The Saga of Crystals

Part II

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Crystals invariably generate the master clock frequency for computers. All other subsidiary frequencies are then derived from the master clock. For instance, TRS-80 colour computers SAM (synchronous address multiplier) chip, which operates as part of the system clock, develops all the frequencies needed to run the computer. The series-resonant crystal oscillator circuit that runs at 14.31818 MHz is the master oscillator. This is the master clock frequency for the computer. To generate a good colour picture, a frequency of exactly 3.579554 MHz must be produced along with the system. This is accomplished by dividing the master frequency by four. However, the CPU needs two frequencies called E and Q frequencies around 0.89 MHz which are 90° out of phase. For this, the master frequency is divided by 16. SAM chips take care of all these aspects which are entirely based on the master crystal oscillator.

A conventional crystal-controlled oscillator that resonates at 12.288 MHz is used in Heathkit H-89A microcomputer which is then divided by six to produce a clock frequency of 2.0488 MHz before it is applied to the CPU Z80. The near obsolete COP 400 series of microcomputers from National Semiconductors uses the externally synchronised crystal oscillator (Fig. 18). Its 8-bit version, INS 8060 called SC/MP, often makes use of a low-pass filter along with the oscillator. The crystal frequency is limited to 4 MHz and the time interval of a micro cycle is four times the time period of the oscillator.

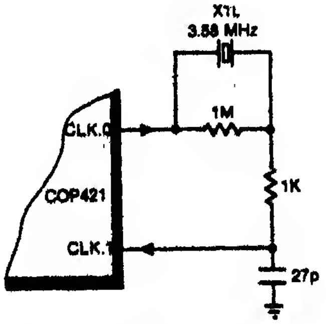


Fig. 18: The COP system clock.

Although 500-nanosecond clock period is standard, many CPUs and clock generators are equipped with dividers in the internal structure. Hence, the clock frequency is fairly higher than the system frequency. For instance, Intel's 8080/9080 CPU makes use of 8224 system clock generator-driver and its XTL1 and XTL2 pins directly absorb the crystal connections. However, the clock frequency cannot be made equal to the crystal frequency since 8224 divides the crystal frequency by nine which means that the usual 500-nanosecond clock requires an 18MHz crystal.

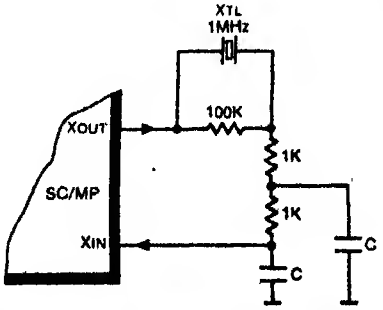


Fig. 19: SC/MP with low frequency XTL and low-pass filter.

On the contrary, since 8085 has its own built-in oscillator section and a divider stage, the clock for the system is half the crystal frequency which is directly available at the CLK pin for any other synchronisation purpose within the microcomputer system. Thus a 6.144MHz crystal provides a system clock of 325 nanoseconds.

This approach is widely appreciated mainly due to the elimination of the clock generator 8224, which requires multiple-step power supplies. Similarly, Motorola's single-chip microcomputers of the MC6800 family are equipped with on-chip clock oscillators often with a divide-by-four circuit. A 4MHz crystal oscillator develops TTL level-processor clock of 1MHz for data synchronisation. Another important aspect of these 4-bit and 8-bit microprocessors is that they operate at a very low system frequency compared with their recent versions of 16-bit MPUs.

A different approach is used for VHF crystals which operate on very high mechanical overtones. In such cases, the overtones both above and below the desired resonance are suppressed using a selective network. The Texas Instruments' TNS microcomputer's clock generator TIM9904 - which is also known in the qualified product list (QPL) of TTL standards as SN74LS362, manufactured by the specifications of low-power schottky technology, hence the 74LS part number—is a representative of these classes of oscillators. An LC tank circuit is used for mode suppression. For instance, TMS9900 microprocessor operating with its standard 3MHz frequency may need a crystal with a resonant frequency of 48 MHz at its third overtone. In Intel's first 16-bit microprocessor—a unique transformation of its earlier products like 8080 and 8085—the clock generator 8284 adopts a similar approach for the tank circuit in the overtone mode as given in Fig. 24.

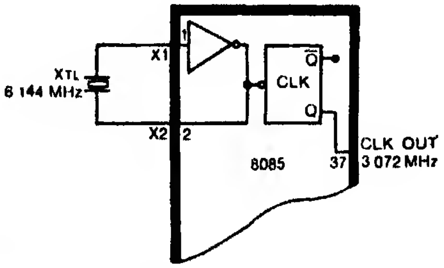


Fig. 20: 8085 system clock.

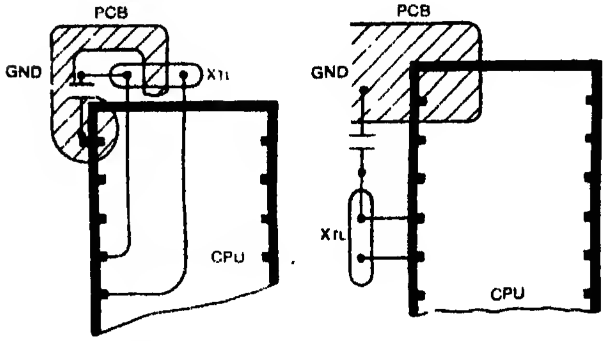


Fig. 21: Two methods to keep XTL leads minimum.

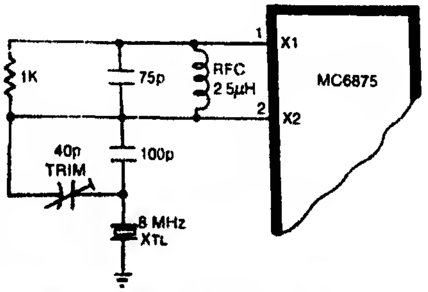


Fig. 22: Motorola's MC6875 clock generator.

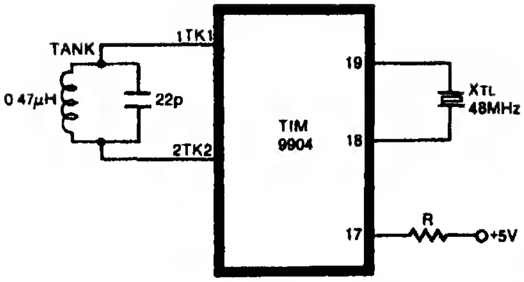


Fig. 23: Third overtone 48 MHz XTL drive for TIM 9904.

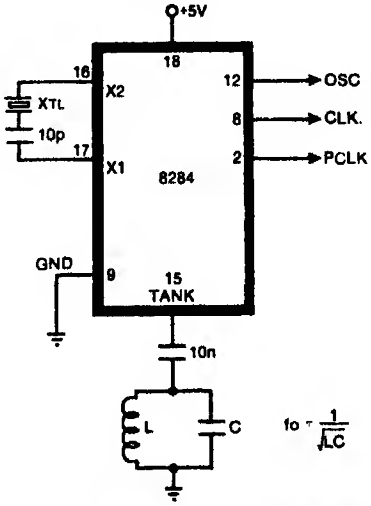


Fig. 24: Overtone XTL clock generator with 8284 for Intel's 8086 CPU.

Growing applications

The number of fields in which the crystal-controlled circuit is providing valuable assistance is continually growing. Purpose-built crystal modules with the facilities for adaptation in a wide range of applications are currently in demand. Temperature compensated crystal oscillator (TCXO), oven control crystal oscillator (OCXO), voltage-controlled crystal oscillator (VCXO), temperature compensated VCXO (TCVCXO), phase locked crystal oscillators (PLXO), digitally compensated crystal oscillator (DCXO) etc are the crystal-based hybrid circuits available in convenient single packages. There is a choice of different modes of crystal oscillators up to 500 MHz and many other options including the power supply range.

The electrical analogue of the quartz crystal assumes the structure of a resonant LCR circuit with a very low value of R. Consequently, the ratio of reactance to resistance or the Q value of the crystal is extremely high. When the frequency of the current through the quartz crystal is varied, the charac-

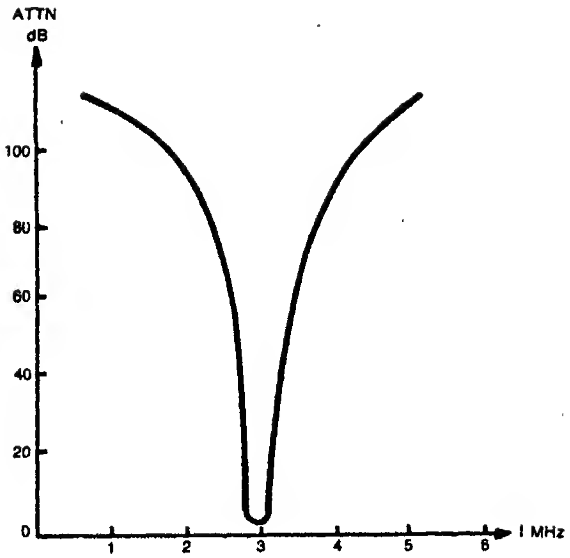


Fig. 25: Attenuation of narrow bandpass XTL filter.

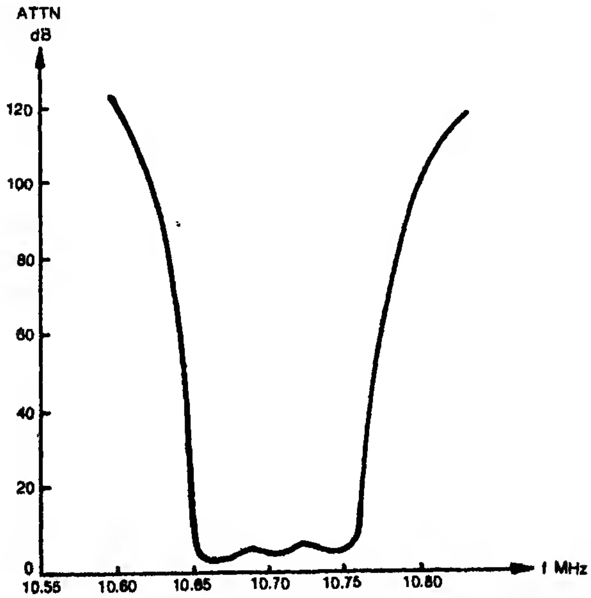


Fig. 26: Attenuation of multielement narrow bandpass XTL filter.

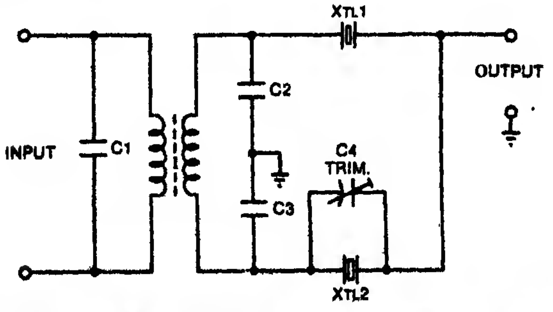


Fig. 27: Half-lattice XTL filter with balancing trimmer for adjacent channel selectivity.

teristic resonant and anti-resonant frequencies are effectively segregated. The crystal presents low impedance to signals at the series resonance and moderately high impedance at off-resonant frequencies. This is exactly what the radio designers need for the construction of IF transformers which are otherwise constantly plagued by a low value of Q (about 300 to 400 at low frequencies) due to leakage inductance, wire resistance, self capacitance and all other sorts of leakage reactance. Dr J. Robinson, a British scientist, first used quartz crystal resonators in radio receivers in 1929, thus heralding the era of super-selectivity.

A conventional bandpass filter incorporating crystal units is given in Fig. 27. The series resonance frequencies of the crystals are separated by the required bandpass and the balancing trimmer connected across the higher frequency crystal steepens the sides of the selectivity curves. This selector circuit has bandpass characteristics combining almost any desired bandwidth with a flat bandpass, steep slopes beyond cut-off frequencies with high-order rejection of unwanted signals in the attenuation band. The selectivity of the receiver can be further redefined by adding crystal units to the filter section as shown in Fig. 28.

A block filter consists of ten or more crystal elements connected in a cascade half-lattice configuration. This type of filter is usually employed in VHF receivers with frequencies between 9 MHz and 10.7 MHz. It is a single quartz plate on which a number of mechanically-coupled resonators are printed. All elements including capacitors and matching transformers are mounted in a single metal housing. Similar crystal-controlled filters are available for band rejection, equalised delay, discriminators and comb-filters. Some of the well known filters like Butterworth, Chebychev, elliptical, Gaussian and Bessel type are also realised within the fabrics of quartz.

The earliest observations of piezoelectricity led to the introduction of the first man-made device called bimorph by the Curie brothers. To form a bimorph, two bars are cut from X-cut plates on opposite diagonals and cemented together. Depending upon the crystal cuts, the bimorph develops emf across the plates when it is pressed or twisted. Bending the bimorph like a cantilever or applying force at its centre also produces a proportional potential difference

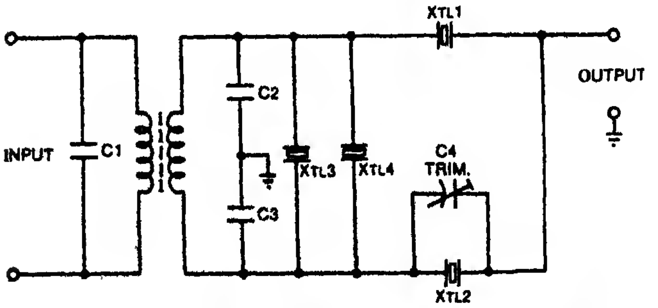


Fig. 28: Half-lattice crystal filter reduce side response using XTL3 and XTL4.

across the metal plates. The opposite effect produces novel features. A potential difference applied to the metal plates causes one bar to contract on one side with an expansion on the other. The net effect is that the bimorph bends to one side. By changing the polarity of the applied potential difference the bimorph bends to the other side. If the polarity of the applied potential difference changes rapidly, a proportional vibration in amplitude can be expected.

Bimorphs were only a humble beginning of a new genre of transducers. The sound pressure wave variation can be used. to bend or press the crystal bimorph by converting one face of the bimorph to a diaphragm. The sensitivity of such a device is increased by stacking a number of bimorphs together, leaving a thin layer of air in between each of them. This is known as the crystal microphone, a high impedance device used for a very short distance operation. There are a host of practical difficulties around this device. First of all, the length of the connecting cable to the amplifier has to be kept at just a few centimeters in order to avoid noise and unusual reduction in the output levels. Secondly, the crystal elements deteriorate rapidly at high temperatures starting from around 45° Celsius. Thirdly, since these are high-impedance devices, the input ends have to be carefully selected and matched. Yet, despite these practical difficulties, crystal microphone is the undisputed leader in VOX (voice operated switch) remote control devices.

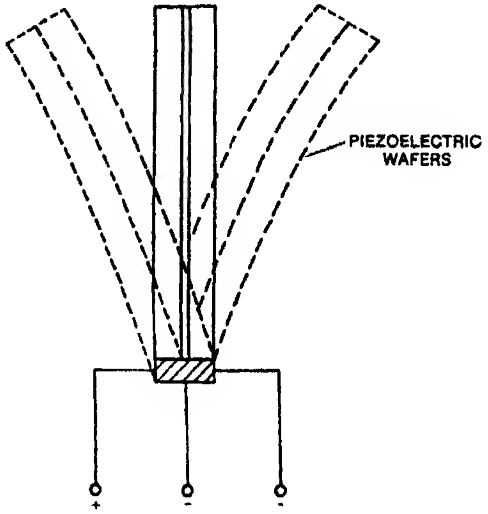


Fig. 29: Piezoelectric bimorph.

Electrical-to-acoustical transducers are also within the crystal's reach. The piezo tweeter horn has a membrane driven by a small plate of piezoceramic material. The impedance offered by this device resembles that of a capacitor. The useful sound levels lie within the upper two octaves of the audio spectrum covering frequencies above 7 kHz. Piezo tweeters have very high efficiency and can be driven by a battery powered circuit. (However, sceptics reject the piezo loudspeaker design for three reasons: crystal impedance is very high; amplitude of oscillation is limited before the margin of fracture of the crystal; and its resonances are too well pronounced to use in octave ranges.) In ultrasonic ranges, especially at the low power region, there is no other choice except piezos.

Piezoelectric relays

Over the past 50 years, a lot of miniature relays have been designed. Most of them suffer from problems such as unwanted noise, heat, spark etc. Furthermore, the majority always has problems with the size of the device. Piezoelectric relays based on the same old bimorph principle seem to be attractive in many ways, especially for the printer type applications. According to the manufacturers, the piezoelectric relay or actuator has a longer life and silent fast switching compared to the conventional electromechanical versions. A piezo relay dot matrix printer operates at a high speed with considerably less heat generation than a solenoid type conventional dot matrix printer. The only problem is centered around the 40-volt actuation potential demanded by the piezoelectric relays.

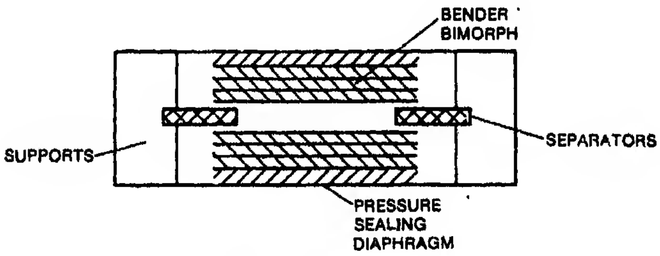


Fig. 30: Construction of the sound cell of crystal microphone.

Piezoelectric effect has systematically found its way to the transducer arena in both active and passive forms. In the active transducers, where the device does not require electrical energy for its operation since it's a self-generating device, the electric properties are made use of. Three most difficult parameters like pressure, force and torque are sensed and calibrated using this technique. In the passive form, where an external electric source is necessary for the operation, piezo-resistive properties are used. Physical parameters like displacement, pressure, force, acceleration and torque are tamed by this approach.

Quartz crystals generate a charge as a result of applied pressure. The strain-induced charge on the quartz crystals is measured using specially designed instruments. These active devices develop not less than 2 mV per psi with appreciable linearity over a wide dynamic range, reproducibility and high-frequency capability. The immediate problem in this type of instrumentation is the need for high-impedance amplifiers for the faithful transfer of information for further processing. With the advent of very high input impedance op-amps, the instrumentation technique looks fairly stable and reliable.

Natural or synthetic quartz wafers are generally useful in the transducers. Quartz is crystallised silicon dioxide. In nature it is formed from molten magma (rock) which crystalises very slowly within the earth's crust giving rise to large crystals. Synthetic quartz, prepared by the hydrothermal process, ensures purity of the crystal which is essential for the manufacture of precision components. A supersaturated solution of quartz is prepared by heating raw quartz in an alkaline solution of water up to 400°C at 100 atm pressure in a sturdy container. A sheet of pure quartz is placed hanging in the solution of superheated water and quartz, to act as a seed for the pure quartz to crystallise on. Quartz crystals of dimensions 50mm by 150mm are obtained in three to four weeks' time. This synthetic quartz has a refractive index between 1.54 to 1.55 and a specific gravity of 2.65, which is very close to that of natural quartz crystals.

Quartz domination in instrumentation as an active transducer is seriously challenged by the passive piezo-junction transducer which is nothing but a p-n junction diode. On this specially designed diode, stress can be applied uniformly over the entire surface of the device or can be applied locally at any point using a blunt element. The former technique is not reliable due to the unpredictable behaviour of the diode on overall distribution of stress. However, the localised stressing technique is found to be extremely rewarding. The band gap of the semiconductor and the concentration of minority carriers show changes in the presence of local stress. Consequently, there is a considerable change in the forward and reverse characteristics of the p-n junction diode.

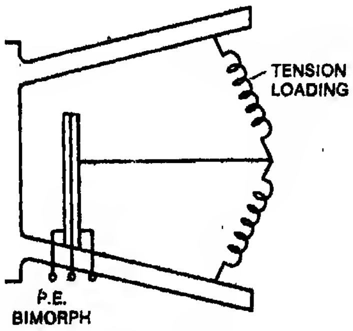


Fig. 31: Schematic of a crystal microphone.

In the year 1965, A. Benjaminson of Hewlett Packard pointed out that the empirical relation existing between the frequency of oscillation of a quartz crystal and its ambient temperature is

$$f(t) = f(o)\,(1+at+bt^2+ct^3..)$$

where a, b and c are the first, second and third order temperature coefficients respectively. For a highly stable frequency generator, the constant 'a' must be very close to zero. This is often referred to as 'alpha quartz'. The crystals which are used in thermometry are oriented in a mode known as the thickness-shear mode and designated as LC cut. In this orientation, the constants b and c, known as beta and gamma, are made equal to zero and the temperature coefficient to 35.4 ppm per degree Celsius. Thus the degree of sensitivity of the LC-cut crystal is controlled by its resonant frequency. For example, a sensitivity of 1 kHz per degree Celsius is derived by cutting an LC crystal for a resonant frequency of 28.249 MHz, which is not at all a difficult task in terms of the state-of-the-art. The issue becomes simpler if we can be less rigid on the degree of sensitivity. A 100Hz/°C deviation from the centre frequency can be produced by an LC-cut crystal which resonates at the frequency of an 2.825 MHz.

Advantages of quartz temperature sensors

The linearity of the quartz temperature sensors ranges from -50°C to 250°C as opposed to the silicon p-n junction range of -55°C to 125°C. Moreover, quartz oscillators can be readily assimilated in the digital circuits whereas in silicon junction sensors, a high precision analogue-to-digital converter is unavoidable. The absence of intermediate conversion processes effectively minimises the possible error sources to a greater extent. A wide variety of error sources is checked in the fabrication of the sensor itself. Hair-thin quartz wafers are electrically contacted over the surfaces of the crystal by gold-deposited electrodes to minimise the contact resistances and corrosion problems. Crystals are placed in transistor cases such as TO-18, TO-72 or TO-5 to make them immune to mechanical drift and local stress and strain. The wafer is then hermetically sealed in a helium atmosphere for better heat conduction. This also provides a long-term stability due to the presence of inert atmosphere. To avoid self-generated thermal problems, the power dissipation in quartz sensors is limited to a fraction of a microwatt—all of which also has a pronounced effect on the costs.

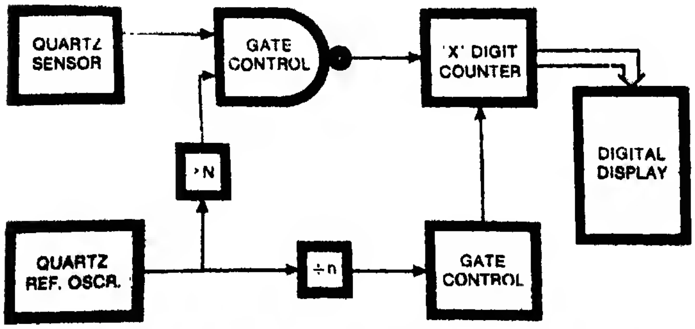
Quartz thermometer circuits make use of hetrodyning principle in extracting the useful information from the resonant frequency. The sensor frequency is mixed with a fixed reference frequency producing a beat frequency which is in direct terms with the actual variations. This is then digitally conditioned for the numerical display so as to detect even milli-Celsius variations. The high frequency characteristic of the sensor is an added advantage in telemetry type applications. The transmitted information is akin to a frequency-modulated system, hence the information recovery is not at all an unusual task. If desired, the sensor output can be sent to distant locations through cables without any serious deterioration in the content. In industrial applications, these properties are really invaluable. Analogue readouts are also possible but are seldom resorted to due to the natural convenience in digitalising the sensed information.

Optical properties of crystals were known much before the 17th century. An optical device for producing plane polarised light was invented in 1828 by William Nicol who was an expert in cutting and polishing gems and crystals. When ordinary light is passed through a tourmaline crystal, the light is polarised and the waves are confined to only one direction, i.e. perpendicular to the direction of propagation of light. In 1669, Erasmus Bartholinus observed a phenomenon called double refraction, in which a ray of light is refracted by a crystal giving rise to two refracted rays of different velocities. This helped in the classification of the minerals too. The value of double refraction is obtained by subtracting the refractive index of the lower ray from the higher one. Due to the relentless work done by Christian Huygens (1629-1695), crystals were again divided in terms of the waveforms of double refraction as positive and negative crystals. Quartz is a positive crystal with a double refraction value of 0.009. But this merely touched the tip of the iceberg and the opticians could only guess at the enormity of the submerged facts.

Integrating optical and piezoelectric approaches

One idea that combines both kinds of approaches, optical and piezoelectric, is now being considered more seriously by the manufacturers. The key feature of a grating array transducer for acoustic surface waves is a material that is both photoconducting and piezoelectric so that light can create conducting regions within the materials. Sections of a block of single crystal CdS are bonded to an aluminium block or lithium niobate ($LiNbO_3$), each half an acoustic wavelength long, and alternately illuminated or kept in the dark. Hence, at the frequency at which each of the stripes is half an acoustic wavelength wide, the structure behaves as a number of half-wave transducers in cascade. The signals generated by the CdS crystal on the application of voltage pulses or mechanical pressure are acoustic waves within the crystal because of the combined action of piezoelectricity and photoconductivity. As in any grating array transducer, the bandwidth varies inversely as the number of striations. Consequently, a method of adjusting bandwidth is by the variation of the number of illuminated stripes. A change in the center frequency of operation can be affected by altering the spacing or by using a variable aperture slit.

By precise manufacturing methods, a grating array piezo-optic transducer will be able to generate, concentrate or deflect sound within a crystal by external optical control. The same structural requirements lead to insufficient photoconductivity which causes incorrect division of voltage in the crystal due to the shunting reactance of the piezoelectric material. Insufficient photoconductivity causes higher degradation at higher frequencies. Another serious threat arises from the light scattering. Although the crystal is illuminated by striated light, its dark areas also appear bright because of internal light scattering. Precision and reliability are severely curtailed by this phenomenon alone.



[illegible]32: Schematic showing the working of a quartz [illegible]ter.

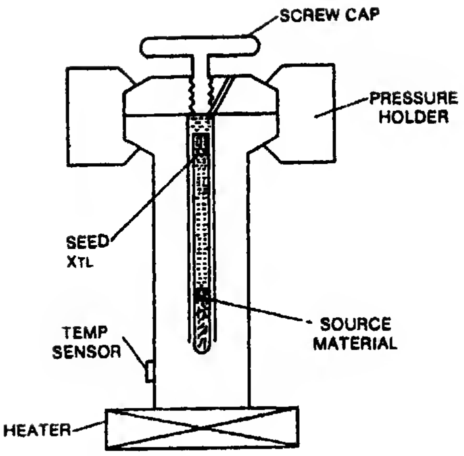


Fig. 33: Hydrothermal method to grow synthetic quartz.

Recent improvements in the development of piezo-optic materials have increased the ease of providing sharp photoconductivity without much degradation. Piezoelectric alpha-HgS (cinnabar or mercuric sulphide), a red-coloured crystal, when coupled with bulk alpha-HgS realises perfect matching in acousto-optical applications. The electromechanical coupling coefficients of cinnabar crystals are approximately two times larger than those of quartz. Measured values of coupling coefficients of alpha-HgS in thickness mode are 0.15 in X-cut and 0.24 in Y-cut, whereas alpha-SiO_2 gives 0.093 in X-cut and 0.14 in Y-cut. Both have a zero coefficient for Z-cut crystals. Indeed, the mercuric sulphide crystal is favourable to obtain wide bands for acousto-optical deflection.

Crystal pick-ups

The early bimorph revolution directly influenced the disc recording and reproduction by the introduction of crystal pick-ups. A typical stereo crystal pick-up consists of two bimorphs of Rochelle or tourmaline salts clamped at a convenient angle. Their free ends are coupled to the stylus mounting so that it receives the vibrations from the groove. Vibrations from the right-hand groove are transmitted to the left-hand arm of the square plastic framework and twist the left-hand bimorph. A proportional voltage is produced for each and every twist and turn. This does not affect the left-hand bimorph to the same extent as the right-hand one because the right-hand arm between the stylus and crystal bends about the elbow. The same level of non-interference is maintained for signals from the left-hand groove to the right-hand bimorph. Since the resulting output voltage is fairly high, equalisation circuits are seldom used for crystal pick-ups. Furthermore, their output is independent of fre-

Table IV
Nominal Values of Crystal Analogue Parameters of AT Cut

Resonant Frequency (MHz)	Series Resistance (ohms)	Series Capacitance Cs (pF)	Parallel Capacitance Cp (pF)	Q Factor X1000
1	400	0.008	2.5	45
3.58	60	0.015	3.5	40
4.00	50	0.025	5	30
5.00	40	0.02	5	20
6.00	30	0.02	6	20
8.00	20	0.02	6	20
14.31818	10	0.0265	6	50
16.0000	10	0.0319	6	50

quency and directly proportional to the magnitude of the mechanical movements. Their main disadvantages are the inferior frequency response and the changes in their characteristics due to ambient temperature and humidity changes. The next favourite, the ceramic pick-ups, are constructed in a similar manner and function almost the same way.

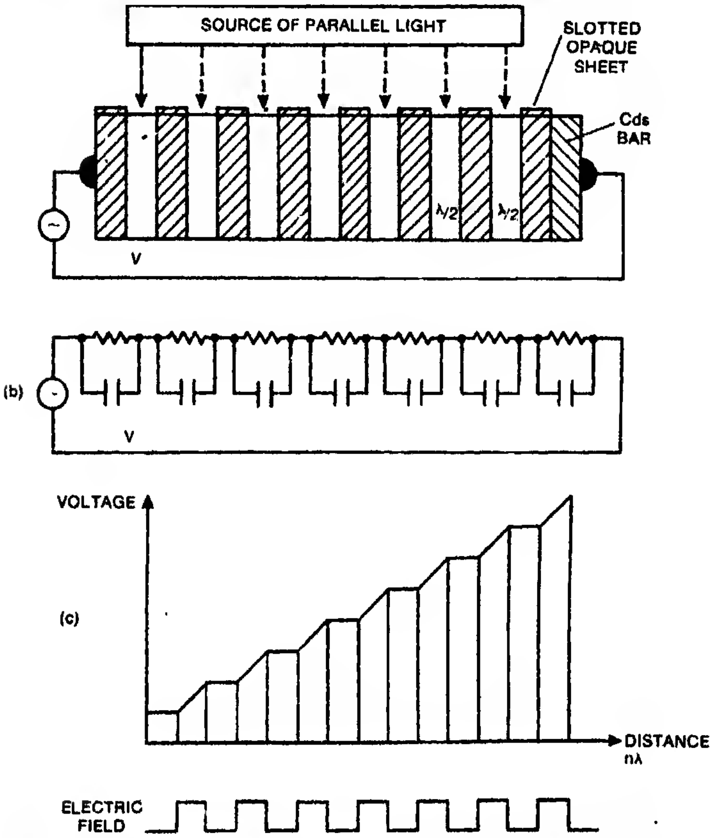


Fig. 34: Grating array transducer. (a) CdS bar with slotted opaque sheet; (b) equivalent circuit; (c) distribution of RF voltage and electric field.

The same principle has proved quite as successful when applied to the design of record-cutter heads. Piezoelectric heads contain a crystal bimorph clamped securely at one end and left free at the other. When a voltage is applied between its faces, it tends to bend or twist which is faithfully imitated by the cutting stylus attached to the free end of the crystal via a convenient linkage. This operation requires less power than the types like moving-coil or moving-iron in cutting the disc surface according to the sound signal. Yet the multiple resonance of the piezoelectric material used in the bimorph which may fall even in the audio range, the fragility of the bimorph material and its affinity towards humidity and temperature changes are some of its disadvantages.

Quartz crystals have an immense commercial viability which has been clearly realised by most manufacturers. Let us examine the case of a quartz fuse. In fact, no piezoelectric magic has crept into it. The fast acting fuse utilises a silver wire or any other suitable metal in a convenient package. When the specified current-time relationship is applied to the fuse, the wire link melts resulting in an open circuit. Usually the cartridge sleeve is covered with ceramic or high grade alumina since it can withstand sufficiently high mechanical and electrical shock. The quartz or silica is only a filler in the barrel. This type of a filler is specially dried before use and deposited within the barrel by mechanical vibrations. This form of quartz has a nominal role in the fast fusing action which is less than 4 milliseconds. When the specific current is exceeded, the heat generated vapourises the silver, and the vapour fuses with silica quartz to form a nonconducting fulgurite.

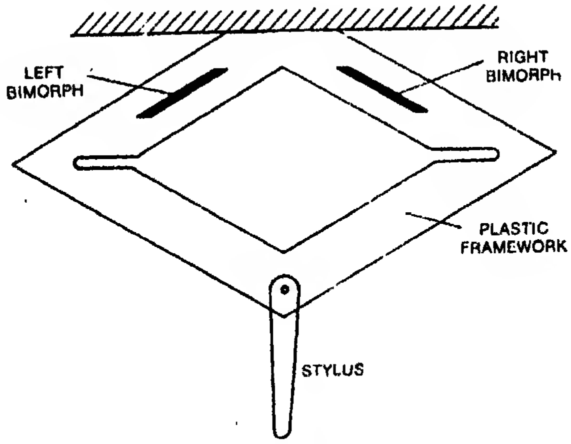


Fig. 35: Schematic of stereo crystal pick-up.

Fused silica or quartz prisms are used as wavelength selectors in spectroscopic instruments between the 0.2 to 2.7 micrometer range. It has an excellent hardness and chemical resistance. The refractive index is 1.54 while the angular dispersion is around 0.063 milliradian per micrometer at a wavelength of 0.598 micrometer as compared with the refactive index 1.7 of flint glass. Hence, quartz prisms are particularly utilised in the ultraviolet region of the electromagnetic spectrum. Renouned Cornu and Littrow prisms are also made of quartz. Even in optics, quartz has an unchallenged and enviable place.

Finally, it seems reasonable to predict that the flexibility and piezo-optic chemical properties of the material will lead to the creation of new and useful devices along with the cost-effectiveness of the integrated-circuit technology. □