Wide-band multiferroic quartz MEMS antennae

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Abstract. We describe a pair of quartz MEMS resonators integrated into a single vacuum package for use as a wide-band RF receiver. The resonators are connected to integrated sustaining circuits for oscillator operation and are used within a phase lock loop in which one oscillator is used as the reference. The other resonator is coated with a magnetostrictive layer which induces a frequency shift proportional to an applied external magnetic field. This frequency shift is detected by the phase lock loop and its feedback signal to a voltage controlled oscillator circuit is used as the antenna output. Thus, the bandwidth of the antenna is determined by the bandwidth of the phase lock loop and not the Q of the resonator.

1. Introduction
MEMS-based multiferroic antennae are currently being studied [1], [2] for high sensitivity, extreme sub-wavelength miniature RF receivers. Using the mechanical gain enhancement of high Q resonators, the sensitivity of resonant-mode piezoelectric RF sensors can approach values typical of much larger dipole antennae, SQUID, or atomic detectors (e.g., <<1 pT/√Hz) [3], [4]. However, the operation is typically limited to very narrow-bandwidth communication (kHz) which severely limits their application. In this paper, we propose the use of a frequency-matched pair of UHF quartz MEMS oscillators within a high-frequency phase lock loop (PLL) to provide wide-bandwidth operation at HF bands and with sensitivities approaching 2.107 times sensitivity improvement over previous reports for magnetoelastic MEMS-CMOS oscillators [5]. Using quartz MEMS fabrication techniques, this sensor can be integrated with electronics [6] in a vacuum packaged chip roughly 2 mm3 in size. In addition, using dual quartz resonators makes this antenna less sensitive to slow thermal drifts compared to Si or AlN resonators.

2. Theory of magnetostriction effect
The detection of magnetic signals of magnetostrictive-based quartz MEMS RF sensors rely on a mechanism of electromagnetic-acoustic coupling, which is usually achieved in the composite ferromagnetic-piezoelectric heterostructure. A magnetostrictive thin film provides the function of converting the RF magnetic signal to acoustic vibration of the composite resonator while the piezoelectric resonator realizes the transduction of acoustic wave to electric signal. By the same principles, a transmission of electromagnetic signal can be achieved on the same resonator through electric input, for example, a voltage drive applied on the two electrode terminals. The interested reader may review the basic effects and mathematical formulations of the magnetostriction phenomenon in references [7] and [8].
Although the magnetostriction phenomenon has a nonlinear nature, we could employ an approximate linear model for small oscillations about a bias point, and figure 1 shows the linearized magnetostriction curve (dashed black line) about a bias point. In our application, a strong static bias field $\mathbf{r}_o$ was applied to establish a bias point on the magnetostrictive curve. Subsequently a relatively small magnitude AC field $\mathbf{r}_e$ (compared to the static bias field $\mathbf{r}_o$) was used to excite the resonator.

The coupling equations between mechanical and magnetic fields when linearized about a bias point take a form similar to the piezoelectric constitutive equations:

$$
\begin{align*}
\mathbf{e} &= \mathbf{s}_\mathbf{H} \mathbf{\sigma} + \mathbf{d}^T \mathbf{H} \\
\mathbf{B} &= \mathbf{d} \mathbf{\sigma} + \mu_0 \mu_r \mathbf{H}
\end{align*}
$$

where $\mathbf{e}$ is the strain tensor, $\mathbf{\sigma}$ is stress tensor, $\mathbf{B}$ is magnetic flux density vector, $\mathbf{H}$ is magnetic field vector, $\mathbf{s}_\mathbf{H}$ is material compliance matrix, $\mathbf{d}$ (dimension $3 \times 6$) is the piezomagnetic coupling matrix, $\mu_r$ is relative permeability of material, and $\mu_0$ is permeability of the vacuum. The format and determination of the $\mathbf{d}$ matrix under different bias field directions was derived by Hirao and Ogi [9].

Specifically, under the assumption that the static bias field $\mathbf{r}_o$ was much stronger than the dynamic AC field $\mathbf{r}_e$, if the bias field was along the X axis, they have shown that there were only two independent components $d_{11}$ and $d_{26}$, which could be calculated from the magnetostriction curve. Figure 2 shows the definition of $d_{11}$ and $d_{26}$ on the magnetostriction curve where $d_{11} = \frac{\partial \mathbf{e}}{\partial \mathbf{H}} |_{\mathbf{H}=\mathbf{r}_o}$ and $d_{26} = \frac{3 \mathbf{e}}{\mathbf{H} |_{\mathbf{H}=\mathbf{r}_o}}$ so that the $\mathbf{d}$ piezomagnetic coupling matrix takes the form as follows:

$$
\mathbf{d} = \begin{bmatrix}
    d_{11} & -d_{11}/2 & -d_{11}/2 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & d_{26} & 0 \\
    0 & 0 & 0 & 0 & 0 & d_{26}
\end{bmatrix}
$$

The dynamic AC field $\mathbf{r}_e$ in the X direction will drive the component $d_{11}$ that provides coupling to the thickness-shear AT-cut quartz resonator.
3. Sensitivity simulation

Under the assumption that a small dynamic field is superimposed on a bias field, the constitutive equation of magnetostrictive material is modeled linearly and described in the previous section. Figure 3 shows the typical magnetostrictive curves of FeGaB with different Boron component percentages that were measured and reported in [10]. The linear coupling matrix $d_{ij}$ was calculated based on the method described above. The variations of components of $d_{11}$ and $d_{26}$ with respect to a static bias field $H_{dc}$ in the X direction are shown for FeGaB (12%) in figure 4.

The variation of the elastic modulus, also called delta E effect, is due to the re-orientation of magnetic domains when the film is subjected to a bias field. This variation for FeGaB has not been measured and reported directly. However, it was reported [11] that changes in elastic moduli of 0.4% to 18% were common in ferromagnetic materials such as nickel and iron. Such changes could be up to 160% in TbDyFe samples subjected to a saturation field. We assumed here that the maximum elastic modulus change was 30% and the saturation field for elastic modulus was the same as the saturation field of the magnetostriction curve. The variation of the elastic modulus with the bias field $H$ is shown in figure 5.

4. Proposed UHF quartz MEMS oscillators

The proposed antenna is shown in figure 6. It consists of a pair of frequency-matched UHF quartz shear-mode resonators (one coated with a magnetostrictive film) integrated with oscillator sustaining circuits, voltage controlled frequency adjustment electronics, and a phase lock loop. $f_r$ = frequency ref. and $f_M$ = frequency of magnetostrictively-driven resonator.

Figure 3. Magnetostrictive curves of FeGaB with various percentages of boron [10].

Figure 4. Piezomagnetic components $d_{11}$ and $d_{26}$ calculated based on the magnetostriction curve of FeGaB (12%).

Figure 5. Variation of the elastic modulus of FeGaB (12%).

Figure 6. The proposed wideband antenna consisting of a pair of frequency-matched UHF quartz shear-mode resonators (one coated with a magnetostrictive film) integrated with oscillator sustaining circuits, voltage controlled frequency adjustment electronics, and a phase lock loop. $f_r$ = frequency ref. and $f_M$ = frequency of magnetostrictively-driven resonator.
the magnetoelastic and magnetostrictive strain-induced frequency shifts of a coated 714-MHz resonator shown in cross-section in figure 7. The FeGaB films are assumed pre-biased near the optimal magnetic field (6 Oe) for the highest magnetostriction with a low-field permeability of 1000. The predicted frequency shifts for a 1.0 nT ac magnetic field applied in the X direction versus dc bias in the X direction are shown in figure 8. The predicted frequency shifts were found to be dominated by strain-induced effects in the quartz resonator, as opposed to elastic modulus changes in the FeGaB films. The optimal value (28 Hz/nT) corresponds to a fractional frequency shift noise of $10^{-10}/\sqrt{\text{Hz}}$ for a RF magnetic field noise of 2.5 pT/√Hz and a corresponding increase in the phase noise of the magnetostriactively modulated oscillator of -163 dBc/Hz at a 5 MHz offset [13]. Since the phase noise floor of our uncoated UHF resonators is -170 dBc/Hz at 5 MHz offset as shown in figure 9, this increase in phase noise represents the noise floor for a high-frequency PLL, assuming negligible phase noise from the phase detector and control loop.

5. Phase Lock Loop analysis

For a phase lock loop using matched frequency resonators, the loop consists of a phase detector, a LP filter/integrator, and a voltage controlled oscillator. No divide-by-N components are needed. Thus, in addition to the VCXO, the only noise sources will be the phase detector and the filter. If one assumes state-of-the-art voltage noise floors for low-noise CMOS electronics of sub nV/√Hz for these components, one can estimate a bandwidth for the antenna.

For a 5-MHz sinusoidal $10^{-10}$ fractional frequency deviation of the 714-MHz magnetostriactively driven oscillator compared to the reference oscillator, the integrated phase error over a 0.1 µs time interval is $2.9 \times 10^{10}$ rad. If the phase detector has a sensitivity of 10 volts/rad [14], then the output of the phase detector would be $2.9 \times 10^{-7}$ V. Assuming a unity gain for the filter, this requires the VCXO to have input referenced noise of 0.13 nV/Hz for detection of the error signal over a 5 MHz bandwidth. This likely represents the current limit for conventional analog PLL technology.

Figure 7. Cross-section of modeled AT-cut resonator.

Figure 8. Frequency shift and frequency sensitivity of proposed UHF quartz MEMS resonator.

Figure 9. Measured phase noise of a HRL UHF quartz resonator compared to a commercial 16 MHz oscillator scaled to the same frequency. Note, the low phase noise of the HRL oscillator at high offset frequencies.
However, all digital implementations are currently being studied, which may improve the bandwidth capabilities in the future.

6. Conclusion
A magnetostrictively driven quartz MEMS resonator coupled within a phase lock loop to a frequency matched uncoated resonator is analyzed for a wide band HF antenna. For a 714-MHz AT-cut resonator, the frequency sensitivity is predicted to be 28 Hz/nT using a 0.2-µm-thick FeGaB magnetic driving layer. We predict a magnetic sensitivity of 2.5 pT/√Hz and a bandwidth of 5 MHz using a low noise PLL circuit. Although requiring more power than a passive on-resonant magnetostrictively driven antenna, the use of two oscillators should provide the ability to detect HF signals with high data content while maintaining ultra-sub-wavelength dimensions and high sensitivity. Since the two oscillators can each run off of sub-mWs of power [6], the entire antenna, including the phase lock loop electronics, should require only tens of mWs of power.

7. References
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