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Scalable, high-performance magnetoelastic tags using frame-suspended hexagonal resonators

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Abstract

This paper presents the analysis, design and experimental evaluation of miniaturized magnetoelastic tags using frame-suspended hexagonal resonators. Magnetoelastic tags—also known as acousto-magnetic or magnetomechanical tags—are used in wireless detection systems—for example, electronic article surveillance and location mapping systems—that electromagnetically query the resonant response of the tags. In order to obtain a strong resonant response for miniaturized tags, a frame-suspended configuration is utilized to diminish the interaction between the vibrating portion of the tag and the substrate. The signal strength can be boosted by utilizing signal superposition with arrayed or clustered magnetoelastic tags. The hexagonal tags with a diameter of 1.3 mm are batch fabricated by photochemical machining from 27 μm thick Metglas$^{\mathrm{TM}}$ 2826 MB, which is an amorphous NiFeMoB alloy. A preferred dc magnetic field bias for these tags is experimentally determined to be ≈31.5 Oe. A single frame-suspended magnetoelastic tag shows quality factors of 100–200. This design provides ≈75X improvement in signal amplitude compared to the non-suspended disc tag with similar size and resonant frequency. Across ten individual frame-suspended tags, the average resonant frequency is 2.13 MHz with a standard deviation of 0.44%, illustrating that this fabrication method provides repeatability. Linear signal superposition of the response has been experimentally measured for sets of frame-suspended tags that include as many as 500 units.

Keywords: acousto-magnetic tags, magnetomechanical tags, electronic article surveillance (EAS), magnetostrictivity, Metglas

(Some figures may appear in colour only in the online journal)

1. Introduction

In magnetoelastic devices, an applied magnetic field generates material strain that results in another magnetic field as a response, thereby allowing wireless interrogation [1–5]. The narrow-band response inherent to the resonant operation of such sensors limits interference from spurious sources. Magnetoelastic resonators (tags) are also passive devices, i.e., no power sources or circuits are required within the tags [6, 7]. These advantages—wireless operation, signal isolation, and passivity—make magnetoelastic resonators very attractive for applications for remotely detecting, locating, or mapping items. Potential applications include, for example: tagging of inventory, wirelessly detecting blockage or leakage in piping systems or sophisticated machines, and sensing parameters in medical implants.

One of the most successful applications utilizes magnetoelastic tags for electronic article surveillance (EAS) systems [8, 9]. There are three types of EAS tags commonly used for theft deterrence in libraries, supermarkets, retail stores, etc. One type of EAS tag, the radiofrequency (RF) label, consists of an inductor–capacitor (LC) tank circuit that absorbs an RF signal at its resonant frequency [10, 11]. The presence of an RF label can be detected by measuring the reduction in the received signal while sweeping the frequency of the transmitted signal near the resonant frequency of the LC circuit. Another type of EAS tag, the magneto-harmonic tag, consists of a ferromagnetic material strip with moderate magnetic permeability, and another ferromagnetic strip that has higher coercivity. When interrogated by an ac magnetic field that spans a predetermined range of frequencies, the tag generates a harmonic signal that is then detected by a receive coil, indicating the presence of the tag [12, 13]. The third type of EAS tag, the magnetoelastic or acousto-magnetic tag, utilizes a magnetoelastic strip, a hard ferromagnetic strip to provide magnetic bias, and a package to provide space for vibration [14–16]. In acousto-magnetic systems, magnetoelastic strips oscillate mechanically at a resonant frequency when interrogated, and generate an ac magnetic flux that can be detected wirelessly by a receive coil. Amongst the three types of EAS tags, magnetoelastic tags provide an attractive price/performance ratio, and hence have gained wide commercial acceptance. In addition, magnetoelastic resonators—with appropriate design and packaging—can be used for a variety of sensing applications.

Despite the great improvements in signal strength and detection range provided by advances in material properties and detection approaches, the miniaturization of magnetoelastic tags remains a challenge. Challenges resulting from miniaturization include signal loss and compromises in dimensional tolerances [17, 18]. Many applications would benefit from miniaturization of magnetoelastic tags. For example, a much smaller magnetoelastic tag would be less conspicuous for anti-theft systems. Miniaturized tags could be helpful in the management of inventories. New applications can be envisioned, including some in medical sectors. For example, tagging of surgical supplies and instruments could reduce procedural errors and allow tracking of items. Tags with different resonant signatures would provide more granularity. Miniaturization also brings other benefits, such as reducing material costs and increasing the resonant frequency. Higher resonant frequencies generally permit smaller antenna dimensions, and can also be helpful in evading $1/f$ noise in interface electronics.

The main concerns for miniaturization include diminished signal and fabrication challenges. Signal strength is directly related to the effective volume of the magnetoelastic material. The typical commercial magnetoelastic tags operating at 58 kHz are about 38 mm long, 12.7 mm or 6 mm wide and 27 μm thick [14]. Smaller tags operating at 120 kHz, with adequate signal strength for commercial use, still have a length of about 20 mm and width of 6 mm [18]. These magnetoelastic tags are usually strips or ribbons and the length-to-width ratio is normally larger than 3:1.

This paper describes miniaturized magnetoelastic tags that are 100X smaller than commercial tags[1]. Each magnetoelastic tag consists of a hexagonal resonator and frame (figure 1). The frame suspension allows a stronger response than other resonators of that size. The work described in this paper also demonstrates that the signal amplitude can be boosted by utilizing signal superposition with arrayed or clustered tags. Section 2 provides a theoretical model of magnetoelastic tagging systems, a geometrical design for the tags, and simulations of the interrogating magnetic field and the resulting resonant response. Section 3 details the fabrication process of the magnetoelastic tags. Section 4 describes the two experimental setups, experimental methods, and results. Section 5 discusses the advantages of miniaturized magnetoelastic tags, remaining challenges, and possible approaches for improving performance. Section 6 provides conclusions.

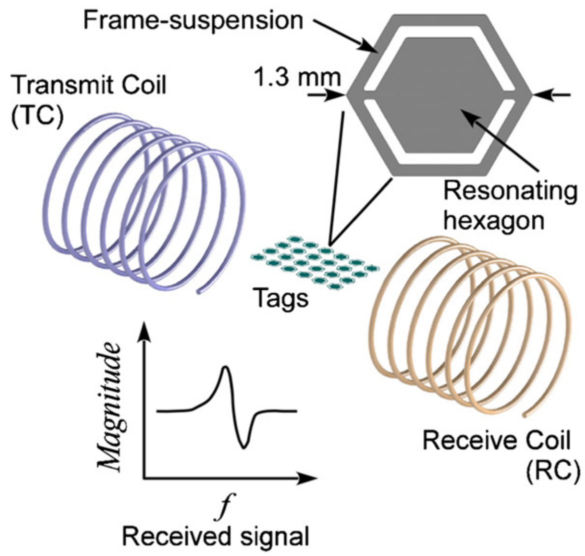

Figure 1. Magnetoelastic tags resonate under an applied ac magnetic field generated by a transmit coil. The magnetic field resulting from the resonant vibration is detected by a receive coil, indicating the presence of the tags.

2. Design and modeling

2.1. Concept

A typical magnetoelastic tagging system includes a transmit coil, a receive coil, magnetoelastic tags and dc bias magnets, as shown in figure 1. In the presence of a dc magnetic field, the magnetoelastic tags can be resonated by an applied ac magnetic field provided by a transmit coil. The magnetic flux resulting from the vibration can be detected inductively by a remotely positioned receive coil. The dc bias can be generated electromagnetically or provided by magnets packaged alongside the tags.

Magnetoelastic tagging systems are not limited to this configuration. The interrogating and detecting approaches can both be different for a variety of applications. For example, a pulsed signal—rather than a continuous wave signal—can be used for the interrogating magnetic field, and the receive coil can detect the signal generated during the post-stimulation 'ring-down' [20, 21]. This allows temporal separation of the tag signal from that induced by the ac interrogating magnetic field. The detection can also be performed by acoustic or optical approaches [22].

[1] Portions of this paper have appeared in conference abstract form in [19].

The frame-suspended resonator is designed to be attached to its package by its frame. Because the tags have a slight out-of-plane curvature that is an artifact of the casting and photochemical machining (PCM) process (described in section 3), the suspension is effective even when unpackaged tags are placed on a flat substrate. With the convex surface away from the substrate, only the perimeter frame of the tag contacts the substrate, allowing the central vibrating part to resonant with minimum interaction with the supporting substrate.

The hexagonal geometry is specifically chosen to allow maximum usage of material for a batch patterning process. The symmetrical geometry is also expected to reduce the signal strength sensitivity to orientations of applied magnetic field. Another benefit of the shape pertains to signal orientation. When excited by an applied ac field, the symmetrical hexagonal tag generates two major magnetic response components, with one parallel and the other orthogonal to the applied ac signal. Consequently, an orthogonally-oriented receive coil couples weakly with the applied signal and strongly with the response of the magnetoelastic tag. This interrogating and detecting approach is used in this study.

2.2. Modeling

A custom magneto-mechanical harmonic finite element technique [4] is used to estimate displacements, mode shapes, and resonant frequencies for the magnetoelastic tags. Although magnetoelastic materials are generally non-linear, it is appropriate to use constitutive equations describing the coupling between magnetic flux density, magnetic field strength, stress, and strain that are linearized at the dc bias point:

$$\vec{\sigma} = [C]\vec{\varepsilon} - \frac{[C][d]^T}{\mu_0\mu_r}\vec{B} \qquad (1)$$

$$\vec{H} = -\frac{[d][C]}{\mu_0\mu_r}\vec{\varepsilon} + \frac{1}{\mu_0\mu_r}\vec{B} \qquad (2)$$

where σ is the stress vector, C is the stiffness matrix, ε is the strain, d is the magnetostrictivity matrix, B is the magnetic flux density vector, H is the field strength vector, μ_0 is the permeability of free space, and μ_r is the relative permeability. Equations (1) and (2) are implemented in this work utilizing COMSOL Multiphysics with coupled magnetic and structural domains for time-harmonic induction current and stress–strain frequency response. Details of the finite element analysis (FEA) implementation for magnetostrictive materials are presented in [23]. Models in this study used the parameters derived from the experimental results of magnetoelastic resonators placed directly on the substrate [4].

2.3. Magnetic field strength

In order to estimate the applied ac magnetic field strength necessary for interrogating the tags, transmit coils were modeled in COMSOL Multiphysics. Because the size difference between the coils and the magnetoelastic tags is large, it is appropriate to first calculate the magnetic field strength generated by the coils in a separate model and then use the calculated values as exciting conditions in the customized magneto-mechanical model that is spatially focused on a single magnetoelastic tag. In this work, two experimental setups were utilized—configurations A and B (figure 2). Detailed descriptions of these two configurations are given in section 4. Modeling results indicated that the applied ac fields per unit electrical current that are available at the locations of interest from configurations A and B are 2.69 Oe/A and 0.85 Oe/A, respectively.

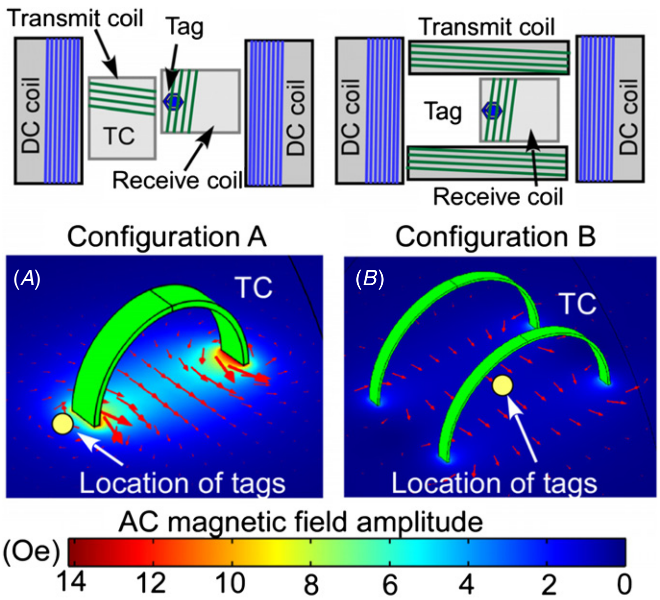

Figure 2. Results of FEA simulations of signal strength generated by transmit coils for configurations A and B. The ratios of the ac magnetic field amplitude to the applied ac current amplitude for configurations A and B are 2.69 Oe/A and 0.85 Oe/A, respectively, at the locations of interest.

2.4. Mode shapes, resonant frequencies of hexagonal and disc magnetoelastic tags

The pre-calculated ac magnetic field was used for modeling the resonant response of hexagonal and disc magnetoelastic tags in the magnetomechanical coupled FEA model described in section 2.2. Figure 3 shows the calculated mode shapes of hexagonal (1.4 mm circumscribed diameter) and disc tags (1 mm diameter) at resonant frequencies of about 2.09 and 2.1 MHz, respectively. The desired mode shape—which exhibits both longitudinal and transverse motion—generates an oscillating magnetic field with one significant response component that is orthogonal to the applied ac field, facilitating the decoupling of the applied ac field from the received signal by orienting the transmit coil and receive coil orthogonally. Because it is difficult to estimate the interaction between the tag and the supporting substrate, the 'free-standing' condition is used for both FEA models of hexagonal and disc-shaped tags. Accordingly, these two types of tags have similar theoretical performance without considering the interaction between the substrate and the tag. In practice, only the frame of the hexagonal tag interacts with the supporting substrate while the central resonator can vibrate freely. In contrast, the entire disc or disc perimeter interacts with the substrate.

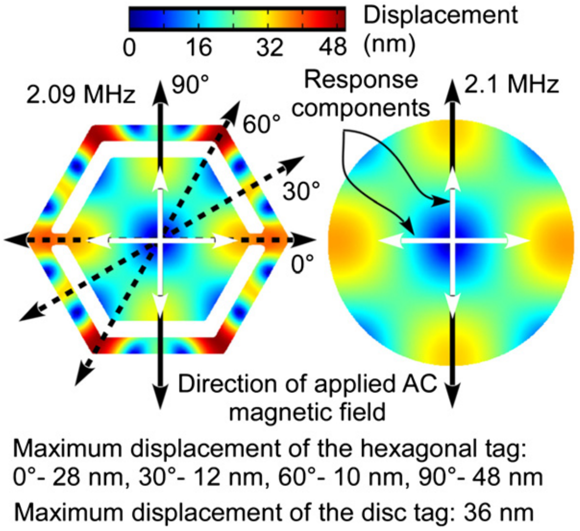

Figure 3. FEA simulation results of hexagonal and disc tags. The hexagonal tag, with a size of ø1.3 mm × 27 μm, resonates at 2.09 MHz. Its response is sensitive to the orientation of the applied ac field. The disc tag, with a diameter of 1 mm, resonates at 2.1 MHz. These simulations do not account for contact with the substrate encountered in practice. Frame-suspended resonators contact the substrate only at the frame whereas the others do so over the entire surface.

Therefore, a significant signal amplitude advantage for the frame-suspended tag is expected. The FEA simulations also show that the frame-suspended tag is sensitive to the azimuthal direction of applied ac magnetic field (figure 3).

In order to compare the azimuthal characteristics of the hexagonal tag with a conventionally-shaped rectangular strip, a strip design of 1 mm × 0.2 mm × 27 μm was also modeled. According to FEA simulations, under different orientations of applied ac magnetic field, the azimuthal variation in the response amplitude was 26.7:1 for the strip. In contrast, for the frame-suspended hexagonal tag, it was only 4:1, indicating that this shape presents an improvement.

3. Fabrication

In the PCM process, magnetoelastic tags are batch patterned from a ≈27 μm thick foil of as-cast Metglas™ 2826 MB, an amorphous NiFeMoB alloy [24], utilizing a 'tabless' approach [25]. In this process, the Metglas™ thin foil is laminated with photoresist film on each side. The photoresist films are then lithographically patterned, resulting in the selective removal of portions of the films and revealing the metal beneath. The exposed metal is etched away by an acid spray, leaving the patterned Metglas™ structures. The etching process is isotropic. Normally, PCM fabricated devices have tabs that keep the devices connected to the foil throughout the etch process. However, the 'tabless' process is utilized in this work because it allows hundreds of tags to 'drop' from the Metglas™ foil automatically during the etching process, eliminating the extra time, cost, and geometrical variability resulting from an additional tab cutting process. Approximately 500 disc tags (resonator only) and 1000 hexagonal tags (resonator and frame) were fabricated. As

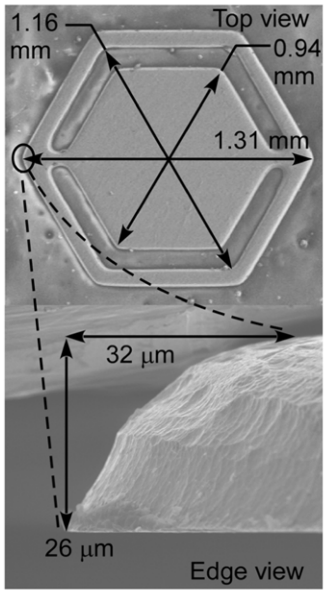

Figure 4. SEM pictures of a frame-suspended hexagonal tag show the maximum sidewall over-etch is about 32 μm. Inspection of fabricated disc tags revealed a similar edge profile.

shown in figure 4, the lateral undercut for sidewalls of a hexagonal tag is 32 μm. This is small compared to the size of the tag, so predictability and consistency is expected in the resonant frequency across a batch of tags. The undercut can be further reduced by utilizing double-sided lithography and etching instead of the one-sided process that is used for this study.

4. Experimental methods and results

4.1. Experimental methods

As noted in section 2.3 in this work, two configurations (A and B) of transmit coils and receive coils were utilized for characterization of small and large quantities of magnetoelastic tags (figure 2). Configuration A is suitable for small quantities of tags, as it provides a strong and concentrated interrogating field. Configuration B is suitable only for very large quantities of tags, as it provides a weaker but more uniform interrogating field.

Both configurations included a network analyzer, an RF amplifier, and a receive coil. For these tests, the magnetic bias necessary for the tags was not provided by a permanent magnet, but instead by dc Helmholtz coils that were included in the setup. The transmit coil(s) and the receive coil were configured orthogonally. This arrangement of coils and symmetrical design of resonators contributed to decoupling the applied ac field from the received signal, reducing the signal feedthrough and emphasizing the response of the tags. The network analyzer provided the input signal, which was sent to the amplifier and then to the transmit coil. The receive coil was connected directly to the network analyzer as well. For all data presented here, the baseline signal feedthrough (without tags present) has been subtracted.

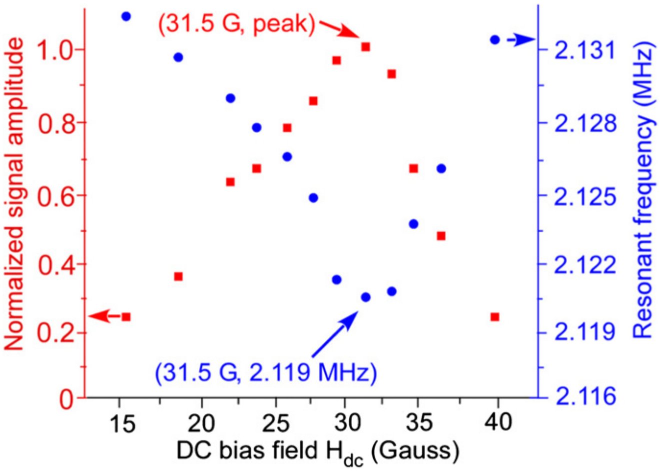

Figure 5. The typical preferred dc magnetic field bias for a single frame-suspended hexagonal tag is experimentally measured to be 31.5 Oe. The signal amplitude is normalized to the peak when a preferred dc magnetic field is applied. At this bias field strength, the resonant frequency and signal amplitude reach a minimum and maximum, respectively.

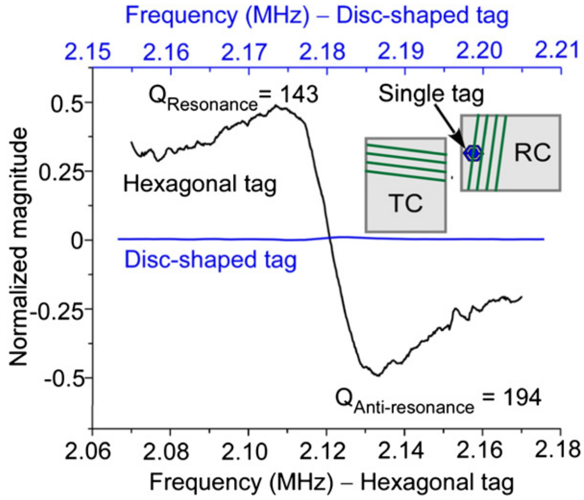

Figure 6. A typical resonant response of a frame-suspended tag, exhibiting quality factors of 100–200 at a resonant frequency of 2.11 MHz.

In configuration A, the transmit coil and receive coils were placed ≈0.5 cm apart. The targeted 1–10 tags were placed close to the transmit coils to provide a strong interrogation field. The transmit and receive coils used in configuration A had four turns of 60-strand 22 AWG Litz wire, in which each individual conducting strand is insulated to reduce impedance at high frequencies. These coils had 3.6 cm diameter and 0.5 cm axial length. In configuration B, which provided a weaker but more uniform field that could accommodate hundreds of resonators, the applied ac field was provided by two Helmholtz coils, each with four turns of the same Litz wire, a diameter of 7.2 cm and an axial length of 0.5 cm. The two Helmholtz coils were separated by 3.6 cm. The receive coil for configuration B was the same as for configuration A. The dc bias field was applied using two additional Helmholtz coils, placed 12 cm apart, each with 12.5 cm diameter and 3.3 cm axial length.

The applied ac current amplitudes for configuration A and B were experimentally measured to be 2.9 and 0.94 A (N2774A current probe, Agilent, Santa Clara, CA). According to the FEA simulated relationship between magnetic field and the ac current (section 2.3), the amplitudes of ac magnetic fields used for experiments at the location of the tags were estimated to be 7.8 Oe and 0.8 Oe for configurations A and B, respectively.

4.2. Experimental results of a single magnetoelastic tag using configuration A

Figure 5 shows the typical measured signal amplitude and resonant frequency of a hexagonal tag as a function of dc bias. The signal amplitude reaches a maximum and the resonant frequency reaches a minimum [26] when a preferred 31.5 Oe dc bias was applied. In a similar study, the required dc magnetic field bias for disc tags was experimentally determined to be 33 Oe.

Because the signal amplitudes of tags vary with different experimental setups and the measuring conditions, signal amplitudes in this paper are normalized to the measured maximum signal amplitude of a single frame-suspended hexagonal tag with a preferred dc bias under the condition that the dc and ac fields are aligned. The measured signal amplitude of a frame-suspended hexagonal tag was 75X that of a disc-shaped tag (without a suspension) that was measured for comparison (figure 6). The resonant response of frame-suspended hexagonal tags showed quality factors of 100–200 (figure 6).

As expected, the response of the frame-suspended hexagonal tags varies in amplitude with the azimuthal orientation of the applied ac magnetic field (figure 7(*a*)). Although signal amplitude varied with angle, it was larger than that of disc-shaped tags in every orientation. In this measurement, the dc bias magnetic field and the applied ac field had the same direction while the axis of the receive coil was orthogonal to the directions of those two fields. Figure 7(*b*) shows the effect of orientations of dc bias field on the signal amplitude while the applied ac field and the received ac field were maintained at angles of 90° and 0° to the tag, respectively. With a 45° offset between the applied ac and dc bias field, the response increased by about 80%. The ac field amplitude was 7.8 Oe, whereas the dc field was 31.5 Oe.

4.3. Experimental results of small quantities of hexagonal tags using configurations A and B

A number of hexagonal tags were measured individually to evaluate the basic variability in resonant frequency. Across ten hexagonal tags, the average resonant frequency was 2.128 MHz with a 0.44% standard deviation. The small process variability facilitates signal superposition when the tags are arrayed or clustered.

Signal superposition for small quantities of hexagonal tags (up to ten) was measured using configuration A. The tags were placed in a 2 × 5 array in the proximity of the ac transmit coil. Evidence of signal superposition was provided by the analysis of four tags (figure 8). When tested individually, the

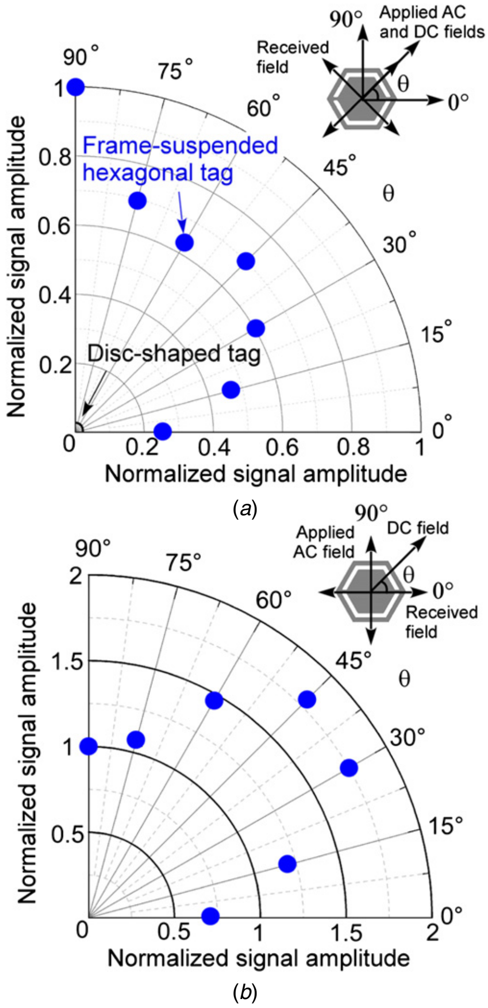

Figure 7. (*a*) The measured normalized signal amplitudes of a typical frame-suspended hexagonal tag and an unsuspended ø1 mm disc-shaped tag as a function of orientation of azimuthal angle of applied ac magnetic field. The dc bias field and applied ac field have the same orientation. (*b*) While changing the direction of the dc bias field, the applied ac field and received field are maintained at 90° and 0° with respect to the tag. All signal amplitudes for (*a*) and (*b*) are normalized to the maximum signal amplitude measured with the applied ac field and dc bias aligned with each other at 90° with respect to the tag, as used in (*a*).

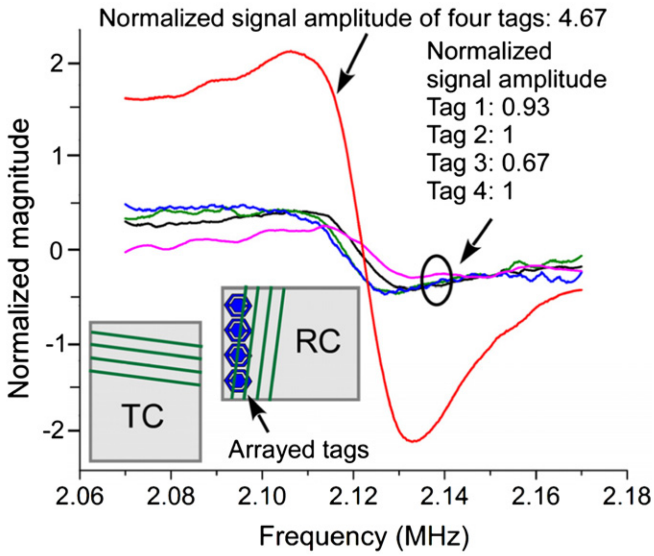

Figure 8. Signal superposition for four frame-suspended tags: the overall signal amplitude of four tags is 4.67, whereas individual tags have signal amplitude of 0.93, 1, 0.67, and 1, normalized to the largest signal amplitude in the group.

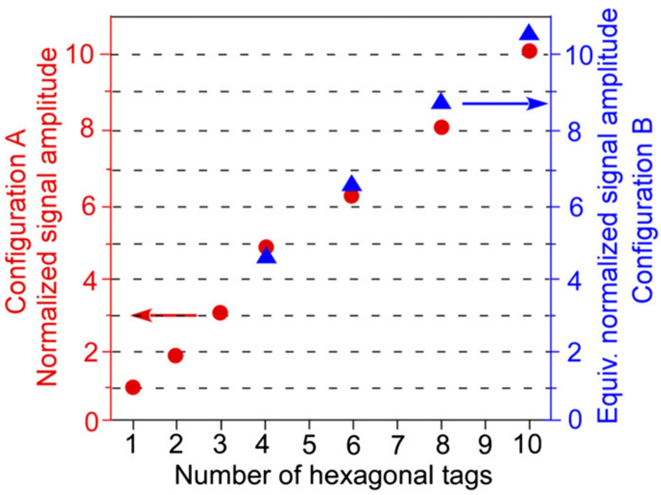

Figure 9. Signal amplitudes of arrayed frame-suspended tags as a function of number of tags ranging from 1–10. The signal amplitudes are normalized to the largest signal amplitude measured amongst ten tags in configuration A. The equivalent normalized signal amplitudes reported for configuration B are corrected by the ratio of the simulated applied magnetic fields in the two configurations.

peak-to-peak amplitude of these tags varied from 100 to 150 μV, and their resonant frequency ranged from 2.118 to 2.127 MHz. When tested together, the peak-to-peak response was 700 μV, and the resonant frequency was 2.123 MHz. As shown in figure 9, the signal strength increased linearly with the number of arrayed tags for modest counts.

The resonant responses of small quantities of tags were experimentally measured by configuration B as well, and normalized to the response of a single tag in configuration A. The equivalent normalized signal amplitudes for 4, 6, 8 and 10 tags in configuration B were calculated by multiplying measured signal amplitudes by the ratio of the simulated magnetic field strengths: 7.8 Oe/0.8 Oe. Figure 9 shows a good match for the normalized equivalent signal amplitudes measured by the two different configurations.

4.4. Experimental results of large quantities of randomly clustered tags using configuration B

The frequency responses of large clusters of hexagonal tags were experimentally evaluated. These tags were randomly clustered because of the difficulty in arraying such large quantities with preferred orientation and with convex surfaces away from the substrate. The inset within figure 10 shows the typical resonant response for 500 randomly clustered frame-suspended tags at a resonant frequency of 2.13 MHz, presenting a signal amplitude that is ≈500X the signal amplitude from a single tag. Figure 10 also indicates that although there may be signal loss due to random orientation

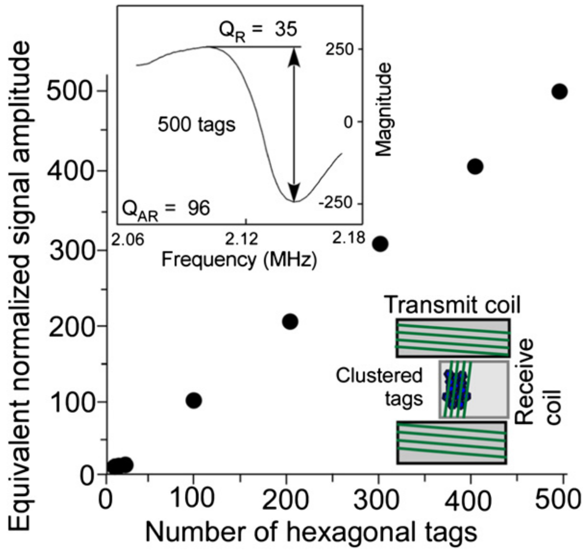

Figure 10. Equivalent normalized signal amplitudes of randomly clustered hexagonal tags as a function of number of tags (up to 500). Test configuration B was used.

and placement of the tags, the signal amplitude varied in approximately linear fashion with the number of tags. Interaction between tags might have contributed to the compensation of the signal loss expected by random tag orientations and placement, but this requires further study that is beyond the scope of this paper.

5. Discussion

In order to maintain the signal strength at millimeter dimensions for magnetoelastic tags, two features were investigated: frame suspensions and signal superposition. Experimental results showed that the frame suspension provides a significant signal amplitude increase for a single magnetoelastic tag. Although the frame suspension was demonstrated for hexagonal tags, a similar approach for performance improvement may also apply to typical conventional rectangular strips. For example, a strip can be suspended by two springs connecting its center to an outer frame.

It was also confirmed that signal superposition boosts the signal strength dramatically for both carefully arrayed or randomly clustered small and large quantities of magnetoelastic tags. The signal superposition for large quantities (up to 500) of clustered magnetoelastic tags was experimentally evaluated. The advantages of miniaturization as demonstrated in this work is the ability to tag small items individually or the ability to distribute tags into networks of small tubes or crevices. Clustered large quantities of these tags can be utilized for applications that require long-range detection.

A package with appropriate support and an integrated dc bias magnetic material requires further consideration. For a product-level implementation, the magnetoelastic tag should be supported by the frame so that the resonant element can vibrate freely. The package should also include a magnetic material that provides the dc field bias. The biasing magnet material—preferably with a geometry similar to that of the tag—should have high coercivity, and a material like Arnokrome^{TM} (an iron–chromium–cobalt alloy) may fit the purpose.

Metglas^{TM} 2826 MB has been used for this work, but other amorphous alloys with high magnetostrictivity, good mechanical properties, and demanding a modest dc bias field might provide better performance than this work. Although the PCM process is appropriate for the fabrication of hundreds of magnetoelastic tags, other low cost fabrication processes capable of producing large quantities may be worthwhile to explore. Metglas^{TM} and other amorphous alloys can be fabricated with desired geometry by metal alloy quenching [27]. Typically, metal powders or granules with preselected portions are melted and homogenized, and then the molten alloy is rapidly quenched on a surface or in a recess with the desired geometry.

Annealing of the magnetoelastic material—especially transverse field annealing—can potentially improve the performance [28]. However, transverse field annealing will likely increase the signal strength sensitivity to the orientation of the applied magnetic field because, unlike the as-cast material, a transverse-field-annealed material has induced magnetic anisotropy. Implementation of a transverse-field-annealed tag would require further study for the specific intended application.

The detection range is normally limited by the interrogation and detection approach— especially in how the approach accommodates transmitter-to-receiver feedthrough. This work employed spatial separation of applied and received signals afforded by the coupled longitudinal and transverse resonant motion of the tags. However, other approaches may complement this approach and further enhance transmitter-to-receiver isolation and thereby increase range. For example, a pulsed interrogating signal can be used, and the magnetic flux generated during the 'ring-down' vibration of tags could be detected so that the excitation signal is temporally decoupled from the received signal. An acoustic interrogating signal, instead of a magnetic field signal, could also be used for decoupling the excitation signal from the receive signal.

6. Conclusion

This paper described the investigation of PCM fabricated hexagonal magnetoelastic tags of about ø1.3 mm × 27 μm, which is approximately 100X smaller than commercial tags currently in use. The preferred dc field bias for the fabricated tags was ≈31.5 Oe. The tags showed quality factors of 100–200. The frame suspension of hexagonal tags resulted in ≈75X improvement in signal amplitude compared to that of non-suspended tags with similar size, frequency, and dc field bias orientation. For the frame-suspended hexagonal tags, misalignment dc bias field by 45° with respect to the applied ac field provided another 80% improvement in signal amplitude. Although the frame suspension is demonstrated in miniaturized magnetoelastic tags, it may also be used to improve the performance of commercial tags or other magnetoelastic sensors. The signal amplitude of a hexagonal tag was a function of the azimuthal orientation of the applied ac magnetic field. Varying signal was observed for different orientations. For 1–10 arrayed tags, the signal amplitudes were at least the sum of the amplitude of each tag. Across ten hexagonal tags, the average resonant frequency was 2.13 MHz, with a standard deviation of 0.44%. Such a small variation of frequency response favors signal superposition and increased signal strength for ensemble detection. Signal superposition was also observed for up to 500 clustered tags.

Acknowledgments

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