High mass Axion Dark Matter (DM) search utilizing *dielectric meta-material (DM)*

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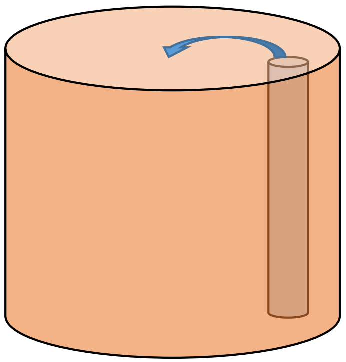
Contents

- Motivation & goal
- Metamaterial
- Anisotropic dielectric construction w/ dielectric metamaterial (DM)
- Axion haloscope cavity w/ DM
- Conclusion & Summary

Cavities used in CAPP-PACE 2018

10KSVZ 1st run

2.45~ 2.50GHz



0.59L copper cavity

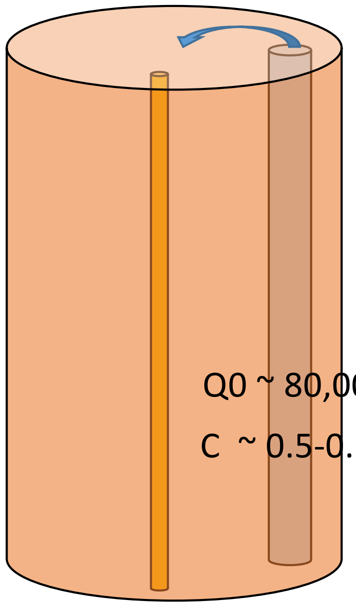
Q0 ~ 100,000

C ~ 0.6-0.65

Sapphire rod tuning

10KSVZ 2nd , 3rd run

2.5~ 2.6GHz



Q0 ~ 80,000

C ~ 0.5-0.6

w/ a fixed copper rod

Tuning by sapphire rod rotation

10KSVZ 4th run

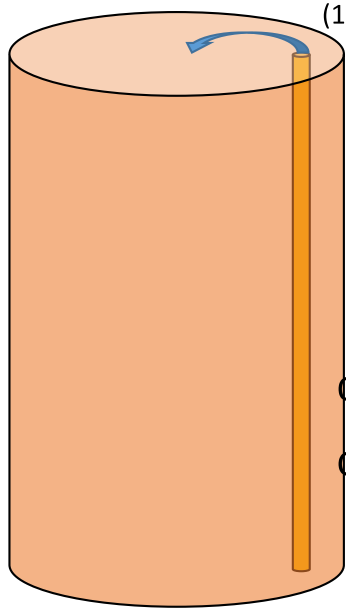
2.59~ 2.7GHz

KSVZ run

2.59GHz

(1MHz bandwidth)

1.12L copper cavity



Q0 ~100,000

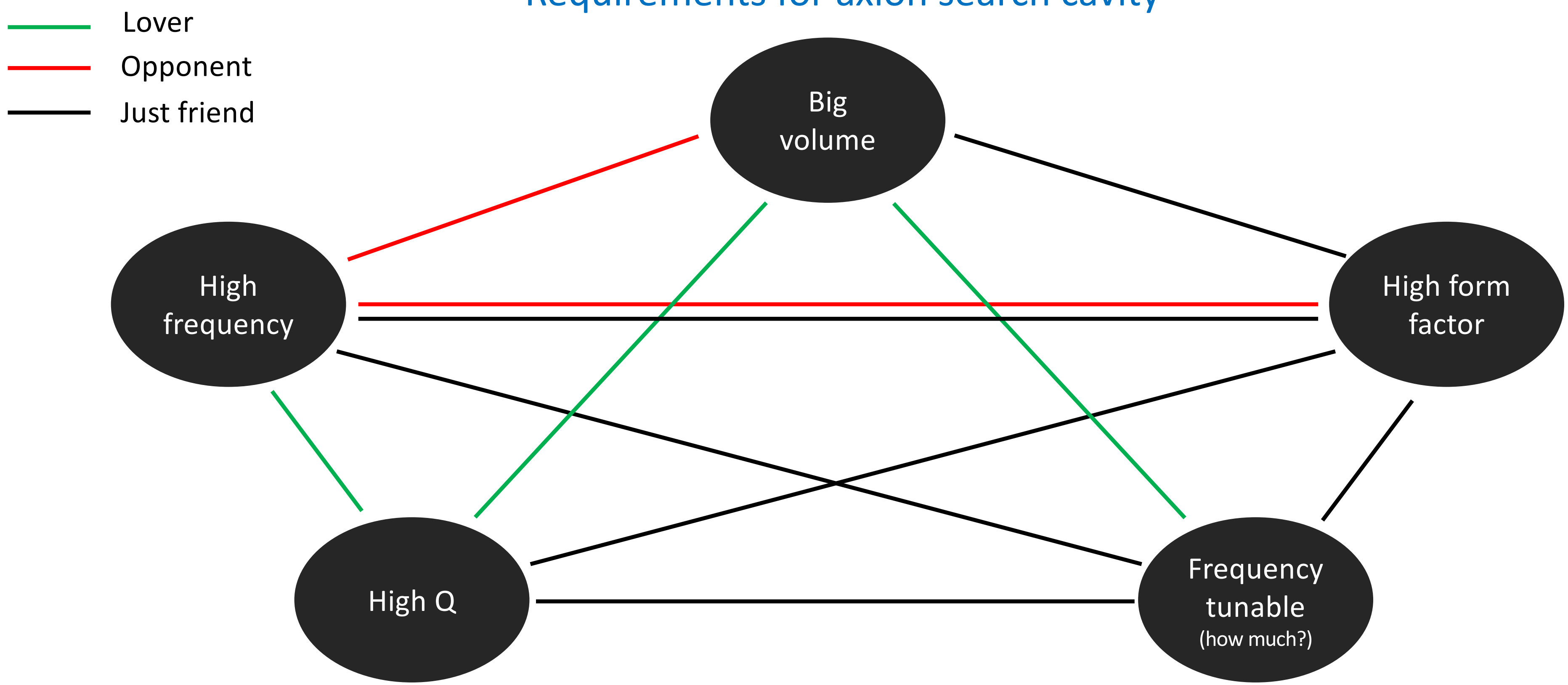
C ~ 0.62-0.66

Tuning by copper rod rotation

For High form factor, high Q

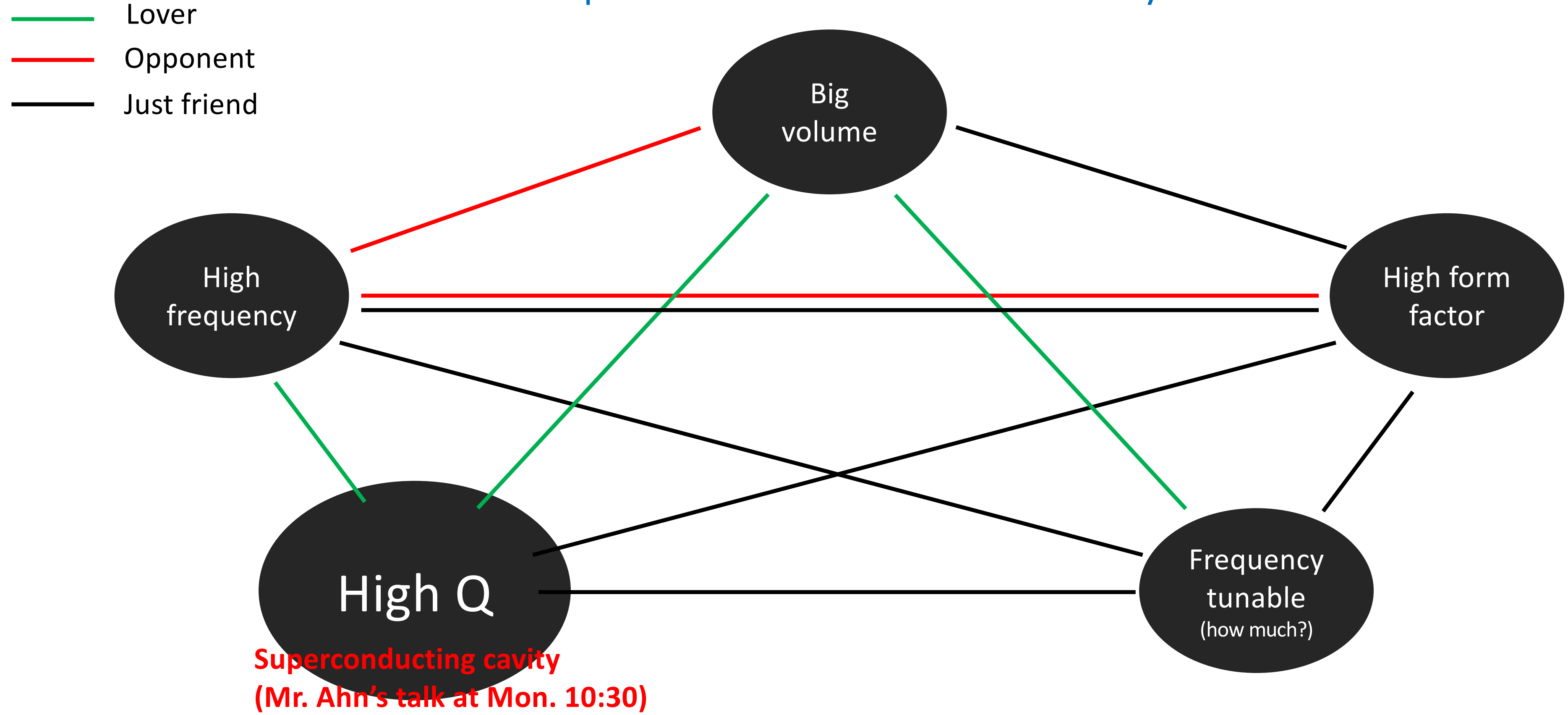
CAPP's microwave cavity R&D

Requirements for axion search cavity



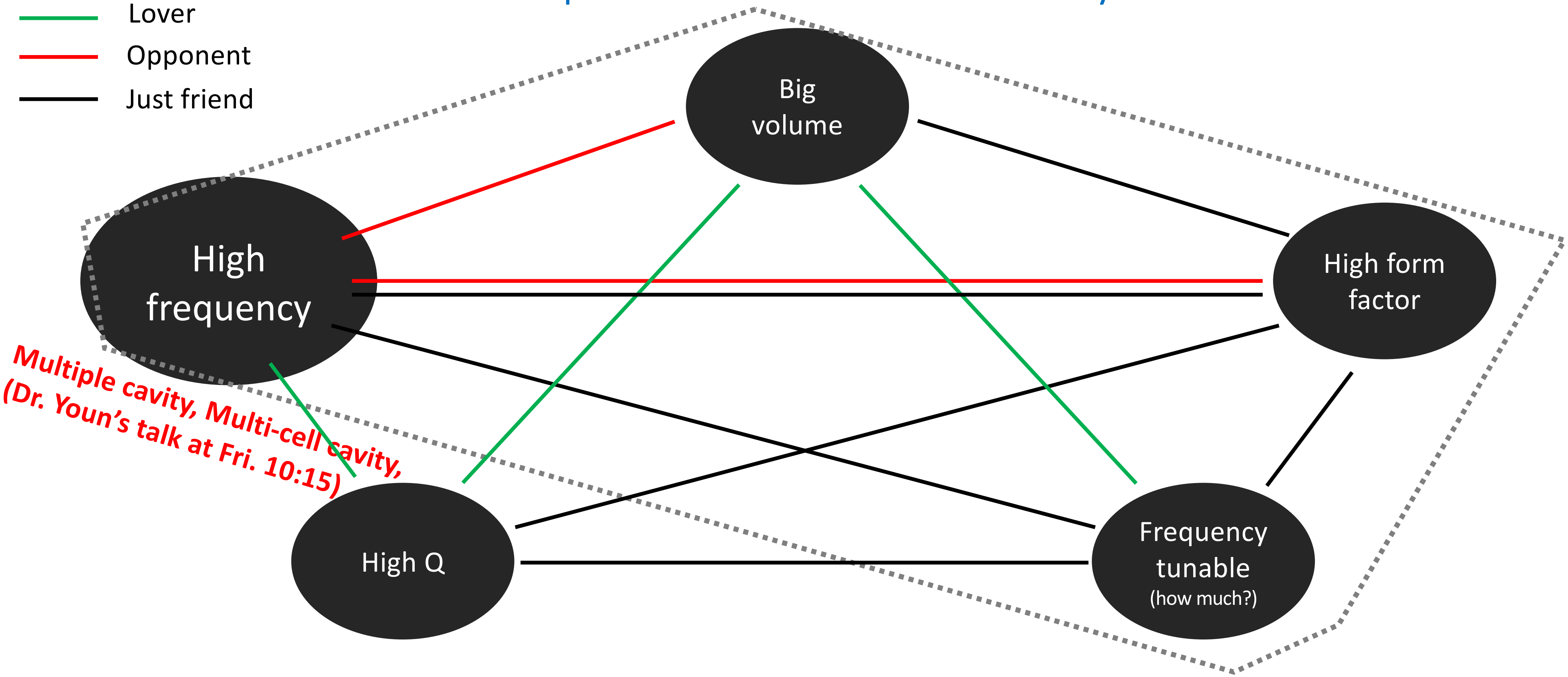
CAPP's microwave cavity R&D

Requirements for axion search cavity



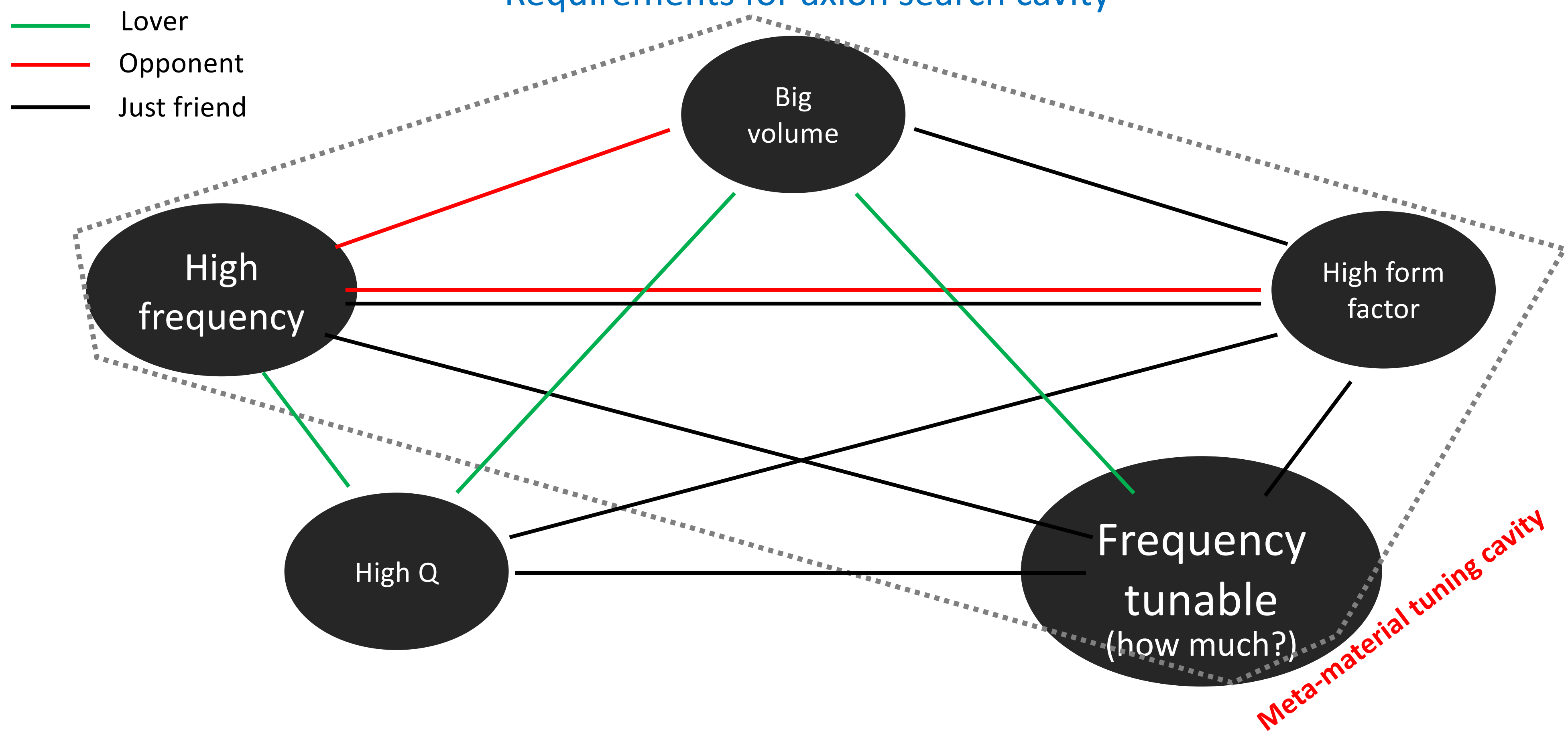
CAPP’s microwave cavity R&D

Requirements for axion search cavity



CAPP’s microwave cavity R&D

Requirements for axion search cavity



Frequency tuning of microwave cavity

(most cases such as accelerator, plasma physics, etc.)
Frequency tuning w/ screws
(Frequency matching w/ operational frequency)

Small range, in-situ tuning not available
$\Delta f / f \ll 1\%$

(Axion search)
In situ frequency tuning by rotating metal rods / dielectric rods

$\Delta f / f > 1\%$
Wide range tuning, field localization or asymmetric field distribution

Frequency tuning of microwave cavity

(most cases such as accelerator, plasma physics, etc.)
Frequency tuning w/ screws
(Frequency matching w/ operational frequency) ➧ Small range, in-situ tuning not available
$\Delta f / f << 1\%$

(Axion search)
In situ frequency tuning by rotating metal rods / dielectric rods ➧ Wide range tuning, field localization or asymmetric field distribution
$\Delta f / f > 1\%$

Ideal frequency tuning method for axion haloscope ➔

1. **Azimuthal symmetric positioning** of ***(low loss)*** dielectric for field symmetry
2. Just change dielectric constant!

Frequency tuning of microwave cavity

(most cases such as accelerator, plasma physics, etc.)
Frequency tuning w/ screws
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Ideal frequency tuning method for axion haloscope ➔

1. **Azimuthal symmetric positioning** of ***(low loss)*** dielectric for field symmetry
2. Just change dielectric constant!

This is almost impossible naturally

Frequency tuning of microwave cavity

(most cases such as accelerator, plasma physics, etc.)
Frequency tuning w/ screws
(Frequency matching w/ operational frequency) ➔ Small range, in-situ tuning not available

(Axion search)
In situ frequency tuning by rotating metal rods / dielectric rods ➔ Wide range tuning, field localization or asymmetric field distribution

Ideal frequency tuning method for axion haloscope ➔

1. **Coaxial positioning** of ***(low loss)*** dielectric for field symmetry
2. Just change dielectric constant!

This is almost impossible naturally

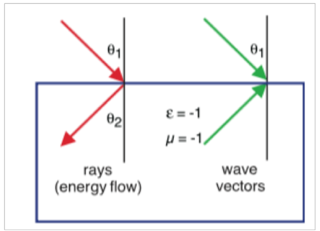
Meta-material ?

artificial electromagnetic materials

“**Meta-**” means “altered, changed” or “higher, beyond”

*Negative index meta-material (NIM)

Left Handed Material (LHM)



Permittivity<0
permeability<0

- Cloaking
- Perfect-lens

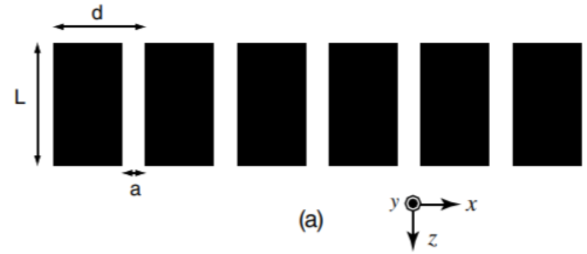
Band gap: photonic crystal

Artificial high refractive index metamaterial ➔ Effective dielectric

*Science **305,** 788 (2004)

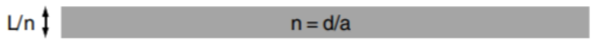
Metallic metamaterial (MM) with a high index of refraction

Metallic metamaterial



(a)

Real dielectric



(b)

TM case Waveguide mode in the slit

Refractive index → $n = d/a$ → $\varepsilon = (d/a)^2$

→ $\varepsilon_{eff} = \varepsilon_x$

TE case evanescent mode in the slit

Refractive index → $\varepsilon_{eff} = \frac{\pi^2 d}{8a}\left[1-(\pi c)^2/(a\omega)^2\right]$

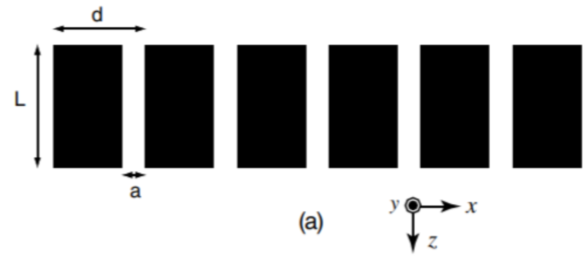
If $a \ll \lambda$, $\varepsilon_{eff} \sim \frac{\pi^2 d}{8a}$

→ $\varepsilon_{eff} = \varepsilon_y$

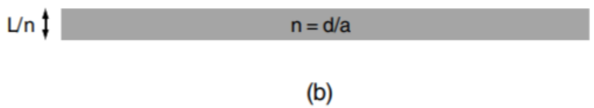
PRL **94,** 197401 (2005)

Metallic metamaterial (MM) with a high index of refraction

Metallic metamaterial



Real dielectric



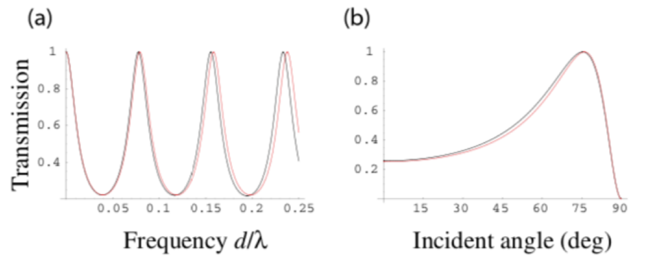


FIG. 2 (color). The transmission coefficient of the metal film (black lines) and the corresponding effective dielectric slab (red lines). The thickness of the metal film is $L/d = 25/4$. The effective refractive index of the slab is $n = d/a = 4$. (a) Spectrum at normal incidence. (b) Transmission at oblique incidence for the frequency $\omega = 0.05 \times d/\lambda$.

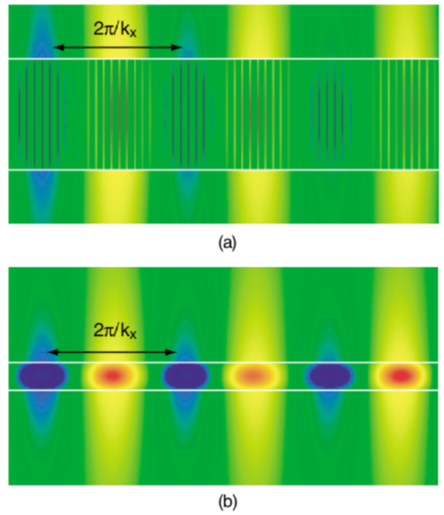


FIG. 4 (color). Snapshots of the H_y field distributions of the fundamental waveguide modes of the metal film [shown in (a)] and the corresponding effective dielectric slab [shown in (b)] for $n = d/a = 4$, $L/d = 25/4$. The red color indicates positive amplitude, while the blue color indicates negative amplitude. The white lines in (a) and (b) outline the film and the slab, respectively. The normalized excitation frequency is $\omega = d/\lambda = 0.0516$. The arrows indicate the periodicity of the field.

Refractive index → $n = d/a$

Dielectric property controllable

lossy

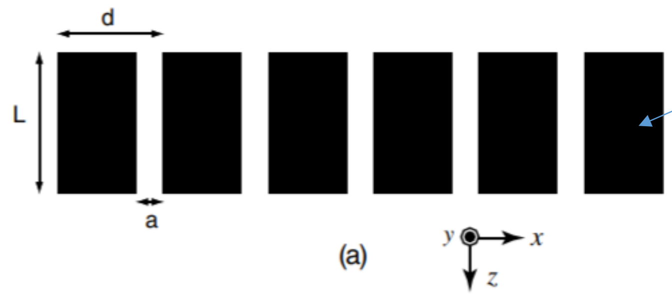
Not easy to make application

PRL **94, 197401 (2005)

What if we change metal dielectric?

Low loss +
easy guess of field distribution → easier manipulation

Suggestion of anisotropic dielectric meta-material (DM)



Just change the material to dielectric !

We can avoid big loss caused by metal

For TM mode (H polarization : y direction)

$$E_{ave} = [E(d\text{-}a)/\varepsilon + Ea]\,/d = [\,(d\text{-}a)/\varepsilon + a\,]\,E/d$$

$$E_{ave} = \frac{(d\text{-}a)/\varepsilon + a}{d}\,E0$$

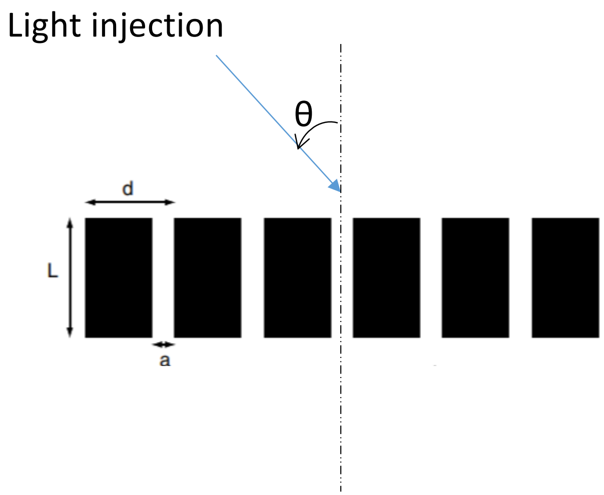
$$\varepsilon_{eff} = \frac{d}{(d\text{-}a)/\varepsilon + a}$$

For TE mode (E polarization : y direction)

$$\varepsilon_{eff} = \varepsilon_{ave} = \frac{a + (d\text{-}a)\varepsilon}{\mathrm{d}}$$

How to prove?

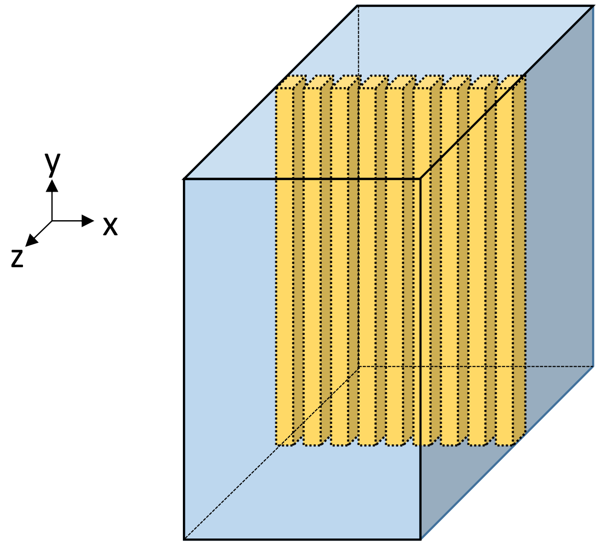
Conventional way in optic



➔ Check transmittance

numerical analysis and experiment

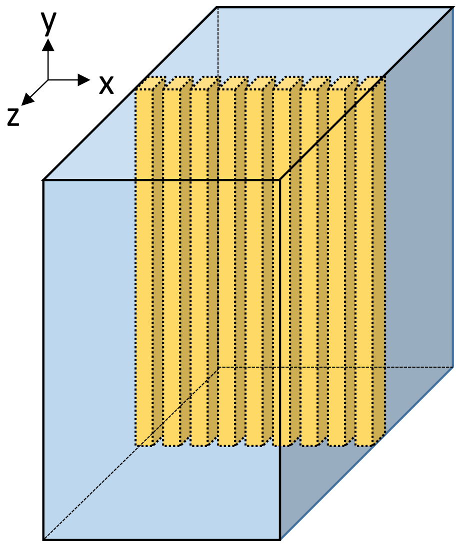
Alternative way using microwave cavity

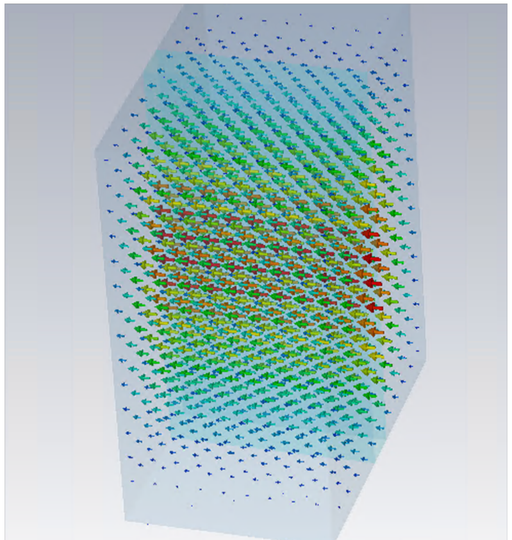


➔ Check TM(TE) modes frequency

How to prove?

By changing the εx, εy, εz, check the mode frequencies below



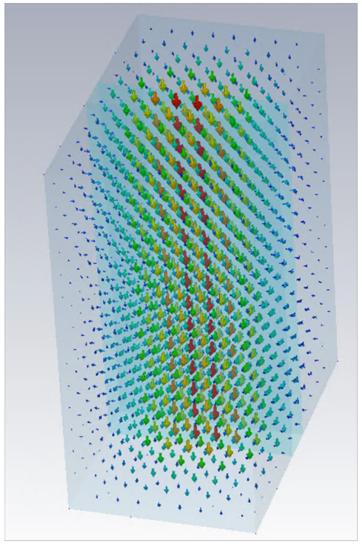


X polarized Transverse mode

In the view of ky, kz: TE01(10)1

In the view of kx: TM110

TE011

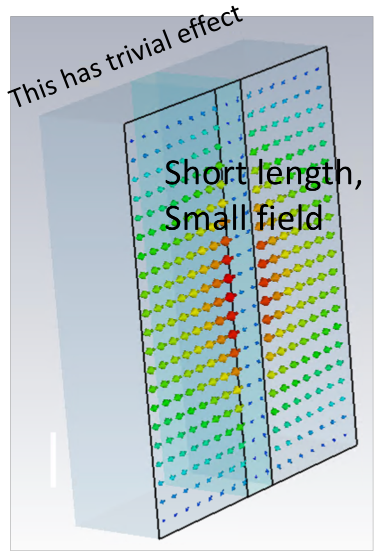


y polarized Transverse mode

In the view of kx, kz: TE01(10)1

In the view of ky: TM110

TE101



z polarized Transverse mode

In the view of kx, ky: TE01(10)1

In the view of kz: TM110

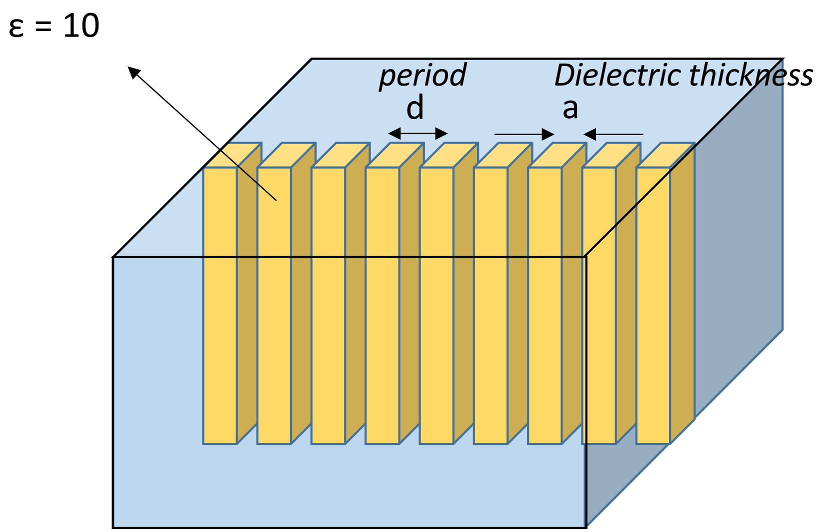
TM110

For convenience, set kz as standard

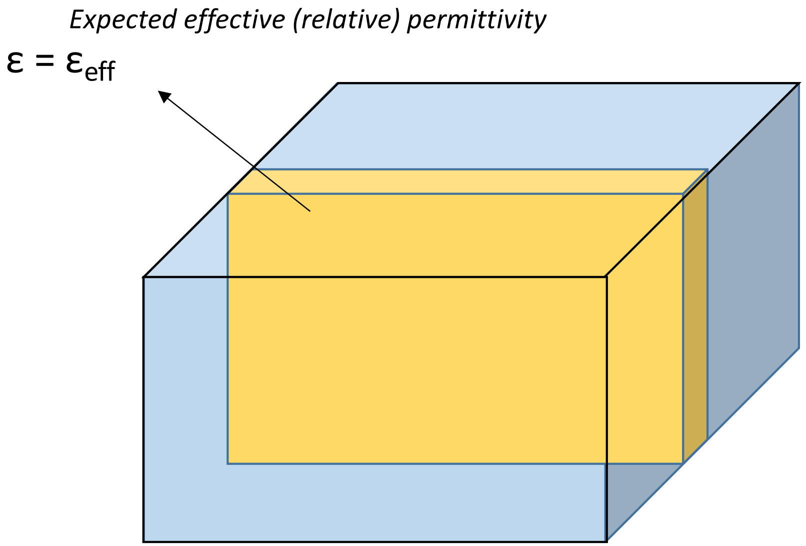
*CST MWS used

Real anisotropic *vs.* Dielectric meta-material

CST MWS used



VS



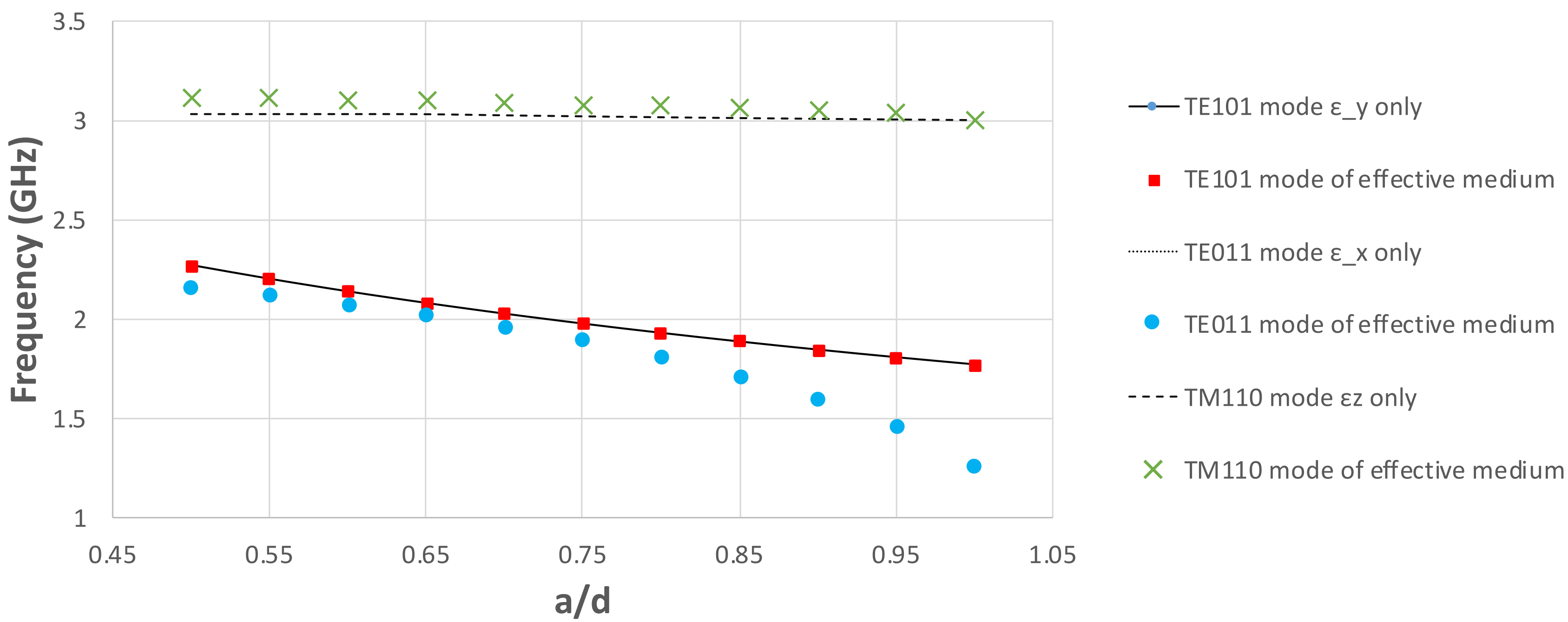
Changing a/d 0.5 ~ 1

Let's compare cavity modes between anisotropic cavity and DM used one

Real anisotropic *vs.* Dielectric meta-material

CST MWS used

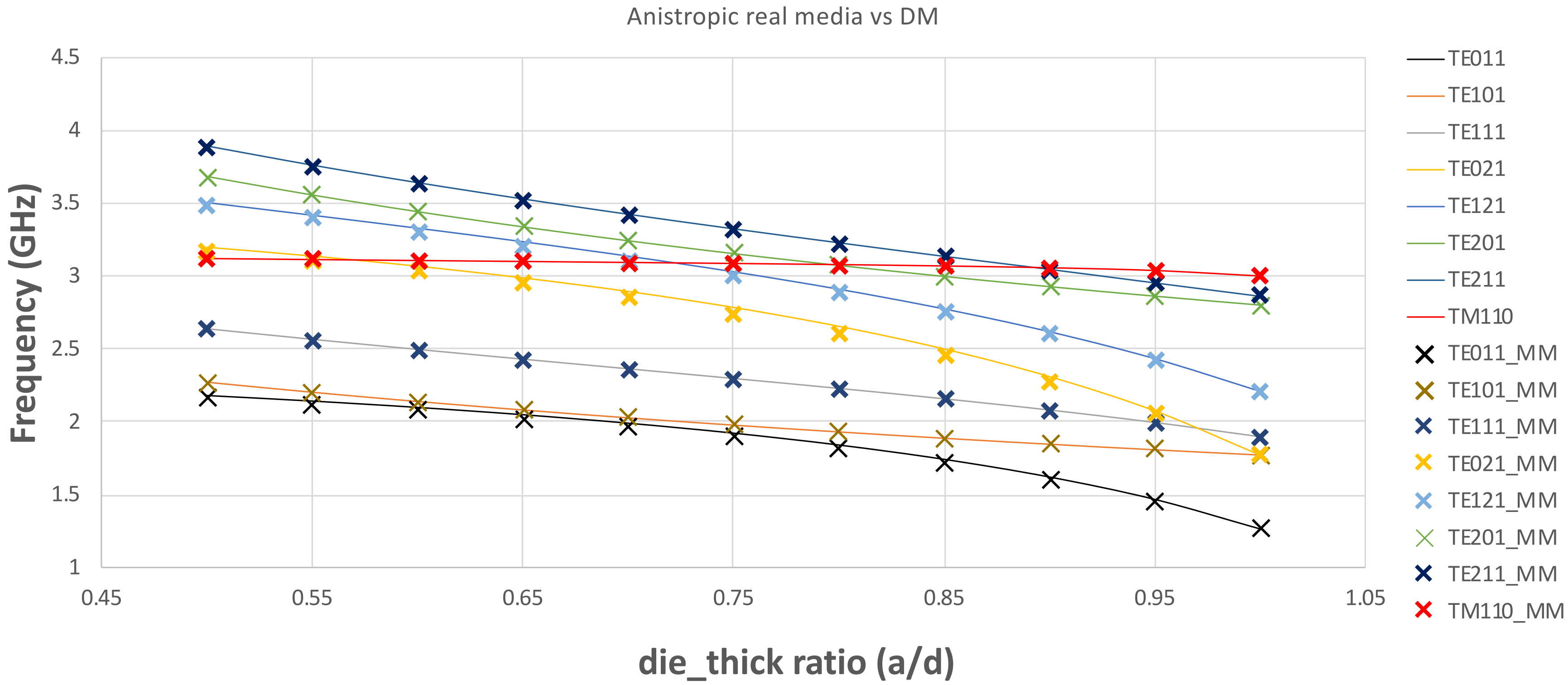
Changing εx, εy, εz respectively



Effective dielectric medium's anisotropic properties well match to real dielectric cases

Real anisotropic *vs.* Dielectric meta-material

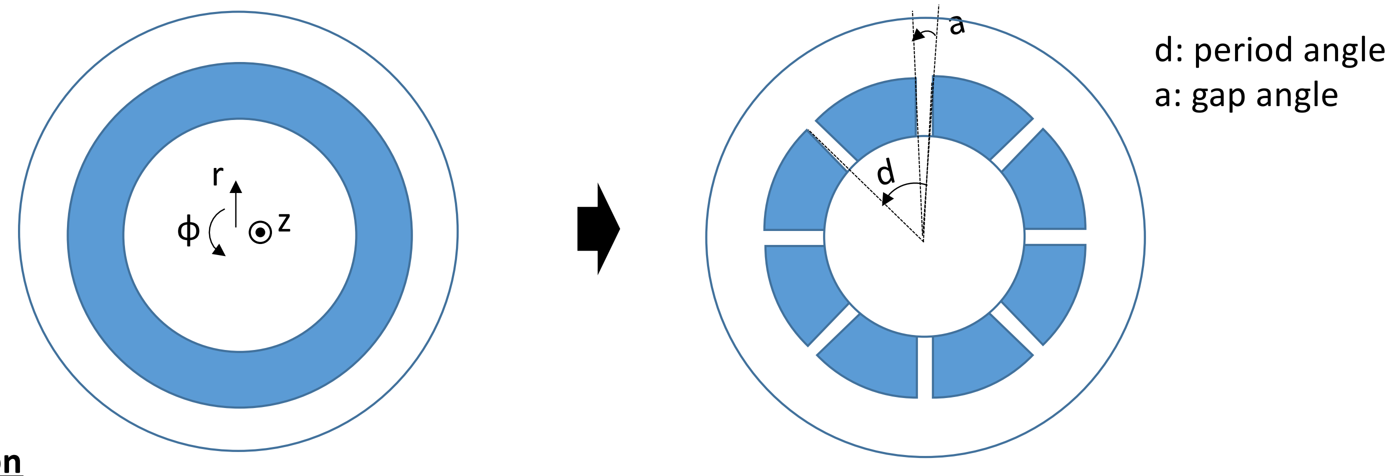
CST MWS used



Effective dielectric medium's anisotropic properties well match to real dielectric cases

Cylinder?

Applying DM to Cylindrical cavity



MY expectation

For ϕ polarized mode (H field : z direction)

$$E_{ave} = [E(d\text{-}a)/\varepsilon + Ea]\ /d = [\ (d\text{-}a)/\varepsilon + a\ ]\ E/d \qquad E_{ave} = \frac{(d\text{-}a)/\varepsilon + a}{d} E0 \qquad \varepsilon_{eff} = \varepsilon_{\phi} = \frac{d}{(d\text{-}a)/\varepsilon + a}$$

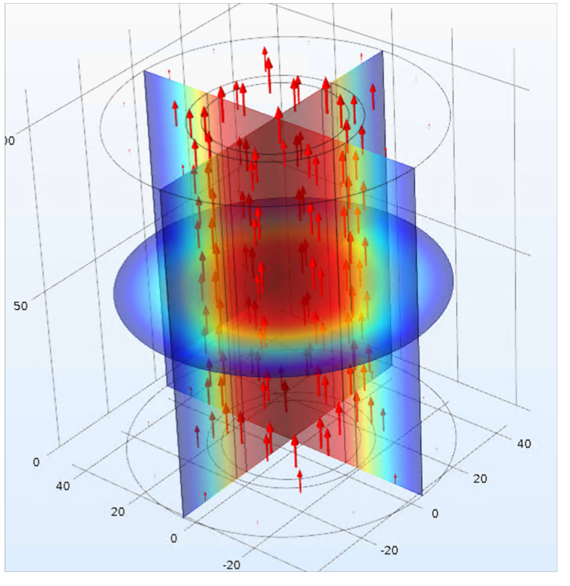
For z polarized mode (H field : ϕ direction)

$$\varepsilon_{eff} = \varepsilon_{ave} = \varepsilon_z = \frac{a + (d\text{-}a)\varepsilon}{\mathrm{d}}$$

Eigen mode analysis on cylindrical cavity with anisotropic behavior simulation

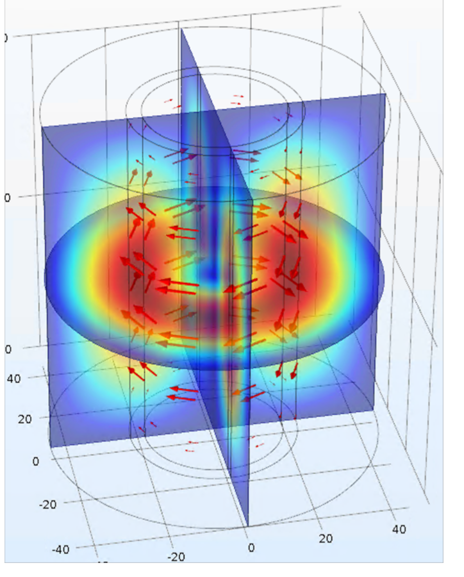
Comsol used

Z polarized mode : TM010



$$\varepsilon_{eff} = \varepsilon_{ave} = \varepsilon_z = \frac{a + (d-a)\varepsilon}{d}$$

ϕ polarized mode : TE011

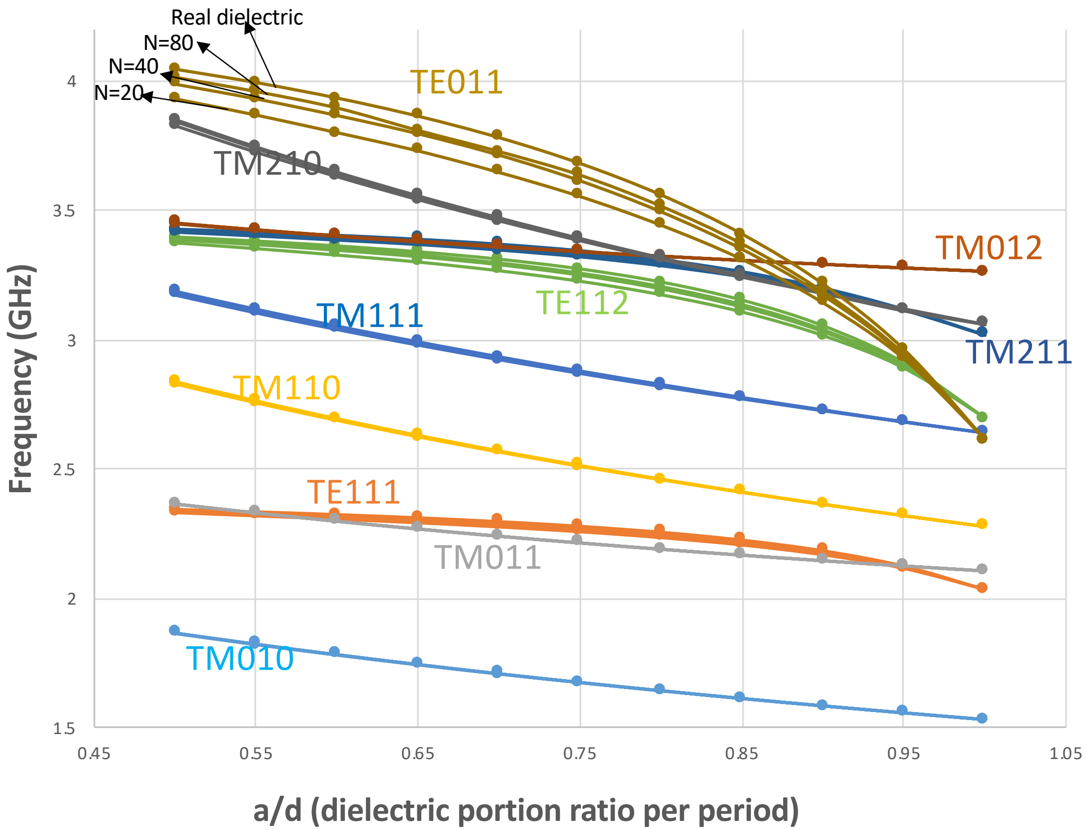


$$\varepsilon_{eff} = \varepsilon_{\phi} = \frac{d}{(d-a)/\varepsilon + a}$$

*R polarization effect would be weak

DM used cavity *vs.* original anisotropic cavity

Comsol used



*The discrepancy happens due to the fringe effect. The deviation decreases as N increases.

εϕ, εz, εr applied altogether

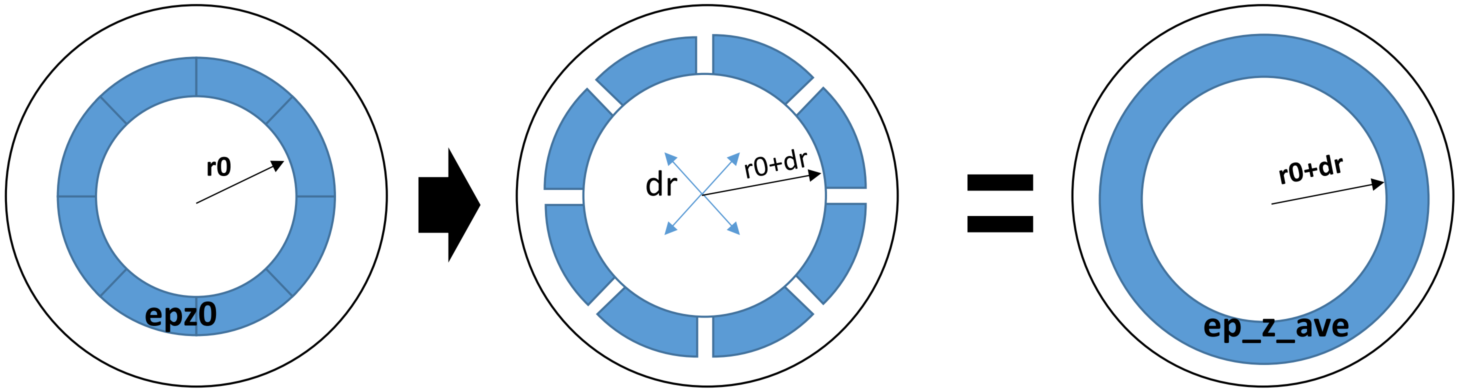
a/d	ε_ϕ	ε_z	ε_r
0.5	1.818	5.5	5.5
0.55	1.980	5.95	5.95
0.6	2.174	6.4	6.4
0.65	2.410	6.85	6.85
0.7	2.703	7.3	7.3
0.75	3.077	7.75	7.75
0.8	3.571	8.2	8.2
0.85	4.255	8.65	8.65
0.9	5.263	9.1	9.1
0.95	6.897	9.55	9.55
1	10.000	10	10

Real dielectric used cavity
&
DM used cavity

Almost equivalent behavior!!

Application on Axion haloscope

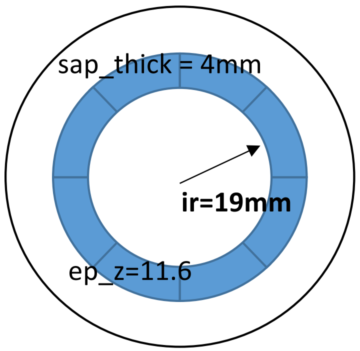
Frequency tuning TM_{0N0} mode



Spreading the dielectric pieces effectively changes
inner radius as well as effective dielectric constant

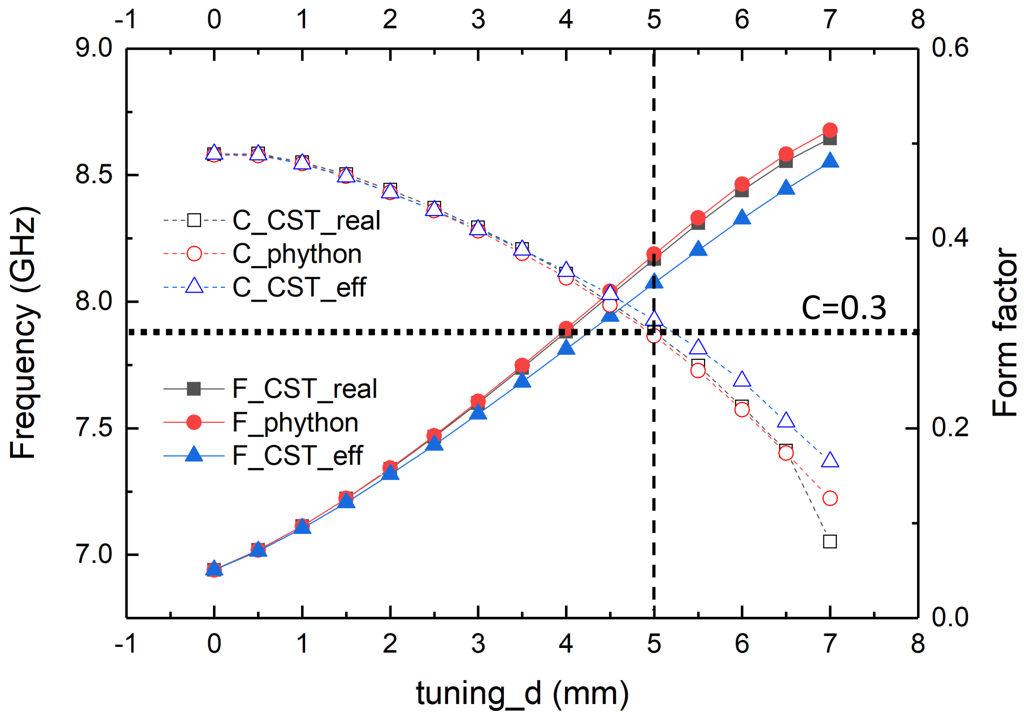
Example: TM030 mode tuning w/ DM

Dielectric: sapphire



cavity_radius = 45mm

(CAPP-PACE cavity radius)



> 1GHz frequency tuning range

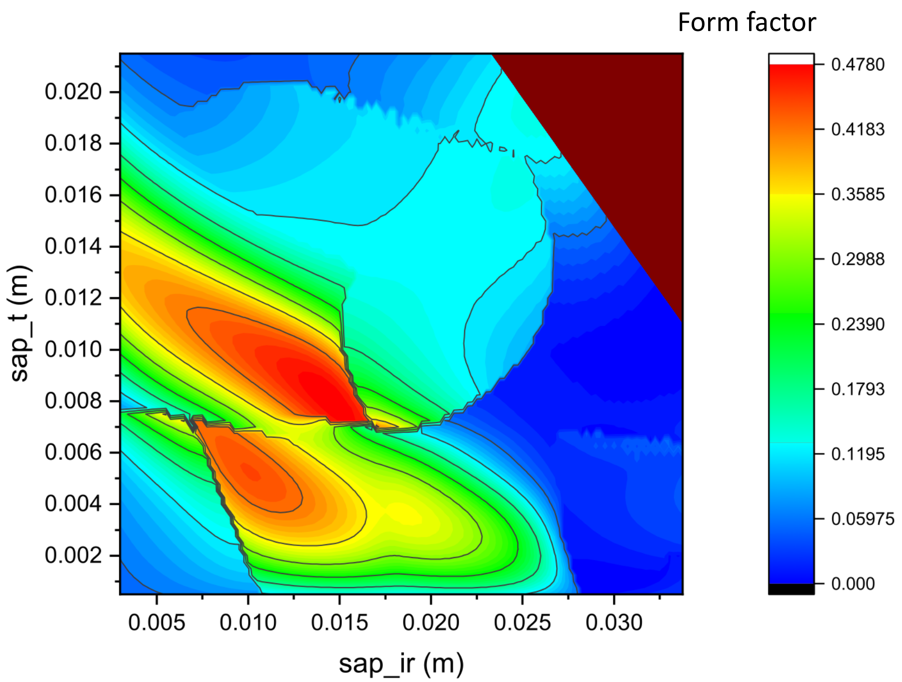
> 0.3 form factor

*CST_eff has N=6, if N is larger, the discrepancy gets disappeared.

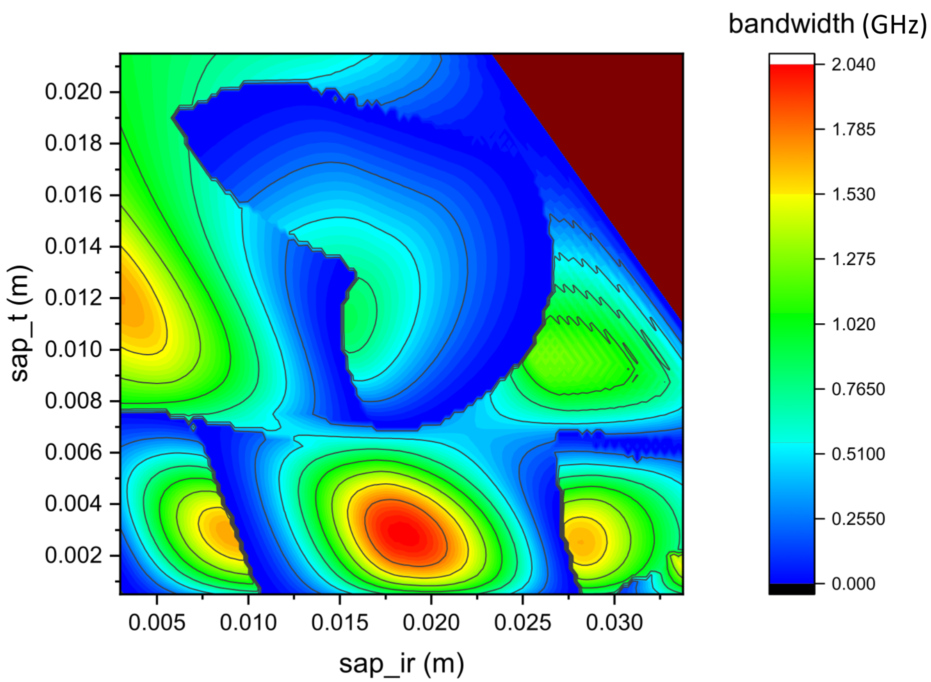
Let's find the best condition !

Figures of merit for TM030

Form factor

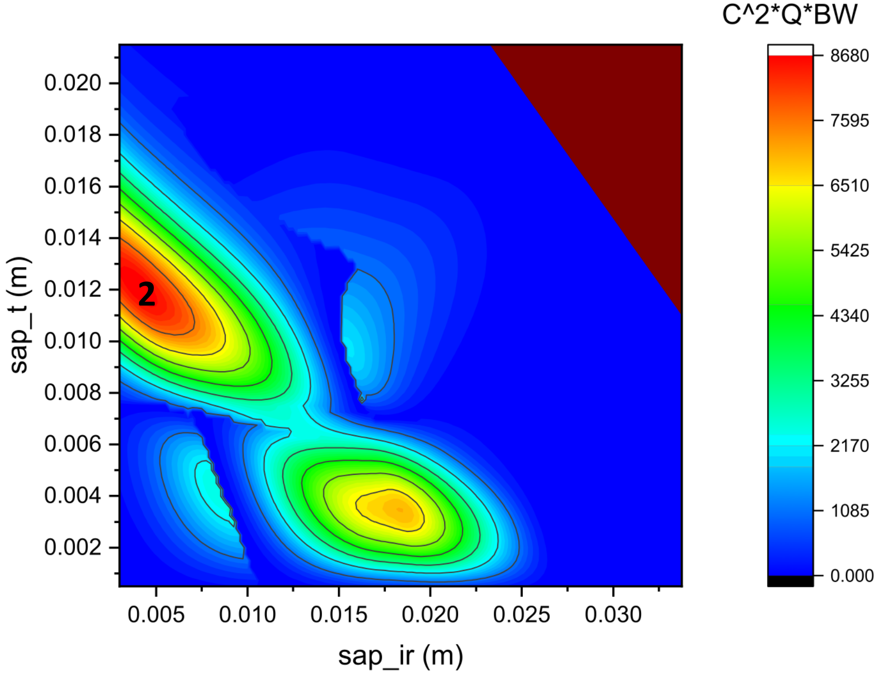


bandwidth

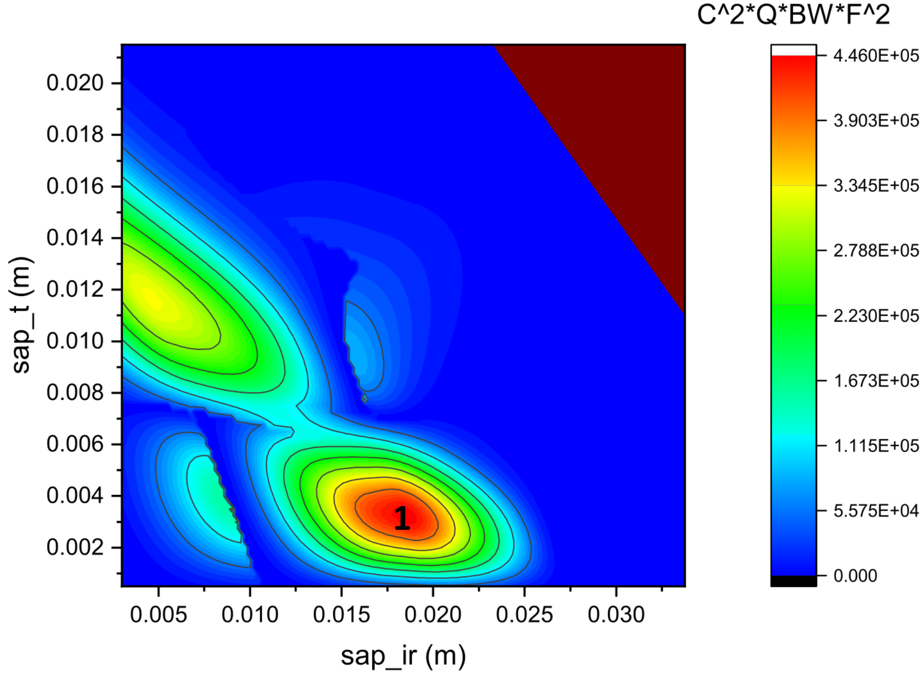


Figures of merit for TM030

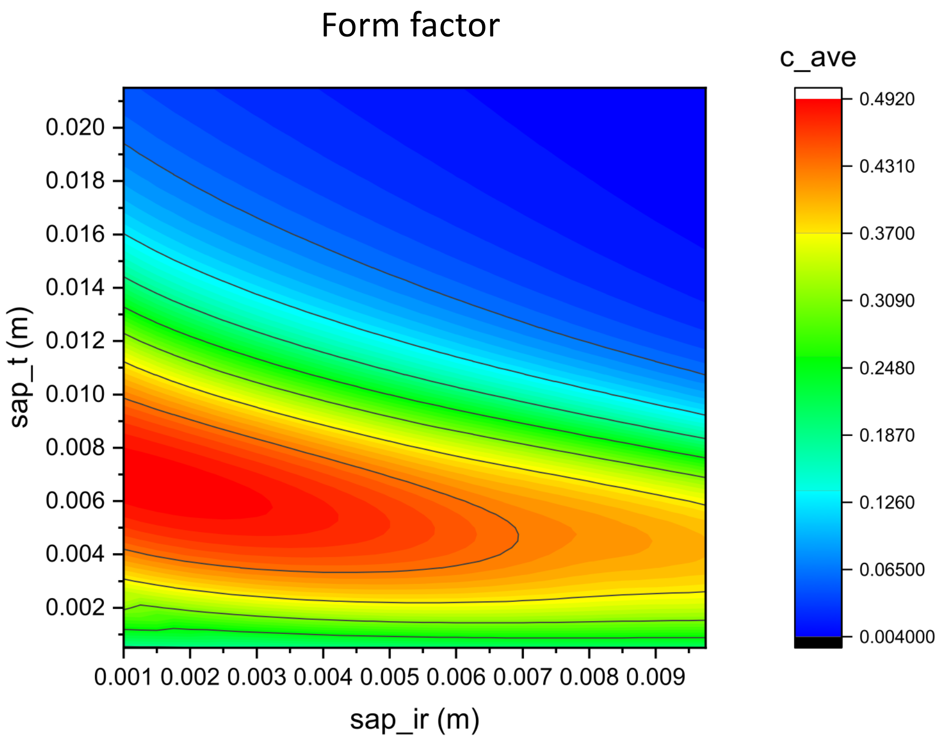
Form factor^2 x Q x bandwidth

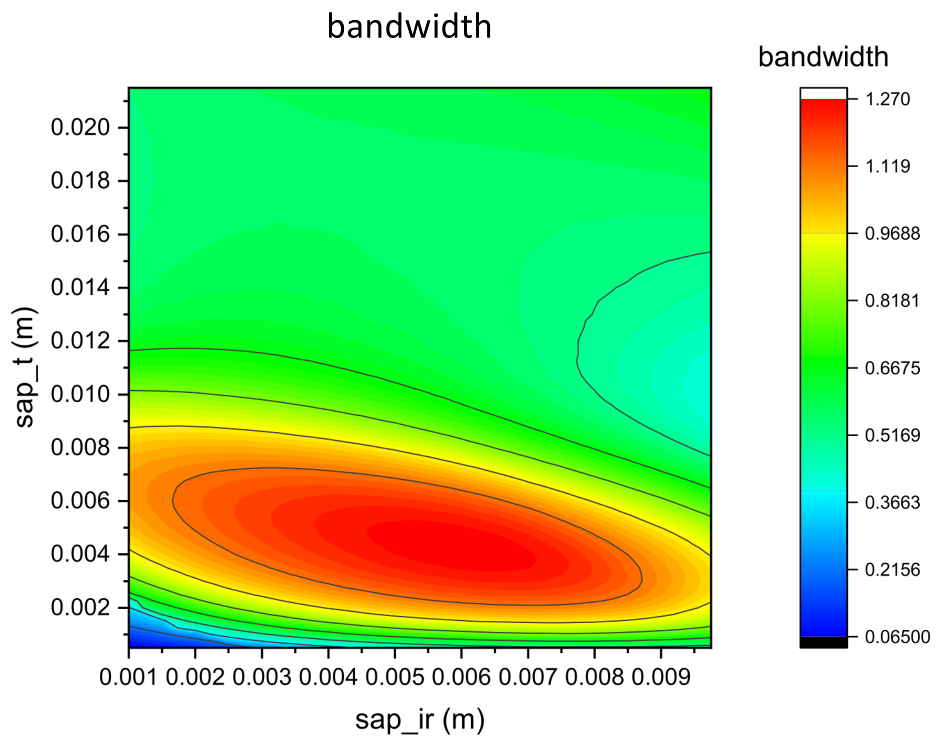


F^2 x Form factor^2 x Q x bandwidth



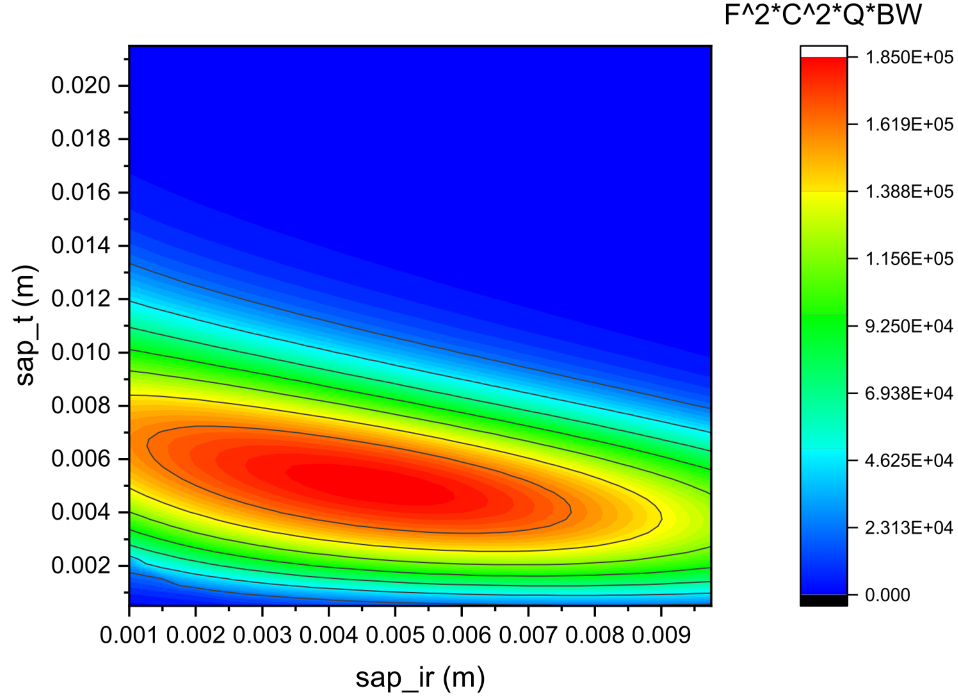
Figures of merit for TM020



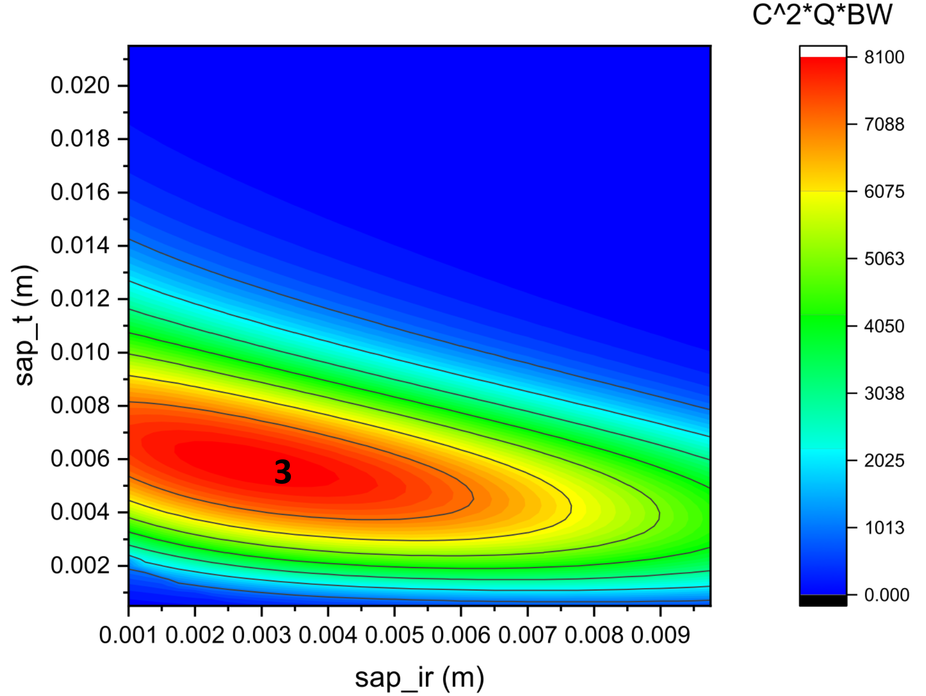


Figures of merit for TM020

Form factor^2 x Q x bandwidth

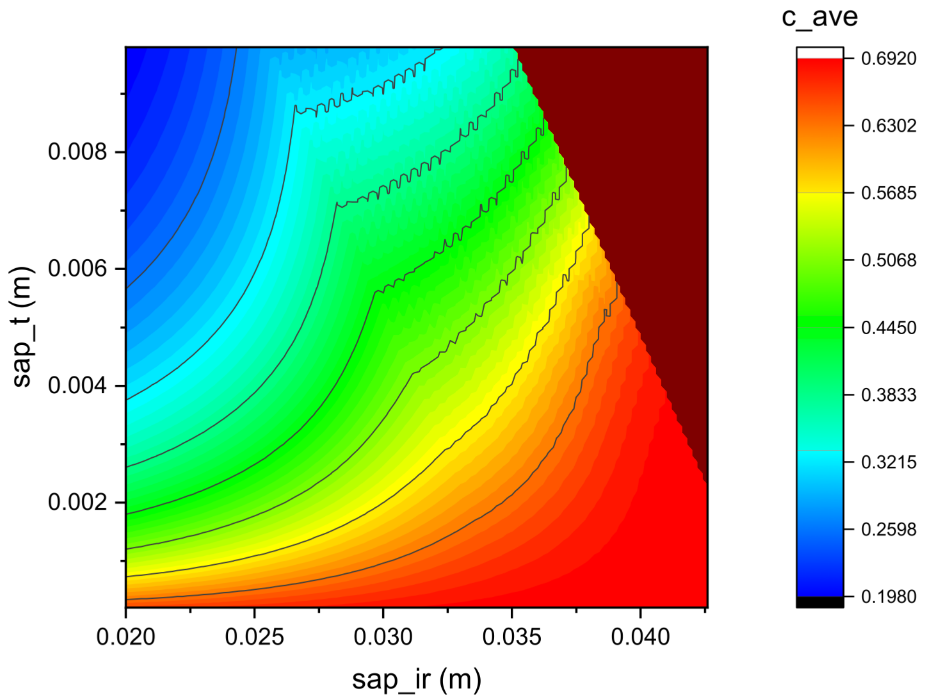


F^2 x Form factor^2 x Q x bandwidth

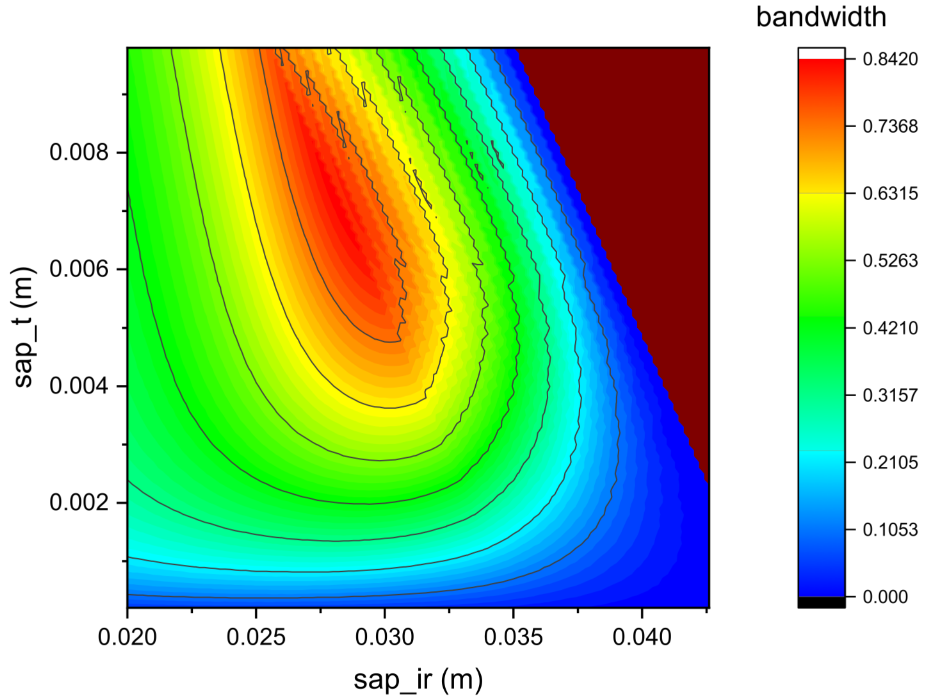


Figures of merit for TM010

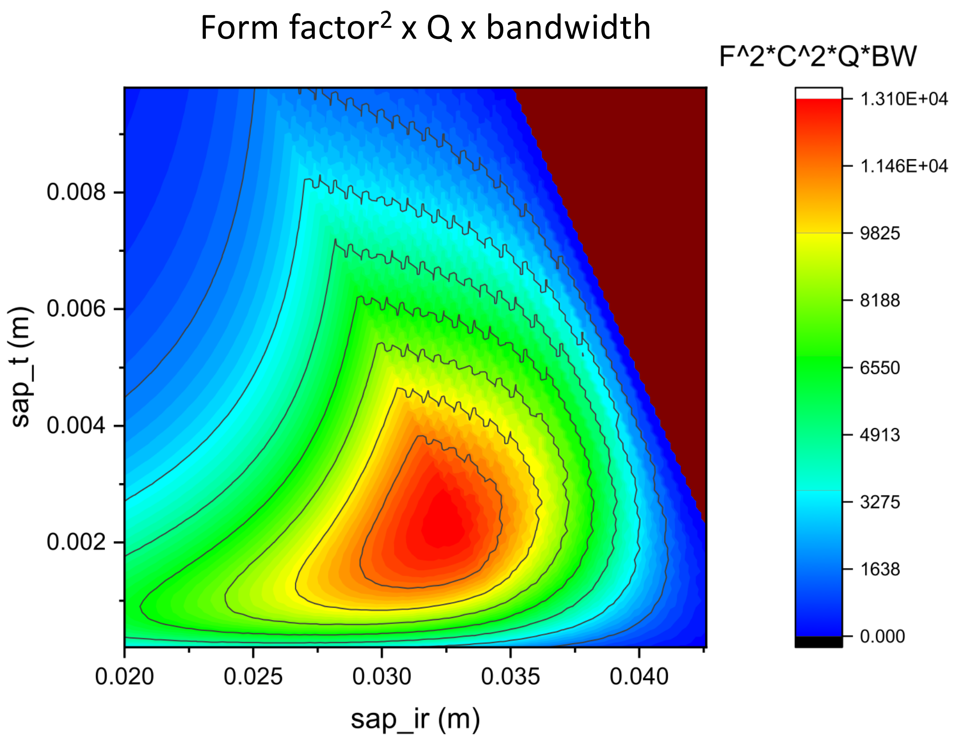
Form factor

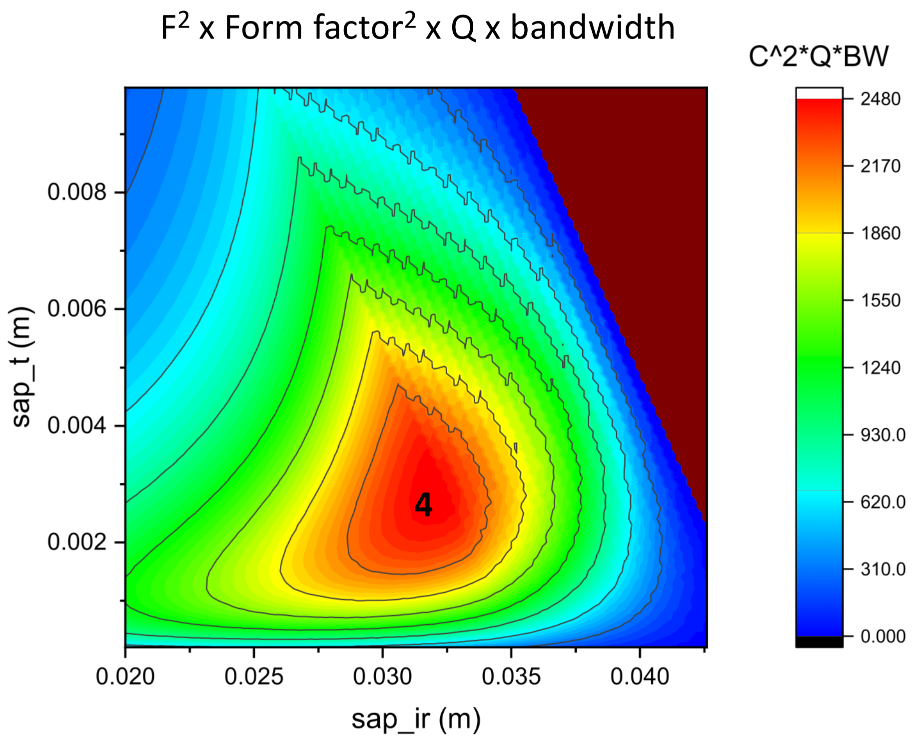


bandwidth

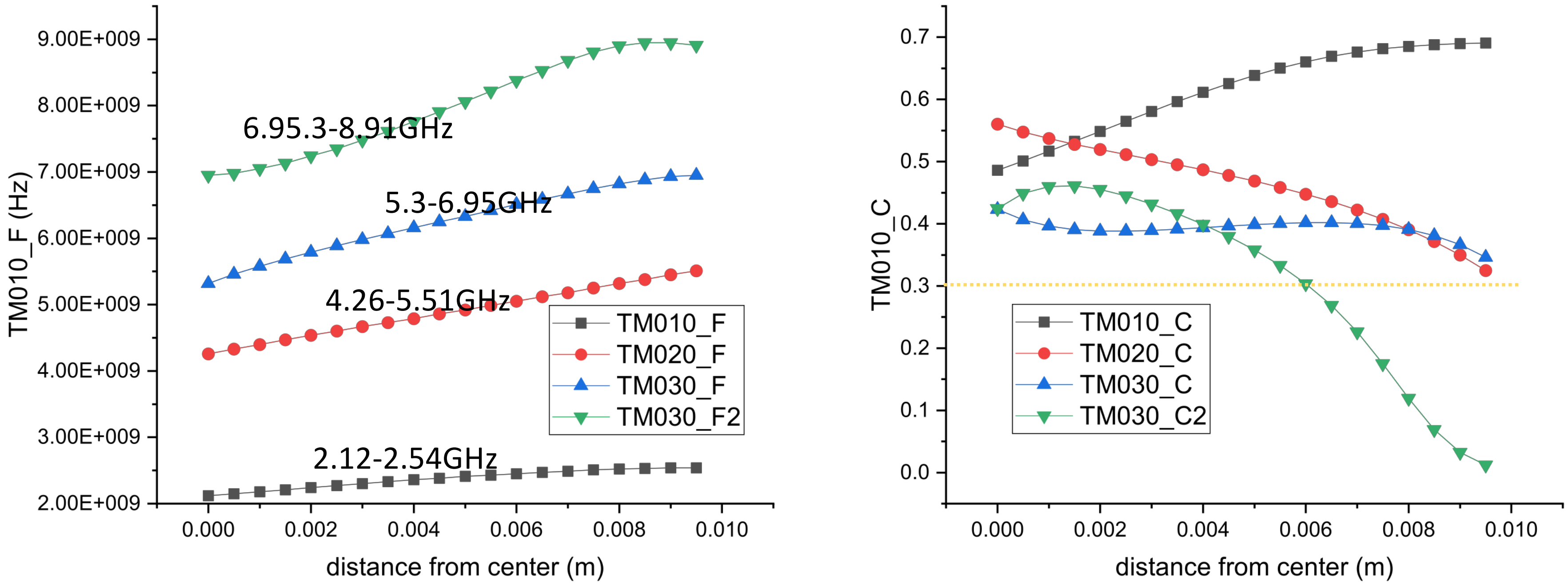


Figures of merit for TM010

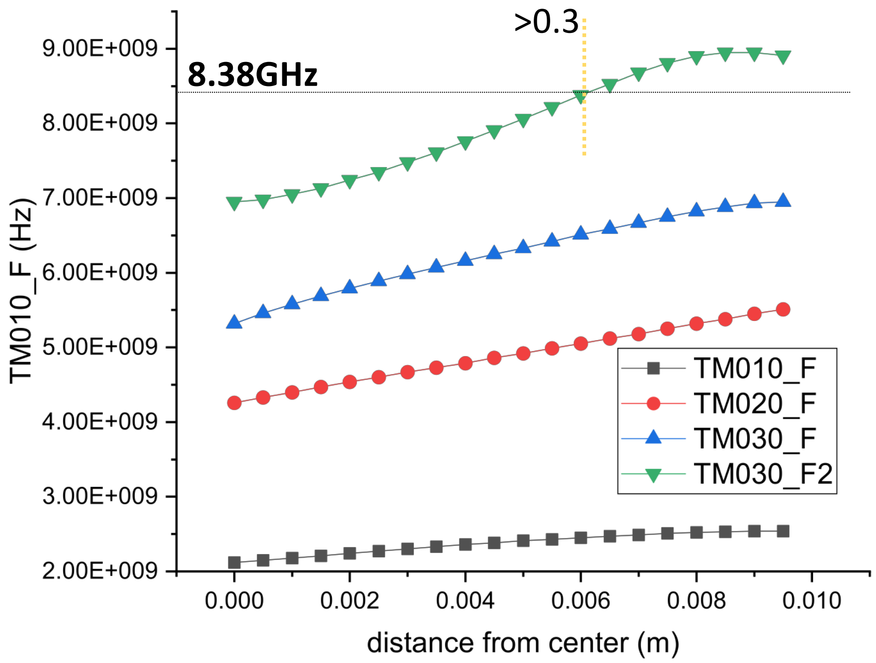


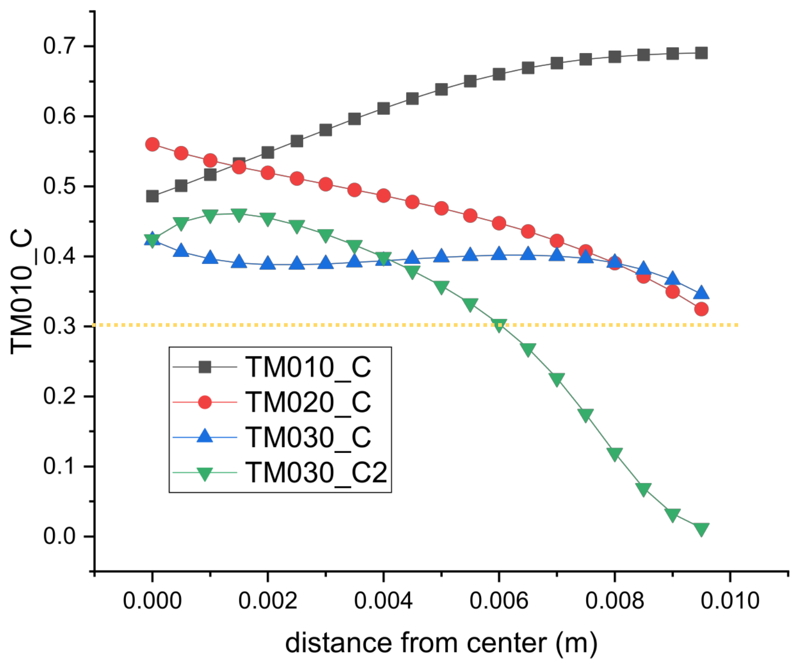


Wide Frequency tuning w/ DM

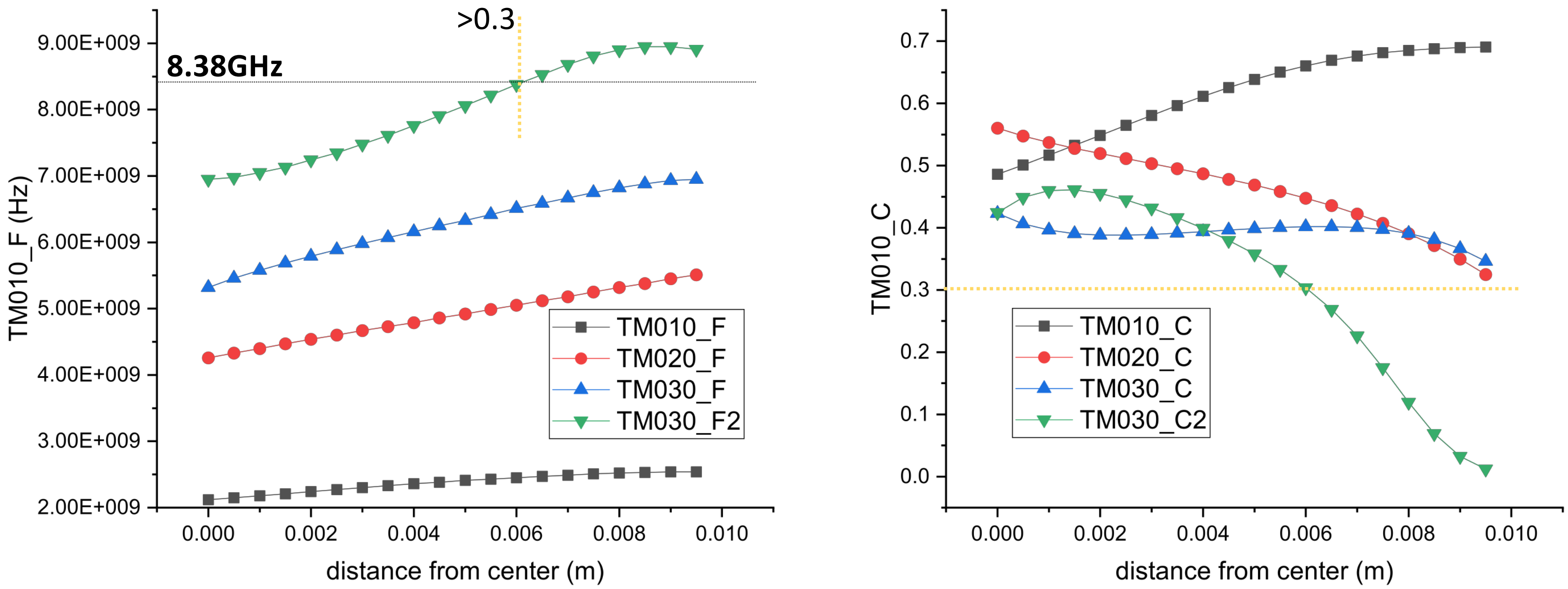


Wide Frequency tuning w/ DM





Wide Frequency tuning w/ DM



4.26 - 8.38GHz tuning available w/ same tuning mechanism

(+2.12-2.54GHz)

Scan rate comparison

(Q is not included/ SC considered)

	CAPP-PACE 1st run	4	3	2	1
V	0.59L	0.59L	0.59L	0.59L	0.59L
F	2.45-2.5 GHz	2.45-2.5 GHz	4.26-5.51 GHz	5.3-6.95 GHz	6.95-8.38 GHz
C	0.6 – 0.64 **0.62**	0.66 – 0.69 **0.675**	0.56 – 0.325 **0.675**	0.43– 0.35	0.46– 0.3
Normalized scan rate	1	**1.18**	**2.3**	**2.6**	**3.9**

Summary

- Arranging dielectric slit periodically, we can make controllable anisotropic dielectric meta-material (DM)
- Using eigen mode analysis, we proved the effective DM works as real dielectric medium.
- DM can be applied even in cylindrical structure.
- We can apply DM to the axion haloscope as a high order mode frequency tuner.
- Using TM020, TM030 mode, we can tune the cavity from 4GHz to 8.4GHz with reasonable form factor, when the cavity diameter is 90mm.