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Information storage in piezoelectric powders

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TABLE I. Details of points a—g in Fig. 2.

	Frequency (MHz)	Loss (dB)
a	57.25	16
b	55.17	5(+16)
c	58.75	5(+16)
d	54.25	15(+16)
e	52.75	59(+16)
f	60.25	55(+16)
g	60.75	35(+16)

referred above. In our rf diode sputtering also, the films were highly oriented with the *c* axis almost perpendicular to the substrate surfaces with an average angle of incline of 2° and a standard deviation of 3–4° from the measurement of the locking curves of a x-ray diffractometer.

Figure 1 shows the unsealed appearance of a filter, which is composed of an industrial glass substrate for a thin-film resistor, a normal generation electrode with 15 finger pairs and an apodized one with 24 finger pairs, and a 20- μm -thick ZnO film. Both finger and space widths are 11 μm . Figure 2 shows the frequency response of the insertion loss of the filter, in which a 1- μH inductor is connected in series to the input electrode. The triple transit echo suppression is more than 30 dB from the signal level. The temperature coefficient of the frequency characteristic is 30 ppm/°C in the temperature range between -20 and +80°C. The aging characteristics have been measured for 400 days to give no significant change in the frequency characteristic of insertion loss, and the filter is still up to standard. In Table I are shown the essential characteristics

of the filter. The coupling coefficient which satisfies $\frac{1}{2}k^2 = (v_\infty - v_0)/v_\infty$ was deduced from the frequency characteristics of the input impedance giving the value of *k* as 10–13.5%. The minimum insertion loss for the maximum coupling coefficient was 13.0 dB.

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Information storage in piezoelectric powders

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In this paper we show that a large amount of information can be stored in a sample of piezoelectric powders. The technique used to write and read the information is based on the principle of phonon echos. It is demonstrated that the frequency can serve as an address of a memory and that a word can be written into each address by selecting an appropriate writing pulse sequence. It is also shown that the information contained in one address can be read out quickly and nondestructively.

PACS numbers: 85.50.Ly, 43.60.+d, 77.60.+v

In a recent publication Kuidersma *et al.*¹ reported a new class of phonon echos in piezoelectric powders and a theory was developed to describe these echo phenomena. It was demonstrated that, similar to a stimulated echo in spin echo experiments,² the reappearance of the echo in a three-pulse sequence is not limited by the transverse relaxation time T_2 but by the longitudinal relaxation time T_1 . In such a three-pulse sequence the system is excited by the first pulse; τ seconds later (where $\tau < T_2$) the time information is "written in" by the second pulse, and the third pulse, at a time $t < T_1$, produces an echo at $t + \tau$ and therefore is able to "re-

call" the time information. The pulse sequence is illustrated in Fig. 1. In a powder sample these echos can be observed over a large frequency range because of the distribution in the particle size as well as the excitation of higher harmonics of the basic frequency corresponding to a particular particle size. In this paper we present some new results which show that a piezoelectric powder can be used as a memory capable of storing a considerable amount of information, with fast random memory access and nondestructive readout.

Using the three-pulse technique to measure the relax-

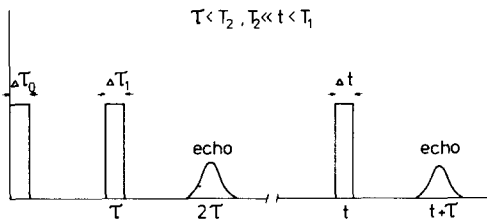


FIG. 1. Artist's conception of a three-pulse stimulated echo experiment.

ation time T_1 of powdered samples of SiO_2 and MEM (TCNQ)₂ we found that T_1 was at least of the order of several weeks. In Fig. 2 we show the echo height as a function of time t as defined in Fig. 1. After about 10 days the echo height was not observed to decrease over a period of a total 5 weeks. It therefore seems that T_1 is essentially infinite. The T_1 measurement was performed by applying pulses of 42-MHz rf (1-kW peak power) to an LC tank circuit containing 1 cm³ of 60- μm crystalline SiO_2 . Pulses of 3- μsec width were first applied at times $t=0$ and $t=9 \mu\text{sec}$. A first echo was obtained at $t=18 \mu\text{sec}$ as in a normal two-pulse echo experiment. At time intervals of several hours we then applied a single pulse at the same frequency and with a width also of 3 μsec and measured the height of the echo which appeared 9 μsec after the single pulse. The long relaxation time displays the memory properties of the system and the nondestructive readout aspect since the single pulses could be applied successively without affecting the echo height as long as the separation of the single pulses was greater than T_2 and the intensity was less than that of the exciting and writing pulses.

Recently, similar long memory times have been reported by Popov *et al.*³ In what follows, however, we report new results which show that information can be stored at many frequencies so that the frequency can be used as an address for information. We also show that multiple-pulse sequences can be used to store in each address a number of bits of information. Gas-pressure-dependent experiments in fact show that the

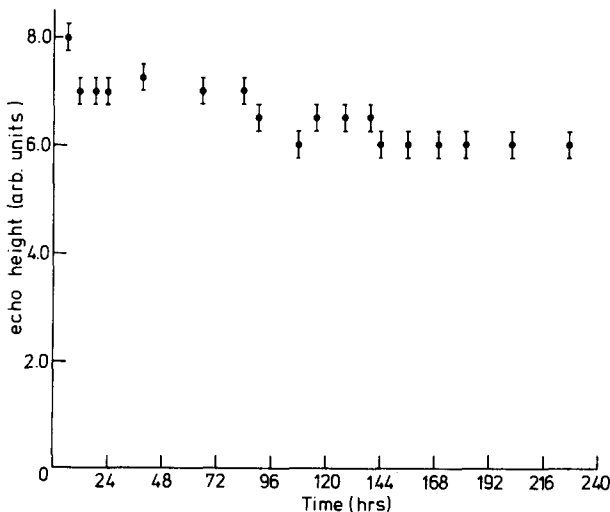


FIG. 2. Echo height after a reading pulse applied at various times after the writing pulses.

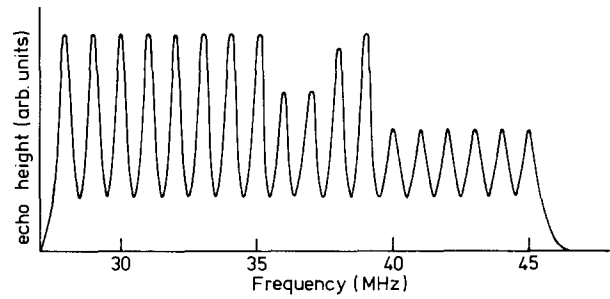


FIG. 3. Echo height vs frequency of reading pulse after a writing pulse sequence as described in the text.

mechanical oscillations damp out in time T_2 . This means that some static frozen state must be responsible for the long memory time. Melcher and Shiren⁴ have recently suggested that this frozen state may be related to a particle orientation effect which would be possible if the piezoelectric constant were anisotropic. Since we certainly expect an anisotropy in the piezoelectric constant we are inclined to agree with this interpretation although clear experimental evidence of particle orientation effects has not yet been presented to our knowledge.

In the following we will use the following definitions: (a) Any first pulse is an exciting pulse. (b) A pulse following an exciting pulse within a time less than T_2 is a writing pulse. (c) A pulse following a writing pulse at a time much longer than T_2 , but shorter than T_1 , is a reading pulse.

The reading pulse thus shows in its echo pattern the information that has been written in by the writing pulses. It shows this information only if it is of the same frequency as the writing pulse(es). Therefore, the frequency serves as an address for the information, its frequency width being determined by the inverse length $(\Delta t)^{-1}$ of the writing pulse(es). To show this we successively applied pairs of exciting and writing pulses at frequencies between 28 and 45 MHz in steps of 1 MHz. In Fig. 3 we have plotted the peak echo height following reading pulses applied successively at the various frequencies. The fluctuation in the peak echo heights is

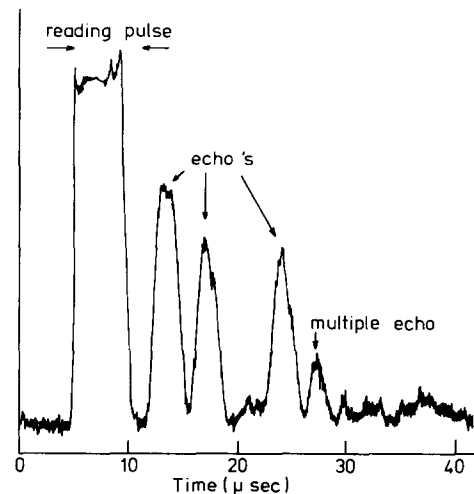


FIG. 4. Echo pattern resulting from a single reading pulse after a three-pulse writing sequence as described in the text.

mainly a result of variation in the output power of the oscillator. We see that a large echo appears at every frequency at which we had previously applied the exciting and writing pulses.

In Fig. 4 we demonstrate that the system remembers more than one writing pulse. After applying an exciting pulse at $t=0$, writing pulses at $t=7 \mu\text{sec}$ and $t=19 \mu\text{sec}$, a reading pulse applied at a time much larger than T_2 thereafter yields echoes at $t+7$, $t+12$, and $t+19 \mu\text{sec}$, corresponding to the three possible time differences in the exciting pulse writing sequence. This demonstrates that a whole word can be written into every address (frequency). One can also add information to the system by applying two or more pairs of exciting and writing pulses at time intervals much larger than T_2 and with different time separations between the exciting and writing pulses. A subsequent reading pulse will yield echos at times corresponding to each of the different time separations written in.

The time separation which can be used between the exciting and writing pulses is limited by T_2 , which for clean quartz powder as we used it is of the order of $200 \mu\text{sec}$. The individual echos have a width determined by the width in time of the writing pulse. Shorter writing pulses, therefore, allow more storage of information per address but, of course, increase the frequency bandwidth required for each address (the total information density being constant).

The results reported here were obtained with a sample of quartz in the coil of an LC circuit. In addition to this we have used a delay line detection circuit for the frequency-dependent measurements. There are, of course, many other ways of carrying out the experi-

ments such as placing the material in a capacitor or by using the material as a filling of a coaxial line. We have investigated these and other methods and have found them all to work satisfactorily, each one having its own advantages and disadvantages. We have presented the data obtained using an LC circuit here because this is the simplest to use if one wishes to quickly demonstrate the effects mentioned. All the measurements reported here were obtained at 77 K. The experiments can, however, also be carried out at room temperature with a decrease in the signal, mainly due to a decrease in T_2 , but without affecting the memory time T_1 .

In conclusion, we have shown that information can be stored in a piezoelectric powder in a novel and, perhaps, completely unexpected, way. Although we have performed experiments only between 10 and 80 MHz, there is no theoretical reason why this range could not be extended to much higher frequencies, thereby increasing the memory capacity. Before we can estimate how much information can be stored in a cubic centimeter in this way we must determine the frequency dependence of T_1 and T_2 . These experiments are in progress and will be reported shortly. Perhaps a suitable name for this new technique could be "writing in sand" or WIS.

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Improved dc dynamic scattering with redox dopants in ester liquid crystals

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Redox dopants are used to improve the dc dynamic scattering (DS) characteristics of phenyl benzoate liquid crystals as compared to the use of salt-type conductive dopants. The redox dopants are selected by their electrochemical properties so that they react preferentially and reversibly at the electrodes, thus providing the current carriers for the dc-DS effect. Low-threshold voltages (~ 2 V), high scattering efficiency (99% at 20 V), and long dc-DS lifetimes (up to 18000 h) are obtained with an ester liquid crystal containing a redox dopant pair consisting of di-*n*-butylferrocene and (2,4,7-trinitro-9-fluorenylidene)malononitrile.

PACS numbers: 81.55.+x, 61.30.+w, 82.45.+z, 72.80.Ph

We have used selected redox dopants to improve the lifetime, threshold voltage, and scattering characteristics of the dc dynamic scattering¹ (DS) of nematic liquid crystals (LC) with phenyl benzoate structures. Results with new redox dopants are compared with those with salt-type dopants. We define redox dopants as donors or acceptors (or both) that readily undergo reversible electrochemical reactions, and which do so at lower

voltages than the electrochemical reactions of the LC components. The redox dopants are thus designed to carry the dc current in LC cells. Salt-type dopants are defined as electrochemically inactive ionic compounds. In related studies, Baise *et al.*² reported that acceptor dopants which form charge-transfer complexes with an azoxybenzene LC lower its dc-DS threshold voltage. Ohnishi and Ozutsumi³ used a hydroquinone-quinone