Dynamical low-noise microwave source for cold-atom experiments

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The generation and manipulation of ultracold atomic ensembles in the quantum regime require the application of dynamically controllable microwave fields with ultra-low noise performance. Here, we present a low-phase-noise microwave source with two independently controllable output paths. Both paths generate frequencies in the range of 6.835 GHz ± 25 MHz for hyperfine transitions in ⁸⁷Rb. The presented microwave source combines two commercially available frequency synthesizers: an ultra-low-noise oscillator at 7 GHz and a direct digital synthesizer for radiofrequencies. We demonstrate a low integrated phase noise of 480 µrad in the range of 10 Hz to 100 kHz and fast updates of frequency, amplitude and phase in sub-µs time scales. The highly dynamic control enables the generation of shaped pulse forms and the deployment of composite pulses to suppress the influence of various noise sources.

I. INTRODUCTION

Atom interferometers belong to today’s most precise sensors with broad applications for navigation, geodesy, time keeping as well as fundamental research. An atom interferometric measurement relies on the determination of the phase difference between two atomic states. In many cases, these atomic states are hyperfine levels in alkali atoms. For magnetic field sensing or frequency measurements, the hyperfine transitions can be directly driven with microwave radiation. For inertial sensors, such as gravimeters, accelerometers or gyroscopes, the hyperfine transitions can be driven by a two-photon optical transition with a microwave frequency detuning. In analogy to optical interferometers, microwave pulses driving these transitions act as beam splitters or mirrors between the atomic states. Phase noise of the microwave is directly converted into fluctuations of the quantity of interest. For the future, we would like to operate the interferometers with microwave pulses of 10 µs length and free evolution times of several tens of milliseconds, such that a fluctuating phase is relevant from 10 Hz up to 100 kHz.

In our experiments, we create entangled many-particle states in Bose-Einstein condensates by spin-changing collisions.¹ The microwave source serves four purposes: The initial preparation of all atoms in a specific hyperfine/Zeeman level, the dressing of Zeeman levels to activate spin-changing collisions, the manipulation of the states in an interferometric protocol, and the final rotation of the state for detection and state analysis. These tasks pose the following requirements on the design of the microwave source.

Variable frequency. For the preparation of the atoms, a sequence of microwave pulses with variable frequencies is desired.

Low phase noise. The high-fidelity manipulation of the atomic states demands a microwave with small phase fluctuations, as the phase serves as the reference for all atomic measurements.² In our atom interferometric applications, the fluctuation of the microwave’s phase during the interferometric cycle is directly converted into fluctuations of the quantity of interest. For the future, we would like to operate the interferometers with microwave pulses of 10 µs length and free evolution times of several tens of milliseconds, such that a fluctuating phase is relevant from 10 Hz up to 100 kHz.

Low intensity noise. For tomographic measurements of the entangled states, the microwave should perform stable couplings between the employed spin levels. To resolve the expected patterns with single-particle resolution, the microwave must offer spin rotations with a relative intensity stabilization ΔI/I < 2/N ≈ 0.02% that is stable for a typical measurement time on the order of one hour.

Fast dynamical adjustments. The spin preparation benefits from short microwave pulses that are executed closely after each other. Short pulses bear the advantage of a low sensitivity to small microwave detunings due to an increasingly broad peak in Fourier space. This is, however, not sufficient for an advantageous spectral distribution. Short pulses can lead to many side peaks in the Fourier spectrum if they are simple box pulses. This may lead to an unwanted population of neighboring levels. The entire width of the spectrum can be drastically reduced by applying tailored pulse shapes instead of rectangular pulses. Pulse shaping requires a microwave amplitude modulation below the microsecond scale and the short pulse durations can only be realized by a source with sufficient microwave power.

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tion of frequency, phase and intensity enables the application of composite pulses, which can be designed to suppress the sensitivity to various technical noise sources.

Intensity-stable dressing field. Finally, we wish to apply an independent microwave dressing field during the experimental sequence to achieve precise control of individual energy levels. This application is particularly sensitive to fluctuations of the microwave field’s intensity because the desired energy shift depends linearly on the power of the microwave signal. Hence, a stable microwave power is desired for quasiadiabatic state preparation by ramped microwave dressing, as we use it for the generation of highly entangled twin-Fock states. Typically, for a 1G magnetic field, we shift the $|F = 1, m_F = 0\rangle$ level via microwave dressing by 72 Hz. For high-accuracy adiabatic generation, we require minimal frequency fluctuations of 10 mHz over typical ramping times of a few seconds, corresponding to microwave intensity fluctuations of 10 mHz/72 Hz = 0.014%. In summary, our experiments require a microwave source with amplitude, frequency and phase modulation in the microsecond range, low phase fluctuations and an independent, stable microwave dressing field.

There exist commercial frequency generators in the microwave regime that allow for a dynamical adjustment of frequency and amplitude. However, these systems typically lack an independent adjustment of the phase or suffer from slow update speeds in the millisecond range. There are important scientific developments towards microwave sources with minimal phase fluctuations, which serve as local oscillators for microwave clocks. Here, we present a microwave source with low integrated phase noise of 480 μrad in the 10 Hz to 100 kHz bandwidth. The microwave frequency is derived from a commercial 7 GHz source and a DDS, which controls frequency, amplitude and phase with high accuracy.
the control system ARTIQ\textsuperscript{19} enables single-parameter updates within 712 ns. The setup does not comprise self-built components and fits into a 19 inch rack. The source consists of two independent DDS-controlled channels, which can be applied for two-photon transitions or for a background dressing field. The described microwave source thus offers the ability to control atomic spins with highest fidelity on short time scales, and the simultaneous application of a dressing field.

The article is organized as follows. Section II covers the system design and the installed components. In Section III we characterize the system regarding phase noise and dynamic features. Finally, we summarize our findings and outline the future application of the system in our spin-squeezing experiments.

II. SYSTEM DESIGN

Figure 1 shows a schematic of the final design of our microwave source and Fig. 2 the corresponding picture. The basic idea is to combine the low phase noise of a multiplied crystal oscillator with the dynamic properties of an FPGA-controlled DDS. Our design presents an easy-to-assemble setup with commercial components\textsuperscript{20} and very low phase noise and our implementation opens up highly dynamical features.

An ultra-low-phase-noise oscillator Wenzel MXO-PLD is used as local oscillator. It provides a stable microwave frequency at 7 GHz through integrated multiplication of a fundamental 100 MHz oscillation, which is accessible through an additional output. The oscillator also has the option of an external reference, which is currently not used in our setup.

For the dynamic parameter change of the radiofrequency component, we employ the commercially available DDS module Urukul\textsuperscript{21}. This module contains four Analog Devices AD9910 DDS chips and associated radiofrequency components for adequate filtering, variable attenuation and switching. Control over the DDS module is achieved by the FPGA module Kasli. A digital I/O module DIO BNC offers the possibility for triggered execution and controlling additional components such as microwave switches. All three modules are part of the Sinara ecosystem and can be bought commercially as a preconfigured device. The DDS module features four independently controllable radiofrequency channels with an adjustable frequency of up to 400 MHz. All channels share a common reference of 1 GHz, given by the local oscillator’s 100 MHz multiplied by 10. The 1 GHz frequency reference allows for direct clocking of the DDS channels. Compared to the case of indirect clocking, where the 1 GHz clock is generated by internally multiplying the local oscillator’s 100 MHz in the DDS module, we measured an improved phase noise performance of 100 µrad. For the microwave source, two of these DDS outputs operate the two individual microwave output stages. In addition to frequency setting, the amplitude and also the phase offset for absolute phase control can be defined (Tab. 1).

For our \(^{87}\text{Rb}\) atoms, we have to apply frequencies at \(f_{\text{Rb}} = 6.835\) GHz with a tuning range of \(\pm 5\) MHz to account for the employed magnetic fields. In both output channels, the frequency is reached by mixing a shared local oscillator (LO) signal at \(f_{LO} = 7\) GHz with an individual DDS frequency of \(f_{\text{DDS}} = 165 \pm 5\) MHz. The lower sideband after the mixing presents the desired resonant frequency at \(f_{\text{Rb}} = f_{LO} - f_{\text{DDS}}\). The two output stages for pulses and dressing include final amplifiers to obtain powers of 40 W and 10 W, respectively.

For the mixing process, a Marki Microwave SSB-0618 single sideband mixer and a Mini Circuits ZMX-8GLH mixer are used for the pulse path and the dressing path, respectively. The single sideband mixer in the more critical channel is used to lower the unwanted peaks at the local oscillator frequency \(f_{LO}\) and the upper sideband at \(f_{LO} + f_{\text{DDS}}\). A narrow Wainwright WBCQV3 bandpass filter with a passband of 20 MHz and 50 dB attenuation for frequencies of \(\pm 250\) MHz from the center frequency enables the reduction of the LO and the upper sideband level in both channels.

Directly after mixing, the pulse and dressing paths measure maximally \(-7.5\) dBm and \(-6.5\) dBm, respectively. Low-noise pre-amplifiers Mini Circuits ZX60-83LN-S+ raise the signal to the desired 0 dBm input for the high-power amplifiers.

Because the internal power switch of the DDS channel

| Parameter | Bits | Range       | Resolution |
|-----------|------|-------------|------------|
| Frequency | 32   | 0 – 400 MHz | 230 MHz    |
| Amplitude | 14   | 0 – 100%    | 0.006%     |
| Phase offset | 16 | 0 – 2π rad | 96 µrad    |

TABLE I. Specification of the adjustable parameters of the DDS. The frequency range is given such that the attenuation due to the reconstruction filter is maximally 3 dB. For a maximum attenuation of 1 dB, the upper frequency bound is 320 MHz.
Phase noise [dBc/Hz]  
Power [dBm]  
-170  -140  -110  -80  -60  -40  -20  0  20  40  
-80  -60  -40  -20  0

FIG. 3. Spectrum of the microwave source for the dressing path (dark blue) and the pulse path (light blue), where the measured power in dBm is plotted as a function of the microwave frequency. The main difference of the two paths is the maximum power and the suppression of the LO frequency as well as the upper sideband. In the inset, the relevant frequency range is presented in more detail. Both spectra have been measured with a resolution bandwidth of 10Hz.

only offers a maximal attenuation of 31.5dB, the source is equipped with additional power switches Mini Circuits ZF3WA2-63DR+ with 25ns rise/fall time and an attenuation of 40dB. The employed switches – designed for frequencies up to 6GHz – are a cost-effective solution, coming with disadvantages of larger insertion loss and reflections. The insertion loss is compensated by the pre-amplifiers. Isolators prevent unwanted back reflections in general, and are installed in front of the switches and the antenna, as well as behind the local oscillator.

For the amplification of the pulse path, a water-cooled 40 W amplifier Microwave Amps AM43 is employed. The amplifier in the dressing path is a Kuhne KU PA 640720-10 A with an output power of 10W. The pulse path contains a −30dB dual directional coupler RF-Lambda RFDDC2G8G30 for monitoring the output power and the power that is reflected from the antenna. A −20dB directional coupler MCLI C39-20 after the dressing amplifier allows for monitoring the dressing power. For addressing the atoms, the microwave frequency is coupled to free space by an impedance-matched, open-ended waveguide. In the following section, the performance of the described microwave source is evaluated.

III. CHARACTERIZATION

A. Spectral properties

First of all, we examine the spectrum of the microwave source to quantify the suppression of disturbing frequencies, that could drive unwanted transitions, resulting in decreased efficiency of the state preparation. Figure 3 shows the spectrum of our microwave source for both the dressing path and the pulse path with a chosen output frequency of 6.835GHz. The spectrum was recorded with a Rohde&Schwarz FSWP8 phase noise and spectrum analyzer.

The unwanted frequency contributions close to the main peak are caused by the DDS, while the two peaks at 7GHz and 7.165GHz are residuals of the local oscillator frequency and the upper sideband of the mixing process. Both of these peaks are suppressed by the narrow bandpass filter: For the pulse path, the local oscillator and the upper sideband peak are suppressed by 69.8dB and 87.9dB, respectively. For the dressing path, the suppression is 79.5dB and 70.3dB due to the different choice for the frequency mixer.

Because of the bandpass filters, the peak power slightly varies with the frequency of the microwave source by about ±0.2dB in the relevant frequency range of 6.835GHz ±5MHz and ±1dB for 6.835GHz ±25MHz. The small effect in the relevant range can be calibrated and the power can be adjusted by the ARTIQ software.

Furthermore, we evaluate the phase noise \( \mathcal{L}(f) = \frac{1}{2} S_\phi(f) \), where \( S_\phi(f) \) is the one-sided spectral density of phase fluctuations and \( f \) is the offset frequency from the carrier. A low phase noise is desired for a high-fidelity state preparation and manipulation (Section II). Figure 4 shows the phase noise contributions for the microwave source, measured for an output frequency of 6.835GHz with the Rohde&Schwarz FSWP8. The colors of the lines correspond to different measurement points in the system, as visualized in Fig. 1.

The phase noise of the two microwave output signals is very
similar, although they follow different amplification paths.

The overall phase noise is limited by the DDS for frequencies from 2kHz up to 20kHz and by the local oscillator for all other frequencies. It is below $-120\text{dBc/Hz}$ above 350Hz and below $-130\text{dBc/Hz}$ for frequencies greater than 2.5kHz, and approaches a floor of $-140\text{dBc/Hz}$ at high frequencies. The small peak at 16kHz stems from residual DDS noise, and may originate from power supply noise. For both paths, we obtain a favorably small integrated phase noise of $\Delta\Phi = 480\text{µrad}$ in the important range of 10Hz to 100kHz (Section I), which provides the central figure of merit of the constructed microwave source.

With a reference connected to the local oscillator, the long-term stability could be improved and therefore the phase noise for small frequency offsets could be decreased.

The amplitude (AM) noise $S_a(f)$ of the presented microwave source is also measured and shown in Fig. 5. Because the amplitude noise is important also for very low offset frequencies and measurements in that range have a very long duration, high sensitivity limits had to be accepted as a consequence. Hence, the amplitude noise of the microwave source can only be given as an upper bound. For the bandwidth of 278µHz (measurement duration of one hour) to 100kHz, it evaluates to an integrated AM noise of 0.015% and therefore an intensity noise of $\Delta I / I = 0.03\%$. It is thus in the desired order of magnitude to achieve Heisenberg-limited resolution.

B. Dynamic features

The dynamics of the microwave source is controlled by the ARTIQ system which is connected to a computer via an optical fiber and a LAN switch. The commands are implemented on the computer in the Python programming language but compiled and executed on the FPGA hardware, thereby allowing for a minimal timing resolution of 4ns. The code generating our experiments is available online.

The AD9910 DDS chip in the Urukul module also provides a 1024x32 bit random-access memory (RAM) to retrieve and output different waveforms that are designed by the user. It is possible to program frequency, amplitude, phase or polar (amplitude and phase) nonlinear ramps with a step width of 4ns into one out of eight profiles. For our purposes, time-independent amplitude functions are used to reduce the effective Fourier width (Fig. 6) and the coupling to unwanted transitions. For the dressing scenario, adiabatic power ramps ensure that the system remains in the desired dressed state.

The phase of the microwave signal is deterministically referenced to the local oscillator phase in a coherent way. This allows for composite pulse techniques, where one single pulse is replaced by a sequence of pulses with different phases, amplitudes and durations to reduce the impact of various noise sources. Figure 7 shows a so-called Knill sequence that reduces sensitivity to both intensity and frequency fluctuations. Besides the phase setting, it is advantageous for this technique to execute the pulses in quick succession to avoid unwanted fluctuations during the dead times. Updates of parameters like frequency or phase require 712ns in our implementation. This corresponds to a minimal pulse duration of a few µs when two totally different pulses should be executed.

\[ \Delta I / I = 0.03\% \]

\[ \Delta\Phi = 480\text{µrad} \]

\[ S_a(f) \]

\[ AD9910 \]

\[ Urukul \]

\[ DDS \]

\[ ARTIQ \]

\[ Python \]

\[ RAM \]

\[ AD9910 DDS chip \]

\[ Urukul module \]

\[ 1024x32 bit \]

\[ random-access memory (RAM) \]

\[ coherent way \]

\[ composite pulse techniques \]

\[ Knill sequence \]
FIG. 8. Phase control of the radiofrequency source. At the top, a Blackman-shaped pulse is shown. The pulse was implemented in a way that the phase is changed in the middle of the pulse. A detailed view is shown at the bottom. The dots correspond to the measured data points, the red lines are a guide to the eye. The grey line indicates the extrapolation of the first half of the pulse, confirming the phase change of half a turn.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts to disclose.

AUTHOR CONTRIBUTIONS

Bernd Meyer-Hoppe: Conceptualization (lead); Investigation (lead); Software (supporting); Visualization (lead); Writing - Original Draft Preparation (equal); Writing - Review.
& Editing (equal). **Maximilian Baron**: Investigation (supporting); Software (lead); Visualization (supporting); Writing – Review & Editing (equal). **Christophe Cassens**: Investigation (supporting); Writing – Review & Editing (equal). **Fabian Anders**: Conceptualization (supporting); Supervision (supporting); Writing – Review & Editing (equal). **Alexander Idol**: Conceptualization (supporting); Supervision (supporting); Writing – Review & Editing (equal). **Jan Peise**: Conceptualization (supporting); Supervision (supporting); Writing – Review & Editing (equal). **Carsten Klempt**: Conceptualization (lead); Funding Acquisition (lead); Supervision (lead); Writing – Original Draft Preparation (equal); Writing – Review & Editing (equal).

**DATA AVAILABILITY**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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