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Micro Magnetic Gyromixer for Speeding up Reactions in Droplets

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Abstract

We report a novel micro magnetic gyromixer designed for accelerating mixing hence reactions in droplets. The gyromixer is fabricated with magnetite-PDMS composite using soft lithography. The mixer spins and balances itself on the droplet surface through the gyroscopic effect, rapidly homogenizing the enclosed reagents by stretching and folding internal fluid streamlines to enhance mixing. We examined the capability of the gyromixer for improving biochemical reactions in droplets by monitoring the biotin-streptavidin binding as a linker in a quantum dot fluorescence resonant energy transfer (QD-FRET) sensing system. The remotely controlled gyromixer exhibits high flexibility and potential for integration in a variety of droplet-based miniaturized total analysis systems (μ TAS) to reduce turnaround times.

Keywords

Magnetic; gyromixer; MEMS; droplet; quantum dot; microfluidics

1. Introduction

Microfluidic technology has made great advances in the past few decades with a great number of systems being developed for a wide range of applications (Whitesides 2006). While microfluidic technology has several advantages such as low reagent consumption and high throughput and portability, new problems arise due to the nature of laminar flow at the micro scale. The most widely recognized challenge of laminar flow is rapid fluidic mixing that is crucial in many assay processes such as cell lysis, molecular bindings and enzymatic reactions (Jones and Young 1994; Ho 2001; Ottino and Wiggins 2004; Stone, Stroock et al. 2004). In the absence of turbulence, fluidic mixing in the microsystems only relies on molecular diffusion, which can be slow and inefficient. To enhance mixing, increasing the interfacial area between fluids is necessary. Toward that end, many micro mixing strategies are realized either by passively stretching and folding fluid streamlines with microchannel configurations (Stroock, Dertinger et al. 2002; Theriault, White et al. 2003) or by actively perturbing the fluid with external actuation schemes (Niu and Lee 2003; Hessel, Lowe et al. 2005).

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In recent years, the development of discrete microfluidic systems has burgeoned (Fair 2007; Teh, Lin et al. 2008; Wheeler 2008). Such systems exploit the advantage of the dominance of surface tension at micro scale, partitioning the fluid into separate compartments that can be addressed individually. The droplet microfluidic systems can be categorized into two major forms. In one form, picoliters to nanoliters sized droplets are created in a closed microchannel through designs that promote the natural development of interfacial instability (Baroud, Gallaire et al.; Korczyk, Cybulski et al.; Teh, Lin et al. 2008). Such systems allow parallel processing of a large number of reactions and show great potential for high-throughput digital biochemical analyses such as digital PCR (Beer, Hindson et al. 2007; Kumaresan, Yang et al. 2008) and single cell screening (Clausell-Tormos, Lieber et al. 2008; Edd, Di Carlo et al. 2008). In the other form, submicroliter to microliter sized droplets are manipulated on an open surface where the droplets function as the fluid containment and transportation units (Pipper, Inoue et al. 2007; Pipper, Zhang et al. 2008; Zhang, Bailey et al. 2009; Zhang, Park et al. 2011). Material transfers and biochemical reactions are realized through moving, merging and splitting the droplets using various actuation methods including surface acoustic wave (Guttenberg, Muller et al. 2005), electrowetting (Paik, Pamula et al. 2003), dielectrophoresis (Fan, Hsieh et al. 2009) and magnetic forces (Pipper, Inoue et al. 2007; Pipper, Zhang et al. 2008; Zhang, Park et al. 2011). Since droplets on the open surface can be individually addressed and manipulated in a valve- and pump-less manner, sophisticated bimolecular assays can be implemented into the droplet microfluidic systems without complex chip designs and the need for external fluidic couplings. Recent advances in open-surface droplet microfluidics have led to fully integrated genetic detection systems with the sample-in-answer-out capability (Pipper, Inoue et al. 2007; Pipper, Zhang et al. 2008; Zhang, Park et al. 2011). In order to perform molecular diagnostics from crude biosamples, one of the prerequisites is the ability to extract and purify the analytes of interest from the complex biomatrix. A genetic molecular diagnostic assay includes steps for cell lysis, DNA/RNA binding, washing and elution followed by PCR amplification and detection. Open-surface droplet microfluidic systems are able to perform all the aforementioned steps within droplets from crude samples and provide answers in a timely fashion, allowing healthcare personnel to make clinical decisions and interventions. Such systems have been applied to detect influenza (Pipper, Inoue et al. 2007), infectious pathogen, and cancer biomarker in blood samples (Zhang, Park et al. 2011), demonstrating great potential for point of care molecular diagnostics.

Compared to continuous flow systems, the open-surface droplet platform faces a greater challenge for efficient mixing as it operates with microliter sized droplets (Pipper, Inoue et al. 2007; Zhang, Park et al. 2011) with a characteristic length (~mm) larger than those of continuous flow systems by orders of magnitude. Nevertheless, mixing techniques that can be applied to open-surface droplet μ TAS platform remain scarce (Nguyen and Wu 2005). An electrical mixing scheme has been demonstrated by oscillating the droplets along an array of electrodes using electrowetting (Paik, Pamula et al. 2003). Drawbacks of this method includes the requirement of an additional parallel electrode plate made of expensive indium tin oxide (ITO) glass to sandwich the droplets, and the need for large chip area for translating droplets to induce chaotic mixing. More recently, a microsphere based active mixer has been proposed (Roy, Sinha et al. 2009), in which microspheres with iron oxide core form short chains that rotate with the magnetic field, which leads to active mixing in droplets. The mixing relies entirely on the self assembly of the microspheres into short chains, in which case the surface chemistry plays a vital role. Many droplet microfluidic assays utilize magnetic microspheres as the solid substrate for molecules and/or cells adsorption. Therefore, the surface of the microspheres is often functionalized using various types of chemistries, some of which would prevent the microspheres from forming short chains.

We report a micro magnetic gyromixer that spins on the surface of a droplet to twist, turn streamlines and promote mixing of fluids inside the droplet (Fig. 1). The shape of the mixer resembles the blades of mixing turbines (Fig. 1a). Six crescent-like blades are equally spaced and extended from the center circle (Fig. 1b). The gyromixer (1.8mm across from tip to tip and 100 μ m thick, Fig. 1c) is fabricated with magnetite-PDMS composite using the softlithography. Unlike continuous microfluidic systems where supporting structures, such as poles, caps and chambers, can be embedded in microchannels to pivot magnetic mixers and to provide rotating axis and containment (Liang-Hsuan, Kee Suk et al. 2002; Ryu, Shaikh et al. 2004; Tian, Zhang et al. 2010), droplet systems operate by moving the droplets freely on an open surface where no supporting structure is available to hold the magnetic mixers in position. As a result, the static micro mixer tilts and falls down onto the ground. To balance the micro mixer on the curved surface, a negative feedback system can be introduced to constantly adjust the position of the mixer. It is conceptually simple but technically intricate. A more practical approach is to exploit the advantage of the spinning motion, allowing the mixer to balance itself on the curved droplet surface through gyroscopic effect (Fowles 1986; Butikov 2006).

2. Experimental

2.1 Micro magnetic gyromixer fabrication

The micro magnetic gyromixer was fabricated by softlithography (Fig. 2) using a magnetite-PDMS composite created by mixing magnetite particles and PDMS with 1:1 weight ratio (Yamanishi, Yu-Ching et al. 2007). The magnetite-PDMS composite has a water contact angle of $90.8 \pm 2.5^\circ$. A 100 μ m thick SU-8 master was first lithographically defined onto the silicon substrate. The gyromixer patterns appeared as protrusion above the substrate. PDMS (Corning Inc.) was casted against the SU8 master. The patterns were transferred to the PDMS replica and appeared as depressions. Next, the PDMS replica was spin-coated with 1 wt% Teflon AF dissolved in FC-40 (DuPont) at 300rpm and baked at 80°C for 1 hour. The purpose of the Teflon coating was to prevent the magnetite-PDMS composite from sticking to the PDMS replica. The depressions on the PDMS replica were then filled with the magnetite-PDMS composite. Excess composite material was removed, leaving the magnetite-PDMS only inside the depressions. After that, the PDMS replica filled with the composite was baked at 80°C for at least 2 hours, during which the composite solidified into the shape of the gyromixers. Last, the magnetic gyromixers were lifted up from the PDMS replica.

2.2 Glass substrate preparation

All the device characterization and mixing experiments were performed on the glass substrate prepared in the same way. The glass cover slips (Fisher Scientific Inc.) were rinsed with isopropanol and distilled water. They were then blow-dried and baked at 200°C for dehydration. The cleaning and dehydration baking described above are optional. Spin coating was done with 1 wt% Teflon AF dissolved in FC-40 at 1000rpm with acceleration of 500rpm/s. Lastly, the Teflon coated glass cover slips were baked at 100°C for 10 minutes and 400°C for 10 seconds.

2.3 Image acquisition and analysis

One experiment was performed under ambient light conditions with food dye. All the other fluorescence based experiments were performed in a dark room with a UV lamp as the excitation source. Proper emission filters were mounted in front of the lens of a high speed digital camera (Casio Pro EX-F1). Videos were taken at 30 frames/second for all fluorescence based experiment. High speed videos were taken at 600 frames/second. Image frames were extracted from the videos using Adobe® Premiere® (Adobe). Time zero was

defined as the moment when the small drip got in contact with the sessile droplet. MATLAB programs were written for automatic image analysis. Please refer to online resource for details (Online Resource 4).

3. Results and Discussion

3.1 Gyromixer operation

We successfully demonstrated the micro gyromixer self balancing on the curved droplet surface through the proposed mechanism (Fig. 1d and 1e). A sessile droplet of 30 μL in volume was dispensed onto a piece of glass coverslip that was placed on a magnetic stir plate. Similar to the gyroscope, the mixer operates either in the sleeping or in torque induced precession (TIP) mode on a magnetic stir plate. The stir plate embeds a rotating circular magnet array that consists of several magnets evenly distributed along the circumference of a cycle. The magnetic field strength at the center measures $\sim 12\text{mT}$. The relative position of the droplet to the stir plate determines the torque that the gyromixer experiences and hence operation mode. When the droplet sits close to the center of the plate, we observe that the gyromixer operates in TIP mode. As the droplet moves outwards the edge of the magnet array, the gyromixer is observed to change to sleeping mode. With current design, we have observed gyromixer operate on the surface of the droplet as small as 3 μL (Online Resource Video 1). As the droplet becomes smaller, the edge of the gyromixer touches the substrate hence would no longer spin.

In sleeping mode, the gyromixer quickly aligns itself from an initial position to a fixed point where the mixer spins at a constant angular velocity and maintains its position on the droplet surface. It is found that the gyromixer always sits on the lower part of the droplet in sleeping mode (Figure 1d and Online Resource Video 2), which suggests under such circumstance there exists an upward component (in positive y' direction) of the magnetic force ($\mathbf{F}_m$) that it is able to counteract the effect of gravity and balance the tangential component of surface tension, resulting in zero net torque that allows the gyromixer to operate in sleeping mode and preventing the mixer from dropping to the substrate (Fig. 3 and Online Resource 4, Supp. Disc).

In TIP mode, the mixer also quickly aligns itself from an initial horizontal level to a fixed horizontal level where the net torque in y' direction is zero. In contrast to sleeping mode, gyromixer is always observed to sit on the upper part of the droplet in TIP mode (Figure 1e and Online Resource Video 3). In this mode, the magnetic force $\mathbf{F}_m$ has a tangential component in negative y' direction, hence is not able to balance the surface tension and gravity in tangential direction, resulting in a net force $\mathbf{F}_{\text{net}}$ in the tangential direction, which in turn produces a torque and induces the precession about the principle axis $\mathbf{Z}$ (Fig. 4 and Online Resource 4, Supp. Disc).

To facilitate the analysis, a rotational coordinate frame $x'y'z'$ is introduced in addition to the principle XYZ coordinate with the origin O being the centre of the droplet (Fig. 4). The rotation frame shares the same origin O . The z' axis coincides with the axis of symmetry of the gyromixer and rotates with gyromixer about $\mathbf{Z}$. The x' axis lies in the XY plane perpendicular to z' , and the y' axis is normal to the $x'z'$ plane. The overall motion of the gyromixer is the superposition of the spinning of the gyromixer about z' and torque induced precession about $\mathbf{Z}$ (Butikov 2006).

The spinning axis s passes through the centre of symmetry and points perpendicular to the top surface (Fig. 5). We numerically calculate the moment of inertia about the spinning axis s and two orthogonal axes t and t' in the transverse plane using SolidWorks based on the geometry (Fig. 5) and the measured density of the magnetite-PDMS composite (1.8 g/cm^3)

$$I_s = 30.6 \left(\mu\text{g} \bullet \text{mm}^2 \right) \quad (1a)$$

$$I_t = I_{t'} = 61.2 \left(\mu\text{g} \bullet \text{mm}^2 \right) \quad (1b)$$

$$I_t = I_{t'} = 2I_s \quad (1c)$$

where $\mathbf{I}_s$, $\mathbf{I}_t$ and $\mathbf{I}_{t'}$ are the moment of inertia about axes s , t and t' . In the current design, it is reasonable to approximate the spinner to be rotationally symmetric about the spinning axis s .

The precession speed can be determined using the fundamental equation of motion for the gyroscope (Fowles 1986)

$$\vec{\tau} = \left(\frac{d\vec{L}}{dt} \right) + \vec{\omega}' \times \vec{L} \quad (2)$$

where $\vec{\tau}$ is the torque, $\vec{L}$ is the angular momentum and $\vec{\omega}'$ is the angular velocity. The torque produced by the net force $\mathbf{F}_{\text{net}}$ is in $\mathbf{x}'$ direction (Fig. 4). The torques along $\mathbf{y}'$ and $\mathbf{z}'$ direction are equal to zero. Therefore, the fundamental equation can be rewritten as

$$\vec{\tau}_{x'} = \left(\frac{d\vec{L}_{x'}}{dt} \right) + \vec{\omega}'_{y'} \times \vec{L}_{z'} + \vec{\omega}'_{z'} \times \vec{L}_{y'} \quad (3a)$$

$$\vec{\tau}_{y'} = 0 = \left(\frac{d\vec{L}_{y'}}{dt} \right) + \vec{\omega}'_{z'} \times \vec{L}_{x'} + \vec{\omega}'_{x'} \times \vec{L}_{z'} \quad (3b)$$

$$\vec{\tau}_{z'} = 0 = \left(\frac{d\vec{L}_{z'}}{dt} \right) + \vec{\omega}'_{x'} \times \vec{L}_{y'} + \vec{\omega}'_{y'} \times \vec{L}_{x'} \quad (3c)$$

The angular velocities and angular moments are given by

$$\vec{L}_{x'} = I_t \vec{\omega}_{x'} = I_t \dot{\theta} \quad (4a)$$

$$\vec{L}_{y'} = I_t \vec{\omega}_{y'} = I_t \dot{\varphi} \sin \theta \quad (4b)$$

$$L_{z'} = I_s (\dot{\varphi} \cos \theta + \dot{\psi}) = I_s S \quad (4c)$$

where we use S to denote spin of the gyromixer about $\mathbf{z}'$.

With Equation S3 and Equation S4, we obtain the following expression,

$$\tau_{x'} = I_t \ddot{\theta} + I_s S \dot{\varphi} \sin \theta - I_t \dot{\varphi}^2 \cos \theta \sin \theta \quad (5)$$

The torque in y' and z' directions are not included because they equal to zero. In Equation 5,

$$\vec{\tau}_{x'} = \mathbf{R} \times \mathbf{F}_{net} = 0.66V^{1/3} \mathbf{F}_{net} \quad (6)$$

where $\mathbf{R}$ is the radius of the droplet. By treating the droplet as a spherical cap sitting on the Teflon AF coated glass substrate with a contact angle of 120° , $\mathbf{R}$ can be expressed in terms of volume $\mathbf{V}$ of the droplet by

$$R = 0.66V^{1/3} \quad (7)$$

We ignore the effect of the negligible nutation and assume θ remains constant, which leads to

$$\frac{d\vec{L}_{x'}}{dt} = I_t \ddot{\theta} = 0 \quad (8)$$

Substitute Equation 1c, 6, and 8 into Equation 5. After rearrangement, we obtain the following expression.

$$\dot{\varphi}^2 - \frac{2S}{\cos\theta} \dot{\varphi} + \frac{0.66V^{1/3}F_{net}}{I_t \cos\theta \sin\theta} = 0 \quad (9)$$

Interestingly, both roots of the quadratic equation are physically possible for a given value θ . As a matter of fact, the slower one is usually observed, although the other one can occur under certain initial conditions (Fowles 1986). If the magnetic field is too strong, which leads to larger F_{net} , the real roots of Equation 9 cease to exist. Under such conditions, the gyromixer is no longer operable.

When it operates in TIP mode, the gyromixer spins at ~ 2000 rpm and precesses at ~ 12 rpm. When the spinning speed is far greater than the precession speed, i.e.

$$|S| \gg |\dot{\varphi}| \quad (10)$$

the precession speed can therefore be approximated by

$$\dot{\varphi} \approx \frac{0.33V^{1/3}F_{net}}{I_t S \sin\theta} \quad (11)$$

We estimate the spinning speed, the precession speed and the angle θ in a high speed video clip taken at 1200 fps. The spinning speed is estimated to be ~ 2400 rpm, the precession speed is ~ 12 rpm and θ is $\sim 23^\circ$. Based on Equation (11), F_{net} is determined to be 7.4 nN.

3.2 Mixing in droplets with gyromixer

We monitored the progression of mixing in a droplet by tracing the fluids containing fluorescein. A 30 μ L of water was dispensed onto the substrate and formed a sessile droplet. At time 0, 1 μ L of 100 μ M fluorescein was added to the sessile droplet from the top. To promote mixing, the micro gyromixer was positioned on the sessile droplet. The spinning motion was initiated before adding the fluorescein drip. In sleeping mode (Fig. 6a), radiated from the gyromixer, the fluorescein streamlines swept a sector, extended, twisted and eventually evenly distributed over the entire droplet. In TIP mode, the fluorescein

streamlines were constantly stretched and folded along the path of the precession, which in this case was clockwise about the central axis of the sessile water droplet (Fig. 6b).

The mixing index (**M**) was calculated based on the colour information of the fluorescent images using the following expression (Liang-Hsuan, Kee Suk et al. 2002) (Online Resource 4)

$$M = \sqrt{\frac{1}{N} \sum_{k=1}^N \left(\frac{I_k - \bar{I}}{\bar{I}} \right)^2} \quad (12)$$

where N and $\bar{I}$ were the total number of pixels and the average grey value of those pixels respectively in the region of interest, and I_k was the grey value of pixel k . The mixing indices allowed us to determine the homogeneity (**H**) according to (Erickson and Li 2002):

$$H = 1 - \frac{M_c - M_f}{M_i - M_f} \quad (13)$$

where M_c , M_i and M_f were the current, initial and final mixing indices respectively.

The mixing rate was significantly increased with the assistance of the gyromixer no matter whether it operated in sleeping mode or TIP mode (Fig. 6c). Homogeneity of fluorescein was achieved within ~3 seconds in the sleeping mode and ~8 seconds in TIP mode (Fig. 6d). The difference in mixing rate was possibly due to the disparity in spinning speeds. In sleeping mode, the gyromixer was able to reach up to ~2400rpm. In TIP mode, the fastest spinning speed was ~2000rpm with a precession speed of ~12rpm. In contrast, it took ~120 seconds for the passive diffusion based mixing to reach the same level of homogeneity (Fig. 6c and Online Resource 4, Supp. Fig. S1). Similar results were obtained when characterizing the mixing with food dye (Online Resource 4, Supp. Fig. S2a). We estimated the spinning speed by tracking a mark on the gyromixer in video clips taken at 600fps by a high speed video camera. The highest speed that the gyromixer was able to reach in sleeping mode was ~2400rpm on the magnetic stir plate. The lowest speed for the gyromixer to maintain balance was found to be ~900rpm. We noticed faster spinning speed resulted in a faster mixing rate, although the difference was not significant (Online Resource 4, Suppl. Fig. S2b).

With the assistance of active mixing, reactants inside droplets can be homogenized quickly to improve the reaction rate and ultimately the throughput of the biochemical assays. We further characterize the micro gyromixer by measuring biotin-streptavidin interactions in a quantum dot- mediated fluorescence resonance energy transfer (QD-FRET) sensing system (Zhang, Yeh et al. 2005). QD-FRET has recently been implemented into a variety of highly sensitive bimolecular assays to detect rare biomarkers such as point mutation and DNA methylation for cancer diagnosis and prognosis (Zhang, Yeh et al. 2005; Bailey, Easwaran et al. 2009; Bailey, Keeley et al. 2010). Streptavidin-conjugated quantum dots (QD) are commonly used to bind to target-specific oligonucleotides that are dually labelled with biotin and a fluorophore (Cy5). The binding induces FRET from QD donors to Cy5 acceptors, leading to substantial change in fluorescence for detection and quantification of DNA targets (Online Resource 4, Suppl. Fig. S3).

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As shown in Figure 7a, three droplets of 30 μ L containing 10nM streptavidin-conjugated QDs (Qdot 605, Invitrogen) were dispensed on the Teflon AF coated glass substrate. A micro gyromixer was initiated only in the top droplet and set to highest spinning speed in sleeping mode. 1 μ L drip of 100 μ M DNA, which contained a 27-base oligonucleotide labelled with biotin at 5' terminal and Cy5 at 3' terminal, was added to the top and the middle droplets. 1 μ L of water was added to the QD droplet at the bottom to serve as negative control. Fluorescent quenching of QDs was monitored as an indicator of the biotin-streptavidin interaction. At time 0, all the droplets were equally bright. As the reaction progressed, more and more acceptor fluorophores were brought into close proximity of the QD and the degree of quenching increased. The droplet containing the gyromixer quickly dimmed due to the fast reaction. The intensity of the middle droplet dimmed slowly and eventually reached the same level. The control droplet maintained its intensity level, showing photobleaching was negligible.

Figure 7b plots the normalized average fluorescent intensities as a function of time. Streptavidin-biotin binding demonstrates a fast reaction with a binding rate constant of $\sim 10^6$ – 10^7 M⁻¹s⁻¹ (Srisa-Art, Dyson et al. 2008; Wayment and Harris 2009; Broder, Ranasinghe et al. 2011). However, in the absence of the gyromixer, the two reactants are present in separate streams coalescing in a droplet. As a result, the reaction rate is limited by diffusion. An apparent (pseudo)zero order reaction kinetics is observed in the case. In contrast, with the help of the gyromixer, the reaction reaches the steady state much faster and exhibits the reaction kinetics best described by the biexponential decay due to the heterogeneity of analytes or different affinities caused by multiple binding sites (Srisa-Art, Dyson et al. 2008).

Conclusion

In conclusion, we have presented a micro magnetic gyromixer that can be used to enhance fluid mixing for open-surface droplet microfluidic systems. The gyromixer balances itself on the curved droplet surface through the gyroscopic effect. While the spinning motion helps to balance the gyromixer on the curved droplet surface, it also rapidly perturbs fluid streamlines and homogenizes reagents inside droplets. Significant enhancement of mixing rate with the assistance of the device has been demonstrated by monitoring the mixing of a small fluorescein drip added to a sessile water droplet. Performing streptavidin-biotin binding in a QD-FRET sensing system reveals that the gyromixer significantly improves the chemical reaction rate. This micro gyromixer is controlled remotely by alternating magnetic fields and thus can be easily incorporated into any open-surface droplet platform, irrespective of what droplet actuation mechanisms are used, for developing a fully functional μ TAS.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Fig. 1.

a)–b) Schematic illustration of the proposed micro magnetic gyromixer. c) The conceptual illustration of the micro gyromixer sitting on the droplet surface. d) and e) Pictures of the micro magnetic gyromixer in action. The images are extracted from high speed video clip taken at 600fps. d) The micro magnetic gyromixer is operating in sleeping mode (Online Resource 2). e) The micro magnetic gyromixer is operating in TIP mode (Online Resource 3).

Fig. 2.
Fabrication workflow of the micro magnetic gyromixer.

Fig. 3. Force diagram of the micro magnetic gyromixer operating in the sleeping mode. Only the gravity and the magnetic force in the $y'z'$ plane are shown.

Fig. 4. Force diagram of the micro magnetic gyromixer operation in TIP mode. a) The dimetric projection view b) The view with an angle normal to the $y'z'$ plane. Only the gravity and the magnetic force in the $y'z'$ plane are shown.

Fig. 5.
Micro magnetic gyromixer coordinates.

Fig. 6. Mixing patterns observed by tracing the fluorescein inside water droplet for gyromixer operating in a) sleeping mode and b) TIP mode and the gyromixer precesses clockwise. c) The mixing rates are significantly improved with the assistance of the micro gyromixer compared to passive diffusion based mixing. d) zoomed view of c).

Fig. 7.

a) Streptavidin-biotin reactions in droplets are monitored by QD-FRET. Background is shielded by black colour. (Top) The reaction is carried out with the assistance of the micro magnetic gyromixer. (Middle) The reaction is based on pure diffusion. (Bottom) A negative control droplet contains only QD. b) Normalized QD intensities in three droplets are plotted as a function of time. The intensity profile of the droplet without the gyromixer exhibits (pseudo)zero order kinetics as suggested by the linear fit. The intensity profile of the droplet with the gyromixer exhibits rapid biexponential decay.