Nonlinear Response of $Ba_xSr_{1-x}TiO_3$ Planar and Parallel-Plate Capacitors to Microwave Power: Comparative Study of Power Handling Capability

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***Abstract* — The power handling capability of tunable microwave devices employing planar and parallel-plate $Ba_xSr_{1-x}TiO_3$ film-based capacitors was experimentally measured and analyzed. A microstrip resonator, excited by either harmonic or two-tone microwave signals of elevated power, was selected as an example of tunable test fixture.**

I. Introduction

High microwave (MW) power handling is one of the advantages of paraelectric film-based tunable devices. Traditionally planar structures incorporating paraelectric films (Fig. 1) are used for MW applications. Such structures provide relatively high MW power handling capability (PHC) limited by paraelectric film overheating due to MW power dissipation [1]. However planar structures require a high tuning voltage (up to hundreds of Volts), that limits their use in low voltage applications. On the other hand, due to the small electrode spacing parallel-plate (sandwich) capacitors (Fig. 1) with thin (100-150 nm) paraelectric films [2] require a tuning voltage of 1-10V, which falls into the same range as for semiconductor devices. However, tuning under low voltage can lead to nonlinear distortions, whereas the decrease in the volume of the paraelectric film active area can result in capacitor overheating. Consequently, the PHC of sandwich capacitors is a critical parameter and requires special study.

This paper presents an experimental study of the nonlinear responses to elevated MW power for microstrip resonators loaded with planar and parallel-plate $Ba_xSr_{1-x}TiO_3$ (BSTO) film-based capacitors of the same capacitance and loss tangent. A comparative analysis of the PHC of the resonators tested is presented as well.

II. Results and Analysis

Two measurement techniques were used in experiments. The first technique allows the study of the interference from two MW signals due to BSTO capacitor nonlinearity [3]. The second technique allows the recording of the resonant curve distortion due to averaged capacitance variation under increasing pulsed MW power [4].

Fig.2 presents the results of measurements and simulations of the resonator output power at a fundamental frequency (f_1, f_2) and at the 3-rd order intermodulation distortion (IMD) product frequency ($f_3=2f_2-f_1$) as a two-tone MW signal with the same power per tone is fed to the resonator input. The results were obtained for a resonator employed with sandwich or planar paraelectric capacitors.

Fig.3 shows the results of measurements of the resonant curve of the sandwich capacitor-loaded resonator with increasing incident MW power, P_{inc}. One can see that the difference between resonant curves measured at the leading and trailing edges of the MW pulse enhances with P_{inc} increasing. Photos illustrate the output pulse shape corresponding to different MW signal frequencies.

Two effects can be responsible for BSTO capacitance behavior under elevated MW power. They are MW electric field (E) and thermal (T) effects on BSTO film dielectric permittivity.

To analyze the E-field effect we used the description of the capacitance-voltage curves (CVC) as

$$C(U) = \frac{C(0)}{K}\left[1+(K-1)\Big/\left(1+\left(\frac{U}{U_0}\right)^2\right)\right], \qquad (1)$$

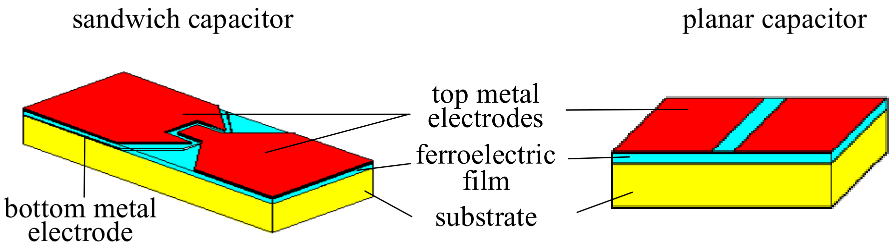

Fig. 1. Schematic structures of sandwich and planar ferroelectric film capacitors.

where $K=C(0)/C(\infty)$ and U_0 are the phenomenological parameters. $K=2.2$, $U_0=150V$ and $K=3.5$, $U_0=3.7V$ for planar and sandwich capacitors under test, respectively. Then for two-tone resonator excitation the incident power corresponding to the 3-rd order intercept point (TOIP) and PHC defined as the incident power corresponding to the allowable level of the 3-rd order IMD product (P^{TOIP}, PHC^{IMD}, respectively) can be expressed through CVC parameters K and U_0 as

$$P^{TOIP} = A\left[\frac{K \cdot U_0^2}{K-1}\right], \quad (2)$$

$$PHC^{IMD} = P^{TOIP}\sqrt{\left(\frac{P_{3out}}{P_{1inc}}\right)_{al}}. \quad (3)$$

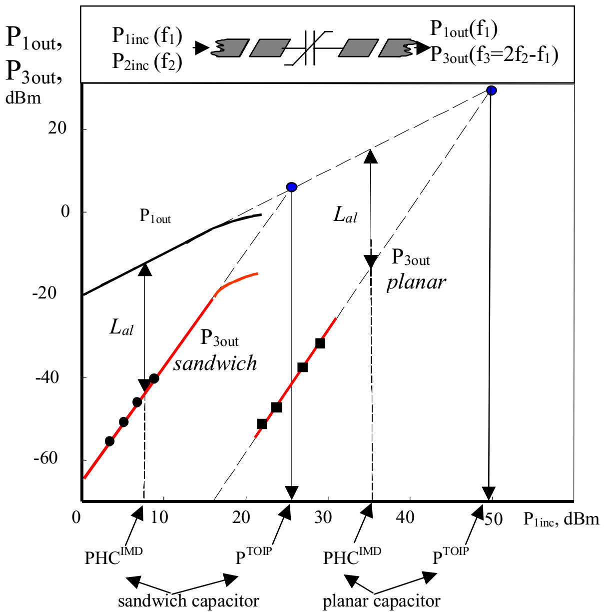

Fig. 2. Experimental results of third-order IMD product measurements (symbols) and simulation (solid lines) for a resonator employed with sandwich and planar ferroelectric capacitors. P_{1inc} is the single-tone incident power; P_{1out} and P_{3out} are the output power at fundamental and third-order IMD product frequencies, respectively. L_{al} is the allowable level of P_{3out}. Data are taken at a frequency of ~7 GHz.

For the pulsed one-tone resonator excitation, PHC is defined as the incident MW power providing the maximum allowable shift in resonant frequency (or frequency of maximal transmission) due to the E-field effect and takes the form

$$PHC^{E} = B\left[\frac{K \cdot U_0^2}{K-1}\right]\left(\frac{\Delta f^{E}}{f_0}\right)_{al}. \quad (4)$$

Factors A and B in (2) and (4) are determined by the resonator parameters and the methods of inclusion of the resonator in the measuring circuit and the capacitor in the resonator.

It is obvious from (2), (3) and (4) that the factor $[K \cdot U_0^2/(K-1)]$ is responsible for the roughly 50dB increase in the IMD product power P_{3out} and the 30dB decrease of P^{TOIP}, PHC^{IMD}, PHC^{E}, registered in experiments with sandwich capacitors in comparison with those using planar capacitors.

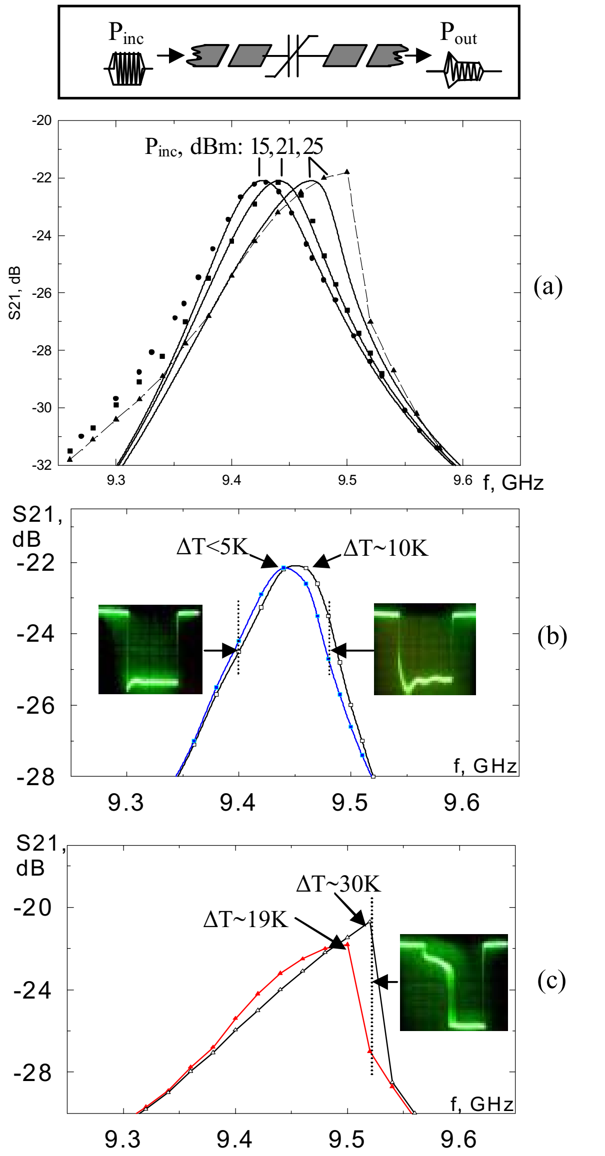

Fig. 3. Resonant curve distortions under different levels of MW power: (a) – experimental data measured at the end of the leading edge of the MW pulse (symbols), solid lines are data simulated for the electric field effect only; (b) and (c) illustrate the difference in data measured at the leading (filled symbols) and trailing (open symbols) edges of the MW pulse of P_{inc}=21 dBm and 25 dBm, respectively. BSTO film overheating due to MW power dissipation is indicated by ΔT. Inserts show the envelope of the MW pulse at the resonator output. Pulse duration is 500 µs and pulse duty factor is 0.05.

For the thermal effect, we estimate the thermal power handling capability as

$$PHC^{T} = D\frac{V}{\tau_T}\left(\frac{\Delta f^{T}}{f_0}\right)_{al}, \quad (5)$$

where V is the volume of BSTO film active area, τ_T is the capacitor thermal time constant. The factor D in (5) is defined by capacitor parameters (C, tanδ), the temperature dependence of capacitance, the thermal capacitance per unit volume of BSTO film and the methods of inclusion of the resonator in the measuring circuit and the capacitor in the resonator. It is obvious that the value of V/τ_T governs the value of PHC^T. For sandwich and planar capacitors under test τ_T falls into nanosecond range and into microsecond range, respectively. In spite of a radical difference in the volumes of BSTO films in planar and sandwich capacitors, the strong difference in τ_T provides about one order difference in V/τ_T, and therefore only a 10dB decrease of PHC^T was obtained for the resonator loaded with a sandwich capacitor in comparison with that loaded with a planar capacitor.

Table I illustrates the values of PHC obtained in our work. One can conclude from these data that the PHC of devices including planar paraelectric film-based capacitors is limited by heating phenomena, whereas for parallel-plate capacitors the dielectric nonlinearity (E-field effect) determines the PHC.

Ferroelectric Capacitor:		Sandwich	Planar
PHC^{IMD}	L_{al}=30 dB	+8 dBm	+38 dBm
	L_{al}=50 dB	-2 dBm	+28 dBm
$PHC^E \left[\left(\frac{\Delta f^E}{f_0}\right)_{al} = 10^{-3}\right]$		+15 dBm	+45 dBm
$PHC^T \left[\left(\frac{\Delta f^T}{f_0}\right)_{al} = 10^{-3}\right]$		+17 dBm	+27 dBm

TABLE I
PHC OF THE RESONATOR EMPLOYED WITH SANDWICH AND PLANAR CAPACITORS

III. CONCLUSION

Currently available parallel-plate capacitors, providing low tuning voltage, have the potential for use in passive tunable MW devices in low power MW systems and can be proposed as nonlinear elements of active devices due to the significant decrease in pump power and the moderate decrease in thermal PHC in comparison with those of planar structures.

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