# FAST TRACK COMMUNICATION

# Tunable magnetoelectric resonance devices

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**Abstract**
We have found that the electromechanical resonance frequency of Terfenol-D/Pb($Zr_x Ti_{1-x}$)$O_3$ laminated composites can be tuned by an applied dc magnetic ($H_{dc}$) bias. With increasing $H_{dc}$ from 0 to 5000 Oe, the resonance frequency ($f_r$) can be shifted over the range of $40 \leqslant f_r \leqslant 55$ kHz. This finding offers a means by which to enhance the effective bandwidth of resonance enhanced magnetoelectric devices.

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

The magnetoelectric (ME) effect has been widely investigated in piezoelectric/magnetostrictive composites, where a giant ME effect has been found in laminate composites such as Terfenol-D/PZT and Metglas/PZT laminates [1–3]. New and unique applications (such as magnetic sensors [4, 5], transformers [6] and gyrators [7]) have been reported for ME composites. A number of these applications are based on an electromechanical resonant (EMR) enhancement of the ME effect, where the ME voltage coefficient is increased by a factor of 10–1000× that at quasi-static frequencies. Energy conversion efficiency is high only near the EMR frequency.

However, the resonance peak is sharp and fixed for ME laminates, limiting the bandwidth of the applications that use the resonant enhancement. Any small aberrancy at the resonance point will result in a dramatic decrease in the ME voltage. The simplest method of widening the resonance frequency is to select a low mechanical quality factor ($Q$) material; however, this will result in a notable decrease in the peak amplitude value. Alternatively, a series of laminates with different lengths could be used to broaden the bandwidth of an operational device [8], but the effective peak would not be smooth. Also, in this case, at any specific frequency, only one of the laminates in the series might work at its resonance condition: all the others would not make a significant contribution to the total output voltage at any particular frequency. In the microwave frequency range, ME composite

resonators and phase shifters are known to have a dual electric and magnetic field tunable ferromagnetic resonance frequency (FMR) [9–13]. The FMR is shifted due to a change in the piezoelectric deformation or the magnetostatic spin wave. In effect, these result in a broadening of the bandwidth of the microwave devices based on ME composites.

Here, we report that the effective bandwidth of the EMR enhancement of the ME coefficient can be notably broadened by magnetic field tuning. Our studies show that Terfenol-D/PZT laminates are well suited for such tunable resonance devices because of a large magnetostriction (up to 1600 ppm) in Terfenol-D, which is 40× larger than that of Metglas or nickel ferrite. The large magnetostriction of Terfenol-D is necessary in order to impose a large strain on the PZT; thus, enabling a dramatical shift of the resonance frequency under applied magnetic field.

The ME laminates we used in this investigation were a tri-layer sandwich structure, as shown in the inset of figure 1. The top and bottom layers were Terfenol-D ($28 \times 6 \times 1.2$ mm$^3$) and the inner layer was PZT ($30 \times 6 \times 1$ mm$^3$). The Terfenol-D and PZT layers were glued together by hard epoxy. The PZT layer was poled along its thickness direction. During measurements, both dc ($H_{dc}$) and ac ($H_{ac}$) magnetic fields were applied along the longitudinal direction of the laminate. The working mode was the so-called longitudinal magnetization–transverse polarization or L–T mode.

First, we measured the magnetostriction of Terfenol-D/PZT laminates under mechanical free conditions by

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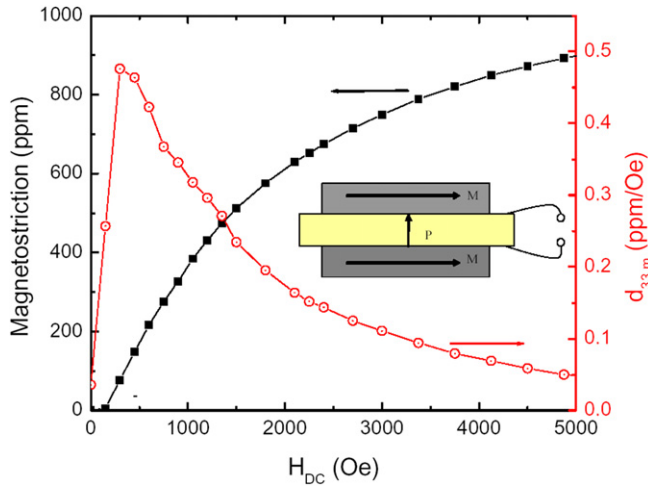**IOP** FTC ▶▶▶

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**Figure 1.** Magnetostriction and piezomagnetic constant of the Terfenol-D/PZT laminate as a dependence of $H_{dc}$ from 0 to 5000 Oe. Inset shows a schematic graph of the Terfenol-D/PZT sandwich structure laminate.

attaching a strain gauge on the surface of the Terfenol-D layer. Figure 1 shows the measured strain as a function of the applied magnetic field. Note that the magnetostriction of Terfenol-D tends towards saturation (900 ppm) at a field near $H_{DC} = 5000$ Oe, at which point its effective linear piezomagnetic constant $d_{33,m}$ tends to a minimum. In addition, under a large applied magnetic field, the elastic stiffness of Terfenol-D will be affected, resulting in a shift of the resonance frequency. To achieve a large strain of 800 ppm by applying an electric field to PZT, a field of $E = 20 \, kV \, cm^{-1}$ would be needed. This would require a large voltage to be applied to the bulk laminates. If the ME laminates operate in the LL or push–pull mode, voltages as high as 10 kV may be required. Clearly, electric tunable designs are not very feasible for bulk composites.

Next, we measured the resonance enhancement of our laminate under different magnetic biases. The measurement method was the same as the previous one [14] and the ac magnetic field used here is 0.1 Oe. Figure 2(a) shows the frequency dependence of the ME voltage coefficient under various $H_{dc}$. The resonance frequency can be seen to be notably increased with increasing dc bias. These results demonstrate a pronounced shifting of the resonance frequency from $f_0 = 40 \, kHz$ for $H_{dc} = 0$ Oe to $f_0 = 55 \, kHz$ for $H_{dc} = 5000$ Oe. Furthermore, the peak resonance enhancement of $V_{ME}$ was increased with increasing bias for $H_{dc} \leqslant 3000$ Oe. The maximum resonance enhanced value of $V_{ME}$ was ~46 V cm$^{-1}$ Oe$^{-1}$ under a $H_{dc} = 3000$ Oe: above which point, further increases in $H_{dc}$ resulted in a decrease in $V_{ME}$. This trend is different from that for the quasi-static ME voltage coefficient which is shown in figure 3. The optimum bias condition is $H_{dc} = 300$ Oe for the quasi-static case, which has a value 10× smaller than that at the EMR.

In figure 2(b), we show the resonance frequency $f_0$ and mechanical quality factor $Q$ as a function of $H_{dc}$. The value of $f_0$ increased with increasing dc bias due to an increased elastic stiffness induced by magnetostriction. For $H_{dc} < 300$ e, $f_0$ was only slightly changed with increasing bias, and the resonance ME voltage coefficient was small. In



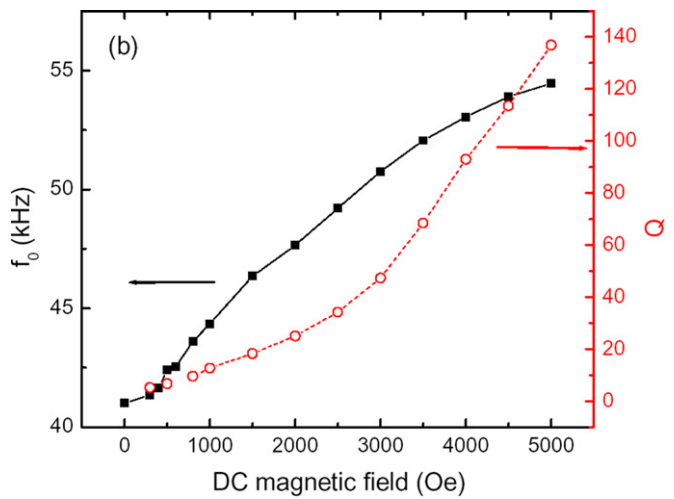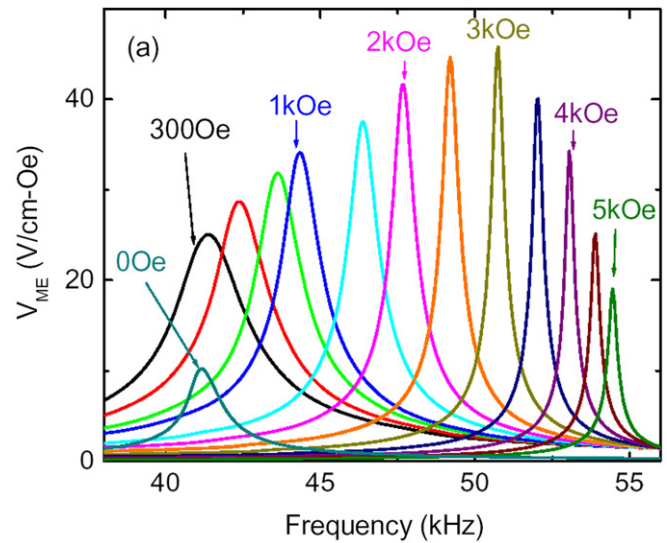**Figure 2.** (*a*) Frequency dependence of the ME voltage coefficient at various $H_{dc}$ from 300 to 5000 Oe and (*b*) resonance frequency and $Q$ of the Terfenol-D/PZT laminate as a dependence of $H_{dc}$ from 0 to 5000 Oe.
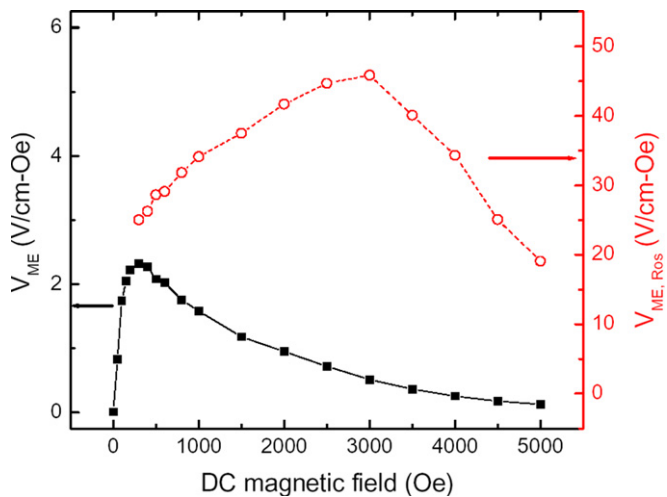


**Figure 3.** Quasi-static ME voltage coefficient and enhanced resonant ME voltage coefficient of the Terfenol-D/PZT laminate as a function of $H_{dc}$ from 0 to 5000 Oe.

this figure, it can also be seen that $f_0$ increased much more dramatically in the range $1000\,\text{Oe} \leqslant H_{dc} \leqslant 4000\,\text{Oe}$; whereas when $H_{dc} > 4000\,\text{Oe}$, $f_0$ increased only gradually with further increasing bias, as the magnetostriction of Terfenol-D tends towards saturation. Correspondingly, it can be seen that $Q$ increases notably with increasing bias, indicating that the loss mechanism may be controlled by the magnetostrictive phase, where the $Q$ value increases with $H_{dc}$.

It is relevant to note that our observed trend in the peak value of the resonance enhanced value of $V_{ME_{Res}}$ as a function of $H_{dc}$ is notably different from that at quasi-static frequencies. For comparisons, figure 3 shows the value of $V_{ME}$ for our laminate at a sub-resonant frequency of 1 kHz. In this figure, it can be seen that $V_{ME}$ reached a maximum value of $\sim 2\,\text{V cm}^{-1}\,\text{Oe}^{-1}$ under $H_{dc} = 500\,\text{Oe}$. At higher bias levels, the value of $V_{ME}$ can be seen to decrease continuously with increasing bias for $500 < H_{dc} < 5000\,\text{Oe}$, approaching a value of $0.2\,\text{V cm}^{-1}\,\text{Oe}^{-1}$ under $H_{dc} = 5000\,\text{Oe}$. Comparison of this quasi-static $V_{ME}$ data with that taken at the EMR will demonstrate significantly different trends with increasing $H_{dc}$.

For the LT mode, the quasi-static ME voltage coefficient can be calculated by [15]

$$V_{ME}^{LT} = \frac{n d_{33,m} d_{31,p}}{n \varepsilon_{33}^{S} s_{11}^{E} + (1-n) s_{33}^{H} (\varepsilon_{33}^{S} + d_{31,p}^{2}/s_{11}^{E})}, \qquad (1)$$

where $n$ is the magnetic phase thickness ratio; $s_{11}^{E}$ and $s_{33}^{H}$ are the elastic compliances of the piezoelectric and magnetostrictive layers; $\varepsilon_{33}^{S}$ is the dielectric constant of the piezoelectric material at constant strain and $d_{31,p}$ is the transverse piezoelectric coefficient. Under various dc magnetic biases, all parameters except $d_{33,m}$ will remain the same. The trend of the piezomagnetic coefficient with $H_{dc}$, as shown in figure 1, is similar to that of the quasi-static ME voltage coefficient.

Finally, we measured the frequency dependence of the ME voltage coefficient under various $H_{dc}$, as shown in figure 3. For $H_{dc} = 0$, the resonance ME voltage coefficient was only $5\,\text{V cm}^{-1}\,\text{Oe}^{-1}$: this is because Terfenol-D has only a small remanent magnetization. The maximum resonance ME voltage coefficient was $45.85\,\text{V cm}^{-1}\,\text{Oe}^{-1}$ under $H_{dc} = 3000\,\text{Oe}$. For $H_{dc} > 3000\,\text{Oe}$, the resonance ME voltage coefficient was dramatically decreased with increasing $H_{dc}$. This trend is different from that of the quasi-static ME voltage coefficient, shown in figure 3. The optimum dc bias was only $3000\,\text{Oe}$ at the EMR, which was $10\times$ larger than that at the quasi-static frequency.

The resonant ME voltage coefficient at the EMR can be estimated by [16]

$$V_{ME}^{Res} = \frac{8Q n d_{33,m} d_{31,p}}{\pi^2 [n \varepsilon_{33}^{S} s_{11}^{E} + (1-n) s_{33}^{H} (\varepsilon_{33}^{S})]}. \qquad (2)$$

For $H_{dc} < 3000\,\text{Oe}$, the resonant of enhanced ME coefficient increases with increasing bias because $Q$ increases faster than $d_{33}$ decreases. Although $d_{33}$ decreased from $0.5\,\text{ppm Oe}^{-1}$ to $0.1\,\text{ppm Oe}^{-1}$ for $300\,\text{Oe} < H_{dc} < 3000\,\text{Oe}$, $Q$ increased from 5.2 to 47.3. However, for $H_{dc} > 3000\,\text{Oe}$, the magnetostriction of Terfenol-D approaches saturation and the piezomagnetic coefficient becomes very small; thus, the resonant enhanced voltage coefficient decreases with further increasing $H_{dc}$.

In summary, we have demonstrated that the resonance frequency of ME laminates can be continuously tuned by a magnetic field over a wide range from 41 kHz to 55 kHz. This large tunability is due to the large magnetostriction of Terfenol-D. It results in a dramatic increase in the bandwidth over which devices might take advantage of the resonance enhanced ME coefficient.

## Acknowledgment

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