

Optical decay from a Fabry-Perot cavity faster than the decay time

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The dynamical response of an optical Fabry-Perot cavity is investigated experimentally. We observe oscillations in the transmitted and reflected light intensity if the frequency of the incoupled light field is rapidly changed. In addition, the decay of a cavity-stored light field is accelerated if the phase and intensity of the incoupled light are switched in an appropriate way. The theoretical model by M. J. Lawrence *et al.*, JOSA B 16, 523 (1999) agrees with our observations.

I. INTRODUCTION

Optical Fabry-Perot cavities are common in laser spectroscopy and interferometry and are frequently used for the stabilization of laser sources [1,2]. A novel application for high-finesse cavities was proposed in the early 90's in the upcoming field of cavity-QED: Single atoms are strongly coupled to a cavity-stored photon field such that the mutual coherent oscillatory exchange between both sub-systems is much faster than their individual decay rates. A number of experiments, in both the optical [3] and in the microwave regime [4], have shown that this cavity-atom coupling can indeed be used for quantum information processing [5], where single quantum systems such as atoms or photons carry qubits (as the quantum alternative for the well known bits in information science).

We are interested in the physics of Fabry-Perot cavities because they can be used as an interface between static quantum information storage, which is advantageously done in long lived states of trapped atoms, and the transport of quantum information by light [6]. For this we are currently investigating the physical system composed of a single trapped $^{40}\text{Ca}^+$ ion inside the waist of a high finesse cavity [7].

A second major motivation is the use of light forces on atoms in cavities which leads to trapping and cooling, as published recently [8,9]. Here, light fields at the single photon level lead to significant forces due to the large enhancement factor of a high finesse cavity. The next generation of experiments will detect the atom's position [10] and even modify the light field in order to stabilize the atom's trajectory. This, however, not only demands a fast detection method, but also a technique to rapidly alter the photon field inside the optical Fabry-Perot cavity.

In this paper we show how the input light can be modulated to observe enforced evacuation of a cavity-stored light field, within a timescale below the cavity damping time. For this, the phase and intensity of the incoupled light field are switched rapidly such that destructive interference nulls the cavity-stored field. This technique is

obviously interesting for application in the above experiments.

The dynamic response of a Fabry-Perot cavity has been investigated in the context of the Laser Interferometer Gravitational-Wave Observatory (LIGO) by M. J. Lawrence *et al.* [11]. In that publication the transmitted light intensity and the Pound-Drever-Hall (PDH) error signal in reflection [12] are studied when the cavity length or the frequency of the input light field is rapidly changed. The results which we present here complete and generalize those earlier studies since we show how the full control of frequency, phase, intensity and time duration of an input light field leads to a much larger variety of interference effects between cavity-stored light and input field.

The paper is organized as follows: After describing the experimental setup, we first study the response of the transmitted and reflected light when the input field frequency is swept continuously over the cavity resonance. Our results fully recover and confirm the findings of M. J. Lawrence *et al.* [11]. In the following parts we describe more sophisticated implementations of modulating the input, such as frequency switching (covered by section 3) and phase switching (section 4). In the final section we present the unusual response of the cavity field to simultaneous phase and intensity switching, whereby the decay of the cavity field, as measured in the transmitted light, is accelerated much below the cavity decay time.

II. EXPERIMENTAL SETUP

A Titanium-Sapphire laser delivers up to 500 mW of light at 729 nm wavelength. One part of the laser power is focused into a Paul trap and used to excite the narrow $S_{1/2} \leftrightarrow D_{5/2}$ transition of single trapped $^{40}\text{Ca}^+$ ions [13]. A second part is used to generate a PDH error signal from the reflection of a reference cavity with finesse 220000 (mirrors optically contacted to a 20 cm long ULE-spacer). The Titanium-Sapphire laser frequency is stabilized to this reference cavity and we measure a laser

linewidth of less than 100 Hz (using the narrow Ca^+ transition) [14].

A third fraction of the light is coupled into an optical fiber which transports it from the optical table to a vibration isolated platform. The experimental setup on that platform is depicted in Fig. 1. The light from the fiber output is sent through an acousto-optic modulator (AOM: Brimrose Inc. USA, GRP-650) in double-pass such that the light in the first order beam is frequency shifted by twice the AOM driving frequency (which can be varied from 550 to 750 MHz). After passing through an electro-optical modulator (EOM: Linos Inc. Germany, LM0202) to add sidebands at 17 MHz to the light, the light is mode-matched into a second high finesse Fabry-Perot cavity. This cavity consists of a ULE-spacer of 15 cm length with a central bore and two high reflecting mirrors (Research Electro-Optics Inc. USA) optically contacted onto the polished front faces of the spacer. The cavity rests on 4 pins inside a UHV-vessel at $\leq 10^{-8}$ mbar. The UHV-vessel is temperature stabilized to 25 ± 0.05 C. Light transmitted by the cavity is monitored on a photo-diode PD 1 (bandwidth ≈ 0.1 MHz) and a CCD-camera. The reflected intensity is detected by a photo-diode PD 2 (bandwidth ≈ 100 MHz), which is used for the generation of a PDH error signal.

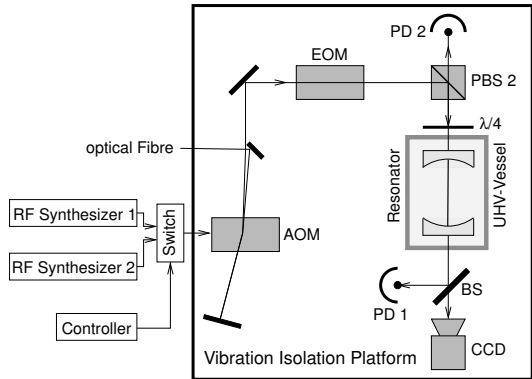


FIG. 1. Optical setup of the high-finesse Fabry-Perot cavity on the isolation platform (PBS: polarizing beam splitter, BS: beam splitter, PD: photo-diode, $\lambda/2$: half-wave plate, AOM: acousto-optic modulator, EOM: electro-optic modulator, see text for further details).

An RF-synthesizer provides the driving frequency for the AOM. The light frequency is varied over the TEM_{00} resonance of the cavity. A second synthesizer of the same type and synchronized to the same timebase can be set to a well-defined frequency and phase offset relative to the first one. An RF-switch (Minicircuits ZYSWA-2-50, switching time 3 ns) is used to switch rapidly between the first and the second RF-synthesizer, in order to generate controlled frequency, intensity or phase jumps of the input light.

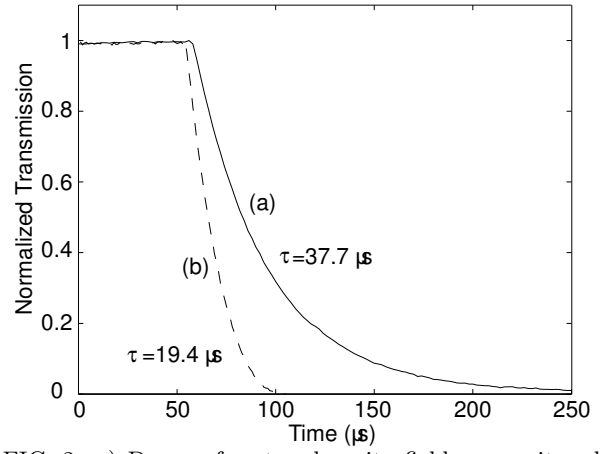


FIG. 2. a) Decay of a stored cavity field as monitored in transmission (solid line). b) The cavity is filled with a resonant light field. We observe accelerated cavity decay (broken line) monitored in transmission, when the phase of the input light field is switched by 180 degree (near $t = 50 \mu s$). Finally, the input light is switched off (near $t = 100 \mu s$). The ratio of both measured decay constants of 1.95(0.05) agrees with the expected factor two.

First, we measured the cavity decay time: The RF-drive of the AOM is switched off when the cavity transmission is near a maximum (TEM_{00} resonance) and the exponential decay of the cavity-stored light field is observed with PD 1 and an oscilloscope, see Fig. 2 a. We find an exponential decay with a time constant of $\tau_s = 37.1(0.3) \mu s$. The finesse F of the cavity is related to decay time $\tau_s = FL/c\pi$, which allows us to determine F to be 233000 ± 2000 .

III. INPUT LIGHT FREQUENCY MODULATION

Consider a linear sweep of the input light frequency and a standing wave cavity of fixed length L . Initially at $t = 0$, the input field with constant amplitude E_0 is at frequency ω_0 , and before the first round-trip the intra-cavity field reads $E_{cav}^{(0)} = i\sqrt{T}E_0e^{-i\omega_0 t}$. Here, T denotes the transmission of the input coupling mirror. After one round-trip, the cavity field is slightly attenuated, which the round-trip loss $\rho = 1 - \pi/F$ accounts for, and interferes with the transmitted input field, which is now at different frequency ω_τ . We obtain $E_{cav}^{(1)} = \rho e^{-i\omega_0(t-\tau)} + i\sqrt{T}E_0e^{-i\omega_\tau\tau}e^{-i\omega_\tau(t-\tau)}$. For n round-trips, a recursion equation is found [11] for $E_{cav}^{(n)}$, which finally leads to the differential equation

$$E_{cav}/d\tilde{t} = -(1 - i\nu_\omega\tilde{t})E_{cav} + i(\sqrt{TF}/\pi)E_0, \quad (1)$$

with $\tilde{t} = t/\tau_s$, the cavity decay time τ_s defined as above, and $\nu_\omega = 2FL\dot{\omega}\tau/\pi c$ which denotes the normalized scan

rate. As discussed in reference [11], the cavity transmission signal and the PDH error signals exhibit oscillations,

which appear for $\nu_\omega \geq 1$.

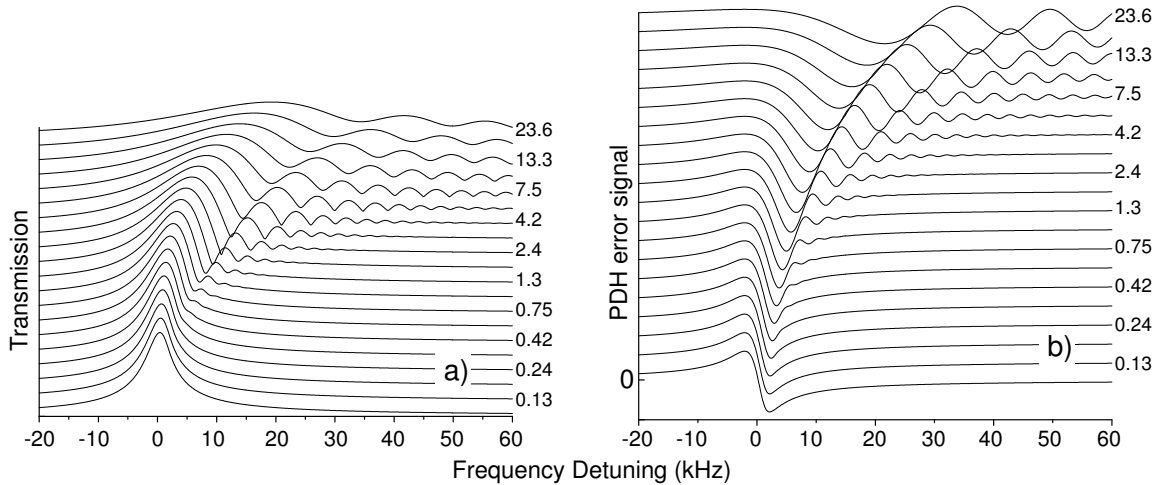


FIG. 3. a) Simulation of the cavity intensity transmission, when the input frequency is varied over the resonance. We plot $|E_{cav}|^2$ of Eq.1. For this picture, the scan rate ν_ω is chosen 0.1 for the lowest trace and increased by 133% each step in 20 steps, as indicated at the right hand side of the plot (for clarity, the curves are shifted upwards with increasing ν_ω). As the calculation shows, for high ν_ω , the point of highest transmission is shifted towards higher optical frequency detuning and the transmission level is lowered. b) Simulated PDH error signal, $Re(E_{cav})$, Eq. 8 in reference [11] for different values of ν_ω .

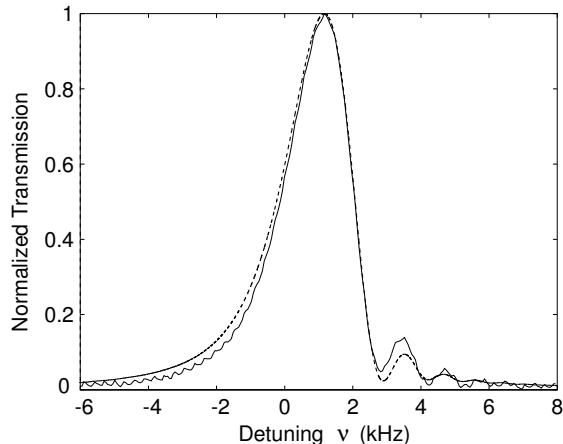


FIG. 4. Cavity transmission as measured (solid line) and calculated (broken) for $\nu_\omega = 1.35$.

Fig. 3 shows a numeric solution of Eq. 1, for different ν_ω . For the simulation, we take the values which are realized in the experiment for a standing wave cavity with $F=233000$ and length of $L=0.15$ m. The frequency axis is calculated using the transformation from time steps of τ_s , as used for the evaluation of the differential equation, to the frequency detuning in Hz , by multiplying τ_s with $\nu_\omega \cdot c/(4FL)$.

The experimental result for a cavity transmission signal is shown in Fig. 4, together with the simulation. The frequency scan rate was $\dot{\omega} = 2\pi \cdot 64$ MHz/s which results in a ν_ω of 1.27. Fig. 5 shows PDH error signals, as obtained from the de-modulated signal of PD2. Again, for values of ν_ω approaching one, the error signal is distorted,

and shows oscillations.

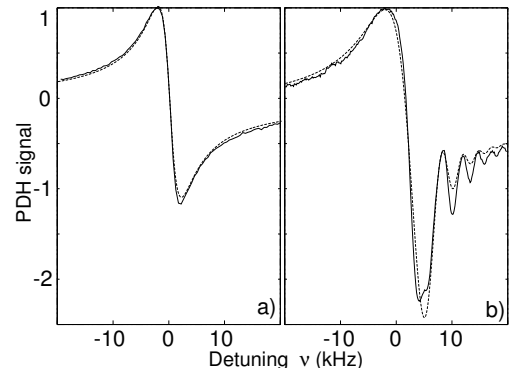


FIG. 5. PDH error signal as measured for different ν_ω of 0.01, and 1.35 (experiment: solid line, simulation: dotted line).

IV. SWITCHING THE INPUT LIGHT FREQUENCY

In another experiment, we used two RF-synthesizers to switch the frequency of the input light field. First the input is kept in resonance with the cavity and the cavity is filled. Then the frequency of the input light is switched by 46 kHz and the output light intensity behind the cavity is monitored. We observe an exponential decay, which is sinusoidally modulated at the beat frequency between the two input fields, see Fig. 6 for the data. We observe that the initial phase of this modulation is changed when the phase between both synthesizers varies.

V. PHASE MODULATION RESPONSE

As in the previous section, we use two synthesizers to generate the drive for the AOM. Both frequencies are kept in resonance with the fundamental cavity mode. The cavity is filled with the first source, then we switch to the second source whose phase is at 180 degree to the first one. The intensity behind the cavity is monitored. Our result is shown in Fig. 2b, where we observe an exponential decay and fit a decay constant of $19.4(0.4)\mu s$. Note that this decay is a factor of $1.95(0.05)$ faster than the free cavity decay, observed after simply cutting off the input light (Fig. 2a). This experimental finding agrees well with the expected factor of two, since the input field intensity was kept constant. The second light field, with opposite phase to the first one, builds up inside the cavity and leads there to destructive interference. At the instant, when the transmitted light from the cavity vanishes, we cut the second input field to leave the cavity empty (Fig. 2 b, $t \simeq 100 \mu s$). One may wonder how the stored light energy escapes: It leaves the cavity via the input coupling mirror, where it interferes constructively with the input light field. These findings lead immediately to the idea that the decay time of light in the cavity can be shortened even beyond a factor of two if phase *and* intensity of the second input field are chosen properly.

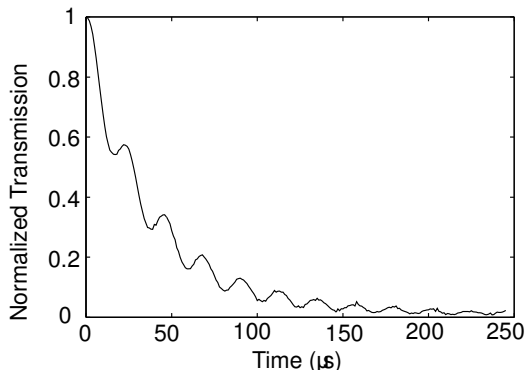


FIG. 6. The cavity is filled at resonance, then at $t = 0$ the input frequency is switched by 46 kHz.

VI. PHASE AND INTENSITY MODULATION AND ACCELERATED CAVITY DECAY

As in the previous section, two input fields are used. The first, on resonance, fills the cavity and the second

is used to induce a cavity decay as fast as possible. We set the intensity to twice that of the first input field, and indeed observed a ~ 2.3 -times faster decay, with $16.9(0.7) \mu s$. However, for the intensity switching, the AOM drive power is increased, which also transiently affects the phase. Thus, with the used setup it was impossible to adjust the second light field's phase to be exactly opposite to the first one and to achieve an even faster cancellation of the cavity field.

VII. CONCLUSION

We have shown experimentally interference effects which occur when the input light field of an optical cavity is rapidly altered in frequency, phase and intensity. The transmitted intensity is monitored to reveal a strongly modified cavity decay. In addition, the Pound-Drever-Hall error signal in reflection, as used for laser frequency stabilization, shows oscillations when the laser frequency is scanned quickly over the cavity resonance. The PDH signal, usually an antisymmetric signal with a zero crossing (locking point) exactly at cavity resonance, may then even exhibit a few oscillations and multiple zero crossings (for $\nu_\omega \geq 1$), and loses completely its shape. The consequence is clear: If an ultra high finesse cavity (with narrow linewidth) is used for the frequency stabilization of a laser with high frequency fluctuations, the servo-loop for the frequency locking will initially have some problems to stabilize the laser's frequency within the reference cavity's linewidth. Thus, a pre-stabilization [2] of the laser becomes necessary to reduce its initial frequency jitter.

We have shown how the cavity decay time can be decreased below its normal value. This could have future applications if a stored cavity field has to be changed rapidly. All observations agree well with the theoretical predictions, which are based on the interference of electromagnetic fields, and which are outlined in this paper and in M. J. Lawrence *et al* [11].

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