IOP Publishing | Smart Materials and Structures
Smart Mater. Struct. **20** (2011) 025016 (7pp) doi:10.1088/0964-1726/20/2/025016

Radio frequency magnetic field detection using piezoelectric coupled microcantilevers

Dhiraj Sinha, Simone Pisana and Andrew J Flewitt

Centre for Advanced Photonics and Electronics, Division of Electrical Engineering, University of Cambridge, Cambridge, UK

E-mail: ds396@cam.ac.uk

Received 30 June 2010, in final form 6 December 2010
Published 14 January 2011
Online at stacks.iop.org/SMS/20/025016

Abstract
We report on measurement of radio frequency magnetic fields using a stack of piezoelectric material coupled with microcantilevers. The time varying magnetic field of the radio frequency excitation induces a voltage in the piezoelectric stack and the resulting mechanical vibration is amplified by microcantilevers coupled to it under resonance and is measured by a laser–photodetector system. The method of measurement combines the objectives of a radio signal sensor and a microfilter. We have detected magnetic fields of the order of 1.8 pT at room temperature conditions. The results can lead to the development of novel micromechanical radio signal sensors.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The coupling between free space radio frequency electromagnetic waves and metallic coils has been known since the initial work of Hertz [1]. Interest in the miniaturization of electronic devices has led to a need for development of ultra-small sensors of radio frequency (RF) magnetic fields which are integral elements of communication systems [2], magnetic resonance imaging [3] and nuclear quadrupole resonance based detection systems [4]. In most RF magnetic field sensors, a metallic coil senses the radio signal which is filtered using an inductive–capacitive (LC) circuit. The LC circuits are precisely tuned to a few frequencies and they become extremely bulky when they have to operate over a broad frequency range because of problems related to frequency tuning. They also suffer from parasitic effects, losses and have very low quality factor which limits their sensitivity. Hence, there is an urgent need for a technology having a novel sensing mechanism integrated with ultra-small filters.

Here we report on the measurement of radio frequency magnetic fields using piezoelectric materials coupled with microcantilevers as filters. The measurement technique has some advantages in terms of filtering capability in comparison to metallic coils and LC circuits as it integrates the objectives of radio signal sensing and microfiltering. As microcantilevers can be fabricated at micrometric scales using standard microfabrication technologies, an array of microcantilevers having different lengths and resonant frequencies mounted on a piezoelectric material can filter radio signals sensed by the piezoelectric material at a number of different frequencies.

Faraday's law of induction is equally applicable in all media, which implies that a time varying radio frequency (RF) magnetic field should induce a voltage in a piezoelectric stack and hence induce vibrations, which can then be subsequently transferred to microcantilevers mounted over it. When the RF frequency is near the mechanical resonant frequency of a cantilever, the amplitude of the cantilever's vibrations is greatly enhanced and the RF signal is thus amplified. Optical detection can be used to measure the cantilever's vibrations.

The hypothesis was verified through experiments on an atomic force microscope (AFM) and a source of RF magnetic fields.

2. Experiments on RF magnetic field measurement

2.1. Experiments using an atomic force microscope

The experimental set up comprised an AFM (Veeco, Explorer) with a silicon microcantilever (Sb-doped Si (0.01–0.025 Ω cm), length: 125 μm, thickness: 4 μm, width: 30 μm,

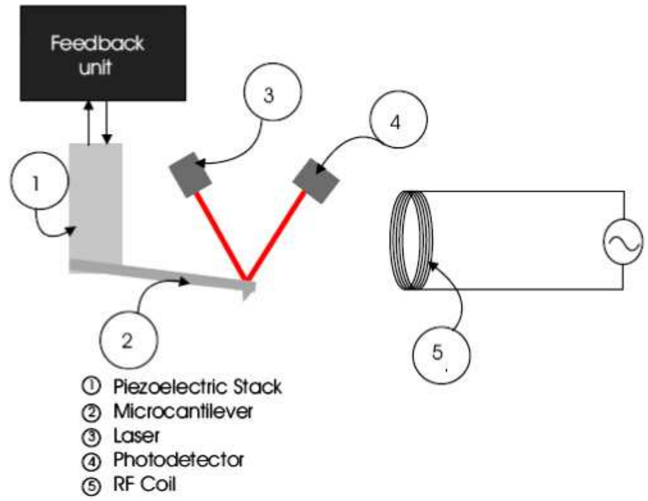

Figure 1. An AFM with a microcantilever, a laser diode, a photodetector system and an RF coil for wireless magnetic field excitation.

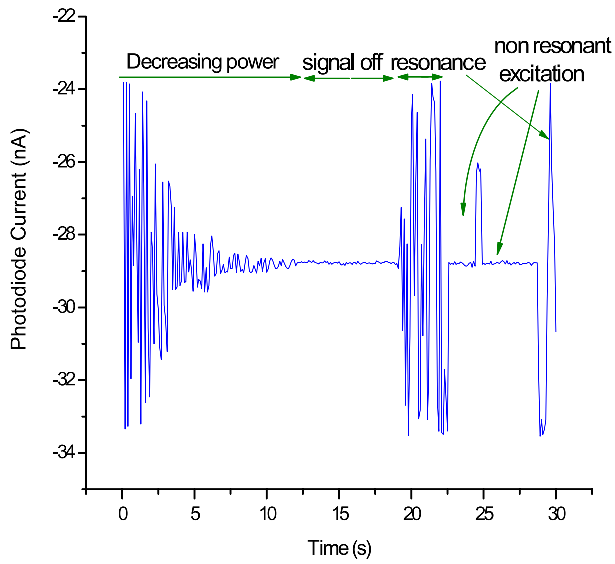

Figure 2. Effect of the variation of the RF magnetic field intensity on the piezoelectric–cantilever system of an AFM.

spring constant: 42 N m^{-1}) mounted over a lead zirconium titanate (PZT) piezoelectric stack as the sensing element and a multi-turn RF coil of diameter 4.5 cm excited by a signal generator (Agilent Technologies, 33120A) as the source of RF magnetic field. A schematic diagram of the set up is shown in figure 1. The vibration of the microcantilever was measured by shining a laser beam on its tip and allowing the reflected beam to hit a quadrant photodetector which generates a constant photodiode current in proportion to the sinusoidal oscillations of the microcantilever of the order of tens of nanoamperes. When the microcantilever oscillation is modulated from its sinusoidal behaviour, the photodiode current shows corresponding changes.

The microcantilever of the AFM is mechanically excited by electrically exciting the piezoelectric stack on which the microcantilever is mounted (figure 1). The piezoelectric stack is connected to an internal signal generator through wires. We can call this method of mechanically vibrating the microcantilever wired electrical excitation.

During the first phase of experiments, the piezoelectric–microcantilever system of the atomic force microscope was simultaneously subjected to wired electrical excitation at a fixed frequency and voltage and a wireless radio frequency magnetic field excitation applied using a multi-turn copper coil of radius 2.75 cm with varying power and frequency. The multi-turn coil, placed at a distance of 6.5 cm from the piezoelectric–microcantilever system of the AFM, was excited by the signal generator at 293.00 kHz, within 100 Hz of the 293.1 kHz resonant mode of the microcantilever. The PZT stack on which the microcantilever was mounted was subjected to a wired RF electrical excitation at 0.5 V and 293.0 kHz, resulting in high amplitude mechanical vibrations measured as a current output from the quadrant photodetector. Figure 2 shows the result of superposition of the wired RF electrical excitation and the wireless RF magnetic excitation of the piezoelectric–microcantilever system in detail. The root mean square (rms) amplitude of the microcantilever's vibration in the absence of a wireless RF excitation was recorded as a constant photodiode current of ~29 nA. The amplitude of the photodiode current is proportional to the amplitude of the microcantilever vibration. Any modulation in the sinusoidal oscillation of the microcantilever is reflected as a modulation in the photodiode current.

The power level of the signal generator connected to the RF coil was first varied from 23 dB m (3.16 V) to −22 dB m (17.76 mV) in steps of 5 dB m (0.4 V). This induced a variation in the magnetic flux density from 1.598 μT (23 dB m) to 2.75 nT (−22 dB m), at a distance of 6.5 cm from the coil. Its result on the piezoelectric–microcantilever system of the AFM is shown as a modulation in the microcantilever's vibrations which is measured as a changed in the photodiode current around its mean value. The decay of the signal between 0 and 12.5 s along the time axis on the graph of figure 2 is caused by the decreasing magnetic flux density. Following this, the RF source connected to the coil was switched off at 12.5 s and switched back on at 23 dB m at 18.5 s. Next, the RF magnetic field excitation frequency was changed to 303 kHz, resulting in the absence of enhanced cantilever vibrations at 22.5 s. The photodiode current drops to its lowest value of 29 nA.

The frequency of RF excitation was swept back through the resonant frequency at approximately 24.9 s, resulting in another peak in the graph. This peak amplitude was reduced because the resonant frequency was maintained for a short time as it was changed to 303 kHz. The frequency of the RF magnetic field was finally changed to the cantilever's resonant frequency at 30 s. These results clearly indicate that the off-resonance condition is similar to switching off the wireless RF magnetic excitation applied through the signal generator and the RF coil, thus demonstrating a narrow detection bandwidth. Sweeping the RF magnetic excitation frequency through the cantilever's resonant frequency does not induce an instantaneous response (figure 2, at 24.9 s), showing that building up of mechanical oscillations takes

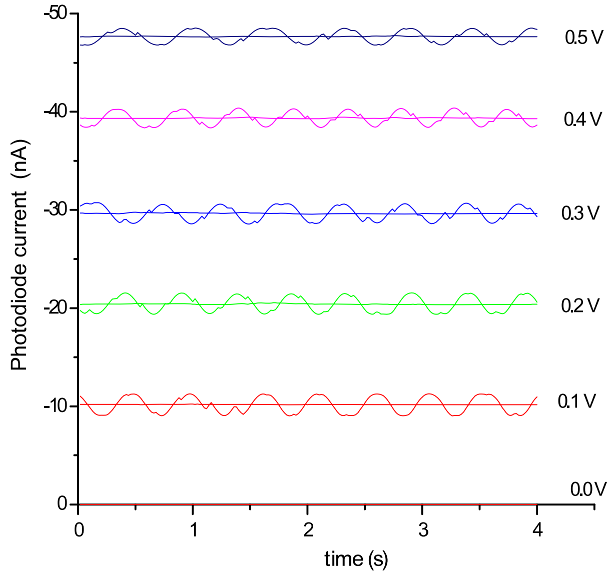

Figure 3. Beat formation due to superposition of wired and wireless excitations.

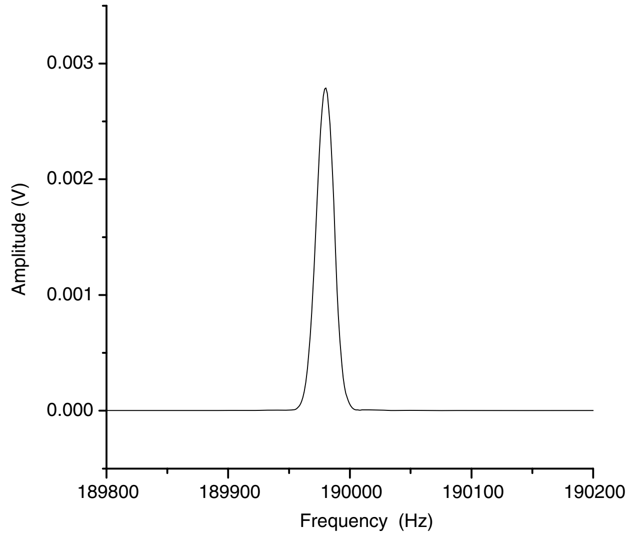

Figure 4. Photodetector signal of amplitude 2.79 mV under wired RF electrical excitation applied to the microcantilever through the piezoelectric stack at a frequency of 189.98 kHz and an amplitude of 10 mV.

some finite time. This can be explained in view of the quality factor of the microcantilever, which was measured to be close to 300 at room temperature. The resonant frequency of the microcantilever was 293.10 kHz which corresponds to a time period of 3.41 μs. Over a period of 300 cycles of oscillations, the microcantilever achieves its peak amplitude which corresponds to 1.02 ms. As the wireless RF magnetic excitation was maintained for approximately half of a millisecond at the resonant excitation frequency during its sweep, the photodiode current was −26 nA.

The vibrations of the microcantilever from the wired excitation alone resulted in an rms photodiode current of 28.75 nA, which corresponds to an rms oscillation of the cantilever's tip of 37.84 nm. The amplitude deviation from this steady state was 9 nA or 11.844 nm for a wireless RF generator output of 23 dB m. This value decreased with a reduction in wireless radio power to a fraction of a nanometre at −22 dB m. Changing the wireless signal frequency by ±10 kHz had approximately the same response as switching the source off altogether. The beats resulting from the mixing of the signals could be observed more conspicuously if the frequency difference between the wired electrical and wireless magnetic RF excitations was reduced to ∼1 Hz.

Figure 3 shows beats of approximately 0.6 Hz when the wireless excitation was set within 1 Hz of the wired excitation at 329.11 kHz (the resonant frequency of the microcantilever used in this experiment). The combined response of the system was found to be dependent on the amplitude of the wired RF electrical excitation applied to the piezoelectric stack. When the voltage amplitude was varied from 0.1 to 0.5 V in steps of 0.1 V, the effect of wireless RF magnetic excitation dropped, resulting in a decrease in the deviation of the microcantilever vibrations about the mean position. The amplitude of beats was highest in the case of piezoelectric excitation of 0.1 V and lowest in the case of piezoelectric excitation of 0.5 V. The amplitude of the signal from the microcantilever was drastically reduced when the wired RF electrical excitation applied to the piezoelectric material was switched off. However, the effect of the RF magnetic field was still discernible when the coil was brought closer to the piezoelectric stack, at a distance of 1 cm. As expected, the signal disappeared when the field from the RF coil was shielded by a copper plate placed between the coil and the piezoelectric stack.

2.2. Experiments using a piezoelectric–cantilever system

The experiments were repeated on a similar experimental set up comprising of an array of eight silicon microcantilevers (Concentris) of length 750 μm, width 100 μm and thickness 2 μm, mounted on a stack of PZT with a strain constant of 17 nm V^{-1} of dimensions $2 \times 5 \times 5$ mm^3 (Noliac), an RF coil made of copper having a radius of 2 cm and 5 turns, a mechanically manoeuvrable laser diode (635 nm, 3.5 mW, Thorlabs), a quadrant photodetector (frequency response: 250 kHz, noise: 15 nV $Hz^{-1/2}$, gain: 80 dB, Phreshphotonics) and signal generators.

The resonant modes of the cantilever were found at 189.98, 482.7 and 596.4 kHz. When the piezoelectric–microcantilever system was subjected to a wired RF electrical excitation at 189.98 kHz and 10 mV, the photodetector response was measured to be 2.79 mV as shown in figure 4. Subsequently, the wired RF electrical excitation was switched off and the wireless RF magnetic excitation was switched on by exciting the coil, placed at a distance of 2 cm from the PZT stack, by a signal generator at a voltage of 1 V. The photodetector response with amplitude of 215.3 μV is shown in figure 5.

In the next phase of the experiment, the piezoelectric–microcantilever system was simultaneously excited by wired and wireless RF excitations. The wired RF electric excitation

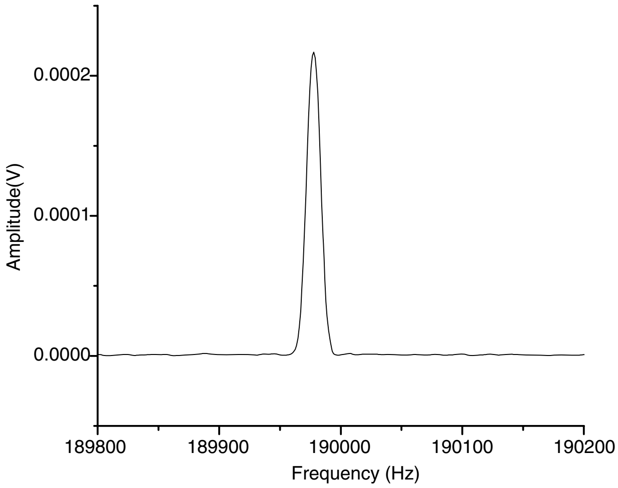

Figure 5. Photodetector signal of amplitude 215.3 μV under wireless RF magnetic excitation of the piezoelectric–cantilever system at a flux density of 2.0 μT and a frequency of 189.98 kHz.

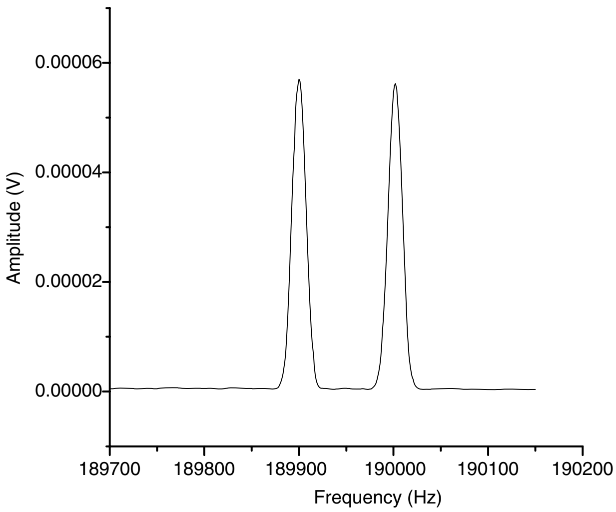

Figure 6. Photodetector signal under the simultaneous wired and wireless excitations.

to the piezoelectric material was set at 190.88 kHz, 1 mV and the wireless RF magnetic excitation was set at 190.98 kHz, 1 V which generated a magnetic flux density of 2.0 μT at a distance of 2 cm along its axis. The net signal resulting from these combined excitations resulted in the formation of beats at a frequency of 100 Hz. These beats were similar to those observed in the experiment with the AFM. The output from a spectrum analyser showed two closely spaced Fourier components with an amplitude of 59 μV (figure 6). The experiments suggest that the wired and wireless radio excitations can get superimposed, resulting in the formation of beats and reproducing the results obtained using an AFM.

The exact nature of the coupling between the wireless RF magnetic field excitation and the piezoelectric–microcantilever system can be understood by considering the internal structure of the PZT stack, which consists of several layers of piezoelectric material as shown in figure 7 [5]. Each of these piezoelectric layers (shown in grey) has silver films along the top and bottom surfaces (shown in red), ending in a layer of tin (shown in blue) which is connected to wires permitting electrical excitation. A change of magnetic flux coupling in the PZT stack leads to a time varying potential within the horizontal cross-section of the piezoelectric stack under wireless RF magnetic excitation. This was further verified by shorting the wires from the PZT stack together to form a loop. In this case, the signal level under wireless excitation was measured to be higher by a factor of 10–50 depending on the size of the coiled loop. This occurred because the total cross-sectional area through which the magnetic flux was varied was increased by the formation of a loop. When the wires were not connected into a loop, their presence did not seem to have any measurable impact on the effect of time varying magnetic field excitation. The response of the piezoelectric–cantilever system was independent of any external wires projecting out from the sidewalls.

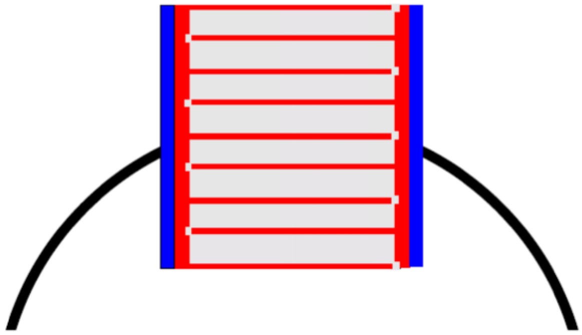

Figure 7. Interconnection of stacked PZT layers [3]. The PZT layers are shown in grey, silver layers are shown in red and the tin electrodes are shown in blue. The metallic leads connected to the tin electrodes are represented by black lines.

2.3. Effect of electrodes

In order to study the effect of electrodes on the response of wireless radio frequency magnetic field excitation, the metallic leads (shown in black in figure 7) connected to the piezoelectric stack were removed from the piezoelectric stack and no difference in the response of the piezoelectric–microcantilever system was found under wireless radio excitation. In the next phase, piezoelectric stacks without tin electrodes (shown in blue in figure 7) were used and still the response did not show any significant variation. However, when the connecting leads were connected in the form of a loop, the total area of the piezoelectric stack increased leading to an enhancement of response under wireless RF excitation. The response was dependant on the area of the loop created by the leads.

In the case of wired radio excitation, the metallic electrodes of the piezoelectric stack generate some differential voltage which is transferred to the piezoelectric material, and it shows a deflection. The wavelength of the radio signal at a few 100 kHz is of the order of kilometres. The piezoelectric stack appears as a lumped element at such frequencies. Under such a situation, at a certain instant of time, both the electrodes are excited by the same voltage peak of the RF signal. Thus, it cannot be argued that the metallic electrodes generate some differential voltage independent of the piezoelectric stack and transfer the voltage to the piezoelectric stack under wireless radio excitation because the wavelength of the radio signal is much longer in comparison to the dimensions of the whole piezoelectric stack and the electrodes.

The presence of metallic electrodes in the piezoelectric material facilitated electrical excitation of the system under wired excitation which was crucial for the quantification of the results.

2.4. *Effect of electric field*

The piezoelectric–microcantilever system was not found to respond to the electric field generated by a dipole antenna.

An infinitesimally small dipole antenna of length L oriented along the z axis carrying a current I produces an electric field E (along the vertical axis) at a distance r in the near field region which is given by (1)

$$E = -\mathrm{j}\eta \frac{kIL}{4\pi r}\left[1 + \frac{1}{\mathrm{j}kr} - \frac{1}{(kr)^2}\right]\mathrm{e}^{-\mathrm{j}kr} \qquad (1)$$

where η is the impedance of free space and k is the wavenumber.

When a dipole antenna of length 2 cm and an impedance of 2.94 kΩ (300 kHz) is excited by 1 V, the current developed in it is 0.34 mA. The electric field at a distance of 2 cm along its axis is 16.56 V m^{-1}, which should be enough to create an effect in the vibrations of the piezoelectric–microcantilever system if the electric field were to have any response. The electric field remains at the same order of magnitude for other frequencies and it does not have any observable effect on the vibrations of the microcantilever. The reason behind the unresponsiveness of the system to RF electric field might be linked to the attenuation of the electric field within the piezoelectric stack due to its high value of electrical permittivity.

3. Theoretical perspective

The piezoelectric constitutive equation for the inverse piezoelectric effect is given by

$$S_i = M_{ij}^E T_j + d_{ij} E_j. \qquad (2)$$

Here, S is the strain, M is the mechanical compliance at constant electric field E, T is the stress, d is the strain piezoelectric coefficient, i and j are integers.

In the context of the present experiments, an external electric field is associated with the time varying magnetic flux associated with wireless RF magnetic field excitation and the stress is zero, hence the equation simplifies to

$$S_i = d_{ij} E_j. \qquad (3)$$

The piezoelectric material used in the experiments was designed to show a displacement along one dimension only, hence we can neglect other terms and we get

$$S = dE. \qquad (4)$$

When a voltage is applied the resultant electric field can cause displacements given by

$$S = \frac{dV}{x}. \qquad (5)$$

This suggests that a time varying voltage should induce time varying vibrations in a piezoelectric material.

An alternative way of looking at the piezoelectric material is through the Butterworth–Van Dyke model of a piezoelectric material [6, 7], according to which a piezoelectric stack can be modelled as a series RLC circuit around its resonant frequency. Below its resonant frequency, it behaves like a capacitor, at its resonant frequency as a resistor, while above the resonant frequency the inductive properties of the system dominate. An RF magnetic field applied to such a system can induce voltage in the inductive elements of the piezoelectric stack. This model allows us to further evaluate the coupling mechanism between RF magnetic fields and the piezoelectric–cantilever system and to evaluate the results more quantitatively.

A 10 mV wired RF electrical excitation was fed to the PZT stack with an impedance close to 1 Ω with a signal generator having an output impedance of 50 Ω. Because of the large difference in the impedances between the PZT stack and the signal generator, only a very small amount of this voltage appeared across the stack. At 190 kHz, this resulted in the development of a voltage of 186.8 μV across the PZT stack and a photodetector signal of 2.79 mV (figure 4). Thus the ratio of photodetector signal to effective wired radio excitation was found to be 15, and it will be referred to as R_{wired}. The magnetic flux density of a loop of radius a, number of turns N, carrying a current I at a distance r is given by

$$B = \mu_0 N \frac{a^2 I}{2(a^2 + r^2)^{3/2}} \qquad (6)$$

where μ_0 is the magnetic permeability of free space. Therefore a coil of radius 2 cm and 5 turns, excited by a signal generator at 1 V, resulted in a current of 36.093 mA in the coil and a magnetic field of 2.00 μT at a distance of 2 cm along the coil's axis. This was experimentally verified by measuring the induced voltage in a coil of radius 1 cm under the effect of the time varying magnetic field. The time varying magnetic flux created by the RF coil induced a voltage along the metallic layers of the rectangular cross-sectional area of the PZT stack, which was calculated to be 23.94 μV using Faraday's law of electromagnetic induction. This is the total voltage drop across the entire PZT stack assuming it to be in the form of a loop of wire. The effective voltage across the opposite side leads of the piezoelectric stack is only half of the voltage drop across the entire loop. Its value is 11.97 μV. The photodetector signal was measured to be 215.9 μV (figure 5), resulting in a ratio of photodetector signal to wireless radio excitation of 18. This may be defined as R_{wireless}, and it is comparable to the value found for R_{wired} of 15. The values of these ratios for other frequencies corresponding to the resonant modes of the cantilever are given in table 1. $R_{\mathrm{wireless}}/R_{\mathrm{wired}}$ is nearly constant for all cantilever resonant modes, indicating that the RF magnetic field is coupled with the piezoelectric stack of the piezoelectric–microcantilever

Table 1. Ratios of photodetector signals to electrical signals induced on the PZT stack for wired (R_{wired}) and wireless (R_{wireless}) RF excitations.

f (kHz)	R_{wired}	R_{wireless}	$R_{\mathrm{wireless}}/R_{\mathrm{wired}}$
189.98	14.95	18.00	1.20
227.9	6.11	4.014	0.66
292.4	8.02	13.14	1.64
354.0	10.6	19.95	1.88
429.1	20.7	16.86	0.81
482.68	3.48	5.65	1.62
540.6	2.16	3.63	1.68

system. This points towards the fact that voltage generated within the piezoelectric stack, irrespective of electrical or time varying magnetic field excitation, results in an equal amount of microcantilever deflection and photodiode current.

The sensitivity of the detection process is limited by noise present in the system. The thermal noise of the piezoelectric–cantilever system was calculated and verified by experiments. The power spectrum density $S_{zz}(\omega)$ associated with thermal noise in a microcantilever is given by [8]

$$S_{zz}(\omega) = \frac{4KT}{Qk\omega_0} \frac{1}{(1-\omega^2/\omega_0^2)^2 + \omega^2/Q^2\omega_0^2} \tag{7}$$

where Q is the quality factor, k is the spring constant, ω_0 is the resonant frequency of the microcantilever and K is Boltzmann's constant. In this case, the microcantilever is operated close to the resonant frequency, so taking $\omega \approx \omega_0$ we get

$$S_{zz}(\omega \approx \omega_0) = \frac{4KTQ}{k\omega_0}. \tag{8}$$

For the microcantilever used in this study, Q has been measured to be ∼220 by measuring the microcantilever vibrations at those frequencies at which the amplitude of the microcantilever dropped to $1/\sqrt{2}$ of its peak amplitude. The spring constant can be estimated from the following equation:

$$k = \frac{Ebh^3}{4L^3} \tag{9}$$

where h, b and L are the thickness, width and length of the microcantilever, and E is Young's modulus. The cantilever has an additional 40 nm layer of gold coated over the 2 μm thick silicon, therefore its effective Young's modulus is 158 GPa (silicon's $E = 160$ GPa, gold's $E = 75$ GPa). It follows that the cantilever's spring constant is 0.0795 N m^{-1} and $S_{zz} = 3.86 \times 10^{-23}$ m^2 Hz^{-1}. Given a bandwidth for our noise signal of 500 Hz, this gives a mean cantilever deflection of 138 picometres (pm). This calculation is consistent with formulations and results on noise calculation in an AFM by Butt and Jaschke [9].

The PZT stack used in the experiment had a strain constant of 17 nm V^{-1}. The cantilever motion was mechanically amplified by its quality factor at resonant frequencies. Due to the projection of the cantilever in space and its limited stiffness, for any mechanical excitation applied to the base, the tip shows additional deflection by at least a factor of 10. Therefore, for a Q-factor of 220 at a frequency of 189.98 kHz, the response of the microcantilever to an applied voltage to the stack was $220 \times 17 \times 10$ nm V^{-1} = 37.4 μm V^{-1}. As previously mentioned, a wired electrical excitation of 10 mV applied to the PZT stack resulted in 186.8 μV across its leads giving a photodetector signal of 2.794 mV and hence the cantilever deflection was 37.4 μm V^{-1} $\times$ 186.8 μV = 6.98 nm. Thus, a typical value of photodetector signal per unit microcantilever deflection was 2.794 mV/6.98 nm, i.e. 0.40 mV nm^{-1}.

For a noise level of 138 pm within a bandwidth of 500 Hz, the noise voltage comes out to be 0.04 mV nm^{-1} $\times$ 138 pm = 55.2 μV. This is of the same order of magnitude as the noise voltage measured by the spectrum analyser of 10–15 μV using a 500 Hz bandwidth.

The sensitivity of the device can be raised by using a larger piezoelectric stack and by using proper impedance matching circuits. The stack's low impedance (0.2 Ω at 290.1 kHz) compared to the impedance of free space (377 Ω), results in a reduced degree of coupling between the RF field and the piezoelectric–microcantilever system. Using a piezoelectric stack of size $18 \times 5 \times 5$ mm^3 and an impedance matching circuit comprising a coil of inductance 1.0 μH in parallel to it and a capacitance of 80 nF in series, RF magnetic fields of the order of 1.81 pT were detected by the system at room temperature conditions. The RF coil was placed at a distance of 1 m from the piezoelectric–microcantilever system and it was excited by a current of 36 μA at 290.1 kHz.

4. Conclusion

We demonstrate the detection of very low values of wireless RF magnetic fields using a piezoelectric–microcantilever system. The piezoelectric stack senses the radio signal which is filtered by the microcantilevers. As conventional inductance–capacitance based filters are bulky and lossy at medium and high frequency ranges, microcantilever based filters integrated with piezoelectric materials may find some commercial applications in radio frequency signal sensing provided the system has an array of microcantilevers vibrating at different resonant frequencies. Other microstructures like membranes which normally have a broader frequency range integrated with a piezoelectric material may also be used.

Microcantilevers integrated with piezoelectric materials are increasingly used in sensing of chemical and biological samples [10]; a wireless means of excitation of the piezoelectric–microcantilever system will result in a better means of monitoring such a system.

The system's sensitivity can be increased by raising the quality factor of the microcantilevers using vacuum environments [11], suitable electronic circuits [12] or novel designs to reduce damping [13]. The optical detection system for the measurement of vibrations can be replaced by a self-sensing mechanism that employs microcantilevers with integrated piezoresistive sensors [14, 15] or by using integrated field effect transistors [16]. The resonant frequency of the microcantilevers can be raised to the gigahertz range, corresponding to GSM frequencies, by reducing their size to a few microns [17, 18] or by depositing high stiffness silicon carbide films on microcantilevers [19].

Acknowledgments

The authors are grateful to Jack Luo and Paul Roberston for theoretical discussions and Mohamed Boutchich and Iskandar Samad for providing help with developing the experimental set up. DS is supported by the Wingate Foundation and the Cambridge Commonwealth Trust. A part of the work was supported by the Defence Science and Technology Laboratory, Ministry of Defence, UK.

References

[1] Hertz H R 1888 Ueber die Ausbreitungsgeschwindigkeit der electrodynamischen Wirkungen *Ann. Phys. Chem.* **34** 155–60
[2] Balanis C A 1982 *Antenna Theory, Analysis and Design* (New York: Harper and Row) chapter 2
[3] Axel L and Hayes C 1985 Surface coil magnetic resonance imaging *Arch. Physiol. Biochem.* **93** 11–8
[4] Garroway A N, Buess M L, Miller J B, Suits B H, Hibbs A D, Barrall G A, Matthews R and Burnett L J 2001 Remote sensing by nuclear quadrupole resonance *IEEE Trans. Geosci. Remote Sens.* **39** 1108–18
[5] Mitarai S, Kobayashi M, Murai A, Sugiura A, Sato K and Mizuno I 2002 Stacked piezoelectric device and method of fabrication thereof *US Patent Specification* 6,462,464 (Oct. 8)
[6] Butterworth S 1915 On electrically maintained vibrations *Proc. Phys. Soc.* A **27** 410–24
[7] Van Dyke K S 1925 The electric network equivalent of a piezoelectric resonator *Phys. Rev.* **25** 895–6
[8] Shusteff M, Burg T P and Manalis S R 2006 Measuring Boltzmann constant with a low cost AFM: an undergraduate experiment *Am. J. Phys.* **10** 873–9
[9] Butt H J and Jaschke M 1995 Calculation of thermal noise in atomic force microscopy *Nanotechnology* **6** 1–7
[10] Wee K W, Kang G Y, Park J, Kang J Y, Yoon D S, Park J H and Kim T S 2005 Novel electrical detection of label-free disease marker proteins using piezoresistive self-sensing micro-cantilevers *Biosens. Bioelectron.* **20** 1932–8
[11] Albrecht T R, Grtitter P, Horne D and Rugar D 1991 Frequency modulation detection using high Q cantilevers for enhanced force microscope sensitivity *J. Appl. Phys.* **69** 668–73
[12] Degen C L, Meier U, Lin Q, Hunkeler A and Meier B H 2006 Digital feedback controller for force microscope cantilevers *Rev. Sci. Instrum.* **77** 043707
[13] Abdelemoneum M A, Demirci M U and Nguyen C T 2003 Stemless Wing glass mode disk micromechanical resonators *IEEE 16th Int. Conf. on Microelectromechanical Systems (Kyoto)* pp 698–700
[14] Lee C, Itoh T and Suga T 1999 Self excited piezoelectric PZT microcantilever for dynamic SFM with inherent sensing and actuating capabilities *Sensors Actuators* **72** 179–88
[15] Rogers B, Manning L, Sulchek T and Adams J D 2004 Improving tapping mode atomic force micrscopy with piezoelectric cantilevers *Ultramicroscopy* **103** 267–76
[16] Shekhawat G, Tark S H and Dravid V P 2006 MOSFET embedded microcantilevers for measuring deflection in biomolecular sensors *Science* **311** 1592–5
[17] Kawakatsu H, Kawai S, Saya D, Nagashio M, Kobayashi D, Toshiyoshi H and Fujuta H 2002 Towards atomic force microscope up to 100 MHz *Rev. Sci. Instrum.* **73** 2317–20
[18] Li M, Tang H X and Roukes M L 2006 Ultra-sensitive NEMS-based cantilevers for sensing, scanned probe and very high-frequency applications *Nat. Nanotechnol.* **2** 114–20
[19] Huang X M H, Zorman C A, Mehregany M and Roukes M L 2006 Nanodevice motion at microwave frequencies *Nature* **421** 496–7