

Magnetic Microfluidics Biosensor for Environmental Applications: A Simulation Approach

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Summary:

At the nano scale, certain magnetic materials eliminate hysteresis in their magnetization curves which provide new tools of sensing. In this study, a magnetic sensor including the microfluidics structure between two magnetic coils for sensing the biomaterials or pathogens is simulated by COMSOL Multiphysics. The special characteristics of magnetic nanoparticles, help us to employ the frequency mixing technique for biosensing applications. The magnetic biosensor system is simulated based on previous experimental works that detects pathogens in plants and toxic substances in agricultural products.

Keywords: Biosensor, Magnetic Nano Particles, Frequency Mixing Technique , Microfluidics

Introduction

Magnetic Nano Particles (MNP) with diameters in the order of tens of nanometers exhibits superparamagnetic behavior. The magnetization of MNPs is characterized by a hysteresis-free magnetization curve, featuring both linear and non-linear regions, and reaching saturation at high field strengths in both directions. This special characteristic of the magnetization curve of MNP motivates scientists to develop a detection mechanism which is named Frequency Mixing Magnetic Detection (FMMD) [1,2]. In FMMD, two excitation signals at low and high frequencies are applied to two coils in order to generate two magnetic fields at two distinct frequencies f_1 and f_2 . In the central zone of magnetic fields, the MNPs are placed. Based on its magnetization curve, it will induce a small magnetic field in the third coil (pick-up coil) at different frequency components, including two exciting frequencies and their intermodulation combinations. The mass of MNP in the central zone defines the amplitude of the induced signal in the pick-up coil. To leverage the MNPs' nonlinearity, the response is measured at the frequency f_1+2f_2 , enabling the detection and quantification of them. This is a simple and fast technique to measure the mass or concentration of MNP in the central zone of the magnetic field. FMMD has been proposed for biosensing applications as well as bioimaging and material characterization [1,3].

Designing and optimizing such structures traditionally relies on multiple fabrication and experimental cycles, resulting in increased cost and

time. Our study aims to provide an accurate modeling approach that directly incorporates measured MNP properties to streamline micro-channel development.

Experimental setup

In this section, the main parts of the experimental setup are briefly explained, with detailed descriptions available in [2,4]. The first part includes magnetic excitation and response signal measurement circuits. It is needed to generate low-frequency (LF) and high-frequency (HF) excitation signals. The power of the response signal, measured by the third coil, is very small, and it is amplified by lock-in amplifiers. By applying Fast Fourier Transform (FFT) to the measured signal, the amplitude of the response signal at frequency f_1+2f_2 would be measured. The concentration of MNP in the sample solution is directly proportional to the signal amplitude at this frequency.

The second part of the experimental setup is a microfluidics chip containing the MNP sandwich with target pathogen or biomaterial. The target pathogens or molecules are connected to MNP on one side, and on the other side, they are fixed on the surface of the microfluidic chip. The volume of the microfluidic chip is almost 15 microliters, fabricated by PDMS bonded to the glass, as shown in Fig. 1.

Simulation

The system was modeled using COMSOL Multiphysics through a series of multi domain simulations. These simulations help us to optimize

the microstructure by considering some factors such as the magnetization of nanoparticles, in order to estimate the sensitivity and magnetic field intensity.

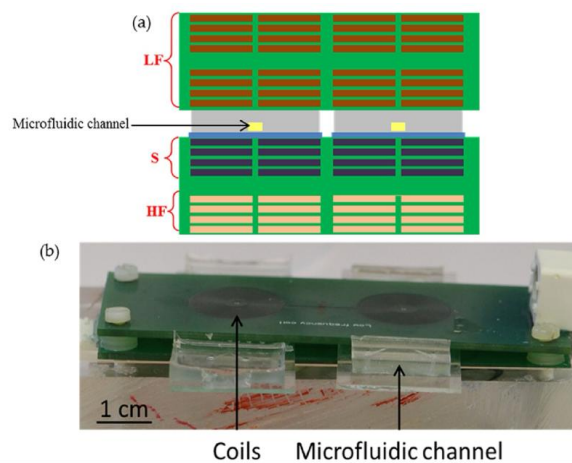


Fig1. (a) Schematic of layers: two green blocks for PCB coils (LF, S, HF); PDMS layer (gray) with microfluidic channel (yellow) bonded to glass (blue). (b) PCB/microfluidic prototype detection structure [4].

The impedance of the coils and the magnetic field intensity at the surface of the detection and sensor coils were measured using an impedance analyzer and a Gaussmeter, respectively. The same conditions are simulated in COMSOL, and the comparison of results, is presented in Table 1.

Table1. Comparison of simulated (S) and measured (M) coil resistance, inductance, and surface magnetic field under input DC voltages of 3V, 4V, and 6V.

				Magnetic Field (mT)		
		R (Ω)	L(mH)	@ 3V	@4V	@6V
HF	M	35	176	697	890	1.3
	S	24	192	727	969	1.45
Sensor	M	44	265	708	1.00	1.45
	S	29.7	245	984	1.31	1.97
LF	M	90	950	581	715	1.11
				600	807	1.39
	S	58	891	604	806	1.2
				706	941	1.4

In addition, two simulations are carried out for cylindrical and serpentine microfluidics channels, as shown in Fig2. In addition, the MNP material was defined in COMSOL, based on the measured magnetic properties by experiments. The experimental results exhibit superparamagnetic

behavior of MNP as shown in Fig. 3. To evaluate and compare the entire sensor measured signals with the simulation results, we applied consistent electrical settings to both the simulation and the measurement. The LF coils operated at 65 Hz, powered by a 48 Vpp signal, while the HF coils functioned at 40 kHz, powered by a 40 Vpp signal. The results showed that considering the same mass of nanoparticles, the simulation predicted 12.72 mV which is near to the measured value 14mV.

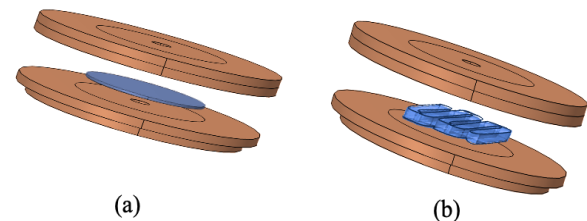


Fig 2. Simulation of different microfluidic structures

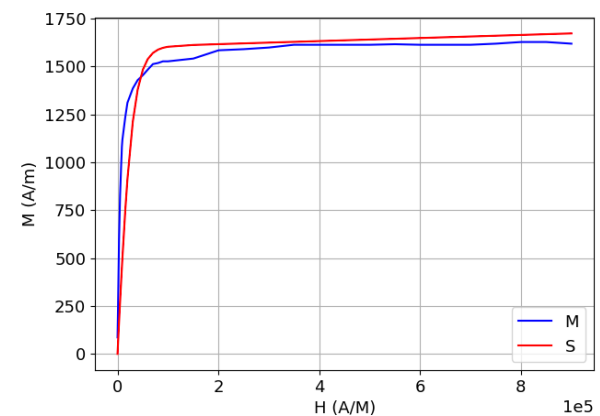


Fig 3. Comparison of nanoparticle material properties in simulation (S) and measurement (M).

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