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Design and Characterization of TE-mode Cavity for Digital Communication using Rubidium atoms

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Abstract

Digital communication utilizes a three-level lambda(Λ) atomic configuration, cyclically connecting two distinct ground hyperfine levels to a common excited state. The microwave field applied between the ground hyperfine levels drives a weak magnetic dipole transition. The microwave cavity plays a prominent role in strengthening the magnetic dipole transition driven by the microwave field. This leads to numerous applications, including the conversion of microwave signals into the optical domain, atomic receivers, and many more. A high-quality factor cavity has been specifically designed to operate at the ground hyperfine separation frequency of Λ level system in 85 Rubidium (Rb) atoms, tailored for its use in digital communication and transmitting quantum signals over fiber. The performance of the cavity is evaluated using a vector network analyser to confirm its working concerning the targeted atomic transition at 3.035 GHz.

Keywords: Cavity; EIT, Rubidium vapor cell; quantum communication

1. Introduction

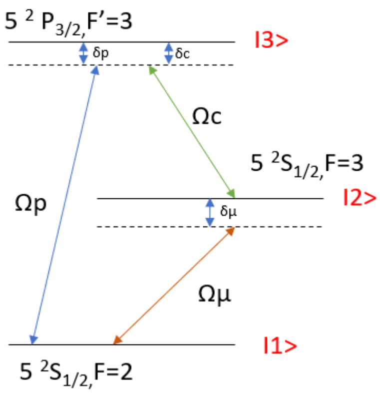
Electromagnetically induced transparency (EIT), a phenomenon first realised by Harris et al. in 1989, has become a pivotal concept in various fields of physics and engineering. Initially proposed through coherent population trapping [1], EIT involves manipulating the absorption properties of a medium through the interaction of electromagnetic fields with atoms or quantum systems. The alkali atoms have been utilized specifically for sensing RF fields and enabling communication utilizing microwave and optical frequencies [2-5]. Other applications of EIT and its associated phenomenon include atom-based sensors, atomic antennas for radio over fiber systems, and receivers designed to enable optical communication across microwave and optical frequency domains [6-8]. In recent times, there has been notable development in using cyclic energy level structures (Λ atomic systems) of alkali atoms to establish coherent and phase-dependent connections between microwave and optical frequencies. This approach has leveraged the cavity-based EIT effect, leading to demonstrations such as the generation of optical fields [9], microwave-activated optical switches [10] transmission of analog signal modulated over microwave carrier [11], and amplification of optical fields controlled by the phase of microwave signals [12]. Three-dimensional microwave cavities are being used from last several years to amplify interactions with magnetic systems [13], superconducting-circuit artificial atoms [14], and electro-mechanical resonators over the last few decades [15]. Cavities based on similar design principles are being employed to boost interactions between microwaves and atoms.

In this work, we utilise a three-level cyclic arrangement for 85 Rb atoms for its application in digital communication using one microwave field and two optical fields. Although, electric dipole transition between the ground states is prohibited, but the microwave field can drive a magnetic dipole transition though very weak. This weak transition can be enhanced by utilizing a cavity for coupling microwave field. We position the vapor cell within a cubical microwave cavity. This cavity is designed to sustain the TE_{011}, TE_{101}, TE_{110} modes of the microwave field which strengthen the interaction of magnetic dipole between atoms and microwave field.

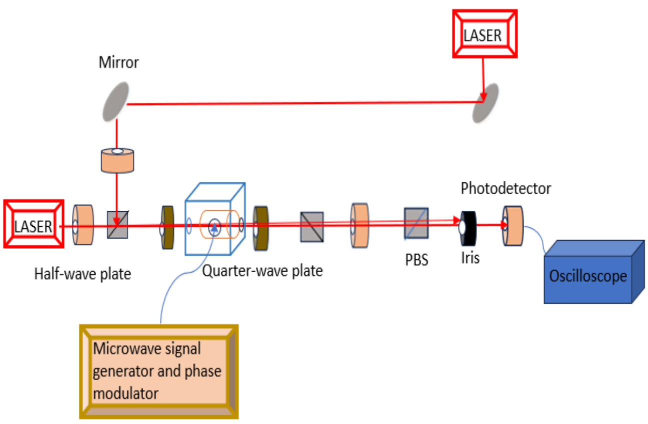
In this paper, we assess the performance of the designed cavity by employing a vector network analyser to verify its functionality concerning the intended atomic transition for its application in digital communication[16]. The advantage of the proposed cavity over the available cylindrical cavities is that the proposed cavity can be designed with smaller size and high-quality factor for the same operating frequency. Therefore, the size of the overall setup can be reduced by using this cavity in place of cylindrical cavity or the waveguide structures given in the available literature [10-11,16-17].

2. Design of experimental set-up

This work employs a Λ configuration within the D2 manifold of 85 Rb, utilizing three hyperfine energy levels. These levels are interconnected cyclically through the influence of one microwave field and two optical fields. This arrangement creates closed Λ system responsive to changes in relative phase between the fields, commonly referred to as delta (Δ) system as illustrated in Figure 1(a). The detuning and Rabi frequencies of probe, coupling and microwave fields are represented by δp, Ωp, δc, Ωc and $\delta \mu$, Ωμ respectively. The probe beam, characterized by a Rabi frequency Ωp, interacts between the atomic states |1⟩ and |3⟩, while the coupling beam, with Rabi frequency Ωc, interacts between the atomic states |2⟩ and |3⟩. Both transitions are permitted electric dipole transitions. Additionally, a microwave field, with Rabi frequency Ωμ, interacts between atomic states |1⟩ and |2⟩, facilitating magnetic dipole transition between these states following the selection rules. To enhance the coupling of microwaves with the atoms, the vapor cell, our atomic antenna is placed inside the cavity as shown in Figure 1(b) and (c). For practical experiment, two external cavity diode lasers (ECDL) tuned at 780 nm, one acting as a probe and the other as a strong coupling beam are mixed via a beam splitter and then passed through the cavity. The microwave cavity employed in these experiments confines the microwave field within the central region of its structure. The vapor cell is exposed to RF field of 3.035 GHz which is which is the separation between hyperfine levels of 85 Rb. The cyclic atomic scheme responds to the interacting fields' relative phase. As a result, it has the ability to embed a signal within the phase of a microwave field. The phase of the microwave field undergoes modulation through digital schemes such as B-PSK, Q-PSK and are detected by observing changes in the intensity of the optical field with the help of a photodetector and a high-bandwidth oscilloscope, eliminating the requirement for an external demodulator as shown in Figure 1(b) and (c).



(a)



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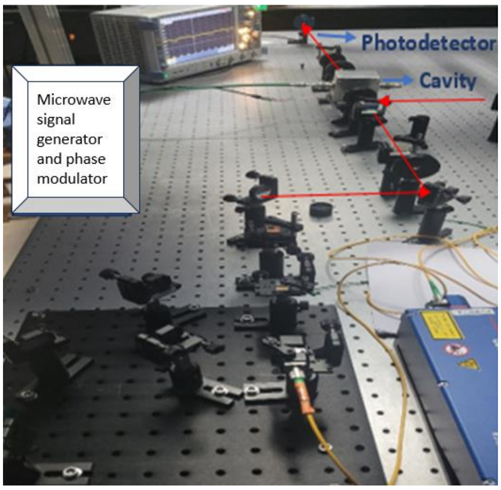


(c)

Figure 1 (a)Hyperfine energy level diagram within a Δ configuration in 85 Rb.; (b) Schematic of set-up for digital communication (c) Experimental set-up for the proposed digital communication

2.1 Design of cavity

A cubical cavity is designed with dimensions of 7×7×7 cm^3 resonating at 3.03 GHz which is the separation between hyperfine levels of 85 Rb, corresponding to the transition frequency between the hyperfine levels of the ground state. Figure 2 illustrates the cross-section of the proposed cavity. This cavity is designed using aluminium material to support the TE_{101}, TE_{110}, and TE_{011} modes, ensuring optimal coupling between the microwave field and the atoms. The resonance frequencies for these modes are calculated using equation (1) [18].

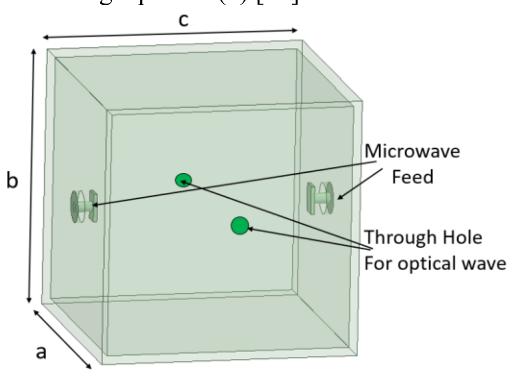


Figure 2. Proposed waveguide Cavity.

$$f_{mnp} = \frac{c}{2\sqrt{\varepsilon_r \mu_r}} \sqrt{\left\{\left(\left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{c}\right)\right)} \quad (1)$$

Here, ε_r is the dielectric constant, μr is magnetic permeability. Whereas, a, b, and c are the cavity's width, height, and length. Their corresponding mode numbers are m, n and p, excluding m=n=p=0. However, the required modes for analysis of EIT and corresponding frequency are given in Table I.

Table I. Required Modes and corresponding resonance frequencies.

S No.	Operating modes	Resonance Frequency (GHz)
1	TE_{110}	3.03 GHz
2	TE_{101}	3.03 GHz
3	TE_{011}	3.03 GHz

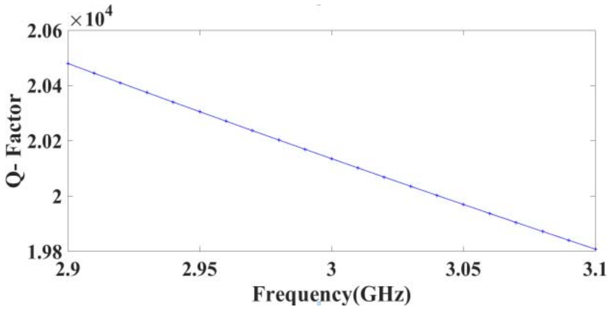


Figure 3. Calculated quality factor vs frequency of the designed cavity.

Another effective parameter of the cavity is the quality factor calculated using equations (2) and (3).

$$Q = \frac{1.11\eta}{R_S} \frac{2b}{(a+2b)} \quad (2)$$

$$Rs = \sqrt{\frac{\pi f \mu r}{\sigma}} \quad (3)$$

Where, $\mu r = 4\pi \times 10^{-7}$, σ is the conductivity and $\eta = 120\pi$. The calculated quality factor vs. frequency graph of the cavity is given in Figure 3 and the value of Q at 3.035 GHz is approximately 20034. The advantage of cavity is the uniform field distribution over the area where rubidium cell is placed. The simulated E field distribution of the cavity is shown in Figure 4.

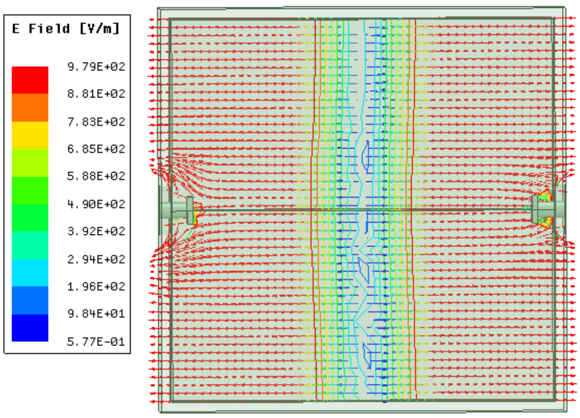


Figure 4. Simulated E-field graph of cavity.

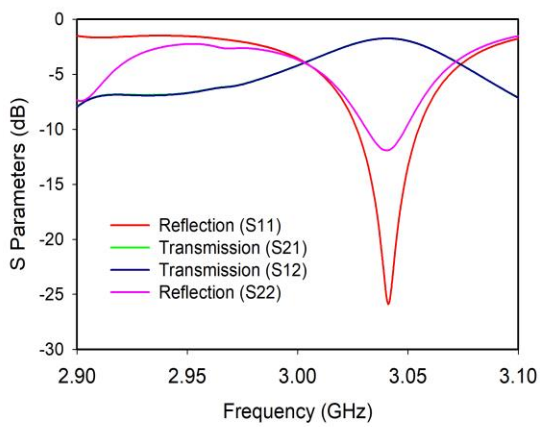
The designed cavity is fabricated using an aluminium sheet and the RF feed is applied using the N type connectors. The cavity has two through holes on both sides of the cavity as shown in Figure 2. These holes are used to pass the laser beam from one end to the other end. The Scattering (S) parameters of the designed cavity are measured using Rohde & Schwarz vector network analyser (VNA).

3. Results and Discussion

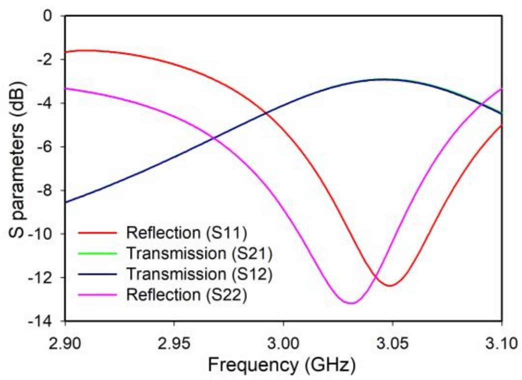
Figure 5(a) shows the experimental setup for measuring S-parameters of the cavity. When the medium inside the cavity is air, the measured working frequency bandwidth for designed modes is 3.02-3.05 GHz with a peak reflection of -25.88 dB at 3.035 GHz as shown in Figure 5(b). Ideally, the reflection graphs of both ports must be identical. However, the S-parameters of the designed cavity are having a slight variation because of the inhouse fabrication using a manual process.

For validation of compatibility in the setup for atomic transition, a cylindrical vapor cell of size 19 mm × 25 mm containing natural rubidium is then placed inside the cavity. The performance of this overall setup is then observed. The measured working frequency range for designed mode of operation is 3.029 - 3.06 GHz with a peak reflection of -10.92 dB at 3.035 GHz as given in Figure 5(c). It is observed that the overall performance has a slight change in S-parameters of the cavity as well as in the working frequency bandwidth. However, at 3.035 GHz the reflection curve is below -10 dB range, it confirms that more than 90 % input power is coupled to the other end. This validates that the proposed cavity can be efficiently used in the setup for quantum communication.

(a)



(b)



(c)

Figure 5. (a) S parameters measurement setup of the cavity; (b) Measured S-parameters of the empty cavity; (c) Measured S-parameters of the cavity containing vapor cell filled with natural Rb.

4. Conclusion

The designed cavity is observed to be working proficiently at the ground hyperfine transition frequency of Λ system in 85Rb atoms. The introduction of cavity in this system ensures strong coupling of microwave fields carrying information with optical fields. The designed cavity will be used for digital communication utilizing the phase-sensitiveness of the system and for future conversion of quantum signals in radio-over-fiber technology. The cavity can also be used for various other applications that leverage ground hyperfine levels, such as atomic clocks, gyroscopes, quantum memory, and numerous additional uses.

5. References

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