La(Mg$_{0.5-x}$Me$_{x}$Sn$_{0.5}$)O$_3$-based (Me = Ca, Sr) dielectric resonator antenna for use in a wireless high-temperature sensor

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The microwave dielectric properties of La(Mg$_{0.5-x}$Me$_x$Sn$_{0.5}$)O$_3$ (Me = Ca, Sr) ceramics are studied, in order to develop a wireless dielectric resonator antenna temperature sensor. The microwave dielectric properties of La(Mg$_{0.5-x}$Me$_x$Sn$_{0.5}$)O$_3$ (Me = Ca, Sr) ceramics are determined using X-ray diffraction patterns, Rietveld refinement measurement, Raman spectra, and by observing the microstructures. La(Mg$_{0.5-x}$Me$_x$Sn$_{0.5}$)O$_3$ (Me = Ca, Sr) ceramics are prepared using a conventional solid state method. As the degree of substitution of Ca$^{2+}$ and Sr$^{2+}$ increases, the position of the $A_{1g}(O)$ Raman vibration mode shifts toward a lower frequency. The La(Mg$_{0.49}$Ca$_{0.01}$Sn$_{0.5}$)O$_3$ ceramic exhibits a minimum full width at half maximum for the $A_{1g}(O)$ Raman vibration mode in the series of La(Mg$_{0.5-x}$Me$_x$Sn$_{0.5}$)O$_3$ (Me = Ca, Sr) ceramics. La(Mg$_{0.49}$Ca$_{0.01}$Sn$_{0.5}$)O$_3$ ceramics that were sintered at 1600°C for 4 h have an apparent density of 6.57 g/cm$^3$, a dielectric constant ($\varepsilon_r$) of 19.9, a quality factor ($Q\times f$) of 94,300 GHz, and a temperature coefficient at the resonant frequency ($\tau_r$) of $-87$ ppm/°C. The development process and test results for a dielectric resonator antenna temperature sensor that uses La(Mg$_{0.49}$Ca$_{0.01}$Sn$_{0.5}$)O$_3$ ceramics are recorded. The resonant frequency is 9.35 GHz and the 3 dB bandwidth measured at room temperature is 6.4 MHz. A sensitivity of $-1.03$ MHz/°C is achieved.

Key-words : X-ray diffraction, Raman scattering, Dielectric properties, Temperature sensor

1. Introduction

Temperature sensors are used in turbines in many industrial production environments. The turbine’s temperature is monitored by connecting the sensor to the control center via a network. Maintenance time can be predicted using big data analysis, which reduces production cost and increases production efficiency. There are many commercial wired temperature sensors, such as thermocouples and fiber optic sensors. However, cables and connectors are prone to failure at high temperature, which limits their use in harsh environments. Wireless temperature sensors eliminate the requirement for wiring. Wireless temperature sensors take the form of either electronic chip-based wireless sensors or chip-less wireless sensors.$^{[1,2]}$ Electronic chip-based wireless temperature sensors have a drawback in that they operate at a temperature that is lower than the operating temperature of electronic chips. Chip-less wireless temperature sensors are classified as either surface acoustic wave resonators$^{[3]}$ or electromagnetic resonators. The frequency of an electromagnetic resonator is higher than the frequency of a surface acoustic wave resonator. In electromagnetic resonators, the quality factor for a dielectric resonator (DR) is much larger than the quality factor for a micro-strip line resonator. A DR is also smaller and lighter than a waveguide resonator. Therefore, a DR can be used in a harsh environment because it is small, has a high quality factor, and is rugged.

A cylindrical DR antenna (DRA) supports transverse electric (TE), transverse magnetic (TM), and hybrid electromagnetic (HEM) modes. In the HEM mode of DRA, the radiation quality factor increases as the dielectric constant increases. The higher the dielectric constant, the smaller is the DRA temperature sensor. The higher the radiation quality factor, the shorter is the reading range for the DRA temperature sensor. There is a trade off between the size and reading range when a DRA operates in HEM mode. However, in TE and TM modes, the dielectric constant has no significant effect on the radiation quality factor.$^5$ That is for a DR with a high dielectric constant, the radiation characteristics of the DRA temperature sensor are not degraded. In addition, the dielectric quality factor for the TE mode is higher than that for the TM mode, which gives a narrow bandwidth and a long gating window. Therefore, this study uses a TE-mode DRA temperature sensor. A compact DRA temperature sensor is realized that has a long reading range and a high resolution.

For a DRA temperature sensor, the microwave dielectric properties of the DR must have a high dielectric constant, a high temperature coefficient at the resonant frequency, and a high dielectric quality factor.$^5$ The high dielectric
constant and high temperature coefficient at the resonance frequency mean that a small DRA temperature sensor with highly sensitive. The quality factor is representative of antenna loss. Typically, there are several losses: dielectric loss, conduction loss, and radiation loss. The total quality factor is affected by all of these losses. Dielectric and conduction losses result in a reduction in the gain and efficiency of the DRA, but radiation loss results in an increase in the gain and efficiency of the DRA. All of these losses affect the reading range and the resolution for a DRA temperature sensor.

In recent years, Al2O3 ceramics has been identified as one of the most powerful materials for harsh environmental applications. The dielectric constant of Al2O3 ceramic is strongly dependent on temperature and monotonically increases to 1600°C, which is ideal for temperature sensors. Al2O3 ceramics have a dielectric constant of 9.8, a loss factor of 0.0003, and a temperature coefficient at the resonant frequency (τr) of −55 ppm/°C. However, small and light weight DRA temperature sensors are preferred because they must be installed on the device. The size of the DRA temperature sensor decreases as the dielectric constant of the DR increases. In addition, the larger the DRA temperature sensor, the higher the heat capacity, and the longer it takes to react to temperature changes, thus preventing real-time measurements. Therefore, by selecting a dielectric constant in the range of 10 to 50, the size of the DRA temperature sensor can be reduced. In this study, compared to the DRA temperature sensor design, more emphasis was placed on improving the microwave dielectric properties of DR for use in DRA temperature sensors. A complex Perovskite ceramic A(B0.5B’0.5)O3 has excellent dielectric properties at microwave frequency, La(Mg0.5Sn0.5)O3 (LMS) ceramic that is sintered at 1550°C for 4 h has a dielectric constant of 15.6, a Q × f value of 30,600 GHz, and a temperature coefficient of resonant frequency of −83 ppm/°C.11) LMS ceramic has excellent properties for application in temperature sensors compared to Al2O3 ceramic, due to its higher dielectric constant and higher temperature coefficient of resonant frequency. However, the formation of this second phase La2Sn2O7 affects the microwave dielectric properties of LMS ceramics. Therefore, this paper studies improve the microwave characteristics by removing the moisture content using a starting material of 4MgCO3·Mg(OH)2·4H2O. The ionic polarizability and ionic radius of Ca2+ and Sr2+ ions, in order to improve the microwave dielectric properties for application in DRA temperature sensors. The microwave dielectric properties of La(Mg0.5−xMeSn0.5)xO3 (Me = Ca, Sr) ceramics are shown to vary with the degree of substitution. The microwave dielectric properties are determined using densification, X-ray diffraction (XRD), Rietveld refinement patterns, Raman spectra, and by observing the microstructures. On the basis of these results, La(Mg0.5−xMeSn0.5)xO3 (Me = Ca, Sr) ceramics are used to produce materials with better microwave dielectric properties for use in a DRA temperature sensor. The microwave dielectric properties, including the high dielectric constant, the high dielectric quality factor, and the high absolute value of the temperature coefficient at the resonant frequency mean that a small DRA temperature sensor with high resolution and sensitivity can be produced.14-16) In addition, this paper studies a LMS-based DRA temperature sensor, and examines the high-temperature sensing applicability of the sensor. It is believed that the results of this study will provide feasibility for application DRA temperature sensors in ultra-high temperature and harsh environments.

2) Experimental procedure

La2O3 (99.99%), 4MgCO3·Mg(OH)2·4H2O (MgO powders obtained from them is 43.5%), CaCO3 (99.9%), SrCO3 (99.9%), and SnO2 (99.9%) powder were used as the starting chemicals. The prepared composition was La(Mg0.5−xMeSn0.5)xO3 (Me = Ca, Sr). Samples were prepared using a conventional mixed-oxide method. The La2O3 was dried at 1000°C for 4 h to remove moisture content and the raw material was then weighed in a stoichiometric ratio. The raw material was ball-milled in alcohol for 12 h, dried, and then calcined at 1200°C for 4 h. The calcined powder was re-milled for 12 h using Polyvinyl Alcohol solution as a binder. The fine powder was then axially pressed at a pressure of 2000 kg/cm2 to produce pellets with a diameter of 11 mm and a thickness of 6 mm. The samples thus obtained were then sintered in air at a temperature of 1600°C for 4 h. Both the heating rate and the cooling rate were set to 10°C/min. After sintering, the phases of the samples were determined by XRD. The X-ray Rigaku D/MAX-2200 uses Cu Kα radiation (at 30 kV and 20 mA) and a graphite monochromator in the 20 range of 10–110°. The characteristics of the crystal structural of the specimens were determined by Rietveld refinements of the XRD patterns using GSAS software. Raman measurements used a Horiba Jобin Yvon HR 550 Raman spectrometer in the 100–800 cm−1 range. A 488 nm light source was used for the measurements. Scanning electron microscopy (JEOL JSM-6500F) was used to determine the microstructure of the sample. The apparent density of the specimens was measured using the liquid Archimedes method, using distilled water as the liquid, according to
ASTM C373-72. The A&D GF-300 digital scale is used to measure apparent density. The precision of the A&D GF-300 Digital Scale is 0.001 g. The microwave dielectric properties of the samples were measured using a post-resonance method that was developed by Hakki and Coleman. This method uses a cylindrical sample of diameter \( D \) and length \( L \). The postresonator scheme adopted a specimen in the form of a cylinder of diameter \( D \) and length \( L \). The specimen was 7.9 to 8.1 mm in diameter and 3.9 to 4.1 mm in length. The specimen for which the microwave dielectric properties were measured had an aspect ratio \( D/L \) of approximately 2.0, which is within the permitted range that was determined by Kobayashi and Katoh. The cylindrical resonator was sandwiched between two conducting plates. Two small antennas were positioned in the vicinity of the specimen to couple the microwave signal power into or out of the resonator. The other ends of the antennas were connected to an Keysight N5224A microwave network analyzer for the microwave dielectric properties measurements at frequencies between 10 and 12 GHz. The resonance characteristics depended on the size and microwave dielectric properties of the specimen. The microwave energy was coupled using electric-field probes. The TE\(_{011}\) resonant mode was optimal for determining the dielectric constant and the loss factor of the specimen. The technique that was used to measure \( \varepsilon_f \) was the same as that which was used to measure the dielectric constant.

A commercial electromagnetic simulator was used to simulate the DRA temperature sensor, in order to reduce the trial error design cycle. The DR is composed of \( \text{La(Mg}_{0.5-x}\text{Ca}_x\text{Sn}_{0.5})\text{O}_3 \). It has diameter of 7.3 mm and a dielectric constant of 20.1. Changing the effective dielectric constant of the DRA, which is related to the temperature characteristic of the DR, changes the resonance frequency of the DRA temperature sensor. The DRA temperature sensor was placed over a thermostat between 25 and 200°C. A patch array antenna was used as an interrogator antenna. The 10 dB return loss bandwidth for the patch array antenna is 419 MHz (8,624–9,043 MHz). The achieved bandwidth is enough for measurements, covering the required DRA temperature sensor for 8,741–8,968 MHz. Backscattering power is described using frequency or time domains. In the frequency domain, unlike flat thermal noise, the intensity of the returned signal that is reflected from the interrogator antenna and the DRA temperature sensor decreases as the frequency moves away from the resonance frequency. It is difficult to determine the resonant characteristics of a DRA temperature sensor because of the superposition of reflected signals from the interrogator antenna. Therefore, this study measures the resonance frequency using a time domain gating technique.

3. Results and discussion

Figure 1 shows the XRD patterns for \( \text{La(Mg}_{0.5-x}\text{Ca}_x\text{Sn}_{0.5})\text{O}_3 \) and \( \text{La(Mg}_{0.5-x}\text{Sr}_x\text{Sn}_{0.5})\text{O}_3 \) ceramics that are sintered at 1600°C for 4 h in the 2\( \theta \) range 20–80°.

![Fig. 1.](image)
amounts of La$_2$Sn$_2$O$_7$. The diffraction peak (1 1 0) for the La(Mg$_{0.5-x}$Ca$_x$Sn$_{0.5}$)O$_3$ and La(Mg$_{0.5-x}$Sr$_x$Sn$_{0.5}$)O$_3$ ceramics shifts to a lower angle as $x$ is increased, perhaps because Ca$^{2+}$ ions (0.1 nm) and Sr$^{2+}$ ions (0.118 nm) have a larger ionic radius than Mg$^{2+}$ ions (0.072 nm). As $x$ increases from 0 to 0.05, the respective tolerance factor for La(Mg$_{0.5-x}$Ca$_x$Sn$_{0.5}$)O$_3$ and La(Mg$_{0.5-x}$Sr$_x$Sn$_{0.5}$)O$_3$ ceramics decreases from 0.816 to 0.811 and 0.816 to 0.808. The decrease in the tolerance factor results in increased octahedral tilting.

A schematic crystal structure for LMS double perovskite is given in Fig. 2. Figure 3 shows the Rietveld refinement patterns for La(Mg$_{0.5-x}$Ca$_x$Sn$_{0.5}$)O$_3$ and La(Mg$_{0.5-x}$Sr$_x$Sn$_{0.5}$)O$_3$ ceramics that are sintered at 1600°C for 4 h in the 2θ range of 10–110°. Table 1 shows that the $R_{wp}$ and $R_{wp}$ values are less than 7 and a goodness of fit factor is less than 1.5. The observed XRD data is in good agreement with the calculated refinement data. The crystal structural data that is obtained from the Rietveld refinement includes lattice parameter, unit-cell volume, the amount of main phase, and the mount of second phase, as listed in Table 1. Because Ca$^{2+}$ ions (0.1 nm) and Sr$^{2+}$ ions (0.118 nm) have a greater ionic radius than Mg$^{2+}$ ions (0.072 nm), the unit cell volume of La(Mg$_{0.5-x}$Ca$_x$Sn$_{0.5}$)O$_3$ and La(Mg$_{0.5-x}$Sr$_x$Sn$_{0.5}$)O$_3$ ceramics increases as $x$ increases from 0 to 0.05.

This results in a shift in the XRD peak at 31–32°, as shown in Fig. 1. The increase in the unit cell volume results in an increase in lattice parameters $a$, $b$, and $c$. Although $a$ and $b$ increase, lattice parameter $c$ remains relatively stable, possibly because there is distortion of the BO$_6$ octahedron. La(Mg$_{0.5-x}$Me$_x$Sn$_{0.5}$)O$_3$ ceramics with different degrees of Ca$^{2+}$ and Sr$^{2+}$ substitution have a main phase of more than 98%. La(Mg$_{0.5-x}$Me$_x$Sn$_{0.5}$)O$_3$ ceramics that use 4MgCO$_3$·Mg(OH)$_2$·4H$_2$O as the raw material have a higher amount of main phase than is noted in Ref. 21.

The characteristics of the bonding between the cation and the oxygen ion in the oxygen octahedron change with the amount of Ca$^{2+}$ and Sr$^{2+}$ substitution. Table 2 shows that as the degree of substitution of Ca$^{2+}$ and Sr$^{2+}$ is increased, the bond between the cation and the oxygen ions in the oxygen octahedron increases in length. The partial bivalent cation substitution at $B$' or $B$' sites in the LMS complex Perovskite structure lead results in a change in the lengths of the individual bonds between the cations and oxygen ions in the oxygen octahedron. The bond valence is calculated using Eqs. (1) and (2):\(^{23}\)

$$V_i = \sum_j V_{ij}$$

$$V_{ij} = \exp \left( \frac{R_{ij} - d_{ij}}{b} \right)$$

where $R_{ij}$ is the bond valence parameter, as defined in Brese’s report, $d_{ij}$ is the bond length between the cation and the oxygen ion and $b$ is a constant that is equal to 0.37 Å. The $R_{ij}$ of La$^{3+}$, Mg$^{2+}$, Ca$^{2+}$, Sr$^{2+}$, and Sn$^{4+}$ are 2.172, 1.693, 1.967, 2.118, and 1.905, respectively.\(^{24}\)

Table 2 shows that an increase in the value of $x$ has an opposite effect on the bond valence.

Figure 4 shows the Raman spectra for La(Mg$_{0.5-x}$Ca$_x$Sn$_{0.5}$)O$_3$ and La(Mg$_{0.5-x}$Sr$_x$Sn$_{0.5}$)O$_3$ ceramics that are sintered at 1600°C for 4 h. A mode for which the highest wave number is greater than 660 cm$^{-1}$ is attributed to a pattern that is similar to the $A_{1g}(O)$ vibration mode, which corresponds to symmetric stretching of the oxygen octahedron. Because oxygen atoms are displaced along the Mg–O–Sn axis; the frequency is mainly determined by the distance and binding force of Mg–O and Sn–O.\(^{25}\) The three modes in the range of 170–270 cm$^{-1}$ are derived from the $F_{2g}$ vibration of the A site cation. The four modes in the range 300–430 cm$^{-1}$ correspond to the 1:1 ordered phase in the B site. As the symmetry decreases, the splitting of the cubic $F_{2g}$ pattern into doublet and triplet peaks becomes more pronounced.\(^{26}\) Table 3 shows that as the value of $x$ increases, the Raman peak for the $A_{1g}(O)$ vibration mode shifts to a slightly lower frequency. When Mg$^{2+}$ is replaced with Sr$^{2+}$, Raman shift for the $A_{1g}(O)$ mode for La(Mg$_{0.45}$Sr$_{0.05}$Sn$_{0.5}$)O$_3$ decreases by 4.343 cm$^{-1}$. This is associated with the bond length in the oxygen octahedron. The longer the bond length, the smaller is the bond energy, so the Raman peak shifts to the lower frequency. The full width at half maximum (FWHM) for the $A_{1g}(O)$ mode determines the order of the B-position cations.\(^{27}\) As the cation order increases, the $A_{1g}(O)$ peak becomes narrower.\(^{28,30}\)

Figure 5 shows the microstructures of the La(Mg$_{0.5-x}$Me$_x$Sn$_{0.5}$)O$_3$ (Me = Ca, Sr) ceramics that are sintered at 1600°C for 4 h for which there are different degrees of Ca$^{2+}$ and Sr$^{2+}$ substitution. The microstructure of the La(Mg$_{0.5-x}$Ca$_x$Sn$_{0.5}$)O$_3$ ceramics that are sintered at 1600°C for 4 h shows that there is an increase in the average grain size from 1.08 to 1.24 μm as $x$ increases from 0 to 0.05. The morphology of La(Mg$_{0.5-x}$Ca$_x$Sn$_{0.5}$)O$_3$ and La(Mg$_{0.5-x}$Sr$_x$Sn$_{0.5}$)O$_3$ ceramics shows a dense grain and clear grain boundary. These results show that the sample is well crystallized.
Fig. 3. Rietveld refinement patterns for (a) La(Mg0.45Sn0.5)O3, (b) La(Mg0.49Ca0.01Sn0.5)O3, (c) La(Mg0.47Ca0.03Sn0.5)O3, (d) La(Mg0.45Ca0.05Sn0.5)O3, (e) La(Mg0.49Sr0.01Sn0.5)O3, (f) La(Mg0.47Sr0.03Sn0.5)O3 and (g) La(Mg0.45Sr0.05Sn0.5)O3 specimens that are sintered at 1600°C for 4 h.
This result is associated with the FWHM for the Raman peak. A small FWHM is associated with the ordering distribution of the ions, so it indicates a high quality factor. For La(Mg0.49Ca0.01Sn0.5)O3 ceramics, the minimum FWHM for the A1g(O) Raman vibration mode is 25.972 cm⁻¹ in the series of La(Mg0.5−xMe0.5x)O3 ceramics. The FWHM for the A1g Raman mode for La(Mg0.49Ca0.01Sr0.5)O3 ceramics is the smallest and the Q×f value for La(Mg0.49Ca0.01Sr0.5)O3 ceramics is the largest.

The negative τf value for La(Mg0.5−xMe0.5x)O3 (Me = Ca, Sr) ceramics is associated with in-phase and anti-phase tilting of the octahedron.35) For Perovskite ceramics, τf is related to tilting of the oxygen octahedron, which is controlled by the degree of tolerance factor for Perovskite ceramics. The value of τf becomes negative as the degree of the tolerance factor increases.34,35) The decrease in the value of τf as the degree of substitution increases is more significant for La(Mg0.5−xSr0.5)O3 ceramics than for La(Mg0.5−xCa0.5)O3 ceramics. This is associated with the tolerance factor. The decrease in the tolerance factor as x increases is greater for La(Mg0.5−x−Sr0.5)O3 than for La(Mg0.5−x−Ca0.5)O3 ceramics.

La(Mg0.49Ca0.01Sr0.5)O3 ceramic has excellent properties for application in temperature sensors compared to Al2O3 ceramic, due to its higher dielectric constant (about 2.1 times the dielectric constant of Al2O3 ceramic), lower loss factor (about 0.4 times the loss factor of Al2O3 ceramic), and higher temperature coefficient of resonant frequency (about 1.5 times the temperature coefficient of resonant frequency of Al2O3 ceramic). La(Mg0.49Ca0.01Sr0.5)O3 ceramics with a high dielectric constant, low loss factor, and high temperature coefficient of resonant frequency had potential for application in the DRA temperature sensors.

Figure 6 shows the simulation dielectric, the radiation and the loaded quality factors for the DRA temperature sensors.

Table 4 shows the relative density and the microwave dielectric properties for La(Mg0.5−x−Me0.5x)O3 and La(Mg0.5−x−Sr0.5)O3 ceramics that are sintered at 1600°C for 4 h. The relative density of La(Mg0.5−x−Me0.5x)O3 ceramics that are sintered at 1600°C for 4 h and which undergo Ca²⁺ and Sr²⁺ substitution to different degrees exceeds 97%. This shows that the relative density has a negligible effect on the microwave dielectric properties of La(Mg0.5−x−Me0.5x)O3 ceramics. For microwave dielectric properties measurement, the standard deviation of experimental errors is 0.05. These results show that substituting some of the Mg²⁺ ions with Ca²⁺ or Sr²⁺ ions does not result in a significant variation in the dielectric constant. This is because the molar volume, ionic polarization, and a Raman shift for the A1g(O) mode (670 cm⁻¹). The respective polarizations of Mg²⁺, Ca²⁺, and Sr²⁺ ions are 1.32, 3.16, and 4.24 Å³.31,32) A larger ionic polarization produces a larger dielectric constant. Raman active vibration is related to molecular polarization and a change in polarization affects the vibrational spectral energy of each bond. Since the Ca²⁺ and Sr²⁺ ions are more highly polarized than Mg²⁺ ions, Ca₂O and Sr₂O bonds have a lower scattering energy than Mg₂O bonds, so there is a red shift in the A1g(O) vibration mode. The measurement results show that the dielectric constant for La(Mg0.5−x−Ca₀.₅)O₃ and La(Mg0.5−x−Sr₀.₅)O₃ ceramics increases as x increases. Therefore, the Raman shift can be used to predict the change in the dielectric constant for a complex Perovskite structure. However, the dielectric constants of La(Mg0.5−x−Me₀.₅)O₃ (Me = Ca, Sr) ceramics did not increase as x increased. This fact may be explained by the molar volume. A larger molar volume is associated with a smaller dielectric constant.

The highest Qxf value of 91,400 GHz is obtained for La(Mg0.49Ca₀.₀₁Sr₀.₅)O₃ ceramics that are sintered at 1600°C for 4 h. The loss factor is 0.00012 at 11.0 GHz.
Table 2. Bonding characteristics of La(Mg_{0.5-x}Me_xSn_{0.5})O_3 (Me = Ca, Sr) ceramics obtained from the Rietveld refinement

| Compound                    | Substitution (x) | 0.0  | 0.01 | 0.03 | 0.05 |
|-----------------------------|------------------|------|------|------|------|
| La(Mg_{0.5-x}Ca_xSn_{0.5})O_3 | MgO_6-octahedron | 2.076 | 2.082 | 2.088 | 2.093 |
|                             | Mg/Sn-O(1)×2 (Å)  | 2.091 | 2.097 | 2.101 | 2.103 |
|                             | Mg/Sn-O(2)×2 (Å)  | 2.033 | 2.038 | 2.041 | 2.042 |
|                             | Mean (Å)          | 2.067 | 2.072 | 2.077 | 2.080 |
|                             | V_{bf}           | 2.261 | 2.249 | 2.236 | 2.227 |
|                             | SnO_6-octahedron  | 2.090 | 2.092 | 2.091 | 2.098 |
|                             | Sn/Mg-O(1)×2 (Å)  | 1.992 | 1.991 | 1.996 | 1.996 |
|                             | Sn/Mg-O(2)×2 (Å)  | 2.051 | 2.053 | 2.052 | 2.053 |
|                             | Mean (Å)          | 2.044 | 2.045 | 2.046 | 2.049 |
|                             | V_{ns}           | 4.001 | 3.992 | 3.979 | 3.953 |
|                             | LaO_8-polyhedron  | La-O(1)×1 (Å) | 2.880 | 2.876 | 2.872 | 2.869 |
|                             | La-O(1)×1 (Å)     | 2.736 | 2.735 | 2.729 | 2.732 |
|                             | La-O(1)×1 (Å)     | 2.334 | 2.332 | 2.328 | 2.322 |
|                             | La-O(2)×1 (Å)     | 2.855 | 2.845 | 2.842 | 2.841 |
|                             | Mean (Å)          | 2.568 | 2.564 | 2.561 | 2.564 |
|                             | V_{bf}           | 2.633 | 2.627 | 2.623 | 2.621 |
|                             | SnO_6-octahedron  | La-O(3)×1 (Å) | 2.531 | 2.523 | 2.533 | 2.531 |
|                             | Sn/Mg-O(1)×2 (Å)  | 1.992 | 1.997 | 1.998 | 1.994 |
|                             | Sn/Mg-O(2)×2 (Å)  | 2.051 | 2.051 | 2.053 | 2.052 |
|                             | Mean (Å)          | 2.044 | 2.048 | 2.049 | 2.047 |
|                             | V_{ns}           | 4.001 | 3.962 | 3.955 | 3.971 |
|                             | LaO_8-polyhedron  | La-O(1)×1 (Å) | 2.880 | 2.615 | 2.619 | 2.621 |
|                             | La-O(1)×1 (Å)     | 2.736 | 2.790 | 2.792 | 2.788 |
|                             | La-O(1)×1 (Å)     | 2.334 | 2.692 | 2.696 | 2.695 |
|                             | La-O(2)×1 (Å)     | 2.855 | 2.698 | 2.690 | 2.696 |
|                             | Mean (Å)          | 2.568 | 2.357 | 2.354 | 2.355 |
|                             | V_{bf}           | 2.633 | 2.853 | 2.841 | 2.839 |
|                             | SnO_6-octahedron  | La-O(3)×1 (Å) | 2.531 | 2.597 | 2.597 | 2.589 |
|                             | Sn/Mg-O(1)×2 (Å)  | 1.992 | 1.997 | 1.998 | 1.994 |
|                             | Sn/Mg-O(2)×2 (Å)  | 2.051 | 2.051 | 2.053 | 2.052 |
|                             | Mean (Å)          | 2.044 | 2.048 | 2.049 | 2.047 |
|                             | V_{ns}           | 4.001 | 3.962 | 3.955 | 3.971 |

Table 3. Peak position and FWHM for the A_{1g}(O) vibration mode in the Raman scattering spectrum

| Compound                    | Substitution (x) | 0.0  | 0.01 | 0.03 | 0.05 |
|-----------------------------|------------------|------|------|------|------|
| La(Mg_{0.5-x}Ca_xSn_{0.5})O_3 | Raman Shift of A_{1g} mode (cm^{-1}) | 670.561 | 669.197 | 669.037 | 668.062 |
|                             | FWHM of A_{1g} mode (cm^{-1}) | 26.591 | 25.868 | 25.972 | 26.025 |
| La(Mg_{0.5-x}Sr_xSn_{0.5})O_3 | Raman Shift of A_{1g} mode (cm^{-1}) | 670.561 | 668.995 | 667.719 | 666.218 |
|                             | FWHM of A_{1g} mode (cm^{-1}) | 26.591 | 25.972 | 26.382 | 26.974 |

The relationship between loaded quality factor, the dielectric and radiation quality factors is defined as:

\[
\frac{1}{Q_L} = \frac{1}{Q_d} + \frac{1}{Q_r}
\]
Figure 7 shows the simulation radiation efficiency and the peak electric field intensity for the DRA temperature sensor. The radiation efficiency for a DRA temperature sensor is defined as:

$$\eta = \frac{Q_L}{Q_r}$$ (4)

There is no significant variation in radiation efficiencies with height and all of the values exceed 99.5%. The peak electric field intensity for the DRA temperature sensor also varies with height. The highest peak electric field intensity of 0.999 V/m is obtained for a DR thickness of 7.3 mm, which gives high directivity. Therefore, directivity is adjusted by changing the height of the DR. Figures 6 and 7 show that the dielectric quality factor and the radiation efficiency meet the requirements for a DRA temperature sensor, regardless of the height of the DR. A DR with a height of 7.3 mm gives the longest sensing distance.

Figure 8 shows the time domain backscattered signal converted from the measured S_{11} parameter for the DRA temperature sensor in frequency domain. Initially, the backscattered signal due to reflection from the interrogator antenna is significant. The signal intensity from 5 ns to around 150 ns deviates significantly, when the DRA temperature sensor is added or not added. When the DRA temperature sensor is added, it absorbs the incident signal from the interrogator antenna and then radiates it back to the interrogator antenna. The gating start time was 5.0 ns.
The gating stop time was determined as the point at which the signal intensity is the same with and without the DRA temperature sensor. The gating stop time was 150 ns, which gives a gating window of 145 ns.

**Figure 9** shows the measurement return loss for the DRA temperature sensor after time gating. The resonant frequency decreases from 8.97 to 8.74 GHz when the temperature is increased from 25 to 200°C. Clearly, the return loss decreases as the operating temperature is increased, because there is an increase in the dielectric loss for microwave ceramics as temperature increases. At the ambient temperature of 25°C, the 3 dB bandwidth is 10.0 MHz for the DRA temperature sensor, which corresponds to a 3 dB bandwidth of 0.11%. The 3 dB bandwidth is correlated to the loss tangent for the DR. The narrower the bandwidth,
the greater is the resolution of the DRA temperature sensor. The resonant frequency decreases as the operating temperature increases. This is in agreement with the temperature characteristic for a DR that is composed of La(Mg0.49Ca0.01Sn0.5)O3, which shifts up or down with the operating temperature, as expected. The variation between 25 and 200°C is 227 MHz, which corresponds to a sensitivity of −1.29 MHz/°C. This demonstrates that the proposed sensor is practicable. The linearity of the proposed DRA temperature sensor is 4.3%. A DRA temperature sensor that uses La(Mg0.49Ca0.01Sn0.5)O3 has a low loss tangent and is sensitive. These features mean that La(Mg0.49Ca0.01Sn0.5)O3 is eminently suited for the construction of a high temperature DRA temperature sensor.

4. Conclusions

This study determines the effect of the degree of Ca2+ and Sr2+ substitution on the microwave dielectric properties of La(Mg0.5–xMe0.5Sn0.5)O3 (Me = Ca, Sr) ceramics. The microwave dielectric properties of La(Mg0.5–xMe0.5Sn0.5)O3 (Me = Ca, Sr) ceramics are improved by substituting Mg2+ ions with Ca2+ or Sr2+ ions. As the composition of x increases from 0 to 0.05, the unit cell volume increases. The bond between the cation and the oxygen ions in the oxygen octahedron becomes longer as the composition of x increases. In the Raman spectra, the Raman shift for the 1g(O) mode decreases as the composition of x increases. The dielectric constant at 1600°C for 4 h have an apparent density of 6.57 g/cm3, a dielectric constant of 20.1, a Q×f of 94,300 GHz, and a temperature coefficient at the resonant frequency (τf) of −85.1 ppm/°C. The dielectric constant of La(Mg0.5–xMe0.5Sn0.5)O3 (Me = Ca, Sr) ceramics depends on the molar volume, ionic polarization, and the Raman shift for the A1g(O) mode. The quality factor and the value of τf for La(Mg0.5–xMe0.5Sn0.5)O3 (Me = Ca, Sr) ceramics are respectively determined by the FWHM for the A1g(O) mode and tolerance factor. This study proposes a practicable design for a DRA temperature sensor. The sensitivity is −1.29 MHz/°C and the linearity is 4.3%. Its robustness, low loss tangent, and high sensitivity mean that a DRA temperature sensor that is composed of high quality factor ceramic is eminently suited to applications in harsh industrial environments.

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