AN IN-PLANE COBALT-NICKEL MICRORESONATOR SENSOR WITH MAGNETIC ACTUATION AND READOUT

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ABSTRACT

We present magnetic microresonators that utilize magnetic actuation and readout for use as mass sensors. A magnetic readout method was developed for the detection of microresonator vibration. Together with wireless actuation, the wireless magnetic readout results in completely passive microresonators. The magnetic readout is based on the induced voltage on a pair of differential pick-up coils, which is generated by the movement of the magnetized microresonator. The successful operation of the readout was demonstrated with CoNi microresonators under atmospheric pressure and in water. The microresonator can be readily functionalized and used as a mass sensor for bio-applications.

KEYWORDS

Magnetic actuators, wireless readout, passive microresonator, cobalt-nickel.

INTRODUCTION

Microresonators provide high sensitivity, rapid detection, and easy operation [1-2]. They can be used as chemical, physical, or biological sensors. Through the accumulation of the target biomaterial on the resonator surface, the mass load on the microresonator increases resulting in a change in vibration characteristics under excitation (i.e. change in resonance frequency). Microresonator sensors work based on adsorption of species on the functionalized surfaces. Through this functionalization, molecular recognition is directly transduced into mechanical response.

We present a complete magnetic microsystem that utilizes magnetic actuation and readout for use as a mass sensor for bio-applications. The microresonator is made of electroplated CoNi that has low coercivity and high saturation magnetization. Many magnetic microresonators have been reported [3], most of them utilizing optical readout methods. In [4], a contactless magnetic readout method that works based on induced eddy currents on a conductive non-magnetic MEMS device is presented. Here, we present a contactless magnetic readout method for a soft magnetic microresonator. Under applied loads the resonance frequency of the microresonator shifts, and this shift can be accurately detected using the wireless magnetic actuation and readout system.

FABRICATION

The fabrication of the microresonator is shown in Fig. 1. The microfabrication of the device is based on two lithography steps, an electroplating step and a sacrificial layer etching step. A 25 nm adhesion Ti layer (not shown) and 500 nm sacrificial Cu layer are evaporated on a Si substrate by e-beam evaporation (1). The Cu layer also acts as a seed layer for subsequent electrodeposition. The device layer is defined by the first lithography (2) and formed by electroplating CoNi. After electrodeposition the photoresist is removed (3). An 80 µm-thick layer of SU-8 is applied over the devices (4) and a second photolithography step forms anchors (5). The microdevices are released from the substrate by etching the sacrificial Cu layer. The fabricated microresonator is shown in Fig. 2.

ACTUATION

An electromagnet is used to actuate the magnetic microresonator and positioned so that its axis is parallel to the normal of the microresonator plate. Two coils are placed in a Helmholtz configuration to generate uniform magnetic fields to magnetize the microresonator plate in-plane as shown in Fig. 3. The electromagnet generates a gradient in both axial and radial directions of the coil. The size and the location of the coils were optimized by FEM simulations with COMSOL Multiphysics. The magnetic force, $F \text{[N]}$, on the microresonator depends on the magnetization of the plate, $M \text{[A/m]}$, and magnetic field gradient generated by the actuation coil [5].

Figure 1: Fabrication of the CoNi microresonators with SU-8 anchor.
\[ F = \mu_0 \nu (M \cdot \nabla)H \]

where \( \mu_0 \) \([\text{N/A}^2]\) is the permeability of free space, \( \nu \) \([\text{m}^3]\) is the volume of the microresonator, \( \nabla \) is the gradient operator, and \( H \) \([\text{A/m}]\) is the applied magnetic field. Due to the in-plane magnetization of the plate forced by the Helmholtz pair, the microresonator experiences an in-plane force. The plate is actuated near the in-plane resonance frequency of the microresonator. Once the magnetization of the CoNi plate is known, the calculation of force is straightforward. Since the microresonator is intended to be actuated in-plane, the relatively stronger DC field generated by the Helmholtz coils magnetizes it in the deflection direction. The effect of magnetic field generated by the AC coil is negligible for the magnetization of the microresonator. However, the AC coil generates the magnetic field gradient needed for force generation.

In order to find the damped resonant frequency and the quality factor of the microresonator, the excitation frequency is swept over a band that includes the resonance frequency of the microresonator. At the resonant frequency, the deflection amplitude of the microresonator is maximum, and the phase lag between excitation signal and the deflection signal changes distinctively. Either phenomenon can be used to detect the resonant frequency.

READOUT

Figure 3 shows the setup used for the actuation and readout of the CoNi microresonator. In addition to the AC actuation coil and Helmholtz coils, a pair of symmetrically positioned pick-up coils and a probe coil are utilized for the magnetic readout (Fig. 4). The probe coil generates the probe field necessary for the detection of the microresonator vibration. The probe field is superimposed on the excitation field and generates an additional magnetization on the microresonator. The pick-up coils are placed symmetrically with respect to the probe coil and connected differentially to cancel the voltage induced by the probe field. The differential configuration is necessary to increase the sensitivity of the system.

The magnetization of the microresonator generates a spatially changing magnetic field. The magnetic field intensity decays with increasing distance from the microresonator. When the microresonator deflects by an amount \( x_d \) the spatial magnetic field moves accordingly in space. At the pick-up coil locations, the magnetic field changes with the microresonator deflection and induces a voltage on the pick-up coils given by:

\[ U_{\text{pickup}} = -\frac{d}{dt} \int_{S_{\text{pickup}}} B \cdot dS \]

where \( U_{\text{pickup}} \) is the induced voltage on the pick-up coils, and \( S_{\text{pickup}} \) is the effective area of pick-up coils. The induced voltage on the pick-up coil closer to the microresonator is significantly higher than the induced voltage on the distant one. The differential voltage can be used to determine the microresonator vibration.

The microresonator is magnetized by the DC magnetic field generated by the Helmholtz pair. At the same time the excitation field and the probe field magnetizes the microresonator at the excitation frequency \( f_e \) and probe frequency \( f_p \), respectively. The total magnetization of the microresonator is the sum of all these components \( M_{\text{DC}}, M_{\text{AC}}, \) and \( M_p \). The magnetic field generated by the magnetized microresonator is determined by \( M_{\text{DC}}, M_{\text{AC}}, \) and \( M_p \), and, hence, it is...
modulated by the alternating parts $M_{AC}$ and $M_p$. This results in a magnetic field with different frequency components. The microresonator deflection gives rise to an amplitude modulation of the magnetic field at the pick-up coil. We are particularly interested in a specific frequency component. The resonator structure vibrating at $f_m$ induces a side band at $f_p \pm f_m$ due to the amplitude modulation. This side band signal is proportional to the deflection amplitude, so the readout of the microresonator can be done at the side band of the probe signal. Additionally, the side band signal is amplified by the probe frequency, $f_p$. Therefore, the readout sensitivity and signal-to-noise ratio (SNR) can be improved significantly. The probe frequency is an independent parameter and can be selected relatively high. The only limitation on the probe frequency is the bandwidth of the electronics, the coils, and the magnetization characteristics of the microresonator. As the microresonator deflects in the $x$ direction, the readout signal is proportional to the surface integral of $\partial B_z / \partial x$ field induced by the probe magnetization of the microresonator (Fig. 5).

In the readout system, the induced voltage in the differentially coupled pick-up coils is first amplified and the intermodulation distortion is compensated with a custom signal-conditioning circuit. The signal is then recovered by a lock-in amplifier (Zurich Instruments HF2LI) (Fig. 4).

The location of the pick-up coil with respect to the microresonator and the geometry of the pick-up coil are critical for successful readout. The optimal shape of a pick-up coil can be found by analyzing $\partial B_z / \partial x$. The MATLAB simulation of the $\partial B_z / \partial x$ field of the magnetic microresonator at a distance of 300 $\mu$m with 1 kA/m magnetization is shown in Fig. 5. The coordinate frame origin is selected at the center of the resonator plate. The line which represents the edge of the pick-up coil shows the optimum position for readout.

RESULTS

First, the microresonator was characterized for reference using a planar motion analyzer (Polytec MSA-500) under magnetic excitation. An in-plane resonance frequency of 4.68 kHz was measured under atmospheric pressure. Next, the magnetic actuation and readout using the fabricated CoNi microresonator was successfully demonstrated. The excitation frequency was swept to find the resonance frequency. Fig. 6 shows the frequency response of the microresonator under atmospheric pressure and in water. As expected, a lower quality factor was observed in water when compared to operation under atmospheric pressure. This is due to the higher viscosity of water, which results in a higher damping factor. Additionally, a shift in resonant frequency was detected.

The microresonator can be readily functionalized and used as a bio-mass sensor [1-2]. As a proof of concept polystyrene microspheres were loaded on the microresonator and a frequency shift of 82 Hz was observed under atmospheric pressure (Fig. 7). However, the sensitivity of the microresonator could not be quantified as the exact mass of beads attached to the microresonator plate could not be determined.
CONCLUSION

A magnetic readout method was developed for CoNi microresonators. Together with wireless actuation, the wireless magnetic readout created completely passive microresonator sensors. This significantly simplifies their fabrication and packaging. It also provides many advantages, especially in bio-applications, as no wiring or on-board power sources are necessary for the device. The magnetic readout works based on the induced voltage on a pair of differential pick-up coils generated by the movement of the magnetized microresonator. To enhance the signal-to-noise-ratio and sensitivity of the readout, a probe field was applied and the readout was carried out at the side band of the probe frequency (the probe frequency plus the mechanical vibration frequency). This amplifies the readout signal by the probe frequency. The resonance peaks of the microresonators were found by sweeping the input signal over a band containing the resonance frequency. The successful operation of the readout was demonstrated with CoNi microresonators under atmospheric pressure and in DI water. As a proof of concept for mass sensing, micro-sized polystyrene beads were loaded onto the microresonator and a clear resonance frequency change was observed. Future work is focused on characterization and improvement of sensitivity.

REFERENCES


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**Figure 6:** The frequency response of the CoNi microresonator under atmospheric pressure and in water measured with the magnetic readout.

**Figure 7:** Magnetic readout of the microresonator with and without load.