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Estimation of RF voltage on the ion trap through a capacitive voltage divider

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Abstract

Three-dimensional confinement of charge particles within a radiofrequency (RF) ion trap is achieved using an oscillating electric field (RF) along with the static field. The combination of DC and the RF field provides the force gradient to confine the ion to the saddle point of the quadrupole shaped spatial distribution of the electric field. Helical resonators are commonly used for efficient delivery of high voltage RF to the trap electrode. In order to achieve better control on the trapped ions, its essential to know the amplitude of the RF voltage being delivered at trap electrodes. This article describes the design and development of a capacitive voltage divider circuit for analyzing high voltage RF being delivered to the ion trap through a helical resonator. The voltage divider is connected parallel to the ion trap to access a minor fraction of voltage being delivered at the trap electrodes (with a ratio of 1:1000) to detect the value of high voltage being delivered to the ion trap.

1. Introduction

Atomic ion trapped and laser cooled within a radiofrequency ion trap attracted an immense interest in recent times for their potential applications towards developing several state-of-the-art quantum technologies[1]–[3]. Trapped and laser cooled ions are being used for quantum information processing, quantum computation and quantum simulation, frequency standards, etc. Three-dimensional confinement of charge particles cannot be achieved using only static (DC) electric field[4], so an oscillating electric field (RF) along with the static field is applied for the above purposes. The combination of DC and the RF field provides the force gradient to confine the ion in the saddle point of the quadrupole shaped spatial distribution of the electric field. At CSIR-NPL work in progress towards developing an optical frequency standard based on a single trapped 171Yb ions where the ions are being trapped within a specially designed RF trap, commonly known as end cap type Paul trap[5]. This Paul trap has two inner rod electrodes surrounded by two concentric tube as end cap electrodes and these rod electrodes are used for applying high voltage RF for creating oscillating electric field and the outer endcap electrodes are connected with DC voltages. DC voltage can be applied to those electrodes directly through a DC voltage source but for delivering high voltage RF to those electrodes many factors need to be considered,[6]–[9] like impedance of the trap and the source must be matched because impedance mismatching between source and load can damage the source through the reflected signal. The trapping potential generated through a RF ion trap for confining ions is given by

$$\Phi = \frac{\Phi_0(t)}{2r_0^2}(r^2 - 2z^2)$$

Here r_0 is the size of the ion trap, i.e., radius of the inner electrode and $\Phi_0(t) = U + V_0\cos\Omega(t)$ = is the amplitude of potential, this potential is the combination of both DC and Oscillating field. U, V_0, and Ω are the amplitude of DC voltage, amplitude of oscillating voltage and frequency of the oscillating voltage respectively. Average restoring force generated by oscillating electric field towards the center of the quadrupole trap with averaging field E_Ω at some radial distance r, is represented as:

$$U_{eff} = \frac{e^2 E_\Omega^2(r)}{4m\Omega^2}$$

The oscillating field of the Paul trap must be higher enough to trap the ions produced from the thermal atoms and this oscillating field is generated by the high voltage RF applied to the end cap electrodes, typically in the range of several hundreds of Volts and the frequency of oscillating field must be ranging from 5MHz to 25MHz for stable confinement of ions. Another key factor for confining the ions is the stability of the RF voltage, supplied for trapping those ions. The RF voltage delivered to the ion trap must be very stable in terms of frequency and amplitude for storing the ions over a long period of time. Helical resonators are commonly used for efficient delivery of high voltage RF to the trap electrodes.

2. Working Principle

Helical resonators are commonly used in ion trap experiments for delivering RF voltage of hundreds of volts to the trap electrodes. The resonance frequency of the helical resonator at unloaded condition mainly depends on its dimensional parameter like, length of the resonator, diameter of the helical coil and its number of turns etc. However, the resonance frequency of the resonator decreases as soon as it's connected with the ion trap because of its capacitive load and as a thumb rule the resonator is designed in such way that its resonance frequency at unloaded should be 1.5 times of the targeted resonance frequency, i.e., resonance frequency at loaded condition[10]. The resonant frequency of the resonator at loaded condition shows a dynamic change over a long period of time due to some environmental perturbation or movement of any conducting elements in nearby regions. For countering this dynamic shift of the resonant frequency and for delivering constant voltage of at the trap electrodes, the output voltage delivered through the resonator needs to be stabilized. In this stabilization technique the reflected signal from the resonator is monitored and the input RF frequence is tuned to achieve lowest reflected power. Although, this technique is quite feasible to transfer highest voltage to the trap electrodes. The exact value of the voltage delivered at the trap electrodes cannot be estimated through this technique, it only stabilizes the voltage relative to some unknown constant voltage by tuning the input RF frequency. So, we adopted another approach for estimating voltage delivered at the trap electrodes through a capacitive voltage divider. Since the load voltage of the ion trap plays a major role in defining the loaded resonance frequency of the helical resonator, the equivalent capacitance of the voltage divider connected parallel to the trap capacitance must be verry small so that it will not affect the resonance frequency of the resonator. The setup consisting of the helical resonator connected with the ion trap and the voltage divider connected is shown in fig 1(a). In this setup an RF source (Rhode & Schwarz hameg HM8134-3) is connected to connected to the primary coil of the helical resonator through an amplifier (Minicircuits ZHL-5W-1+). The output voltage of the helical resonator is connected to the end cap ion trap through an electrical feedthrough for delivering the desired high voltage RF. A capacitive voltage divider with very low equivalent capacitance compared to the trap capacitance is connected parallel to the ion trap from the output of the helical resonator. The output of the divider is connected to a spectrum analyzer (Rhode & Schwarz FSV40) at 50 Ω input impedance, as the complete setup is designed for 50 Ω impedance that no instability arises due to impedance mismatch. Fig 1(b) depicts the picture of the capacitive voltage divider without shielding and with shielding, here shielding is required to minimize the effects of external perturbations.

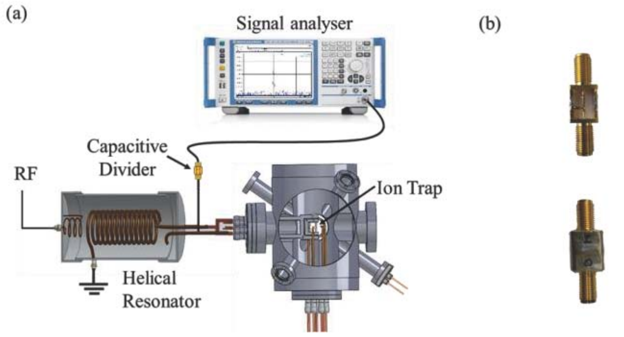

Fig 1. (a) The Schematic of the RF delivery setup consisting of the helical resonator, ion trap and a voltage divider connected to it. (b) picture of the capacitive voltage dividers without and with shielding of aluminum.

3. Capacitive voltage divider

A voltage divider circuit is used to get the value of the voltage delivered at the ion trap. In this scheme the divider circuit can make impact on the load voltage delivered by the helical resonator and will also affect the loaded resonance frequency. So, for this circuit we use capacitors which have very low equivalent series resistance and inductance. The equivalent capacitance of the divider circuit must be very low as compared to the trap capacitance. The schematic presentation of the divider circuit along with its connection in parallel to the ion trap has been presented in Fig 2. The specially designed ion trap used in this setup has already been characterized and has capacitance of 21.98 pF[11]. We are using Panasonic multilayer ceramic capacitors of ECU series as C1 = 1 pF (ECU-V1H010CCN) and C2 = 1000 pF (ECU-V1H102JCX) in the divider circuit as shown in Fig 2.

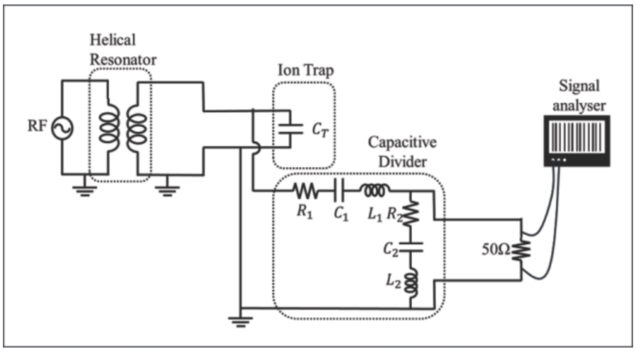

Fig 2: Schematic of the setup consisting of the voltage divider circuit connected parallel to the ion trap.

Considering C_T is the trap capacitance of 21.98 pF, a parallel voltage divider circuit is connect having resistance R_1 & R_2, capacitance C_1 & C_2, and inductance L_1 & L_2. The equivalent impedance of the voltage divider is:

$$Z_D = \left(R_1 + \frac{1}{i\Omega C_1} + i\Omega L_1\right) + \left(R_2 + \frac{1}{i\Omega C_2} + i\Omega L_2\right)$$

Here we have used the capacitors having verry low equivalent series resistance and inductance (ESR & ESL), so they have minimal effect of on the output impedance. Now without considering the resistance and inductance terms of above equation., the output voltage measured at the divider circuit can be expressed as:

$$V_D = \frac{X_{c2}}{Z_D} V_T, \qquad V_D = \frac{C_1}{C_1 + C_2} V_T$$

Where $X_{c2} = {}^{1}\!/_{i\omega C_2}$ is the impedance of the capacitor C_2, and Ω is the frequency of the RF applied and V_T is the voltage transmitted to the ion trap.

The capacitive voltage divider should be designed to match the impedance of the resonator to avoid reflections and losses. The values of C_1 and C_2 are selected in such a way that their measurement does not affect the trap capacitance. In our case the trap capacitance is ~ 22 pF, so the value of C_1 and C_2 are chosen so that they satisfy the following relations: $C_1 < 22$ pF and the value of $C_2 >> C_1$. The impedance of the capacitor C2 should be negligible as compared to the characteristic impedance of the measuring instrument[12] i.e. $X_{c2} \ll 50\,\Omega$. By adjusting the values of C_1 and C_2 we can adjust the dividing ratio of the voltage divider by considering the above conditions.

4. Results and Discussion

The capacitors with the divider circuit need to be chosen very carefully to achieve the desired voltage ratio ensuring proper resonance conditions of the helical resonator. We have designed and developed the capacitive voltage divider with C_1 = 1pF and C_2 =1000 pF, this will generate an output voltage at the divider circuit which is 1/1000 times lower than the RF voltage being delivered at the ion trap electrodes. These circuits have a minimum effect on the resonance frequency of the helical resonator. Since the loaded resonant frequency of the helical resonator is ~ 13 MHz so the impedance of the divider circuit i.e., $X_{c2} = {}^{1}/_{i\omega C_2}$ is very much less than the impedance of the measuring instrument (50Ω) and eventually it will not cause impedance mismatching for the helical resonator. By using the capacitive voltage divider, the resonance frequency of the helical resonator is shifter from 12.78 MHz to 11.59 MHz in loaded condition. Here, Fig 3 shows the output of the different voltage dividers which divides in ratio 400, 700, 1000 and 2000-times voltage of the ion trap voltage.

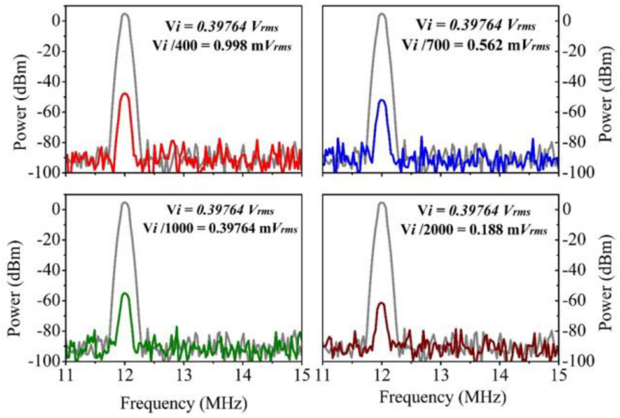

Fig 3: Output of the Capacitive voltage dividers for different dividing ratios. Here the grey line represents the input of 5dBm (0.39764 Vrms) at frequency 12 MHz and the red, blue, green, and wine color represents the output of the dividers with dividing ration 400, 700, 1000, 2000 respectively.

To verify if the voltage divers are working properly before mounting it to helical resonator first, we have characterized it by applying an RF voltage of 12 MHz of power 5 dBm from a stable RF generator (Keysight 33500 B) and the output is monitored on a spectrum analyzer (Rhode and Schwarz FSV-40). We have used C_2 = 390pF, 680pF, 1nF and 2nF with a fixed value of C_1= 1pF, for achieving voltage division of 400, 700, 1000 and 2000 times at the divider end respectively. Since the input power is 5dBm which corresponds to 0.39764 V_{rms} (shown in grey color in each graph in fig 3) and we get 0.998 mV_{rms}(red), 0. 56167 mV_{rms}(blue), 0. 39764 mV_{rms} (green) and 0.188 mV_{rms} (wine) for the dividers respectively, this shows that the output of the voltage divider nearly in same ratio as we have defined as shown in fig 3.

Now, to study the frequency response of the voltage dividers we have scanned the frequency of the input signal at power 10 dBm for all the four voltage dividers. As it is evident from fig 4 that the output of the voltage dividers shows consistent behavior throughout the scanned range, but it remains constant for the range 5 MHz-20 MHz without any major fluctuations maintaining the dividing ratio, which is suitable for trapping a single ion. The output of the dividers shows depreciation in the input power of 10 dBm with 57 dBm for 1:700 divider, 60 dBm for 1:1000 divider and 67 dBm for 1:2000 voltage divider. As high voltage RF signal to be used in the ion trapping experiment, there are maximum chances that the signal will cause interference by other conductive elements present near the helical resonator or the capacitive divider. This coupling with the other conductive elements will create capacitive and inductive imbalance of the system leading to a frequency shift of the helical resonator. So, to maintain the frequency stability of the system the capacitive voltage divider must be shielded very well by a shielding material, we have used aluminum sheet for shielding the capacitive divider.

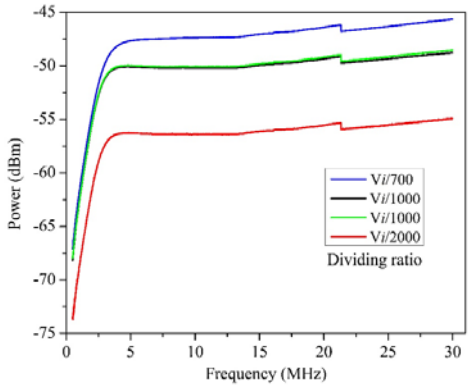

Fig 4: Frequency response of different voltage dividers with input power 10 dBm and measured Rf power for them.

To study the performance as well as effectiveness of the voltage divider, it was connected with the helical resonator and parallel to the ion trap assembly as shown in fig 1(a). An RF frequency ~ 11.5 MHz of power ~ 30 dBm is applied to primary coil of the helical resonator through a stable RF source followed by an amplifier (Minicircuits ZHL-5W-1+). To monitor the reflected RF signal, the amplified input RF signal is applied to the primary coil of the helical resonator through a Bi-directional coupler (Minicircuits ZFBDC20-62HP-S+) and the reflected signal is monitored through a spectrum analyzer. To optimize the power transfer efficiency between the primary antenna and secondary helical coils of the resonator, the position of the primary antenna is adjusted for achieving the lowest possible reflected signal from the isolator. As the primary coil is coupled to the helical coil at resonance, the lowest reflected signal maximum ensures the maximum transmitted signal at the output of the resonator. As can be seen from fig 5 that at resonance the reflected signal shows its minimum value, and the transmitted signal achieves its maximum as measured through the bidirectional coupler voltage divider respectively.

It has been observed that while the voltage divider circuit is connected to the resonator, its loaded resonance frequency is shifted from 12.78 MHz to 11.59 MHz due to change of load impedance. The helical resonator has a quality factor (Q) ~ 250 (RF) and the measured voltage at the divider output is 0.3 Vrms and now considering the attenuation factor (1/1000) of the voltage divider, the volage delivered at the ion trap end is estimated to be ~ 300 Vrms. If the quality factor of the helical resonator is improved by optimizing its parameter or coupling between the primary and helical coil, the transmitted power will also increase. The output of the voltage divider can also be locked to a desired level so that there will be no fluctuation of voltage delivered at the ion trap. So, this technique is quite suitable for measuring as well stabilizing the RF voltage delivered to an ion trap.

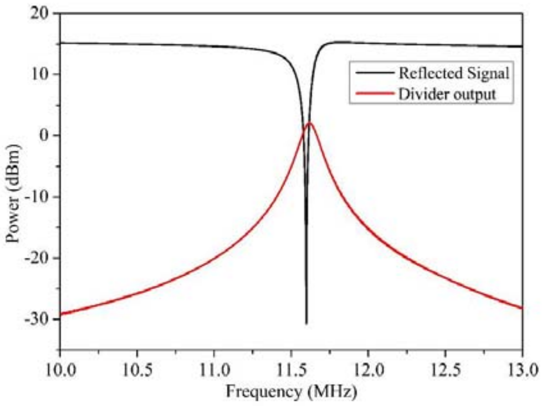

Fig 5: Frequency response of the reflected and transmitted signal of the helical resonator measured through a directional coupler and voltage divider circuit respectively.

5. Conclusion

This article describes the design and development of a capacitive voltage divider circuit for analyzing high voltage RF being delivered to the ion trap through a helical resonator. By using this technique, a small fraction of the voltage delivered to the ion trap can be accessed through a capacitive voltage divider. The voltage divider is connected parallel to the ion trap to access a minor fraction of voltage being delivered at the trap electrodes (with a ratio of 1:1000) and consequently the loaded resonance frequency of the resonator is shifted from 12.78 MHz to 11.59 MHz and the voltage delivered at the trap electrode is estimated to be 300 Vrms. The frequency response of the voltage divider circuit has also been characterized over a frequency range 1 to 30 MHz, and it has been observed that the response of the divider circuit remains unaltered over a frequency range of 5to 20 MHz. Both the transmitted and reflected signal of the helical resonator were simultaneously monitored through the voltage divider and bidirectional coupler, and they show consistent behavior near while input frequency of the resonator was scanning near its resonance.

6. Acknowledgements

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7. References

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