FIBER-COUPLED AND MONOLITHIC CRYOGENIC OPTICAL RESONATORS

C. Braxmaier, O. Pradl, H. Müller, B. Eiermann, A. Peters, J. Mlynek, and S. Schiller*

Fakultät für Physik, Universität Konstanz, D-78457 Konstanz, Germany, Tel.: ++49-7531-88 3842, Fax: -072, e-mail: claus.braxmaier@uni-konstanz.de, http://www.uni-konstanz.de/quantum-optics

* *Institut für Experimentalphysik, Heinrich-Heine-Universität Düsseldorf, D-40225 Düsseldorf, Germany*

Abstract

We have developed a fiber coupled cryogenic optical sapphire resonator for the frequency stabilization of a Nd:YAG laser. With this method a frequency instability of $2 \cdot 10^{-15}$ for τ =1 hour integration time has been achieved. This is among the lowest values ever obtained for optical oscillators.

We also present a new approach to test the time-independence of the fine structure constant, based on the use of a single monolithic resonator. Preliminary results on the development of suitable resonators are described.

Introduction

The development of cryogenic optical resonators (COREs) is motivated by the need for more stable reference resonators for high-resolution spectroscopy, and as a tool for fundamental physics tests. With sufficient long-term stability (integration times of months), resonators could play a role in performing improved tests of special and general relativity.

In previous work we had shown that with cryogenic sapphire resonators an instability of $3 \cdot 10^{-15}$ can be reached at $\tau = 1$ min [1]. Moreover, the resonators do not exhibit any discernible drift, with the current limit being less than 4 kHz over 6 months [2]. In those experiments the laser beams were coupled to the COREs through windows in the cryostat, and on time scales longer than tens of minutes the drift of the laser beam alignment limited the stability of the lock. We have therefore proceeded to implement a coupling via a fiber whose end is stably positioned relative to the CORE.

Cryogenic fiber-coupled sapphire reference cavities

The basic set-up we have employed is shown in Fig. 1. All components, especially fiber end and CORE, are maintained in relative positions that are very stable, thanks to the small thermal expansion of components and housing at liquid Helium temperature. The monomode nonpolarizing fiber is glued into a holder that is attached to the aluminum housing. The light is mode-matched to the CORE by a micro lens (L). A polarizer (P) ensures that the polarization interrogating the CORE is fixed. A beam splitter (BS) serves to detect the light reflected from the cavity and to obtain an error signal for frequency locking. Photodiodes (PD) are also provided to monitor the incident light power

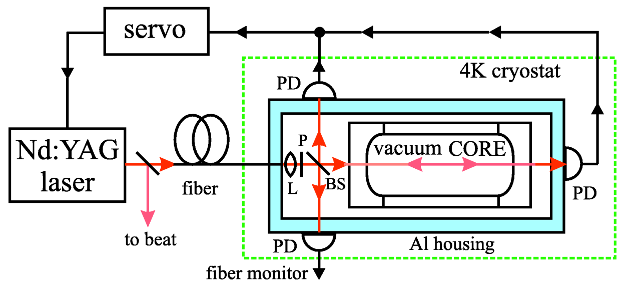

Figure 1: Schematic of the fiber-coupled CORE.

and the power transmitted through the cavity, in order to be able to study systematic effects. The photodiodes are standard InGaAs, with shielded cables leading to the amplifiers mounted on the liquid nitrogen heat shield. The fiber coupling was implemented on the CORE that in previous CORE-CORE comparisons had shown the largest sensitivity to laser beam alignment changes. We then performed a beat frequency measurement between the fiber-coupled CORE and another, free-space-coupled CORE located in a different cryostat on the same optical table.

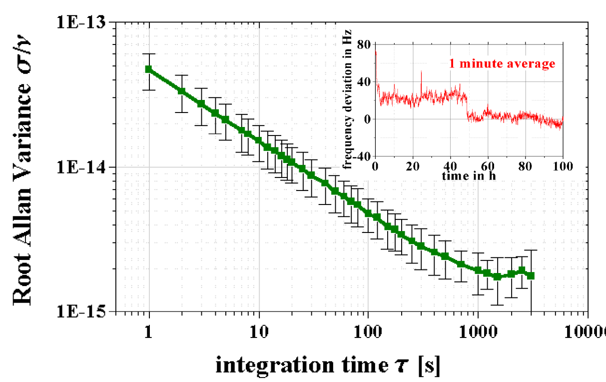

Figure 2: 100 h beat between a fiber-coupled and a free beam coupled CORE, and the resulting Allan deviation.

Fig. 2 shows a 100 hour run. Previously observed large beat frequency changes when the cryostats were refilled are now absent. The jump at 47 h is due to an accidental bumping of one cryostat.

A frequency instability floor of $2 \cdot 10^{-15}$ was obtained at 3000 s integration time. This value is comparable to the lowest instabilities achieved in the optical domain (CO_2/OsO_4 standard). The reasons responsible for the occurrence of the floor are currently under investigation.

A new approach for a test of $d\alpha/dt$

Here we propose a method for a test of the time-independence of α necessitating only a *single* resonator, which must contain a dispersive medium. A potentially feasible implementation could be based on a monolithic crystalline resonator. Assuming the bound electron model of the polarizability, with a resonance frequency that scales with the Rydberg energy and thus with α^2, the index of refraction n of a medium has the following dependence on $\alpha : \frac{dn(\omega)}{d\alpha} = -\frac{2}{\alpha}(\omega\frac{dn(\omega)}{d\omega})$. Two approaches are possible. In the first (Fig. 3), two frequencies ω_1 , ω_2 are locked to an optically isotropic monolithic resonator. Their frequency difference is measured as a function of time. If α is time-dependent, a change in the difference $\omega_1 - \omega_2$ results from the different dispersions $dn(\omega_1)/d\omega \neq dn(\omega_2)/d\omega$. In practice, ω_2 should be close to a harmonic of ω_1, so that a single laser ω_1 can produce ω_2 using standard nonlinear optical frequency conversion.

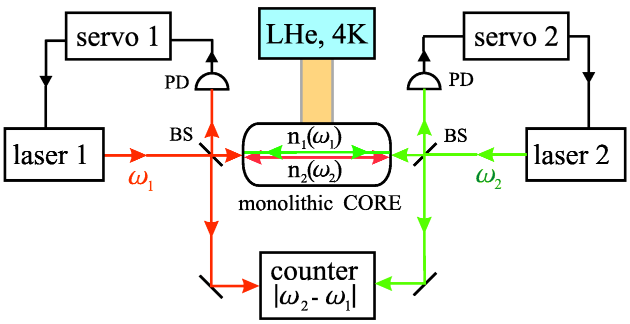

Figure 3: Proposed scheme. Two frequencies derived from a single laser are locked to modes of a cryogenic monolithic resonator. A beat frequency is obtained and its dependence on time is recorded.

Alternatively, a dispersive anisotropic medium can be used. One can then lock two orthogonally polarised waves (o and e) of nearly the same frequency $\omega_1 \approx \omega_2$ to the birefringent cavity, making use of the fact that their dispersion differs, $dn_{o,e}(\omega_1)/d\omega \neq dn_{e,o}(\omega_2)/d\omega$. In this case ω_2 is generated from ω_1 by acoustooptic or electrooptic modulation. A combination of both effects could also be used.

An estimate of the effect can easily be derived. Taking $\omega_2 = m \cdot \omega_f$ (for practical reasons, m will be an integer) and $\omega_1 \approx \omega_f$, the change in the beat frequency due to a supposed change $\Delta\alpha$ may be written as: $\Delta(\omega_1 - \omega_f) = A(\Delta\alpha/\alpha + \Delta L/L) + \Delta\Omega_1 - \Delta\Omega_2/m + \omega_1\big((1+\bar{n}_2)^{-1}\Delta n_2/n_2 - (1+\bar{n}_1)^{-1}\Delta n_1/n_1\big)$. This expression includes the α-dependence of L, $L \sim \alpha^{-1}$. The influence of drifts of the resonator length, ΔL, and the indices, Δn, due to creep or temperature drift, as well as of lock errors, $\Delta\Omega$, has also been included. Here $A = \omega_1((1+\bar{n}_2)^{-1} - (1+\bar{n}_1)^{-1})$ is a material parameter, with the normalized dispersion $\bar{n} = n^{-1}\omega dn/d\omega$. In the case of a birefringent cavity, $n_1 = n_{o,e}(\omega_1)$, $n_2 = n_{e,o}(\omega_2)$. The table shows values for $\tilde{A} = |A| \cdot 10^{-12}$ Hz/2π for a few low-loss materials, taking λ_1=1064 nm and λ_2=532 nm.

	$\tilde{A}^{\lambda_1,\lambda_2}_{o,o}$	$\tilde{A}^{\lambda_1,\lambda_2}_{o,e}$	$\tilde{A}^{1,2}_{e,o}$	$\tilde{A}^{1,2}_{e,e}$	$\tilde{A}^{1,1}_{o,e}$	$\tilde{A}^{2,2}_{o,e}$
CaF_2	2.0	-	-	-	-	-
MgF_2	1.3	1.4	1.3	1.3	0.06	0.2
Al_2O_3	4.7	4.6	4.7	4.6	0.03	0.2
SiO_2	3.0	3.2	2.9	3.1	0.10	0.3

We can deduce that in order to achieve a limit $|\alpha^{-1}d\alpha/dt| < 2 \cdot 10^{-15}$/year in an integration time of 1 month, a beat frequency resolution of 0.1 mHz must be available, implying that over this time the locking errors $\Delta\Omega/2\pi$ must be below 0.1 mHz, the relative length drift below $1 \cdot 10^{-16}$ and the refractive index drift below $1 \cdot 10^{-18}$, if Δn_1 and Δn_2 are uncorrelated. These values are extremely low and one will necessarily have to use a cryogenic resonator with very narrow linewidth.

Experimental results

We have studied the properties of a 4 cm long birefringent monolithic standing-wave resonator made out of nominally highly pure single-crystal sapphire, with dielectric mirrors for 1064 nm coated on the endfaces. The crystal axis was oriented perpendicular to the cavity axis. We have measured mirror transmissions of less than 2 ppm, but the internal losses were high, 600 ppm per round-trip, leading to strong impedance-mismatch, and very low incoupling. A laser calorimetric measurement of the crystal absorption gave 20 ppm/cm (V. Loriette and A.C. Boccara, ESPCI Paris), indicating that additional loss was present in the resonator.

Due to the difficulty in finding a source of ultrapure sapphire that could lead to a suitable monolithic resonator, single-crystals of CaF_2 and MgF_2 were studied as possible alternatives. Calorimetry showed extremely low loss at 1064 nm, below 2 ppm/cm. These materials are thus promising for the next generation of crystalline monolithic resonators, and their fabrication and testing is under way.

Conclusion

A significant improvement of CORE stability for $\tau = 1$ hour has been demonstrated. We believe further improvements will be possible by enhancing the signal-to-noise ratio of the error signal. The possibility of performing a test of $d\alpha/dt$ with a single resonator is a strong motivation to develop monolithic COREs. This requires a search for a crystalline material with unprecedented low optical loss. Potential candidates have been identified.

REFERENCES

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[2] R. Storz et al., Opt. Lett. **23**, 13 (1998).