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Tunable microwave devices using low-sintering-temperature screen-printed barium strontium titanate (BST) thick films

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Abstract

A tunable microwave phase shifter composed of a low-sintering-temperature, screen-printable barium strontium titanate (BST) film and silver metallization was fabricated on an alumina substrate and co-fired at 900 °C for 3 h. The dielectric properties of the films were characterized in a frequency range of 0.8–8 GHz using scattering parameter measurements and a quasi-static coplanar waveguide transmission line model. The temperature dependency of the films was measured through capacitance measurements in a frequency range of 0.5–2.5 GHz. The figure of merit (phase shift/dB of insertion loss) of the phase shifter was found to be 14.6 at 3 GHz with an applied bias field strength of 2.5 V/μm. The performance of the phase shifter is briefly discussed and compared with other phase shifters fabricated by direct screen-printing of BST films.

Keywords: Ferroelectric properties; Functional applications; Delay line phase shifter

1. Introduction

Progress in modern wireless communication has led to intense research of electronically tunable microwave devices.[1–6] Ferroelectric materials are one of the candidates that are considered for use in these applications. These materials feature a change in dielectric permittivity as a function of an applied electric field, and this property can be utilized in tunable electronic devices.

Barium strontium titanate (BST) is one of the most studied ferroelectric materials for applications at microwave frequencies. Research of BST materials as a functional part of tunable microwave devices has been mainly focused on BST thin films.[7] Using screen-printed thick films, instead of thin films, would enable low-cost application of tunable microwave material and offer potential for integration into other systems on ceramic substrates. The use of BST thick films in tunable microwave devices such as phase shifters has been demonstrated by several authors.[8–11] However, the high-sintering-temperature (>1250 °C) of the materials used in these experiments leads to reactions between the BST film and alumina[12] and does not allow the use of co-fired silver as an electrode material. The high-sintering-temperature also necessitates either extra processing steps or the use of expensive and high-resistivity refractory metals such as platinum or palladium. Valant and Suvorov[13] have proposed a method for reducing the sintering temperature of BST to 900 °C. We recently employed the proposed method to develop a low-sintering-temperature screen-printable BST thick film paste compatible with silver electrodes.[14]

This paper presents phase shifters that utilize BST thick films. The dielectric properties of the low-sintering-temperature BST thick films were characterized in the frequency range of 0.8–8 GHz based on scattering parameter measurements of coplanar waveguide (CPW) transmission line structures. Furthermore, the temperature dependency of relative permittivity and losses of the BST films were also measured from varactor samples in the frequency range of 0.5–2.5 GHz. The acquired data was used to design a delay line-type phase shifter. The electrical properties of the phase shifter are presented, discussed and compared with the properties of thick film BST phase shifters presented in the open literature.

2. Experimental procedure

The preparation and low-frequency dielectric properties of low-sintering-temperature BST paste have been reported in our earlier work.[14] The paste used in this work was prepared in a similar manner. A commercial $0.99Ba_{0.55}Sr_{0.45}TiO_3 + 0.01TiO_2$ (BST–TIO) powder (Praxair Specialty Ceramics, Woodinville,

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WA, USA) and Li_2CO_3 (Alfa Aesar GmbH & Co., Karlsruhe, Germany) as a sintering aid were used to fabricate the ceramic powder for the paste. A final doping level of 0.8 wt.% Li_2O was achieved by adding a corresponding molar fraction of Li_2CO_3 and pre-reacting the powders at 500 °C for 10 h. The thick film pastes were prepared by adding 80 wt.% of BST powders, 16 wt.% of an organic medium (CV-6, Electro Science Labs, Pennsylvania, USA) and 4 wt.% of a dispersant (809, Electro Science Labs, Pennsylvania, USA), and mixing them in a triple roll mill for 30 min.

To characterize the dielectric properties of the BST material, films with a thickness of 25 μm were printed on 0.635 mm thick alumina substrates and sintered at 900 °C for 3 h. Coplanar waveguide (CPW) transmission lines were fabricated on the sintered films by using standard photolithography and thin film processes. First, a vacuum evaporation technique was used to deposit a 250 nm Cu seed layer on the BST thick films, followed by a 5 μm thick spin-coated layer of AZ4562 photo resist. UV light and a mask with a desired pattern were used to expose and develop the resist. Finally, an electrolytic process was used to deposit a 3 μm Cu layer to form the final circuitry, and the remaining seed Cu layer was removed by etching. The varactor and phase shifter components were prepared by sequentially screen-printing BST paste and silver conductor paste (DuPont 6160) on alumina substrates. The structures were fired at 900 °C for 3 h.

The *S* parameters of the structures were measured with a vector network analyzer (HP8719C, Hewlet Packard Co., Alabama, USA) using microwave probes (Cascade Microtech Inc., Oregon, USA). An external voltage source (HP6675A, Agilent Technologies Inc., California, USA) and bias-T components (SHF BT 45 A, SHF Communication Technologies AG, Berlin-Marienfelde, Germany) were used to supply a DC bias voltage along with a RF signal. A SMA connector (292-07A-5, Southwest Microwave Inc., Arizona, USA) was mounted to the varactor component used in the temperature dependency measurements. The capacitor component was measured inside a temperature chamber (SU-261, ESPEC Corp., Osaka, Japan). Surface roughness of the CPW copper metallization was measured with a surface profilometer (DekTak 8, Veeco Instruments Inc., California, USA).

3. Component design and structure

A schematic diagram of the CPW transmission line structure used in the BST film characterization is shown in Fig. 1. The length of the CPW transmission line is 2 mm, its thickness is 3 μm, and the center conductor width is 100 μm. The gap width between the center conductor and the ground conductors is 40 μm. This gap width and the maximum output voltage of the external power source (200 V) used in the measurements limits the characterization of the films to bias fields to 5 V/μm.

The structure of the varactor component used in the temperature dependency measurements is presented in Fig. 2. The BST film is placed between the center conductor and ground of a 50 Ω CPW transmission line. A SMA connector was attached to the CPW line to enable measurement inside a temperature chamber without using microwave probes.

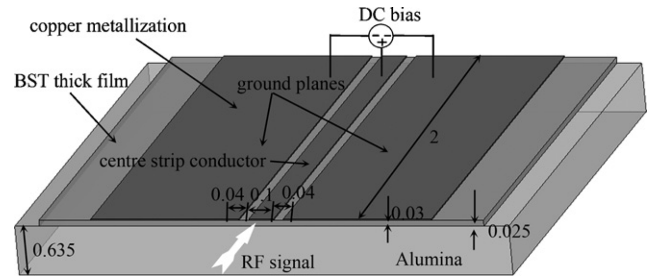

Fig. 1. Schematic diagram of the copper CPW transmission line patterned on the BST film/alumina substrate (dimensions are in mm).

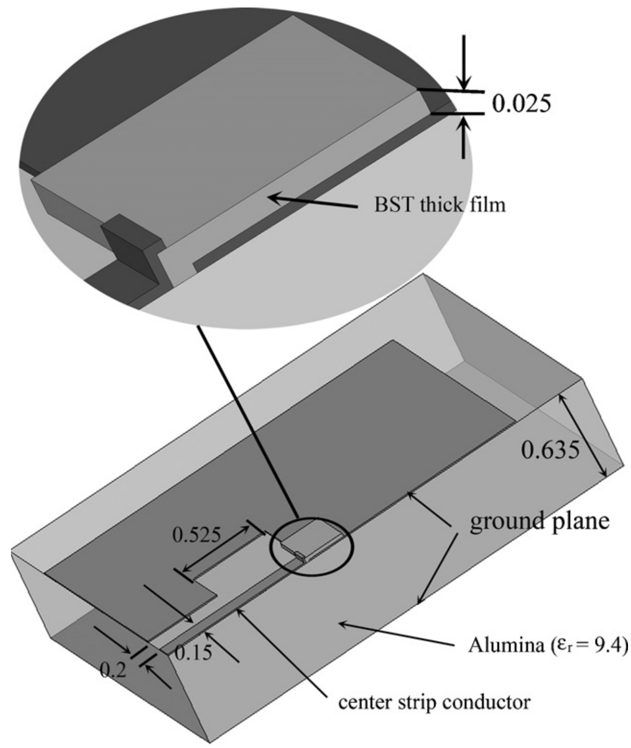

Fig. 2. Cross-sectional view of the varactor (dimensions are in mm).

The designed CPW delay line phase shifter is presented in Fig. 3. The BST thick film is sandwiched between the center strip conductor and the ground planes of the phase shifter. The

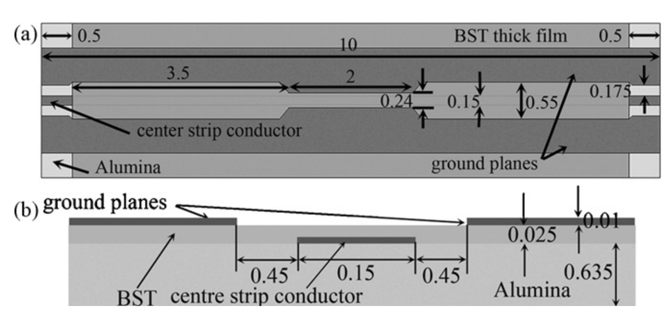

Fig. 3. Schematic layout of the CPW phase shifter with the integrated BST thick film: (a) top view and (b) cross-sectional view of the phase shifter line section (dimensions are in mm).

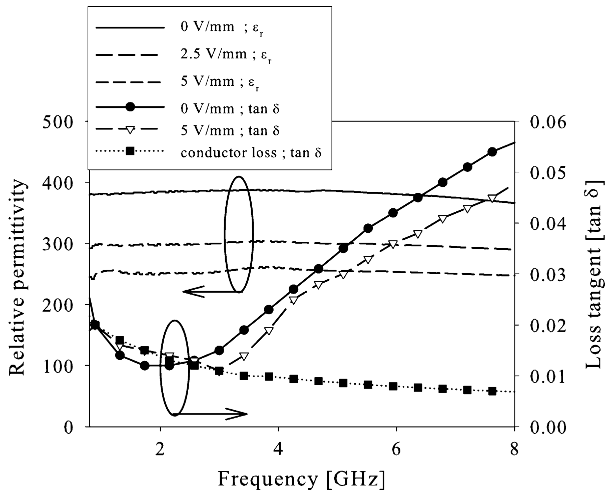

Fig. 4. Measured relative permittivity and extracted dielectric loss tangent of the low-sintering-temperature BST thick film.

change ineffective permittivity results in a change in the propagation constant of the CPW, thus producing a phase shift. A λ/4 matching line section 3.5 mm in length designed for 3 GHz was interposed between the phase shifter line and the 50 Ω line section on alumina, as shown in Fig. 3. The λ/4 matching line section reduces signal reflection of a microwave signal traveling though the conductor line by matching the impedance of the 50 Ω line sections to that of the low-impedance phase shifter line. A buried centre strip conductor CPW configuration is used in the phase shifter and λ/4 line sections. This approach has two advantages. Firstly, it enables a smaller spacing between the centre strip conductor and ground planes, which is otherwise difficult to realize in conventional screen-printing technology. Secondly, the buried centre strip conductor CPW configuration has advantages over conventional CPW lines, especially when designing low-impedance line sections.[15]

4. Results and discussions

The relative permittivity of the BST film was extracted from the measured *S* parameters by means of a conformal mapping method (CMM).[16] The conductor loss was calculated theoretically using the known resistivity of the copper metallization and the measured rms surface roughness.[17] The loss tangent of the BST thick film was determined from the known conductor losses, measured line loss and known permittivity of the BST thick film.[18] Fig. 4 shows the extracted relative permittivity and dielectric loss tangent of the BST thick film with different bias electric field strengths. Relative permittivity decreases from 385 to 254 with an increase in the bias electric field strength from 0 to 5 V/μm. Tunability n ($n = (\varepsilon_r(E_0) - \varepsilon_r(E_{MAX}))/\varepsilon_r(E_0)$) of 34% is thus observed. The dielectric loss tangents show a monotonic increase within the frequency range of 3–8 GHz, being 0.015 and 0.01 at 3 GHz, corresponding to electric field strengths of 0 and 5 V/μm. The losses increase at low frequencies (<3 GHz) due to the predominance of conductor losses arising from a thinner conductor (~3 μm, $\delta_{cu} \approx 1.2$ μm at 3 GHz), and the loss value due to the conductor alone can also be seen in Fig. 3. Similar trends in loss tangent values have been reported previously.[19]

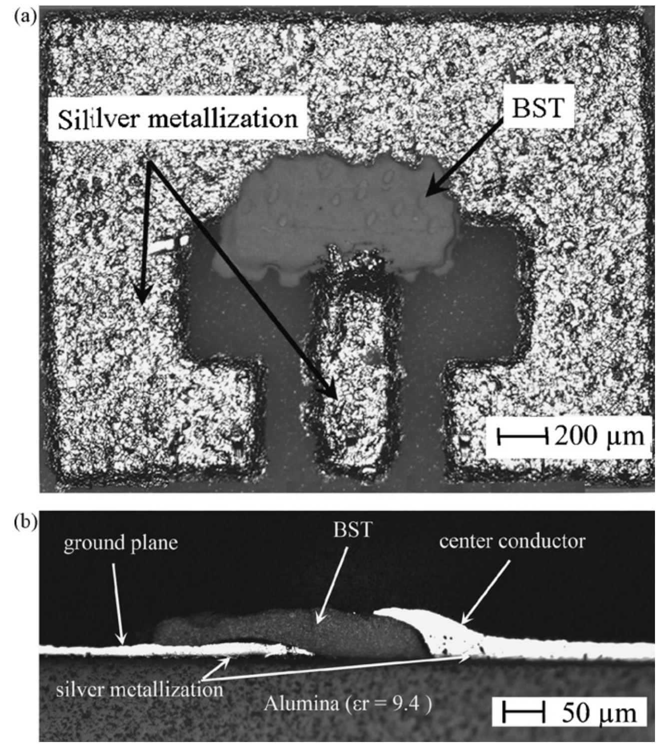

Fig. 5. Photo of (a) the fabricated BST varactor and (b) cross-sectional view of the BST varactor (SMA connector not shown in the figure).

The fabricated BST varactor and its cross-section are presented in Fig. 5(a) and (b), respectively. Temperature dependency of the capacitance and *Q* factor of the BST varactor at 1.5 GHz is plotted in Fig. 6(a). Maximum capacitance and a minimum *Q* factor can be seen at temperatures around −18 °C. These characteristics are attributed to the phase transition of BST from a high-temperature cubic to a tetragonal phase. In comparison with previous work with lower frequencies,[14] the maximum capacitance, which is directly proportional to relative permittivity, shows a more distinct peak with less diffuse transition characteristics, even with a higher Li_2O doping level of. This difference is probably due to some slow relaxation processes, which are negligible at higher frequencies. The transition region with maximum capacitance and a minimum *Q* factor is still markedly broadened, and therefore it offers the lowest temperature dependency. On the other hand, the dielectric loss of the material increases significantly when moved closer to the transition temperature. At temperatures above the transition temperature, capacitance decreases and the *Q* factor increases nearly linearly, as expected. The nature of the *Q* factor's temperature dependency implies that it can be mainly attributed to the dielectric loss of BST. In Fig. 6(b), the capacitance and *Q* factor of the BST varactor are presented as a function of frequency in the range of 0.5–2.5 GHz. Dependencies are plotted at 6 different temperatures ranging from −50 to 100 °C. The trend shown in Fig. 6(a) at 1.5 GHz continues over the whole frequency range. In the vicinity of the Curie temperature, the temperature dependence of the material is sufficiently low and it increases strongly

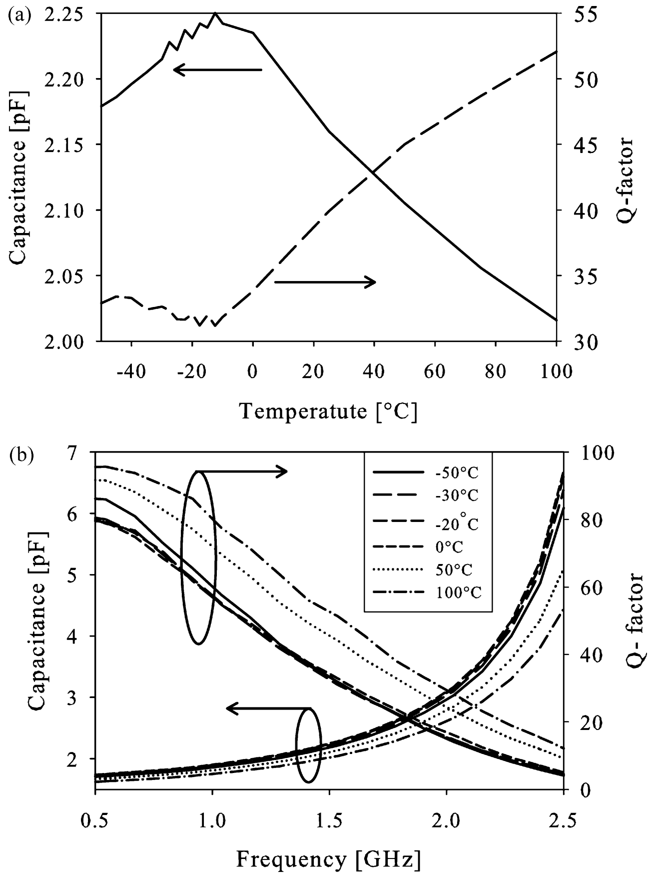

Fig. 6. Capacitance and Q factor of the printed varactor: (a) as a function of temperature at 1.5 GHz frequency and (b) as a function of frequency from −50 to 100 °C.

at higher temperatures. When the frequency increases, there is an absolute increase in capacitance and decrease in the Q factor. However, there is no relative change throughout the frequency range.

Photographs of the fabricated BST phase shifter and its cross-section are shown in Fig. 7(a) and (b), respectively. Fig. 8 shows the measured insertion and isolation loss of the phase shifter with different electric field strengths in the frequency range of 1–5 GHz. Insertion loss is less than 2 dB over the frequency range of 2.75–3.5 GHz in all bias states and return

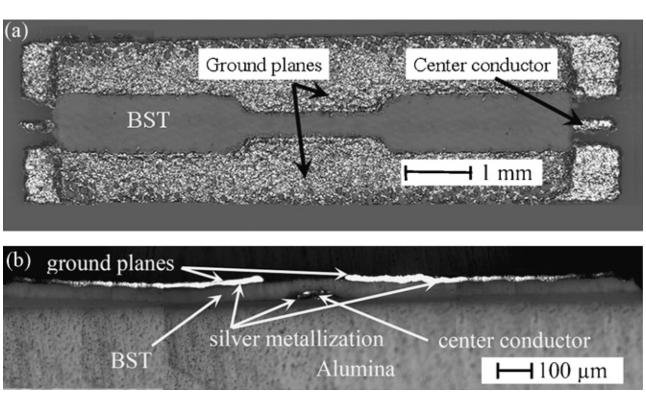

Fig. 7. Photo of (a) the fabricated BST phase shifter and (b) cross-sectional view of the BST phase shifter line section.

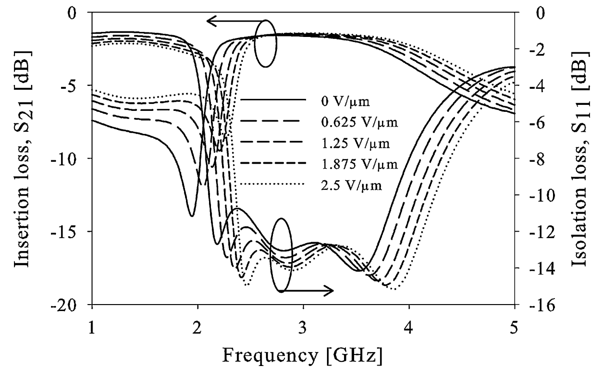

Fig. 8. Insertion and return losses of the phase shifter with different bias DC electric field strengths in the frequency range of 1–5 GHz.

loss higher than 14 dB was measured. Fig. 9 shows the relative phase shift and the Figure of Merit FoM (FoM = phase shift in degrees/insertion loss in dB) of the phase shifter with respect to phase at 0 V/μm as a function of frequency with four different bias field strengths. A relative phase shift of 20° and a FoM of 14.6°/dB was measured at 3 GHz with an applied biasing field of 2.5 V/μm, which increased linearly with frequency, as shown in Fig. 9.

Table 1 contains information on the phase shifters fabricated by direct screen-printing of BST paste. Phase shifter designs using discrete capacitors (reflection, all-pass network) in[9,10] showed a higher FoM value (13.5) compared with transmission line phase shifters (8). However, large size of such phase shifters limits their use in applications requiring miniaturization. The FoM of the proposed phase shifter in this work is comparable with.[9] In addition, the proposed phase shifter is compatible with silver metallization and LTCC technology, unlike that in.[9–11]

The proposed method of fabricating a phase shifter with a buried centre strip conductor decreases the spacing between the center strip conductor and the ground planes, consequently decreasing the required bias DC voltage while still maintaining compliance with standard screen-printing technology. It would be possible to improve the FoM of the phase shifter by decreasing the spacing between the centre strip conductor and the ground

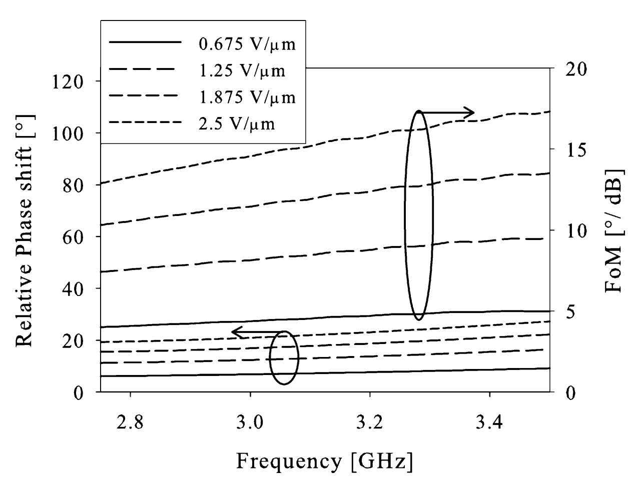

Fig. 9. Relative phase shift and figure of merit (FoM) with different bias DC electric field strengths with respect to phase at 0 V/μm.

Table 1
Information on different phase shifters fabricated by direct screen-printing BST paste.

	Ref. 9		Ref. 10	Ref. 11		Proposed phase shifter
Type of phase shifter	Coplanar strip transmission line (CPS-TL)	Reflection	Reflection	Reflection	All-pass network	Coplanar waveguide transmission line (CPW)
Frequency of operation (GHz)	30	2	2.4	2.5	2.5	3
Bias field strength (V/μm)	1	4	4	4	4	2.5
FoM (°/dB)	8	54	21	58	21	14.6
FoM (°/dB), normalized to 1 V/μm field strength	8	13.5	5.25	14.5	5.25	5.84
Size	Small	Large	Large	Large	Large	Small
Sintering temperature (°C)	1300	1300	1300	1200–1260	1200–1260	900

planes, thereby increasing the biasing field with the same applied biasing voltage, hence increasing relative phase shift and FoM. Furthermore, an improvement in manufacturing accuracy can be achieved by using μ-screen technology.[20]

5. Conclusions

The dielectric properties of low-sintering-temperature ferroelectric thick films in the frequency range of 0.8–8 GHz were characterized and integration into tunable microwave devices was demonstrated. The BST thick film had a relative permittivity of 385 with 0 V/um and 34% tunability under a static electric field of 5 V/μm. The dielectric loss tangent remained below 0.015 in all bias states at 3 GHz. The temperature dependency of the BST films was studied through varactor measurements in the frequency range of 0.5–2.5 GHz. The FoM of the fabricated phase shifter was 14.2°/dB at 3 GHz. The integrated and co-fired BST phase shifter devices based on thick film technology offer key advantages of compatibility with silver metallization and low-cost production. The performance of the proposed phase shifter was found to be comparable with the phase shifters found in the literature, and in addition, compatibility with LTCC technology was maintained.

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