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REDUCING LIGHT-SHIFT EFFECTS IN OPTICALLY-PUMPED GAS-CELL ATOMIC FREQUENCY STANDARDS

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Abstract – **We investigate a novel method to suppress the light-shift effect in laser-pumped passive rubidium frequency standards. The reduction of the light-shift due to additional frequency components in the pumping light is studied theoretically and compared to experimental results obtained with a frequency-modulated DBR laser diode as a pumping light source. In this way, a reduction of the light shift by a factor of 55 was successfully demonstrated. Complete cancellation of the light shift can be reached with a suitably adjusted modulation index and frequency.**
***Keywords* - rubidium frequency standard, light shift, optical pumping, modulation.**

I. INTRODUCTION

Many types of atomic frequency standards use discharge lamps or diode lasers for optical pumping and/or probing, cooling, etc. In these standards the light shift (or AC stark shift) is of major concern for the clock performance. In the field of optically pumped vapor-cell standards, which find applications spanning from satellite navigation over telecommunication to industrial applications, the signal-to-noise ratio is significantly improved when optical pumping is achieved by a laser instead of the widely-used discharge lamps. On the other hand, in the case of optical pumping with a narrow-band laser the strong frequency dependence of the light shift makes it necessary to have excellent control over the laser frequency [1]. Concepts for an efficient reduction of the light shift are thus of great interest in order to improve the clock performance or to relax the demands on the laser frequency stability [2].

In this paper we present an experimental verification of our previous theoretical studies [3] on light shift suppression in optically pumped clocks using additional frequency components in the pumping light field. These additional frequencies can be created in an easy way by frequency modulation of the pumping laser. In this respect the demonstrated method is similar to the light-shift reduction in vapor-cell frequency standards based on coherent population trapping (CPT) studied in [4,5].

II. METHOD DESCRIPTION

The main idea of the proposed method is to realize optical pumping of the Rb vapour not by using monomode laser field, but a multi-frequency field with controlled amplitude and spectral interval between the frequency components, with less demanding requirements to the frequency stabilization. Thus, self-compensation of the light shifts of the clock transition due to the different components is accomplished.

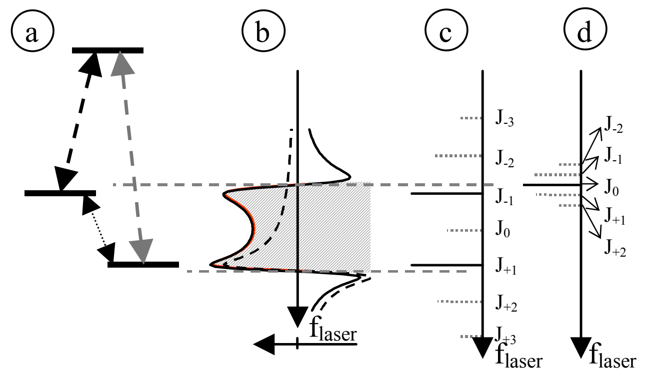

Fig. 1. Atomic level scheme (a), light shift (b) of the clock transition induced by a single-frequency laser field, and laser spectra for CPT (c) and optical pumping (d). Solid lines: laser frequencies required for the respective process, dotted lines: additional frequencies for light shift reduction

A. Light shift in vapor-cell Rb clocks

Fig. 1a shows a sketch of the relevant atomic level diagram for atomic clocks based on both optical pumping and CPT. In the optically pumped clock only one of the ground-state hyperfine components is pumped by a light field (black, dashed arrow) and the ground-state splitting (i.e. the clock transition) is probed by a microwave field (black dotted arrow), while in the case of CPT the level coupling is accomplished not by microwave, but by a second light field (gray, dotted arrow). As indicated in Fig. 1b, the light shift of the clock transition due to a single frequency component exhibits a steep slope at the frequency positions of the two ground-state levels, quantified by the parameter

$$\beta = \Delta f_{clock} / \Delta f_{laser} . \quad (1)$$

If several light fields are present, the total light shift Δf_{clock} of the clock transition is given by the sum over all atomic levels and light fields involved. Thus due to the opposite sign of β at the two transitions, for the two-frequency case of CPT (Fig. 1c, solid lines) the linear dependence of the light shift on laser frequency can be made

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to cancel and only the higher order contributions remain. By adding more light field components via, e.g., frequency modulation (Fig. 1c, dotted lines) [4,5] additional contributions to the total light shift can be introduced, which are positive for frequencies in the shaded frequency region of Fig. 1b and negative elsewhere. Therefore the light shift can be completely cancelled in CPT via controlling the modulation sideband strengths. In the following we will describe how one can obtain a similar light shift suppression in an optically pumped frequency standard.

B. Light shift reduction with optical pumping

In an optically pumped clock the light field consists of only one frequency component (Fig. 1d, solid line). Therefore the clock transition is subject to the full linear light shift caused by this pump light, resulting in β about 10–100 times larger than in CPT vapor cell clocks. However, also in this configuration one can exploit the frequency dependence of the light shift in order to reduce it.

When sidebands are produced in the laser spectrum (Fig. 1d, dotted lines) by frequency modulation of the laser light, the negative-order sidebands give rise to a positive light shift while for the positive-order ones the light shift is negative. For an appropriately chosen modulation index of $M \approx 2.4$ the carrier is depleted and only the contributions from the positive and negative sidebands remain, which have opposite sign, respectively, and thus cancel out for a symmetric light shift curve.

The optimum modulation frequency is equal to half the width of the optical transition, because in this case the first-order sidebands coincide with the extrema of the light shift curve where β is essentially zero. Furthermore, if the laser (carrier) frequency drifts by a small amount compared to the optical linewidth, the light shift change due to the positive and negative sidebands, respectively, largely compensate each other. This gives rise to an entire frequency *interval* of reduced light shift, spanning several tens of MHz centered around zero laser detuning, which we will refer to as the "self-correction plateau."

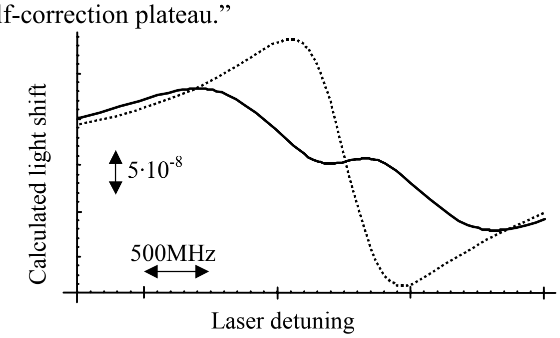

Fig. 3. Calculated light shift around the pumping frequency on the F=1 transition of the D_2 line of ^{87}Rb. Dotted line: no modulation, solid line: modulation index of 2.4 and 400 MHz modulation frequency. The vertical arrow indicates the relative clock (or atomic) frequency shift.

Our calculations [3] of the light shift for ^{87}Rb take into account the full hyperfine structure of both ground states and the excited state involved, and selected results are shown in Fig. 2. The self-correction plateau of strongly suppressed light shift can be clearly seen.

III. Experimental Verification and Results

A. Experimental setup

The setup used for the experimental verification of the proposed scheme is sketched in Fig. 3. A commercial three-section DBR diode laser is used as a light source. This laser has a modulation bandwidth large enough so that the required modulation indices of $M \approx 2.4$ can be conveniently obtained using reasonable rf modulation power. The DBR chip is temperature stabilized and its emission frequency is tuned by varying the injection current. At the operating frequency of 780 nm mode-hop free tuning over more than 8 GHz could be obtained, covering the entire absorption spectrum of the rubidium D_2 lines.

The emitted laser beam is collimated, slightly expanded, and sent into a modified, commercial Rb space clock module (RAFS series, Temex Neuchâtel Time) whose Rb lamp was removed for this purpose. The laser frequency was slowly scanned across the atomic resonance by applying a ramp signal to the injection current, and the output frequency of the clock module was compared to a H-maser reference using a frequency counter.

In order to obtain sufficient measurement resolution, a high total pump light intensity of 47 μW/cm^2 was used. Frequency scaling as well as absolute frequency calibration was accomplished by directing parts of the laser power towards a Fabry-Perot resonator and a saturated absorption spectroscopy setup, respectively. At fixed rf modulation power, the resulting laser spectrum was measured by the beat note spectrum with an extended-cavity diode laser independently stabilized onto a different Rb hyperfine transition.

As the vapor cell of the clock module contained both Rb isotopes in their natural abundance, partial absorption of the upper modulation sidebands by the ^{85}Rb, *F*=3 component has

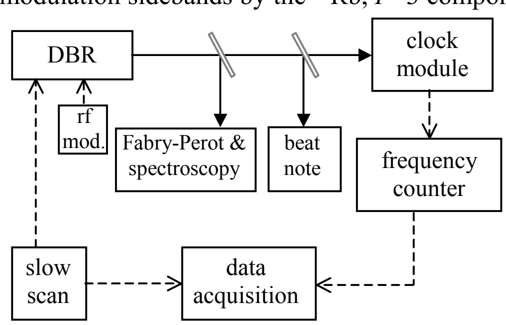

Fig. 2. Block diagram of the experimental setup

to be taken into account when the laser is tuned to the ^{87}Rb, F=2 component only about 1 GHz away. In the experiments this effect was largely avoided by tuning the laser to the ^{87}Rb, F=1 component, where the interfering absorption lines due to transitions from ^{85}Rb, F=2 are more than 2 GHz detuned.

B. Results

Fig. 4 shows the variation of the clock frequency with pump laser detuning due to the light shift for some selected values of the rf modulation power. Compared to the data obtained with the unmodulated laser, the slope of the light shift curve at line center is reduced already for a modulation power of 10dBm. This is mainly due to the reduced power in the carrier and reflects the intensity dependence of β for this frequency component. As with increasing rf power the modulation index approaches $M \approx 2.4$ and the carrier gets depleted, only the contribution to the light shift stemming from the modulation sidebands remains. The experimental data clearly shows the existence of the self-correction plateau around zero laser detuning, which has a width of several hundred MHz.

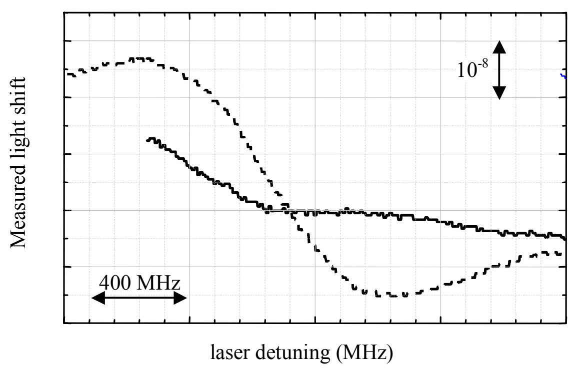

Fig. 4. Light shift around the F=1 transition measured experimentally. Broken line: unmodulated laser, solid line: with modulation (16 dBm sent to the laser). The flat self-correction plateau around zero laser detuning is well represented in the latter case.

From the light shift spectra of Fig. 4 numerical values for β at the atomic resonance frequency were extracted by a linear fit and are shown in Fig. 5 as a function of the rf modulation power sent to the laser. Again, the light shift suppression is obvious, with a zero-crossing of the β coefficient around 40 mW. Thus the light shift can be completely suppressed by proper choice of the modulation power.

IV. Conclusion

We have analyzed both theoretically and experimentally a simple method for the suppression of the light shift effect in optically pumped gas-cell atomic frequency standards. It was demonstrated that the light shift in principle can be completely suppressed by choosing the appropriate rf modulation power. The successful reduction of the light shift coefficient β by at least a factor of 55 was demonstrated experimentally. This reduces β to a level comparable to those

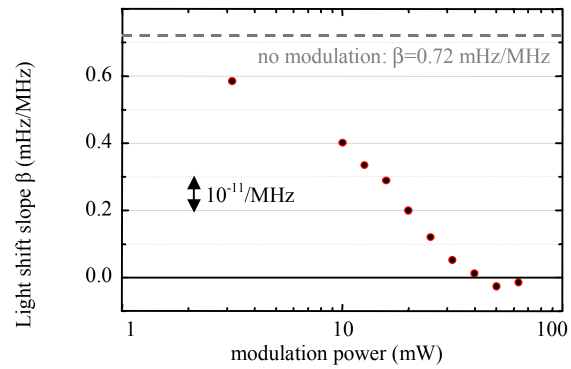

Fig. 5. Suppression of the light shift slope β as a function of rf modulation power.

of CPT gas-cell atomic clocks, in which the light shift is intrinsically small.

At the optimum modulation depth, the novel self-correction plateau around the atomic resonance frequency, where the light shift coefficient is most strongly suppressed, has a width of several hundred MHz. Thus for a given clock stability the requirements on the laser frequency stability can be largely relaxed.

Compared to similar techniques for CPT-based frequency standards, the applied modulation frequency of about 500 MHz is much lower and therefore relaxes the demands on the modulation bandwidth of the laser source used.

While in the CPT-approaches [4,5] the strong first-order modulation sidebands are used for frequency stabilization, in the optically pumped clocks the strongly depleted carrier frequency has to be locked to the atomic transition. This problem might not be too severe, however, because of the relaxed requirements on the laser frequency stability due to the self-correction plateau at the carrier frequency.

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