An Improved Design of Atomic-Beam Fluorescence Collector

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***Abstract*—Efficient fluorescence detection is crucial in the field of precision spectral analysis. This paper presents an improved design of an atomic-beam fluorescence collector that utilizes the convergence characteristics of ellipsoidal surfaces and the reflection characteristics of spherical surfaces. It calculates the parameter relationship for achieving full-angle fluorescence collection. The study fine-tunes the structural parameters and simulates the fluorescence collection efficiency and losses under different conditions when emitting from a non-ideal point light source. The improved fluorescence collector captures photons with nearly 4π solid angle coverage, allowing photons to be reflected at most twice before reaching the photodetector, thereby increasing collection efficiency. This improved collector can be used in various fields for detecting weak fluorescence signals.**

Keywords*—*fluorescence detection, fluorescence collector, collection efficiency, fluorescence losses

I. INTRODUCTION

Fluorescence detection is a widely used optical technique essential for the precise spectral analysis of atoms, molecules, and plasmas [1-3]. Fluorescent photons have weak energy and radiate in all directions, making them difficult to collect. The intensity of the fluorescence signal is proportional to the collection efficiency of the collector. Therefore, achieving high-efficiency fluorescence collection is crucial for precise spectral analysis.

Existing fluorescence collectors use structures such as light-guiding pipes [4], lenses [5], and spherical combinations [6]. Among these, collectors designed with spherical combination structures are widely used in compact optically pumped cesium beam atomic clocks due to their large collection angles. However, these spherical combination structures often use hemispherical surfaces with limited focusing capability. Some fluorescence photons at certain angles reflect multiple times inside the structure, unable to reach the photodetector and thus fail to become useful signals. This issue is especially severe in practical situations with non-ideal point light sources, where fluorescence losses are more significant.

In this paper, we propose an improved design for atomic-beam fluorescence collectors that capture photons with near 4π solid angle coverage and allow photons to be reflected at most twice before reaching the photodetector. This design combines ellipsoidal and spherical surfaces to optimize the parameter relationship for the selected sphere and photodetector, ensuring full detection of photons emitted from the center. Using optically pumped cesium beam atomic clocks as an example, we simulated the collection efficiency and fluorescence losses under different ellipsoidal parameters by fine-tuning the structural parameters. The optimal structural parameters were ultimately determined.

II. THEORY

It is well known that ellipses have an important optical property: light emitted from one focal point converges at the other focal point when reflected by the ellipse. This property also applies to ellipsoidal surfaces. Using this optical property, we design an improved atomic-beam fluorescence collection structure that combines an ellipsoidal surface with a spherical surface. In this combined structure, the center of the fluorescent emitter is the first focal point of the ellipsoidal surface and the center of the spherical surface. A low-noise photodetector is placed near the second focal point.

Fig. 1 shows a schematic diagram of the improved fluorescence collection structure, illustrating the structural parameters and light path. The ellipsoid (orange) has a major axis of $2a$, a minor axis of $2b$, and a distance between the two focal points $|F1F2|$ equal to $2c$. The radius of the sphere (green) is R. The diameter of the photodetector (stripe) is Φ. According to Fig. 1, for the selected sphere radius and photodetector, photons emitted from the central position reach the photodetector when the following condition is satisfied:

$$\frac{2R^2}{2R+\Phi} < |F_1F_2| < \frac{2R^2}{2R-\Phi} \tag{1}$$

where the two endpoints of the parameter range correspond to Fig. 1(a) and 1(b).

Based on the focal length condition, we can further calculate the range of the major and minor axes of the ellipsoidal surface. These ranges, derived under ideal point light conditions, could serve as a reference for optimizing fluorescence collectors for finite-size emitters.

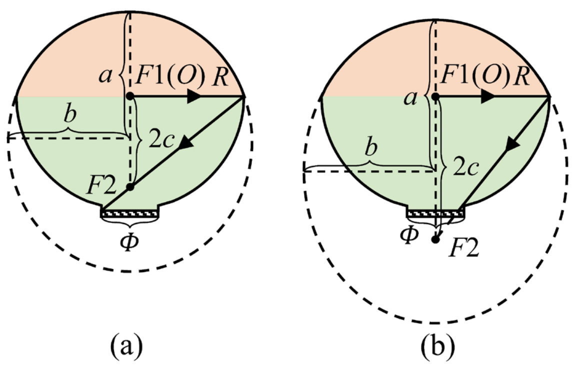

Fig.1. Fluorescence collection structure.

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III. Simulation and Results

In the practical application of fluorescence detection, many of the emitted fluorescence photons do not originate from a point light source but from emitters with a certain volume.

To investigate the effect of emitters on the collection efficiency of fluorescence collectors, we use the fluorescence detection module in the pumped cesium beam atomic clock as an example. The fluorescence collector is constructed as shown in Fig. 2(a). The blue ellipsoidal surface and the yellow spherical surface form a cavity. The green cylinder represents a cesium atomic beam with a cross-sectional size of 3 mm × 1 mm, and the red area represents a laser beam with a cross-sectional diameter of 3 mm. Their intersection is the fluorescent emitter, with its center coinciding with the center of the spherical surface. The purple area is a low-noise photodetector (PD) placed at the square hole (10 mm × 10 mm) at the bottom of the spherical surface. Holes are necessary for passing through the atomic and laser beams and placing the photodetector. Fluorescence photons that fall in these areas cannot be effectively detected by the photodetector and are considered fluorescence losses.

Before exploring the aforementioned effect, we simulate the emission of photons with deviations from the center by distances of 0 mm, 1.5 mm, and 3 mm, as shown in Fig. 2(b). The density distribution of fluorescence photons on the photodetector is illustrated in Fig. 2(c)-(e). The results indicate that within a certain range, the deviation distance of the radiation center ensures that the vast majority of fluorescent photons fall on the photosensitive surface of the photodetector. This confirms that the fluorescence collector is suitable for finite-volume emitters

Referring to the parameter range given in Part II, we calculate the range of values for the major and minor axes of the ellipsoid when R = 20 mm and Φ = 10 mm. Within this range, we simulate the relationship between fluorescence collection efficiency and ellipsoidal parameters, as well as the relationship between fluorescence losses and ellipsoidal parameters, as shown in Fig. 3. The results show that for the optimal major axis $2a$ = 47.62 mm when the minor axis $2b$ is within the range of 41.72 mm to 43.52 mm, the fluorescence collection efficiency can exceed 98% without losses on the reflection surface. The total losses comprise hole losses and wall losses. Within the specified range, the primary source of fluorescence losses is attributed to hole losses.

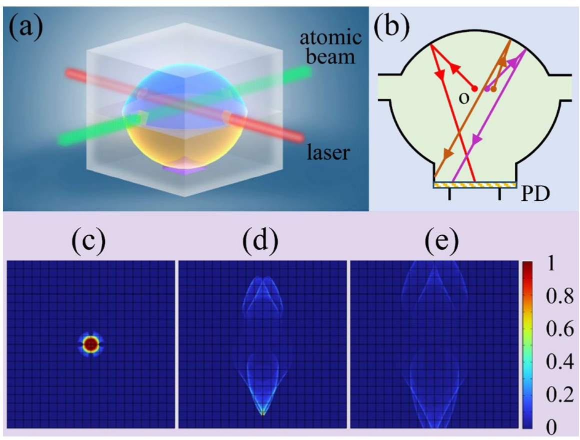

Fig. 2. (a) A fluorescence collection used in the pumped cesium beam atomic clock. (b) Emission points at different positions. (c) Distribution of fluorescence density with 0mm. (d) Distribution of fluorescence density with 1.5 mm. (e) Distribution of fluorescence density with 3 mm.

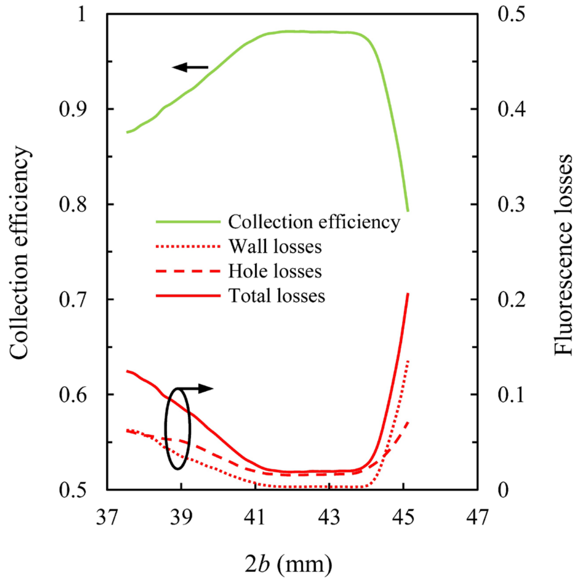

Fig. 3. Parameters optimization

IV. Discussion and Conclusion

In summary, we present an improved design for atomic-beam fluorescence collectors. We demonstrate the calculation of the parameter range necessary for full-angle fluorescence collection and the achievement of high-efficiency fluorescence collection through fine-tuning structural parameters. The improved collector can achieve higher collection efficiency by increasing the sphere's radius and applying a high-reflection coating. Furthermore, the design allows for miniaturization to meet specific requirements.

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