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Original Article

Real-time monitoring of position and motion of a non-stationary object with a highly sensitive magnetic impedance sensor

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A B S T R A C T

The real-time monitoring of the position and speed of a moving object is crucial for safety compliance in industrial applications. The effectiveness of current sensing technology is limited by sensing distance and messy environments. In this work, a position and speed sensor based on the giant magneto-impedance effect was fabricated using a Joule annealed Co-rich magnetic microwire. The fabricated GMI sensor response was explored over a frequency range of 1 MHz–1 GHz. The impedance spectrum showed a high GMI ratio and high field sensitivity response at low magnetic fields. The GMI sensor based longitudinal effect was found to be more sensitive than a commercial Gaussmeter. The practical utility of the high sensitivity of the sensor at weak magnetic fields for far-off distance monitoring of position and speed was demonstrated. This GMI-based sensor is highly promising for real-time position detection and oscillatory motion monitoring.

1. Introduction

Real-time position and speed monitoring of a non-stationary object finds wide ranging applications in robotics, industrial manufacturing and processing, collision prevention assistance, and autonomous vehicles, etc. [1–5]. In particular, the real-time monitoring of a moving object is crucial for a feedback loop process and safety compliance [2,5]. Magnetic sensors play an essential role in these technologies and also have superior advantages to other types of sensors [6–9]. For instance, they provide precise, contactless measurements and are able to operate in dirty, high temperature, and/or non-transparent environments. A variety of magnetic sensors, such as those based on magnetoresistance (MR) [10], the Hall effect [11], induction [12], and superconducting quantum interference device (SQUID) [7] have been developed for magnetic field detection. Among them, sensors based on the Hall effect [5], giant magnetoresistance (GMR) [8], and inductive proximity [1] effects have been extensively used for position and speed detection owing to their robustness and cost effectiveness [1,2,6,13]. However, the signals become diminished and the noise disturbance increases when these sensors are located at far-off distances from a weak field source [6,14]. Therefore, there is a pressing need for developing new magnetic sensors that can sense weak fields from far working distances.

In recent decades, the giant magneto-impedance (GMI) effect in soft ferromagnetic microwires has been extensively studied to promote the GMI response at high working frequency [15–18]. The GMI effect in soft ferromagnetic microwires refers to a large change in the complex impedance when the wires are subjected to an external magnetic field along their axis [19,20]. Recently, a large and pronounced GMI response and field sensitivity in Co-rich microwires at RF excitation frequencies have been developed through a Joule heating technique [15,21,22]. When the exciting frequency increases, the ac excitation field tends to concentrate near the surface of the microwire due to the skin effect [23]. As a result, the circumferential magnetic anisotropy attributed to the outer shell domain structure becomes significant and a double peak feature of the complex impedance is observed [17,24]. With the Joule annealing treatment, the magnetic microwires possess an ultra-high sensitivity to small magnetic fields (below the anisotropy field, H_k, of the microwire), which is highly promising for weak

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magnetic field sensing at room temperature. In addition, the excellent mechanical properties and cost effectiveness of this metallic glass microwire make them attractive for the industrial applications [25,26]. Therefore, a GMI-based sensor employing a Co-rich microwire is a suitable candidate for active position and speed detection from a far-off distance [27,28].

In this study, a contactless GMI-based sensor is constructed with a Joule-annealed Co-rich microwire. The high frequency magneto-impedance response of the GMI-based sensor is characterized. The potential sensor's sensitivity, stability and reliability are shown. A comparison between the field sensitivity of the GMI-based sensor and a commercial Gaussmeter is performed. Then, the GMI-based sensor is employed for real-time position and oscillatory motion monitoring from a test source. A thorough discussion on existing sensing technologies and the promise of GMI-sensor for an active position and speed detection is provided.

2. Experimental

2.1. Optimization of melt-extracted microwires

Co-rich magnetic microwires with a nominal composition $Co_{69.25}Fe_{4.25}Si_{13}B_{12.5}Nb_1$ were fabricated by a melt-extraction technique described elsewhere [25]. The obtained magnetic microwires are typically 30–60 microns in diameter and 10–50 cm in length. After rapid quenching, the microwires have a cylindrical shape and possess excellent mechanical properties. The surface morphology and the nominal elemental composition were investigated using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS), respectively. The EDS spectra shows 69.3 wt% of Co (used as the normalized element), 4.6 wt% of Fe (sd = 0.2 wt%), 14.4 wt% of Si (sd = 0.4 wt%), and 1.0 wt% of Nb (sd = 0.1 wt%). The amorphous nature of the as quenched microwires was characterized by high-resolution transmission electron microscopy (HRTEM) and an x-ray diffractometer (XRD) previously described in Ref. [22,25], respectively.

In this experiment, an as quenched microwire with 50 μm diameter and 7 mm in length was selected and cut from a long microwire strand. The sample was then soldered to SMA ports, which are amounted to a micro-strip Cu ground plane (see Fig. 1). The multi-step Joule heating procedure used to tailor the magnetic and mechanical properties of the microwire is given here: the mounted sample was subjected to increasing current intensity from 20 mA to 100 mA in steps of 20 mA. During each step, the microwire is subjected to a constant current for 10 min and then stopped for 10 min to reach ambient temperature. This multi-step current annealing process has been shown to optimize the GMI effect in melt-extracted microwires in previous studies [21,25].

2.2. High frequency impedance spectroscopy

The impedance spectrum of the annealed microwire was measured over the frequency range (1 MHz–1 GHz) using an Agilent 4191A RF-impedance analyzer through transmission line methods [29]. In this measurement, the standard calibration using short-, open-circuits, and 50-Ω standard was performed, respectively. A fixed 50 cm coaxial cable and the 50-Ω terminator were employed to facilitate and match the input impedance of the analyzer. The 4191A determines the complex reflection coefficient (Γ) of a measurement frequency test signal applied to the terminated transmission line. The complex impedance of a test sample can be determined by

$$Z = 50\left(\frac{1+\Gamma}{1-\Gamma}\right) = R + jX, \tag{1}$$

where R is the resistance, X is the reactance, and j is the imaginary unit.

For each frequency measurement, an axial magnetic field in the range ±114 Oe was generated and applied along the longitudinal direction of the sample using a pair of Helmholtz coils. We define the GMI ratio (ΔZ/Z) as follows [30]:

$$\frac{\Delta Z}{Z}(\%) = 100 \times \frac{Z(H) - Z\left(H_{ref}\right)}{Z\left(H_{ref}\right)}, \tag{2}$$

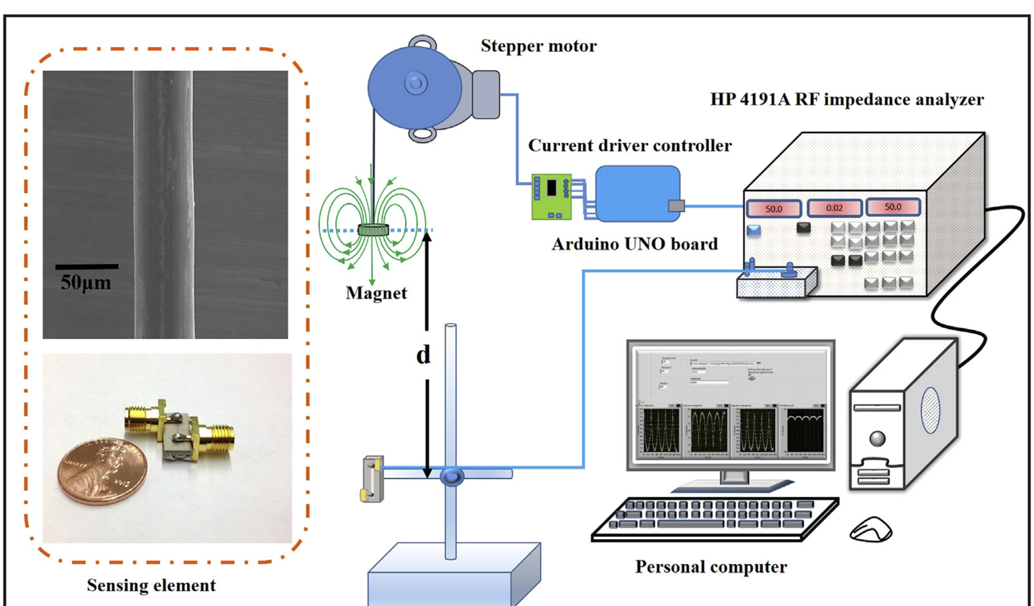

Fig. 1. Schematic of the experimental setup. The Agilent 4191A RF-impedance analyzer was employed to measure an impedance spectrum over high frequency range. Inset shows SEM micrograph of the sensing element and the mounted sample onto SMA port, respectively.

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