The History of Ceramic Filters

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***Abstract*—The history of ceramic filters has been surveyed here. Included is the history of piezoelectric ceramics. Ceramic filters were developed using technology similar to that of quartz crystal and electro-mechanical filters. However, the key to this development involved the theoretical analysis of vibration modes and material improvements of piezoelectric ceramics. The primary application of ceramic filters has been for consumer-market use. Accordingly, a major emphasis has involved mass production technology, leading to low-priced devices. A typical ceramic filter includes monolithic resonators and capacitors packaged in unique configurations.**

I. Introduction

Applications of the piezoelectric effect have expanded into many fields since the Curie brothers discovered this effect in 1880-1881. Since then, based on the type of piezoelectric materials, four stages of historical development may be identified. The first material was single-crystal quartz, the second was single-crystal Rochelle salt, the third was barium titanate ceramics, and the fourth was lead-zirconate-titanate (PZT) ceramics.

Quartz crystals were first used for underwater transducers during World War I, and then for quartz crystal oscillators. Rochelle salt was used for underwater transducers and phonograph pickups. Barium titanate ceramics were discovered at the end of World War II and were first used for underwater transducers, communication devices, and dielectric components such as capacitors. PZT ceramics were discovered in 1954 and replaced barium titanate ceramics in all fields of piezoelectric applications. At present, single-crystal quartz is still the most important piezoelectric material. Of the ceramic materials, PZT ceramics are the most widely used because of their high electromechanical coupling factor, good frequency-temperature characteristics, and suitable quality factor. With this as background, a history of the key development work on ceramic materials and ceramic filters is presented.

II. The History of Barium Titanate

Barium titanate ceramics were discovered by E. Wainer and N. Salomon [1] in the USA in 1942, by T. Ogawa [2] in Japan in 1944, and by B. M. Vul [3] in the Soviet Union also in 1944. All discoveries were made independently with no communication between the researchers because of World War II. At first, the discoverers suggested that barium titanate ceramics were typical ferroelectric materials and had no specific piezoelectric advantages. However, in 1947, S. Roberts [4] of the USA discovered the piezoelectric properties of the material resulting from poling the material with a high DC voltage. This prompted W. P. Mason [5] and others to study the piezoelectric properties of the material. By the early 1950s, piezoelectric transducers based on barium titanate ceramics were becoming well established in a number of consumer and military applications.

Piezoelectric barium titanate ceramics were good materials for electro-mechanical transducers because of their non water solubility, high coupling coefficient, and ease of production. However, this material had a serious weak point—a poor temperature coefficient of resonance frequency caused by the second phase transition of crystal [6] just below room temperature. The second problem was excessive aging because of the material's low Curie point. Many researchers tried to improve the temperature characteristics by shifting the second phase transition. One method was to add other materials such as Ca or Pb [7], [8]. Especially, the addition of Pb had a drastic effect in shifting the Curie point to a temperature >120°C and the second phase transition to <-20°C. Study of the phase transition in lead titanate and lead zirconate led to the discovery of PZT ceramics [9], [10], which had much better temperature and aging characteristics than barium titanate.

III. The Clevite Corporation

The Clevite corporation was formed by the 1952 merger of the Cleveland Graphite Bronze Corporation and the Brush Development Company. Brush, in the 1930s, manufactured the first electronically amplified phonograph elements using Rochelle salt bimorphs and, in the late 1940s, marketed commercial piezoelectric quartz crystals produced by a hydrothermal process. Also, in the late 1940s, Brush manufactured the first commercial magnetic tape recorders. At the time of the merger, the piezoelectric branch of Brush's business manufactured barium titanate and Rochelle salt elements for photograph pickups, barium titanate, and ammonium dihydrogen phosphate (ADP) transducers for underwater ultrasonics and performed pilot production of synthetic quartz crystals. With the discovery of the strong piezoelectric effect in PZT by B. Jaffe, Clevite [11] initiated an effort to improve these new piezoelectric materials by chemical modification. This led first to materials with higher permittivity (by an isovalent sub-

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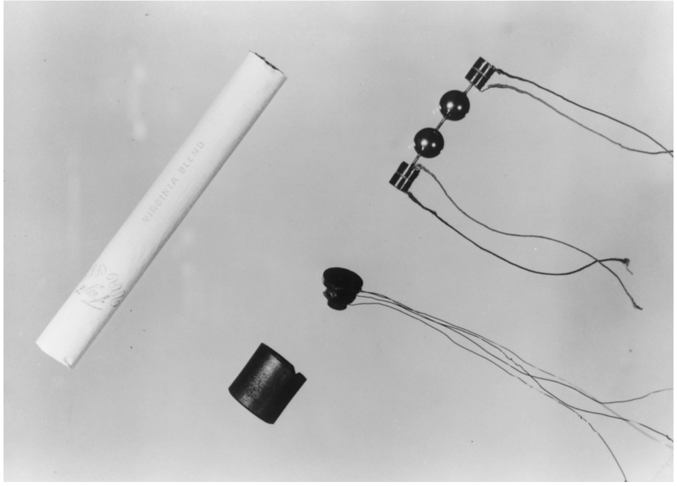


Fig. 1. Inner structure of a 455-kHz mechanical filter using steel balls and Langevin-type transducers with barium titanate.

stitution of Ca and Sr for Pb) [12]. These modified materials also had somewhat improved high driving voltage characteristics. Later, a La substitution for Pb and a Nb and Sb donor substitution for Zr and Ti yielded materials with higher piezoelectric coupling, higher permittivity, and much lower aging; however, high voltage drive characteristics were more limited [13]. Finally, new modified materials with Cr, U, Mn, and Mg (these being identified as variable valence additives) were found to provide materials suitable for electro-mechanical filters. These compositions have high mechanical Q, very low aging, and very good temperature stability of resonance frequency (on the order of 0.1 to 2% from −40° to +85°C). Furthermore, different formulations provided a electromechanical coupling range suitable for filters with bandwidths from 0.5 to 20%. The formulations of these materials were never published, but patents were applied for and issued some years later [14], [15], [16]. Work on these materials led to a cooperative relationship between Clevite and the Murata Manufacturing Company. Clevite first concentrated on high quality military and commercial filters. Most of these were ladder filters with up to 17 disc resonators packaged in Hermetically sealed metal cases. In the mid 1960s, there were efforts to develop consumer filters for AM radios, especially automobile radios, but cost goals were not met. However, beginning about 1967, development efforts turned to 10.7-MHz coupled-mode ceramic filters for FM automobile radios. The resulting filter design consisted of a ceramic wafer with two acoustically isolated coupled-mode filter sections and a coupling capacitor, which was deposited on an unpoled region of the wafer [17]. A large quantity of the filters was delivered to Philco-Ford starting in 1970. Previously, Gould Inc. had bought Clevite and then turned around and sold the Piezoelectric Division to Vernitron in 1970. These moves effectively terminated the promising filter program initiated by Clevite.

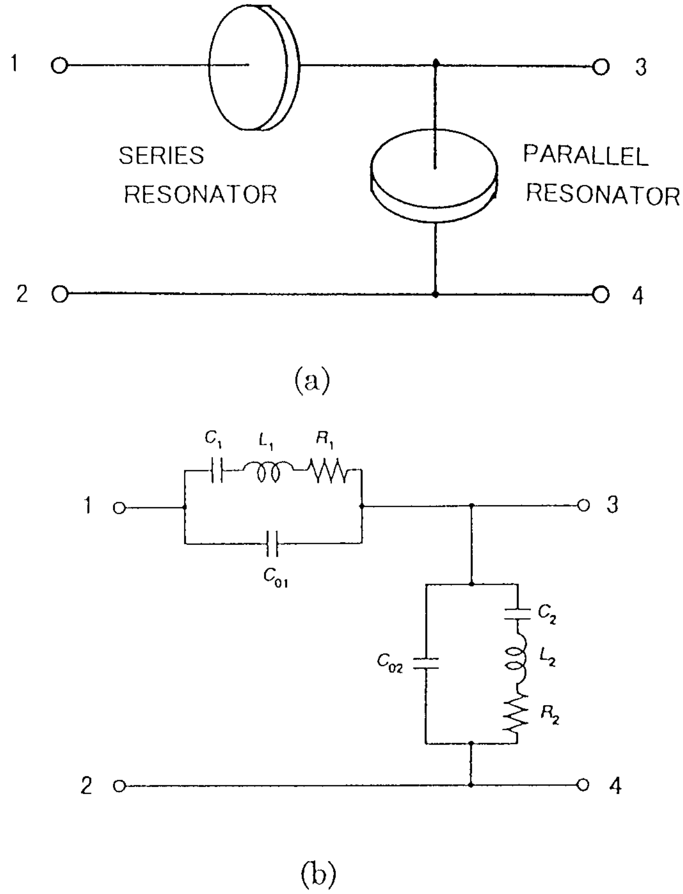
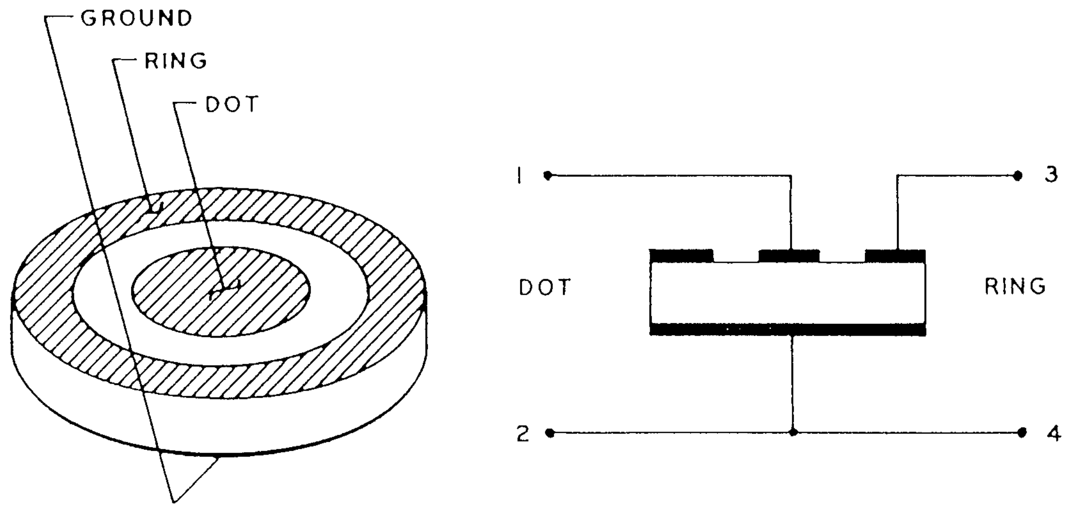


Fig. 2. (a) An L-section of a ladder-type ceramic filter with ceramic resonators in the series and parallel branches and (b) the equivalent circuit.

IV. The Murata Manufacturing Company

The Murata Manufacturing Co., Ltd. was founded by A. Murata [18] at 23 yr of age in 1944. He left Kyoto high school, finishing before graduation because of sickness, but learned ceramic technology at home from his father who was chairman of Murata Pottery Manufacturing Co. After his father died, A. Murata founded the Murata Manufacturing Co., Ltd., starting with only 10 workers to produce electro-ceramic components such as steatite and titanium capacitors. After World War II, Mr. Murata met Professor Tanaka of Kyoto University who had a great interest in the research and development of barium titanate ceramics. Prof. Tanaka loaned him a book entitled *The Miracle of Glass*. It was the story of a man named Zeiss, who founded the famous German optical instruments company Carl Zeiss. The book was about how Zeiss, under the guidance of Prof. Abbe, a lens researcher at Jena University, built up his small lens-making factory into the world's foremost maker of optical instruments. After reading the book, A. Murata asked Prof. Tanaka to give him the same sort of guidance that Zeiss got from Prof. Abbe. Prof. Tanaka agreed, and a long cooperative relationship to create new products using barium titanate ceramics was begun.



(a) (b)

Fig. 3. (a) The physical configuration of a "Transfilter" and (b) its symbolic circuit.

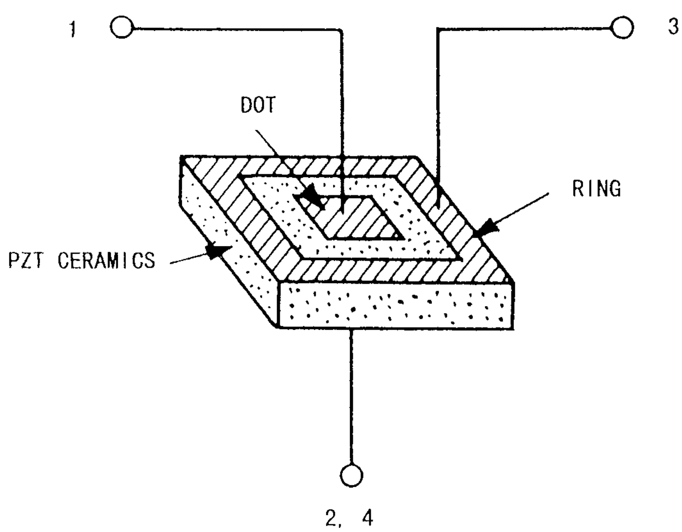


Fig. 4. The physical configuration of a 455-kHz ceramic filter.

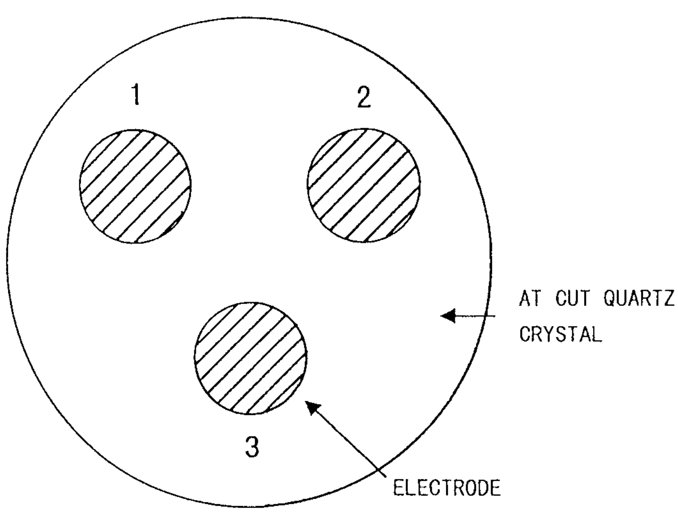


Fig. 5. Electrode arrangements on a quartz crystal "Uni-wafer."

V. The Barium Titanate Application Research Committee

To consider jointly the anomalous characteristics of barium titanate, Prof. Tanaka, A. Murata, and Dr. Itoh gathered together numerous academics to form the Barium Titanate Application Research Committee [19]. Mr. Murata volunteered to serve as secretary. Dr. Itoh was a technology officer in the navy and wanted to create a large-scale research program, not only for Murata Mfg. Co. and Kyoto University, but for companies and universities nationwide. The society existed from 1952 to 1977, meeting nearly 300 times and generating roughly 2000 reports. The group's target became that of developing practical applications of barium titanate ceramics, so there were heated discussions between the material and application groups. The first products using piezoelectric barium titanate ceramics were 50-kHz Langevin type underwater transducers for fish-finding SONAR [20]. The next products were transducers for mechanical filters [21]. Regarding the development of mechanical filters, A. Murata said "since the price of filters for communications radios was higher than 10 000 yen each, the market need for filters of that price would be less than only 1000 pieces per month, and, therefore, the sales volume would be $<$ 10 million yen. If we could succeed in developing 455-kHz mechanical filters for consumer radios at about 100 yen, the sales would be $>$ 100 million yen because the market quantity for consumers would be $>$ 1 million parts/m. Therefore, we should aim at the consumer radio market." Following A. Murata's policy, in 1956, S. Fujishima began the development of low cost mechanical filters. First, he developed 455-kHz mechanical filters that used the radial vibration mode of steel balls made for ball bearings as shown in Fig. 1. However, the yields were poor because of unwanted vibration modes. Finally, Fujishima succeeded in developing low cost mechanical filters using directly coupled 455-kHz Langevin-type transducers

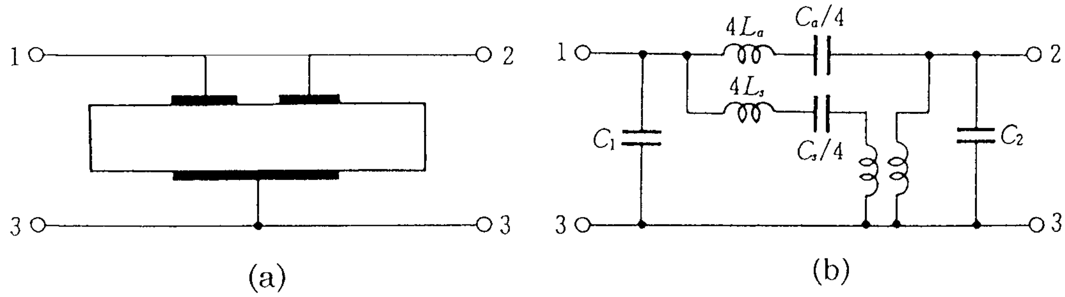


Fig. 6. The symbolic circuit of a crystal filter using multi-energy trapping vibration modes and (b) the equivalent circuit.

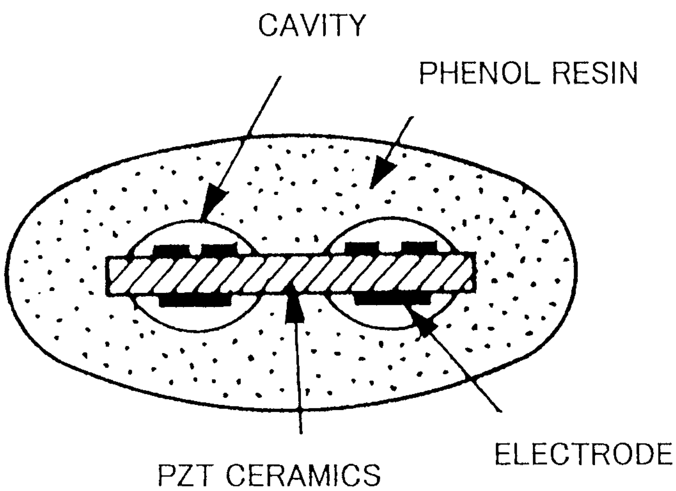


Fig. 7. The package of a 10.7-MHz ceramic filter.

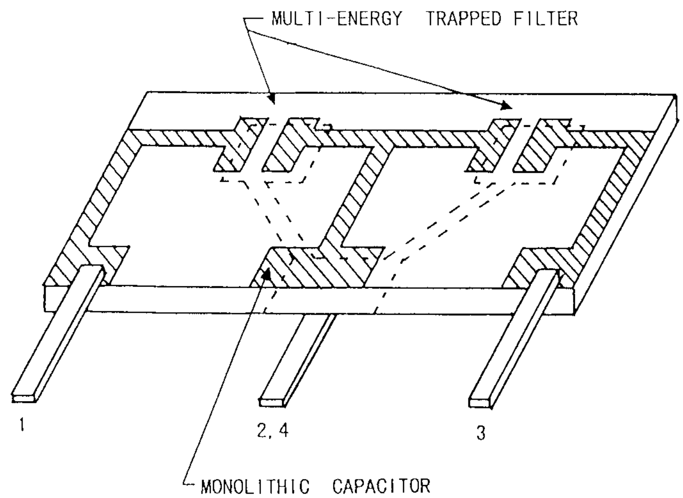


Fig. 8. The physical configuration of a monolithic ceramic filter with a monolithic capacitor.

without the steel balls. Unfortunately for this program, the consumer radio business in Japan started to use transistors instead of ordinary vacuum tubes. The market then moved toward miniature-sized filters. The Langevin type transducers were suitable for mechanical filters, but it was difficult to make these filters sufficiently small. In 1960, Fujishima decided to tackle the development of ceramic filters using the vibration mode of the ceramic body itself (i.e., the ceramic without metal). He asked the material group to find new piezoelectric ceramic materials better than barium titanate for the desired ceramic filters. Murata found that the Clevite Corp. held the patents for PZT ceramics [22] and that the patents were valid throughout the world. After 4 yr of negotiation, Murata agreed to pay a 5% royalty (partially underwritten by Japan's MITI) on all products exported to the countries covered by the patent.

VI. Development of Ceramic Filters

From 1958 to 1960, the group within Clevite led by D. R. Curran developed the PZT disc-type ceramic filters shown in Fig. 2. These filters were developed for military uses under various contracts with the U.S. Army Signal Supply Agency. The main products were 455-kHz and 4.3-MHz ladder-type ceramic filters using the radial mode of the ceramic disc resonators. This work was followed by 455-kHz ceramic IF filters for commercial communication equipment, shown in Fig. 3, named "Transfilter." These filters also used radial-mode resonators but with split electrodes. "Transfilter" was a combined term for transformer and filter, the device realizing an input-to-output impedance transformation and bandpass frequency response.

Fujishima's group in Murata then developed 455-kHz ceramic filters using the expansion mode driven by split electrodes on a ceramic square plate, as shown in Fig. 4. Their target was to make the smallest and lowest cost ceramic filters for transistor radios. In 1963, after SONY sold AM transistor radios that used the ceramic filters, other Japanese companies began to use the filters in their own AM radios. Then, within a short time, FM broadcasts began. The situation was different with regard to FM in that all of the companies, at once, asked Murata to develop 10.7-MHz IF ceramic filters for their radios.

Meanwhile, Curran at Clevite developed 4.3-MHz crystal filters named "Uni-wafer" filters using the thickness shear vibration mode of separated electrodes on an AT-cut quartz crystal plate in 1961, as shown in Fig. 5 [23] and also 10.7-MHz ceramic filters using the thickness-expansion vibration mode of separated electrodes on a PZT disc. He achieved simple lattice filters using exter-

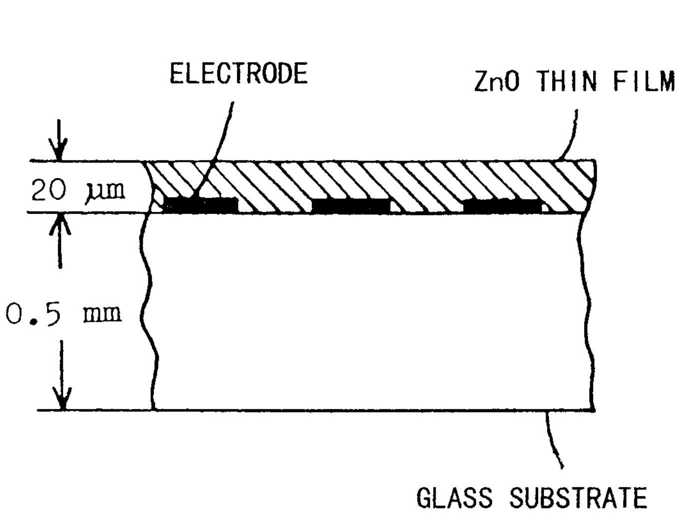


Fig. 9. Cross-sectional view of a 58-MHz SAW filter using ZnO thin film on glass.

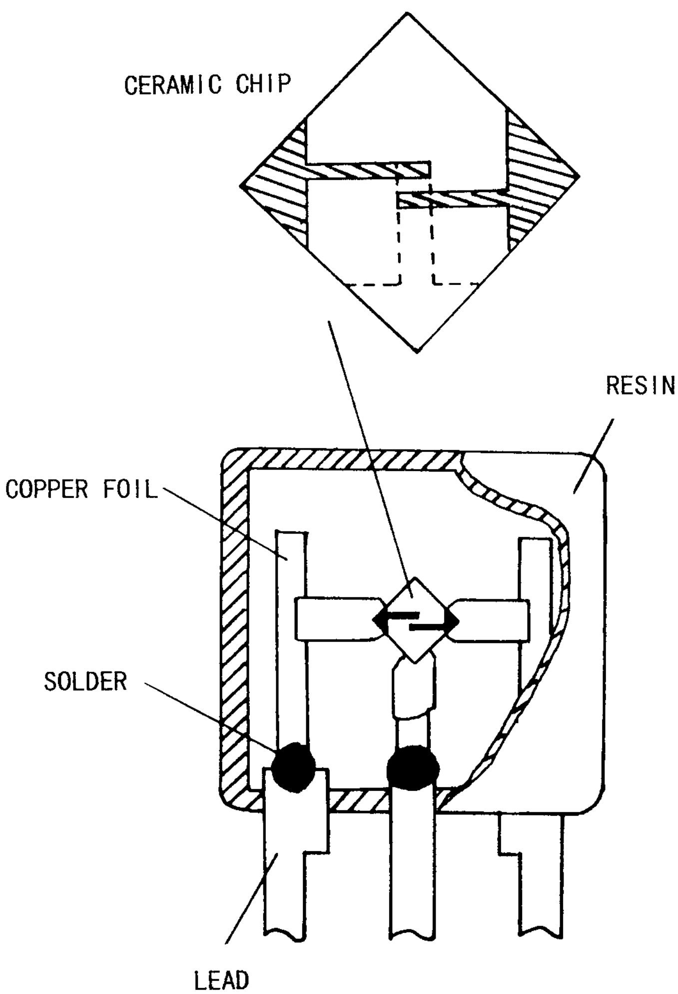


Fig. 10. The physical configuration of a 57-MHz double-mode ceramic resonator for video IF.

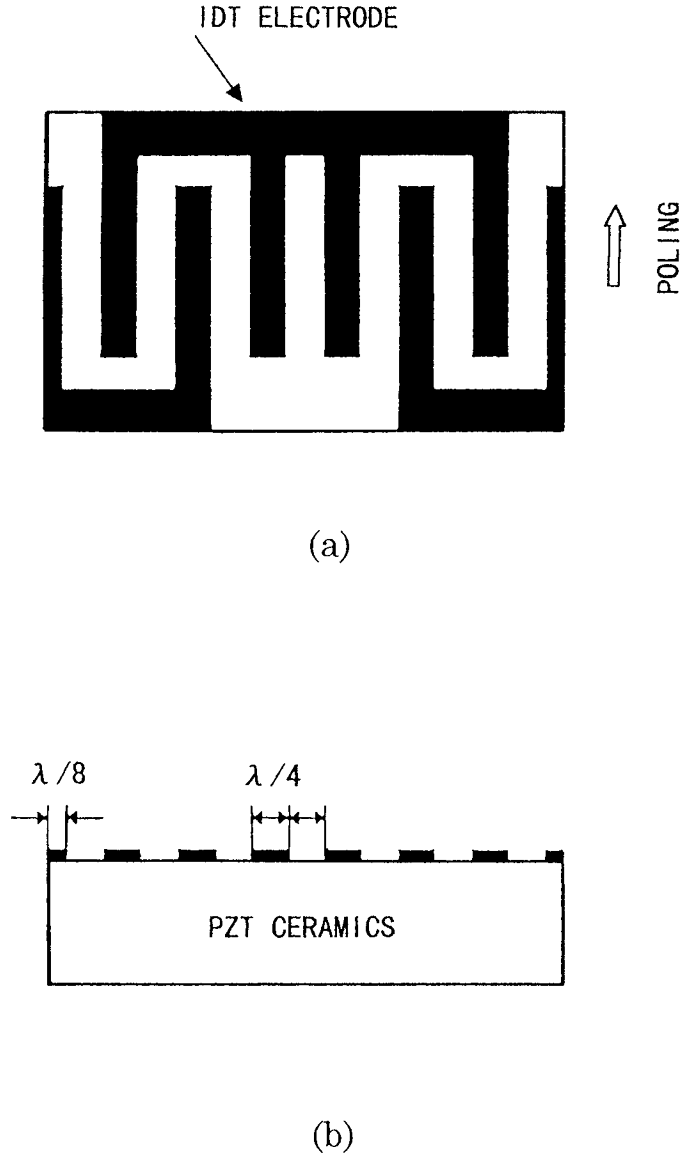


Fig. 11. (a) Electrode arrangements of a 40-MHz BGS wave resonator and (b) cross-sectional view of the resonator.

nal capacitance and inductance where required. The electrodes were deliberately separated to prevent acoustic interaction. Nakazawa at Toyocom developed a double-mode resonator as two acoustically coupled single resonators in 1962 [24]. In 1963, Dr. William Shockley, who at this time was working for Clevite, reported his theoretical work on energy trapping with a wave guide theory [25]. In 1964, Prof. Onoe developed 10.7-MHz crystal filters using multi-energy trapping mode of thickness shear vibration [26], [27]. He succeeded in realizing a two-pole bandpass filter response without external inductance by splitting a dot electrode to create coupled symmetric and antisymmetric vibration modes as shown in Fig. 6. In 1966, Fujishima [28] developed 10.7-MHz ceramic filters using trapped thickness-expansion modes.

Murata started the mass production of 10.7-MHz ceramic filters for sale to the FM transistor radio industry

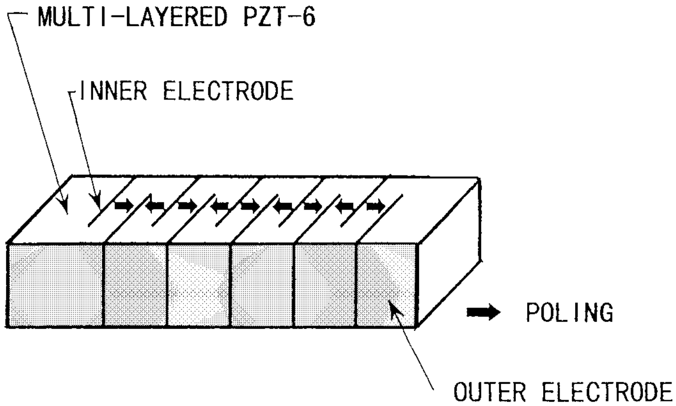


Fig. 12. The physical configuration of a 450-kHz ceramic resonator using multi-layered PZT ceramics.

in 1967. However, it was very difficult for them to increase their volume of production because of a poor yield of $< 5\%$. The yield was improved by unique ideas like the packaging shown in Fig. 7 [29] and the monolithic capacitor [30] shown in Fig. 8. This enabled Murata, in 1970, to succeed in the mass production of the 10.7-MHz ceramic filters with the use of automatic machines. The world's first use of these filters in car radios was by Delco in 1971 soon followed by Philco-Ford. Fujishima developed 10.7-MHz ceramic filters using surface acoustic waves for high fidelity FM tuners [31] in 1975 and 58-MHz SAW filters for TV using ZnO thin films on glass as shown in Fig. 9 [32] in 1976. Zinc oxide thin films are categorized as piezoelectric ceramics because of their oriented poly-crystal structure. Kitani group in Matsushita developed 57-MHz ceramic filters for TV using double mode ceramic resonators as shown in Fig. 10 [33] in 1976. Kadota developed 40-MHz ceramic filters using BGS (Bluestein, Gulyaev, and Shimizu) waves for TV as shown in Fig. 11 [34] in 1991. Inoue developed 450-kHz surface mount ceramic filters for pocket telephones using the thickness-vibration mode in multi-layered PZT ceramics as shown in Fig. 12 [35] in 1998.

Acknowledgments

Overall, the development of ceramic filters has been achieved by close cooperation between researchers and companies in the USA and Japan. The author wishes to thank each of the persons who contributed material for this history. Especially, he expresses appreciation to Mr. Berlincourt, Fellow, IEEE, who wrote the history of the Clevite Corporation's contributions for this paper. He is entitled to state that "the history of ceramic filters was the history of the good cooperation of the Clevite Corporation and Murata Manufacturing Co., Ltd." The author accepts full responsibilities for any corrections that may be due.

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In 1950, he worked at the Japan Radio Company, Tokyo, Japan. In 1955, he moved to Murata Manufacturing Co., Kyoto, Japan. Since then, he has been working on the application of piezoelectric ceramics. His research interests include underwater transducers, bulk wave ceramic filters, surface acoustic wave filters with ZnO thin films, vibrating gyroscopes, and audio speakers with piezoelectric ceramics.

Dr. Fujishima received the Minister Award of Science-Technology in Japan in 1983, the Blue Ribbon Award in 1988, High Decoration from Emperor in 1997, and the Achievement Award of the Acoustic Society of Japan in 1998. He is a member of IECE and the Acoustic Society of Japan.