Received: 28 December 2021 | Revised: 5 March 2022 | Accepted: 14 March 2022

DOI: 10.1002/mop.33249

RESEARCH ARTICLE

WILEY

Analysis of etalon filter in quantum memory

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Funding information
National Natural Science Foundation of China, Grant/Award Numbers: 62122044, 61925503, 11904218, 12147215; Key Project of the National Key R&D program of China, Grant/Award Number: 2016YFA0301402; Program for the Innovative Talents of Higher Education Institutions of Shanxi; Program for the Outstanding Innovative Teams of Higher Learning Institutions of Shanxi; Fund for Shanxi 1331 Project Key Subjects Construction

Abstract

For quantum on-demand storage and retrieval of nonclassical light, the memory noise at shot noise limit is a necessary condition. And an optical filter is widely used to filter out the strong control mode when the signal mode is maintained. Thus we construct and analyze an etalon filter with the planar monolithic geometry. The signal mode resonant with the etalon is selected and the unwanted modes are filtered out by precisely controlling the etalon temperature. The noise suppression factor for control mode is 0.053 while the transmissivity for signal mode is 97% with a fluctuation of 1.7% within 30 min. Our analysis can provide a direct reference for optimizing the performance of quantum memory.

KEYWORDS

etalon, noise suppression, quantum memory

1 | INTRODUCTION

Quantum memory is the building block of quantum repeater-based quantum communication,[1] distributed quantum computation,[2] and quantum sensing.[3] And the nonclassical states of light have been widely applied in quantum information protocols,[4–6] thus quantum storage and retrieval of nonclassical light is a long-standing goal.[7–10] Electromagnetically induced transparency (EIT) is one of the effective on-demand approaches to store and release the nonclassical signal mode, and the strong control mode with different wavelengths is used to control the reading and writing operation.[11–15] However, the control mode should be totally filtered out and only signal mode is allowed to enter the detection system. Like electric filters, optical filters, such as the etalon[16–19] and resonant notch filters,[20–22] can cancel the unwanted optical modes while the signal mode is maintained for quantum information processing. A solid etalon filter or a cavity filter enables the transmission of a specific weak signal mode, while the other intense off-resonance noise modes are filtered out simultaneously.[23,24]

In quantum memory, an optical filter is widely used to filter out the strong control mode, when the signal mode is maintained. However, the long-term stability of optical filters is required for practical applications. In this article, we construct and analyze a stable etalon filter with the planar monolithic geometry, which consists of an etalon with a long-term temperature-controlled system. The etalon is placed inside a temperature-controlled copper oven, which is enclosed in a temperature maintainer to minimize environmental influence. Furthermore, the signal mode resonant with the etalon is selected and the unwanted modes are filtered out by precisely controlling the etalon temperature. A high

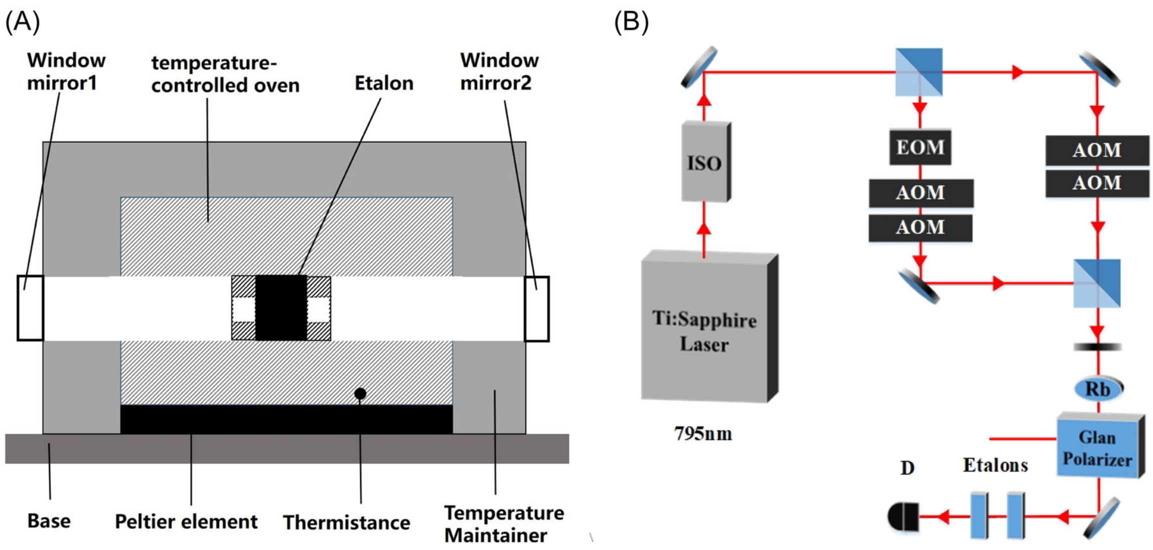

FIGURE 1 (A) The structure of the etalon filter. (B) Experimental setup. AOM, acousto-optic modulator; EOM, electro-optic modulator; ISO, optical isolator; Rb, rubidium atomic cell

precision temperature control system with the long-term stability of 0.02°C is used. Due to no active optical locking of the mirror separation, the experimental simplification, the long-term mechanical stability, the isolation of environment, and the stable high precision temperature control system, the etalon filter provides not only high transmission and desirable noise suppression factor but also long-term stability. Besides, the optimized parameters have been applied in the experiment by analyzing the transmission and noise suppression based on the frequency response of the transmitted modes. The etalon filter provides the noise suppression factor of 0.053 for unwanted control mode when the resonant signal mode is selected with a transmissivity of 97%. The stable structure enables long-term stability and the transmitted power fluctuation is 1.7% within 30 min. Therefore, this optimized etalon filter is suitable for high-performance quantum memory, which provides the direct reference for experimentally implementing quantum memory.

2 | PRINCIPLE OF ETALON FILTER

In EIT quantum memory, the signal mode can be stored on-demand and released in the atomic medium with the help of the strong control mode. But the residual control mode will influence the measurement of the released optical mode. After the strong control mode passes through the polarizer, the residual control mode is canceled out by the etalon filter. The etalon filter is a flat glass plate with two parallel outer surfaces coated with a certain wavelength reflection film, and the length of the etalon with two reflective surfaces can be finely tuned by precisely controlling the temperature.

The transmission of signal mode is required to be as high as possible to reduce the loss of nonclassical light. The free spectral region is the frequency interval between adjacent transmission peaks:

$$\mathrm{FSR} = \frac{c}{2nl}, \tag{1}$$

where n is the refractive index of etalon and l is the length of the etalon filter. The transmission bandwidth is half-intensity points:

$$\mathrm{FWHM} \approx \frac{c}{2nl}\frac{1-g_m}{\pi\sqrt{g_m}}, \tag{2}$$

where $g_m = \sqrt{R_1R_2(1-L)}$, $R_1 = R_2$ is the reflectivity of the etalon surfaces (both sides are coated to be identical) and L is the etalon loss. Thus, the fineness of the etalon filter is the ratio of the FSR and FWHM:

$$F = \frac{\mathrm{FSR}}{\mathrm{FWHM}} = \frac{\pi\sqrt{g_m}}{1-g_m}. \tag{3}$$

The transmittance T of the etalon filter is the ratio of the transmitted intensity I_{out} and the incident intensity I_{in}.[25]

$$T = \frac{I_{\mathrm{out}}}{I_{\mathrm{in}}} = T_1T_2\frac{e^{-4\alpha l+i\delta_\phi}}{|1-g(\nu)|^2}, \tag{4}$$

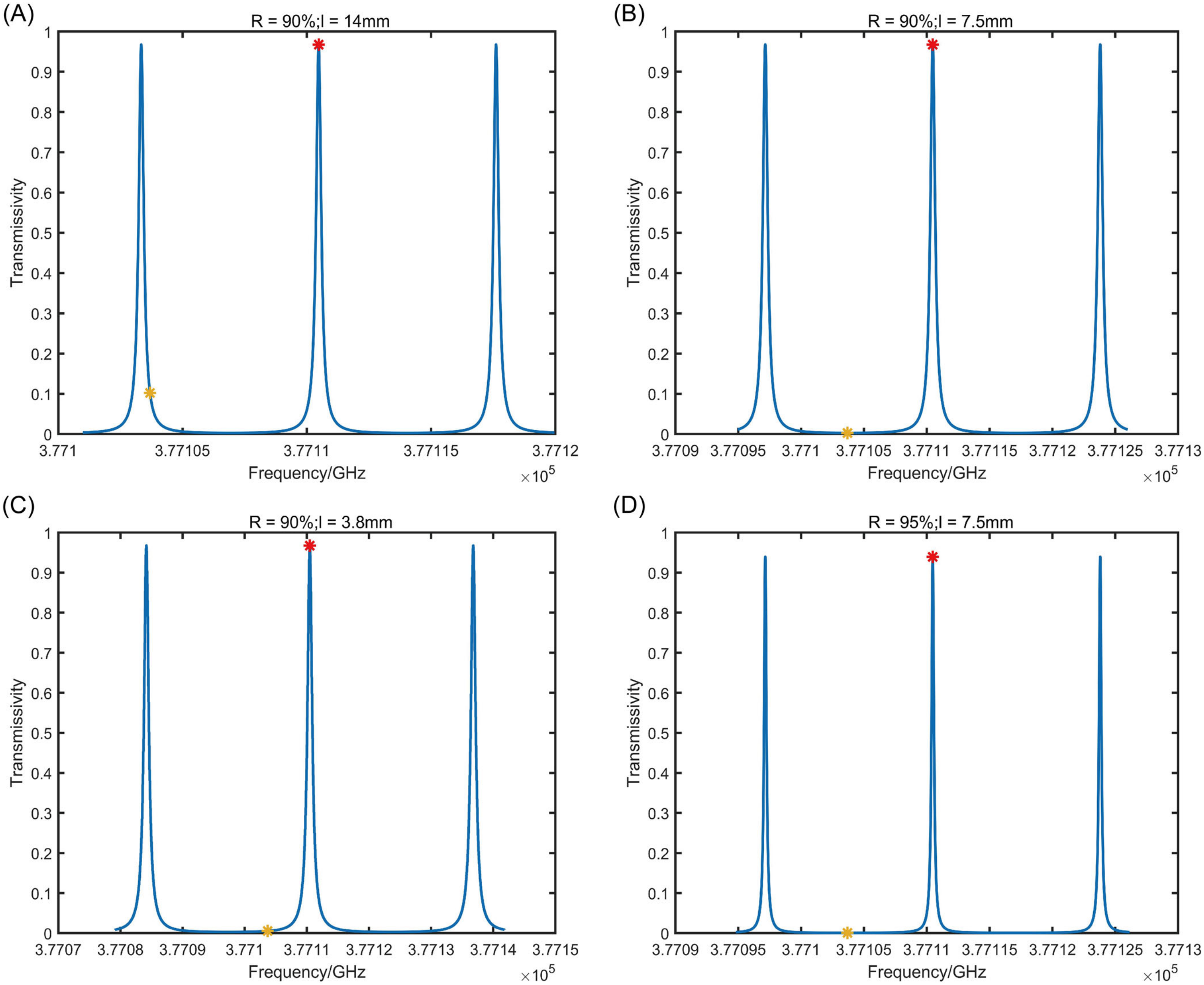

FIGURE 2 Transmission spectra of etalon filter with different etalon lengths and reflectivities: (A) the reflectivity is 90% and the length is 14 mm; (B) the reflectivity is 90% and the length is 7.5 mm; (C) the reflectivity is 90% and the length is 3.8 mm; (D) the reflectivity is 95% and the length is 7.5 mm

where $\delta_\phi = \frac{4\pi\nu}{c}nl$ is the phase difference between two adjacent beams, α is the loss coefficient for internal absorption or scattering, $g(\nu) = g_m e^{-i\delta_\phi}$, $R_1 + T_1 = 1$, $R_2 + T_2 = 1$. Therefore, the selected signal mode of the etalon filter is determined by controlling its length.

The noise suppression factor for control mode is used to characterize the filter effect. The general expression for the noise suppression factor is[26]

$$S = \frac{1 - \mu_s e^{i\phi_s}}{1 - \mu_c e^{-i\phi_c}}, \tag{5}$$

where the μ_c and μ_s are the round-trip at the control and signal amplitude transmissions; and the ϕ_c and ϕ_s are the round-trip phases at the control and signal frequencies, respectively.

3 | EXPERIMENTAL SETUP

Figure 1A is the structure of the etalon filter. The etalon consists of a planar mirror with the high-reflectivity coating R. Three etalons with lengths of 14, 7.5, and 3.8 mm coated with $R = 90\%$ at 795 nm, and one etalon with a length of 7.5 mm coated with $R = 95\%$ at 795 nm are used to analyze the performance of etalon filter. The fused quartz Corning 7980 is used as the substrate material, owing to its high transmission in the near-infrared and its high coefficient of thermal expansion.

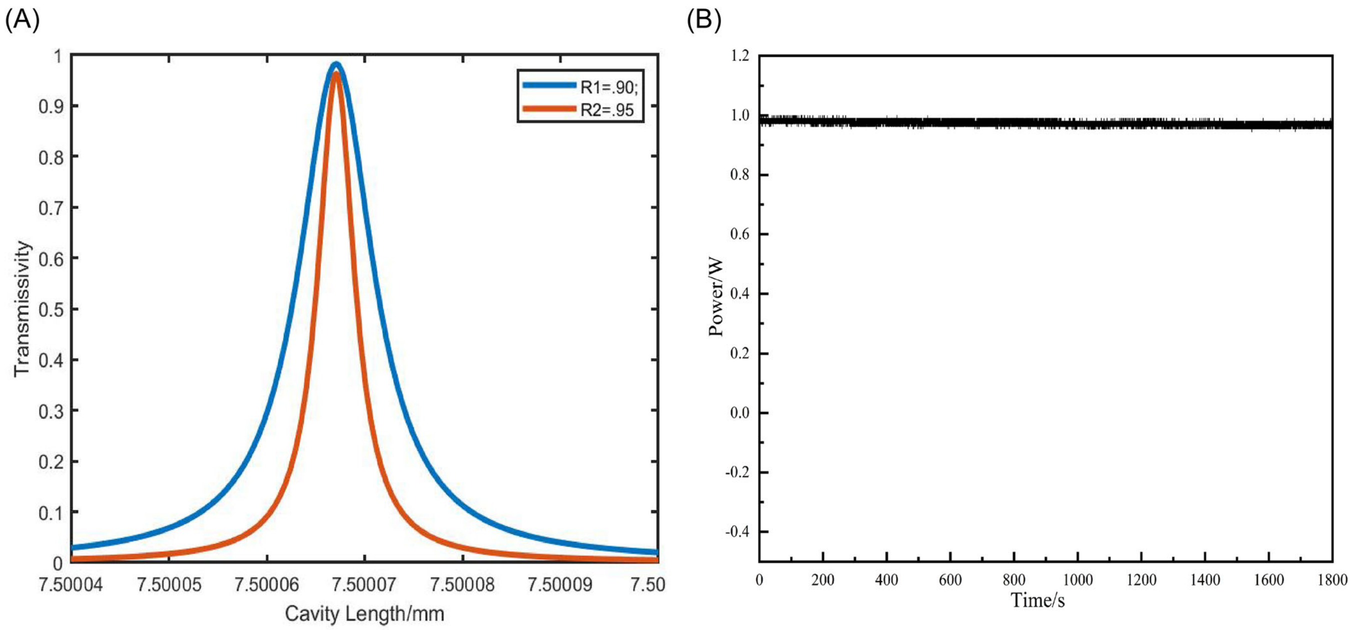

FIGURE 3 The dependence of the transmissivity of etalon filter on its length (A) and the stability of transmitted power (B)

The etalon is placed in a stable copper mount with a thermally coupled *AD*590 sensor measuring the temperature, and the temperature control feedback is realized by a Peltier thermoelectric element, which couples the mount to a large heat sink made of an aluminum block. The temperature sensor and Peltier element are connected to a standard proportional integral differential temperature control system with the long-term stability of 0.02°C. The entire etalon filter system is enclosed in a temperature maintainer to minimize environmental coupling.

Figure 1B is the experimental setup. The output 795 nm light field is divided into two parts by PBS after passing through the isolator, and one part of the light is chopped into signal mode pulse by a pair of acousto-optic modulators (AOMs). The control mode is obtained by the frequency shift of 6.8 GHz through EOM, which generates a control mode pulse by a pair of AOMs. The signal and control modes are coupled on PBS and injected into the rubidium atomic ensemble for quantum memory. The released signal mode filtered by Glan Polarizer and cascaded etalon filters finally enters the detection system.

4 | EXPERIMENTAL RESULTS

In reality, the transmission between the transmitted and incident signal modes is not unity due to the imperfect experimental conditions. In the actual experiment, the residual control mode is obviously suppressed after passing through the etalon filter. The full-width-at-half-maximum (FWHM) of the etalon filter is 455 MHz. The Q-factor is 8.29×10^5 for our filter. The mode matching efficiency is 99%. Figure 2 is the transmission spectra of the etalon filters with different etalon lengths and reflectivities: (A) is for the reflectivity of 90% and the length of 14 mm; (B) is for the reflectivity of 90% and the length of 7.5 mm; (C) is for the reflectivity of 90% and the length of 3.8 mm; (D) is for the reflectivity of 95% and the length of 7.5 mm. By comparison of Figure 2A-C, it can be found that the suppression factor for control mode can reach the minimum value of 0.053 when the etalon length is 7.5 mm. The shorter and longer etalon length will make the noise suppression factor worse. From Figure 2B,D, we can see that the noise suppression factor is improved from 0.053 to 0.026 with the same etalon length of 7.5 mm when the reflectivity is increased from 90% to 95%. When the reflectivity of the etalon filter increases gradually, the filtering effect of the control light is better and better.The stability of the etalon filter depends largely on the accuracy of the temperature-control system and the copper mechanical structure. Figure 3A er on its length, which is precisely determined by its temperature. However, the transmission of the etalon is reduced from 97% to 94% for larger reflectivity of etalon filter, which is harmful for the nonclassical state of light. The transmitted power stability of the etalon filter is obtained by monitoring the transmission fluctuation of signal mode, and the performance of the etalon filter can be retained for several days and only a small adjustment is needed if the transmission degrades. Figure 3B shows the power transmission stability, from which it can be seen that the transmission fluctuation for signal mode is 1.7% within 30 min. Thus, the etalon filter with reflectivity of

90% and etalon length of 7.5 mm is selected to achieve better performance in the experiment.

5 | CONCLUSIONS

In the experiment, the filtering performance of the etalon filter is analyzed by comparing them with different reflectivity and length. The results show that the filtering effect of control mode in EIT memory can be improved by optimizing the length and reflectivity of the etalon filter. In the experiments of quantum memory, where the cascade filters are used to make the filtering effect effective, an etalon filter with reflectivity of 90% and a length of 7.5mm can be selected. If the etalon loss is improved, an etalon filter with reflectivity of 95% may be used to realize a better effect for quantum memory.

ACKNOWLEDGMENTS

This study was supported by the National Natural Science Foundation of China (Grants No. 62122044, 61925503, 11904218, 12147215, 61775127 and 11834010), the Key Project of the National Key R&D program of China (Grant No. 2016YFA0301402), the Program for the Innovative Talents of Higher Education Institutions of Shanxi, the Program for the Outstanding Innovative Teams of Higher Learning Institutions of Shanxi and the fund for Shanxi 1331 Project Key Subjects Construction.

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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How to cite this article: Li R, Lei X, Ma L, Yan Z, Jia X. Analysis of etalon filter in quantum memory. *Microw Opt Technol Lett*. 2022;1-5. doi:10.1002/mop.33249