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macQsimal

Miniature **A**tomic vapor-**C**ell **Q**uantum devices for **S**ens**I**ng and **M**etrology **A**pp**L**ications

Deliverable 7.7

Summary of performance and quantum enhancement

WP7 – Atomic GHz & THz sensors and vector imagers

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Abbreviations

ADC	Analog-to-digital converter
CPW	Coplanar waveguide
FFT	Fast Fourier transform
GHz	Gigahertz
GNSS	Global navigation satellite system
MEMS	Microelectromechanical systems
MHz	Megahertz
MW	Microwave
OD	Optical depth
PEEK	Polyether ether ketone
RF	Radio frequency
SA	Spectrum analyzer
sCMOS	Scientific complementary metal-oxide semiconductor
UV	Ultraviolet
UWB	Ultrawide bandwidth

Partner short names

accelCH	accelopment Schweiz AG, CH
CSEM	CSEM SA – Centre Suisse d'Électronique et de Microtechnique, CH
UNIBAS	Universität Basel, CH
UNINE	Université de Neuchâtel, CH

Contents

Executive Summary

This deliverable summarizes the performance of the microwave field imaging setup at UNIBAS operating in spectrum analyzer mode. In discussions with the industry advisory board member from Rohde & Schwarz, this operation mode was identified as the most promising for applications in the microwave communications industry. A device demonstrator of the atomic microwave spectrum analyzer was developed and validated in the UNIBAS laboratory and its performance is summarized here. Based on the results, future development into a microwave spectrum analyzer with wide instantaneous bandwidth seems feasible.

1 Motivation

Microwave (MW) spectrum analysis with wide instantaneous bandwidth is of great importance in communications, navigation, and defense. Limited by the performance of the analog-to-digital converters (ADCs) and a large amount of processing computational burden, the bandwidth of current devices based on digital fast Fourier transform (FFT) is up to several GHz [1]. Although together with a sweep-tuned superheterodyne configuration, the frequency range can be expanded to tens of GHz, the instantaneous analysis bandwidth is still bottlenecked by the performance of the FFT module [2], easily leading to missing detections for MW signals of wide bandwidth. The requirement is particularly critical in the application field of frequency hopping communication, unknown microwave frequency assessment, ultra-wide bandwidth (UWB) signal detection, and the global navigation satellite system (GNSS).

Here we present a MW spectrum analyzer based on ^{87}Rb atoms in a microelectromechanical systems (MEMS) atomic vapor cell. The cell is placed in a strong magnetic field gradient, which maps the frequency spectrum of incoming MW signals into spatial "fringe" patterns on laser absorption images of the vapor cell. Using magnetic field gradients to distinguish RF transitions at MHz frequencies has been demonstrated in the 1970s [3]. Here we use strong magnetic field gradients, Rabi coupling and absorption imaging in the pulsed regime [4-6] for spectral analysis of MW signals of more than 10 GHz frequency. In a few mm-sized cell, we observe a frequency span of 500 MHz, with a few MHz frequency resolution. In an improved setup with a larger cell, microwave spectral analysis with wide instantaneous bandwidth (more than 30GHz) seems feasible.

2 Experimental setup

In this section, we briefly describe the experimental setup of our atomic MW spectrum analyzer, including a schematic to introduce the elements and measurement scheme, the feature of the MEMS atomic vapor cell, the design and field simulation of the MW guiding structure.

2.1 Schematic and principle

As is shown in Figure 1 (a) and (b), the experimental setup contains a MEMS atomic vapor cell and a coplanar waveguide structure (CPW), both of which are placed near the surface of a pair of large profile permanent magnets. The magnetic field gradient across the cell region generates different Zeeman splittings for ^{87}Rb atoms at different locations. To avoid fast spatial averaging, the movement of the atoms inside the cell is slowed down by nitrogen buffer gas. The cell is heated to 130°C in an oven made of polyether ether ketone (PEEK) material (not shown in Figure 1).

For ^{87}Rb atoms at a specific position, the ground and excited state energy levels of the D2 line at 780 nm are shown in Figure 1 (c). We use two 780 nm lasers to address the D2 transitions (the red arrow in Figure *1* (a)). The pump beam propagates perpendicular to the magnetic field direction and optically pumps with its σ^- polarization component the Rb atoms from one ground state to others. The probe beam, linearly polarized with the polarization axis along the magnetic field direction, drives the π transition from the same ground state. The MW field is guided on the CPW to the cell and its resonant spectral component drives Rabi oscillations between the two ground states of opposite electron spin projection m_J in the same nuclear spin m_I manifold.

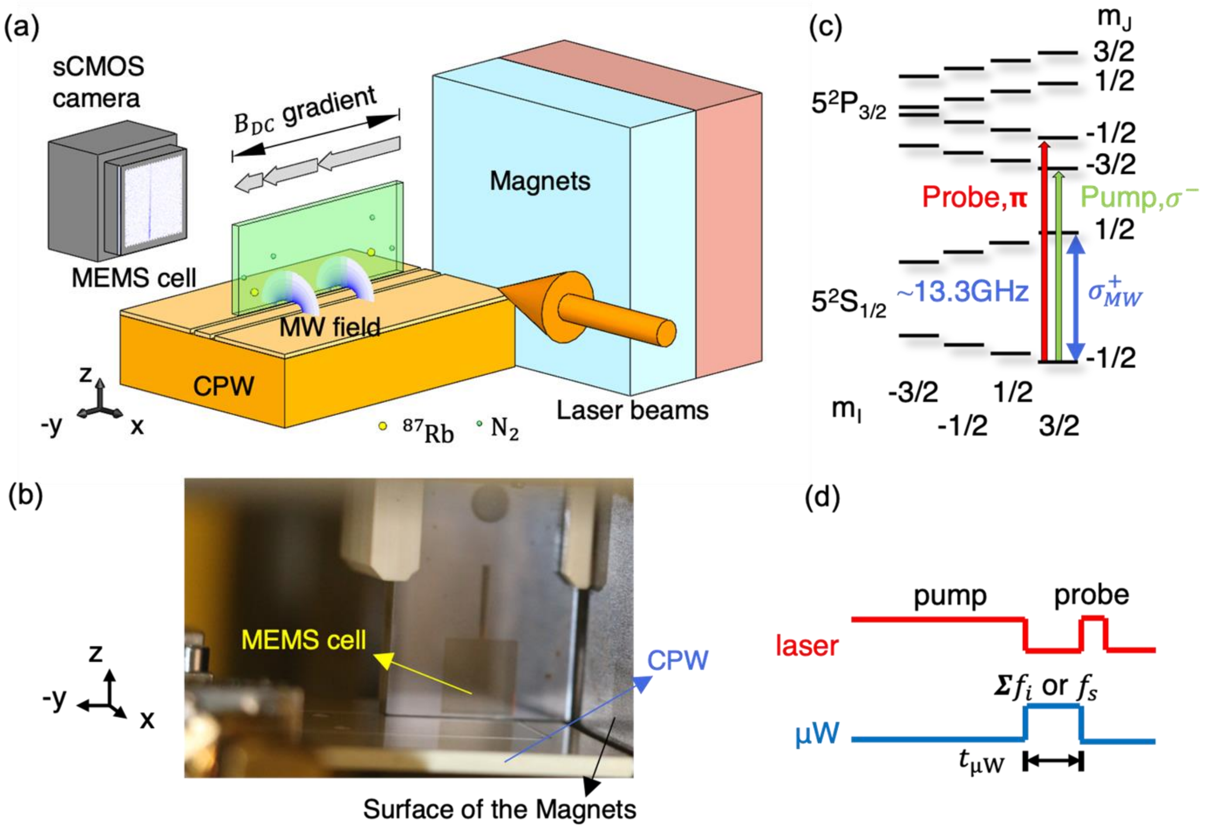


Figure 1: a) 3D illustration of the experimental setup: the light green box represents the lower portion of the measurement cavity of the MEMS cell, the blue contours represent MW field distribution, and the red arrow represents both the pump and probe beams; b) a close-up of the setup from the same view orientation as a); c) optical and MW transitions; d) pulse sequence.

We record absorption images with the probe beam onto a camera to determine the change in optical depth of the vapor due to the applied microwave field in a spatially resolved way. The experimental sequence is shown in Figure 1 (d). First, an optical pumping pulse of large intensity prepares a population difference, i.e., an optical depth change (ΔOD_{pump}) compared to the thermal equilibrium optical depth (OD) of the vapor on the transition interrogated by the probe. Then the MW signal pulse drives Rabi oscillations between two Rb ground states, leading to an optical depth change ΔOD_{MW}, which is the signal to be measured. Finally, a short probe beam pulse creates an image of the vapor on a scientific complementary metal-oxide semiconductor (sCMOS) camera. We record an image of ΔOD_{MW} by comparing an image obtained with the MW field turned on, as in Figure 1 (d), with a reference image where the MW field is off (not shown). The resulting "fringe" patterns in ΔOD_{MW} represent the frequency spectrum of the input MW signal (an example fringe pattern is shown on the sCMOS camera in Figure *1* (a) and see details in Section 3).

2.2 MEMS atomic vapor cell

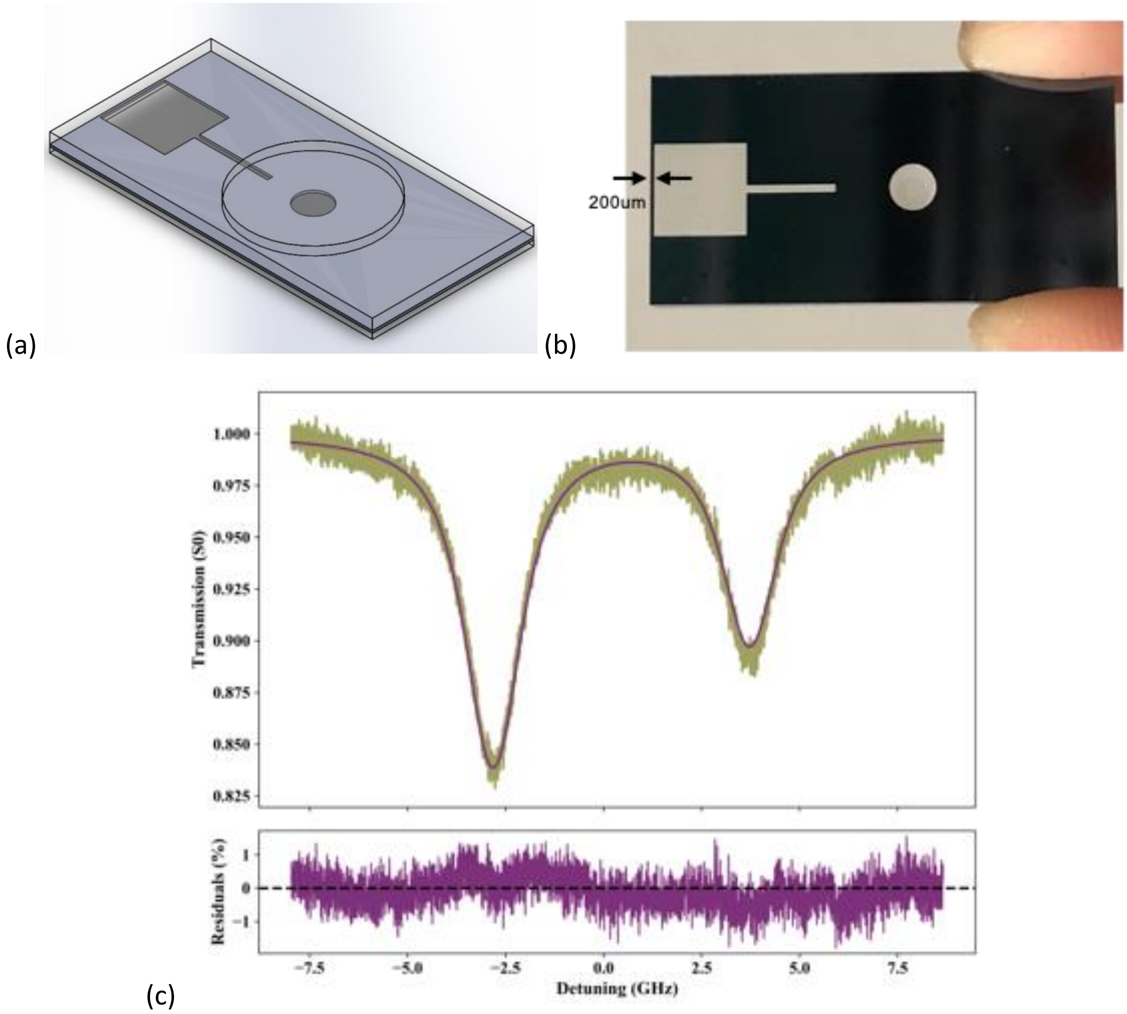


Figure 2: (a) 3D design of the MEMS cell; (b) close-up of the fabricated MEMS cell; (c) absorption spectroscopy of the MEMS cell to measure the buffer gas pressure (by Elecsus).

The atomic vapor cell used in this experiment is a MEMS vapor cell, jointly designed by macQsimal partners UNIBAS and CSEM, and manufactured by CSEM. It has 15mm x 30mm lateral dimensions and is composed of one silicon layer (200um thickness) sandwiched between two glass layers (Figure 2 (a,b)). The main working region is a 6mm x 6mm x 200um measurement cavity, containing pure ^{87}Rb and nitrogen buffer gas. A cylindrical compensation cavity is connected to the measurement cavity via a thin channel. The cell was initially filled with $^{87}RbN_3$ and fabricated by anodic bonding. After shining with UV light, the $^{87}RbN_3$ decomposed into saturated Rb atomic vapor and nitrogen buffer gas. After a careful absorption spectroscopy measurement (Figure 2 (c)), the nitrogen buffer gas pressure is found to be 110mbar at a temperature of $130°C$, obtained from fitting optical spectra including the buffer gas collisional broadening and shifts of optical transitions of ^{87}Rb based on the Elecsus tool [7].

The MEMS cell features a 200um thin sidewall, which can be seen in Figure 2 (b), enabling a close distance to the MW near field on the CPW.

2.3 Coplanar waveguide design and simulation

The CPW structure used in the experiment is shown in Figure 3. It is designed to guide the MW field with minimum loss and reflection in a frequency range of 1-20GHz. The cell position is also shown as a thin block in the figure. The blue region represents the magnet surface, implying that the magnetic gradient is along the y direction.

In Figure 4, the MW magnetic field used to drive MW transitions between the ground states of ^{87}Rb has been simulated with the software package COMSOL. For a given z position, the MW field is relatively homogeneous along both x (laser propagation direction) and y (magnetic field gradient direction, i.e., the frequency direction).

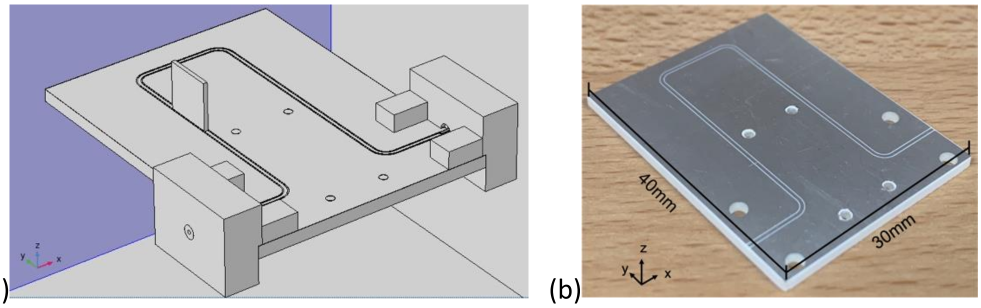
(a)  (b)

Figure 3: CPW structure design and cell position, with blue surface representing magnet; (b) manufactured CPW.

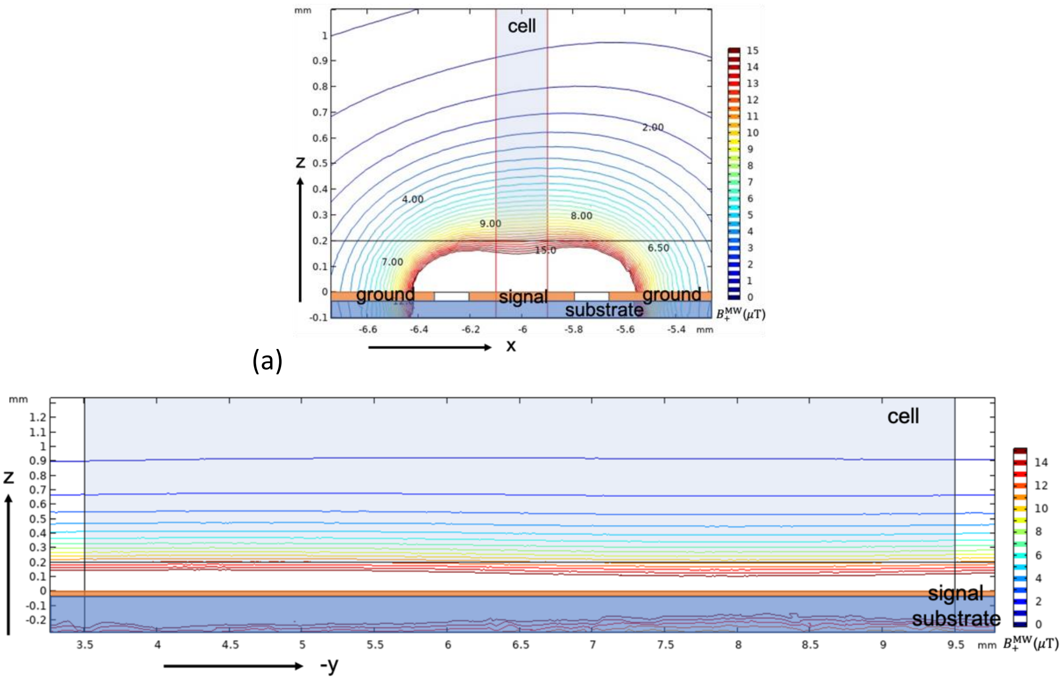


Figure 4: The MW magnetic field simulation above the CPW (a) in the Oxz plane and (b) in the Oyz plane. The light blue region is the MEMS atomic vapor cell.

3 Measurement results of the atomic spectrum analyzer

In this section, we present measurement results with the atomic spectrum analyzer. We first show the spectrum of a single-tone input MW signal and analyze the full width half maximum (FWHM) frequency resolution. We then show recorded spectra of multi-tone input MW signals to determine the analysis bandwidth of the current cell in the magnetic field gradient. We also show the corresponding calibration measurements with a conventional spectrum analyzer.

3.1 Single-tone signal analysis and frequency resolution

We first set the MW frequency to 13.2675 GHz, which is generated with a MW signal generator. The MW input power before coupled into the CPW is around 23dBm after a preamplifier. We measure 100 absorption images and show the averaged ΔOD_{MW} image in Figure 5 (a). A single fringe can be seen on the image, representing the Rb atoms that respond resonantly to the MW field. The MW frequency corresponds to a magnetic field of 2634.773 Gauss. The FWHM linewidth of the fringe can be estimated from a Gaussian fit (Figure 5 (b)) to be around 2.2 pixels. It is equivalent to 6.5MHz in the frequency domain, calculated from an auxiliary calibration measurement.

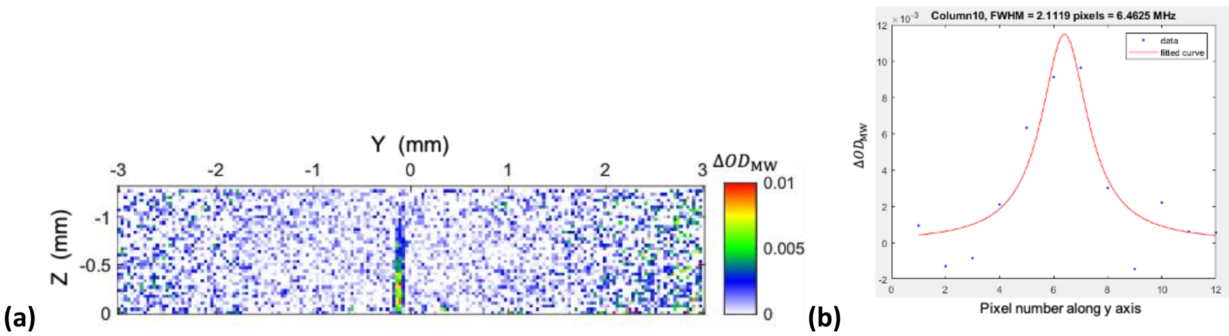


Figure 5: Single-tone microwave frequency measurement. (a) Δ OD MW image data; (b) Signal integrated along z to obtain the spectral resolution.

3.2 Multi-tone signal analysis and frequency span

When applying multi-tone input MW signals, patterns of multiple fringes are visible on the absorption images (Figure 6 and Figure 7), representing the frequency components of the incoming MW signals. In Figure 6, an eight-tone MW signal with 30MHz equal splittings is recorded. As a comparison, we measured the same signal simultaneously with a commercial spectrum analyzer (Rohde & Schwarz FSVR), shown in Figure 6 (b).

To investigate the frequency span of the current vapor cell (6mm along y-direction), we apply a three-tone signal with 250MHz spacings. In total, a bandwidth of 500MHz can be measured simultaneously, which represents the instantaneous analysis bandwidth of the current setup. It is limited by the size of the cell and the applied magnetic field gradient and can be significantly increased in an optimized design.

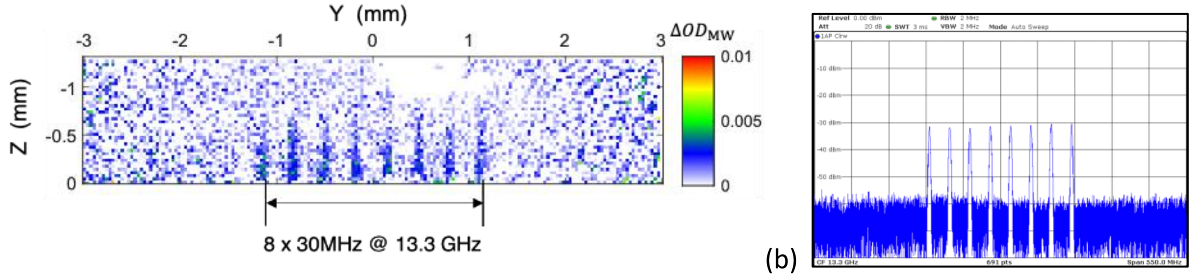


Figure 6: Eight-tone signal measurements. (a) ΔOD_{MW} image data; (b) measurement with a commercial SA.

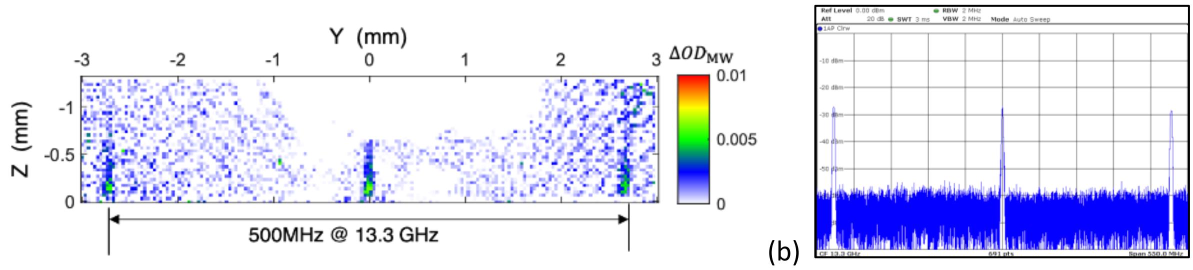


Figure 7: Measurement of the frequency span with a three-tone signal. (a) ΔOD_{MW} image data; (b) measurement with a commercial SA.

4 Summary and outlook

We have demonstrated an atomic microwave spectrum analyzer based on a MEMS atomic vapor cell. Using a magnetic field gradient, the frequency spectrum of the microwave signals of interest can be precisely mapped to the position-dependent fringe pattern on absorption images of the vapor cell. The frequency span in the current setup is around 500MHz, limited by the small size of the cell and the available magnetic field gradient. The frequency resolution is several MHz. With an optimized setup, we expect to obtain more than 30GHz frequency span at similar frequency resolution, which is promising for applications as a wide instantaneous bandwidth MW spectrum analyzer. Further improvements are possible, such as increasing the sensitivity with a thicker vapor cell, an optimized waveguide design that delivers the MW field to the atoms, and an improved imaging system.

5 References

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