

Non-Imaging Fluorescence Detection System with Hemispherical Dome Reflectors

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Abstract— We report efficient non-imaging emission collection optics for compact fluorescence detection systems. A combination of hemispherical dome mirrors redirects and integrates the isotropic fluorescent emission toward the photodetector, and significantly enhances the fluorescence signal level.

Biosensors; Fluorescence detection; Non-imaging optics

I. INTRODUCTION

Fluorescence detection techniques have been widely used for biochemical analysis and diagnostics applications because of their sensitivity and efficiency [1, 2]. Conventional fluorescence detectors are mostly based on refractive optical lenses under the imaging configuration, and require accurate alignments between the sample target and the imaging system. Although lens-based detection systems, such as microscopes, can obtain the accurate two-dimensional images of fluorescence distribution for image analysis, there also exists a need for compact, portable, and simple fluorescence detection systems for on-site, point-of-care diagnostic applications that do not necessarily require the precise information of spatial fluorescence distribution [3]. In such applications, the fluorescence detectors need to determine the existence and absence of certain fluorescence emissions at the target wavelengths for quick on-site decisions, instead of obtaining the detailed two-dimensional fluorescent images.

We introduce a non-imaging optical system design that can significantly improve the fluorescence collection efficiency in a small form factor with reflective optics. Side-coupled excitation beam is essentially trapped inside the hemispherical dome reflectors, and illuminates the sample multiple times. At the same time, the fluorescence emission from the sample is efficiently collected and integrated by the reflective optics, analogous to the integrating spheres.

II. OPTICAL SYSTEM DESIGN

Figure 1 shows the schematic diagram of the proposed fluorescence detection system, which is composed of an excitation light source (a light emitting diode (LED) in our implementation), excitation and emission bandpass filters, metal-coated hemispherical dome mirrors with different radii, and a photodetector. For the dome reflector surface, silver thin film was e-beam evaporated on the plastic shells to obtain high

reflectivity of more than 90% for the visible wavelength range. A sample droplet, which contains the target fluorescent molecules, is placed on the center of the hemispherical dome mirrors by the supporting nylon threads (See the inset of Fig. 1). The diameters of the upper and lower dome reflector are 25 mm and 27 mm, respectively.

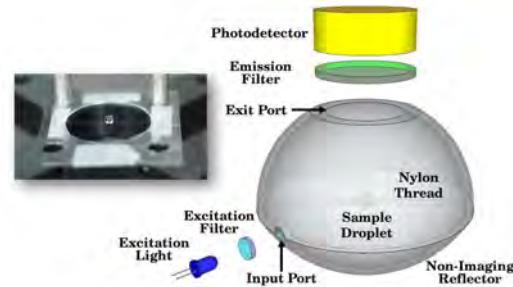


Figure 1. Schematic diagram of the proposed fluorescence emission detection system with non-imaging reflective optics. The inset shows a picture of a loaded sample droplet on the supporting threads.

The light emission from the fluorescence molecules in the sample covers the whole 4π steradians [4]. Due to its finite numerical aperture (NA), conventional lens-based optical microscopes cannot collect the entire fluorescence emission. Lens-based detection systems do not only waste a large fraction of fluorescence emission, but also becomes bulky and expensive especially when high-NA lenses are employed to achieve higher collection efficiencies [3].

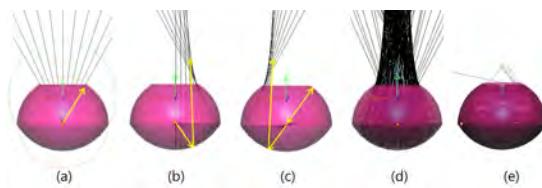


Figure 2. Ray tracing patterns of the radiation from the center (a-d) and the side (e). (a) Direct optical path to the photodetector. (b) Downward emission reflected by the lower dome mirror. (c) Upward emission exiting the output aperture after two reflections from the upper and lower dome mirrors. (d) All of the radiated rays from the sample position are shown. (e) The side-coupled light from the input port (defined in Fig. 1) is essentially trapped inside the dome reflectors.

From the ray optics point of view, there exist three possible ways for the emitted fluorescence from the sample droplet to arrive at the photodetector in our optical design. The first way is the direct optical path

from the sample to the sensor (Fig. 2 (a)). Second, the downward emission is reflected from the lower dome reflector and then arrives at the photodetector as shown in Fig. 2 (b). For this second pathway, the fluorescent signal is reflected only once. The last possibility is to arrive at the photodetector after reflected by both upper and lower hemispherical domes (Fig. 2 (c)). Note that the majority of the fluorescent light emission from the center of the non-imaging reflector (sample position) is nearly collimated and directed toward the photodetector with two or less reflections as described in Fig. 2 (d). The proposed dome reflector design is also efficient in separating the excitation beam from the fluorescent emission (Fig. 2 (d) and (e)). As shown in Fig. 2 (e), most of the light from the excitation input port is kept inside the structure.

III. RESULTS AND DISCUSSION

In our experiments, a blue LED with a 470 nm peak wavelength and ~40 nm spectral bandwidth was used to excite coumarin-derivative fluorescent molecules whose absorption spectrum has a good overlap with the LED emission (Fig. 3). A laser light source can also be used for excitation, but recent LED technologies provide enough optical pump power at various emission wavelengths while consuming smaller electrical power. Moreover, the proposed optical system design efficiently collimates the LED beams and recycles the unused pump beam by trapping the side-coupled LED light inside the non-imaging reflectors as indicated in Fig. 2 (e). The emission and excitation filters are used to reject the unwanted long wavelength components from the excitation beam and to improve the signal-to-noise ratio. The band edge wavelengths for the emission and excitation filters are 550 nm and 500 nm, respectively.

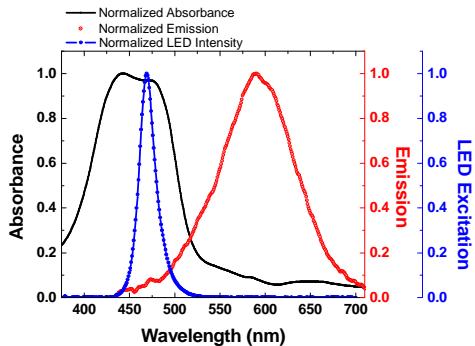


Figure 3. Absorption and emission spectra for the fluorescent molecule used in our experiments. The emission spectrum from the LED (blue curve) is also shown.

Photocurrents from the silicon photodetector were measured with various sample droplet volumes (Fig. 4). The sample droplets were either the fluorescent molecule solution (41 μM concentration) or water for control experiments. Each droplet is loaded on the sample position inside the hemispherical dome reflectors with a micropipette which can control the droplet volume with 0.2 μL accuracy.

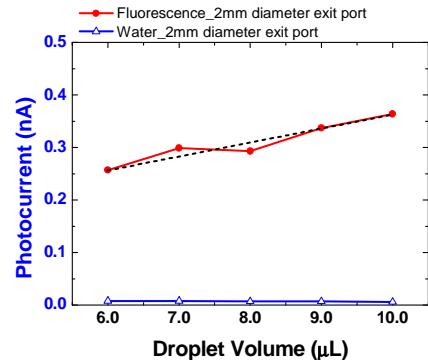


Figure 4. Measured photocurrents from the fluorescent (red curve) and water (blue curve) droplets with different droplet volumes.

The red curve in Fig. 4 shows the photocurrent when the fluorescent droplet is loaded. The fluorescence signal increases with the droplet volume (and therefore the total dose of the fluorescent molecules), and its signal-to-noise ratio at 10 μL droplet volume is ~59. The blue curve represents the results of control experiments using non-fluorescent water droplets. The excitation light scattered from the droplet and reflectors is mostly blocked by the emission filter in front of the photodetector, and only the photodetector dark current is detected.

IV. CONCLUSION

In summary, we demonstrated a compact and efficient fluorescence detection system with non-imaging integrating reflectors and an LED light source, which can be implemented in a cost-effective manner. The device dimensions can be further miniaturized, and the whole system can be integrated in a smaller form factor (currently 25 mm diameter). The prototype system detects the fluorescent signal with the signal-to-noise ratio of ~59 from a ~10 μL sample volume at ~41 μM concentration.

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