



LIFGO: A modular laser-induced fluorescence detection system based on plug-in blocks

Meng-Ting Zhang^{a,1}, Ya-Mei Peng^{a,1}, Jian-Zhang Pan^{a,b,**}, Xiao-Xia Fang^a, Han-Yang Li^a, Xiao-Yang Zhang^a, Yu-Cheng Liao^a, Jia-Kang Yao^a, Ming-Lin Wu^a, Yuan-Yang Yao^a, Qun Fang^{a,b,c,d,*}

^a Institute of Microanalytical Systems, Department of Chemistry, Zhejiang University, Hangzhou, 310058, China

^b Hangzhou Innovation Center, Zhejiang University, Hangzhou, 311200, China

^c Key Laboratory of Excited-State Materials of Zhejiang Province, Zhejiang University, Hangzhou, 310007, China

^d College of Chemistry, Zhengzhou University, Zhengzhou, 450001, China

ARTICLE INFO

Keywords:

Laser induced fluorescence detection system
Modular construction
LEGO blocks
3D printing

ABSTRACT

In this work, a laser-induced fluorescence (LIF) detection system built in a modular assembling mode was developed based on commercial LEGO blocks and 3D printed blocks. We designed and fabricated a variety of 3D printed building blocks fixed with optical components, including laser light source, filters, lens, dichroic mirror, photodiode detector, and control circuits. Utilizing the relatively high positioning precision of the plug-in blocks, a modular construction strategy was adopted using the flexible plug-in combination of the blocks to build a highly sensitive laser-induced fluorescence detection system, LIFGO. The LIFGO system has a simple structure which could be constructed by inexperienced users within 3 h. We optimized the structure and tested the performance of the LIFGO system, and its detection limits for sodium fluorescein solution in 100 μM i.d. and 250 μM i.d. capillaries were 7 nM and 0.9 nM, respectively. Based on the LIFGO system, we also built a simple capillary electrophoresis (CE) system and applied it to the analysis of DNA fragments to demonstrate its application possibility in biochemical analysis. The separation of 7 fragments in DL500 DNA markers were completed in 600 s. Because of the features of low cost (less than \$100) and easy-to-build construction, we introduced the LIFGO system to the experimental teaching of instrumental analysis for undergraduate students. The modular construction form of the LIF detection system greatly reduces the threshold of instrument construction, which is conducive to the popularization of the LIF detection technique in routine laboratories as well as the reform of experimental teaching mode.

1. Introduction

Laser-induced fluorescence (LIF) detection is one of the most sensitive spectroscopic detection techniques with sub-picomolar detection limits [1,2]. LIF detectors are frequently used as optical detectors in capillary electrophoresis (CE), flow cytometry, and high-performance liquid chromatography systems [3–5], for the analysis of amino acids, lipids, polysaccharides, peptides, proteins, and nucleic acids, as well as for the analysis and sorting of cells and bacteria [6–9].

A typical LIF system generally has complex optical structure consisting of a laser light source, optical modules (such as filters, lens,

dichroic mirror), detector, and control circuits with a bench-top instrument size. To build a LIF system in a laboratory usually needs to be carried out on an optical regulation platform, and has relatively high requirements on the professional optical, electronic and mechanical skills and assembly capabilities of the builder. In recent years, with the urgent demand for in-situ analysis such as Point-of-Care Testing (POCT), some miniaturized and portable LIF detection systems have been developed. In 2005, Fruetel et al. [10] reported a handheld CE analyzer with a total size of 11.5 × 11.5 × 19.0 cm³, in which a LIF module with dimensions of 7.5 × 5.5 × 3 cm³ was integrated. The LIF module incorporates a 405 nm laser diode (LD), two 0.60 numerical aperture (NA)

* Corresponding author. Institute of Microanalytical Systems, Department of Chemistry, Zhejiang University, Hangzhou, 310058, China.

** Corresponding author. Institute of Microanalytical Systems, Department of Chemistry, Zhejiang University, Hangzhou, 310058, China.

E-mail addresses: kelvonpan@zju.edu.cn (J.-Z. Pan), fangqun@zju.edu.cn (Q. Fang).

¹ Meng-Ting Zhang and Ya-Mei Peng have equal contribution to this work.

aspherical lenses, a photomultiplier tube (PMT) and other optical components with detection limits of 10^{-11} M for fluorescent dyes and 10^{-9} M for fluorescing amine-labeled proteins, respectively. Singh et al. [11] also reported an immunoassay chip-based platform for point-of-care testing of biological toxins in body fluids in 2009. The platform, with a total size of $23 \times 20 \times 13$ cm 3 , included an immunoassay chip, a miniaturized LIF system, fluid handling components, and other control systems. It was used in microfluidic electrophoretic immunoassays for staphylococcal enterotoxin B, Shiga toxin I, and ricin with detection limits of 0.3, 0.5, and 20 nM, respectively. In a work by the authors' group [12] in 2009, a concave LED and a photodiode were used to construct a LIF detector that collects fluorescence at a 45° angle. The module has dimensions of $5 \times 12 \times 6$ cm 3 and a detection limit of 0.92 μM sodium fluorescein at a cost of less than \$50. In 2010, Mathies' group [13] developed a compact laser-induced fluorescence detection scanner with a total size of $30 \times 30 \times 20$ cm 3 . To excite the sample in a 96-channel microchip, a rotating rhombic prism was used so that the laser beam sequentially scans the 96 channels. The detection limit of the fluorescent dye is ~20 pM. In 2012, Pu et al. [14] developed an economical fluorescence detector that used an LED as the excitation source and a low-cost avalanche photodiode (APD) module as the photonic sensor. The system size was $15 \times 7 \times 24$ cm 3 , the cost of the whole system was close to £150 (including the support frame and dark box), and the detection limit was 0.2 nM for sodium fluorescein. A handheld PCR instrument with dimensions of $7.1 \times 12.1 \times 4.7$ cm 3 was developed by Lin et al. [15] in 2014, which integrated an orthogonal LIF detector, using a diode-pumped laser as the light source and a PMT as the photodetector. The system could be used as a stand-alone device, and combining the system with CE resulted in detection limits of 6.3 and 7.2 pg/μL for 100 and 200 bp DNA fragments, respectively. The authors' group [9] developed a compact handheld LIF detector based on a quasi-confocal optical configuration in 2016. It integrates a 450 nm laser diode light source, an optical module, a photomultiplier tube, and a signal recording, processing, and display unit with a total size of $9.1 \times 6.2 \times 4.1$ cm 3 . It could be used as a stand-alone detector and flexibly connected to various analytical systems. In 2018 [16], we developed another miniature handheld high-speed capillary system with an integrated orthogonal LIF detection module. The fluorescence was collected in a plane perpendicular to the laser beam at an angle of 45° to the capillary. The size was only $90 \times 75 \times 77$ mm 3 and the instrument cost was reduced to ca. \$500, with a detection limit of 1.02 nM for sodium fluorescein solution. In 2018, Guan's group [17] developed a compact and low-cost LIF detector based on a 450 nm LD and a Si photodetector instead of a PMT, which significantly reduced the detector's total size and cost to 1/2–1/3 and less than 1/3 to commercial LIFs, respectively. In 2021, the authors' group [18] built a handheld LIF detection system with a size of only $50 \times 20 \times 46$ mm 3 , with a cost of \$380 and a detection limit of 10 pM for sodium fluorescein. Although the size and cost of these miniaturized LIF systems have been significantly reduced, their construction process still requires precise adjustment of the optical path and professional machining and assembly capabilities.

In this work, a LIF detection system built in a modular assembling mode based on commercial LEGO blocks and 3D printed blocks of optical components and modules was developed. The system named LIFGO has simple structure and low cost, which could be constructed by inexperienced users in a short time. We applied the LIFGO system to the CE separation of DNA fragments and the experimental teaching of instrumental analysis for undergraduate students.

2. Experimental section

2.1. Reagents and materials

All chemicals were reagent grade. Sodium fluorescein served as fluorescent dye was purchased from Shanghai Biotech Co. In the separation of DNA fragments, Super Gel Blue (Bayside, Suzhou, China)

labeled DNA markers (50–500 bp, Takara, Dalian, China) and polyvinyl pyrrolidone (PVP, 437,190, Sigma, St. Louis, USA) dissolved in 1 × TBE (pH 8.0) (Sangon Biotech, Shanghai, China) were used as the DNA model sample and sieving substrate, respectively. The preparation procedure for DNA sample and sieving substrate was similar to that described previously [19].

2.2. Fabrication of optical module based on 3D printed building blocks

In this work, 3D printing technique was used to fabricate the building blocks for fixing optical components to form the modules of light source, lens, capillary, dichroic mirror and detector. These blocks made of polylactic acid (PLA) were produced by a 3D printer (Flsun, Portland, USA). Their bottoms were fabricated with the plug-in fixing structure similar to those of commercial LEGO blocks, so that they can be completely matched and tightly fixed with commercial LEGO blocks.

The light source module (Fig. 1A) included a laser diode and its

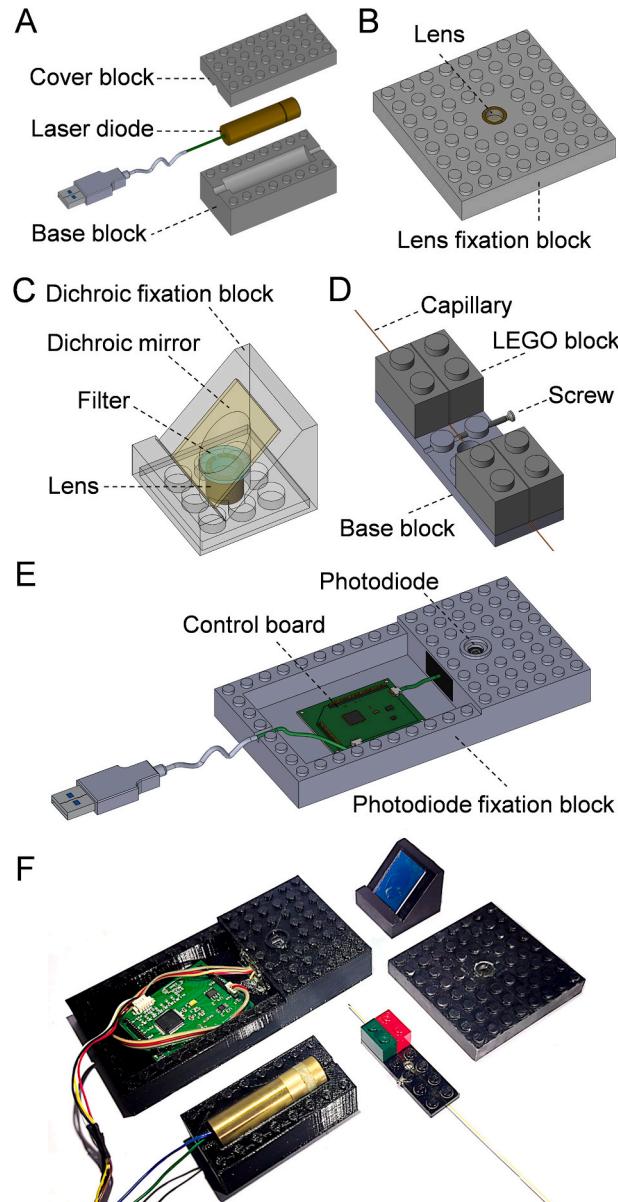


Fig. 1. 3D printed building blocks and corresponding modules used in the LIFGO system. (A) Light source module; (B) Lens module; (C) Dichroic module; (D) Capillary fine-tuning module; (E) Detector module; (F) Photos of these modules.

fixation blocks. The fixation blocks consisted of a base ($63.8 \times 31.8 \times 19.2 \text{ mm}^3$, length \times width \times height) and a cover ($63.8 \times 31.8 \times 9.6 \text{ mm}^3$) blocks with a cylindrical cavity (19 mm length, 12.9 mm diameter) in the center of the block to load the laser diode (488 nm, PL488B, Osram, Munich, Germany). Two small holes were fabricated on both sides of the block to allow the laser beam and the light source wire to pass through, respectively.

The lens fixation block was used to fix the laser focusing lens (1.0 numerical aperture, 8.0 mm working distance, Leimai Electronics, Guangzhou, China) with a size of $63.8 \times 63.8 \times 9.6 \text{ mm}^3$, in which a through-hole with a diameter of 8.8 mm was fabricated. The inside of the through hole was tapped to produce internal threads, and the lens with external threads could be screwed into the hole to different depths to realize the fixing of the lens and the adjustment of the distance between the lens and the capillary (Fig. 1B).

The dichroic mirror module (Fig. 1C) was built based on a 3D printed 45° slope block ($31.8 \times 31.8 \times 27.6 \text{ mm}^3$) where a dichroic mirror (505 nm, DM505, HB Optical Technology Co., Shenyang, China), a filter (525-nm bandpass, BP525, HB Optical Technologies, Shenyang, China) and a fluorescent collection lens (1.0 numerical aperture, 8.0 mm working distance, Leimai Electronics, Guangzhou, China) were installed. A vertical through-hole was produced in the center of the block for light transmission.

The capillary fixation module was composed by four LEGO bricks 1×2 ($7.8 \times 15.8 \times 9.6 \text{ mm}^3$) and a LEGO plate 2×6 ($47.8 \times 15.8 \times 3.2 \text{ mm}^3$) as the base plate. A small hole with a diameter of 4 mm was produced in the center of the LEGO plate to transmit the excitation light and a small screw was installed on a cylinder on the plate to finely adjust the position of the capillary on the horizontal plane (Fig. 1D).

In the detection module (Fig. 1E), two chambers were produced by a set of building blocks, one chamber ($20 \times 10 \times 26 \text{ mm}^3$) was used to install the photodiode (S8745-01, Hamamatsu Photonics, Hamamatsu, Japan), and the other chamber ($48 \times 32 \times 12 \text{ mm}^3$) was used to fix the control circuit board. A thin block covered the control circuit board chamber.

2.3. Building of the LIFGO system

The construction flow chart of the modular LIF detection system is shown in Fig. 2. During the construction of the system, the detection module was first installed as the bottom block (Fig. 2A). Then, the light source module and the dichroic mirror module were fixed on the photodiode module according to the instruction in Fig. 2B to achieve the alignment of the optical path by using the positioning function of the LEGO blocks. Some general LEGO blocks were used to surround the two optical modules to form an outer frame (Fig. 2C). The lens module was installed on the top of the dichroic module with the lens aligned with the center of the dichroic mirror (Fig. 2D). Finally, the capillary fixation module was installed on the lens module and the capillary on the module was roughly aligned with the center of the lens (Fig. 2E). An exploded view of the structure of the modular LIF system with a dimension of $128 \times 64 \times 70 \text{ mm}^3$ is shown in Fig. 2F.

The modular LIFGO detection system has a quasi-confocal optical configuration (Fig. 3), which consists of a laser diode, a filter, a dichroic mirror, two lenses, a photodiode detector, and a control circuit. The laser diode with 488 nm wavelength in the light source module is used to excite the fluorescence. The laser beam is reflected by the dichroic mirror with high reflectivity below 505 nm and high transmittance above 505 nm and focused onto the center of the capillary channel by the lens in the lens module. The laser spot at the focal point excites the fluorescent analyte in the sample solution inside the capillary. The fluorescence emitted by the analyte in the capillary channel is collected by the same lens, passes through the dichroic mirror and the 525-nm bandpass filter in the dichroic mirror module, and finally is detected by the photodiode in the photodiode module. The fluorescence signals are converted into electrical signals via the data acquisition module.

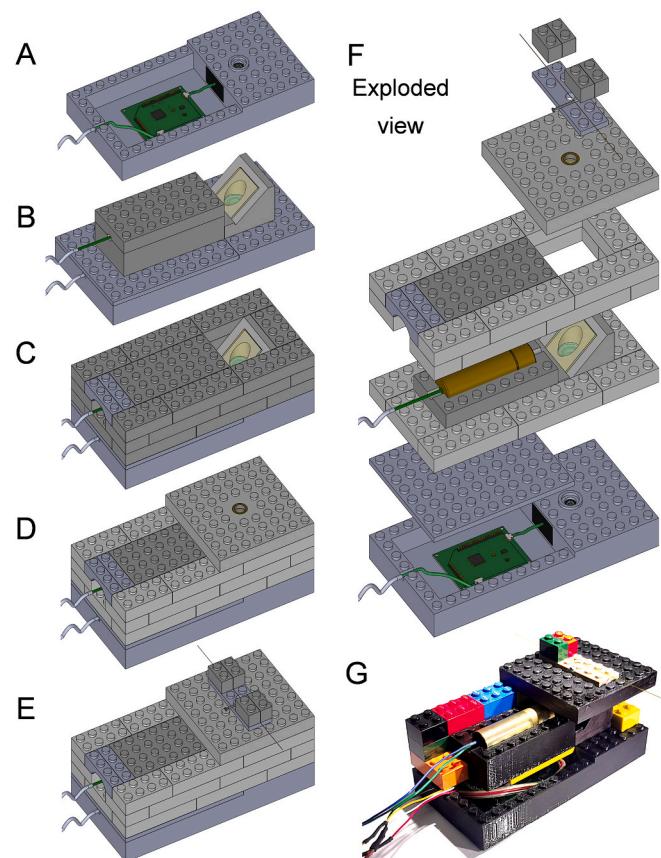


Fig. 2. Schematic diagram of the construction process (A–E), exploded view (F), and actual photo (G) of the LIFGO system.

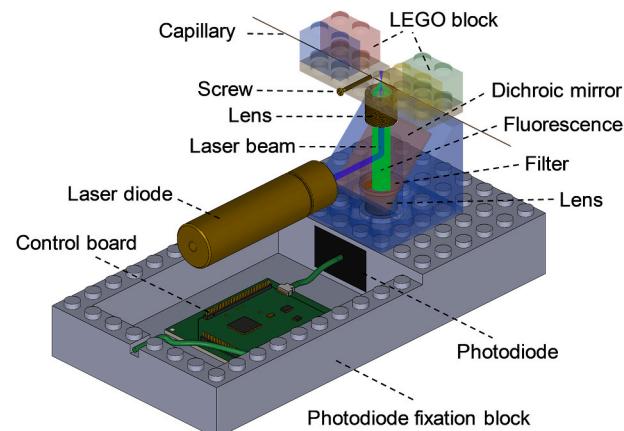


Fig. 3. Schematic diagram of the optical path structure of the LIFGO system. The gray color of the blocks is used only for clearly exhibit the structure of the system, while black blocks are actually used in all optical modules. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.4. Construction of a CE system based on LIFGO

Based on the modular LIF detection system, we built a high-speed CE system with a slotted-vial array [19–23] for sample injection. A fused silica capillary (12 cm long, 375 μm o.d., 100 μm i.d.; Refine Chromatography Co., Yongnian, China) was used as the separation channel. The slotted-vial array for loading samples, running buffer, and waste solution was produced by horizontally fixed 200 μL PCR tubes (Axygen,

Union City, USA) with a 1–2 mm slot in their bottom. The slotted-vial array was fixed in alignment with the capillary inlet, allowing that the capillary inlet end could be immersed into the solution in the target slotted vial through the slot, and the switching of different solutions to the capillary inlet could be performed by linearly moving the slotted vial array. A small high voltage power supply (DW-P602-0.2F76, Dong-wen Co., Tianjin, China) was used to provide variable high voltages in the range of 0–6000 V for sample injection and CE separation by inserting two Pt electrodes in the sample, running buffer and waste vials, respectively.

2.5. Procedures

2.5.1. Fluorescence detection with LIFGO

In the fluorescence detection experiment of the LIFGO system, sodium fluorescein was used as model sample and a 12-cm-long fused silica capillary (250 μm i.d., 375 μm o.d.) with a detection window located at about 8 cm from the capillary inlet which was produced by removing 0.5-cm long polyimide coating of the capillary. To focus the laser beam on the center of the capillary channel, a 100 nM fluorescein solution was first introduced into the capillary by using a 1.0 mL syringe connected with the capillary via a Tygon tube (0.25 mm i.d., 2.5 mm o.d.) to aspirating the solution, and then the focusing lens located in the lens module and the small screw in the capillary fixation module were finely adjusted until the maximum fluorescence signal was obtained. The fluorescence signals detected by the photodiode were recorded and displayed on a notebook computer screen under the control of a homemade LabVIEW program.

For the measurement of different sample solutions, the syringe was used to sequentially aspirate the solutions into the capillary for detection. For avoiding the cross contamination between different samples, a washing solution of deionized water was introduced into the capillary before the introduction of a new samples to wash its channel until the fluorescence signal reached the baseline level.

2.5.2. Instrumental analysis teaching experiment with LIFGO

In the exploratory experiment based on the LIFGO system of the instrumental analysis course for undergraduates or graduates, the students participating in the class can be divided into groups with 2–4 people in each group. After briefly introducing the LIF working principle and the procedure guide for building the LIFGO system, the students begin to build their own LIFGO systems as described in section 2.3. Each 1–2 group of students are assigned with an assistant to guide the construction operation and help the students solve the problems arose during the construction process. After the device is set up, a detection performance test experiment is carried out, including preparing a series of sodium fluorescein standard solutions, sequentially introducing these standard solutions into the capillary channel with a syringe, measuring the fluorescence signals, drawing a standard curve and calculating the limit of detection of the LIFGO system as described in section 2.5.1.

2.5.3. Separation of DNA fragments with the LIFGO-based CE system

Before the experiment, Super Gel Blue dye (Bayside, Suzhou, China) serving as the fluorescent dye, was added to 6% (v/v) and polyvinyl pyrrolidone (PVP, 437,190, Sigma, St. Louis, USA) solution as sieving medium with a mixing volume ratio of 1:10,000. The height of the slotted-vial array was adjusted so that the slotted vial in the array and the waste vial at the capillary outlet were on the same level. Then, 30 μL sieving medium and 30 μL DNA sample were added to the slotted vial and 30 μL sieving medium to the waste vial, respectively. The capillary was filled with the sieving medium solution and then fixed on the capillary fixation plate. The inlet and outlet of the capillary were inserted into the sieving media solution filled in the sieving medium vial and the waste vial through the slots, respectively. A high voltage was applied between the two electrodes inserted in the slotted sieving medium vial and the waste vial. The sample injection was performed by

linearly moving the slotted vial array to allow the inlet end of the capillary to immerse in the DNA sample for a definite time under the driving of high voltage, and then to remove from the sample solution and immerse in the sieving medium vial for sample separation.

2.6. Safety considerations

To avoid laser damage to the eyes, the intensities of all the lasers used in the experiments should be pre-reduced to 4 mW, and laser protection goggles should be worn when the laser light sources are illuminated.

3. Results and discussion

3.1. System design

In this work, we aimed to design an integrated and low-cost LIF detection system that can be easily built by the means of modular assembly of building blocks in routine laboratories or even in classrooms of experimental teaching.

The LEGO blocks are known for their high structural accuracy and easy and flexible assembly, and usually the positioning accuracy of the plug-in operation between LEGO blocks can reach 20 μm . In recent years, the application of LEGO blocks in building low-cost scientific instruments and equipment has been reported [24–27]. Due to these characteristics and applications, we also chose the LEGO blocks as the basic structural units in building the present modular LIF detection system. However, because the LIF detection system is an optoelectronic instrumental device with complex structure, only relying on commercial LEGO blocks cannot achieve the fixation and assembly of the optical components of the LIF system. For example, due to the irregular appearance and size of the optical components, such as laser diode, lens and photodiode, it was difficult to couple them directly with the commercial LEGO blocks. To solve this problem, we designed special building blocks for these optical components that were fabricated by 3D printing technique. These 3D printed building blocks could not only be coupled fixedly with the system components including the laser diode, lenses, filter, dichroic mirror, and photodiode, but also fabricated with the pillar array in each block similar to LEGO blocks to realize the plug-in combination with other blocks. We tested the positioning precision of the LEGO blocks and blocks fabricated by the stereolithography appearance (SLA) and fused deposition modeling (FDM) 3D printing method, and the positioning precisions of these blocks were ca. 28, 29 and 27 μm , respectively. Thus, the 3D printed blocks have the similar positioning precision to the commercial LEGO blocks. This positioning precision ensured the direct alignment of most of the optical components fixed on the blocks in the optical path, including the laser, filter, dichroic mirror, focusing lens, fluorescent filter, and photodiode, by simply relying on the pre-positioning of the components on the 3D-printed blocks and the plug-in operation of the building blocks during the construction process of the system. Even for the alignment of the capillary with the laser focus spot, this plug-in method could be used to achieve the preliminary positioning of the capillary to the laser spot. This construction mode significantly simplifies the building operation of the LIFGO system, allowing it can be successfully set up in a routine laboratory without the need of a professional optical platform and professionals.

In the LIFGO system, some fine-adjusting structures were designed in the building blocks to achieve higher positioning precision. A threaded structure on the lens fixation block was designed to match the lens so that the height of the laser focusing point could be adjusted by simply rotating the lens. A screw was also installed on the capillary fixation block. The screw could be rotated to push the capillary to slightly change the horizontal position of the capillary relative to the laser beam. This adjustment method has the features of small device size, low cost, simple and convenient operation compared with the traditional adjustment method based on an optical stage.

3.2. Alignment of the laser spot on detection channel

The alignment of the laser focusing spot to the center of the capillary channel is critical to ensure the detection sensitivity of a LIF system. In some previous LIF systems, several methods of laser focusing spot alignment were used, such as visual and real-time imaging focusing [2, 28], laser radiation temperature measurement [29], and microscope focal plane alignment [18] methods. These systems usually require the use of sophisticated measurement instruments and are cumbersome and time-consuming in alignment operation.

In present work, we used an easy method for laser focusing spot alignment using a translucent tape as the imaging screen for the laser spot to assist in the initial focusing. More accurate focusing was achieved by monitoring the signal changes of the LIFGO system during the focusing process. For the initial focusing, a piece of a translucent tape (4 mm × 15 mm) was moved up and down along the laser beam to seek the vertical position of the focal spot of the laser beam, where the smallest and brightest laser spot could be observed on the tape. Then, the capillary fastened on the capillary fixation block was located on the plane of the focal spot. We designed the simple and easy-to-operate method for fine adjustment of the capillary horizontal position based on a small screw. This method only needs to install a small screw on the building block on the side of the capillary without the requirement of additional accessories such as an optical table, with which the horizontal position of the capillary could be finely adjusted within the range of 2 mm. It could align the center of the capillary channel with the laser focusing spot with the aid of the feedback to the fluorescence signals of the fluorescent dye filled in the capillary. The spot alignment accuracy obtained by this method is comparable to those obtained with the professional equipment such as imaging cameras or microscopes.

When the LIFGO system was used in teaching experiments for students, we also used a simpler laser spot alignment method with the aid of the relatively high positioning accuracy of the building blocks. A capillary with a larger inner diameter (such as 150 μm or 250 μm i.d.) was used to reduce the alignment difficulty. The capillary was pre-fixed in a V-shaped groove in the center of the capillary fixation block, and the rough alignment of the capillary channel and the laser spot could be realized directly through the plug-in operation of the building block without the need of additional adjustment operation.

3.3. Positioning accuracy test of the building blocks

In the modular LIFGO system, the positioning accuracy of the building blocks is a crucial factor for the detection performance of the system as well as the reliability and reproducibility of the system construction.

The positioning precisions of the capillary fixation blocks fabricated by both the FDM and SLA 3D printing techniques were tested. The capillary fixation block was repeatedly installed 20 times, and the variations of the relative position between the block and the adjacent LEGO blocks were measured by taking images of the blocks under a stereo microscope. The deviations of the block position fluctuation were calculated to be 28.9 μm and 27.4 μm for the SLA and FDM methods, respectively.

In addition, the precision of the laser spot alignment in a 100-μm-i.d. capillary fixed in a block fabricated by the SLA technique was tested. The block was installed 20 times, and the range and deviation of the laser spot position fluctuation in the capillary channel were 20.2 μm and 4.5 μm, respectively, showing the good positioning reliability of the LIFGO system.

3.4. Performance of the LIFGO system

Sodium fluorescein solutions with different concentrations were used as sample solutions to investigate the detection performance of the LIFGO system. As calculated from the data shown in Fig. 4, the detection

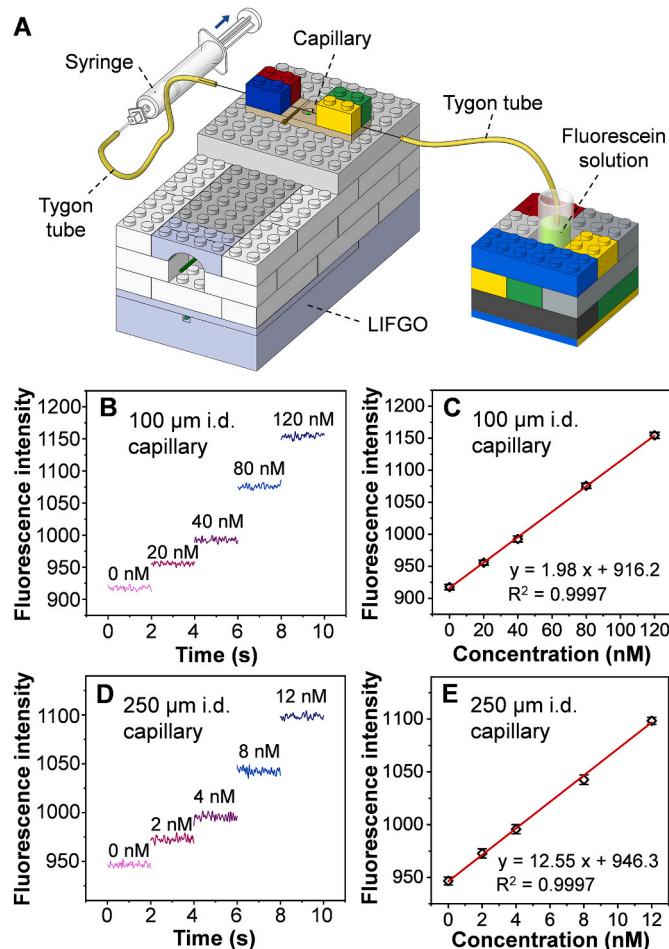


Fig. 4. (A) Schematic diagram of the LIFGO system for performance test; (B–E) Fluorescence signal recordings and calibration curves of series of standard fluorescein solutions in the detection performance test of the LIFGO system using capillaries with inner diameters of 100 μm and 250 μm, respectively.

limits of the LIFGO system for sodium fluorescein solution in 100 μm i.d. and 250 μm i.d. capillaries were 7 nM and 0.9 nM ($S/N = 3$), respectively. The repeatabilities of the fluorescence intensities of 10 nM and 5 nM fluorescein solutions in 100 μm i.d. and 250 μm i.d. capillaries were 2.3% and 1.8% (RSD, $n = 6$), respectively, indicating the good precision of the LIFGO system. These detection performances are comparable to many reported LIF systems [30–34].

3.5. Application to capillary electrophoresis separation of DNA fragments

Based on the LIFGO system, we built a capillary electrophoresis (CE) system by using the LIFGO system as a fluorescence detector and adopting a lab-constructed slotted-vial array system for sample injection. We applied the CE system in the separation of DNA fragments, using 6.0% PVP with 1 × TBE (pH 8.0) as the separation buffer as in the previous work [19]. Under the low electric field strength injection mode, the optimized conditions of 170 V/cm separations field strength, 5 s injection time, and 50 V/cm injection field strength were used to separate seven Super Gel Blue labeled DNA markers (50–500 bp, Fig. 5). The separation was completed in 600 s with a separation efficiency of 171, 970–369,350 N/m. The LIFGO based CE system offers the advantages of low cost and easy operation.

3.6. Application to instrumental analysis teaching experiments

Because of the modularity and low-cost features of the system, since

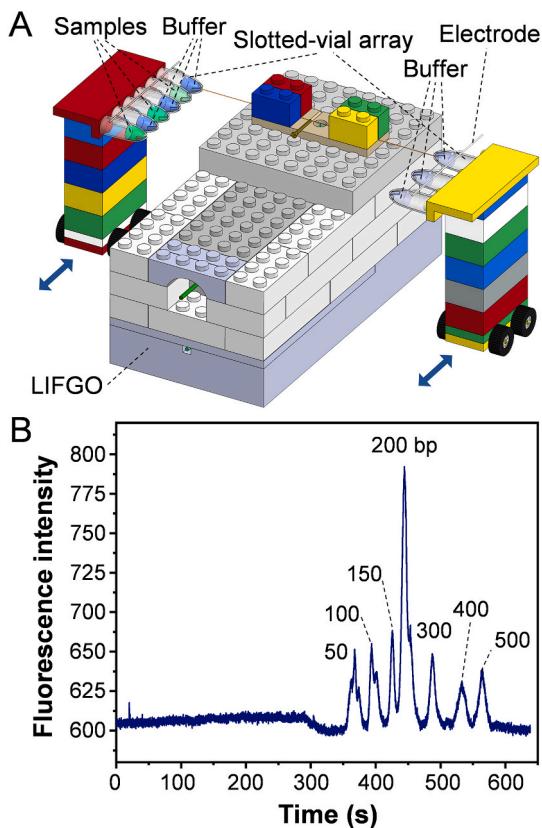


Fig. 5. (A) Schematic diagram of capillary electrophoresis system based on the LIFGO detector; (B) Electropherogram of gel electrophoresis separation of DNA fragments by the LIFGO-based CE system.

2013, we introduced the construction experiment of the LIFGO system in the teaching of instrumental analysis for undergraduates (Fig. 6). During the experiment, the students were grouped and instructed to use the provided LEGO blocks and 3D printed optical blocks to build the LIFGO system according to the procedure as shown in Section 2.3, and use the sodium fluorescein solutions with different concentrations to test the detection performance of the system as shown in Section 2.5.1.

This experiment has been carried out for eight years in the

instrumental analysis teaching experiment for second-year undergraduates in the Department of Chemistry of Zhejiang University. During these years, we continuously optimized the module structure, construction procedure and system testing method of the LIFGO system. Currently, most students participating in the experiment can complete the construction and testing of the LIFGO system within 3 h.

In traditional instrumental analysis experiments, students usually use commercial instruments (such as absorption spectrometers, chromatographs, and mass spectrometers, etc.) to complete the experiments according to the operating procedures, without the instrument building and disassembling process. The LIFGO-based experiment uses an open teaching mode. During the construction of the modular LIF detection system, students not only deepen their understanding of the principle of fluorescence analysis and the structure of the LIF detection system, but also improve their hands-on ability and problem-solving ability. This kind of exploratory experiment can significantly arouse students' interest and enthusiasm in learning instrumental analysis. In addition, in order to further expand students' scientific vision and innovative consciousness, during the experiment, we also encouraged students to use the provided building blocks to try a variety of different building block combinations to build a modular LIFGO system with different optical structures and configurations (Fig. 6).

4. Conclusions

In the present work, we developed a modular laser-induced fluorescence detection system based on LEGO blocks and 3D printed blocks. The LIFGO system has the characteristics of simple structure, small size, low cost, easy to build, and convenient to use. The modular construction form of the LIF detection system greatly reduces the threshold of instrument construction, allowing inexperienced users to complete the construction of a highly sensitive LIF system in a short time according to the operation procedure, which is conducive to the popularization of the LIF detection technique in routine laboratories. The detection performance of the constructed LIFGO enables it can be applied to general chemical and biochemical analysis as well as analytical chemistry teaching experiments. In particular, the experimental form of self-assembled modular instruments can broaden the mode for conducting experimental teaching. Furthermore, such a modular construction mode of instruments with building blocks can also be extended to the rapid construction of other types of analytical instruments, such as a capillary electrophoresis or flow injection analyzer.



Fig. 6. Field photos of undergraduate teaching experiments based on different generations of LIFGO systems.

Credit author statement

Meng-Ting Zhang: Investigation, Conceptualization, Methodology, Theoretical analysis, Writing - original draft, Ya-Mei Peng: Investigation, Conceptualization, Methodology, Jian-Zhang Pan: Conceptualization, Investigation, Methodology, Supervision, Project administration, Xiao-Xia Fang: Investigation, Conceptualization, Methodology, Han-Yang Li: Investigation, Conceptualization, Methodology, Xiao-Yang Zhang: Methodology, Yu-Cheng Liao: Methodology, Jia-Kang Yao: Methodology, Ming-Lin Wu: Methodology, Yuan-Yang Yao: Methodology, Qun Fang: Conceptualization, Investigation, Methodology, Theoretical analysis, Supervision, Writing - review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Financial supports from National Natural Science Foundation of China (Grant 21974122, 21827806, 32027802) are gratefully acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.talanta.2021.123063>.

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