An efficient high-current circuit for fast radio-frequency spectroscopy in cold atomic gases

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We design and implement an efficient high-current radio-frequency (RF) circuit, enabling fast and coherent coupling between magnetic levels in cold alkali atomic samples. It is based on a compact shape-optimized coil that maximizes the RF field coupling with the atomic magnetic dipole, and on coaxial transmission-line transformers that step up the field-generating current flowing in the coil to about 8 A for 100 W of RF power. The system is robust and versatile, as it generates a large RF field without compromising on the available optical access, and its central resonant frequency can be adjusted in situ. Our approach provides a cost-effective, reliable solution, featuring a low level of interference with surrounding electronic equipment thanks to its symmetric layout. We test the circuit performance using a maximum RF power of 80 W at a frequency around 82 MHz, which corresponds to a measured Rabi frequency $\Omega_R/2\pi \approx 18.5$ kHz, i.e. a $\pi$-pulse duration of about 27 $\mu$s, between two of the lowest states of ${}^6$Li at an offset magnetic field of 770 G. Our solution can be readily adapted to other atomic species and vacuum chamber designs, in view of increasing modularity of ultracold atom experiments.

I. OVERVIEW

Over the past two decades, the ability to coherently manipulate the internal state of atoms and molecules has proven an essential tool in the field of precision measurements, as well as for the realization of ultracold synthetic matter and atomic quantum simulators of important many-body problems. In particular, a key experimental probe of many-body physics in ultracold atomic systems is radio-frequency (RF) spectroscopy, by which an applied RF pulse is used to couple atoms from one hyperfine state to another unoccupied state. Addressing the RF transitions that connect hyperfine sublevels with different interaction properties allows for accessing the spectral properties of elementary excitations in Fermi- and Bose gases, as well as fundamental thermodynamic quantities. In this context, a significant demand is the implementation of strong coherent RF drives, which are especially important to precisely trigger and probe non-equilibrium many-body dynamics governed by short-range interactions, tuned through Feshbach resonances upon varying a static magnetic field applied to the sample.

In quantum degenerate Fermi gases, a natural time scale $\tau_F = h/\epsilon_F$ is set by the Fermi energy $\epsilon_F$ of the system, where $h$ is the reduced Planck constant $h/2\pi$. The dynamics at short times $t$ are expected to be universal, revealing the emergence of elementary excitations in real time, and serving as a valuable benchmark for many-body theories. In order to experimentally investigate such ultrafast dynamics in ultracold Fermi gases, it is necessary to control the spin state of the atoms over time scales on the order of $\tau_F$, whose typical values range between 5 $\mu$s and 50 $\mu$s depending on the experimental sample density and atomic mass. The experimental time resolution in controlling the atomic spin state is set by the Rabi frequency $\Omega_R$, characterizing the strength of the coupling between an external electro-magnetic (EM) field and the dipole moment associated with the atomic spin. For a given dipole moment, the only way to increase $\Omega_R$ is to increase the amplitude of the driving field experienced by the atoms. At the same time, it is important that the circuit generating the RF field does not perturb the sensitive electronics within the surrounding apparatus. This makes the realization of quiet and efficient RF systems a priority in cold atom laboratories. Moreover, as experimental setups become more complex, including large-aperture imaging systems and multiple laser beams, critical space constraints call for unobtrusive and versatile RF circuit designs.

Here we present the design and implementation of a flexible, compact and low-cost high-current circuit for efficiently coupling a large RF magnetic field to the spin of alkali atoms, whose transitions within the ground-state manifold typically lie in the 10–200 MHz range, allowing for spin manipulations with $\Omega_R \sim \epsilon_F/h$. Significant complexity results from the fact that atomic samples are trapped inside a ultra-high vacuum chamber by laser light potentials, and are subject to a strong static magnetic field $B_0$ produced by Feshbach electromagnets. Fulfilling all design requirements, the realized system shows an excellent electronic performance, in agreement with simulations. It has been tested in a typical application case by driving the transition between two ground-state magnetic sublevels of lithium atoms, characterized by a frequency $\nu_0 \approx 82$ MHz. Moreover, it features a very low level of interference with nearby laboratory electronic equipment, as demonstrated by an observed static B-field fractional stability of about $10^{-5}$ for $B_0 \approx 770$ G. The paper is organized as follows: in Section II, we describe our approach to the RF circuit design and its main advantages with respect to common solutions, and we present the realization of the different components of the RF circuit, namely the coil, the matching network and the transmission-line transformers; in Section III, we report on the characterization of the system performance with an ideal Fermi gas of lithium atoms; in the concluding Section, we summarize and provide some outlook.

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II. THE CIRCUIT

A. Essentials of atom spin interactions with RF fields

Energy shifts between hyperfine levels of an alkali atom depend on the applied static magnetic field, which sets the quantization direction $z$, and within the $J = \frac{1}{2}$ ground-state manifold they can be precisely computed through the Breit-Rabi formula.$^{23,24}$ Since transitions between hyperfine levels or Zeeman sublevels are electric-dipole forbidden, they have an extremely narrow natural linewidth, notably exploited for atomic clocks. External magnetic fields interact with the atom only through the magnetic dipolar interaction.$^{23,24}$ In the case of ground-state Zeeman sublevels, the energy splittings for typical $B_0$ values correspond to RF frequencies $\nu_0$ in the so-called very high frequency (VHF) range, roughly between 10 and 100 MHz, making RF magnetic fields the simplest method to couple different levels with one another.

Let us consider both static and RF magnetic fields that are spatially homogeneous over the scale of the atomic sample, and that the RF field is linearly polarized. We may define the static offset field as $B_0 = B_0 \hat{e}_z$, and focus on a pair of adjacent magnetic sublevels, split by an energy $\hbar \omega_0$ associated with $B_0$. These realize an effective atomic spin-1/2 system, as they coincide with the eigenstates $|m\rangle$ of the spin projection $S_z$ along the quantization axis.$^{25}$ The interaction of an atomic spin $S$ with a RF magnetic field $B_{RF}(t) = B_{RF} \cos(\omega t + \varphi) \hat{e}$ is given by $V_{RF} = \mu B_{RF} \cos(\omega t + \varphi) S \cdot \hat{e}$, where $\mu$ is the magnetic moment of the atomic spin$^{23}$, $\varphi$ is the field phase offset, and $\hat{e}$ is the RF B-field polarization unit vector. In order to couple the two $|m\rangle$-levels with one another, the RF field polarization must have non-zero projection in the $x - y$ plane, and its frequency must be close to resonance$^{23,24}$, i.e. $\omega = 2\pi\nu_0$. This is the principle behind the phenomenon of nuclear magnetic resonance (NMR). Taking now $\hat{e} = e_y$ to maximize the coupling $V_{RF}$, we can define the Rabi frequency $\Omega_R = \mu B_{RF}/(2\hbar)$, characterizing the oscillation of populations between the two atomic levels.$^{23,26}$ The coupling strength of the RF field with an atomic spin is therefore proportional to its magnetic moment, which is fixed by the atomic isotope and the static offset field, and to the amplitude of the RF field component orthogonal to the quantization axis. The main objective of our design is maximizing the latter quantity for a given set of spatial constraints.

B. Design constraints

Atomic physics experiments require a RF B-field having the largest feasible amplitude within the sub-mm region of space occupied by the atomic sample. In many setups, atoms are however shielded inside a metallic vacuum chamber, which has only a few optical apertures. A pair of reentrant glass viewports located at cm-distance from the atoms is often included, to grant large optical access for laser beams and high-resolution imaging optics, representing also the best location where to place a RF field applicator. The RF frequency range of atomic hyperfine transitions, e.g. $\nu_0 \approx 80$ MHz for the ground-state transitions of lithium atoms, combined with the typical dimensions of the viewports and their distance from the sample, determine working conditions characteristic of magneto-quasistatic fields.$^{27}$ In our apparatus, the reentrant viewports have a diameter of about 60 mm and their outer glass surfaces are situated at a distance of 20 mm from the sample – to be compared with RF wavelengths of at least few meters. The standard emitter to generate such quasistatic field at the near-field location of the atomic sample consists of a small coil of conductive wire. The amplitude $B_{RF}$ in the near-field is proportional to the current flowing in such inductive loop$^{27}$, which must be placed as close as possible to the sample, considering that the field strength of a magnetic dipole decays with the cubed distance.

A possible strategy to minimize the distance between the RF coil and the sample, and to optimally orient the generated B-field polarization $B_{RF} \perp B_0$, is to accomodate the coil inside the vacuum chamber. This solution has recently become somewhat more common, but must obviously be planned...
C. Circuit concept and design

A common approach for maximizing the B-field is to maximize the power transfer from the RF generator towards the coil via impedance matching, by interposing a suitable network of elements between the generator and the coil\textsuperscript{35-37,39,40}. However, a coil with such small dimensions has a tiny radiation resistance of a few tens of m\(\Omega\) at most for VHF frequencies, much smaller than its own loss resistance on the order of 1 \(\Omega\), and negligible with respect to the 50 \(\Omega\) output impedance of the generator. Matching the impedance of the generator is thus practically infeasible, potentially leading to damage of the generator, unless one resorts to resistive elements which limit the transmitted current. Since the B-field hinges on the current, this approach increases the required amplifier output and it is not scalable to achieve a large \(B_{\text{RF}}\). Moreover, widely different loads entail very high currents and voltages across the LC elements of the interposed matching network, leading to power losses\textsuperscript{32}. It is also important to note that, in the absence of intended resistive loads, matching the circuit impedance to the 50 \(\Omega\) of the generator effectively means to transfer the RF power to the resistive losses of the coil and matching network. As a consequence, this approach eventually leads to the destruction of the matching network whenever the RF generator is turned on at sufficiently high power for a time exceeding a few milliseconds, because LC elements are not intended for efficient dissipation. Finally, since the matching network must be placed at the location of the coil inside the reentrant viewport in order to avoid that the feedline becomes part of emitter, it is highly impractical to adjust the resonant frequency of the circuit in situ, as this location is usually inaccessible.

Rather than attempting to match the field-emitter to the 50 \(\Omega\) output impedance of the generator, we follow a different approach aimed essentially at maximizing the field-generating current in the coil\textsuperscript{33}. The basic underlying idea is to dissipate the RF power into an impedance-matched dummy load, and to interpose the coil between the generator and the load, such that the high current flowing to the load flows entirely through it, as part of a low-impedance transmission line. This concept has the additional benefit of facilitating a symmetric circuit design, which prevents undesired common-mode currents flowing on the feedline. Further, with a required generator power on the order of 100 W, our design has advantages in terms of generator cost, laboratory compatibility and reduction of the thermal stress of the entire system.

The main blocks are illustrated in Fig. 1(a), where we can see five cascaded elements: (i) RF generator with an output impedance of 50 \(\Omega\); (ii) a step-down transformer towards a lower impedance to raise the current in its “secondary” side\textsuperscript{34}; (iii) a matching network that compensates the self-inductance of the coil; (iv) a step-up transformer to match a load with 50 \(\Omega\) impedance; (v) a 50 \(\Omega\) dummy load that receives and dissipates the majority of the generator power. As seen from the generator, the load has a 50 \(\Omega\) impedance. As we will describe in the following, our design realizes the following relevant goals: (a) achieving a large RF coupling \(\Omega_B\) with the atomic spin for the given available generator power; (b) allowing simple adjustment of the central frequency by a single component situated sufficiently far from coil, and wide bandwidth so to require minor tuning; (c) realizing non-critical matching and stable operation over time under temperature or mechanical deformations; (d) good mechanical and electrical robustness; (e) Electromagnetic compatibility (EMC) compliance to avoid as much as possible RF dispersion in the laboratory\textsuperscript{35}, causing undesired interference effects such as audio rectification\textsuperscript{36}.
D. The coil

A high B-field can be obtained with a coil consisting of several turns, but the self-inductance rises with the square of the number of turns. High values of the self-inductance yield a reactance that is difficult to compensate. In addition, as described previously, the generated field must be polarized orthogonally to the atom quantization axis z, i.e., $\mathbf{B}_{RF} \perp \mathbf{B}_0$. Since $\mathbf{B}_0$ is produced by strong electromagnets also installed in the reentrant viewports, z is directed to the viewport surface. We have considered various three-dimensional loop shapes, fulfilling the constraint of preserving a large optical access to the viewport, ranging from tilted ellipses to off-centered asymmetric profiles. The best trade-off was found with a two-turn loop shaped as a half-annulus, as depicted in Fig. 2(a), improving upon previously reported bean-shaped loops. This planar coil geometry maximizes the field component orthogonal to $\varepsilon_z$ [see Fig. 2(b)] for the fixed minimum distance between the atoms location and the coil. Moreover, as the generated field is almost fully polarized in the $x$-$y$ plane, it is nearly homogeneous over several millimeters around the atomic sample location, rendering the design robust to manufacturing imperfections. The coil has been realized using the same coaxial cable used for transmission-line transformers (see next paragraph). Using coaxial cable is not essential, as RF currents flow only on the braid and the central conductor is inactive, but it simplifies the construction and makes it reliable even for high powers.

E. Circuit implementation and simulation

The circuit is implemented according to the schematic in Fig. 1(b). Figure 3 shows a simulation of the whole circuit carried out with the Qucs software, which guided the choice of the actual components and parameters. To match the impedance from 50 $\Omega$ (generator) to a lower value suitable to increase the current in the coil, a $\lambda/4$ transmission-line transformer has been used. The relationship between the characteristic impedance of the line $Z_0$, and the impedances seen at the input side $Z_{in}$ and output side $Z_{out}$ of the transformer is given by:

$$Z_{out} = \frac{Z_0^2}{Z_{in}}$$

Thus, to have a large impedance variation towards lower values, it is necessary to have low-impedance transmission lines. Lines with characteristic impedance between 10 $\Omega$ and 75 $\Omega$ are available, but for simplicity we have chosen to use only 25 $\Omega$ coaxial cables. Using two 25 $\Omega$ coaxial cables in parallel (or equivalently four 50 $\Omega$ cables), has approximately the same effect of using a single 12.5 $\Omega$ cable, with the added advantage of power sharing between different cables, such that small ones can be used. With this choice, the impedance seen after the transformer towards generator is ideally 3.125 $\Omega$, namely 16 times lower than the original value such that the current is 4 times higher. More dramatic impedance reductions are feasible by adding further cables in parallel, but parasitic resistances of a few 100 m$\Omega$ of the coil (skin effect) and solder connections become a limiting factor.

The matching network, which includes series capacitors and 25 $\Omega$ coaxial cables and incorporates the coil, serves to cancel the inductive reactance of the coil itself. The 25 $\Omega$ cable sections also facilitate the installation and the manual capacitance tuning in the intricate environment close to the experimental chamber. After the last (tunable) capacitor C1, another $\lambda/4$ transformer rises again the impedance from 3.125 $\Omega$ to 50 $\Omega$, matching that of the dummy load. As can be seen from simulations shown in Fig. 3, in addition to a good matching, the current $I_1$ is greatly increased compared to what would be obtained using simply a 50 $\Omega$ generator giving 100 W, over a relatively wide frequency bandwidth of about 10 MHz. Other graphs show the voltages $V_1$ and $V_2$ across capacitors C1 and C2, which are well below the maximum working voltage of ceramic capacitors such as the ATC 100B series.

In our simulations, the coil has been modeled as a LR series,
whose values are based on vector impedance measurements of the actual coil build [see Fig. 2(c)]. Given the low RF frequencies involved and the small dimensions, no parasitic resonance was observed, so the model turned out to be particularly simple – no parallel capacitance is included. As described in the following paragraphs, measurements and simulations are in close agreement.

F. Realization

Figure 4 shows a sketch of the realized circuit. We opted to use an extra transmission-line section of 180 mm length, to reach the vacuum viewport of the experiment while keeping the tuning capacitor C1 at reach. The system is built using a \( Z_0 = 25 \Omega \) coaxial cable (QAXIAL RG316/25-FLEX) with non-magnetic conductors and high-power handling of \( \sim 500 \text{ W at 80 MHz} \), and high-voltage porcelain multilayer SMD capacitors from American Technical Ceramics (ATC 100B series, non-magnetic). All ATC capacitors are able to withstand 1 kV. To hold the coil in shape, a plastic support has been realized with a 3D printer, increasing the robustness of the system and facilitating the insertion of the coil in the vacuum viewport mechanic clearance. The step-down and step-up transformers are realized using two couples of 620 mm-long coaxial sections, corresponding to \( \lambda/4 \) segments at 80 MHz. The matching network includes: (i) Capacitors C2 and C3, used to create a matching between the loop and the line; (ii) A pair of coaxial cables with characteristic impedance \( Z_0 = 25 \Omega \) which link the C2/C3 board to the network matching (and tuning) board; (iii) Capacitors C1 and C4, realized with 2 fixed capacitors and a tunable trimmer capacitor, necessary for finely tuning the resonance frequency. The latter is implemented by an air dielectric trimmer capacitor from Johnson Technology, with a voltage rating of 500 V, a capacitance range of 1 pF – 30 pF and a Q-factor > 800 at 100 MHz.

III. CIRCUIT PERFORMANCE

A. Electrical network measurements

The measurement phase started with the characterization of the coil impedance to determine the actual L and R parameters to input in the circuit model. The matching network has been designed, realized and tested on the workbench. Subsequently, the coil has been inserted in the viewport and the complete system tested in situ. Illustrative measurements performed with a vector network analyzer (VNA) are shown in Fig. 4(b)-(c). The circuit resonant frequency can be shifted over a range of about 2 MHz varying the value of C4 by 30 pF without visibly reducing the impedance matching.

B. Testing the system on atomic samples

We have tested the system in our experiment with ultracold degenerate gases of fermionic lithium atoms\(^2,19\). We have addressed the transition between the second-lowest and third-lowest magnetic sublevels of \(^6\text{Li} \) ground state, usually labeled \( |2\rangle \) and \( |3\rangle \), respectively. In the experiment, offset fields in the range \( B_0 \approx 570 \text{ G} – 900 \text{ G} \) are used\(^2\), covering the position of two broad Feshbach resonances at 690 G and 832 G between states \( |2\rangle \) and \( |3\rangle \), and the lowest hyperfine level \( |1\rangle \). For such \( B_0 \) values, nuclear and electron spins of the atom are largely decoupled\(^2\), and the spin system formed by states \( |2\rangle \) and \( |3\rangle \) has a low magnetic moment \( |\mu_L|/\hbar \lesssim 10 \text{ kHz/G} \) (still about 10 times larger than the nuclear magnetic moment \( \mu_N \approx \mu_B/1836, \) with \( \mu_B \approx 1.4 \text{ MHz/G} \)).

A spectroscopic measurement of the \( |2\rangle \leftrightarrow |3\rangle \) transition in an ideal (spin-polarized) degenerate Fermi gas at \( B_0 \approx 770 \text{ G} \) is displayed in Fig. 5(a). A sinc-shaped line centered around 82 MHz is observed, associated with the 1 ms-long square pulse at 50 mW of RF power, used for the spectroscopic transfer shown here. A spectral stability below 100 Hz is observed during several minutes necessary for a full spectroscopic measurement, corresponding to an offset B-field stability below 10 mG, or a fractional stability around \( 10^{-5} \).

In order to benchmark the performance of our RF system at high power, we have performed Rabi oscillation measurements at the measured resonance of the \( |2\rangle \leftrightarrow |3\rangle \) transition. Illustrative results are displayed in Fig. 5(b)-(c), where a coherent sinusoidal evolution of the state populations is visible for two different driving powers. The intrinsic lifetime of the hyperfine states is much longer than the typical measurement time scales, guaranteeing that visible damping originates only from dephasing from magnetic field fluctuations. Since no measurable damping is observed over the time scales of the evolution, we conclude that our RF setup does not significantly influence the surrounding electronic equipment, used to actively stabilize the value of \( B_0 \) (comprised of current transducers, analog PID loops, and DC regulated power sup-
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DATA AVAILABILITY STATEMENT

ACKNOWLEDGMENTS

IV. CONCLUSIONS

In this paper we have described an alternative approach to the generation of quasistatic RF magnetic fields for atomic physics experiments. This provides an efficient, low-cost and uncomplicated solution to achieve large coupling strength with atomic spins, without introducing detrimental disturbances or reliability issues. In principle, the realized circuit is able to withstand short pulses with larger RF power $P > 100 \, \text{W}$, further increasing the maximum Rabi frequency.

Our design can be readily adapted to address relevant transitions between adjacent magnetic sublevels of other fermionic and bosonic alkali atomic species, such as K, Rb, Na or Cs, with frequencies lying in the 10–200 MHz range, and to different optical apertures or positioning constraints – possibly also for in-vacuum coils, where tilted or deformed circular loops may be considered. For frequencies exceeding 200 MHz, the RF coil features a typical radiation resistance around $1 \, \Omega$, and thus its behavior crosses over to that of a small-loop antenna, for which the radiated power becomes significant. We believe our system may constitute a standard solution for RF field coupling to alkali atom spins in forthcoming experimental setups, where large optical access and modularity have nowadays become a must.

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DATA AVAILABILITY STATEMENT

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

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