Modulation Transfer Spectroscopy in Rubidium at 20 MHz.

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Abstract

Laser spectroscopy stabilizes laser frequency to atomic resonances for cooling, clocks, and interferometry. Modulation Transfer Spectroscopy (MTS), a variant of Saturated Absorption Spectroscopy (SAS), locks a laser by modulating a single beam for precise, stable frequency control.

We characterize MTS on the D2 lines of ^{85}Rb and ^{87}Rb using an electro-optic modulator. First, we study power broadening by symmetrically increasing probe and pump intensities. Next, we keep the probe near saturation while increasing pump power to optimize the locking signal [1, 2].

Using 20 MHz rather than the conventional 5 MHz places the system in a fast-modulation regime where atoms cannot follow the modulation adiabatically. The MTS signal is dominated by four-wave mixing between the carrier and well-separated sidebands [1, 3], which reduces the zero-crossing slope (lower Hz/V sensitivity) and complicates the line shape. Fast modulation can nonetheless improve rejection of low-frequency technical noise, reduce sensitivity to slow system drift, and separate the desired signal from other modulations present in the setup [3, 4].

The 20 MHz choice therefore trades slope for noise immunity. We propose controlled power broadening as a practical route to mitigate the complex line-shape effects encountered in fast-modulation MTS [1, 3, 4].

Introduction

→ MTS is a nonlinear spectroscopy technique in which a phase-modulated pump beam

$$E_{\rm pump}(t) = E_0\, e^{i\omega t + i\beta\sin(\Omega t)} = \sum_{n=-\infty}^{\infty} J_n(\beta)\, E_0\, e^{i(\omega+n\Omega)t}$$

transfers its modulation to a probe beam $E_{\rm probe}$ via four-wave mixing (FWM), where β is the modulation index and ω is the modulation frequency.

→ The (unmodulated) counter-propagating probe beam interacts in the atomic medium via $\chi^{(3)}$ [5] and part of the pump phase modulation is converted into amplitude modulation on the probe:

$$P^{(3)}(t) \;=\; \varepsilon_0\,\chi^{(3)} : E_{\rm pump}(t)\, E^*_{\rm pump}(t)\, E_{\rm probe}(t).$$

→ The beating between the carrier and the pump sidebands, "mixed" with the probe beam, creates collinear conjugate sidebands on the probe. By demodulating at Ω with reference phase ϕ, the sub-Doppler component is isolated.

→ This (1f) signal can be written as a sum of absorption $L_n(\Delta)$ (Lorentzian-shaped, imaginary part) and dispersion $D_n(\Delta)$ (derivative of a Lorentzian, real part) contributions evaluated at detunings $\Delta - n\Omega$.

$$S(\Omega,\Delta) \;\propto\; \sum_n J_n(\beta) J_{n-1}(\beta)\left[\, L_n(\Delta)\cos\phi \;+\; D_n(\Delta)\sin\phi\,\right],$$

$$L_n(\Delta) \;=\; \frac{\gamma_{\rm eff}}{\gamma_{\rm eff}^2 + (\Delta - n\Omega)^2} \qquad D_n(\Delta) \;=\; \frac{\Delta - n\Omega}{\gamma_{\rm eff}^2 + (\Delta - n\Omega)^2}$$

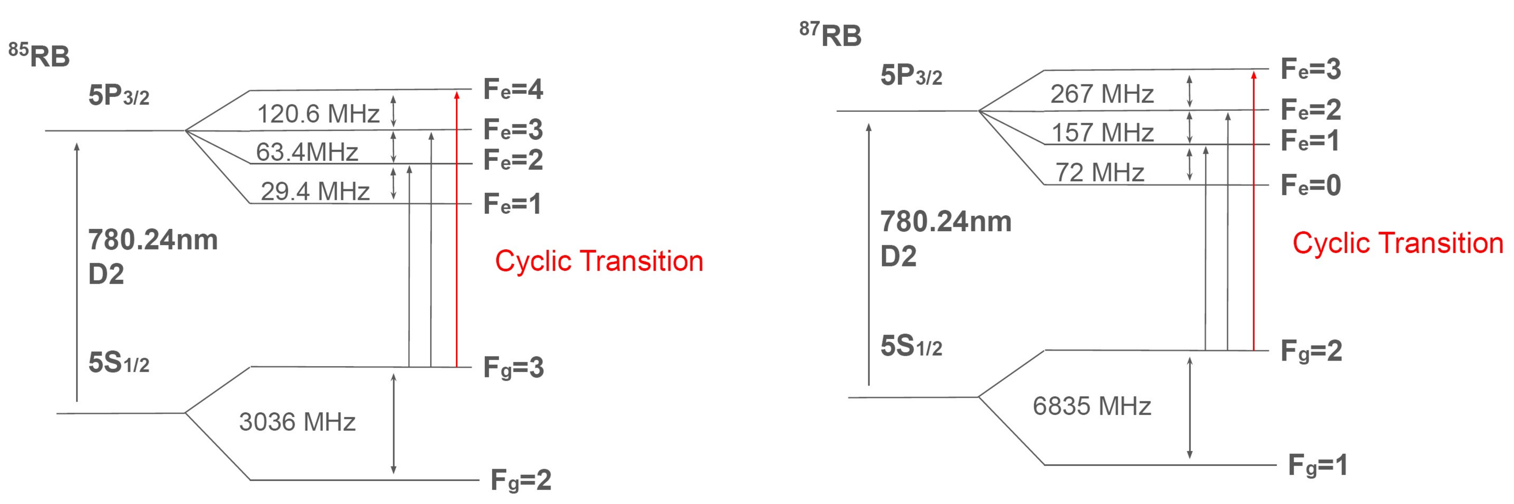
with an effective linewidth $\gamma_{\rm eff} = \Gamma_{\rm eff}/2$.

→ The phase ϕ "rotates" the $L - D$ balance. Therefore, ϕ is used for optimizing the error signal at the zero crossing by maximizing the slope at $\Delta = 0$.

The D2 line in Rb: the $5S_{1/2} \rightarrow 5P_{3/2}$ transition

→ MTS is ideal for laser locking: sub-Doppler signal, flat baseline, well-defined zero crossing at the center of the resonance.

→ For instance, MTS is widely used in laser cooling and trapping experiments for locking a laser to the cycling transition between the upper hyperfine levels of the ground $5S_{1/2}$ and excited states $5P_{3/2}$.

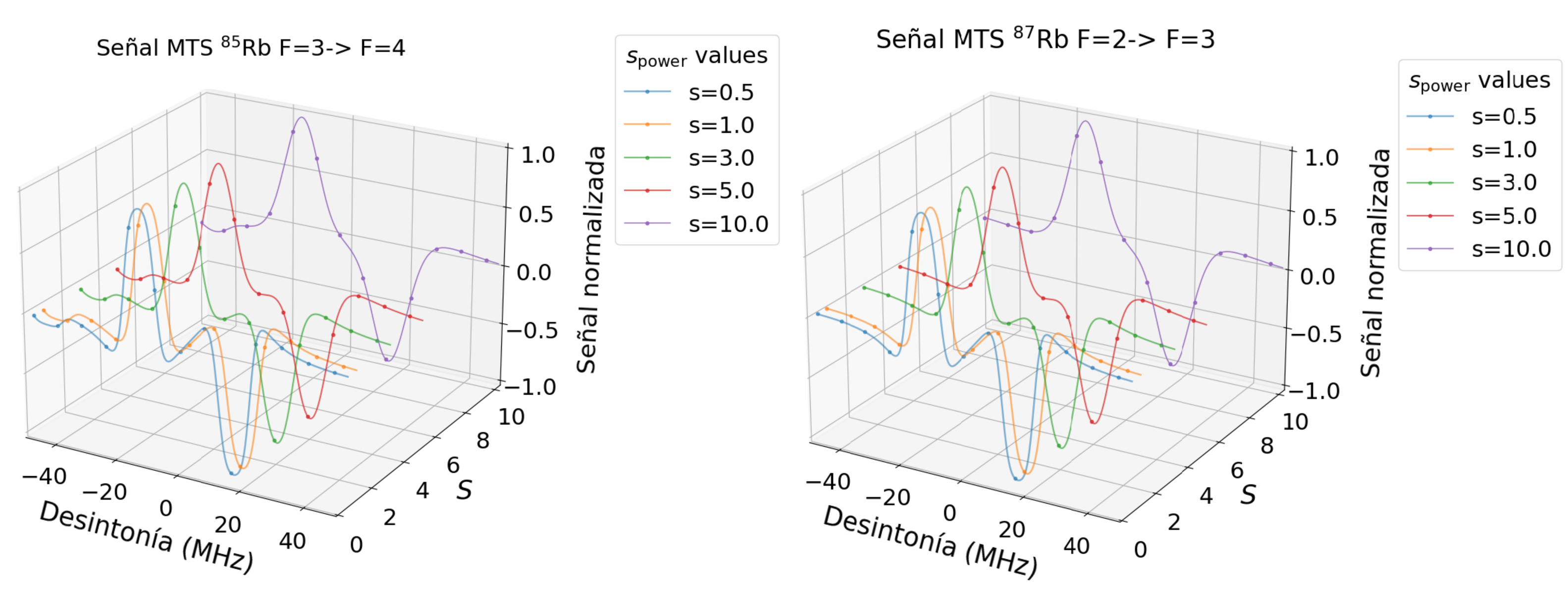


→ The natural linewidth is $\Gamma = 6.06$ MHz [6], but the observed linewidth on resonance increases with light intensity due to power broadening.

$$\text{FWHM: } \Gamma_{\rm eff} = \Gamma\sqrt{1+s} \qquad \left(\text{HWHM: } \gamma_{\rm eff} = \tfrac{\Gamma}{2}\sqrt{1+s}\right)$$

with $s = I/I_{\rm sat}$ as the saturation parameter and $I_{\rm sat}$ the saturation intensity.

The MTS signal can be tuned via power broadening by increasing laser intensity.



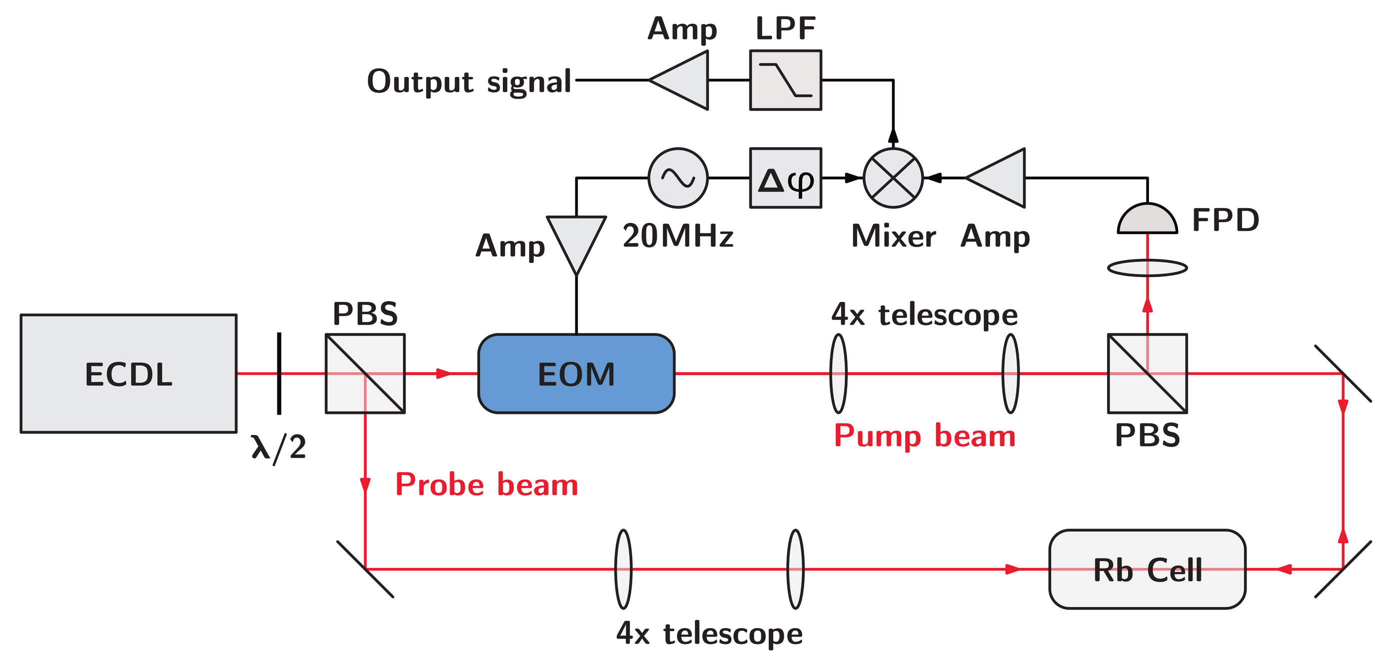
Experimental setup

→ A 780 nm laser is scaned across the D2 resonances of atomic Rb.

→ The beam is split with a PBS. The pump beam is sent through the EOM (20 MHz) and through a Rb vapour cell.

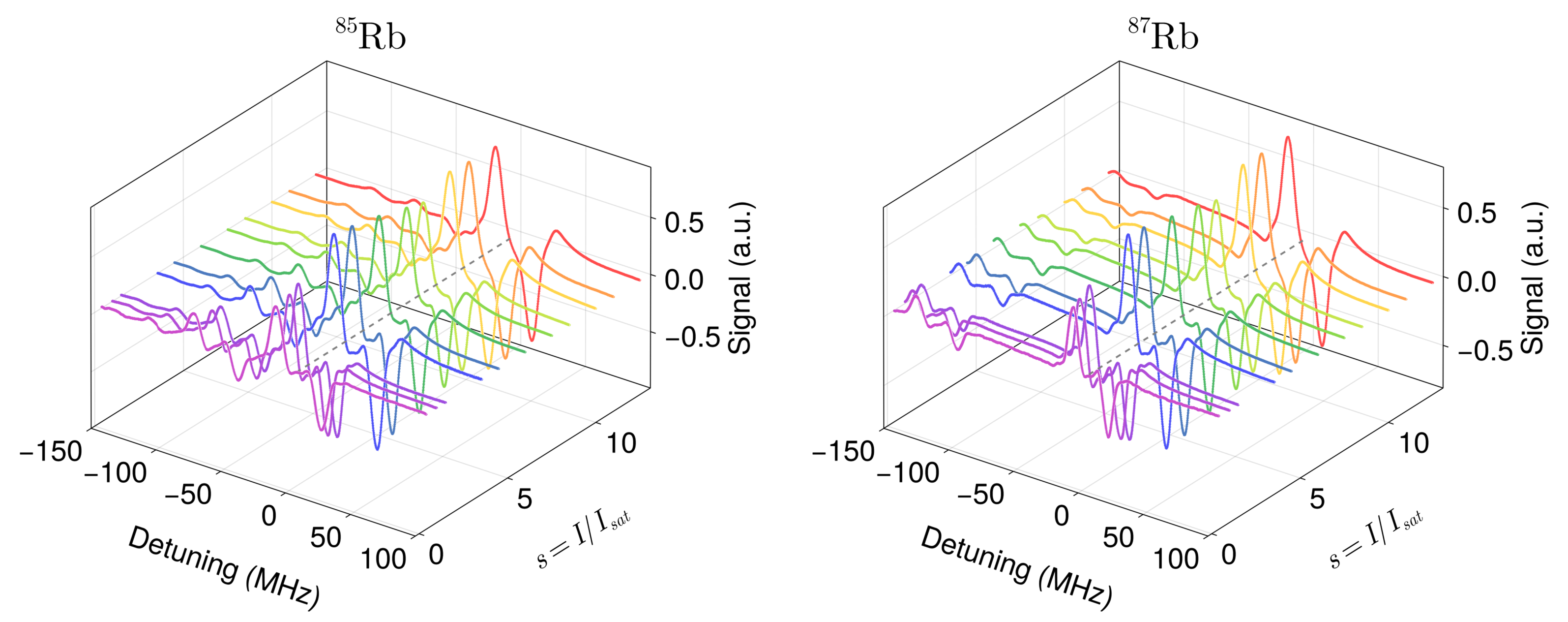
→ The unmodulated probe beam is also sent through the cell counterpropagating and superposed with the pump beam.

→ The probe beam is detected with a fast photodiode; its signal is mixed with the 20 MHz reference (adjusting the phase if needed), demodulated with a low-pass filter, and amplified, yielding the MTS signal.



Results

As the intensity increases, the MTS signal becomes more linear and shows a clear zero crossing. Intensities of a few times the saturation intensity are required for obtaining a slope useful for laser locking. In exchange, a wide locking region of the order of the modulation frequency Ω is obtained, which can be useful for stabilizing the laser emission in the vicitiny but not necessarily at the centre of the atomic resonance.



This is a work in progress that aims at identifying the optimal operation conditions of the MTS system for a large modulation frequency Ω.

Conclusions

MTS spectroscopy is a powerful tool not only for the development of laser locking techniques, but also for studying the hyperfine transitions. In this work, it is shown that for a given modulation frequency Ω, the effective linewidth $\Gamma_{\rm eff}$ can be tuned by means of the intensity of the laser light components to produce dispersive signals useful for laser locking.

Acknowledgements

This work was supported by DGAPA-UNAM projects PAPIIT IN118723, IN110623 and IN120326, as well as by SECHITI via the National Laboratory for Quantum Matter (LANMAC) 2023-51 and the project CF-2025 I-331.

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