FERROELECTRIC FILMS: NONLINEAR PROPERTIES AND APPLICATIONS IN MICROWAVE DEVICES

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ABSTRACT

Small signal dielectric properties (ε, tanδ) of highly oriented ferroelectric $SrTiO_3$ and $(Ba,Sr)TiO_3$ films at 1MHz, 3GHz, 10GHz, and 20GHz were under investigation. Microstrip resonator with tunable planar ferroelectric capacitor was the object of investigation of the resonator response to elevated single tone microwave (MW) power (up to 100W), to two-tone MW power (intermodulation distortion measurements) and to video pulse voltage. As a result speed of resonator tuning and MW loss variation were measured. 1.9GHz phase-shifter and 20GHz tunable filter operating at T=300K are presented.

INTRODUCTION

Earlier studies of nonlinear dielectric behavior and microwave losses of ferroelectric (FE) $SrTiO_3$ (STO) and $(Ba,Sr)TiO_3$ (BSTO) bulk ceramics and single crystals have demonstrated the potential of these materials for microwave electronics [1]. For modern microwave integrated microelectronics the use of thin FE films is preferable to bulk elements. The nonlinear properties of STO and BSTO films with respect to dc tuning voltage enable a new class of tunable microwave devices such as filters, channel switches and phase shifters to be realized [2, 3]. These devices employing FE films distinguish by their great speed of tuning, low MW losses, low drive power, high radiation resistance and low cost.

The prior publications on the investigation of STO and BSTO films as a rule were devoted to small signal properties of these materials. However, the information about the behavior of these films under elevated microwave power is practically absent. The data about speed of tuning of devices employing STO and BSTO films under controlling voltage video pulses are absent as well. The present work compensates for a deficiency in this direction and makes it possible to estimate the power handling capability and speed of the tuning of devices employing ferroelectric films. The potentialities of STO and BSTO film applications are demonstrated with MW phase-shifters.

EXPERIMENTAL RESULTS

Small signal dielectric properties of STO and BSTO films were extracted from measurements of capacitance and losses of FE planar varactors (insert in fig.1). Measurements were carried out at low frequency (f =1MHz) over the temperature range T=(4.2-300)K and on microwaves (3, 10, and 20GHz) at T=(78-300)K.

Fig. 1 presents the typical low and microwave frequency capacitance versus temperature for STO capacitor at two dc bias voltages (U_b=0V, 100V).

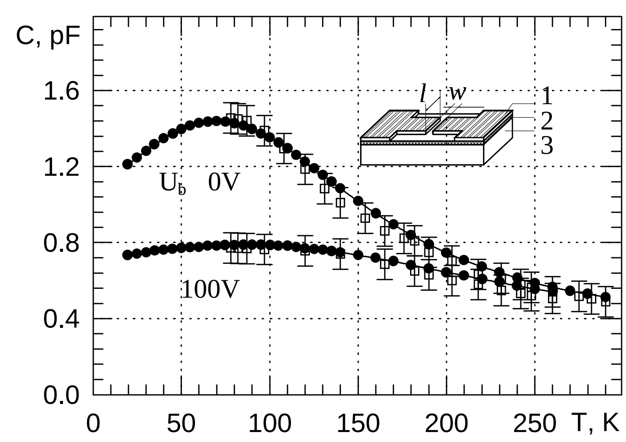

Fig.1. Temperature dependences of capacitance of planar STO capacitor at low and microwave frequencies.
(—●—) - 1 MHz,   - 10 GHz.
Insert - planar STO capacitor (1- electrodes, 2 - FE film, 3 - substrate; *l*=1mm, W=10μm).

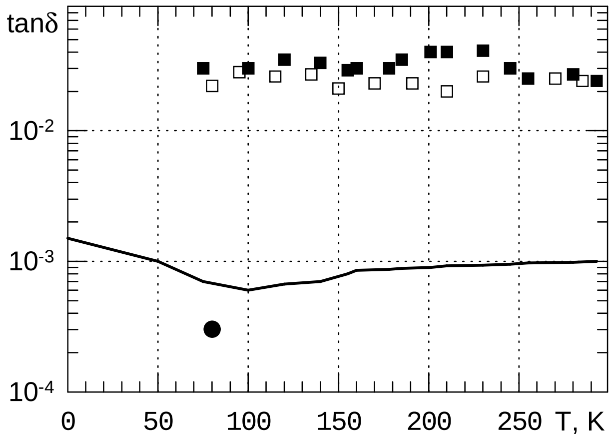

Fig.2. Temperature dependences of microwave losses in STO films (□ - 3 GHz, ■ - 10 GHz) and in STO bulk single crystal (— 10 GHz [1], • - 1GHz [4]).

Within the limits of experimental error, the capacitance value measured at 1MHz, 3GHz and 10GHz are the same, that is why the results corresponding to 3GHz measurement are not presented in fig.1. Microwave losses in ferroelectric films investigated are shown in fig.2 in comparison with the losses in bulk single crystal materials [1, 4].

Figure 3 shows the typical dc bias voltage dependence of capacitance for STO varactor. The dielectric constant tunability K= $\varepsilon(0V)/\varepsilon(U_b)$ is about 2 for U_b=100V. The typical dc bias voltage dependence of microwave dielectric losses in STO films at 77K is shown in fig.3 as well.

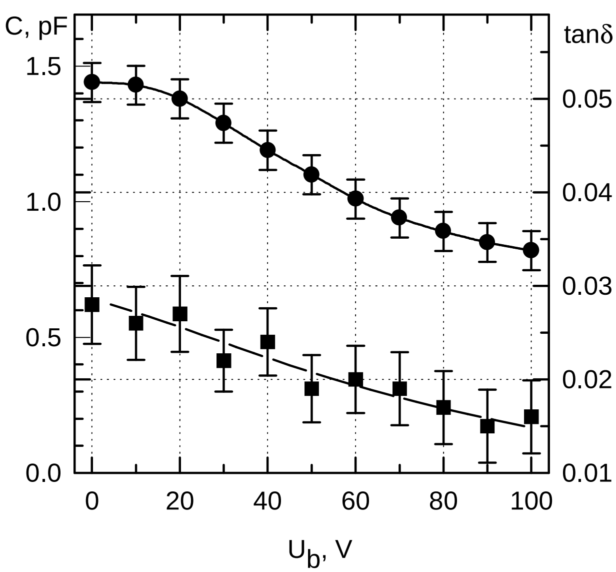

Fig.3. Typical bias voltage dependencies of capacitance (—•—) and dielectric losses (—■—) for STO film capacitor at T=77K and f=10GHz.

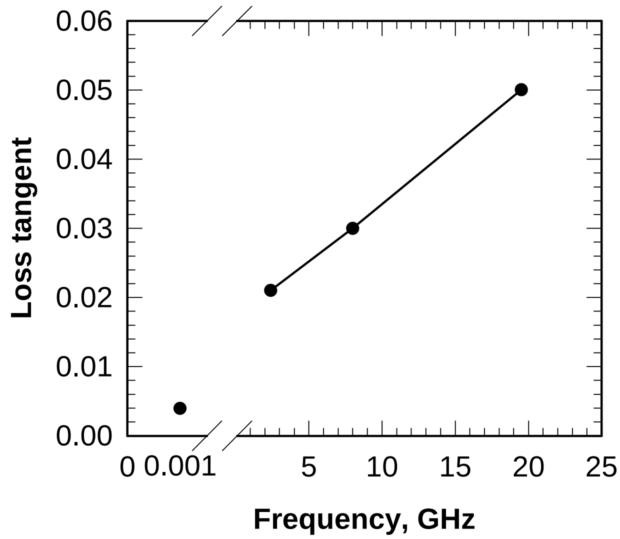

Fig.4. Frequency dependence of MW losses for BSTO planar varactors.

The tanδ of STO films slightly decreases with bias voltage increasing which is contradictory to the behavior observed for bulk single crystals [4]. The dielectric properties of STO films reported above are typical for more than hundred STO film samples investigated. The analogous measurements for varactors based on BSTO films were carried out as well. As an example, the frequency dependence of microwave losses for BSTO varactors is shown in fig.4.

Nonlinear response of STO planar capacitor to elevated MW (2GHz) power level was investigated by intermodulation distortion (IMD) product measurement technique. STO capacitor was included at the short circuited end of a copper microstrip resonator. Two sinusoidal MW fundamental tones of the same power P_{1inc} at slightly different frequencies f_1 and f_2 were applied to the resonator input. MW power at the fundamental frequency (P_{1out}) and at the third-order IMD product frequency $f_3=2f_1-f_2$ (P_{3out}) were measured at the resonator output as a function of the incident power per tone (all indicated frequencies f_1, f_2, f_3 were located within the resonator pass-band). Typical results of IMD measurements at T=78K are shown in fig.5. The scale of MW voltage amplitude per tone applied across the FE capacitor is presented at the added abscissa in fig.5. Analysis of experimental results demonstrates that the amplitude of MW electric field of the order of ~10^6V/m corresponding to the incident fundamental power per

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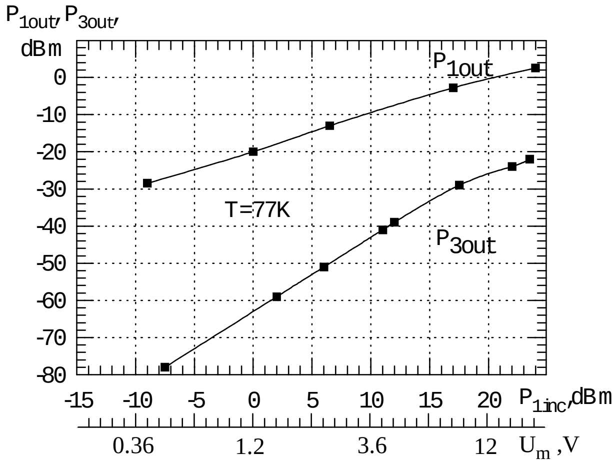

Fig.5. Output fundamental (P_{1out}) and third-order IMD (P_{3out}) product power versus incident power of fundamental tone.

tone $P_{1inc}\cong 20$dBm results in the third-order IMD products of about 25dB below output power at fundamental frequency. The application of the dc electric field of the strength 10^7V/m across the STO varactor leads to additional 10dB suppression of P_{3out} with respect to P_{1out}.

Nonlinear response of STO and BSTO varactors to single tone elevated MW (~10GHz) power up to 100W was under investigation. From results obtained it follows that for MW devices containing STO or BSTO planar varactor the power handling capability

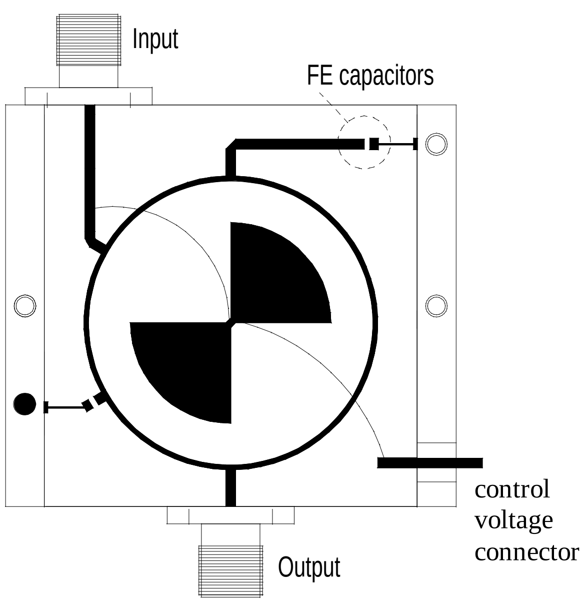

Fig.6. The layout of phase shifter.

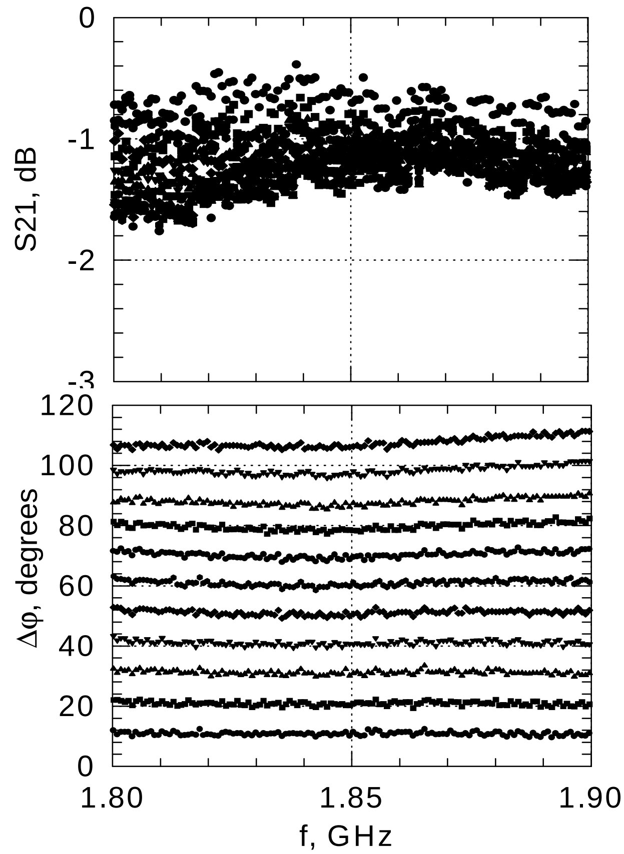

Fig.7. Performance of the analog FE phase shifter (operation temperature is 300K).

electric field of the order of $(0.5\text{-}1)\cdot 10^6$ V/m.

The speed of the central frequency tuning of the MW resonator employing FE planar varactor under the effect of voltage video pulses were studied. Video pulses of duration from 1μs to1ms with the front duration of 30ns were used in experiments. Results of the investigation allow to conclude that the response time of STO varactor to bias voltage is less than 30ns. For BSTO film elements along with the dominant process of fast tuning (≤30ns) a slow process of tuning with a response time ~20μs was observed.

The layout of phase-shifter and its characteristics with BSTO varactors are presented in figs.6 and 7. The construction contains rat-race hybrid coupler, two reflective terminations and bias circuit. The reflective terminations consist of series combination of ferroelectric capacitor and inductor. BSTO film capacitors were manufactured by planar technology. Operation temperature of the device was 300K. The following experimental results was achieved:

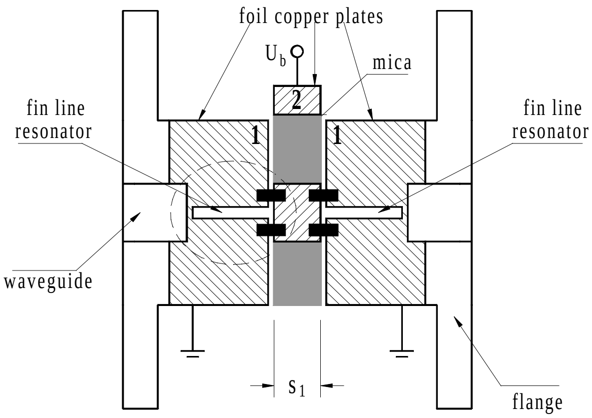

Fig.8. Construction of the tunable filter.

controlling voltage range, the figure of merit is 100 deg/dB, relative phase shift error less than 3% in operation frequency range 1.8÷1.9GHz and insertion losses are 1.0±0.4dB.

The tunable filter with four BSTO varactors based on symmetrical fin-line in a rectangular waveguide is shown in fig.8. The fin construction is comprised of three foil copper plates with thickness of 0.2mm placed at the center of waveguide along its longitudinal axis. Two lateral plates (1) with shorted end fin line resonators are grounded due to the contact with waveguide. Central plate (2) is insulated for dc voltage from waveguide by mica and is intended for the control voltage application (U_b) to BSTO varactors. Two ferroelectric varactors are soldered in the end of every fin line resonators between plates 1 and 2. The frequency response of the filter employing four BSTO varactors is shown in fig.9. In the frequency range of the tuning $\Delta F \approx 1.8$ GHz (~9%) the filter demonstrates the insertion losses L_0 not more than 3.5dB and the bandwidth $\Delta f/f \cong 3.5\%$ at the level $L_s = L_0+3dB = 6.5dB$. The reflection coefficient for the central frequency was not more than -20dB for the any point of the tuning range. The number of bands Δf of the filter which contained in the frequency range of tuning ΔF was equal to $\Delta F/\Delta f = 2.6$.

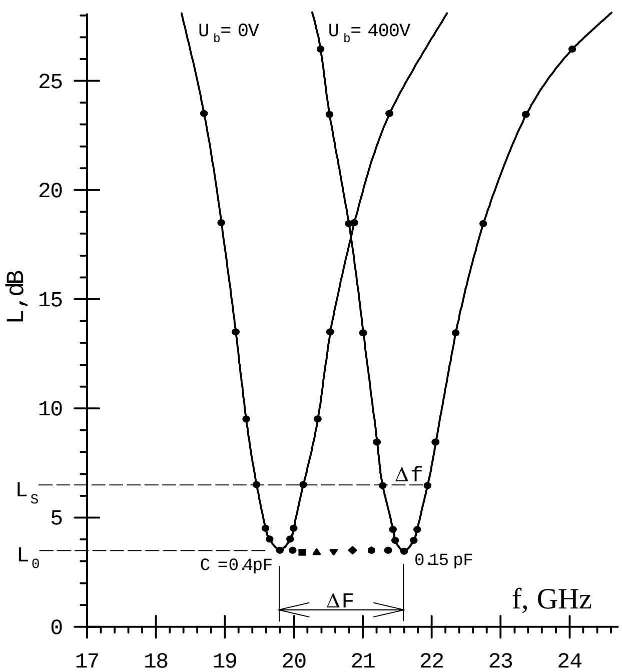

Fig.9. Frequency response of the tunable filter.

CONCLUSION

Generalize picture of nonlinear properties of STO and BSTO film varactors under dc bias voltage, video-pulse voltage and MW signal is presented. This makes it possible to estimate the range of frequency tuning, fast tuning capability and handling power capability of microwave devices based on the FE films. The possibility of the FE film application on MW is illustrated by phase-shifter and tunable filter performance.

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