TEMPERATURE STABLE MICROWAVE DIELECTRIC RESONATORS UTILIZING FERROELECTRICS

by

J. K. Plourde
Bell Telephone Laboratories, Incorporated
Allentown, Pennsylvania 18103

Abstract

Temperature stable dielectric resonators suitable for high quality microwave filter applications have been obtained with composite structures utilizing either $LiTaO_3/TiO_2$ or $LiNbO_3/TiO_2$. These resonators yield $\varepsilon \sim 50$ and $Q \sim 5000$ at 4 GHz.

Introduction

The use of dielectric resonators in microwave filters may permit small, high quality filters to be designed which are compatible with microwave integrated circuit technology. The unavailability of high dielectric constant, high dielectric Q, temperature stable dielectric resonators has prevented these applications. For example, TiO_2, a material commonly used in resonator studies possesses $\varepsilon \sim 100$ (dielectric permittivity) and $Q \sim 10{,}000$ (dielectric $Q = 1/\tan\delta$) but its excessive temperature coefficient of frequency ($\tau_f = \frac{1}{f}\frac{df}{dT} \sim 425$ ppm/°C) precludes its use for most applications.

Temperature Compensation

Temperature compensation schemes employing mechanically coupled TiO_2 resonators have been demonstrated.[1] This mechanical approach has the advantage of utilizing the excellent dielectric properties (except for τ_f) of TiO_2. It has very serious problems with spurious resonances, mechanical complexity and a lack of compensation for temperature transients caused by incident power variations. In addition, an important advantage of dielectric resonators, the integratability, is lost. A dielectric resonator inherently temperature compensated is required for such applications.

The behavior of the temperature coefficient of dielectric permittivity ($\tau_\varepsilon = \frac{1}{\varepsilon}\frac{d\varepsilon}{dT} = -2\tau_f$) versus ε for paraelectric materials is adequately explained by the Clausius-Mosotti equation which yields

$$\tau_\varepsilon \simeq K - \alpha_\ell\,\varepsilon \qquad (1)$$

where α_ℓ is the thermal expansion coefficient (typical value 10 ppm/°C) and K is a constant (Figure 1). The range of values for K is such that temperature compensation occurs for many materials with ε in the 20 to 30 region but is highly unlikely for significantly higher ε materials as these have large negative τ_ε values.

Two approaches toward resonator development have promise. In the first approach, suitable high Q, temperature compensated paraelectrics possessing dielectric constants somewhat exceeding the usual 20 to 30 values can be sought. The zirconates and the $BaTi_4O_9$ results reported by R. C. Kell, et al,[2] and D. W. Readey, et al,[3] respectively, are examples of this appoach. Paraelectrics are unlikely to provide a temperature compensated dielectric significantly above the $\varepsilon \sim 30$ to 40 region, however.

The work described here utilizes a second approach which considers ferroelectric materials in an attempt to avoid the paraelectric limitations. Ferroelectrics possess ε and τ_ε values over a wide range and may provide either a high ε, temperature compensated, material directly or a high ε positive τ_ε material which can be temperature compensated by combination with a paraelectric (negative τ_ε) such as TiO_2. Unfortunately, most ferroelectric materials possess high microwave losses. In seeking suitable ferroelectrics, those with high transition temperatures should be considered.

Ferroelectric Resonators

Characterization of poled single crystal $LiTaO_3$ and $LiNbO_3$ has yielded the properties of high Q together with high permittivities and positive temperature coefficients at 4 GHz for electric fields perpendicular to the optical axis. This orientation is applicable to the case of a resonator excited in the $TE_{01\delta}$ mode in which the optical axis of the ferroelectric is parallel to the resonator cylindrical axis.

	ε_{11}	$\tau_{11\varepsilon}$	Q_{11}
$LiTaO_3$	42	+295 ppm/°C	4200
$LiNbO_3$	44	+276	4400

The Qs are sensitive to the crystal quality and the percent of poling and may be less than the above values for low quality crystals. The results for $LiTaO_3$ temperature compensated resonators are presented below. Similar results were obtained with $LiNbO_3$. Although many geometries are possible, only the two simplest geometries which approximate the two extreme cases of dielectric mixing, i.e., parallel mixing and series mixing, were considered. Except for a sensitivity to the characteristics of the adhesive used to bond the components, the series composite structure yielded results similar to the parallel structure and will not be discussed further.

The electric field for the dielectric resonator mode of interest, the $TE_{01\delta}$ mode, is parallel to the dielectric interface in the parallel composite structure. To a very good approximation, the parallel mixing rule describes the dielectric mixing and predicts the component volume ratio required for temperature compensation. The resonator structure and the mixing rule are presented in Figure 2 along with the resulting frequency stability, resonator Q and effective dielectric constant. A composite resonator Q of 5100 is obtained when the $LiTaO_3$ and TiO_2 possess Q = 4200 and 10,000, respectively. The resonant frequency shift is only 1.25 MHz over a 100°F temperature range compared to a shift of 3.9 MHz for a copper waveguide resonator and 96 MHz for a TiO_2 resonator under the same conditions. In addition, a temperature exists at which the resonator is perfectly temperature compensated.

For applications where rapid temperature changes (50°C/hr, for example) are encountered, a small resonant frequency versus temperature hysteresis effect is observed. This hysteresis has been found to be related to the pyroelectric effect and the frequency shift can be described in terms of the dielectric properties and the pyroelectric coefficient. It has been found that the hysteresis effect can be eliminated where desired by providing a discharge path across the ferroelectric component as shown in Figure 3, where a Ta_2N_5 thin film path was used. The discharge path need only possess a resistance of less than 10^{12} ohms in order to reduce the time constant associated with the hysteresis to $T < 10$ seconds, for example. Alternatively, a conductive pattern may be used to function both as a discharge device and as a mode suppressor.

For filter applications, both the resonator Q degradation and the resonant mode separation must be considered. Measurements indicate that the resonator clearance need only be approximately equal to the resonator radius to prevent excessive Q degradation due to nearby conducting surfaces. This results in a compact housing structure. The frequency of the $TE_{01\delta}$ cylindrical mode is well separated from higher order modes for a resonator aspect ratio $H/Dia \simeq 0.4$ as the measurements presented in Figure 4 indicate. The proximity of the substrate and housing walls in a resonator filter application may result in some frequency shifting of the resonator modes. However, this effect can be accounted for by readjustment of the aspect ratio.

CONCLUSION

The consideration of ferroelectric materials for dielectric resonator applications has yielded two high ε, high Q, positive τ_ε materials ($LiTaO_3$ and $LiNbO_3$) which permit temperature compensated composite structure resonators to be formed. Although many geometries can be considered, the resonators can simply utilize two cylindrical disc components. These resonators with $\varepsilon \sim 50$ and $Q \sim 5000$ at 4 GHz in addition to a temperature stability superior to copper waveguide filters are suitable for high quality dielectric resonator filter applications.

Other suitable ferroelectrics may exist and should also be considered for these applications. Ceramic mixtures utilizing paraelectric and ferroelectric materials may provide suitable temperature compensated ceramic resonator materials.

ACKNOWLEDGMENTS

The author wishes to acknowledge the assistance of D. F. Linn in providing the microwave measurements. The assistance of A. A. Ballman in providing some of the lithium tantalate crystals used in this investigation is also gratefully acknowledged. The TiO_2 ceramic was provided through the cooperation of J. Thomson, Jr.

REFERENCES

1. W. H. Harrison, "Microwave Filters Utilizing Dielectric Resonators," Rantec Division, Emerson Electric Co., Calabasas, California, Final Report, Contract DA 28-043 AMC-02088(E), July 1967.

2. R. C. Kell, E. E. Riches, C. Brigginshaw, G. C. E. Olds, A. J. Thomas, R. F. Mayo, and D. F. Rendle, "Novel Temperature-Stable Ceramics for Microwave Dielectric Resonators and Microstrip Substrates," Electron. Lett., Vol. 6, pp 614-616, 1970.

3. D. W. Ready, C. P. Hartwig, E. A. Maguire and D. J. Masse, "Microwave High Dielectric Constant Materials," Raytheon Company, Waltham, Massachusetts, Quarterly Repts., 1-4, Contract DAAB07-69-C-0455, November 1969 - October 1970.

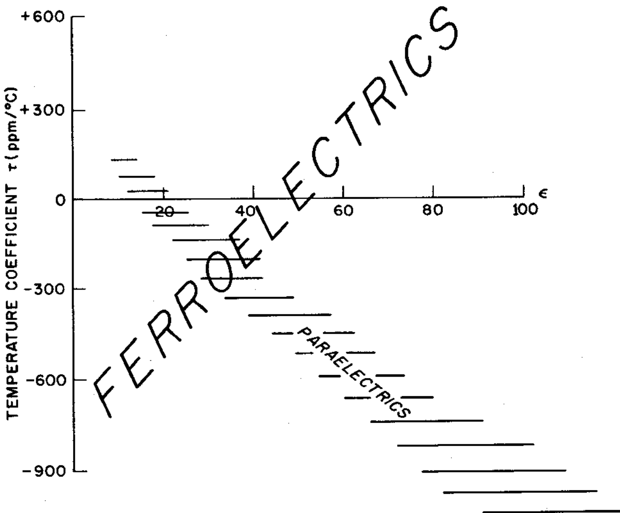

FIG. 1 BEHAVIOR OF HIGH DIELECTRIC CONSTANT MATERIALS

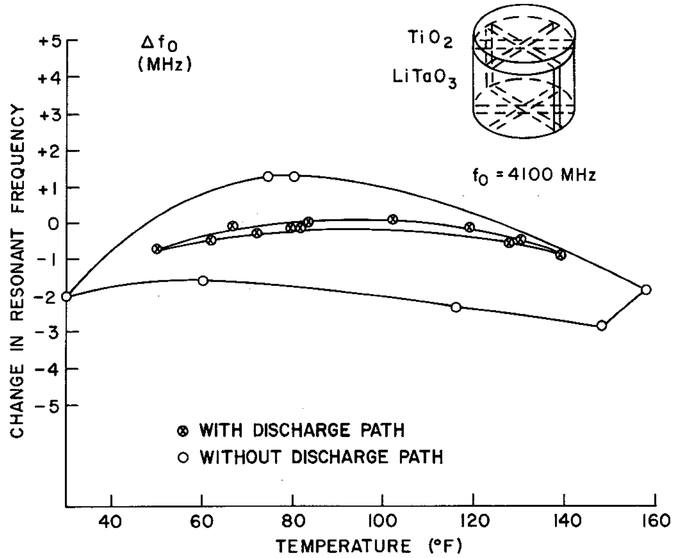

FIG. 3 TEMPERATURE COMPENSATED PARALLEL COMPOSITE RESONATOR WITH DISCHARGE PATH

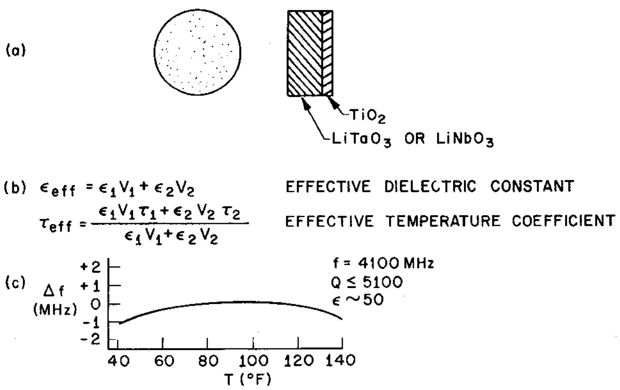

FIG. 2 PARALLEL COMPOSITE RESONATOR
(a) GEOMETRY;
(b) PARALLEL MIXING RULE;
(c) FREQUENCY STABILITY

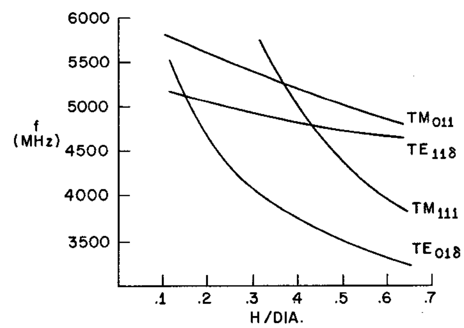

FIG. 4 RESONANT FREQUENCY VERSUS ASPECT RATIO