Microwave Characterization of Ferroelectric Thin Films for Novel Compact Tunable BST Filters

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Introduction

Modern wireless communications systems require **tunable**, **compact**, **low-cost**, and **highly integrated** components → **$Ba_xSr_{1-x}TiO_3$ (BST) ferroelectric thin film**

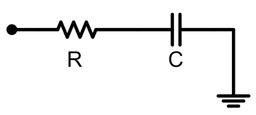
<u>Application</u> : Novel compact tunable based on BST capacitors by ST Microelectronics

Test Capacitors → **BST Parameters Extraction** → **Tunable Filter**

Test Capacitors

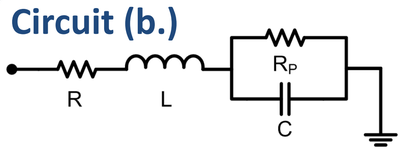
Equivalent Circuits

Circuit (a.)



The resistance includes every loss component

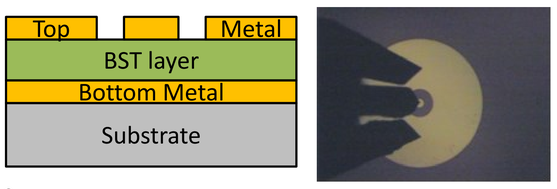
Circuit (b.)

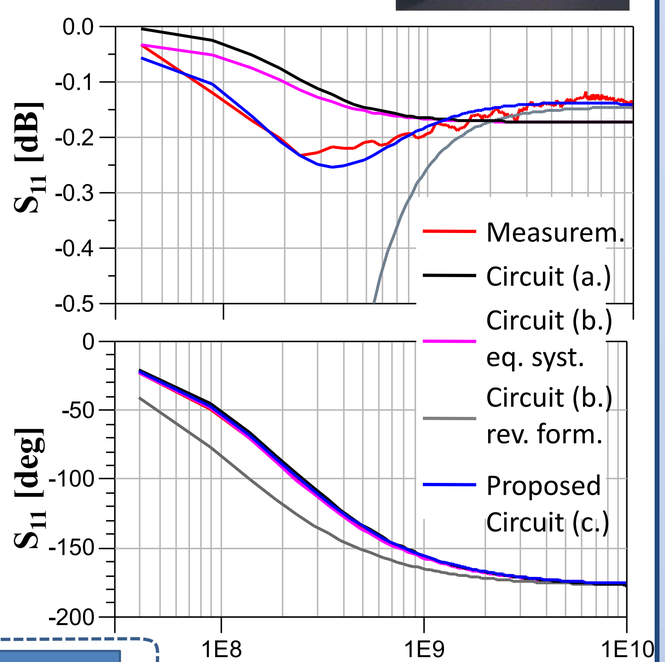


$$Z(\omega) = R + j\omega L + \frac{R_P(1 + j\omega C R_P)}{1 + (\omega C R_P)^2}$$

system of 4 equations in 4 unknowns — **reverse formulas provided in [1]**

[1] H.T. Lue, C.Y. Liu, and T.Y. Tseng, "*An Improved Two-Frequency Method of Capacitance Measurement for $SrTiO_3$ as High-k Gate Dielectric*," IEEE Electron Device Letters, 2002.

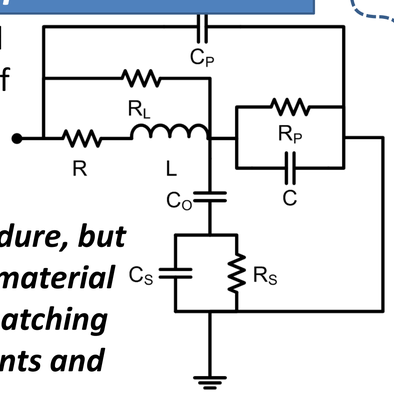


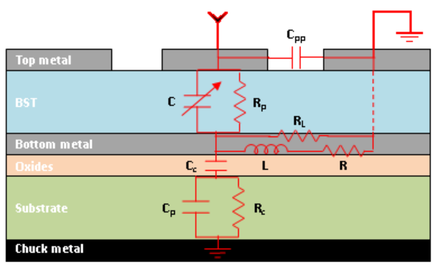


MIM structure <u>without via holes</u>: simple fabrication, difficult integration

Circuit (c.) — ***fully comprehensive equivalent circuit***

It takes into account every loss and parasitic mechanism of both metals and dielectrics



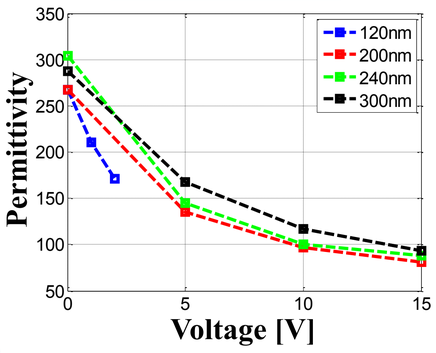


Time consuming procedure, but reliable extraction of material parameters (better matching between measurements and simulations)

BST parameters

- Frequency: 40 MHz-10 GHz
- BST thickness: 120 nm, 200 nm, 240 nm, 300 nm
- Applied bias voltage: 0-15 V (electric field: 0-520 kV/cm)

Permittivity



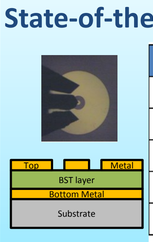
Loss Tangent

$tan\delta \approx 0.03$

Tunability = 72%

$(\varepsilon_r(V_{min})-\varepsilon_r(V_{max}))/\varepsilon_r(V_{min})$

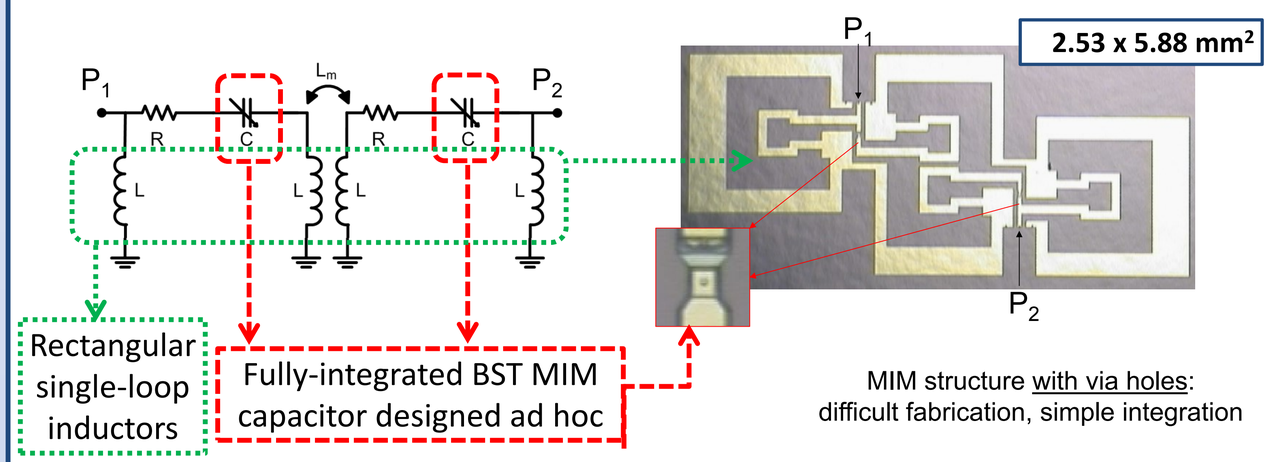
State-of-the-art of BST MIM capacitor with ring structure



Reference	Permittivity @ 0V	Loss Tangent	Tunability
Gevorgian [2003]	150	0.01 @ 20 GHz	40 %
Gevorgian [2004]	158-169	0.025 @ 45 GHz	40 %
Gevorgian [2006]	208	0.02 @ 10 GHz	
Lancaster [2008]	300	0.02	
Ong [2009]		0.03 @ 10 GHz	30 %

Tunable filter

Coupled resonators implemented by **lumped elements** → **Compact size** with respect to conventional λ/4 lines

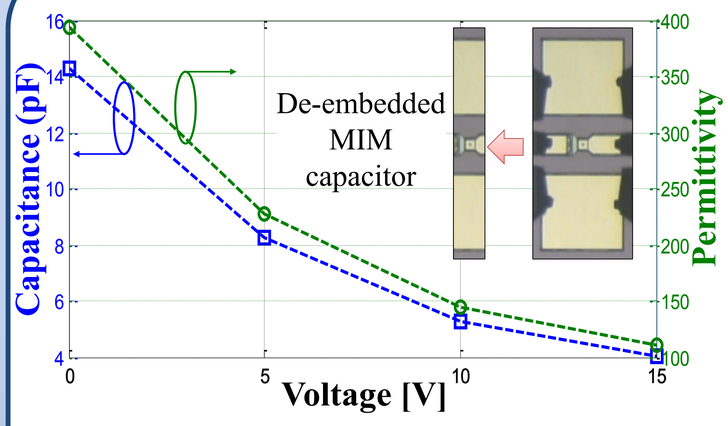


MIM structure <u>with via holes</u>: difficult fabrication, simple integration

Filter tuning: under bias voltage application the center frequency f_0 of the filter increases as the capacitance value decreases

<u>Preliminary fabrication by ST Microelectronics</u>: development of the technological process to achieve <u>via holes in BST</u> and to deposit a <u>thicker top metal</u> for loss reduction (the BST properties are not the main target) → BST parameter are slightly different from the values previously extracted and used in the filter design

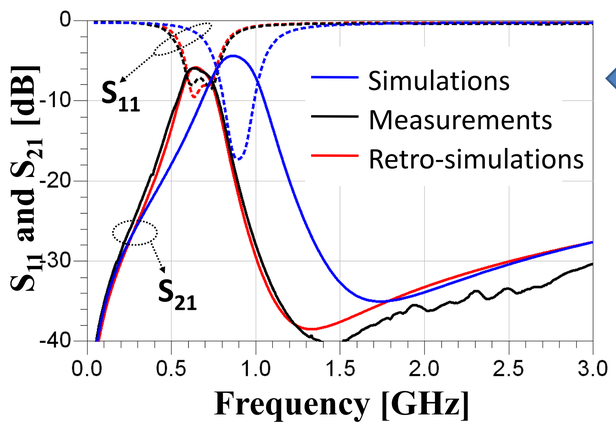
Results

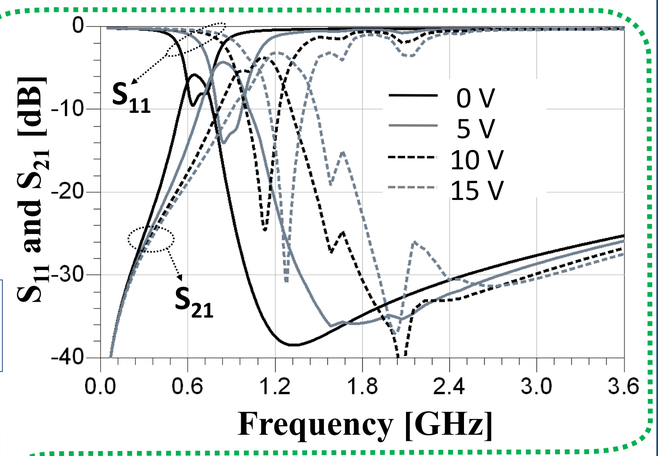


Tunability: 72% as expected
Thickness: 250nm instead of 300nm
Permittivity: 400 instead of 270
Loss tangent: 0.03 as expected
Input impedance: 55 Ω instead of 50 Ω

→ Deterioration of S-Parameters and reduction of the working frequency

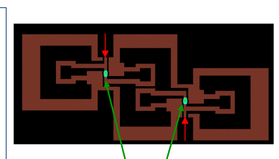
→ **Retro-simulations** to give ground and take into account the deviation between simulations and measurements





<u>Preliminary design</u>: no bias lines (the only measurable filter configuration is at 0 V)

Combination of measurement results and full-wave simulations to valuate filter performance under bias voltage



MIM measured S-Parameters under bias voltage

The reliability of the method is garanteed by the good fitting at 0 V (retro-simulations)

Filter Tunability = 88%

$(f_0(V_{min})-f_0(V_{max}))/f_0(V_{min})$

Ref.	f_0 (GHz)	Bias (V)	Frequency tunability	Bandwidth @–3dB(%)	Insertion loss (dB)	FoM (dB^{-1})
Nath [2005]	2.44	200	18%	24.6-31.3	5.5-3.3	0.14
Courreges [2009]	8.35	30	6%	7.8-7.8	5.7-3.5	0.16
Courreges [2009]	10.04	20	7.4%	19.9-23.2	2.9-1.95	0.14
Sigman [2008]	8.75	100	25.3%	19.4-15.5	4-8	0.23
	11.7	100	22.2%	12-14	6-10	0.20
Papapolymerou [2006]	11.5	30	21.7%	15.7-15.9	5.4-3.3	0.29
Keis [1998]	19.86	400	9.1%	3.5-3.2	3.5-3.5	0.73
Courreges [2009]	29	30	17.2%	15.5-15.5	6.9-2.5	0.23
Su [2008]	2.7	200	29.6%	9.3-8.6	25.7-14.3	0.15
Pleskachev [2004]	4.4	150	7.7%	2.6-2.4	14.8-7.8	0.27
Subramanyam [2001]	16.68	100	2.9%	7.6-9.5	8.1-5.25	0.05
Delprat [2011]	6.3	30	9%	17.9-15.1	6-6.3	0.08
	6.95	30	30.2%	23.3-15.8	8.4-9.4	0.15
This work	**0.66**	**15**	**88%**	**30-30**	**5.8-3.2**	**0.52**

$$FoM_{dB^{-1}} = \frac{f_0(V_{max}) - f_0(V_{min})}{\sqrt{\Delta f(V_{max}) * \Delta f(V_{min})} * \sqrt{IL(V_{max}) * IL(V_{min})}}$$ [3]

Good performance if compared to the state-of-the-art of ferroelectric band-pass filters [3]

[3] S.L. Delprat, J.H. Oh, F. Xu, L. Li, E.E. Djoumessi, M. Ismail, M. Chaker, and K. Wu, *"Fully Distributed Tunable Bandpass Filter Based on $Ba_{0.5}Sr_{0.5}TiO_3$ Thin-Film Slow-Wave Structure,"* International Journal of Microwave Science and Technology, 2011.

Conclusions

1) **Microwave characterization of $(Ba,Sr)TiO_3$ thin films** (120 to 300nm): **permittivity**, **loss tangent**, and **tunability** under 0 to 15 V extracted by fitting between measurements and a **fully-comprehensive lumped element equivalent circuit**

2) **Compact tunable filter** based on BST capacitors (total size 2.53 x 5.88 mm^2):
- ✓ Central frequency tunability = 88% (657 MHz-1235 MHz)
- ✓ Fractional bandwidth constant at 30%
- ✓ Insertion loss = 3.2 - 5.8 dB
- ✓ Return loss < -9 dB
- ✓ Out of band rejection (at $2f_0$ and at $3f_0$) < -25 dB

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