FERROELECTRIC BASED HIGH POWER COMPONENTS FOR L-BAND ACCELERATOR APPLICATIONS

Supported by the DOE SIR DE-SC0007630, Phase II

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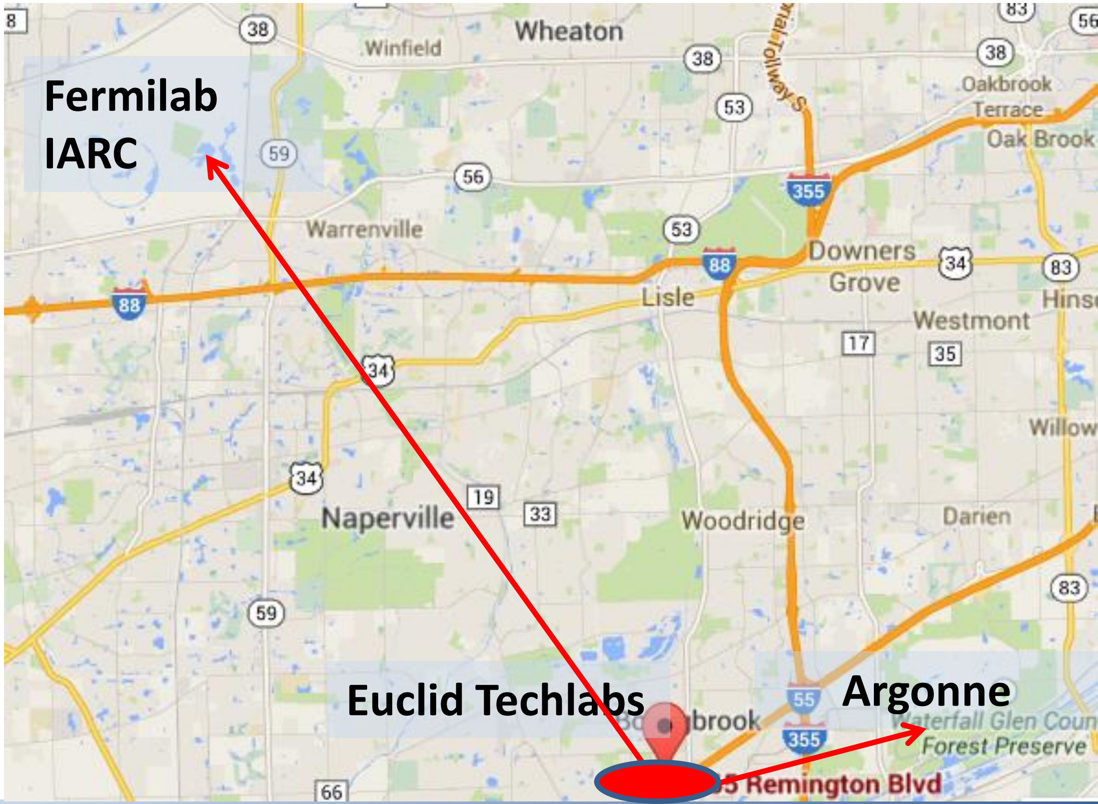
Euclid Techlabs LLC
On behalf of Euclid Techlabs/BNL/FNAL collaboration

Department of Energy SBIR/STTR Exchange Meeting
August 8-9, 2017

Euclid Techlabs LLC

Euclid TechLabs LLC, founded in 1999 is a company specializing in the development of advanced materials and new designs for beam physics and high power/high frequency applications. Additional areas of expertise include dielectric structure based accelerators and "smart" materials technology and applications.

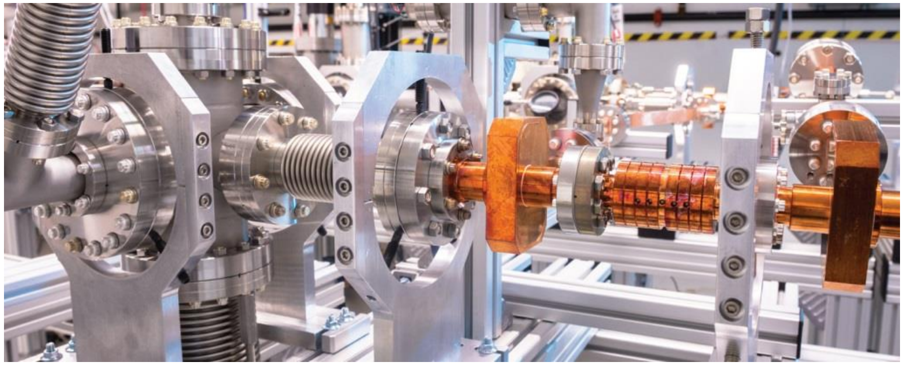
- 2 offices: Bolingbrook, IL (lab) and Gaithersburg MD (administrative).
- Tight collaborations with National Labs: Argonne, Fermi, BNL, LBNL, LANL.
- Actively participate in Accelerator Stewardship DOE Program
- Joined Fermi/IARC lately



NEW LAB FACILITY IN BOLINGBROOK IL

- Compact electron accelerator test facility (bunker)
- Time resolved TEM beamline
- Clean room/magnetron sputtering (TiN, copper, dielectrics)
- Field Emission cathode DC test stand
- Femtosec laser
- RF lab
- …other beam physics related equipment - www.beamphysics.com

8000 sq. ft. - total
1000 sq.ft. – office
7000 sq.ft. - lab

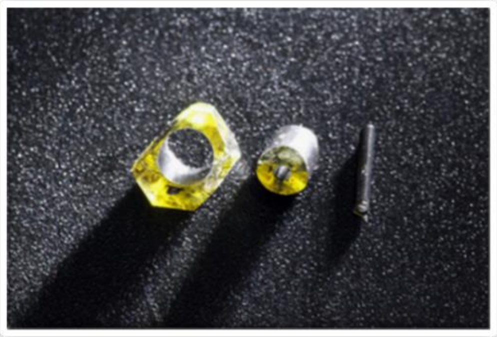


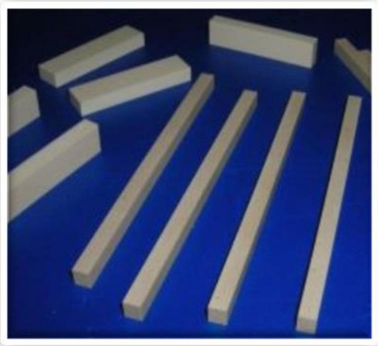
ANL/AWA accelerator, ANL/CNM - FE UNCD,
ANL/APS- diamond based X-ray optics
Fermi: SRF tests

Key Euclid's technologies:

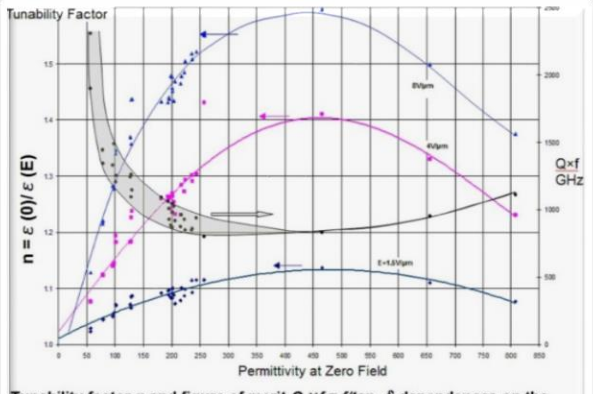
1. Ultra-compact low energy accelerator (DLA)
2. L-band high peak current LINAC (ANL Wakefield Accelerator (AWA, 75 MeV, 100 nC)
3. Photo-injector (design, fabrication installation)
4. UNCD based FE and photo cathodes
5. Accelerator high power components (RF windows, couplers, accelerating structures)
6. SRF Structures and Components
7. THz structures and components
8. Diamond based components
9. Microwave low loss ceramics and ferroelectrics

Products and Projects: smart materials

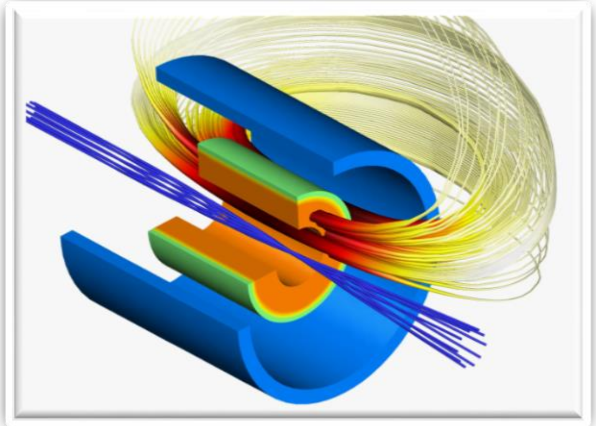




Synthetic diamonds



Tunability factor *n* and figure of merit *Q* × *f* = *f*/*tan δ* dependences on the permittivity for BST (M) ceramics. Data based on Euclid Techlabs research.

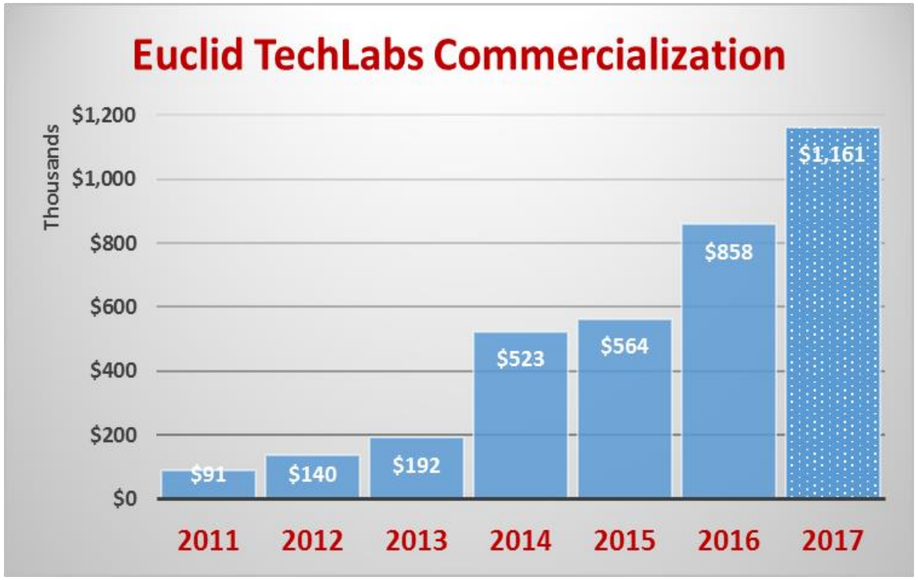


Linear and non-linear ceramics low loss; various form factors

Software, modeling, consulting

Commercialization

- Two periods:
  2003-2014 - spinoff from Argonne Wakefield Accelerator group (DOE SBIR)
  2014- now - commercialization of advanced material technologies and TEM.



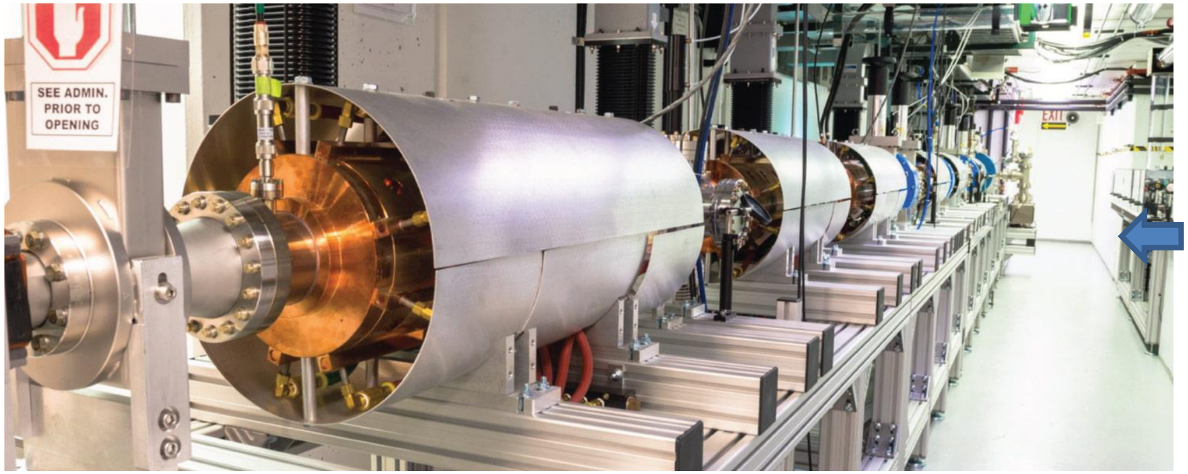
8 patents +12 currently in progress

- Latest Noticeable Contracts:

JEOL, Inc. installation at the US facility, then BNL and NIST

NIST (2016) – "Time Resolved TEM" $680K
GWU (2017) – "UNCD Emmision Chamber" - $115K
UMD (2016) – "Single Crystal Diamond FET" $325K/ + NRO/DOD - $450k
Shanghai JU (2015) – "Photoinjector", "Thermionic Gun" - $320K

Research on Dielectric Wake Field Accelerating (DWFA) structures



Experiments with DWFA were done by Euclid Techlabs at Argonne,

- Externally powered dielectric structure: Naval Research Lab

- designs: 7-26 GHz
- scalable to THz

Brookhaven, SLAC

History: Tunable Dielectric-Based Accelerator

PRL **106,** 164802 (2011) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2011

Experimental Demonstration of Wakefield Acceleration in a Tunable Dielectric Loaded Accelerating Structure

C. Jing,[1,2] A. Kanareykin,[1] J. G. Power,[2] M. Conde,[2] W. Liu,[2] S. Antipov,[1,2] P. Schoessow,[1] and W. Gai[2]
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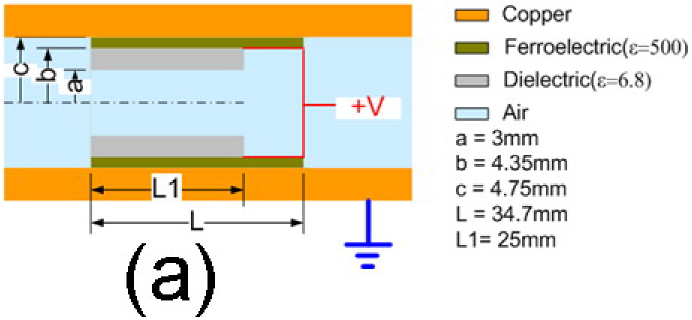
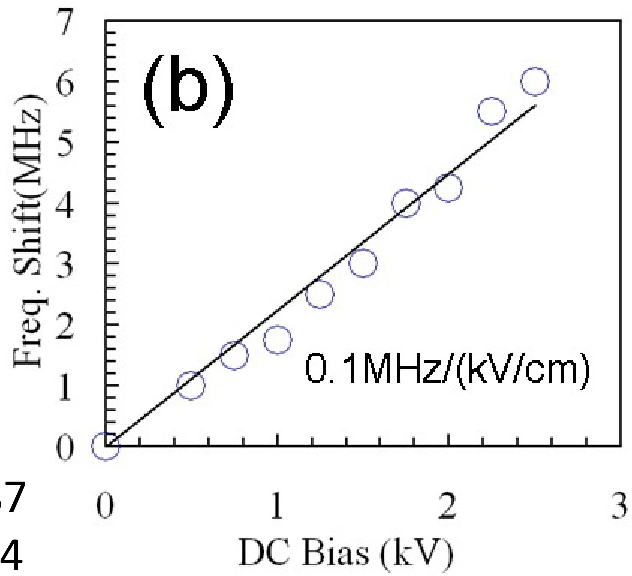
(Received 28 January 2011; published 21 April 2011)

We report on a collinear wakefield experiment using the first tunable dielectric loaded accelerating structure. By introducing an extra layer of nonlinear ferroelectric, which has a dielectric constant sensitive to temperature and dc bias, the frequency of a dielectric loaded accelerating structure can be tuned. During





ε(E) for ferroelectric dielectric composite

NONLINEAR CERAMIC

US patent 7,768,187
US patent 8,067,324

Ferroelectric Based Tuner (Ultrafast Phase Shifter) for SRF Accelerator Operation

Motivation

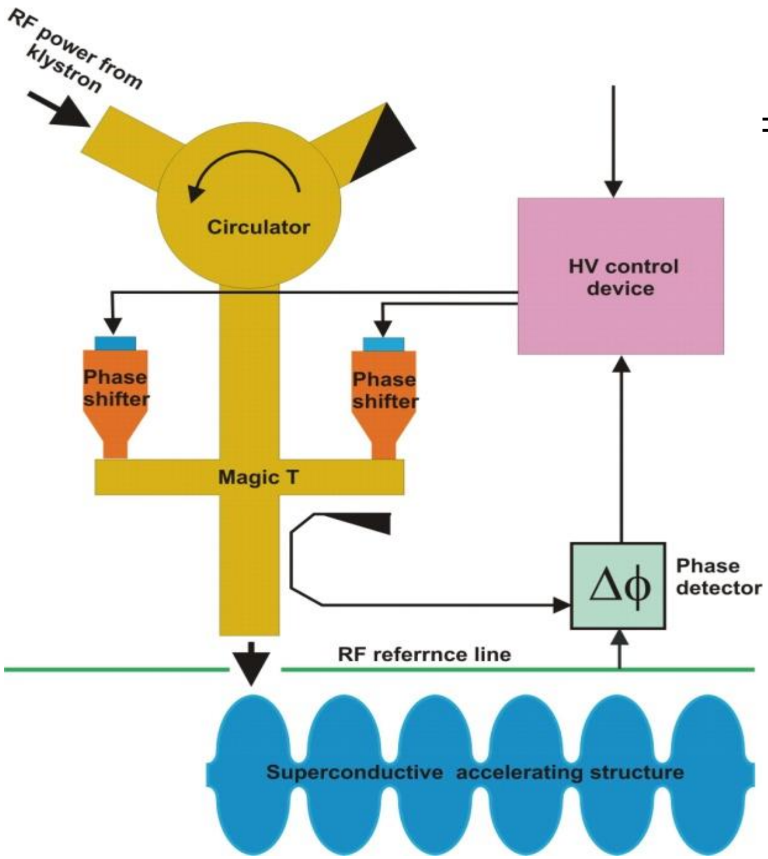
- A fast controllable phase shifter would allow microphonics compensation for CW SRF accelerators supporting ERLs and FEL.

- Nonlinear ferroelectric microwave components can control the tuning or the input power coupling for rf cavities. Applying a bias voltage across a nonlinear ferroelectric changes its permittivity. This effect can be used to cause a phase change of a propagating rf signal or change the resonant frequency of a cavity. The key is the development of a low loss highly tunable ferroelectric material.

- Topic was suggested by BNL (I.Ben-Zvi) for eRHIC cavity tuning

Tuner Requirements

$$P_g = P_{loss} + \omega W / Q_0 \qquad \Delta\omega = 2Q_0 / \omega. \quad P_{g,\max} = W\delta\omega$$



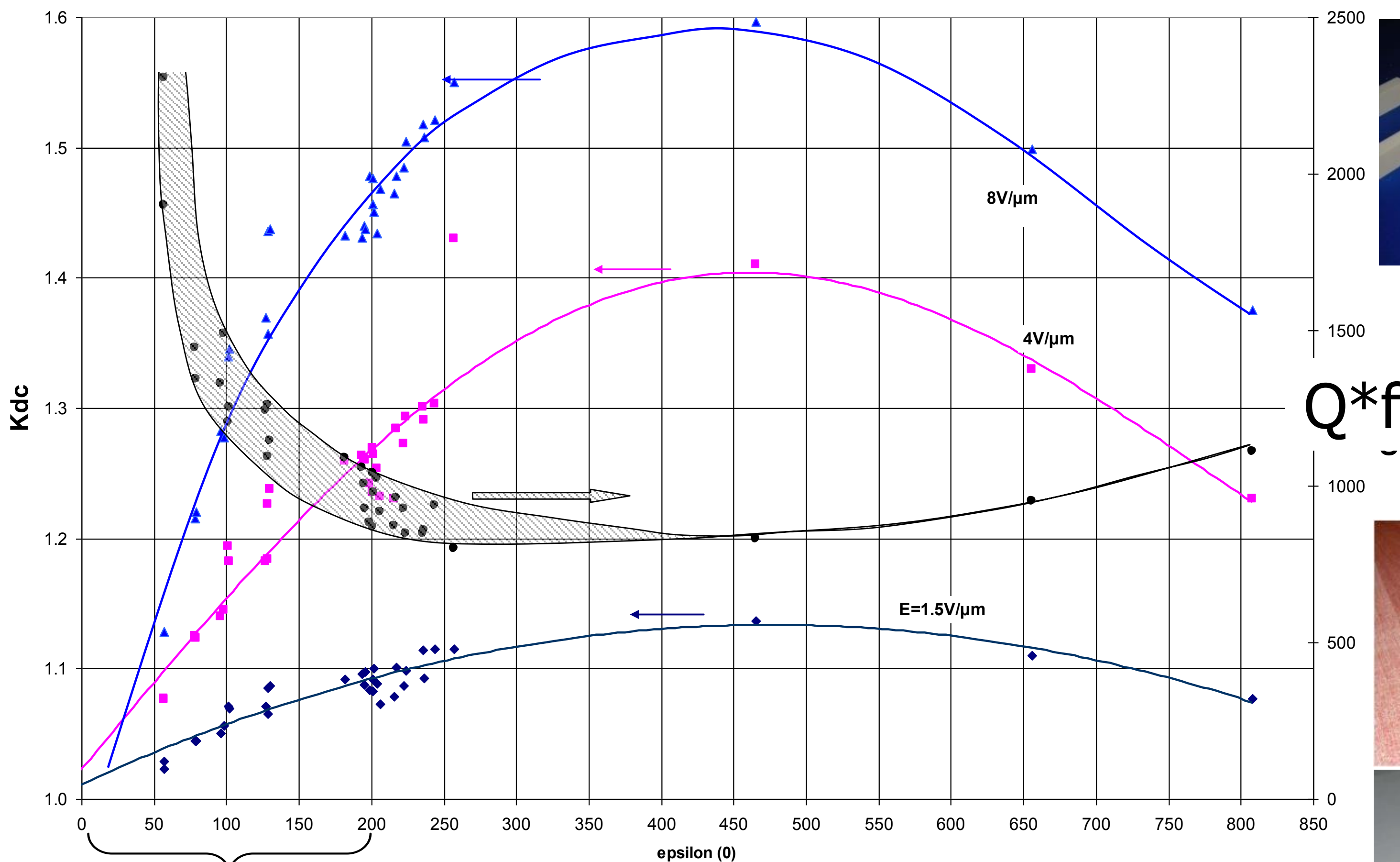
$$= P_g / P_{g,\max} = \delta\omega / \Delta\omega \left(1 - 4tn\delta \frac{\eta(\varphi_0)\varepsilon}{\Delta\varepsilon} \right).$$

for BNL ERL and the tuner described in the Euclid Proposal φ_0= 135°

For a typical ferrolectric tuner needed for ERL SC cavity excitation, on need ferroelectric material having the tunability of 6% and loss tangent of ~10^-3.

Progress on BST Material Development

$(Ba, Sr)TiO_4$+Mg oxides



BST(M), ε~50-150

record low values of dielectric constant and loss tangent at relatively high tunability level required for high power bulk tuner operating in air (< 30 kV/cm) and in vacuum (up to 80 kV/cm).

Ferroelectric ceramic properties

Parameters	Value
dielectric constant, ε	50-450
tunability, $\Delta\varepsilon$	>30@15kV·cm^{-1} of the bias field
response time	< 10 ns
loss tangent at 1.3 GHz, tanδ	~1×10^{-3}
breakdown limit	200 kV/cm
thermal conductivity, *K*	7.02 W/m-K
specific heat, *C*	0.605 kJ/kg-K
density, ρ	4.86 g/cm^3
coefficient of thermal expansion	10.1×10^{-6} K^{-1}
temperature tolerance, $\partial\varepsilon/\partial T$	(1-3) K^{-1}

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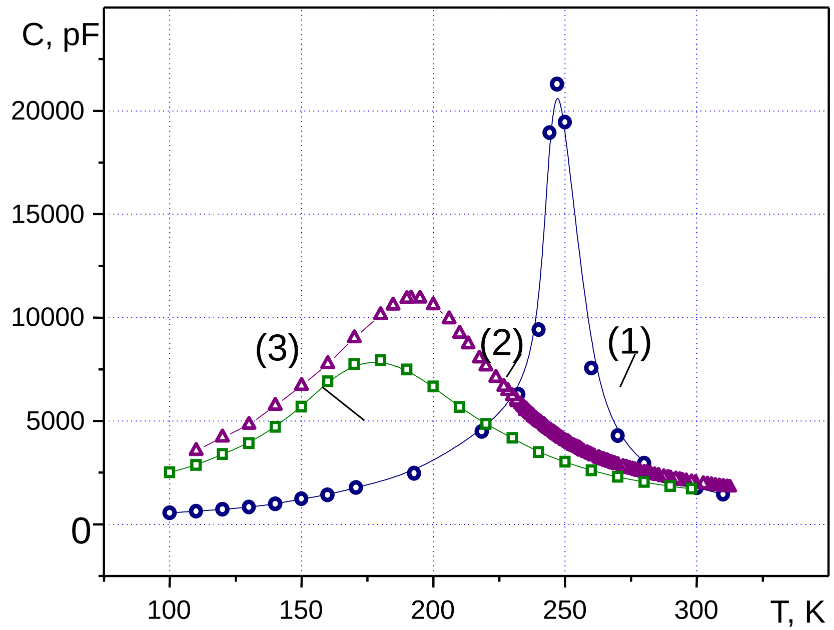
Issues with the ferroelectric elements

- Dielectric constant has to be low (~ 100)
- Loss factor has to be low ~ 1.0 ×10^{-3} at 1 GHz
- Tuning range has to be high ~ 6-8% at 20kV/cm
- Residual effects have to be mitigated

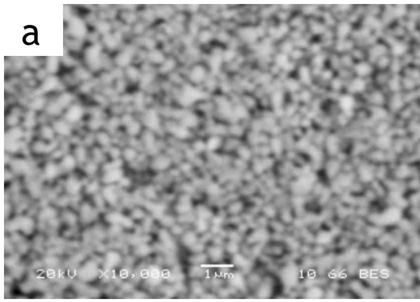


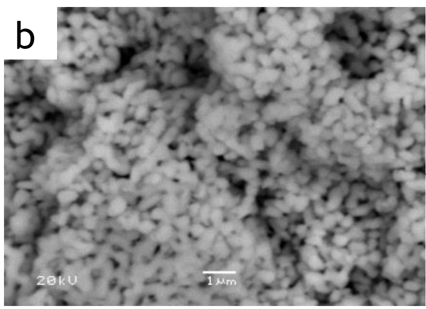
(Ba, Sr)TiO_4+Mg oxides

Ferroelectric composite materials

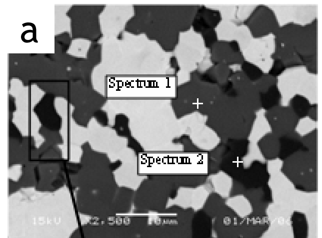
Patent US 8,067,324 B2, Nov. 29, 2011

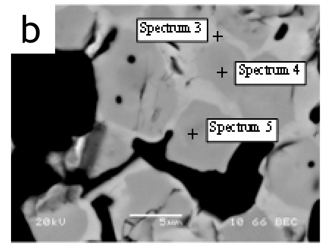
Powders → Ceramics

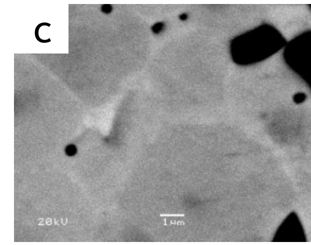


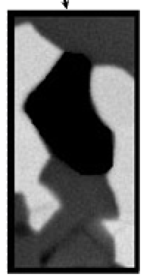


SEM-image of the initial powders of barium titanate (a) and strontium titanate (b)



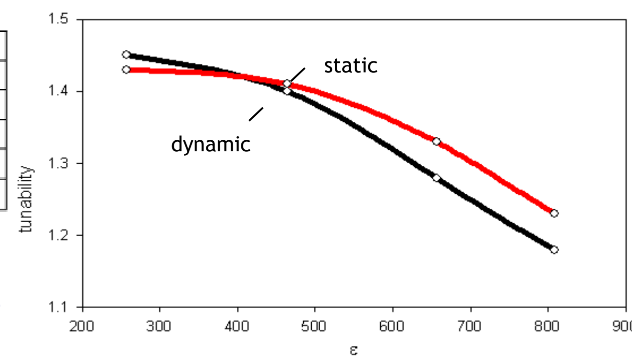






Spectrum	Mg	Ti	Sr	Ba	O	Total
Spectrum 1	29.66	27.47	1.39	2.99	38.49	100.00
Spectrum 2	59.89	0.19	0.26	0.06	39.60	100.00
Spectrum 3	0.19	22.57	16.33	38.09	22.82	100.00
Spectrum 4	0.14	22.62	21.85	32.23	23.16	100.00
Spectrum 5	0.25	23.36	27.91	24.64	23.84	100.00

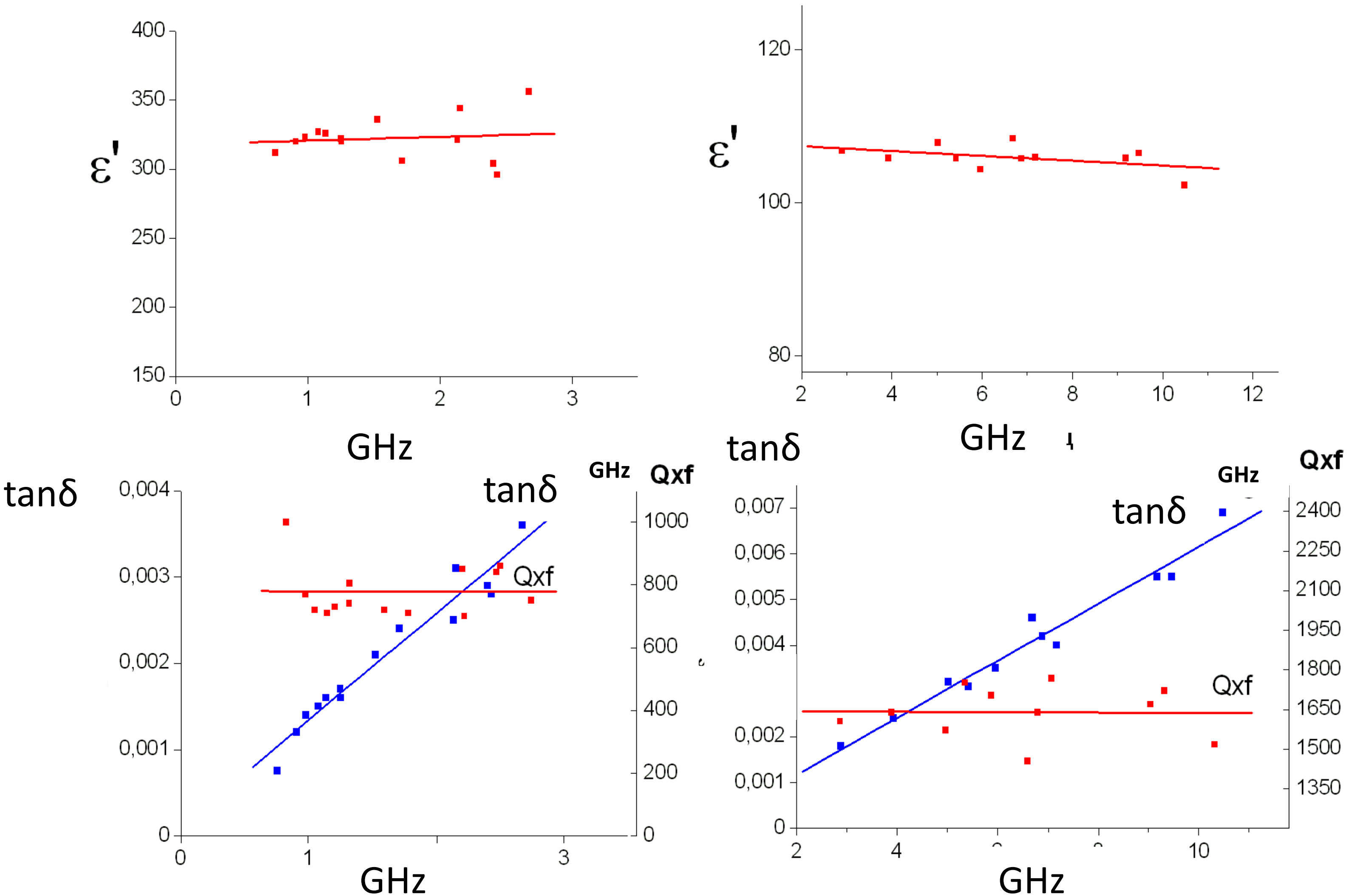
SEM images and EDS data of the sample on the basis of BST ferroelectric with linear Mg - containing additive (T = 1420 ° C) (a, b) and (T = 1400 ° C) (c).



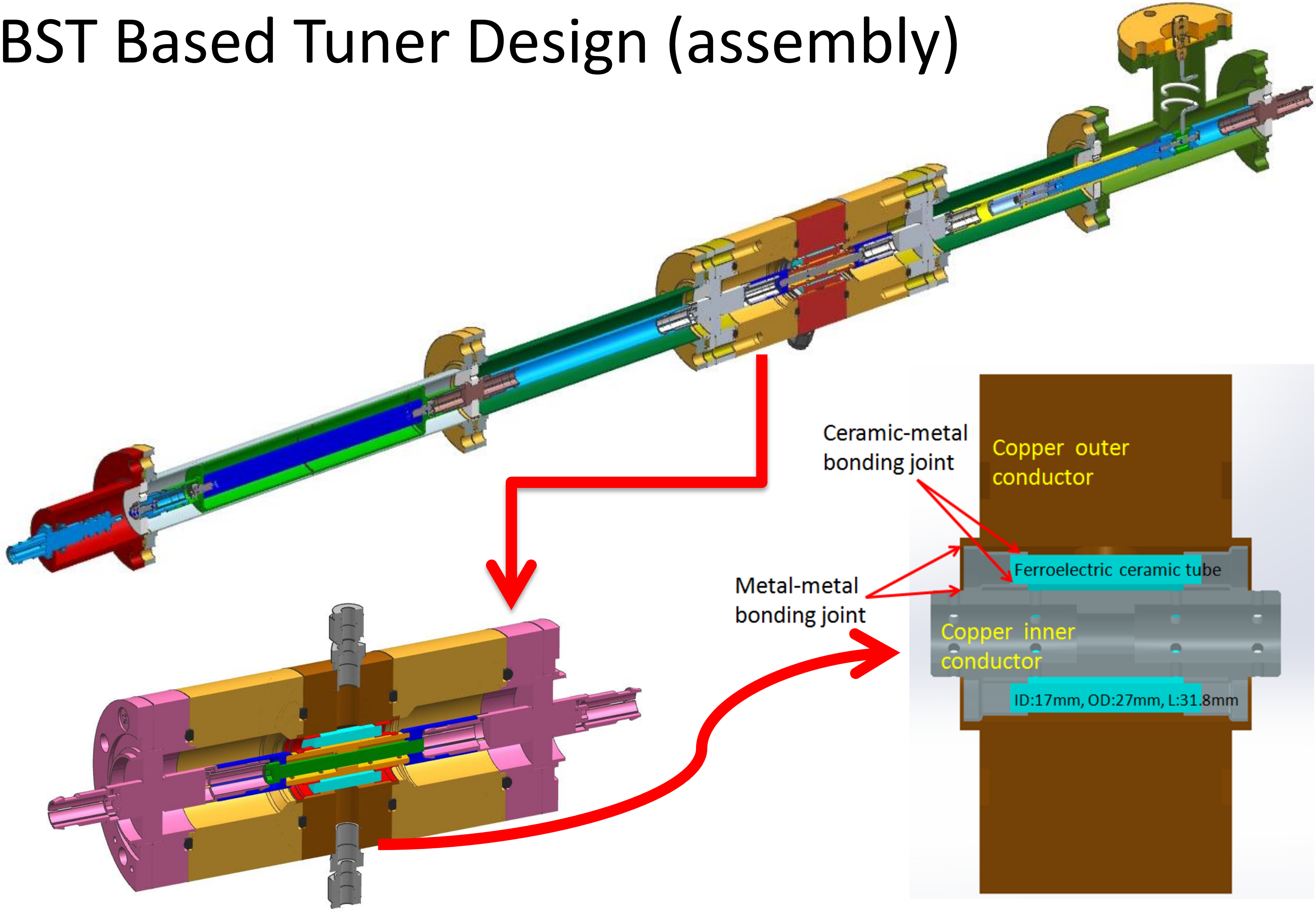
Static and dynamic tunability as a function of the permittivity

SEM image of the boundary interface region in between the grains of the BST-MgO-Mg_2TiO_4 composite material.

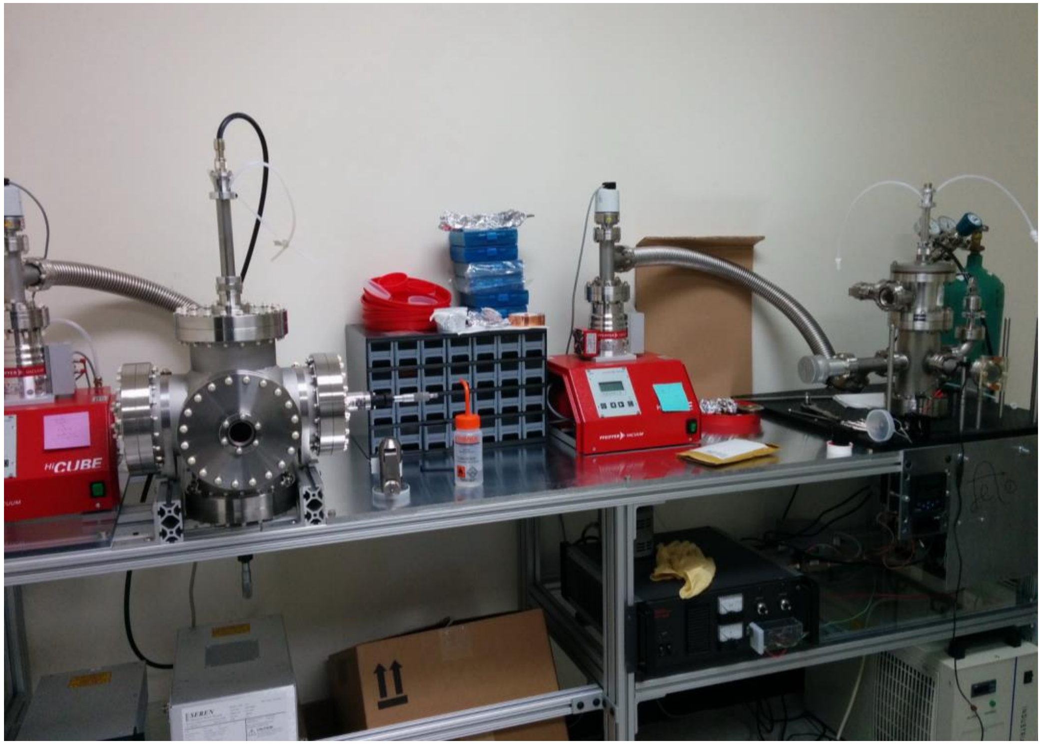
Frequency dependence of ε and tanδ for the ferroelectrics with low permittivity

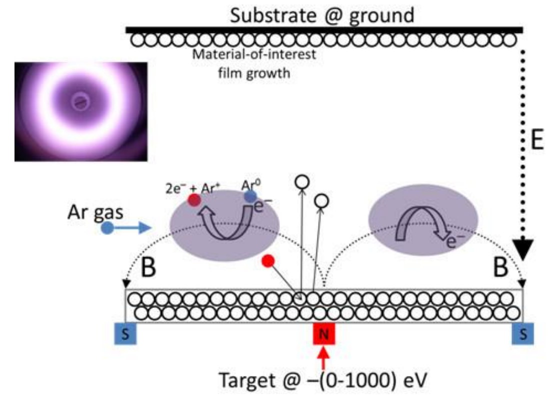


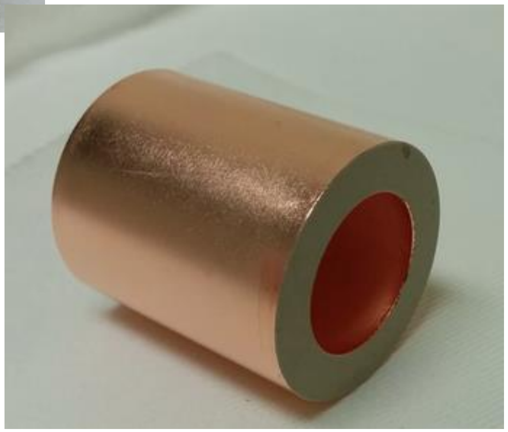
BST Based Tuner Design (assembly)



Euclid's Sputtering System, Bolingbrook IL

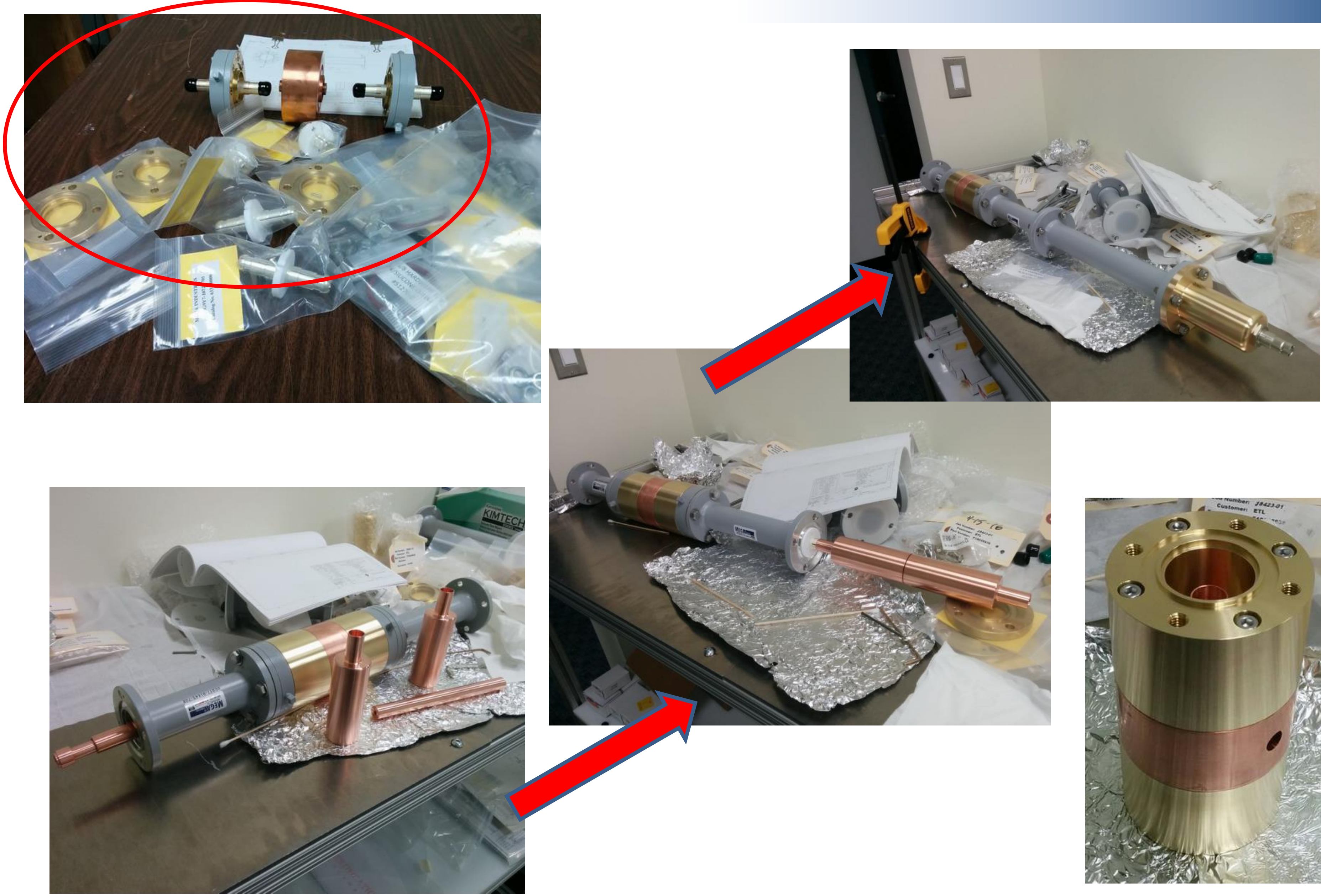






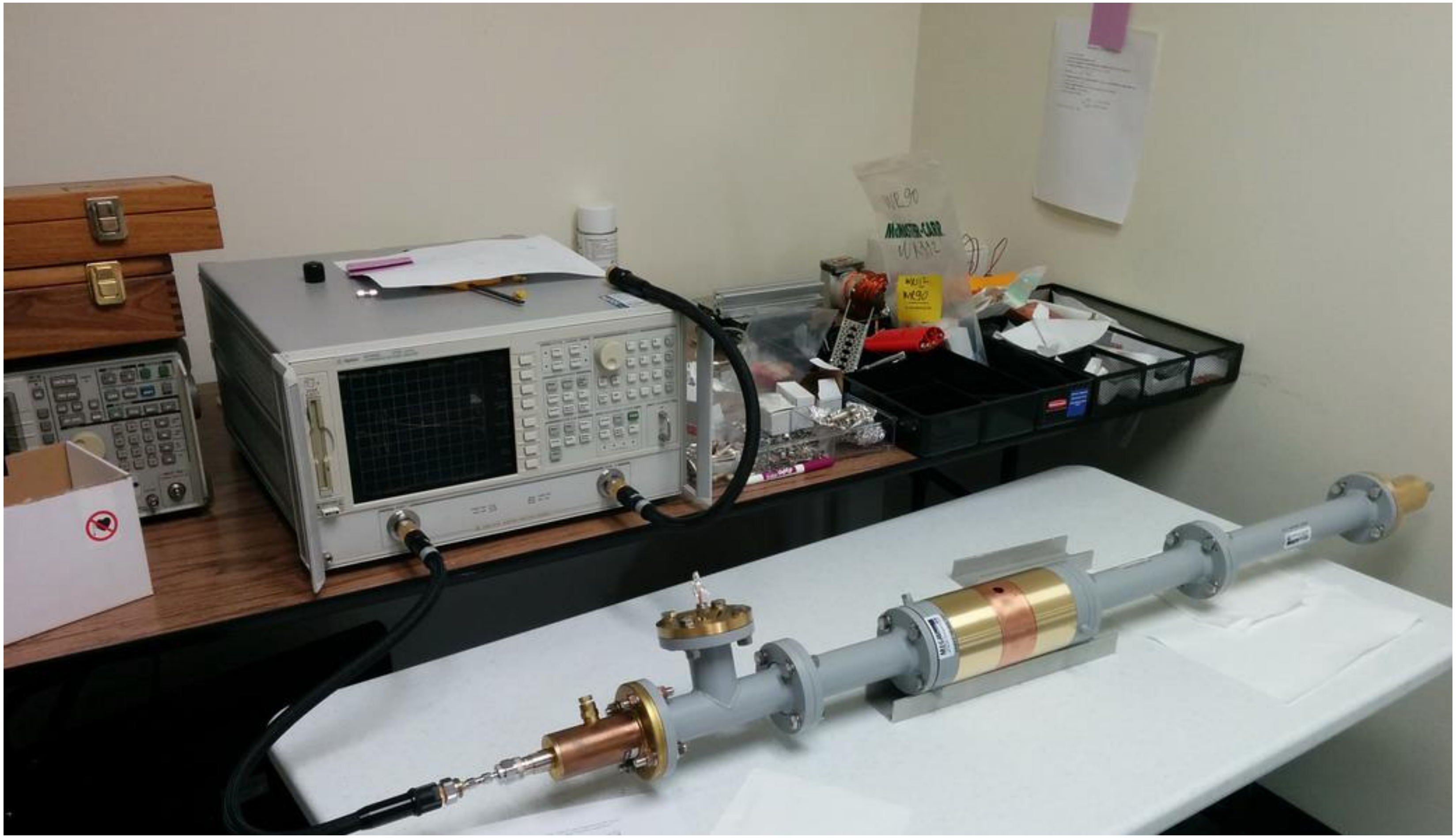
Copper deposition with sublayers

Euclid has developed a sputtering system for depositing of a variety of metallization and dielectric deposition applications.

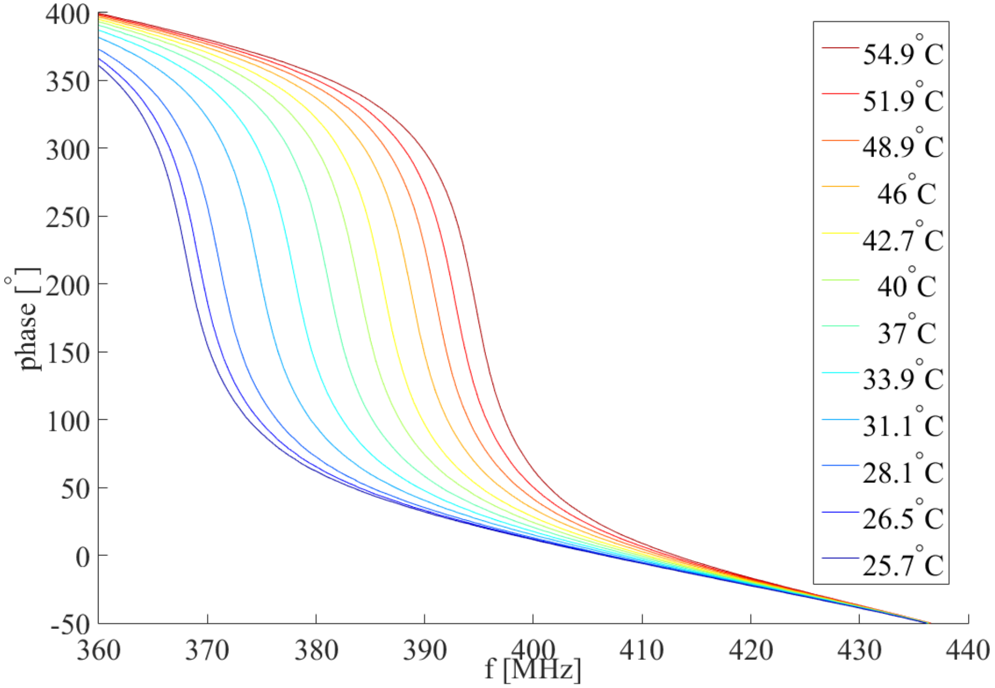


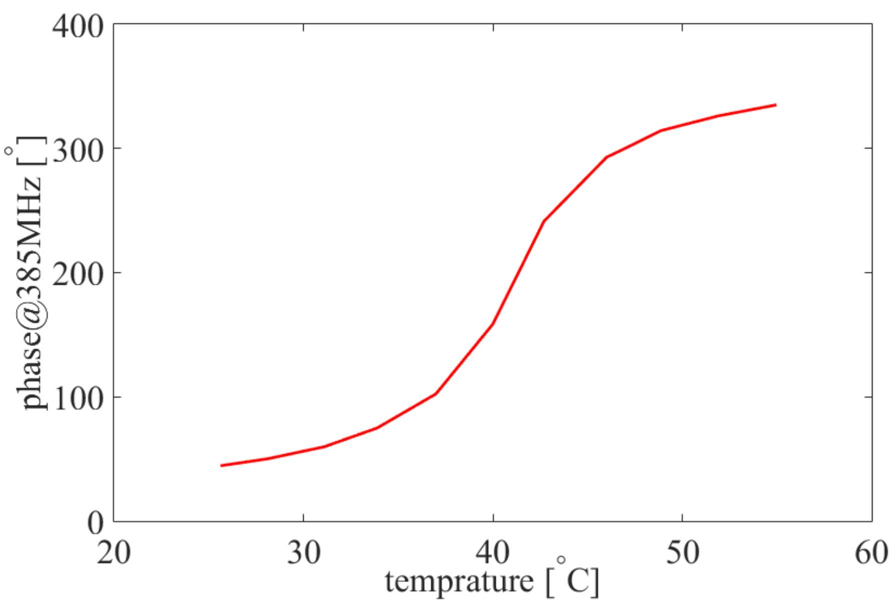
Partial assembly

Ferroelectric Tuner full assembly

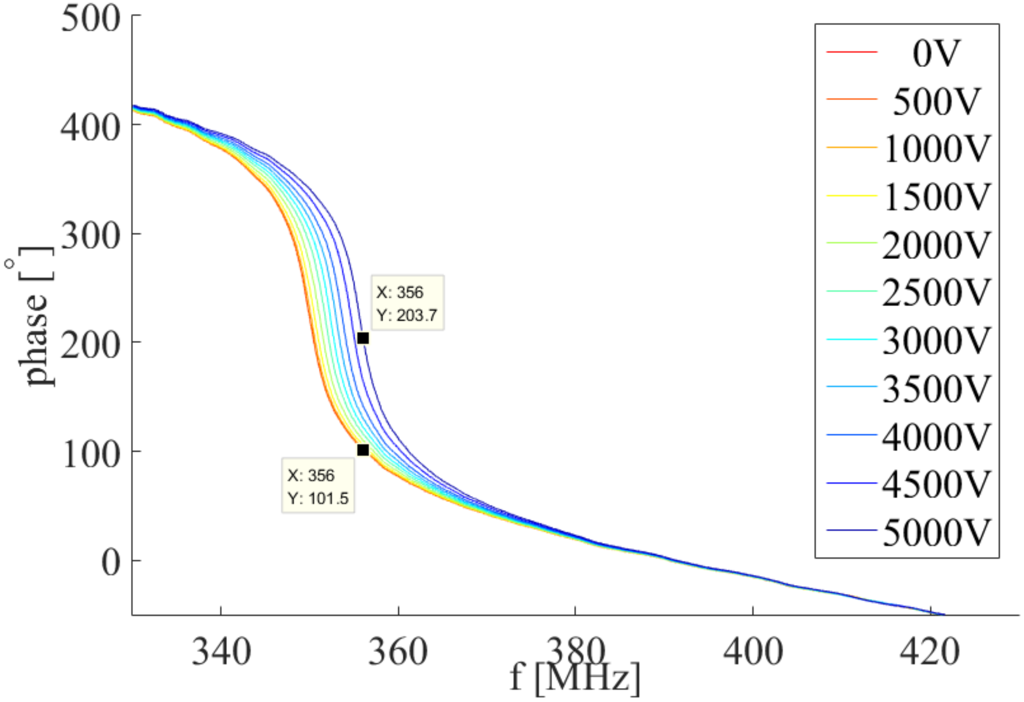


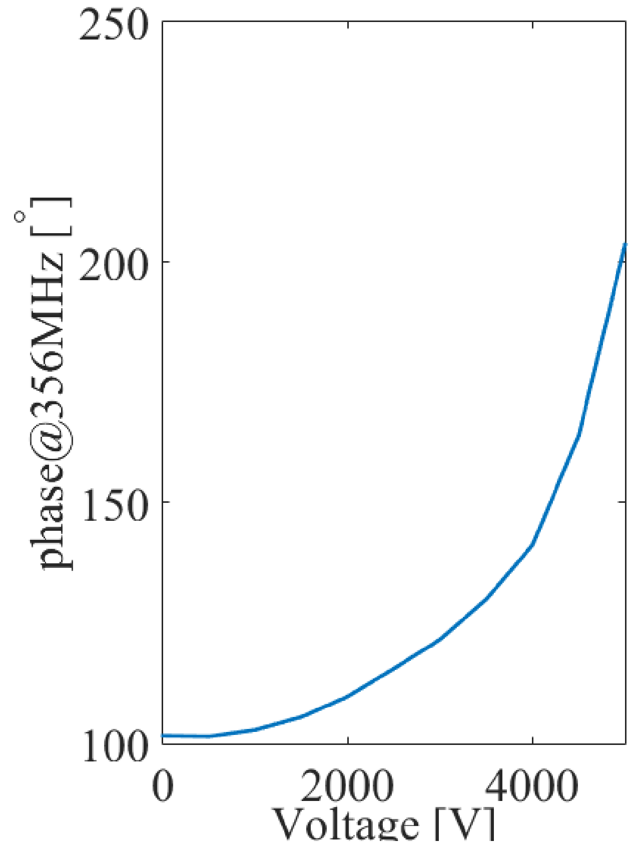
Tuning with temperature



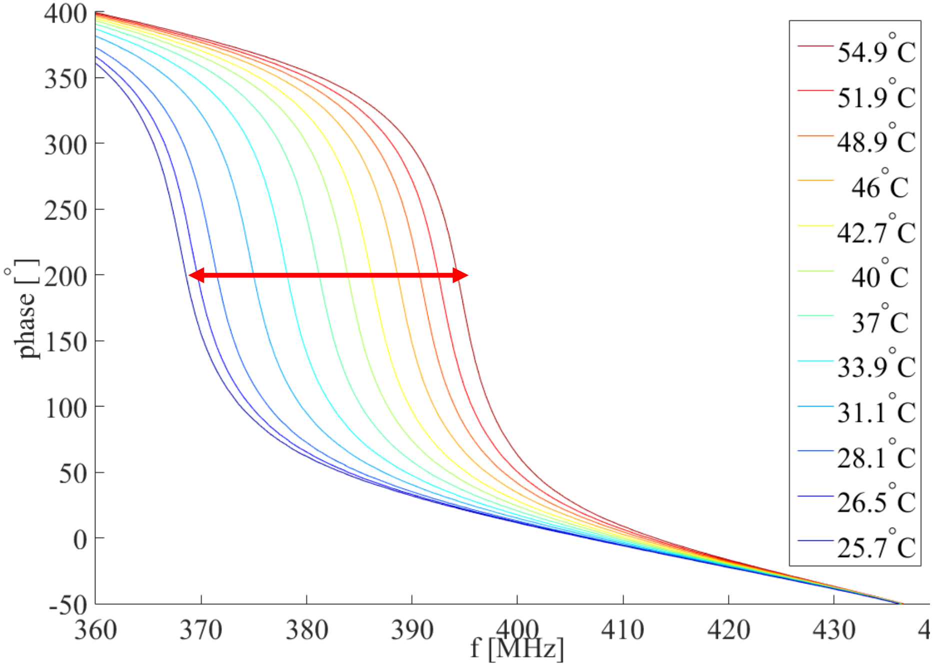


Tuning with DC bias

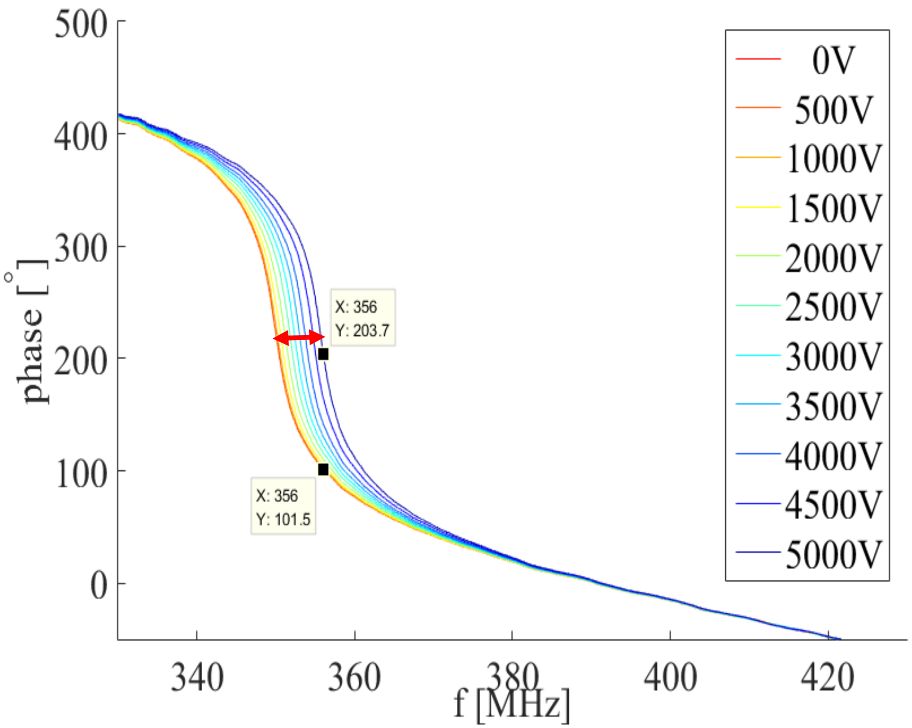




Tuning with temperature and DC bias

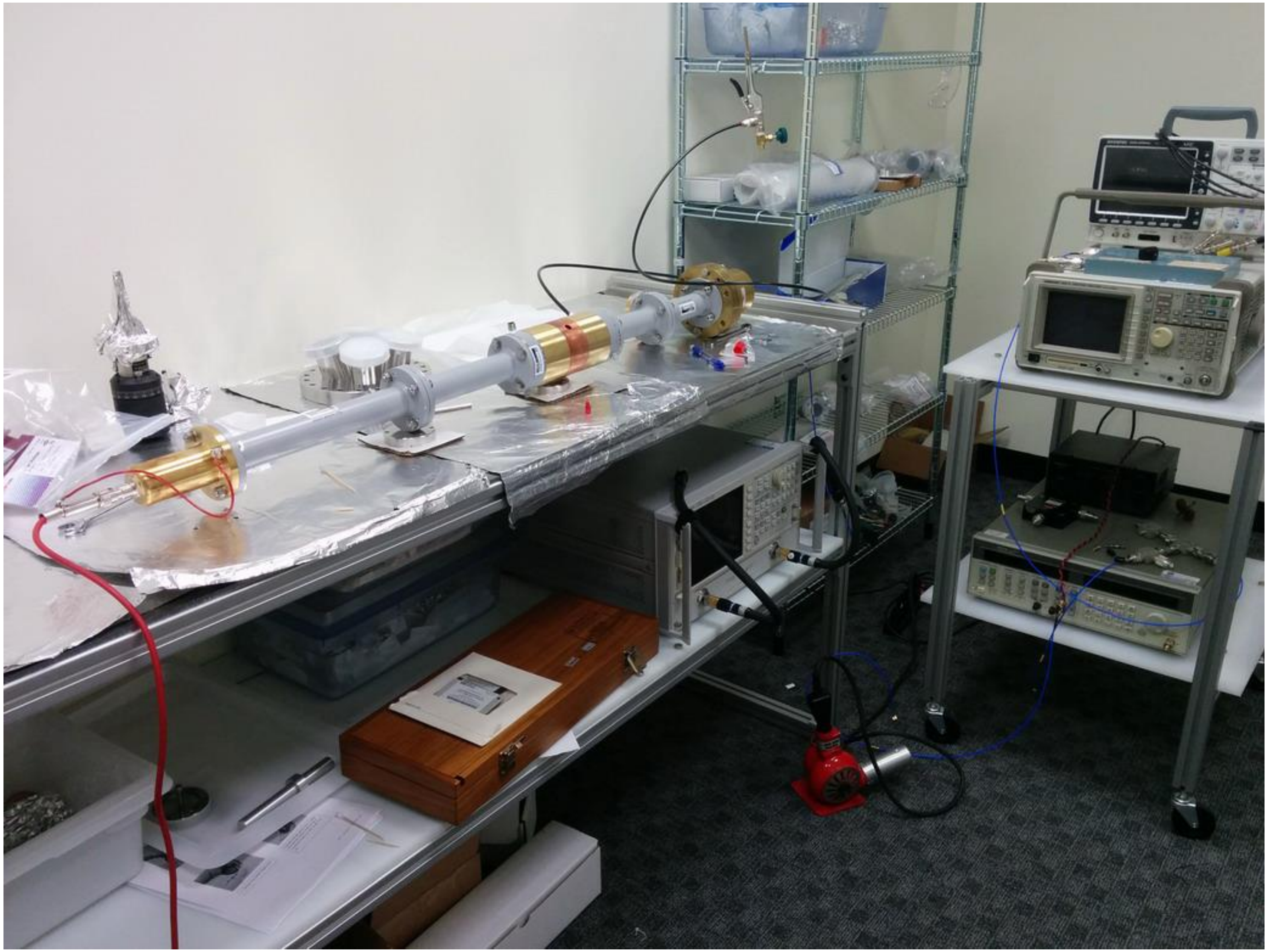


Temperature: slow but wide tuning range

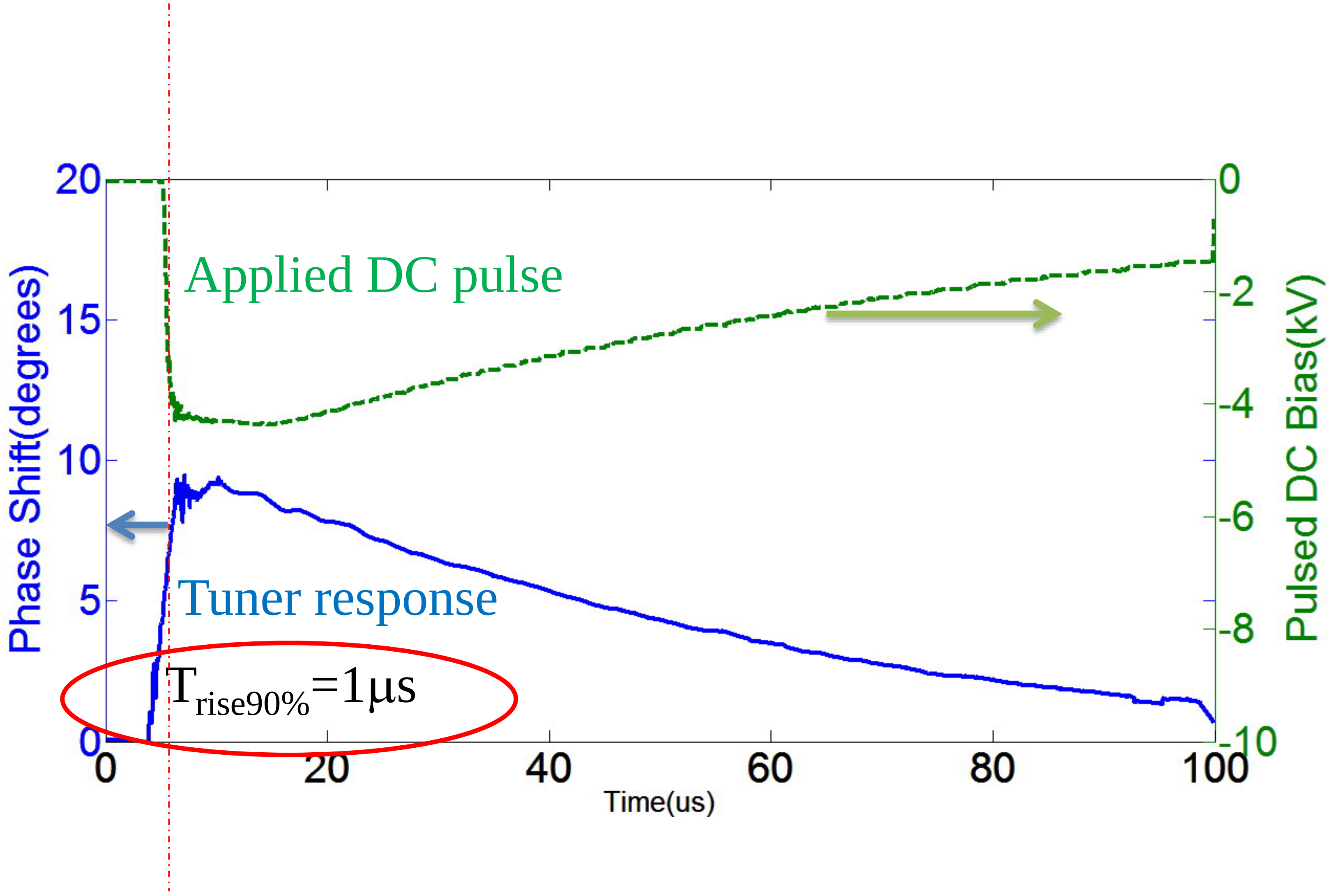


DC voltage: fast but narrow tuning range

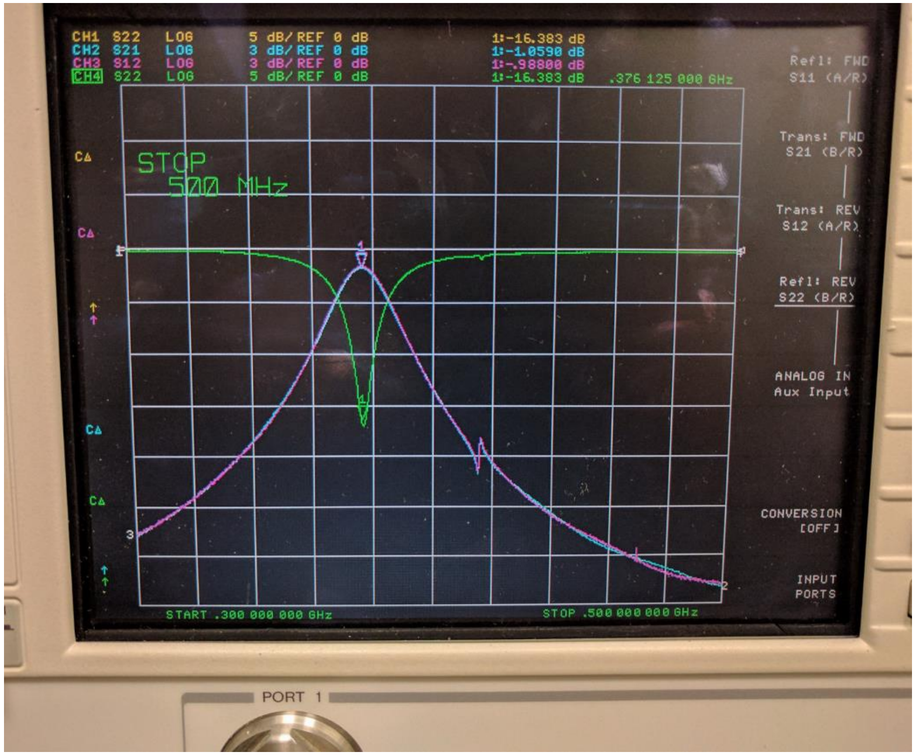
Tuning with the fast <μs range DC pulser



Tuning with fast DC pulse



RF Power Loss



Just measured, the new metalized ferroelectric element has -0.9dB S21 equivalent to 20% rf power loss, which is a big improvement from the first measurements (-2.6dB or 45%), while the bare tube RF loss is -0.5dB or 10% .

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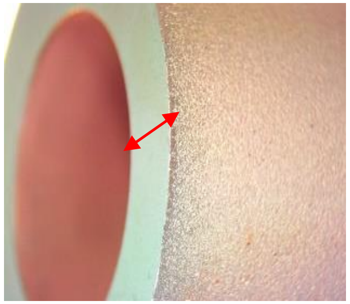
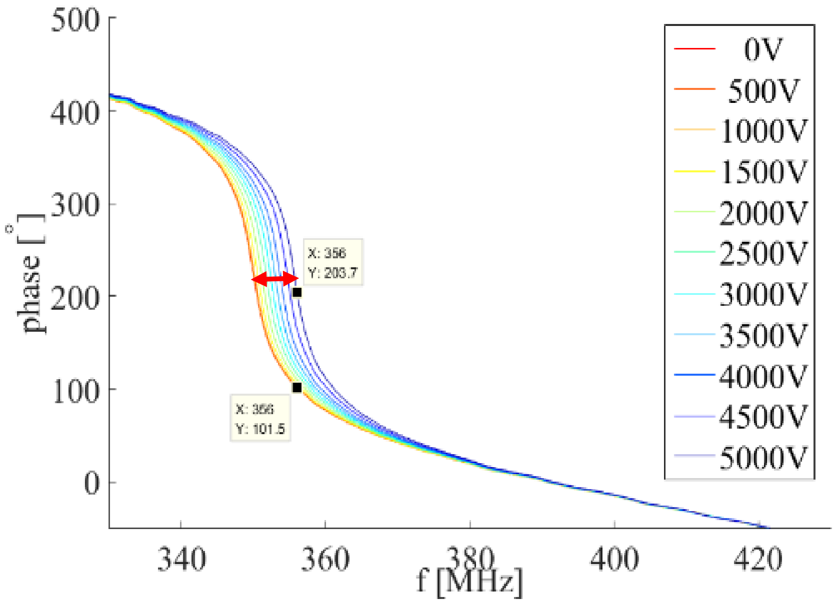
Pass to the High Power Test

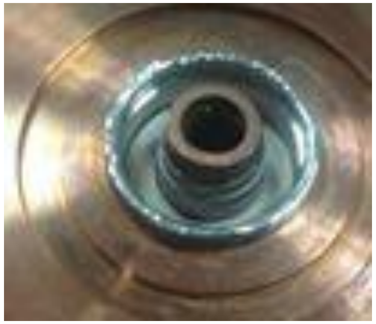
(1) RF Losses control, surface
DC breakdown prevention



Euclid sputtering system



(2) Brazing of the new developed BST/MgO ferroelectric ceramic to copper



In collaboration with FNAL/CPI (?), BNL , JLAB

- New 2017 Phase I NP "A High Power CW Input Coupler with Reduced Static and Dynamic Losses"

Tasks

- Task 1: Design simulation studies for the ferroelectric phase shifter design.
- Task 2: Development of a ferroelectric material having a dielectric constant in the range 80-150, tunability 5-6% at 15-20 kV/cm and Q×f ~ 1500-1700.
- Task 3: Final design optimization of the tuning elements to further minimize losses and to improve efficiency. A HV connector design.
- Task 4: Engineering design for the phase shifter.
- Task 5. Phase shifter manufacturing and assembling.
- Task 6: Low power tests of the ferroelectric phase shifter under temperature and high dc bias control voltages. Fast < μs switching demonstration.
- Task 7: High-power test.

(need to work close with industry/BNL/FNAL on brazing issue)

Commercialization (1)

J.F.Scott, Science, 2007.

Base-metal-electrode capacitors. **BST-based ceramic capacitors** are a commodity and account for the bulk of all condensers used in electronics (billions per year). These are multilayer capacitors with Ag/Pd electrode stacks. Present efforts are to **increase high voltage performance to higher breakdown voltages and to further reduce costs** by replacing silver-palladium with base metals, especially nickel.

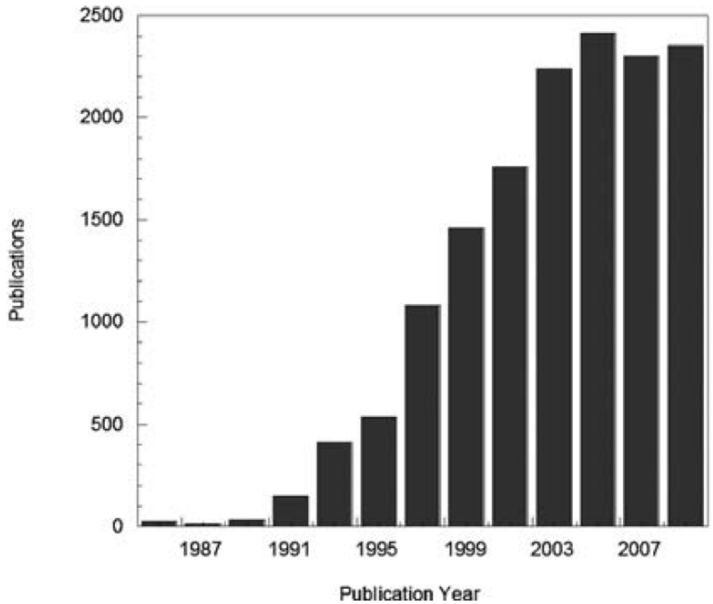


Fig. 1 Number of publications in the Web of Science database with "ferroelectric" and "film" as keywords excluding "multiferro" and "polymer" for two years intervals from 1985 to 2009.

Phased-array radar. Thin-film ferroelectrics exhibit a large decrease in dielectric constant with application of modest voltages. This suggested that they could be **used as the active phase-shift element** in phased-array radar, a **project studied carefully by researchers at Grumman and TRW** in the United States

Commercialization (2)

Multi-band radios are necessary nowadays to provide optimal data rates in a network with a varied and greasy landscape of coverage areas (3G, HSPA, LTE, etc.). As required the number of bands are increased, the total cost of discrete RF filters justifies **the use of tunable RF filters.** The main requirements for a tunable filter are high unloaded quality factor, wide tuning range, high tuning speed, high linearity, and small size. ….**Thanks to the numerous technology and the recent developments in design and implementations of the tunable RF filters, usage of these filters has increased exponentially.**

Barium Strontium Titanate Tunable Filter:

BST has been found as one of the most suitable ferroelectrics for the tunable filter application as it has a higher dielectric constant, lower losses and higher tunability. Moreover, its high capacitance density allows for construction of higher capacitor values within a smaller area. Unlike conventional varactor diodes, **BST varactor** have no forward conduction region and **perform well in applications involving high RF voltage swings over the full range of the DC tuning voltage.**

K.Thilagavathi, M. Balakumar. Review on RF Tunable Filters, IJIET, 8, 42, 2017.

Commercialization (3)

Properties	Varactor Diode	MEMS	BST	DTC	YIG
Tunability (High Q)	Good	Low	Good	High	High
RF loss	Moderate (Q < 60 typically)	Very Good (Q < 200)	Moderate (Q < 100 typically)	Moderate (Q < 50 typically)	Very good (Q < 200)
Control Voltage	< 10V	< 60V	<5-30V	< 30V	< 28V
Tuning Speed	Fast 1-5 nanoseconds	Slow > 5 microseconds	Fast < 30 nanoseconds	Fast < 12 nanoseconds	Slow > 1 milliseconds
Power Handling Capability	Poor	Excellent	Trades with control voltage	Excellent	Excellent

K.Thilagavathi, M. Balakumar. Review on RF Tunable Filters, IJIET, 8, 42, 2017.

Commercialization (4)

M.Haghzadeh et al. IEEE Transactions on Microwave Theory and Techniques (Volume: 65, Issue: 6, June 2017) 2030 – 2042.

All-Printed Flexible Microwave Varactors and Phase Shifters Based on a Tunable BST/Polymer.

This paper presents all-printed varactors and phase shifters using direct-ink writing methodologies on flexible organic films. The key enabler is a novel ferroelectric nanoink that allows printing high dielectric constant, low loss, and electrostatically tunable dielectrics at extremely low temperatures. …Unlike conventional ferroelectric ceramics, this ferroelectric dielectric requires no sintering and can be printed on any substrate. After printing**, it is cured at temperatures below 200 °C. A high relative permittivity of ε_r = 38 and a very low dielectric loss of tan δ = 0.002 at f = 10 GHz** were measured for the printed sinterless dielectric.

Microstructural Evolution of Bulk Composite Ferroelectrics and Its Effect on the Microwave Properties

J. Synowczynski et al.Proceedings of American Ceramic Society 2016

A study was conducted to determine the influence of the processing conditions on the microstructural evolution and subsequent **microwave properties of (BST) MgO composites**. ……Experiments were designed to determine the effect of the processing at **three different stages during the fabrication process: powder processing, green body densification, and sintering schedule**… These compacts were then sintered at **three sintering temperatures (i.e, 1250C 1350C, and 1450C)** for 2 hours. ….The effect of these results on the microwave properties will be discussed in further detail.

Summary

The ultimate goal of the Phase II project is (1) design a ferroelectric element based on BST(M) material with the required parameters; (2) development of metallization technology with no residual effects; (3) the tuner engineering design; (4) the fast tuner fabrication; (5) fast < μs switching time demonstration (6) RF power loss

- Ferroelectric element has been designed and fabrication, ε ~ 100-150; loss factor ~ 1.0×10^{-3} at 700 MHz; tuning dielectric constant ~ 6% at 20kV/cm; residual effects can be mitigated with metallization technology
- the tuner assembled, bench tested, temperature (slow) tuning demonstrated with 360^0 range,
- dc voltage (fast) tuning demonstrated at < 1 μs ~100^0 range with successful mitigation of the residual effects on the ferroelectric-metal interface along with the -~0.9dB loss level of the overall loss factor of the high power tuner.