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Limitations of the frequency stability transfer in the near infrared using a fiber-based ring cavity

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Abstract

We describe a fiber ring cavity for transferring frequency stability from a metrological optical reference at 1542 nm to tunable lasers covering a hundred nm around 1.55 μ m and show a stability transfer to the 10^{-15} level in relative value. The optical length of the ring is controlled by two actuators: a cylindrical piezoelectric actuator (PZT) on which a portion of the fiber is coiled and glued for fast corrections (vibrations) acting on the length of the fiber and a Peltier module for slow corrections acting on its temperature. We characterize the stability transfer and analyze the limitations imposed by two critical effects in the setup: Brillouin backscattering and the polarization modulation generated by the electro-optic modulators used in the error signal detection scheme. We show that it is possible to reduce the impact of these limitations to a level below the detection threshold imposed by the servo noise. We also show that in the long term, the limitation to the stability transfer is a thermal sensitivity of -550 Hz/K/nm which could be reduced by active control of the ambient temperature.

1- Introduction

Due to their high-quality factor, high finesse optical cavities are often used in metrology and spectroscopy applications to provide spectral purity to lasers [1][2]. In addition, the stability of the cavity which is transferred to the laser is sufficient in many applications of atomic physics [3]. For improving the frequency stability of lasers, the cavity must be locked to an optical reference [4] whose stability may be transferred to any laser locked on the cavity, even at wavelengths far from the reference [5], [6]. Fiber-based interferometers such as Fabry-Perot [7] or ring cavities [8], [9] lead to compact metrological devices giving significant linewidth reduction [10] and frequency stability performances [11] for reasonable costs. Such devices offer the wideband transparency of the optical fiber allowing to achieve stability transfer from visible to mid-infrared ($>2\mu$ m for IR fused silica glass) [12].

We have implemented this simple approach of cavity locking for the stability transfer from a metrological reference at 1542 nm to the light emission band of a semiconductor frequency comb at 1550 nm by optical injection locking [13].

We present a single mode fiber cavity based on SMF fiber (ITUT-G652) for the frequency stability transfer from an optical reference to tunable lasers in a wide range of wavelengths. Thanks to the low losses in fibers, our setup allows us to reach a quality factor of 1010 simply with suitable fiber cavity length. We show that with these characteristics, the frequency stability transfer is done at the level of 10^{-15} in relative value for a volume of only a few liters. However, the sensitivity of the chromatic dispersion in the fiber to the thermal environment of the cavity limits the long-term stability of the transfer.

We firstly describe the principle of stability transfer, the experimental implementation of the cavity stabilization and the improvement of the spectral purity of the tunable sources. Then we present the characterization of the cavity and the effects limiting its short- and long-term stability. We demonstrate experimentally the capability of the cavity to transfer the frequency stability at distant wavelengths with a level of 10^{-15} in relative value. We conclude on the performances obtained with this device and we give some perspectives to improve them.

The metrological reference at 1542 nm is delivered by the REFIMEVE+ network [14]. A continuous wave Erbium-doped fiber-laser emitting at 1542.13 nm is stabilized onto an ultra-stable Fabry-Perot cavity. For long-term stability, it is referenced onto a hydrogen-maser, ensuring stability better than 10^{-15} until 105 s of integration time. The laser light is transferred to our lab through a 43 km long single-mode fiber. The propagation noise along the fiber, mainly thermal and acoustic noise, is actively compensated.

The goal of our work is to transfer the frequency stability of this reference to external cavity diode lasers (ECDL) that can be tuned to a hundred nanometers around 1550 nm. For this aim, we use a fibered transfer cavity. The principle of transfer is illustrated in Fig. 1(a). One mode of the cavity is frequency-locked to the reference, which increases the stability of all other modes of the locked cavity. The frequency of a tunable laser is then locked on another mode of the cavity. The lock of the cavity to the reference is achieved by controlling its optical length via two actuators, either by acting on its length or by changing the temperature of the fiber. The lock of an ECDL onto a cavity resonance is performed by controlling optical frequency via its current.

Our setup gives us the possibility to lock simultaneously two ECDL sources to the same cavity. As our equipment only performs beat measurements up to 34 GHz, this allows us to characterize the transfer in two ways as shown in Fig. 1(b). We can study the absolute frequency stability of one ECDL locked to a cavity mode from the beat note between ECDL and reference (close transfer beat note). We can also deduce the relative frequency stability between two ECDLs, when they are locked to cavity modes at other wavelength (far transfer beat note). Thanks to the excellent recopy of the reference stability by the cavity, a transfer up to 34 GHz is sufficient to study limitations scaled by the transfer range.

2- Experimental set-up

The metrological reference at 1542 nm is delivered by the REFIMEVE+ network [14]. A continuous wave Erbium-doped fiber-laser emitting at 1542.13 nm is stabilized onto an ultra-stable Fabry-Perot cavity. For long-term stability, it is referenced onto a hydrogen-maser,

ensuring stability better than 10^{-15} until 10^5 s of integration time. The laser light is transferred to our lab through a 43 km long single-mode fiber. The propagation noise along the fiber, mainly thermal and acoustic noise, is actively compensated.

The goal of our work is to transfer the frequency stability of this reference to external cavity diode lasers (ECDL) that can be tuned to a hundred nanometers around 1550 nm. For this aim, we use a fibered transfer cavity. The principle of transfer is illustrated in Fig. 1(a). One mode of the cavity is frequency-locked to the reference, which increases the stability of all other modes of the locked cavity. The frequency of a tunable laser is then locked on another mode of the cavity. The lock of the cavity to the reference is achieved by controlling its optical length via two actuators, either by acting on its length or by changing the temperature of the fiber. The lock of an ECDL onto a cavity resonance is performed by controlling optical frequency via its current.

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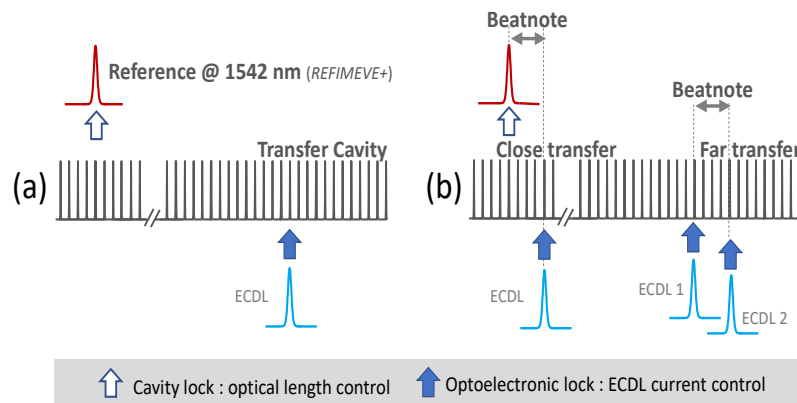


Fig. 1. Principle and characterization of frequency stability transfer. (a) Frequency stability transfer from the metrological reference to an ECDL through the cavity; (b) Characterization scheme: absolute frequency stability close to the reference with the reference/ECDL beat note and transfer at different wavelength with the ECDL1/ECDL2 beat note.

The ring cavity is realized with 200 m of SMF fiber and a 10/90 optical coupler. The free spectral range is 1 MHz, the mode width is 23 kHz which corresponds to a quality factor of 1010 at 1550 nm. The cavity is enclosed into a box providing passive thermal and acoustic insulation. The experimental setup is described in Fig. 2. The frequency stabilization of the cavity is performed by controlling its optical length with 2 actuators: a Peltier module which acts on the temperature of approximately 1/5th of the fiber length and a cylindric piezo ceramic (PZT) on which 20 m of fiber are coiled and glued ensuring the control of the cavity length. The error signal is obtained by the Pound-Drever-Hall (PDH) method [15]. The reference beam is phase-modulated with a frequency of 200 kHz by an Electro-Optic

Modulator (EOM) at the cavity input and the error signal is detected at the cavity output. An integrator produces the signal controlling the voltage applied to the PZT to correct acoustic perturbations in high frequency range and a pseudo-integrator controls the current in the Peltier module to compensate for residual cavity temperature fluctuations in low frequency range.

The distributed fiber deformation caused by the coiling of the fiber around the PZT induces a stable birefringence which leads to the existence of two families of orthogonal modes in the cavity. The input polarization is adjusted in order to excite only one of them (inset on Figure 2). As for the cavity lock to the reference, the beams from each ECDL are phase-modulated with two different frequencies close to 3.5 MHz at the cavity input with EOMs. The error signals are also obtained by the PDH method. Each detected error signal is applied to an integrator to generate the control signal added to the ECDL's current.

The frequency locking of an ECDL onto the cavity leads to a spectacular reduction of its linewidth (Fig. 3). The linewidth of a free ECDL is about 100 kHz. The frequency locking of the ECDLs on the cavity with servo bandwidths of about 100 kHz results in a beat note between them of 65 Hz. As we use two identical servo loops for ECDLs, this corresponds to a linewidth of about 30 Hz for each locked laser.

The beams from the metrological reference and ECDL 1 are superimposed at the input of the ring cavity. A Bragg filter of 100 GHz bandwidth centered at the reference wavelength is used to separate the beams at the cavity output. The reflected beam is used to stabilize the cavity mode on the reference. The transmitted beam is used to lock the frequency of ECDL 1 on one cavity mode far from the reference.

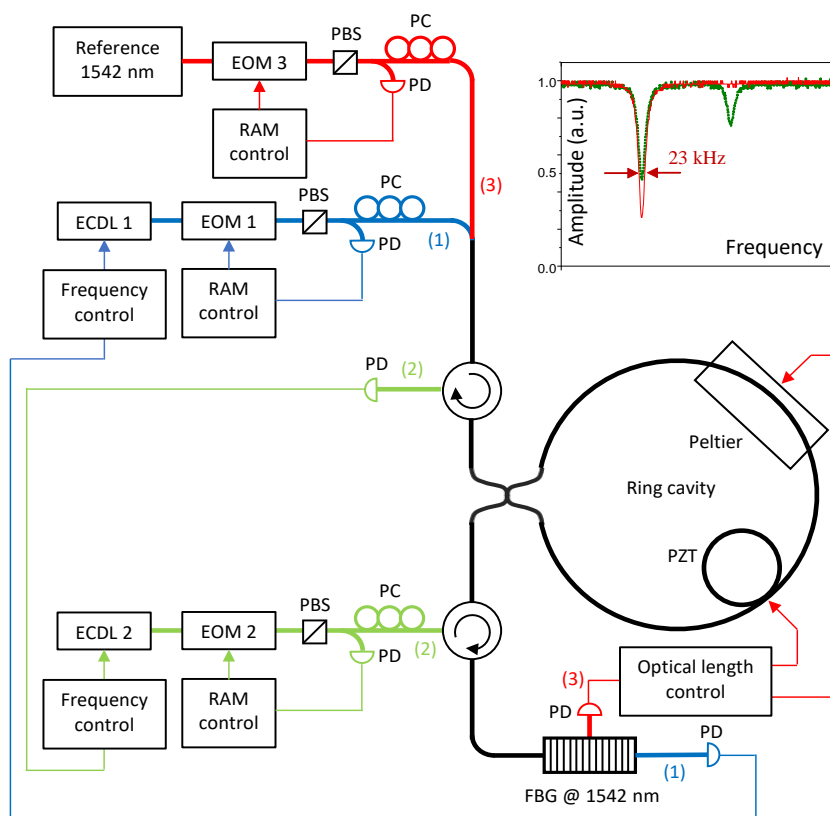


Fig. 2. Experimental setup - EOM: electro-optic modulator; ECDL: extended cavity diode laser; FBG: fiber Bragg gratings filter; PC: polarization Controller; PBS: polarization beam splitter; PD: photodiode. Beam path (1) for ECDL 1, (2) for ECDL2 and (3) for Reference. Inset: For any polarization state at the cavity input, two families of modes are observed (green curve); input polarization is adjusted to have only one family of mode (red curve).

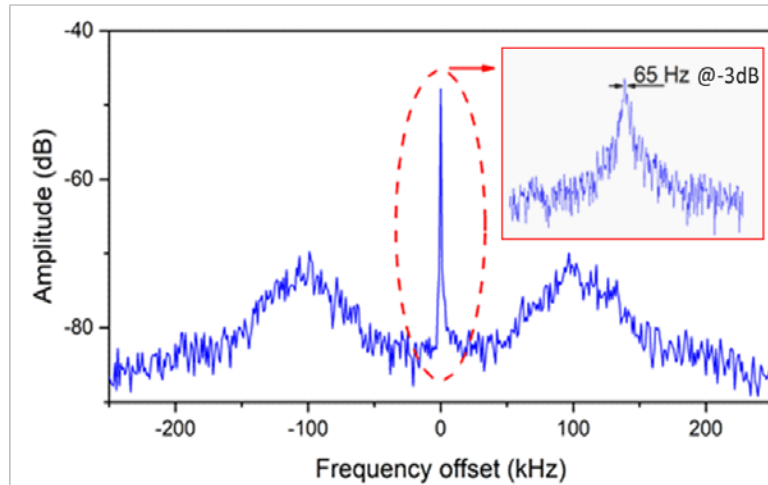


Fig. 3. Beat note spectrum of two identical ECDLs frequency locked on the cavity. The FWHM of the beat note is 65 Hz (inset), corresponding to a linewidth of about 30 Hz for each locked laser.

3- Results

Due to weak losses and very long cavity length, a parasitic laser effect of Brillouin backscattering in the cavity is observed [16]. The laser beam injected into the cavity with sufficient power level leads to the generation of a counter-propagating laser component shifted by $\omega_B=10$ GHz from its frequency. Fig. 4 shows the evolution of the backscattered power as a function of the input beam power from the ECDL source. A first threshold at -3 dBm is observed corresponding to the generation of a counter-propagating Brillouin laser frequency. Then appears a saturation at 5 dBm corresponding to the generation of the second, copropagating Brillouin laser frequency at $2\omega_B$. Then at 10 dBm the generation of a second counter-propagating Brillouin laser frequency at $3\omega_B$ is observed. Considering Fig. 2 again, the presence of a backscattered Brillouin laser saturates the photodiode and degrades the lock of counterpropagating laser. Inset in Fig. 4 shows the noise spectra of the detected error signal in the direction of the first order Brillouin laser component at ω_B as compared to the case of a low input power. According to these results, we limit input power to -5 dBm considering that our experiment is not limited by the beam noise.

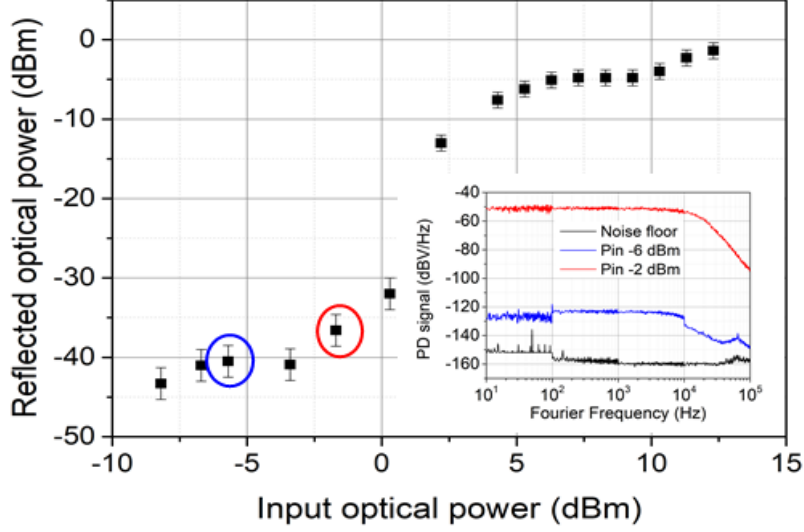


Fig. 4. Power of the resonant Stokes vs input optical power. Inset: Associated noise detected for input power of -6 dBm and -2 dBm.

Another limitation is due to the polarization modulation generated in EOMs, which has two consequences: the error signal's distortion, detected at the output of the cavity and the appearance of a residual amplitude modulation (RAM) [17]. As in practice the polarization of the input beam of the modulator is never strictly linear and misaligned with respect to the modulator axes, the output beam exhibits a modulation of its polarization which results in a periodic evolution of the polarization state at the modulation frequency. Because of its birefringence, the cavity analyzes this polarization along its main axes by separating the polarizations according to the two families of modes, which leads to the distortion of the signal detected at the cavity output. This effect has been demonstrated experimentally in [9] and analyzed theoretically in [17]. On the other hand, RAM at the modulation frequency appears after any component with polarization-dependent losses (PDL) placed downstream of the modulator. It leads to the detection of a continuous background superimposed to the error signal. Consequently, this leads to a shift of the corrected frequency as regard to the top of the resonance in the case of ECDL locking, or as regard to the reference frequency in the case of the cavity locking. Moreover, the RAM is often sensitive to environmental parameters and is a limitation to stability transfer. In particular, Fig. 5(a) shows that this RAM depends periodically on the temperature of the EOM and Fig 5(b) shows that it also depends periodically on a DC voltage superimposed on the modulation signal applied to the EOM. These two dependencies are linked by the relation:

$$Y \propto V_0 \sin(\phi + \alpha T + \beta V_{DC})$$

with Y the detected offset of the error signal, V_{DC} the voltage offset applied to the EOM, α the thermal sensitivity parameter ($2\pi/0.8 \text{ K}^{-1}$) and β the voltage sensitivity parameter ($\pi/5 \text{ V}^{-1}$).

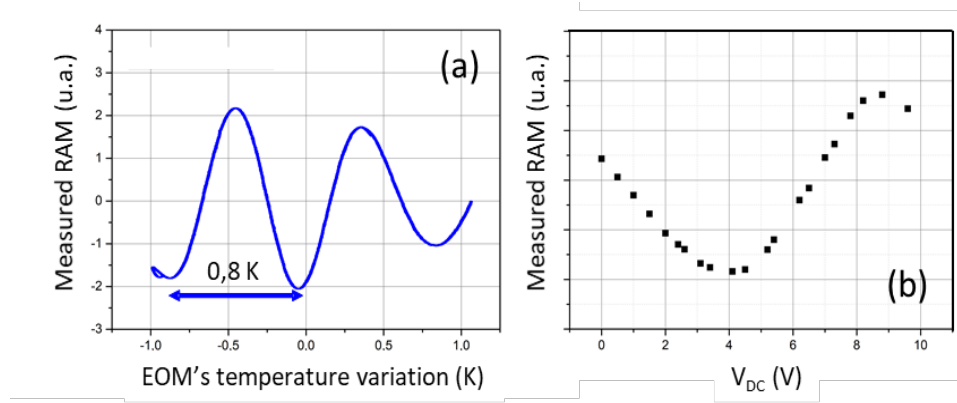


Fig. 5. RAM characterization at the EOM output. (a) Dependence of RAM with the EOM temperature; (b) Dependence of RAM with the V_{DC} offset on the EOM.

A RAM correction of the type proposed in [18] can therefore be implemented. EOMs temperature is stabilized to remain it within the linear region of the RAM thermal sensitivity. According to Fig. 5(a) a control within 0.2 K is sufficient. A polarization beam splitter, placed at each EOM output, completely transforms the polarization modulation into amplitude modulation. RAM is then corrected by applying a continuous level VDC to the modulator. It should be noted that this RAM correction loop also corrects the distortion of the error signal at the cavity output.

The frequency stability transfer measurements are given in Fig. 6. They are obtained by locking one cavity mode to the reference and an ECDL to a mode near the reference. The stability transfer up to 34 GHz is deduced from the beat note of the reference and the ECDL converted to lower frequency by modulating simultaneously both beams into the same Mach-Zehnder amplitude modulator operating up to 17 GHz. The black curve (squares) corresponds to a transfer over 60 MHz without RAM correction and the red curve (circles) to the same transfer with RAM correction. In both cases, the curves are in the 10^{-15} range. The improvement obtained thanks to the RAM correction gives a stability of $5 \cdot 10^{-15}$ for integration times between 4 s and 400 s. The blue curve (triangles) in Fig. 6 corresponds to a transfer over 34 GHz with RAM correction. For integration times smaller than 200 s, the same stability level as for the case of 60 MHz transfer is found, but for longer integration times, an evolution in τ which is the signature of a linear frequency drift is observed. This frequency drift is clearly correlated with the residual ambient temperature evolution as shown in inset in Fig. 6. The value of -550 Hz/K/nm has been measured for the cavity thermal sensitivity, which limits the transfer at distant wavelengths for long integration times. It can be noted that implementing an active temperature control in the box containing the cavity would lead to limit this effect.

This correlation was systematically observed for several transfer intervals from 2 GHz to 34 GHz at 1542 nm (case of close transfer in Fig. 1(b)). Since we have the possibility with our setup to lock 2 ECDLs on the cavity with a stability level in the 10^{-15} range, we have repeated this correlation measurement at 1550 nm (case of far transfer in Fig. 1(b)) and found a sensitivity close to the one achieved in the case of the close transfer (beatnote ECDL 2 with reference). Considering the quasilinear behaviour of the chromatic dispersion in fibers in the range $1.5 - 1.6 \mu\text{m}$ [19], we can consider that this sensitivity of -550 Hz/K/nm can be extrapolated to transfers over several tens of nm.

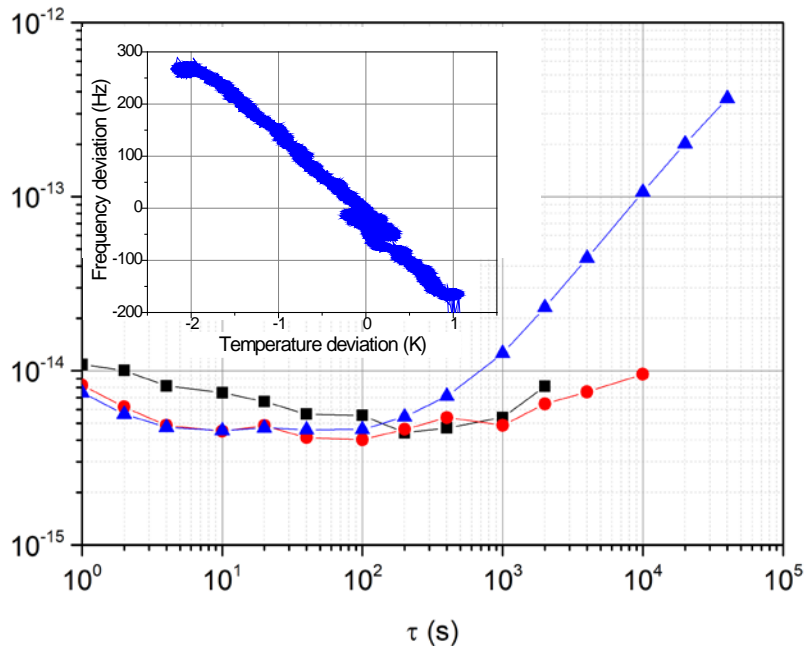


Fig. 6. Stability of the beat note between the reference and the frequency-locked ECDL. Inset: Correlation between frequency and temperature fluctuations.

7- Conclusion

In conclusion, we have presented the transfer stability performances achieved using a fiber ring cavity and we have analyzed the effects that limit these performances. The most critical effects which are not depending on the transfer are the Brillouin backscattering and the RAM. Their impact is limited by controlling their effect. We have shown that with our design, the cavity allows a stability transfer to tunable lasers over 100 nm. Thanks to its quality factor of 1010 within the 1.5 μ m region, the cavity also allows a reduction of the tunable laser's linewidth from 100 kHz to 30 Hz.

The transfer cavity shows a thermal sensitivity which degrades the long-term frequency stability transfer. The value of -550 Hz/K/nm is measured near the reference (with one ECDL) and far from the reference (with two ECDLs at 1550 nm). However, we noticed that active temperature stabilization of the cavity can significantly reduce the impact of this effect.

Consequently, work on conditioning and temperature stabilization is expected to improve our long-term stability results.

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