fibers and ensures resonator's mechanical stability (Fig. 1). The size of these ferule resonators is 1 cm or 2 cm (in this paper, only results obtained with 2 cm resonators are considered). The resonators free spectral range (FSR) is 10 GHz (1 cm) or 5 GHz (2 cm). Longer resonators have also been realized, featuring higher quality factors (Q), with a record value of $5 \cdot 10^9$ and an intrinsic finesse of about 10^5 for a 7 cm resonator (to be published). However, these large size resonators are not embedded in a ceramic ferule and, for laser stabilization application, the best results have been obtained with mechanically stable and short length resonators. The choice of the optical fiber also determines the resonator performances. The two resonators involved in this study are both 2 cm length resonators but the first one is realized with a piece of single mode fiber (SMF) while the second one is a piece of multimode fiber (MMF) with larger effective area.

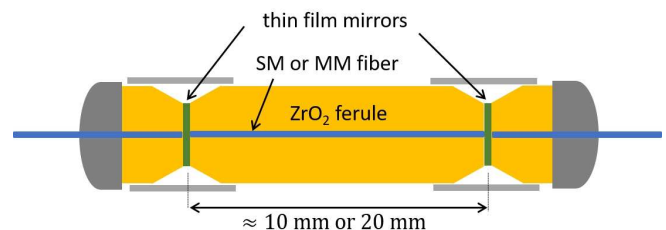


Fig. 1: Fiber Fabry Perot resonator embedded in a zirconium ferule.

The two resonators have been characterized using an RF spectroscopy technique [4] involving the locking of a narrow linewidth semiconductor laser to one resonator mode and exploring the side modes through beating with the central mode by using a fast modulator (MZM), a microwave vector network analyzer (VNA) and a photodetector (PD1). Hence the amplitude and phase of the measured S_{21} parameter display an exact replica in the microwave domain of the optical complex transfer function profile of the measured FFP. The measurement set-up is depicted in Figure 1.

The resonators measurement of optical losses (maximum of resonance curve) and loaded Q factor allows the extraction of the physical parameters: mirror reflectivity R (which also determines the coupling factor) and intra-cavity losses. Table 1 depicts some of these parameters for the two resonators involved in this study.

	FSR (GHz)	L (dB)	Δf_{3dB} (MHz)	Q_L	Q_o	Finesse (int.)
2 cm SMF	5.11	-13.9	5.13	3.8×10^7	4.7×10^7	1250
2 cm MMF	5.08	-3.3	1.01	1.9×10^8	6.1×10^8	15950

Table 1: resonators parameters. L = optical losses at resonance. Δf_{3dB} = 3dB bandwidth. Q_L = loaded Q factor. Q_o = intrinsic Q factor. Finesse = intrinsic finesse (computed from intrinsic Q factor).

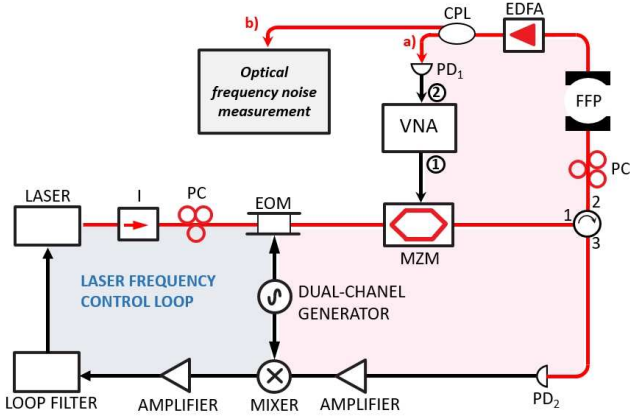


Fig. 2: Resonators measurement set-up using the spectro-RF technique: path a). Measurement of the laser phase noise when it is PDH locked on the resonator: path b). EOM = phase modulator. MZM = Mach Zehnder modulator. PD = photodiode. FFP = Fiber Fabry Perot resonator.

III. INJECTION LOCKING

The first technique used to stabilize a semiconductor laser on these resonators was based on the full optical stabilization approach depicted in Figure 3 [2,5,6]. The laser is a medium power 1550 nm DBF laser without isolator from Gooch & Housego. The signal from the laser passes through the resonator and a portion of it is fed back to the laser. The system is housed in a metal enclosure, shielded from vibrations and temperature fluctuations. The attenuator serves as the sole adjustment parameter (together with laser current) to regulate the strength of the optical feedback. Excessive feedback may destabilize the laser, while insufficient feedback leads to poor phase noise performance.

The locked laser output signal is directed to a measurement system based on a self-heterodyne optical frequency discriminator [7]. The output from this system is

an 80 MHz signal, which is analyzed using a Keysight E5052B phase noise measurement bench. The optical frequency discriminator incorporates a 2 km optical delay line, providing high sensitivity and a low-noise measurement floor crucial for characterizing high-quality optical sources, enabling frequency noise measurements up to 1 MHz offset from the carrier (after correction of the sinc response). The measurement set-up is in a shielded box and protected from vibrations, as depicted in Figure 4.

Frequency noise measurements of the locked and unlocked lasers are depicted in Figure 5. A huge improvement of the laser frequency noise is observed when the laser is locked (more than 50 dB at large offset frequencies). However, there is almost no difference between the performance measured with the two resonators, although the Q factor of the MMF resonator is more than 10 times better than the SMF one. A technical noise of the loop has been probably reached.

The intrinsically large bandwidth of the optical injection locking process allows the noise improvement up to 1 MHz offset (and higher) for both lasers. However, at low frequency offsets ($f < 1$ kHz), a noise typical from mechanical vibrations is observed, with numerous peaks. The set-up, based on an optical loop made of a few meters of fiber, is indeed sensitive to vibrations and probably also to thermal fluctuations. Improvements are however possible through a reduction in length of the fiber and a more rigid fiber maintain.

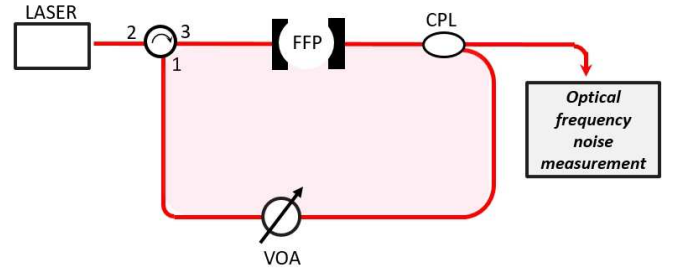


Fig. 3: Set-up for the full optical laser stabilization (self-injection lock). Feedback strength and locking bandwidth are adjusted with the variable optical attenuator (VOA).



Fig. 4: Laser phase or frequency noise measurement system based on a self-heterodyne interferometer with 2 km delay line [6].

The instantaneous linewidth of these lasers can be computed from the measured value of the frequency noise floor ($\Delta \nu_{inst} = \pi S_{\Delta \nu} @ 1$ MHz). From Figure 5 data, its value is approximately 0.3 Hz. More interesting is the integrated linewidth, which takes into account the excess noise at low frequencies (1/f noise, vibration noise...) and which gives a

good estimate of the real linewidth of the laser. For these lasers, the integrated linewidth is approximately 400 Hz (see details in [6]).

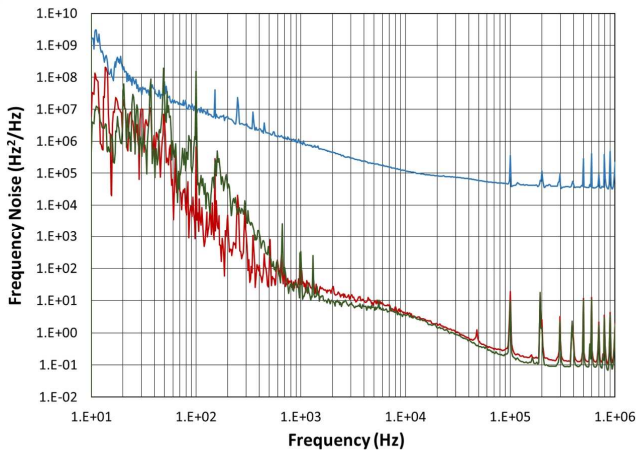


Fig. 5: Measured frequency noise in the self-injection locking mode (Fig 2 set-up). The free running DFB laser noise (blue curve) is reduced of more than 5 decades at large frequency offsets (1 MHz) when it is locked on SMF (red) or MMF (green) resonators.

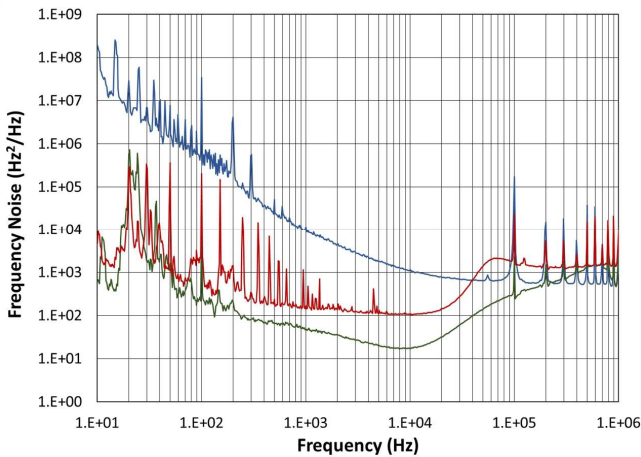


Fig. 6: Measured frequency noise in the PDH locking mode using Fig 1 b) set-up. The free running RIO external cavity laser noise (blue curve) is reduced inside the locking bandwidth. A better performance is observed when the laser is locked on the MMF resonator (green curve) than on the SMF one (red curve).

IV. POUND DREVER HALL TECHNIQUE

A more classical technique to stabilize a laser on a resonator is the Pound Drever Hall approach [8]. The feedback on the laser is, in this case, an electronic feedback. It works with almost any type of laser and the requirements for temperature stability of the fiber between the laser and the resonator are less stringent than for the full optical case. However, compared to the optical injection lock, the locking bandwidth is smaller and limited by the size of the electronic loop and the gain needed to cancel the free running laser noise once locked.

To implement this approach, it is easier to start with a relatively narrow linewidth laser, particularly if the resonator Q factor is very high [9]. This is the case of our system for resonators characterization which uses a RIOTM external cavity semiconductor laser. We have thus measured the optical signal from this system with the laser locked and

unlocked, trying to improve the noise reduction when locked with the loop gain parameter. The optical frequency noise measurements results are depicted in Figure 6.

Very close to the carrier ($f < 200$ Hz), the PDH approach gives a better performance than the optical injection locking approach with the same resonators. However, for higher offset frequencies, the frequency noise improvement is not so impressive and the free running RIO laser noise is found again far from the carrier i.e. above 100 kHz offset.

Contrarily to the injection locking case, a better performance is observed when the laser is locked on the MMF resonator than on the SMF one, but the difference does not completely align on the Q factor difference between the two resonators.

V. CONCLUSION

Optical self-injection locking and Pound Drever Hall approach lead to very different results in terms of frequency (or phase) noise for semiconductor lasers locked on mini fiber Fabry-Perot resonators. The most promising technique is clearly the self-injection locking, because of its large locking bandwidth and strong noise reduction factor. It requires however a control of the entire optical loop in terms of mechanical and thermal parameters. On-going work is focused on the stabilization of this system and on its use with higher Q factor resonators.

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