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A hybrid dielectric resonator antenna based upon novel complex perovskite microwave ceramic

Yih-Chien Chen*, Kuang-Chiung Chang, Da-Yeh Tsai

Department of Electrical Engineering, Lunghwa University of Science and Technology, Gueishan Shiang, Taoyuan County, Taiwan

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Abstract

The microwave dielectric properties of $Nd(Mg_{0.5-x}Ca_xSn_{0.5})O_3$ ceramics were examined to evaluate their exploitation in mobile communication. The X-ray diffraction patterns of $Nd(Mg_{0.43}Ca_{0.07}Sn_{0.5})O_3$ ceramics revealed no significant variation of phase with sintering temperatures. $Nd(Mg_{0.43}Ca_{0.07}Sn_{0.5})O_3$ ceramics that were sintered at 1550 °C for 4 h had the following properties: a density of 6.88 g/cm^3, a dielectric constant (ε_r) of 19.51, a quality factor (Qf) of 100,400 GHz, and a temperature coefficient of resonant frequency (τ_f) of −57.8 ppm/°C. The proposed hybrid dielectric resonator covered the industrial, scientific, medical (ISM), high-performance radio local area network (HIPERLAN), and unlicensed national information infrastructure (UNII) bands. A 12.5% bandwidth (return loss <10 dB) of 2.43 GHz, and a 14.2% bandwidth (return loss <10 dB) of 5.62 GHz were successfully achieved.

Keywords: $Nd(Mg_{0.43}Ca_{0.07}Sn_{0.5})O_3$; Dielectric constant; Quality factor; Temperature coefficient of resonant frequency; Dielectric resonator antenna

1. Introduction

Materials that are used in microwave devices must have three dielectric characteristics—a high dielectric constant, a high quality factor, and a near-zero temperature coefficient of resonant frequency [1]. These characteristics enable small devices with low loss and high temperature stability to be fabricated. The benefits of using complex perovskite ceramics are reportedly associated with their excellent microwave dielectric properties. Many investigations of $Nd(Mg_{0.5}Sn_{0.5})O_3$ ceramics have focused on their potential application in resonators, filters, and antennas in modern communication systems, including radars and wireless local area networks, which are operated at microwave frequencies. Previous research on $Nd(Mg_{0.5}Sn_{0.5})O_3$ ceramics that were sintered at 1550 °C for 4 h reported a dielectric constant of 19.3 and a Qf of 43,300 GHz [2]. Additionally, 0.25 wt% B_2O_3-doped $Nd(Mg_{0.5}Sn_{0.5})O_3$ ceramics that were sintered at 1500 °C for 4 h had a dielectric constant of about 18.9 and a Qf of 32,300 GHz [3]. A density of 6.88 g/cm^3, a dielectric constant of 19.3 and a Qf of 91,200 GHz were obtained for $Nd_{2.94/3}Sr_{0.03}(Mg_{0.5}Sn_{0.5})O_3$ ceramics that were sintered at 1550 °C for 4 h [4]. A dielectric constant of 19.5 and a quality factor (Qf) of 129,200 GHz were obtained for $Nd(Mg_{0.4}Zn_{0.1}Sn_{0.5})O_3$ ceramics sintered at 1500 °C for 4 h [5]. A dielectric constant of 21.1 and a Qf of 50,000 GHz were obtained for $Nd(Mg_{0.5}Sn_{0.4}Ti_{0.1})O_3$ ceramics that were sintered at 1550 °C for 4 h [6]. The fact that the ionic radius of Ca^{2+} (0.100 nm) is relatively larger than that of Mg^{2+} (0.072 nm) motivates this study of the effect of the substitution of Mg^{2+} by Ca^{2+} to form $Nd(Mg_{0.5-x}Ca_xSn_{0.5})O_3$ [7].

In this investigation, $Nd(Mg_{0.5-x}Ca_xSn_{0.5})O_3$ ceramics were synthesized, and some of the Mg^{2+} ions were substituted by Ca^{2+} ions to improve their microwave dielectric properties. Moreover, the effect of the sintering temperature on the microwave dielectric properties of $Nd(Mg_{0.5-x}Ca_xSn_{0.5})O_3$ ceramics was investigated. $Nd(Mg_{0.5-x}Ca_xSn_{0.5})O_3$ ceramics were synthesized using the conventional mixed-oxide method and demonstrated better microwave dielectric properties than $Nd(Mg_{0.5}Sn_{0.5})O_3$ ceramics. The microwave dielectric properties of $Nd(Mg_{0.5-x}Ca_xSn_{0.5})O_3$ ceramics were found to vary with the extent of Ca^{2+} substitution and sintering temperature. To further understand these different microwave dielectric properties, the ceramics were further analyzed by densification. In addition, the X-ray diffraction (XRD) patterns and microstructures of the ceramics were analyzed.

*Corresponding author. Tel.: +886 2 8209 3211; fax: +886 2 8209 9728.
E-mail addresses: EE049@mail.lhu.edu.tw, ycchenncku@yahoo.com.tw (Y.-C. Chen).

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Many commercial applications, including mobile radio and wireless communications, use microstrip antennas. However, these microstrip antennas have a limited range of sizes, bandwidth, and efficiency. On the other hand, dielectric resonator (DR) antenna is attractive due to its small-size, high radiation efficiency, and ease of excitation [8]. Many investigations of DR antenna composed of DR with relatively small dielectric constant around 10 have been examined to enhance radiation capability [9–11]. The use of dual band antennas in wireless local area network (WLAN) has been increasing rapidly in the last decade. Dual band antennas were applied in industrial, scientific, medical (ISM, 2.4–2.484 GHz) in low band of WLAN. At the same time, dual band antennas were also applied in high band of WLAN, including high-performance radio local area network (HIPERLAN, 5.15–5.35 GHz), and unlicensed national information infrastructure (UNII, 5.725–5.825 GHz). Dual band DR antennas were implemented by placing a parasitic element near the radiation part, or stacking many DRs. In this paper, the hybrid DR antenna, consisting of a cylindrical high dielectric constant DR and a rectangular slot, operated in the ISM, HIPERLAN, and UNII bands simultaneously. However, the volume of the hybrid DR antenna did not increase. The radiating resonators in the hybrid DR antenna were assembled tightly and resonated at two frequencies. The characteristics of the hybrid DR antenna, such as return loss, radiation pattern, and gain were measured and discussed.

2. Experimental procedure

The starting raw chemicals were highly pure Nd_2O_3 (99.99%), MgO (98.0%), $CaCO_3$ (99.0%), and SnO_2 (99.0%) powders. The prepared composition was $Nd(Mg_{0.5-x}Ca_xSn_{0.5})O_3$ (x=0.05, 0.07, and 0.1). Specimens were prepared using the conventional mixed-oxide method. The starting materials were weighed and used in appropriate molar ratios. 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 PVA solution as a binder. The fine powder was then crushed into a finer powder using a sieve with a 200 mesh. The very fine powder thus obtained was then axially pressed at 2000 kg/cm^2 into pellets with a diameter of 11 mm and a thickness of 6 mm. These specimens were then sintered at temperatures of 1450–1600 °C for 4 h in air. Both the heating rate and the cooling rate were set to 10 °C/min.

After sintering, the phases of the samples were investigated by X-ray diffraction. An X-ray Rigaku D/MAX-2200 was used with Cu$K\alpha$ radiation (at 30 kV and 20 mA) and a graphite monochromator in the 2θ range of 10–80°. Scanning electron microscopy (SEM; JEOL JSM-6500F) and energy dispersive X-ray spectrometry (EDS) were utilized to examine the microstructures of the specimens. The apparent densities of the specimens were measured by Archimedes' method in distilled water. The microwave dielectric properties of the specimens were measured by the postresonator method developed by Hakki and Coleman [12]. The value of τ_f was measured by the same method as the dielectric constant. The test cavity was placed in a chamber and the temperature was increased from 25 to 75 °C. The τ_f value (ppm/°C) was determined from the change in resonant frequency,

$$\tau_f = \frac{f_2 - f_1}{f_1(T_2 - T_1)}, \tag{1}$$

where f_1 and f_2 are the resonant frequencies at T_1 and T_2, respectively.

The resonant frequency of the cylindrical DR antenna is

$$f_{110}^{TM} = \frac{c}{2\pi r\sqrt{\varepsilon_{ra}}}\sqrt{X_{11}^{'2} + \left(\frac{\pi r}{2t}\right)^2} \tag{2}$$

where $X'_{11} = 1.841$ is the first zero of the equation $J'_1(x) = 0$, and c is the speed of light in vacuum. The parameters r, t, and ε_{ra} are the radius, height, and dielectric constant of the DR, respectively. Fig. 1 shows the configuration of the proposed hybrid DR antenna, consisting of a rectangular slot and a cylindrical high dielectric constant DR. The rectangular FR4 substrate had dimensions of 50.0×50.0 mm^2 and a thickness of 1.6 mm. The cylindrical DR was fed with a microstrip line. The microstrip feed line was placed below the centerline (y-axis in the figure) of the dielectric resonator. Dimensions of the microstrip feed line on FR4 substrate was calculated by close-form formulas, assuming infinite ground plane and finite dielectric thickness. The microstrip feeding line had length L_f of 27.0 mm and width W_f of 6.0 mm. The DR had a dielectric constant $\varepsilon_{ra} = 19.51$, radius $r = 2.5$ mm, and height $t = 5.0$ mm. The DR was a low loss ceramic composed of $Nd(Mg_{0.43}Ca_{0.07}Sn_{0.5})O_3$ that was sintered at 1550 °C for 4 h. The rectangular slot on the front side of the FR4 substrate fed with microstrip line, resonated at approximately half guided wavelength, λgs, where λgs was the guided wavelength of the slot. The length of rectangular slot was 33 mm.

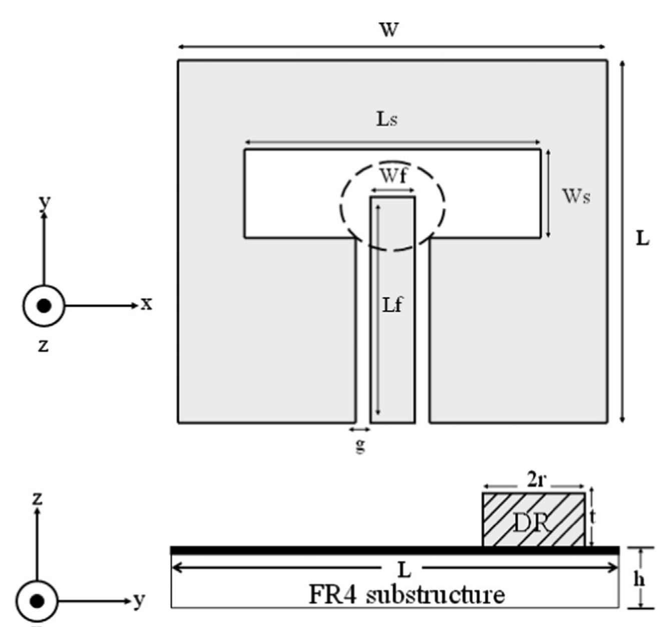

Fig. 1. Configuration of the proposed hybrid DR antenna consisted of a cylindrical high dielectric constant DR and a rectangular slot.