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Short communication

Wireless electrodeless piezomagnetic biosensor with an isolated nickel oscillator

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Abstract

This study presents a fundamental concept of piezomagnetic biochemical sensor driven in a wireless-electrodeless manner. A stepped cylindrical rod of nickel is used as the oscillator, which traps the vibrational energy of axially-polarized surface-shear waves in the central part, where the diameter is slightly larger. A meander-line coil surrounding the oscillator with an air gap can cause and detect the resonant vibrations of the surface-shear waves via the piezomagnetic effect. The resonant frequency of the trapped-mode resonance is continuously measured to detect human immunoglobulin G (IgG). It decreased by 0.08% when a solution containing IgG was injected into the glass cell where the oscillator was placed alone. This oscillator is useful for fundamental studies of various biochemical reactions in a closed system in different environmental gases and different pressures.

Keywords: Biosensor; Magnetostriction; Wireless; IgG; Nickel; Noncontacting

1. Introduction

Piezoelectric oscillators have been intensively studied for the purpose of the detection of biochemical substances. Resonant frequencies of an oscillator decrease when the target substance is adsorbed on its modified surface because of the mass loading and mechanical loss due to the viscoelastic effect of the resonating system. Quartz crystals, especially AT-cut crystals, are most widely used for their high piezoelectricity and low temperature derivatives of the elastic constants. Muramatsu et al. (1987) detected the change of the resonant frequency of the 9-MHz AT-cut quartz plate for quantitative evaluation of concentration of immunoglobulin G (IgG). Suri et al. (1994) detected immunoglobulin M with the 9-MHz AT-cut quartz. Liu et al. (2003a) used the 10-MHz AT-cut quartz crystal with gold electrodes for the study of the real-time monitoring of a molecular recognition between protein and immobilized drug ligand. Halámek et al. (2002) used the 10-MHz AT-cut quartz for the detection of cocaine. Pan and Shih (2004) detected IgG using the 10-MHz quartz crystal with their faces coated by C_{60}-anti-human IgG. Recently, surface-shear-horizontal waves have been adopted for the liquid based sensing systems, showing higher sensitivity and faster measurements (Martin et al., 2004; Hur et al., 2005; Yamazaki et al., 2000). Thus, many researchers employed piezoelectric crystals with metallic electrodes for immunosensors. Most of them, however, required wires and all of them needed electrodes. Our primary purpose in this study is to develop a wireless-electrodeless oscillator for a biochemical sensor. To our knowledge, no wireless-electrodeless biochemical sensor is reported.

There are two challenges for the development of highly sensitive and functional resonator. First is trapping of vibrational energy within an intended part of the oscillator. Acoustic resonators must be mechanically supported and if vibrational energy is significant at the points of contact, a leakage of acoustic energy into the supporting structure occurs and the Q value decreases. Second is establishment of noncontacting-electrodeless measurements. Electrodes deposited on the oscillator affect resonant frequencies, and they sometimes deteriorate resonator's sensing ability. Obviously, an electrodeless oscillator is preferable in the use at elevated temperatures. A wireless measurement enables us to measure changes in resonant frequencies in an isolated system, which contributes to understanding of fundamentals in biochemical reactions with various environment gases and various pressures.

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Recently, we developed a method to generate and detect resonant vibrations of the axial-shear wave in a ferromagnetic cylindrical rod with a noncontacting manner (Ogi et al., 1997, 2002), and moreover succeeded in trapping their vibrational energy in the central part of a stepped rod (Ogi et al., 2004). Following these achievements, we here intend to establish the wireless-electrodeless oscillator for biochemical sensors using the piezomagnetic effect of a nickel stepped rod. This technique is applied to the detection of the human IgG captured by protein A immobilized on the surface of the cylindrical oscillator.

2. Trapped modes of axial-shear waves

Thompson (1979) revealed that surface-horizontal waves can be excited and detected on a ferromagnetic plate using a flat meander-line coil and the static magnetic field applied parallel to the straight parts of the meander-line coil. The coupling is based on the magnetostriction (piezomagnetic) response of the material. The present authors extended his measurement to cylindrical rods and analyzed the excitation and detection mechanisms (Ogi, 1997; Ogi et al., 2002, 2003), and proposed a novel methodology for generation and detection of the axial-shear resonances with a noncontacting manner in a cylindrical rod (Hirao and Ogi, 2003).

The axial-shear wave is a surface shear-horizontal wave, which propagates along the circumferential direction with the polarization along the axial direction. Fig. 1 shows the principle of the wireless-electrodeless acoustic coupling for axial-shear waves. A meander-line coil surrounds the cylindrical rod with an air gap and induces the dynamic fields $\mathbf{H}_\omega$ along the circumferential direction on the rod surface. A permanent magnet placed at an end of the rod applies a static magnetic field $\mathbf{H}_0$ along the axial direction. When a sinusoidal current is applied to the meander-line coil, the total field oscillates about the axial direction at the same frequency as the driving current, producing shearing vibration through the magnetostriction effect. The surface shear wave is then generated to propagate along the circumference direction with the axial polarization, that is called the axial shear wave. The meander-line coil also receives the axial-shear wave through the reverse magnetostrictive effect. An excitation with long tone bursts causes interference of the axial shear waves and a frequency scan detects the resonant peak, at which all the shear waves overlap coherently to produce large amplitude.

For a non-stepped cylindrical rod of infinite long, the frequency equation of the axial-shear-wave resonance is given by (Johnson et al., 1994)

$$n J_n(\tilde{\eta}_n) - \tilde{\eta}_n J_{n+1}(\tilde{\eta}_n) = 0. \tag{1}$$

Here, n denotes the wavenumber in the circumferential direction and it equals the number of turns of the meander-line coil (Hirao and Ogi (2003)). $\tilde{\eta}_n$ denotes the wavenumber in the radial direction normalized by the radius of the rod a. The resonant frequencies ω_c are then determined by

$$\omega_c = \frac{\tilde{\eta}_n v_s}{a}, \tag{2}$$

with the shear-wave velocity v_s.

Johnson (1996) showed that there are torsional-vibration modes in a stepped cylindrical rod, whose vibrational energy is trapped in the central part of the rod where the diameter is slightly larger than those outside the steps. Following his work, we found that vibrational energy of the axial-shear-wave resonances can also be trapped in the central part of a stepped cylindrical rod with sufficiently large steps and derived the frequency equation of the trapped modes of axial-shear-wave resonance (Ogi et al., 2004):

$$\frac{ak_1}{a'|k_2|}\tan\left(\frac{l}{2a}k_1\right) = 1, \tag{3}$$

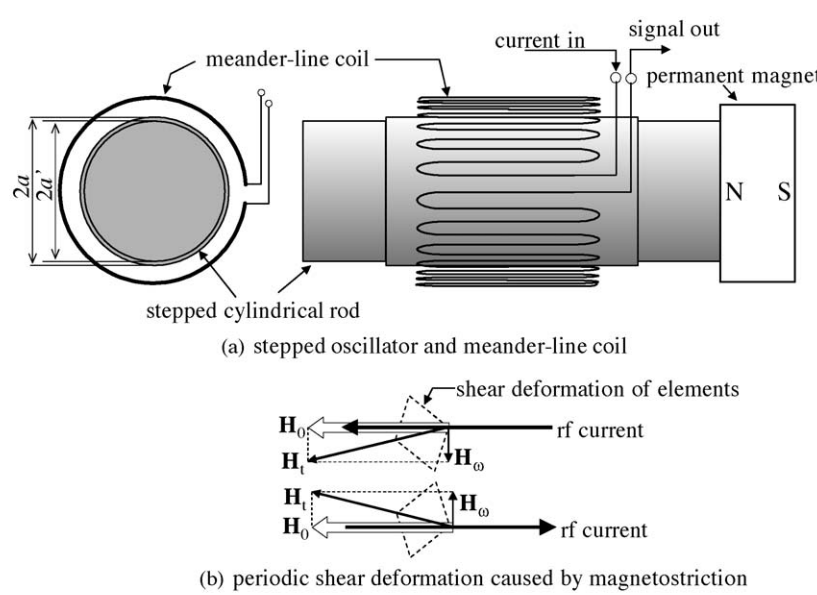

Fig. 1. (a) Generation and detection of the axial-shear-wave resonances by the meander-line coil surrounding the stepped cylindrical rod. (b) Schematic of the generation mechanism of the axial-shear wave by the piezomagnetic effect.