Combined Separated Oscillatory Fields Technique

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***Abstract*—Ramsey's method of separated oscillatory fields (SOFs) has been originally used in beam magnetic resonance apparatuses, which leads to the establishment of atomic definition of time interval and frequency. Since then, various versions of the SOFs technique have been widely used for precise measurement of different physical quantities. Here, we present an alternative method to generate atomic beam magnetic resonance signals by combining two Ramsey cavities with phase differences of 0 and π. It is found that the strength of the resonance signals generated using this combined SOFs technique is approximately twice that of the resonance signals produced by the conventional SOFs techniques. In addition to generating stronger resonance, the combined Ramsey method eliminates the Rabi background superimposed on the Ramsey interference pattern without increasing the Ramsey signal linewidth. Thus, this technique serves a promising tool for high-precision measurements.**

Keywords—resonance, separated oscillatory fields (SOFs), combined SOFs, Ramsey cavity, phase difference, Ramsey pattern

I. Introduction

For decades, Ramsey's method of separated oscillatory fields (SOFs) serves as a powerful tool in spectroscopy-based high-precision measurements and finds its most successful application in atomic clocks [1], [2]. The basic principle of the method is that under the excitation of two coherently SOFs, atoms or molecules can produce a stable, narrow-linewidth Ramsey transition interference spectrum [1], [3]. The Ramsey resonance is less affected by the first-order Doppler effect and is not broadened by field inhomogeneities. Following the idea of the SOFs technique, several typical Ramsey interference patterns have been developed for different applications, including the bright pattern excited by zero-phase-difference SOFs [1], the dark pattern excited by π-phase-difference SOFs [4], and the time-varying pattern excited by frequency-offset SOFs [5]. However, the performance improvement of quantum scientific instruments based on the Ramsey method is still limited by technical noises and related frequency shifts [6-9]. To produce a pure and high signal-to-noise ratio (SNR) Ramsey resonance signal, it is necessary to explore and study various SOFs techniques.

In this work, we propose a Rabi-background-free version of the Ramsey method, which combines zero-phase-difference SOFs and π-phase-difference SOFs to produce a pure Ramsey interference pattern. To validate our method, we theoretically investigate the lineshapes of the combined Ramsey pattern in a hot cesium beam magnetic resonance apparatus. A conceptual beam apparatus and a spectral comparison are used to illustrate the advantages of our proposed method over conventional methods. The results indicate that the strength of the combined Ramsey signals is almost twice that of traditional Ramsey signals, and the width of the Ramsey pattern remains unchanged. This combined SOFs technique significantly reduces common-mode noise and Rabi pulling induced frequency, thus improving measurements.

II. Combined Ramsey Method of Atomic Beam Magnetic Resonance

We start with a brief review of Ramsey' method used in a conventional beam resonance apparatus. The motion of the atom in the drift region between the two SOFs produces an interference effect when there is a frequency detuning Δ from resonance. The probability (near resonance) describing the interference behavior is given by

$$P(\tau) = \frac{4b^2}{\Omega^2}\sin^2\frac{\Omega\tau}{2}\left[\cos\frac{\Omega\tau}{2}\cos\frac{\Delta T+\phi}{2} - \frac{\Delta}{\Omega}\sin\frac{\Omega\tau}{2}\sin\frac{\Delta T+\phi}{2}\right]^2 \quad (1)$$

where τ is the interaction duration between the atom and the applied oscillatory field, b represents the amplitude of the applied oscillatory field, $\Omega = \sqrt{b^2+\Delta^2}$ is the generalized Rabi frequency of the atom in the SOFs, and ϕ is the phase difference between the two oscillatory fields in a single Ramsey cavity. The free evolution duration is represented by $T = L/\upsilon$, where L is the separations of SOFs and υ is the velocity of the atom. The resonance phenomena when $\phi = 0$ and $\phi = \pi$ correspond to the bright Ramsey resonance and the dark Ramsey resonance, respectively.

In the combined SOFs technique presented here, two atomic beams interact with $\phi = 0$ SOFs and $\phi = \pi$ SOFs, respectively, in a vaccum tube. Fig. 1 shows a conceptual apparatus configuration, which is mainly composed of an atomic source, a coil structure, two Ramsey cavities, and two fluorescence colletors. The requirments to produce a purely combined Ramsey pattern are as follows: (1) two highly collimated atomic beams are emitted through the same beam channels, thereby ensuring the same beam intenstiy and velocity distribution; (2) two Ramsey cavities must have the same drift region length but different phase difference; (3) atomic state preparations and transition detections of the two atomic beams must be performed with the same laser; (4) a static magnetic field coil is used to create the same environmnt for the two atomic beams to minimize differences in the Zeeman effect. Careful design and arrangement are of special importance for the combined SOFs technique since the resonance signal arises from differential operation.

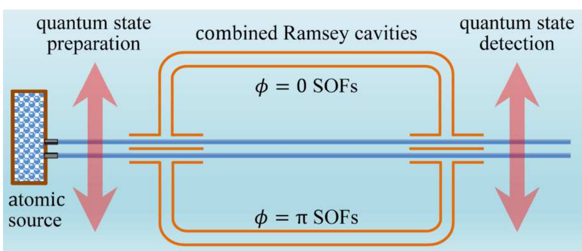

Fig. 1. Beam resonance apparatus employing the combined SOFs.

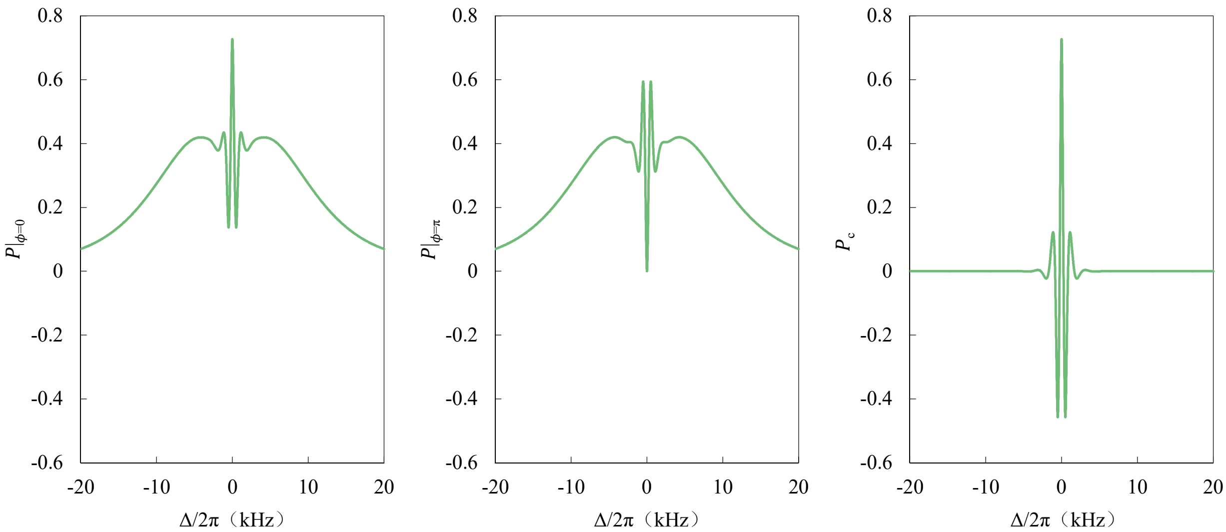

Fig. 2. Ramsey interference patterns under the excitaion of various SOFs. (a) Bright pattern. (b) Dark pattern. (c) Combined pattern.

Through the subtraction of the obtained bright pattern and dark pattern, the transition probability function describing the central pattern of the combined Ramsey resonance can be written as

$$P_c(\tau) = P(\tau)|_{\phi=0} - P(\tau)|_{\phi=\pi} \approx \sin^2(b\tau)\cos(\Delta T) \quad (2)$$

In the actual case where the beams have a certain velocity distribution, the probability function becomes

$$P_c = \int_0^\infty f(\tau)\sin^2(b\tau)\cos(\Delta T)\, d\tau \quad (3)$$

where $f(\tau)$ is the interaction time distribution.

To verify the potential of this method, we take a hot cesium beam apparatus as an example and implement the theoretical calculation. The cesium source is heated to a temperature T of 100°C, producing two collimated beams. The most probable velocity of each beam is $\alpha = \sqrt{2kT/M} = 215\,\mathrm{m/s}$, where k is the Boltzmann constant and M is the cesium atom mass. The physical parameters of SOFs are $L/l = 21$ and $b\tau_0 = 1.62$, where τ_0 is defined as $\tau_0 = l/\alpha$ and l is the length of a single oscillatory field region. The atomic state preparation and transition detection are realized with D_2 line: 4-4' laser and D_2 line: 4-5' laser, respectively.

For comparison, the lineshapes of various Ramsey patterns were calculated. The results, shown in Fig. 2, indicate that the peak-to-valley height of the combined pattern is twice that of the bright/dark pattern while the atomic linewidth is not affected. The contrast of the resonance line is significantly enhanced. Another important feature of the combined Ramsey pattern—in contrast to the traditional one—is that the broader Rabi pedestal, insensitive to the phase difference ϕ, is removed, as clearly indicated in Fig. 2.

III. Conclusion and Future Work

In summary, we propose a combined Ramsey method for enhancing Ramsey signal and eliminating unwanted Rabi background using two Ramsey cavities with phase differences of 0 and π, respectively. We theoretically demonstrate the possibility of producing a pure Ramsey interference pattern using the combined SOFs. The technique presented here has the advantages of being insensitive to common-mode noise, making it a promising method for obtaining high SNR atomic resonance signals. Additionally, the technique can be readily extended to other beam resonance apparatuses.

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