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Thermal tuning study of a microstrip slit-tetragonal resonator with $BaTiO_3$ material filling its gap

Won Woo Cho[a], H. Ohsato[a], G. Zouganelis[b,*]

[a] Department of Materials Science and Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan
[b] Japan Fine Ceramics Center, 2-4-1 Mutsuno, Nagoya 456-8587, Japan

Abstract

Computer Aided Design (CAD) of a microstrip slit-tetragonal resonator with a gap located in the middle of one of its edges has been made, using Finite Difference Time Domain (FDTD). A piece of sintered ferroelectric $BaTiO_3$ with tetragonal crystal structure was placed on the gap of this resonator and was thermally excited using a halogen lamp. Significant change of S-parameters of the device was found in the vicinity of the Curie temperature (T_c) of $BaTiO_3$ for the fundamental resonant mode ($n = 1$), as it is expected from simulations. Electric near field calculations verified the previous behavior.

Keywords: Thermal tuning; Sensors

1. Introduction

Microstrip line ring resonators have been used for many decades for measurement applications, filters, oscillators, mixers, couplers, power dividers/combiners, antennas, frequency selective surfaces, metamaterials, electronic switching [using Positive Intrinsic Negative (PIN) diode] and electronic tuning (using varactor diode).[1]

In this study, we search the behavior of a microstrip tetragonal resonator, when a slit perturbation (gap) created in the middle of one of its edges is filled by a tetragonal piece of $BaTiO_3$ (from now on called BT). Our purpose is to study the tuning of device resonances under local thermal excitation of BT using a halogen lamp and an appropriate focusing lens system.

BT is a well-studied ferroelectric material with known temperature behavior of its complex dielectric constant,[2] which was used in our simulations. One of the useful characteristics of ferroelectric materials is that their real and imaginary dielectric constants show a maxima in the vicinity of their Curie temperature (T_c). Such a change, if it is big enough, can permit the use of slit-resonator/ferroelectric material device in a thermal switch circuit to protect RF circuit power lines from thermal disturbances over the Curie temperature of the ferroelectric material. Except for this possible use, double tetragonal slit-resonators are devices, which are basic construction units of metamaterials structures, which show Negative Refractive Index (NRI) at specific frequency areas.[3] Further understanding of their tuning properties can give new application ideas on the tuning of NRI metamaterials[4] or tuning of reflectarrays used ring resonators.[5]

2. Device structure and experimental

The slit-resonator was fabricated on a Poly Tetra Fluoro Ethylene (PTFE) substrate double-coated with Cu with thickness = 0.867 mm and dielectric constant $\varepsilon_r = 2.2$, by using a rapid Print Circuit Board (PCB) plotter (Protomat C60, LPKF Lasers and Electronics). The thickness of Cu was 0.018 mm. The tetragonal sample of BT had size (width) 3 mm × (length) 4 mm × (height) 1 mm, density = 5.4 g/cm^3, $T_c = 130\,^\circ\mathrm{C}$ and it exhibits a dielectric constant of 5000 at T_c and 550 at 30 °C, respectively.[2] BT was located in the middle of the gap of the slit-resonator firmly attached on it by special glue (Fig. 1). The temperature change of the dielectric constant of BT was tuned with the help of (a) an halogen lamp, made by Shimadzu company, Model AL-100HG, in the voltage area, 4–12 V and (b) a lens focusing system of its irradiation on the top surface of BT. Experimental S-parameters were measured in an Agilent HP 8722D Network Analyzer in the frequency area 2–12 GHz, with a specially made attachment.

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* Corresponding author.
E-mail address: zouganelis.g@nitech.ac.jp (G. Zouganelis).

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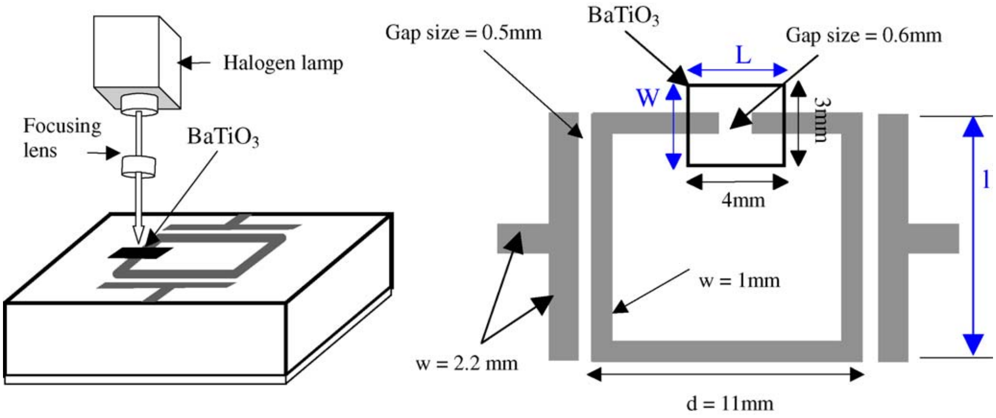

Fig. 1. Configuration of split resonator/$BaTiO_3$ device under thermal tuning.

3. Theoretical background

The resonance frequency of a two-port microstrip tetragonal resonator is given approximately by the relation:

$$f_0 = n\frac{c}{l_r\sqrt{\varepsilon_{\text{eff}}}} \quad (n = 1, 2\ldots) \tag{1}$$

where, c is the velocity of light in free-space, l_r is the length of the resonator, and ε_{eff} is the effective dielectric constant. The existence of a gap in the one of its edges permits parameter n to take also half integer values.[6] Positioning of feed lines closer to the maxima of electric near field in the resonator gives stronger resonant modes.[7] For this reason, we used extended periphery coupling of length l, 11 mm (see Fig. 1) to order to have better coupling with more modes of the resonator (Fig. 1). Substitution

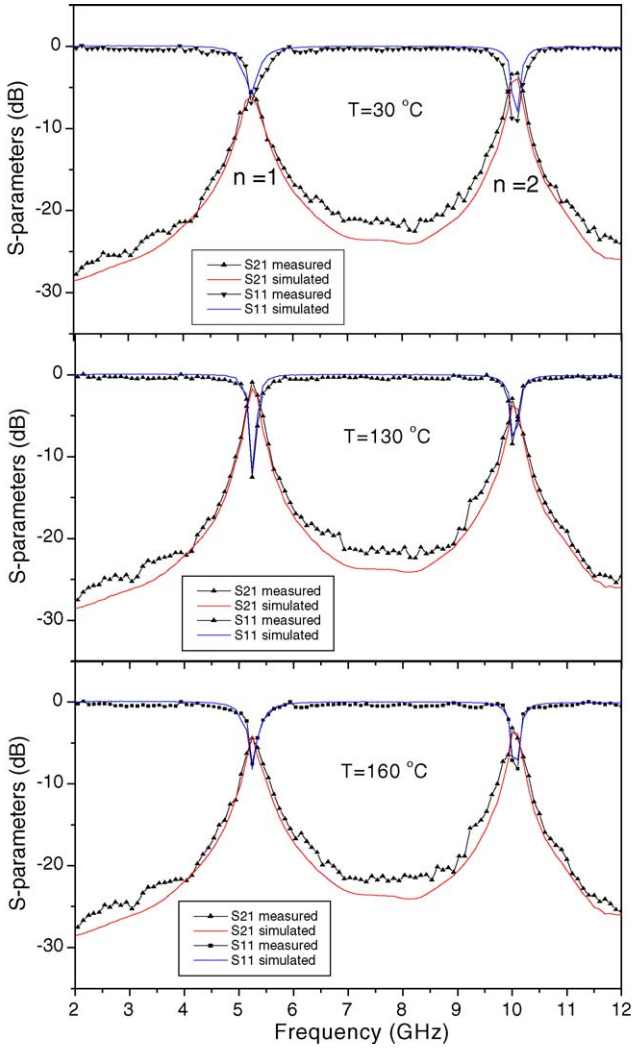

Fig. 2. Simulated and measured S-parameters at 30 (T), 130 (T_c) and 160 °C.

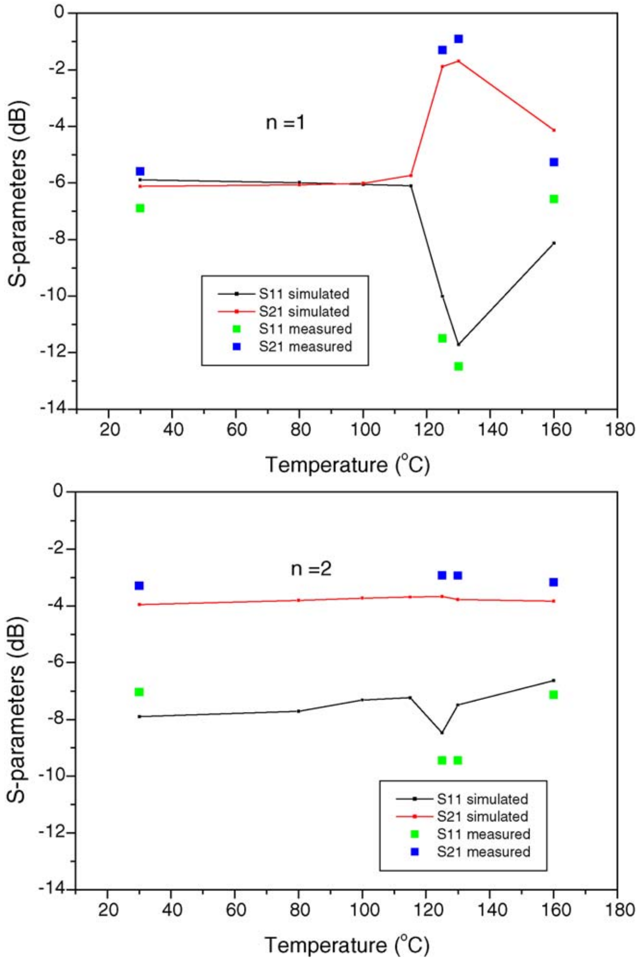

Fig. 3. Variation of S-parameters with temperature for $n = 1$ and $n = 2$.

of gap with BT should change the intensities of resonant peaks (it changes the gap impedance of the resonator) and it should depend on temperature. Electromagnetic simulations have been done using the FDTD method.

4. Simulated and measured results

Fig. 2 shows the simulated and measured S-parameters of the device, which has an electrode size 11 mm, at three temperatures (lower than T_c, at T_c and higher than T_c of BT). In the frequency area 2–12 GHz, two resonant frequencies at 5.36 GHz ($n = 1$) and 10.03 GHz ($n = 2$) are observed, according to relation (1). These values are very close to the resonant frequencies of the resonator, without existence of gap, which are at 5.16 GHz ($n = 1$) and 11.15 GHz ($n = 2$), as can be calculated by FDTD method. In Fig. 2, we observe a large change of the intensity of the resonant mode with $n = 1$ relative to the one with $n = 2$ at the Curie temperature of BT ($T_c = 130\,^\circ C$). This change of S-parameters for each of the two previous modes with temperature is shown in Fig. 3, together with FDTD simulation and measurements at some other temperatures. We observe a maximum of S_{21}-parameter, which is the minimum of S_{11}-parameter, for the fundamental mode at the vicinity of T_c, which corresponds to a change of ∼55% compared to the value at 30 °C. This behavior corresponds to the variation of dielectric constants of BT as measured before.[2] According to the results of Fig. 3, the mode with $n = 1$ can be tuned more compared with the mode with $n = 2$.

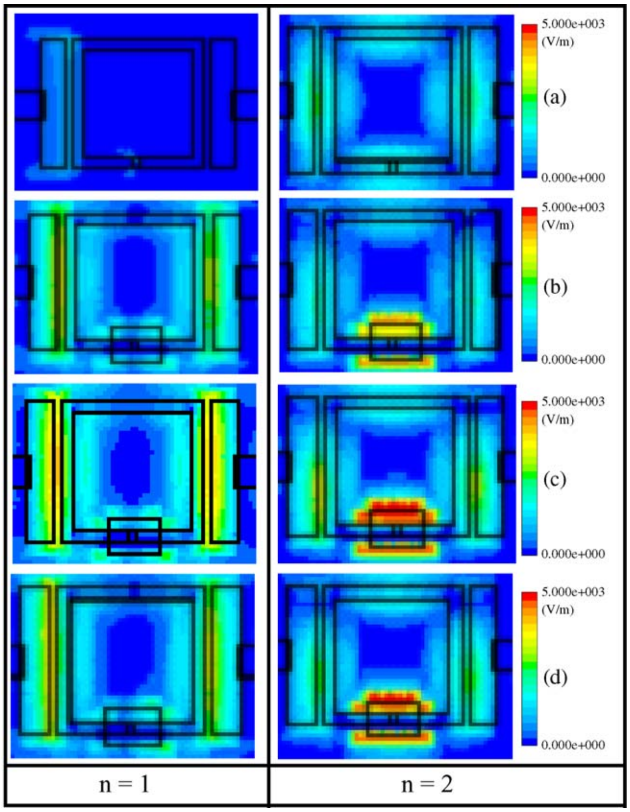

Fig. 4. Near electric field calculations at different temperatures, with: (a) empty gap; (b) gap filled with $BaTiO_3$ at $T = 30\,^\circ C$; (c) gap filled with $BaTiO_3$ at $T = 130\,^\circ C$; and (d) gap filled with $BaTiO_3$ at $T = 160\,^\circ C$.

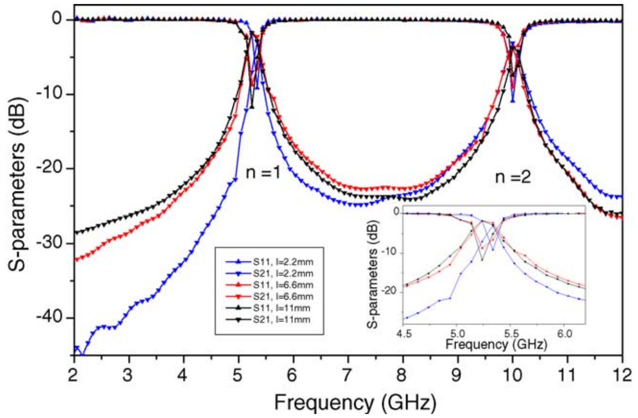

Fig. 5. Size effect of coupling length l to S-parameters at $T = T_c$.

In Fig. 4 shows near electric field calculations in resonator before (a) and after filling its gap with BT (b–d) at three different temperatures (in correspondence with Fig. 2) for $n = 1$ and $n = 2$. In the case of (a), we do not observe any transmission for the mode with $n = 1$, as there are contradictory boundary conditions for the odd modes because of position of feed lines and slit position ($\varphi = \pi/2$).[7] This case is not the same for the even modes ($n = 2$), which are not suppressed. According to Fig. 4 (b–d, right and left side) for the case $n = 2$ no significant change of near electric field is observed, in contrary to the cases with $n = 1$, which shows better coupling. This is in excellent agreement with the increase of the S-parameters below T_c and its decrease above T_c for $n = 1$ according to Fig. 3.

Finally, we try to understand the change of S-parameters at T_c, when the resonator parameters are varied, namely the coupling length l and width W of BT (Fig. 6). In Fig. 5, we observe that a larger coupling length l results in slightly stronger resonances. This behavior is obvious for the fundamental mode ($n = 1$), where the maximum of its near field is located in the middle of the coupling periphery and occupies more coupling space than the second mode (see, also in Fig. 4 the position of maxima for $n = 1$ and $n = 2$, at $T = T_c$). In Fig. 6 shows the change of resonant frequencies with the width W of BT at T_c according to Fig. 1 (thickness equals to 1 mm in all cases). We observe a significant shift of the resonance with the width W of BT for

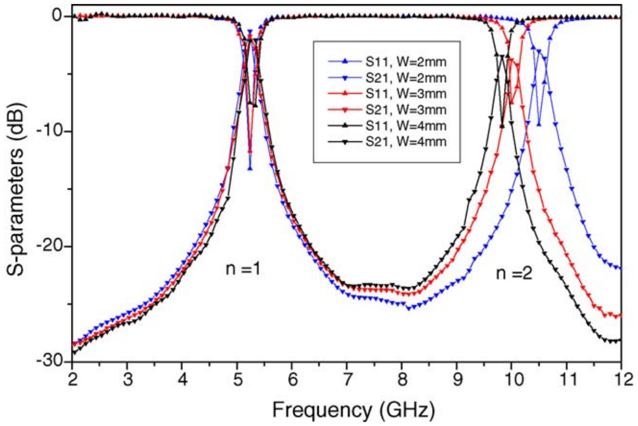

Fig. 6. Size effect of width W of $BaTiO_3$ to S-parameters at $T = T_c$.

$n=2$. This is probably due to an increase in capacitance of the gap, because of its increased area. This increase of capacitance is equivalent to a decrease of effective gap length, which corresponds to an increase of the effective length of the resonator and consequently to a decrease of its resonant frequencies according to formula (1). This shift is more evident to the mode with $n=2$ as the near field maxima are located on the gap against the maxima of mode with $n=1$ (see also Fig. 4).

5. Conclusion

Tuning of resonant characteristics of microstrip gap resonator using ferroelectric material (i.e. BT) has been investigated. A change of ∼50% on S_{21}-parameter makes this device a candidate RF sensor, which can be used inside a thermal switch circuit (at specific frequency). The mechanism presented can be used also for the tuning of metamaterials structures as slit-ring resonators are constituents of NRI metamaterials.

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