

Fabrication of Fluorescent and Magnetic Multifunctional Polystyrene Microbeads with Carboxyl Ends

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Here, we present a strategy to fabricate multifunctional polystyrene (PS) microbeads with carboxyl ends which exhibit magnetism and fluorescence. The strategy includes two steps: the preparation of porous PS microbeads with carboxyl-ends by combination of dispersion polymerization and seeded polymerization, and the facile process of embedding quantum dots (QDs) and magnetic nanoparticles (MNPs) into microbeads. The results indicate that the multifunctional PS microbeads (MFMs) can be dispersed in water stably and are well suitable for target encoding, capturing, and enrichment.

Polymer microbeads, especially those with porous structure, can be used to enrich target molecules or functional nanoparticles and to increase the dynamic range of target detections for their large surface areas.¹ Recent advances in nanotechnology provide various high-quality nanoparticles with fluorescent,² magnetic,³ or electronic⁴ properties. Incorporation of functional nanoparticles into polymer microbeads can combine advantages and widen applications of both materials. For example, QDs encoded microbeads have shown great potential in multiplexed analysis of target molecules.⁵ However, only limited research focused on developing multifunctional microbeads that allow simultaneous target encoding, enrichment, and separation,⁶ it is necessary to develop novel approach to fabricate multifunctional microbeads with high efficiency. Recently, Nie et al. reported the fabrication of dual-function beads by doping QDs and MNPs into mesoporous silica beads,⁷ but in order to improve the biocompatibility and water-dispersibility of resultant beads, the dual-function beads had to be further coated by amphiphilic polymer. In addition, there are no functional groups on the surface of the resultant beads, which seems disadvantageous to integrating target molecules onto the beads.

In this letter, we report the strategy of fabricating carboxyl capped multifunctional microbeads (MFMs) with both fluorescence and magnetism. The strategy includes two steps: preparation of porous PS microbeads with carboxyl-ends by combination of dispersion polymerization, seeded polymerization,⁸ and the facile embedding process of QDs and MNPs by synchronously adding these two kinds of functional nanoparticles into the solution of PS beads. As is well known, MNPs possess excellent superparamagnetic property, and QDs have unique optical and electronic properties such as size-tunable light emission, improved signal brightness, resistance against photobleaching, and simultaneous excitation of multiple fluorescence colors. Therefore, the resultant MFMs are anticipated to be the novel microcarriers which possess surface functional groups, well water-dispersibility, fluorescence, as well as magnetism.

Our two-step strategy is illustrated in Figure 1. For the first step of preparing porous PS microbeads, the 2.76 μm PS seed

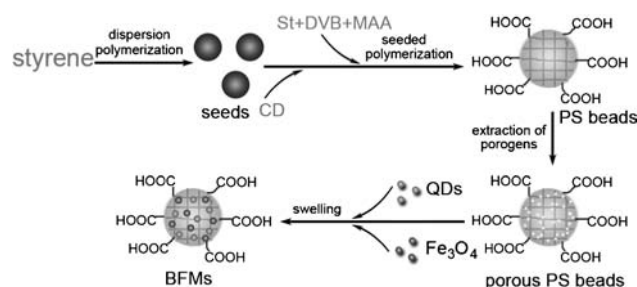


Figure 1. Schematic illustration of our strategy to fabricate multi-functional PS microbeads.

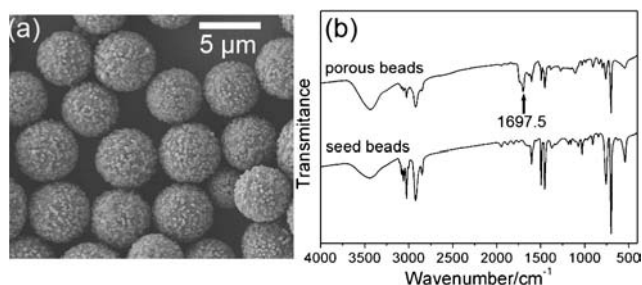


Figure 2. (a) SEM image of carboxyl-capped porous PS microbeads and (b) FT-IR spectra of seed beads and carboxyl-capped porous beads.

beads with $M_n = 17,500$ were firstly produced by dispersion polymerization.⁹ Afterwards, seed beads were activated by hydrophobe chlorododecane (CD) for 24 h, and activated microbeads were swollen with styrene (St), divinyl benzene (DVB), and methyl acrylate acid (MAA) for another 24 h, then the polymerization was initiated by benzoyl peroxide (BPO) and carried out at 70 °C for 24 h. Thereafter, as-prepared microbeads were extracted with dichloromethane for 48 h in a Soxhlet apparatus to remove porogens and obtain porous microbeads. 4-nm CdSe quantum dots coated with oleic acid¹⁰ and 12-nm Fe_3O_4 nanoparticles¹¹ coated with oleic acid were prepared, as we reported previously, and dissolved in chloroform for further use. For the incorporation procedure, 0.5 mL of ca. 10 nM QDs and 0.25 mL of ca. 5 nM MNPs solution in chloroform were simultaneously added into 0.5 mL of microbead solution in chloroform containing ca. 10^7 beads. The solution was stirred in atmosphere at 25 °C until chloroform was thoroughly evaporated. Then, microbeads were washed with butanol and ethanol, respectively, three times to remove unincorporated QDs and MNPs and collected by centrifugation at 6000 rpm for 5 min followed by magnetic separation.

Figure 2a shows the SEM image of carboxyl-capped porous microbeads. The number average diameter and coefficient varia-

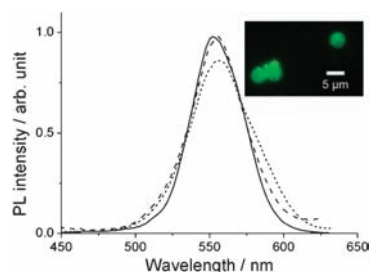


Figure 3. Normalized photoluminescent (PL) spectra of QDs in chloroform solution (solid line), aqueous solution of MFMs immediately after preparation (dash line), and aqueous solution of MFMs 50 days after preparation (dot line). $\lambda_{\text{ex}} = 400$ nm. The inset is a true color fluorescent microscopic image of MFMs.

tion of porous microbeads can be determined as $4.8 \mu\text{m}$ and 4.3% by measuring about 200 random microbeads on SEM images. The uniformity of tailored microbeads facilitates the multiplexed optical coding of fluorescent microbeads. Additionally, the microbeads display obvious porous structure, which originates from the extraction of linear PS porogens. The porous beads are favorable for embedding nanoparticles, because the pores in beads allow rapid and deep diffusion and provide more surface areas for immobilization of nanoparticles.¹² Figure 2b shows the FT-IR spectra of seed beads and carboxyl-capped porous beads. Obviously, the characteristic peak of $-\text{COOH}$ stretching vibration can be detected at 1697.5 cm^{-1} in the spectrum of porous beads, which indicates the presence of carboxy groups. Since MAA is far more hydrophilic than St and DVB, it is reasonable to conclude that carboxyls distribute mainly on the periphery of microbeads. Besides, the zeta potential of PS porous microbeads is -26 mV , which further confirmed the presence of carboxyls on the surface of microbeads.

Figure 3 shows the photoluminescent (PL) spectra and the true color fluorescent microscopic image of MFMs. The half-width of emission spectrum of MFMs was nearly the same as QDs in chloroform solution, and only a slight red shift (ca. 5 nm) was observed, which indicated that QDs were incorporated into the beads without aggregation with themselves¹² or Fe_3O_4 . PL intensity of MFMs 50 days after preparation still maintain ca. 90% compared with MFMs immediately after preparation, indicating very limited escape of QDs from microbeads in aqueous environment. The high brightness of fluorescent microscopic image indicates that as-prepared MFMs are bright enough for the multiplexed encoding of beads, which has potential application in high-throughput biological analysis.

The magnetic property of MFMs was recorded using a vibrating sample magnetometer at 305 K. As shown in Figure 4, hysteresis loop indicates that the MFMs are superparamagnetic with a supersaturation magnetization of 0.5 emu/g , which indicates that the superparamagnetic property of MNPs is not affected by simultaneous encapsulation into microbeads with QDs. As-prepared multifunctional microbeads are easy to be manipulated by an external magnetic field. As shown in the inset of Figure 4, MFMs display obvious fluorescence as excited by an ultraviolet lamp and can move to the side of magnet within a few minutes, which demonstrated their good fluorescence and magnetism. Moreover, considering the abundant carboxyls on the surface of MFMs which are easy to couple with biological agents or molecules, the MFMs can be directly used for biomed-

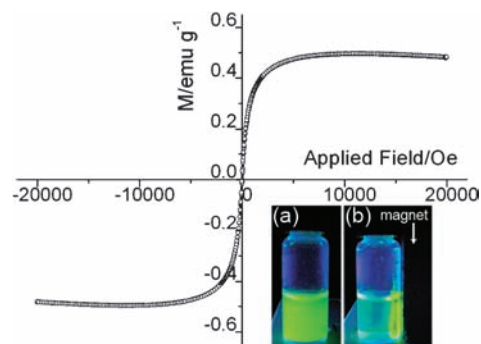


Figure 4. Magnetization curve of MFMs at 305 K. The inset is photographs of aqueous solution of MFMs excited by an ultraviolet lamp (a) without magnetic field and (b) after placing a magnet at the right side of the sample for 10 min. The emission wavelength of MFMs is 569 nm.

ical application without further surface modification.

In conclusion, the MFMs with carboxyl ends, fluorescence, and magnetism have been prepared by our two-step strategy. By combining the excellent superparamagnetism of MNPs and unique optical properties of QDs in carboxyl-capped polymer microcarriers, the resultant MFMs show great potential in multiplexed analysis and magnetic separation of target molecules.

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