Limitations in the Frequency Stability Transfer at 1.5 µm Using a Fiber Ring Cavity

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***Abstract*—In this paper we present recent results on a fiber ring cavity stabilization and some of its limitations such as polarization modulation, error signal line shape distortion due to residual amplitude modulation (RAM), intracavity backscattering and dispersion. Solutions for each limitative phenomenon are proposed. A stability transfer over 30 GHz at the 10^{-14} level is demonstrated which propose a possibility to perform successful frequency stability transfer over several nanometers.**

Keywords*—frequency stability transfer; fiber ring cavity; residual amplitude modulation; backscattering; PDH technique.

I. Introduction

In atomic and molecular physics, it is often necessary to transfer the frequency stability of an optical reference to a target laser. When the frequency gap does not exceed a few GHz the two sources can be directly phase locked [1]. Nevertheless, usually one needs to perform the transfer over several nanometers or more. The most efficient method, using of a femtosecond laser, gives the possibility to extend the frequency transfer over several hundred nanometers, but remains expensive, cumbersome and fragile.

Optical transfer cavities allow the transfer at the equivalent range, while have until more limited stability characteristics. We had presented in [2] a first realization of simple, passive, all fibered alternative. One of the advantages of this cavity was the use of standard telecom components that perform to build a lightweight, robust and compact tool. Its fractional frequency stability was about 10^{-12} for integration times from 1 to 3000 s. In this paper, we present a new fiber transfer cavity. We analyze several physical processes limiting the frequency transfer and propose suitable ways to prevent them.

This paper is composed of three sections. Section II describes the experimental setup. Section III presents the main limitations to transfer such as polarization modulation in the cavity (which causes residual amplitude modulation (RAM), a shift and distortion of the error signal), Raman and Brillouin backscattering, and chromatic dispersion. In each case, we propose a solution to minimize the impact of these effects. Section IV is dedicated to the demonstration of the frequency transfer and to the discussion of some further perspectives.

II. Experimental Setup Description

Our ring cavity (Fig. 1) is built with a 10/90 optical coupler and 200 m of standard SMF-28 optical fiber. The free spectral range (FSR) is 1 MHz and the mode linewidth is 23 kHz (quality factor of 10^{10}). The cavity length is controlled thanks to 20 meters of fiber spooled around a piezoelectric transducer (PZT) tube. 1/6th of the fiber length is controlled in temperature with a Peltier heater/cooler. The entire cavity is enclosed in a box providing thermal and acoustic insulation.

The stability transfer is achieved by locking one cavity mode frequency to a frequency reference by controlling the cavity length (short-term correction) and temperature (long-term correction), and an external cavity laser diode (ECLD) frequency to another mode by controlling its current.

The metrological reference is provided by LNE-SYRTE (Observatoire de Paris) in the framework of the national metrological network Refimeve+ [3]. A single-frequency Erbium-doped fiber-laser emitting at 1542.13 nm (channel 44 of WDM ITU-T grid 13) is stabilized onto an ultra-stable Fabry-Perot cavity [4]. For long-term stability, it is referenced onto a hydrogen-maser, ensuring stability better than 10^{-15} until 10^4 s of integration time. The laser is transferred to our lab through a 43 km long optical fiber [5], [6], where a local laser is phase-locked onto this reference and broadcasted in labs.

Beams from the ECLD and from the reference are both phase-modulated by two electro-optic modulators (EOMs) before being injected in the ring cavity with opposite directions. They are extracted from it with two circulators. Output signals are detected by lock-in amplifiers.

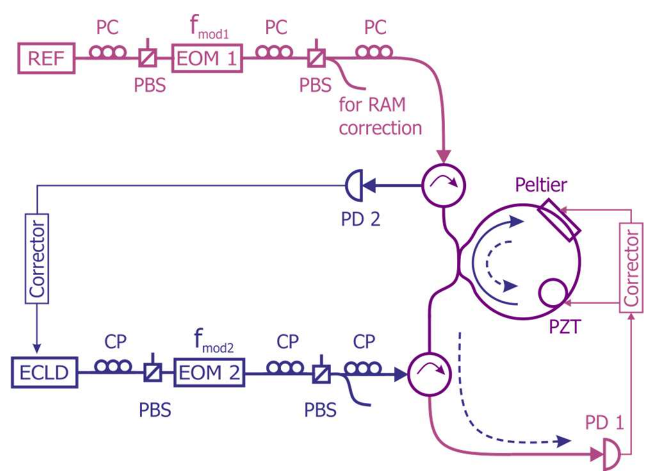

Fig. 1. Frequency stability transfer setup using a fiber ring cavity (REF — metrological reference source, ECLD — extended cavity laser diode, EOM 1, EOM 2 — electro-optic modulators, PC — polarization controllers, PBS — polarization beam splitter, PD 1, PD 2 — photodiodes, f_{mod1}, f_{mod2} — modulation frequencies, PZT — piezoceramic tube, Peltier — temperature controlled zone).

Mechanical stresses caused by the fiber coiling around the PZT lead to a slight birefringence (~10^{-6}) resulting in two families of modes with slightly different FSRs (~1 Hz), corresponding to the main polarization states of the cavity (Fig 2). As a result, the cavity acts as a polarization discriminator by separating the input polarization along both states. Polarization controllers at the cavity inputs are adjusted in order to excite only one family of modes.

III. Limitations to Frequency Stability Transfer

We have studied in detail the various processes limiting the transfer of frequency stability through the cavity. The polarization modulation generated by EOMs leads to a residual amplitude modulation (RAM) of the beams and also to a distortion of the signal detected at the output of the cavity. The Rayleigh and Brillouin backscattering in fibers lead to the detection of spurious signals from the counter-propagating beam. The temperature sensitivity of chromatic dispersion in fibers constituting the cavity modifies its FSR.

These effects are detailed below and the solutions limiting their influence on the stability transfer are discussed.

A. Polarisation modulation

In the setup, the phase modulation of beams is achieved by waveguide $LiNbO_3$ electro-optical modulators in transverse configuration. Ideally, beam polarization at the modulator input should be linear and aligned with one of its principal axes. In practice, residual misalignments, splicing, connectors and PM fiber specific limitations lead to a slightly elliptical and misaligned input polarization state. The polarization extinction ratio (PER) is approximately 25 dB [7]. This results in a residual polarization modulation of the output beam in addition to the phase modulation, due to the different values of the modulation indices along both eigen axis of propagation in the modulator.

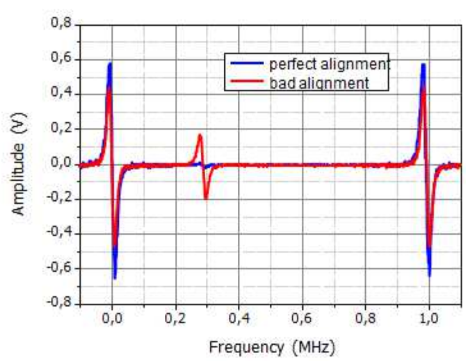

Fig. 2. Demonstration of two cavity family of modes due to fiber birefringence.

B. Lineshape distorsion

Standard fiber components present polarization dependent loss (PDL) with typical value of about 0.10 dB that analysis the polarization modulation generated by EOMs. Consequently, the frequency modulated beams in the setup are also amplitude modulated with a residual amplitude modulation (RAM) whose magnitude depends on various parameters [8]. The detection of this RAM leads to a slight distortion of the detected signal but above all to a background (Fig. 3) [9]. The offset of the detected signal depends from EOM parameters, as

$$Y = \sin\left(\epsilon - \frac{2\pi}{\lambda} L(n_e - n_o) + \frac{\pi}{\lambda}\frac{L}{d}\left({n_e}^3 r_e - {n_o}^3 r_o\right) V_{dc}\right) \quad (1)$$

where ϵ is related to the ellipticity of the EOM input beam, n_o, n_e are respectively the ordinary and extraordinary index of $LiNbO_3$ and r_o , r_e are the corresponding electro-optical coefficients, L is the length of the guide, λ is the wavelength and V_{dc} is a dc voltage applied to the transverse direction of the guide of dimension d.

Those parameters are all sensitive to temperature, which leads to a slow variation of the detected background superimpose to the signal. In our setup, EOMs are thermally insulated in order to limit this effect. Moreover, (1) suggests the possibility of compensating the effect of RAM by a servo-control driving the voltage V_{dc} [8],[10]. Each EOM is followed by such a RAM control device located in the setup after a polarization beam splitter (PBS) in order to fix a linear polarization state, convert the polarization modulation in amplitude modulation. Then the RAM may be suppressed definitively.

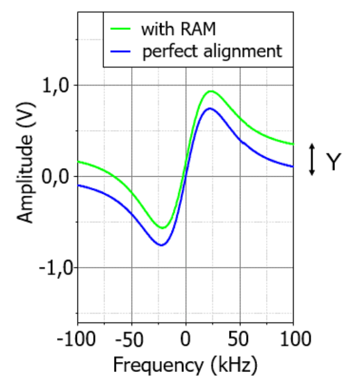

Fig. 3. DC offset and distortion of error signal due to RAM. The RAM is due to the analysis of the polarization modulation generated by EOMs by fiber components with PDL.

A second effect due to the polarization modulation leads to limit the frequency stability transfer. As noted above, the cavity presents two polarization Eigenstates according to which the input polarization is analyzed. As a result, the polarization modulation of the cavity input beam leads to a distortion of the signal detected at the cavity output. In the setup, the rejection of the polarization modulation mentioned above leads to eliminate this distortion.

C. Backscattering

Due to fact that our fiber cavity is a high efficiency waveguide with low losses, it is practically simple to generate/amplify strong scattering phenomena, proportionally to its effective length. In particular, the additional unwanted backscattered optical power (disturbs the detection chain relative to the beam propagating in the opposite direction.

At low input power, spontaneous Rayleigh backscattering (SpRS), proportional to the input optical power is first detected (Fig. 4). This additional optical power increases the shot-noise in the detector. In our setup, we checked this additional shot-noise is negligible for a typical detected optical power of -10 dBm.

Increasing the input power in order to improve signal-to-noise ratio at the cavity output leads to generate a Brillouin laser effect in the cavity due to stimulated Brillouin scattering (SBS), firstly in opposite direction (1st Stokes) [11]. In current configuration, for input powers above -3 dBm, we observe this powerful backscattering wave downshifted by standing acoustic wave in silica (10.8 GHz). For higher input power, the 2nd Stokes propagating in the same direction appears, then the 3rd one in opposite direction, and so on.

Noise analysis shows that the contribution of the backscattering signals is significant for correction loop, up to absolute loss of laser control onto desired cavity mode. Consequently, in practice the input beam power must not exceed -3 dBm to limit these disturbances.

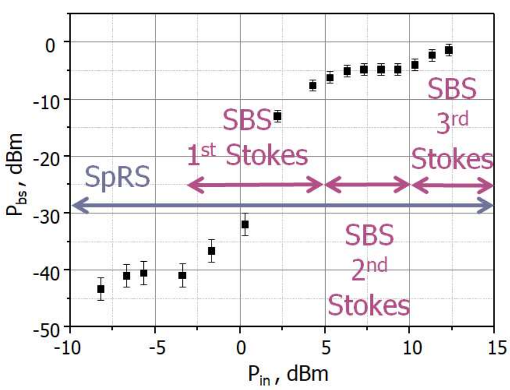

Fig. 4. Backscattering power dependence on the input cavity power. SpRS — spontaneous Rayleigh backscattering, SBS — stimulated Brillouin scattering.

D. Dispersion

When the frequency of a cavity mode is locked onto a frequency reference by the direct control of the cavity length, using a PZT for instance, the frequency of the other modes varies if the temperature fiber is not stable [12], [13]. On the contrary, if the fiber length is controlled through the fiber temperature, the frequency of all cavity modes remains constant.

This approach is adopted in our setup where the control of the fiber temperature ensures the long-term stability. Because of the thermal inertia of the whole fiber, we have chosen to drive the temperature of 1/6th of the fiber length only. The fiber ring is enclosed in a box providing effective passive thermal insulation and the temperature of external environment is stabilized by air cooling system. In those conditions, the free temperature drift of the fiber cannot exceed 1 °C. We compute that the corresponding frequency shift for a frequency transfer between 1.5 µm and 1.6 µm is smaller than 1 Hz.

IV. Results

To test the possibilities of frequency stability transfer offered by our cavity, we have demonstrated a transfer over 30 GHz from the metrological reference to the ECLD and compared it with a transfer over 60 MHz.

The stability of the target laser shifted by 30 GHz is studied from the beat note of the sidebands of both sources modulated at 15 GHz into the same Mach-Zehnder modulator. Besides, measurements at 60 MHz was performed directly form the beat note between the two sources.

In the case of 30 GHz a fractional frequency stability transfer at a level of 10^{-14} in the 0.1-10^3 s range is obtained (Fig. 5). We note a slight short term stability degradation (by a factor of 3) caused by a discrepancy in the experimental settings leading to an excess of white frequency noise in the control loop. In the long term the blue curve joins the red one, which demonstrates the efficiency of the fiber temperature control compensating the effect of thermal sensitivity of dispersion.

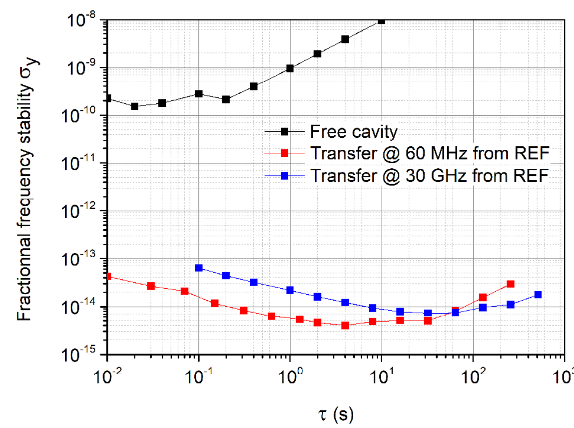

Fig. 5. Frequency stability transfer up to 30 GHz with applied RAM correction, eliminated backscattering effects and cavity temperature control.

V. Conclusion

A detailed study of the limitations in the frequency transfer using an all fibered ring cavity is performed and methods for their compensation are proposed. We have demonstrated our approach by an experimental frequency transfer over 30 GHz without significant stability degradation, in particular, in the long term.

Acknowledgment

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References

[1] Z. Liu and R. Slavik, "Optical injection locking: From principle to applications," Journal of Lightwave Technology, vol. 38, no 1, p. 43-59, 2019.

[2] P. Grüning, A. Chaouche-Ramdane, K. Manamanni, T. Aoudjit, V. Roncin and F. Du-Burck, , "All-fiber ring-cavity for frequency stability transfer at 1.55 µm," Appl. Opt., vol. 58, n° 6, p. 1502-1507, 2019.

[3] http://www.refimeve.fr/index.php/fr/

[4] X. Xie, R. Bouchand, D. Nicolodi, M. Lours, C. Alexandre, and Y. Le Coq, "Phase noise characterization of sub-hertz linewidth lasers via digital cross correlation," Opt. Lett., vol. 42, pp. 1217-1220, 2017.

[5] H. Jiang, F. Kefélian, S. Crane, O. Lopez, M. Lours, J. Millo, D. Holleville, P. Lemonde, C. Chardonnet, A. Amy-Klein, and G. Santarelli,

"Long distance frequency transfer over an urban fiber link using optical phase stabilization," J. Opt. Soc. Am. B, vol. 25, pp. 2029–2035, 2008.

[6] W.-K. Lee, F. Stefani, A. Bercy, O. Lopez, A. Amy-Klein, and P.-E. Pottie, "Hybrid fiber links for accurate optical frequency comparisons," Appl. Phys. B, vol. 123, pp. 123-161, 2017.

[7] https://www.ozoptics.com/ALLNEW_PDF/APN0005.pdf, *Polarisation measurements*, Application note, 1999.

[8] N. C. Wong and J. L. Hall, "Servo control of amplitude modulation in frequency-modulation spectroscopy: demonstration of shot-noiselimited detection," J. Opt. Soc. Am. B, vol. 2, pp. 1527–1530, 1985.

[9] F. Du-Burck and O. Lopez, "Correction of the distortion in frequency modulation spectroscopy," Meas. Sci. Technol., vol. 15, pp. 1327-1336, 2004 .

[10] L. Li, F. Liu, C. Wang and L. Chen, "Measurement and control of residual amplitude modulation in optical phase modulation," Rev. Sci. Instrum., vol. 83, p. 043111, 2012.

[11] Saleh, K., Llopis, O., & Cibiel, G, "Optical scattering induced noise in fiber ring resonators and optoelectronic oscillators", IEEE Journal of Lightwave Technology, 31(9), 1433-1446 2013.

[12] P. Bohlouli-Zanjani, K. Afrousheh, and J. D. D. Martin, "Optical transfer cavity stabilization using current-modulated injection-locked diode lasers," Rev. Sci. Instrum., vol. 77, p. 093105, 2006.

[13] A. Chaouche Ramdane, P. Grüning, V. Roncin, and F. Du-Burck, "Stability transfer at 1.5 µm for metrological applications using a commercial optical cavity," Appl. Opt., vol. 56, n° 1, pp. 8-14, 2017.