A MODERN MICHELSON-MORLEY EXPERIMENT USING ACTIVELY ROTATED OPTICAL RESONATORS

S. HERRMANN, A. SENGER, K. MÖHLE, E. V. KOVALCHUK, A. PETERS
Institut für Physik, Humboldt-Universität zu Berlin
Hausvogteiplatz 5-7, 10117 Berlin
E-mail: sherrma@stanford.edu, achim.peters@physik.hu-berlin.de

We present a new setup of a Michelson-Morley test of the isotropy of the speed of light that achieves an order of magnitude improvement in sensitivity as compared to previous measurements. The experiment compares the resonance frequencies of two orthogonal cavities, implemented in a single block of fused silica and rotated on an air bearing turntable once every 45 s. A preliminary analysis of first data already provides limits on combinations of SME-parameters at the level of 10^{-17}.

1. Introduction

The experiment of A. A. Michelson and E. W. Morley[1], testing the isotropy of the speed of light, has served as a sensitive test of special relativity and Lorentz invariance for more than a century now. Numerous repetitions have been performed so far, increasing the sensitivity by more than six orders of magnitude. During recent years results of several modern versions of this experiment have been used to provide upper limits on test parameters of the photonic sector of the SME[8] down to few parts in 10^{16}. These measurements compared the resonance frequencies of rotating optical[2,3,4] or microwave[5,6,7] cavities, either using active rotation on a turntable or relying solely on Earth's rotation. An anisotropy of the speed of light, as a consequence of broken Lorentz invariance, is currently restricted to a level of $\Delta c/c < 10^{-16}$ by these measurements.

Here, we present a new setup aiming to improve this limit by at least one order of magnitude. The basic scheme of the experiment is depicted to the left in Fig.1: In vacuum the frequency of the TEM_{00} mode of a linear optical Fabry-Pérot cavity is given by an integer multiple of $c/2L$, where c is the speed of light and L is the cavity length. This frequency is read out by stabilizing a laser of frequency ν_1 to the cavity resonance using an electronic feedback loop. A second laser of frequency ν_2 is stabilized to a similar orthogonal cavity and a beat frequency measurement of $\Delta\nu = \nu_1 - \nu_2$ is performed while the whole setup rotates continuously. An anisotropy of c would then lead to a modulation of the beat frequency at twice the rotation rate ω_{rot}:

$$\frac{\Delta c}{c} \sim \frac{\Delta\nu}{\nu_0} = \frac{\nu_1 - \nu_2}{\nu_0} = B \sin 2\omega_{\mathrm{rot}} t + C \cos 2\omega_{\mathrm{rot}} t, \tag{1}$$

where $\nu_1, \nu_2 \approx \nu_0 = 282\,\mathrm{THz}$. If we take into account Earth's rotation at $\omega_\oplus$ and consider the case of $\omega_{\mathrm{rot}} \gg \omega_\oplus$, this leads to a modulation of the amplitudes B and C as described by

$$\begin{aligned} B = B_0 &+ B_{\mathrm{s1}} \sin \omega_\oplus t + B_{\mathrm{c1}} \cos \omega_\oplus t \\ &B_{\mathrm{s2}} \sin 2\omega_\oplus t + B_{\mathrm{c2}} \cos 2\omega_\oplus t. \end{aligned} \tag{2}$$

and

$$\begin{aligned} C = C_0 &+ C_{\mathrm{s1}} \sin \omega_\oplus t + C_{\mathrm{c1}} \cos \omega_\oplus t \\ &C_{\mathrm{s2}} \sin 2\omega_\oplus t + C_{\mathrm{c2}} \cos 2\omega_\oplus t, \end{aligned} \tag{3}$$

where the daily modulation amplitudes B_k and C_k depend on the geographical latitude χ of the laboratory and may carry an annual phase shift due to Earth's orbital motion.

In what follows we describe the actual realization of the basic setup of Fig.1 in more detail. We then present first results on the signal amplitudes B and C of equation (1) which we consider to be a null result and we will give results from an evaluation of the experiment in terms of the SME.

2. The experiment

The experiment employs a pair of orthogonal cavities implemented in a single block of fused silica as shown in Fig 1. The spacer is a $55\,\mathrm{mm} \times 55\,\mathrm{mm} \times 35\,\mathrm{mm}$ cuboid with centered perpendicular bore holes of 10 mm diameter along each axis. Four mirror substrates coated with a high-reflectivity dielectric coating at 1064 nm are optically contacted to either side, forming two crossed optical cavities the length of which is matched to better than $2\,\mu m$. The finesse is 380000 resulting in a linewidth of 7 kHz for each cavity. The cavities are set up in a custom-made vacuum chamber featuring several stages of thermal insulation, combined with high mechanical rigidity. The complete chamber is pumped by an ion pump to a pressure of $< 10^{-5}$ mbar. The innermost stage is designed as an inner vacuum chamber, with the option to be separately pumped to Ultra High Vacuum. To isolate the cavity

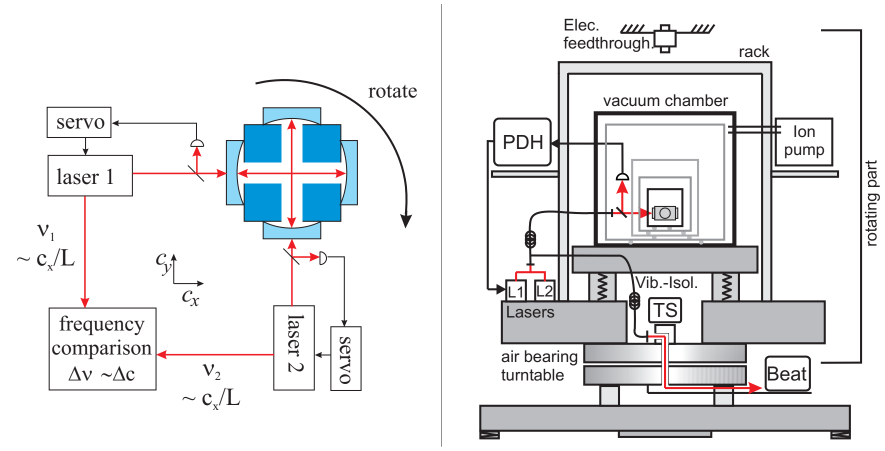

Figure 1. Basic principle of the experiment (left) and schematic of the complete rotating setup (right). TS = Tilt sensor, PDH = Pound-Drever-Hall laser stabilization electronics.

from ambient vibrations, the vacuum chamber is placed on an active vibration isolation system (HWL Scientific 350M), with a resonance frequency of 1.2 Hz and an isolation approaching 40 dB for frequencies well above resonance.

Two Nd:YAG lasers at 1064 nm are used to read out the cavity frequencies. The light of both lasers is overlapped in a polarization-maintaining single-mode fiber (using identical polarizations), which enters the chamber via a vacuum feedthrough. The chamber contains miniaturized optics to couple the light into the cavities, and detectors to detect the reflected light. The laser frequencies are stabilized to the cavities using feedback loops that apply frequency discrimination according to a modified Pound-Drever-Hall method, demodulating the signal at three times the modulation frequency. The lasers are equipped with piezoelectric actuators, which allow tuning and modulation of the laser frequency. The beat frequency measurement between the two stabilized lasers is accomplished by overlapping a fraction of the laser power on a fast photodiode outside the vacuum chamber. The beat frequency on the order of up to half a free spectral range of the cavities (2.7 GHz) is converted down to below 100 MHz and counted at a rate of 1 data point per second. The observed relative frequency stability reaches a optimum close to 1.5×10^{-15} at an integration time of about 20 s (see Fig. 2). The long term relative frequency drift is on the order of 10 mHz/s. Comparison to a third frequency reference based on an independent cavity

shows that this relative drift is reduced by a factor of 100 as compared to the absolute frequency drift of each cavity. This reduction is due to common mode suppression of relative length changes of the spacer block.
The vacuum chamber on the vibration isolation platform, the optical setup, and the laser stabilization electronics are mounted on an optical breadboard which is placed on a precision air bearing turntable (Kugler RTV600) that can be rotated continuously. Electrical connections are made via a 15 channel slip ring feedthrough. The beat measurement and data acquisition is most conveniently done in the non-rotating laboratory frame. Thus, the laser beams that are split off for the beat measurement are overlapped at the center of the turntable, aligned with the downward rotation axis and are transferred to a stationary platform below the table through a center borehole. After passing two quarter-wave plates on axis, one rotating and one stationary, the light maintains a constant linear polarization at the beat detector. Active rotation of the setup on a turntable gives rise to systematic effects that compromise a possible anisotropy signal. The most obvious effects occur due to modulated forces acting on the cavities, such as gravitational bending or centrifugal forces. To minimize these systematics, we use a precision turntable specified for axial and planar true run of better than 1 μrad and 0.1 μm respectively. Slowly varying tilt of the rotation axis against the vertical is reduced to less than 1 μrad by active

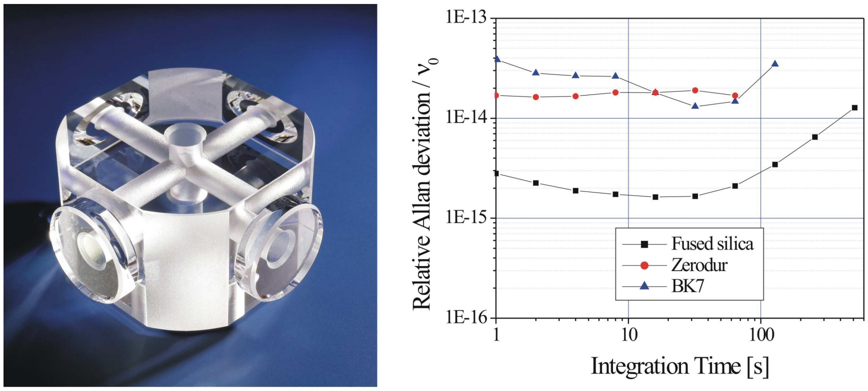

Figure 2. Picture of the crossed resonators (left) and relative frequency stability (right). Also shown are the frequency stability obtained from comparison of two crossed Zerodur resonators of identical design as the fused silica ones and the stability obtained with another set of cavities using BK7 mirror substrates within a previous setup. The achieved ten-fold improvement is attributed mostly to the lower level of thermal noise for fused silica mirror substrates as compared to substrates made from Zerodur or BK7.

stabilization[9] and does not contribute to more than 0.1 Hz systematic beat frequency variation. Varying centrifugal forces are also reduced to below 0.1 Hz systematic beat frequency variation by actively stabilizing the rotation rate. Further measures to reduce systematic frequency variations include balancing the center of mass of the table (estimated to be better than 1 mm offset from the rotation axis) and shielding the lasers and optics outside the vacuum chamber against air currents, temperature gradients etc. The rotation rate of the turntable was set to 45 s. Even faster rotation would have allowed to enhance data integration, but also resulted in an increase of residual systematic effects compromising the measurement. At the chosen rotation rate the observed residual systematic frequency variations occur mainly at $\omega_{\rm rot}$ and are below 1×10^{-15}, while the residual systematic effects at the relevant Fourier component $2\omega_{\rm rot}$ are even less pronounced. Moreover, as long as these systematic effects are reasonably stationary in the laboratory frame, they will be averaged out by Earth's rotation in the following analysis looking for sidereal effects.

3. Preliminary results

Measurements have been performed almost continuously during a time spanning from April 23d to June 4th 2007. The total data includes 926 hours of measurement corresponding to ~ 74000 turntable rotations. For the analysis, the data sets have been divided into samples of ten table rotations each. This corresponds to a time span of 450 s $\ll \omega_\oplus$ such that a

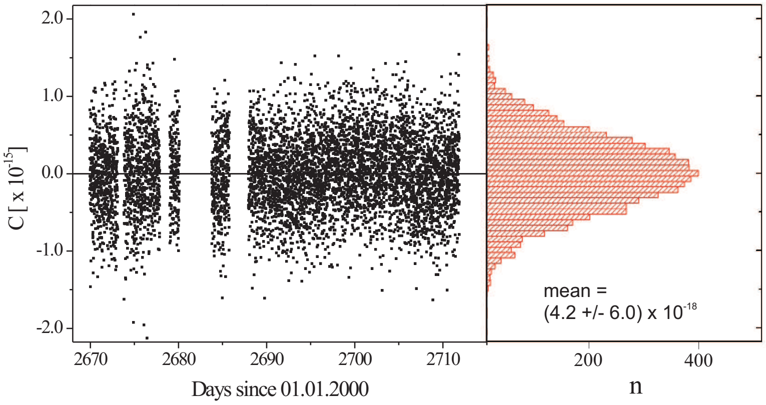

Figure 3. Cosine amplitudes C of frequency variation at twice the turntable rotation. Each point is determined from a sample of 450 s of data comprising 10 table rotations).

variation of B and C due to Earth's rotation can be neglected within a single sample. Each sample is fitted with equation (1) including an offset, a linear drift and signals at $\sin\omega_{\mathrm{rot}}t$ and $\cos\omega_{\mathrm{rot}}t$ to account for the small residual effects at the turntable rotation frequency. The phase of this fit has been set by choosing t=0 when one of the cavities is oriented North-South. The amplitudes $B^{(i)}$ and $C^{(i)}$ obtained from the i.-th sample are assigned with the center time t_i of this sample on a time axis based on the modified Julian date. Every 24 h of data then yield 192 values of $B^{(i)}$ and $C^{(i)}$ equally distributed over t_i as shown in Fig.3 for the C amplitudes of the complete measurement span. The distribution is consistent with zero and features a one sigma error bar $\leq 1 \times 10^{-17}$ for the mean of the distribution (assuming uncorrelated noise, which is consistent with the more detailed SME analysis presented below).

For a further analysis of these results we apply the SME in a similar way as in the analysis of a previous experiment described in[3,9]. The starting point is the photonic sector of the SME, taking into account the Lorentz violating extension as given by [10]

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}(k_F)_{\mu\nu\kappa\lambda}F^{\mu\nu}F^{\kappa\lambda} \tag{4}$$

The tensor k_F possesses the symmetries of the Riemann tensor and thus is left with 19 independent components. Ten of these describe polarization dependent effects and have been restricted to values below 2×10^{-32} by astrophysical observations[10,11]. The remaining 9 parameters are only accessible in laboratory experiments. They can be grouped into one scalar κ_{tr} and two traceless 3x3 matrices, κ_{e-} (symmetric, parity even) and κ_{o+} (antisymmetric, parity odd). The effect of the Lorentz violating extension in (4) on the resonance frequency of an optical Fabry-Pérot resonator has been elaborated by Kostelecký and Mewes[10]. Based on those results we have derived expressions for the signal amplitudes B_k and C_k of equations (2) and (3) that apply to the specific geometry of our experiment[9]. Fitting the resulting expressions to our data following the same procedure as described previously[3,9] yields estimates on the photonic SME parameters as given in Tab. 1. These estimates are generally consistent with zero within one sigma at a level of 1×10^{-17} for the κ_{e-} parameters and 10^{-13} for the κ_{o+} parameters. This is about an order of magnitude more stringent as compared to the previous best limits[7]. Note that due to the limited measurement span of one month we have to assume that no cancelation occurs between κ_{e-} and κ_{o+} terms. In order to reduce this correlation data spanning more than one year would be required.

Table 1. Preliminary limits on SME parameters assuming no cancelation between κ_{e-} and κ_{o+} parameters. All values are $\times 10^{-17}$. $\beta = v/c = 10^{-4}$ accounts for Earth's orbital boost.

κ_{e-}^{XY}	κ_{e-}^{YZ}	κ_{e-}^{XZ}	$\kappa_{e-}^{XX} - \kappa_{e-}^{YY}$	κ_{e-}^{ZZ}
-0.1 ± 0.6	-0.3 ± 1.4	-2.0 ± 0.9	-2.0 ± 1.7	-0.2 ± 3.1
$\beta\kappa_{o+}^{XY}$	$\beta\kappa_{o+}^{YZ}$	$\beta\kappa_{o+}^{XZ}$		
-2.5 ± 2.5	-1.0 ± 1.5	1.5 ± 1.7		

4. Outlook

To conclude, we have set up a Michelson-Morley experiment which after one month of data integration has already improved current limits on a possible violation of Lorentz invariance by one order of magnitude. These limits exclude an anisotropy of the speed of light at a level of $\Delta c/c < 1 \times 10^{-17}$. The experiment applies cavities specially designed for the use in a Michelson-Morley experiment and benefits from a suppression of systematic effects down to a level of few parts in $\Delta\nu/\nu \sim 10^{-17}$. Further improved limits, as well as a completely independent determination of the κ_{e-} and κ_{o+} terms, should be readily obtained by extending the measurement time span to more than one year. In the longer term, it should be possible to overcome the current sensitivity limitations due to mirror thermal noise by combing cryogenic optical resonators[2] and extremely well controlled active rotation in a single experimental setup. Together with a reasonable improvement in the suppression of systematic effects, this would then allow one to test for potential violations of Lorentz invariance in the $\Delta c/c \sim 10^{-20}$ regime.

References

1. A. A. Michelson and E. W. Morley, Am. J. Sci. **34**, 333 – 345, (1887).
2. H. Müller *et al.*Phys. Rev. Lett. **91**, 020401, (2003).
3. S. Herrmann *et al.*, Phys. Rev. Lett. **95**, 150401, (2005).
4. P. Antonini *et al.*, Phys. Rev. A **71**, 050101 (2005).
5. P. Wolf *et al.*, Phys. Rev. D **70**, 051902, (2004).
6. P. Stanwix *et al.*, Phys. Rev. Lett. **95**, 040404, (2005).
7. P. Stanwix *et al.*, Phys. Rev. D **74**, 081101, (2006).
8. D. Colladay and V. A. Kostelecký, Phys. Rev. D **58**, 116002, (1998).
9. S. Herrmann *et al.*, Lect. Notes Phys. **702**, 385 – 400, (2006).
10. V. A. Kostelecký and M. Mewes, Phys. Rev. D **66**, 056005, (2002).
11. B. Altschul, Phys. Rev. Lett. **96**, 201101, (2006).