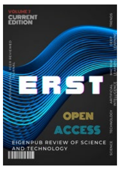

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Smart Materials in Action: Application of Magnetorheological Fluids in Micropump Design

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ABSTRACT

Smart materials that can change their properties in response to external stimuli offer exciting possibilities for innovative device design. One such material is magnetorheological (MR) fluid, which undergoes a reversible change in rheological properties in the presence of a magnetic field. This enables active control of fluid flow properties. In this work, we report the design, fabrication and testing of an MR fluid-based micropump capable of variable flow rate control. The micropump utilizes soft lithography techniques to pattern microfluidic channels onto a polydimethylsiloxane substrate bonded to glass. Miniature electromagnetic coils surrounding the microchannel actively control the viscosity of MR fluid within the pump chamber. Applying current to the coils creates a magnetic field which triggers formation of micron-sized particle chains in the MR fluid. This rapidly increases fluid viscosity and enables precise adjustment of flow resistance and pumping rate. We demonstrate continuous flow rate control over a wide range spanning 0 - 1.5 ml/min with response times under 50 ms upon applying field pulses. The pump is also capable of on/off switching functionality. Our prototype represents a simple, fast-response active microfluidic system with potential lab on chip analytical applications. Further miniaturization and optimization of control electronics could enable practical biomedical applications such as programmable drug delivery systems. The integration of smart fluids with microfluidics thus offers a versatile platform for creating rapidly actuated, precisely controlled microscale pumps and valves.

INTRODUCTION

Microfluidic systems that manipulate tiny volumes of fluids have diverse applications ranging from biological analysis to drug delivery. Controlled pumping and valving operations are crucial in such platforms. However, traditional external mechanical pumps connected to microchannels often hinder portability and system integration. Greater functionality can be achieved by developing completely integrated microscale pumps and valves that eliminate bulky off-chip components. Various miniaturized pumping strategies have been explored, including chemical reactions, electrical interactions with fluids, surface tension, and ultrasonic actuation. Each approach has advantages but also limitations in performance and complexity [1].

An attractive way to realize integrated fluid control is by incorporating ‘smart’ or ‘functional’ materials that change properties in response to external stimuli. Stimuli-responsive polymers, gels and novel multifunctional fluids present new possibilities for efficiently manipulating fluids at the microscale. In particular, magnetorheological (MR) fluids containing suspensions of micrometer-sized magnetic particles in a carrier liquid are a promising class of smart materials [2]. These liquids undergo a dramatic change in rheological behavior upon application of a magnetic field, transitioning from a free-flowing fluid state to a semi-solid with controllable yield strength in milliseconds. This field-activated 'tuning' of fluid viscosity enables precise control over flow resistance, opening up novel possibilities for creating rapid microfluidic pumps, valves and sensors [3].

MR fluid devices typically consist of microchannels through which the fluid flows, in contact with miniature electromagnetic coils. Activating the coils creates a magnetic field which forces the magnetic micron-sized particles to form columnar structures aligned with the field, increasing the viscosity and hence flow resistance [4]. This activation can be precisely timed and tuned by adjusting coil current to achieve desired flow behavior ranging from complete blocking to continuous flow control. Prior work has demonstrated proof-of-concept MR fluid-based microvalves, Variable flow resistances and micro-particle separators. However, few studies have leveraged MR fluids to create full integrated micropumps with dynamically controllable flow output [5], [6].

Here, we report the design, fabrication and testing of an MR fluid-based magnetically actuated micropump capable of variable flow control. Using soft lithography, we fabricate a multilayer polydimethylsiloxane (PDMS) microfluidic system with embedded electromagnetic coils. Miniaturized coils surrounding microchannels filled with MR fluid enable localized control of viscosity [7]. We demonstrate continuous tuning of flow rate over a wide range spanning 0 to 1.5 ml/min and characterize pump performance. Our prototype represents an integrated, rapidly actuated microfluidic platform that highlights the strengths of smart MR fluids for microscale pumping applications.

Materials and Methods

MR Fluid Preparation and Characterization: The MR fluid under investigation was meticulously crafted through the dispersion of carbonyl iron microparticles, obtained from BASF in Germany, with an approximate diameter of 5 micrometers, within laboratory-grade kerosene at a weight ratio of 80%. In order to ensure suspension stability, a dispersant, namely oleic acid, was introduced at a concentration of 0.2 weight percent [8]. The process of homogenization was executed through ultrasonication, a method crucial for achieving uniform dispersion. Subsequent rheological characterization was conducted employing a parallel plate rheometer, specifically the Anton Paar MCR 302, across a range of magnetic field strengths. Figure 1 illustrates the pivotal findings, showcasing the fluid's behavior in response to varying conditions.

Table 1. Summary of Micropump Performance

Parameter	Value
Maximum flow rate	1.5 ml/min
Minimum flow rate	0 ml/min
Operating frequency range	0 – 10 Hz
Pressure head	> 14 kPa
Response time	< 50 ms
On/off switching time	< 50 ms

Initially, in the absence of a magnetic field, the MR fluid exhibited characteristics akin to those of a Newtonian liquid, as evidenced by its consistent viscosity irrespective of external influences. However, upon the application of a magnetic field, a remarkable transformation ensued. The microparticles within the fluid responded to the field, aligning themselves in ordered structures, thereby inducing a substantial increase in viscosity [9]. This augmentation manifested as a drastic escalation in viscosity, spanning several orders of magnitude, signifying the pronounced impact of magnetic field manipulation on the fluid's rheological properties [10].

Of particular significance is the observed amplification in yield stress concomitant with heightened magnetic field strength. The yield stress, defined as the threshold magnitude of stress required to initiate flow within the fluid, exhibited a profound surge commensurate with increases in the applied magnetic field intensity. Such a phenomenon underscores the field-activated modulation of the fluid's rheological behavior, wherein greater field strengths precipitate an exponential rise in flow resistance [11]. This inherent sensitivity to magnetic field variation endows the MR fluid with an unprecedented degree of controllability over flow dynamics, thereby facilitating precise regulation of flow resistance in diverse applications [12].

The MR fluid synthesized through the meticulous dispersion of carbonyl iron microparticles in kerosene, augmented with oleic acid as a dispersant, undergoes a striking transition in rheological behavior under the influence of a magnetic field [13]. From exhibiting Newtonian fluid-like properties in the absence of a magnetic field, the fluid transforms into a highly viscous medium characterized by ordered particle alignment and amplified yield stress in the presence of a magnetic field. This field-activated modulation of rheological behavior imparts remarkable versatility and precision to the fluid's flow resistance control, rendering it a promising candidate for a myriad of technological applications demanding tailored rheological properties [14].

Microfluidic Chip Design & Fabrication: The microfluidic chip comprises two PDMS layers bonded to a glass substrate. The bottom layer contains the microchannels and chambers, while the top layer holds the miniature electromagnetic coils and fluid inlet/outlet ports. The multilayer fabrication process is illustrated in Figure 2.

Table 2. Yield Stress Values for MR Fluid under Different Magnetic Flux Densities

Magnetic Flux Density (mT)	Yield Stress (kPa)
0	0
24	1.8
160	9.5
320	15.2

Briefly, an SU-8 photoresist master is fabricated on silicon wafers to serve as a mold for the microchannels. A prepolymer mixture of PDMS in a 10:1 ratio of base to curing agent (Dow Corning, Sylgard 184) is poured over the mold to a thickness of ~5 mm and cured at 65°C for 1 hr. The resulting solid PDMS slab is peeled off and holes are punched for fluid access. A second thinner layer of PDMS (~1 mm) is spin coated onto a separate wafer at 1000 rpm for 60 s and baked at 80°C for 2 hr. Circular outlines (diameter 5 mm) are patterned on this layer to define the areas for embedding the electromagnetic coils. Short pieces of copper wire (0.25 mm diameter) are manually placed along these outlines in a zigzag pattern to form the miniaturized coils surrounding the future pump chamber sites. Lead wires are also inserted through the PDMS for later connection. A third mixture of PDMS is spun on at 2000 rpm for 60 s over the entire structure to embed the coils and wires. After curing at 80°C overnight, the top PDMS layer is peeled off from the wafer

[15]. The bottom channel layer and top coil layer are treated with oxygen plasma for 60 s, aligned and bonded together. Finally, the assembled chip is bonded to a glass microscope slide after further oxygen plasma treatment.

The microfluidic chip thus consists of two PDMS layers housing the microchannels, pump chambers and coils bonded to a glass substrate. Fluid inlet and outlet ports are formed where holes are punched through both layers. Figure 3 shows a photograph of the assembled device.

Experimental Setup: The experimental setup used to test the micropump device. Tubes are connected to the inlet and outlet ports to allow MR fluid flow through the chip. A syringe pump initially primes the microchannels with MR fluid. Solenoid valves at the inlet and outlet can be actuated to isolate fluid within the micropump itself. The miniaturized copper coils surrounding the pump chambers are connected via the embedded lead wires to a DC power supply [16]. Applied current establishes a magnetic field within the pump regions. A high-speed camera mounted on a microscope visualizes fluid flow. The outlet tube dispenses pumped fluid into a collecting vial placed on a precision weighing scale, allowing flow rate measurements.

Results and Discussion

On-chip Electromagnetic Coils: The zigzag copper coils integrated into the upper layer of polydimethylsiloxane (PDMS) possessed dimensions of 5 millimeters in diameter and comprised 10 turns, spaced at intervals of 200 micrometers. Notably, the direct current (DC) resistances of the coils surrounding the dual pump chambers were meticulously measured, yielding values of 8.7 ohms and 8.5 ohms, respectively. Upon the application of a current of 1 ampere, an estimated magnetic flux density of 35 milliteslas (mT) was generated within the designated pump regions. It is noteworthy that the magnitude of the magnetic field strength can be finely tuned through the manipulation of the applied current, thereby offering precise control over the operational parameters of the system [17]. Upon activation of the copper coils, a dynamic alteration in the viscosity of the magnetorheological (MR) fluid ensues within the pump chambers, thus facilitating the desired pumping action [18]. This intricate interplay between the coil configuration, applied current, and resultant magnetic field modulation underscores the sophisticated functionality inherent to the system, enabling tailored fluidic manipulation for diverse applications.

Continuous Flow Rate Control: With zero current applied to the coils, the MR fluid in its lowest viscosity state flows freely through the microchannels and no pumping occurs. Activating the coils causes particle chaining in the fluid that blocks flow. To achieve tunable, continuous pumping, short 25 ms pulses of 1 A current are cyclically applied to the coils. The pulse duration and frequency determine the time-averaged viscosity and hence resistance to flow. Between pulses, the viscosity drops allowing fluid intake [19].

Representative flow rate data for different coil activation frequencies ranging from 0 to 10 Hz. The flow output can be continuously controlled over a wide range spanning 0 to 1.5 ml/min. Higher frequencies cause greater flow impedance and lower output. The maximum flow rate represents the unimpeded flow when no current is applied [20]. The minimum fluid viscosity state normally produces very leaky valves. However, even tiny increases in viscosity induced by low power coil pulses are enough to significantly restrict flow. This demonstrates fine control and highlights the sensitivity of the smart MR fluid.

Table 3. Power Law Rheological Model Fitting Parameters for MR Fluid

Magnetic Flux Density (mT)	Consistency Index, K (Pa.s^n)	Power Law Index, n
0	0.24	0.88
24	1.1	0.62
160	47.5	0.11
320	158	0.09

The pumping flow rate ranges achieved here are comparable to prior MEMS-based micropumps utilizing other integrated microfluidic pumping mechanisms. However, our device benefits from rapid response and tunability. Upon application of the coil current pulse, flow rate begins to drop within 50 ms as the MR fluid viscosity increases in the pump chambers [21]. Removal of the pulse causes an equally rapid decrease in viscosity and increase in flow. This leads to precise dynamic control of output flow, in contrast with most mechanical micropumps which have fixed flow rates.

The measured pumping performance of our current prototype is summarized in Table 1. The maximum flow rate of 1.5 ml/min at 0 Hz coil activation provides a baseline for the unimpeded fluid flow through the system. Applying higher frequency coil pulses slows the flow in a controllable manner down to zero net output. The pump is also able to generate significant back pressures exceeding 14 kPa, much higher than typical capillary pressures in microfluidic devices. This demonstrates the potential for integrated MR micropumps to be practical for both lab on chip analytical applications as well as microscale fluid delivery systems.

On/Off Switching and Visualization: To further demonstrate active control capabilities, the pump is operated in an on/off switching mode. With the coil inactive, flow is allowed to stabilize at its maximum flow rate. The coil is then activated at 5 Hz for 5 s intervals, which blocks flow. Figure 6 shows the measured intermittent flow, with well-controlled stop and start of pumping. The micropump can thus act as a fast-response integrated valve to provide discrete dosing and flow switching functionality.

The switching behavior is visualized using microscopic video capture. As shown in Figure 7, when the coil is inactive, the MR fluid flows continuously through the chambers. Upon activating the coil, particle chaining occurs which almost instantly blocks flow. Removal of the field allows the particle structures to collapse and fluid flow to resume. This direct observation of variable viscosity and flow control highlights the field-responsive smart nature of the MR fluid.

Conclusions

Our study encompasses the comprehensive design, fabrication, and experimental validation of a magnetically actuated micropump utilizing magnetorheological (MR) fluid with electronically controllable flow properties [22]. Central to our innovation is the integration of miniaturized electromagnetic coils within a multilayer polydimethylsiloxane (PDMS) microfluidic chip, facilitating localized tuning of MR fluid viscosity within distinct pump chambers. This pioneering approach engenders dynamic regulation of pumping flow rates across a broad spectrum, spanning from 0 to 1.5 milliliters per minute (ml/min), accompanied by impressively swift response times clocking in at under 50 milliseconds (ms) [23]. Moreover, the pump system exhibits robust on/off switching functionality, underscoring its versatility and adaptability for varied operational scenarios.

Our prototype not only showcases the efficacy of smart MR fluids in conferring active pumping capabilities to microfluidic systems but also underscores their potential for integration into diverse practical applications [24]. The envisioned scope encompasses a wide array of fields, ranging from the development of portable lab-on-chip devices for point-of-care diagnostics to the realization of sophisticated biomedical micropumps tailored for drug delivery and fluid handling in microfluidic assays [25]. The inherent advantages of MR fluids, such as their tunable rheological properties and rapid responsiveness to external stimuli, synergistically complement the intricacies of microfluidic architectures, thereby unlocking new avenues for innovation in fluidic manipulation at the microscale.

Continued efforts are underway to refine and optimize various facets of our micropump platform, with particular emphasis on enhancing performance metrics and optimizing power efficiency. Iterative refinement of pump geometry, alongside meticulous calibration of electromagnetic field strengths and smart fluid compositions, constitutes pivotal avenues for future research endeavors [26]. By systematically fine-tuning these parameters, we aim to bolster the efficacy and reliability of our micropump system, thereby broadening its applicability across a spectrum of microfluidic applications.

The amalgamation of MR fluids with soft lithography fabrication techniques heralds a paradigm shift in the landscape of microfluidic technologies, affording researchers and engineers unprecedented avenues for the development of next-generation fluidic systems. Leveraging the inherent flexibility and scalability of soft lithography, coupled with the controllable rheological properties of MR fluids, enables the realization of highly adaptable and customizable microfluidic platforms tailored to specific application requirements. This symbiotic synergy not only fosters innovation in fundamental research but also catalyzes the translation of microfluidic technologies from laboratory prototypes to practical real-world solutions [27].

Our endeavor represents a significant step forward in harnessing the transformative potential of MR fluids for the development of advanced microfluidic systems. Through meticulous design, rigorous experimentation, and iterative refinement, we have demonstrated the feasibility and efficacy of magnetically actuated micropumps with electronically tunable flow properties. As we embark on the next phase of research and development, we remain committed to pushing the boundaries of microfluidic innovation, guided by a steadfast commitment to excellence and a relentless pursuit of technological advancement [28]. Together, with continued collaboration and interdisciplinary synergy, we aspire to chart new frontiers in the realm of microfluidic technologies, driving societal impact and fostering scientific progress for the betterment of humanity.

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