Efficient UHF Tunable Waveguide TE10 Mode Filter

Derek J. Small

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Efficient UHF Tunable Waveguide TE10 Mode Filter

Today's Discussion

- Why
- How Size and Operating Mode Influence Efficiency
- Cost of Efficiency
- Average and Peak Power
- Tunable Waveguide Filter
  - Design
  - Test Results

Why Tunable Waveguide Filter?

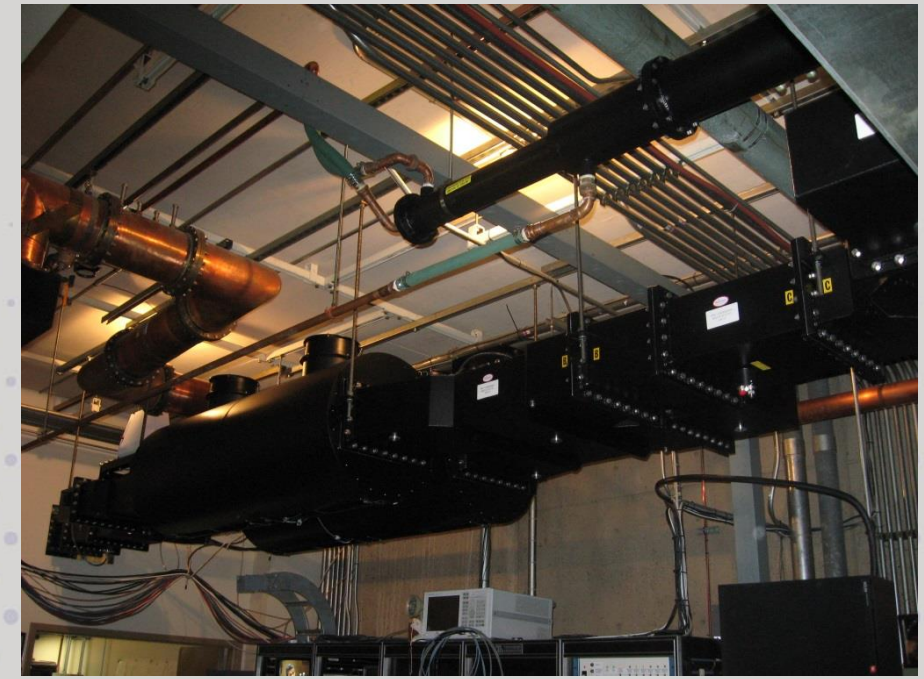
1st Dual-Mode Filter for broadcast television, 1994
First speeding ticket for Karen

Why Tunable Waveguide Filter?

Couldn't Develop a Tunable Dual-Mode Cavity

Efficiency

- Lowers operating cost
- Cooler operating temperature
  - Less heat load
  - Lower loss under power



Re-pack logistics

- Manufacture a "one size fits all" filter
  - Ease manufacturing burden
  - Lower's cost
  - Reduces delivery time
- Consistent install footprint
  - Simplifies and reduces install time
  - Minimizes install resources
  - No liquid cooling to worry about

Increase peak power capability

- More voltage headroom for ATSC 3.0

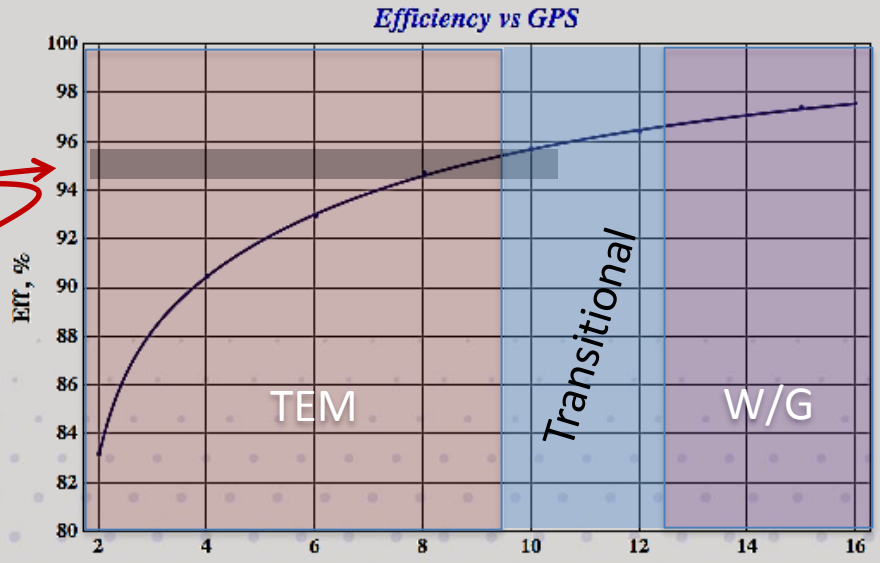
Efficient Tunable Waveguide Filter

Size Matters

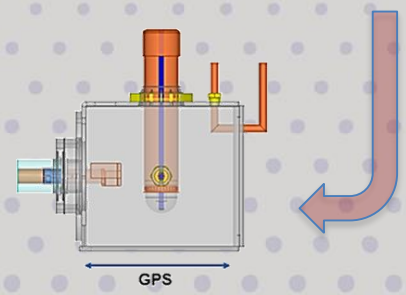
- **Obtain highest theoretical Q**
  - Reduce current/loss densities by distributing over a larger surface
- **Minimize surface protrusions**
  - Tuning devices/resonator
  - Protrusions increase current/loss density
- **Construction technique that aids removal of heat**
  - Radiation
  - Convection
  - Conduction

Cavity Size and Efficiency

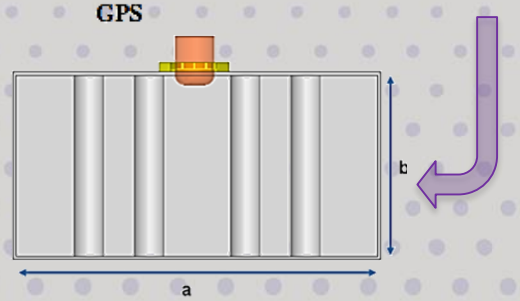
GPS (Inches)	Q (600MHz)	L_0 (dB)	Integrated Loss (dB)	Eff. (%)
2	4500	.72	.8	83.2
4	8300	.39	.43	90.5
6	11,500	.28	.32	93.0
8	15,300	.22	.24	94.7
10	18,900	.18	.19	95.7
12	22,900	.15	.16	96.4
TE10	32,200	.106	.11	97.4



- Q generated from HFSS
- Silver plated cavities
- 600MHz



Coaxial, tunable



Waveguide, fix tuned

Loss, Filter Order and Efficiency

Losses at 20 C 605 MHz	**Loss (dB)**	
	6-pole	
	W/G	Transitional
Q_u	24 K	17 K
f_o	.14	.20
Integrated (ATSC 1.0) +/- 2.69MHz	.16	.23
Integrated (ATSC 3.0) +/- 2.915MHz	.17	.24
Efficiency, ATSC 3.0	96.1	94.6

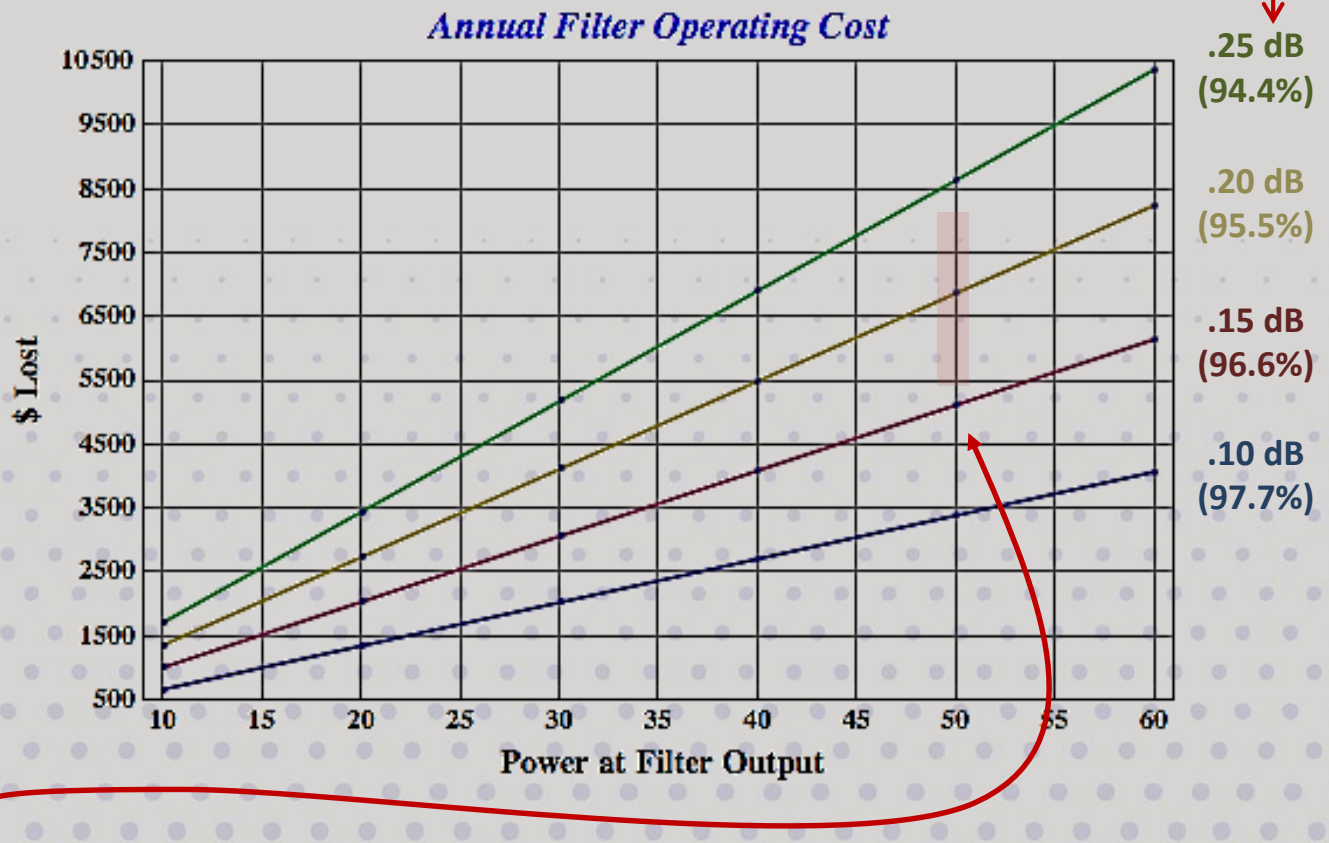
Efficiency and Annual $ Lost

Using ATSC 3.0

- Filter Loss Integrated
  +/- 2.915MHz
- Tx AC/RF Efficiency
  45%
- Utility Cost
  .15 $/kW hr

≈ $2700/yr

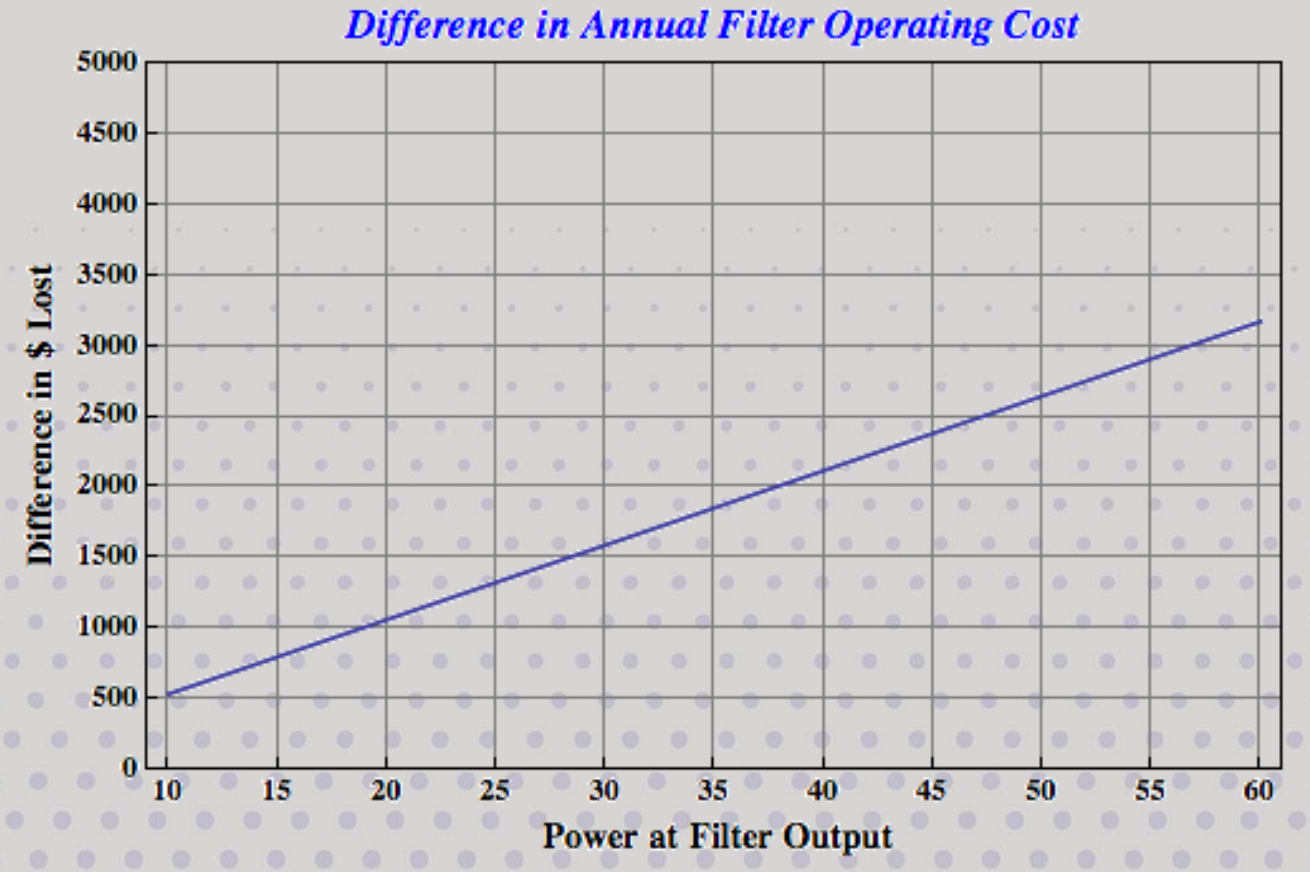
Filter loss
(Efficiency)



Annual $ *Difference*, Transitional vs Waveguide

Using ATSC 3.0

- Filter Loss Integrated
  +/- 2.915MHz
- Tx AC/RF Efficiency
  45%
- Utility Cost
  .15 $/kW hr

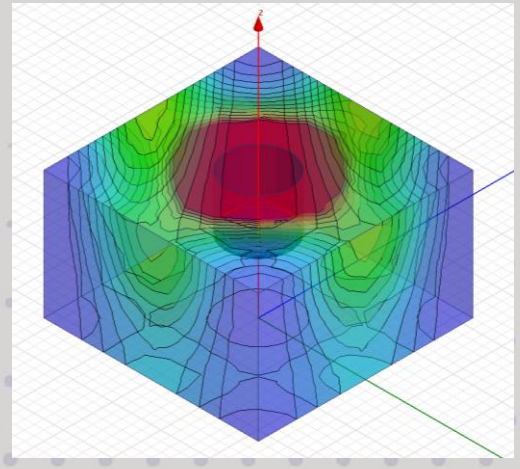


Surface Protrusions and Efficiency

Effect on Surface Loss Density

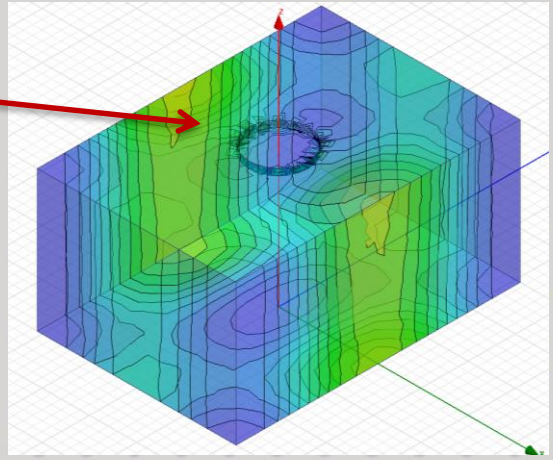
Transitional
Lower Q

Waveguide
High Q



Reduced surface loss density

1nJ of Stored Energy



Tunable coaxial/transitional mode cavity

- 11 inch GPS
- Significant probe penetration
- ***DIFFICULT TO TUNE AND LOCK DOWN***
- ***SUFFERS from MECHANICAL SHOCK***

Fixed tuned waveguide cavity

- Optimized waveguide cavity
- .3 inch probe penetration
- ***EASY TO TUNE AND LOCK, MORE STABLE***
- ***HANDLES MECHANICAL SHOCK***

Reduce current density

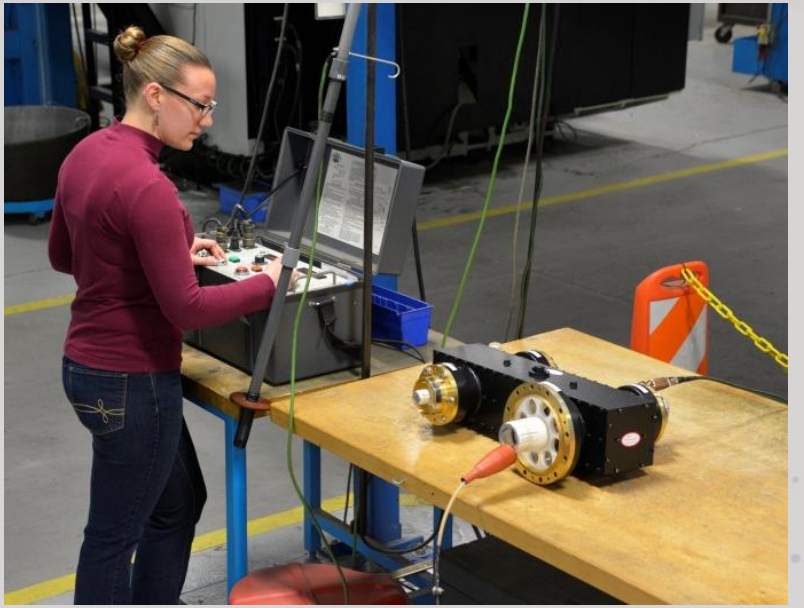
Peak Power

Peak power is limited by the breakdown of gas (air) molecules in the presence of high electric fields.

Small gaps, rough surfaces and sharp edges increase the electric field density and become more susceptible to breakdown.

Breakdown is also a function of air pressure, temperature, frequency and pulse length but will not be included in this paper.

Accepted rule of thumb is to use 2.28 x 10^6 V/m as a breakdown threshold along with an appropriate safety factor.



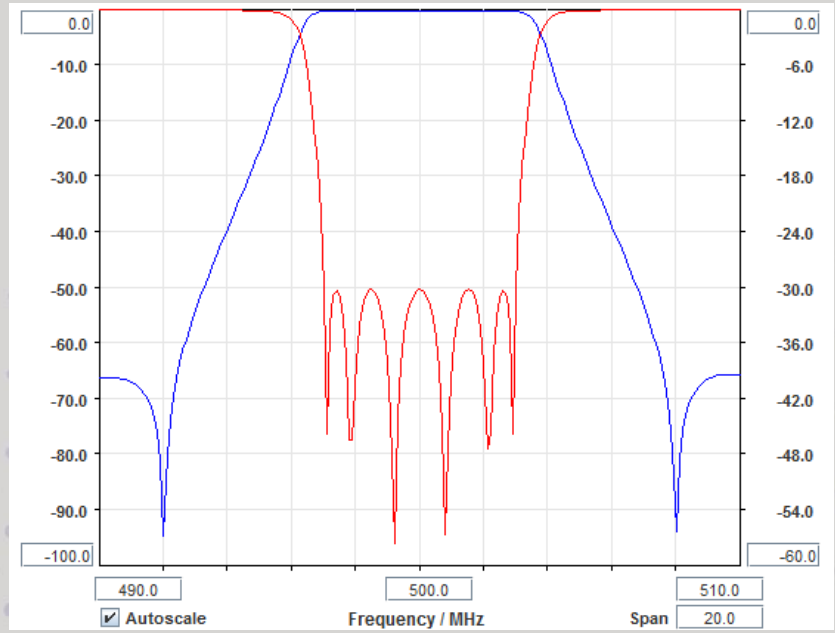
$$E_p = 3.17\ x\ 10^4\ a\ \delta\ (\log\frac{b}{a})(1+\frac{.273}{\sqrt{a\ \delta}})$$

$$E_{rf} = \frac{.7\ E_p}{SF\sqrt{2}}$$

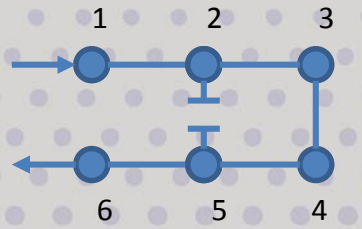
$$P_{pk} = \frac{{E_{rf}}^2}{Z_0}$$

Peak Power, Bandpass Filter

Order:	6-pole
VSWR:	1.065
BW_r:	6MHz
Topology:	Folded, 1 X-coupling
Load VSWR:	1.2



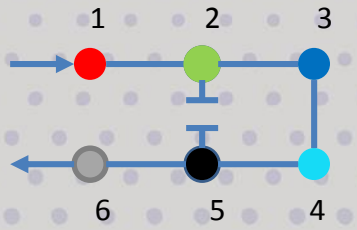
Determine stored energy in each resonator, SE_i

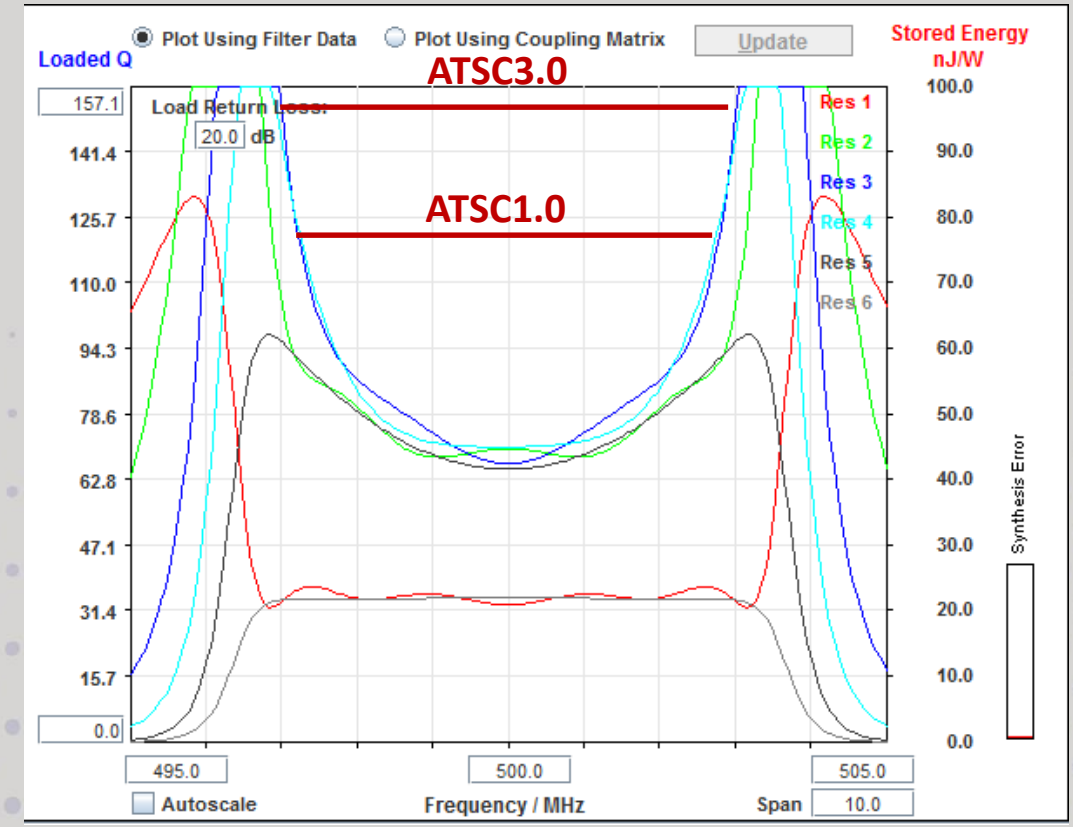


Peak Power, Bandpass Filter

Stored energy in each resonator, SE_i

- Normalized to a nJ/W basis
  simplifies analysis using HFSS
- Integrate over passband
- ATSC 1.0 ≈ 52 nJ/W, resonators *i*= 3 & 4
- ATSC 3.0 ≈ 56 nJ/W, resonators *i*= 3 & 4





Peak Power, Coaxial/Transitional Cavity

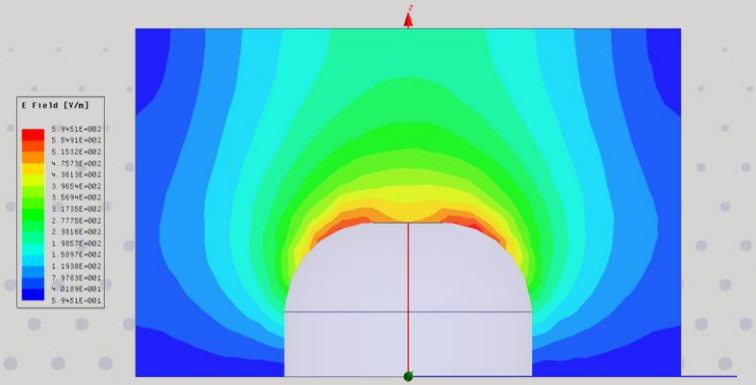
GPS = 11 inches

$$P_{max} = (\frac{E_{max}}{E_{norm,i}})^2 / SE_i \quad *$$

Stored Energy = 1nJ

$E_{norm,i}$ = 590 V/m

- SE_3 = 56 nJ/W *(ATSC 3.0)*
- E_{max} = 2.3 x 10^6 V/m
- P_{max} = 271 kW



** Ming Yu, Power-Handling Capability for RF Filters*

Peak Power, Waveguide Cavity

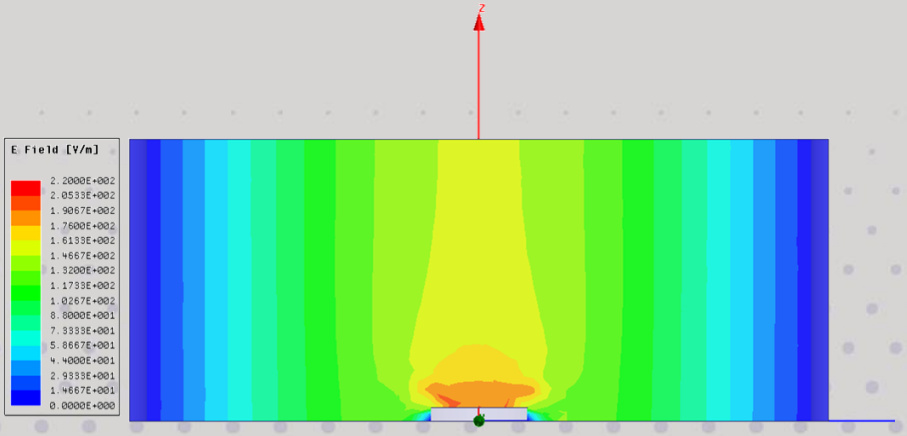
a = 16 inches

$$P_{max} = (\frac{E_{max}}{E_{norm,i}})^2 / SE_i \quad *$$

Stored Energy = 1nJ

$E_{norm,i}$ = 220 V/m

- SE_3 = 56 nJ/W *(ATSC 3.0)*
- E_{max} = 2.3 x 10^6 V/m
- P_{max} = 1952 kW



** Ming Yu, Power-Handling Capability for RF Filters*

x 7.2 Greater Peak Power Handling

Summary

Waveguide

- Increased efficiency
  - From 95% (transitional) to 96.5% (Worse case)
- Reduce operating cost, approx. $2700 @ 50kW
- Produces less heat
- Larger surface area to manage heat removal
- Greater voltage capability
- Easier to Tune
- More Robust

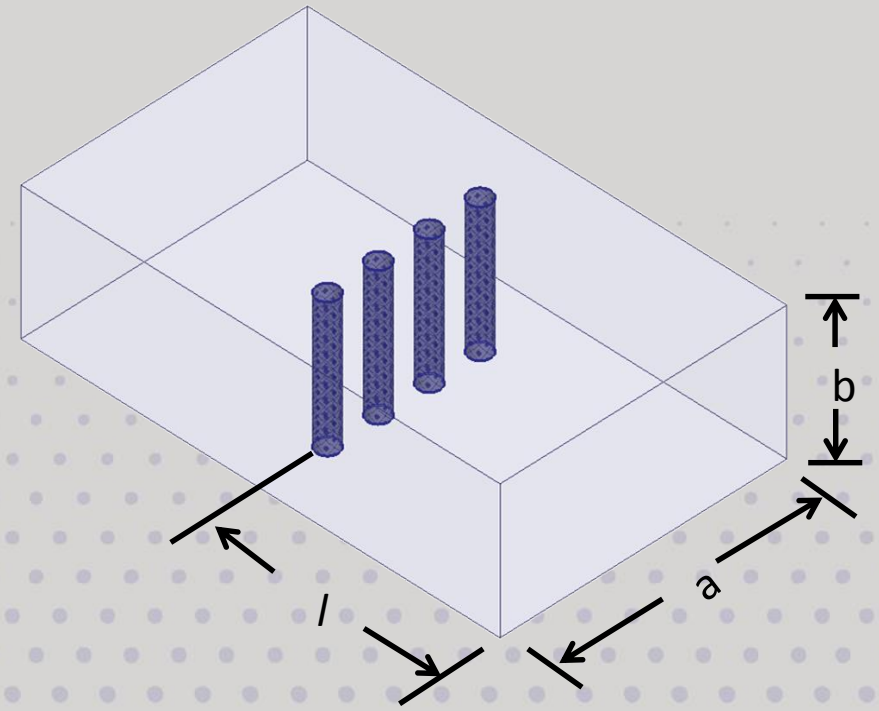
We need to make filters out of waveguide again!

Waveguide TE_{101} Cavity

2 Post Coupled Resonators

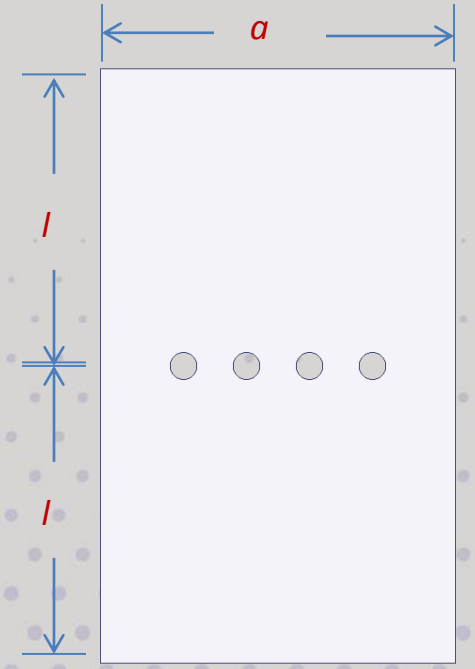
TE_{mnp} resonant frequency

$$f_r = \frac{c}{2\pi}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{p\pi}{l}\right)^2} \quad GHz$$



Waveguide TE_{101} Cavity

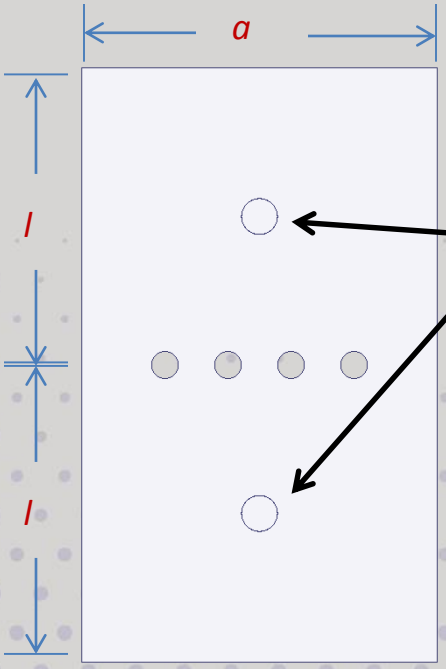
2 Post Coupled Resonators



Top view

Waveguide TE_{101} Cavity

2 Post Coupled Resonators



Top view

Add tuners for fine adjust

Remember, little penetration is important

∴ Cavity lengths need to be accurate

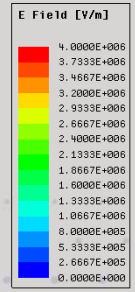
Waveguide TE_{101} Cavity

2 Post Coupled Resonators

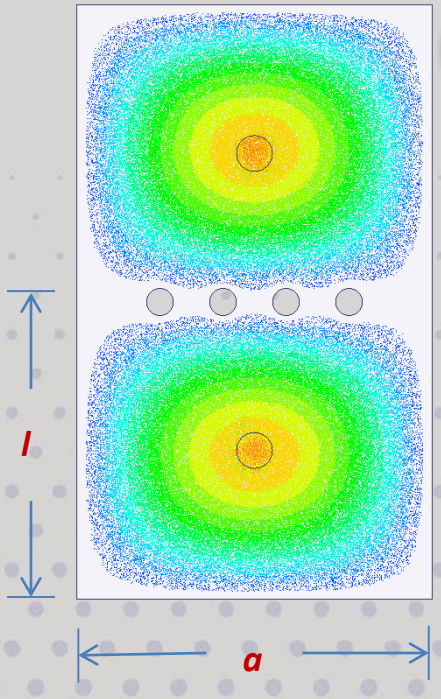
Te_{mnp} resonant frequency

$$f_r = \frac{c}{2\pi}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{p\pi}{l}\right)^2} \quad GHz$$

CH14

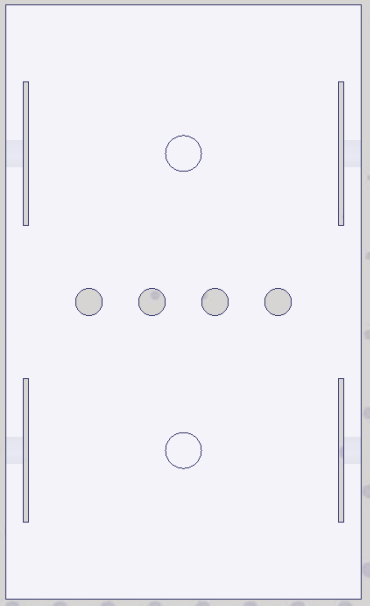


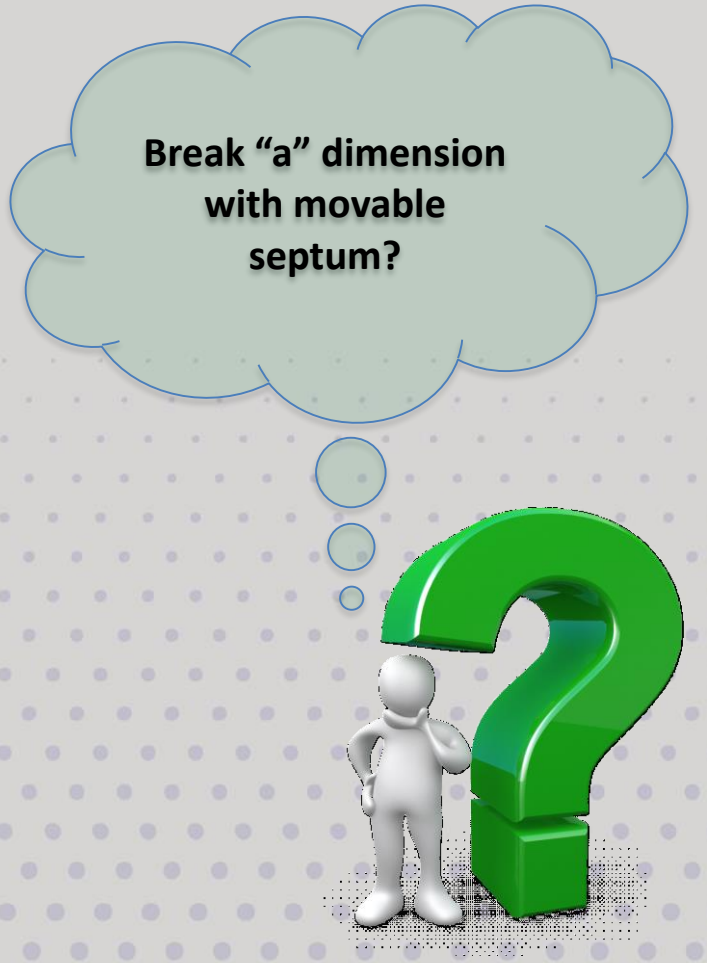
E-Field intensity
HFSS simulation



Waveguide TE_{101} Cavity

2 Post Coupled Resonators

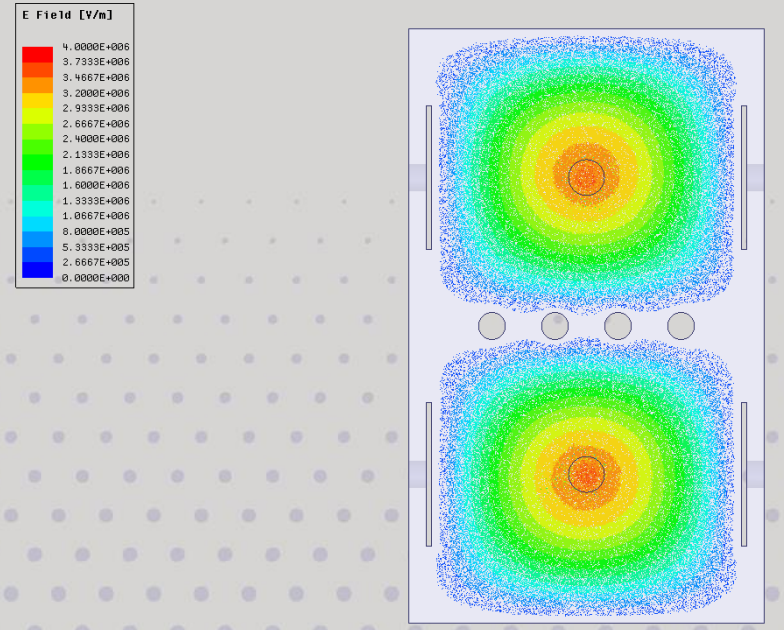




Waveguide TE_{101} Cavity

2 Post Coupled Resonators

CH21

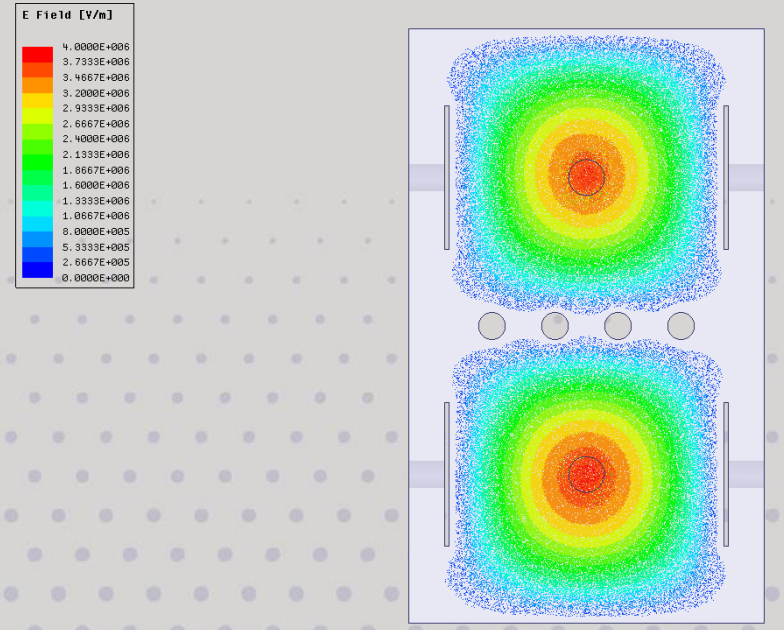


Patents Pending

Waveguide TE_{101} Cavity

2 Post Coupled Resonators

CH28

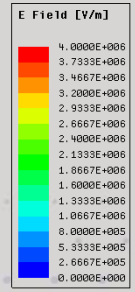


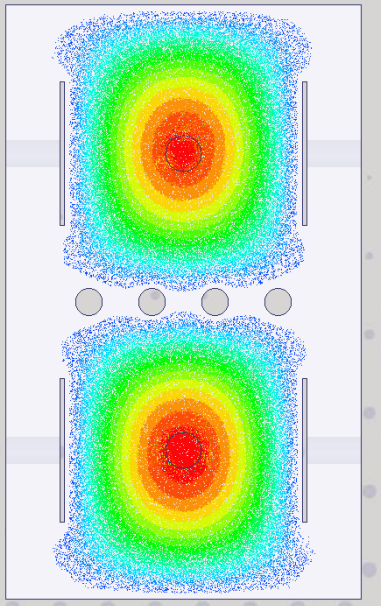
Patents Pending

Waveguide TE_{101} Cavity

2 Post Coupled Resonators

CH35



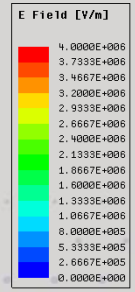


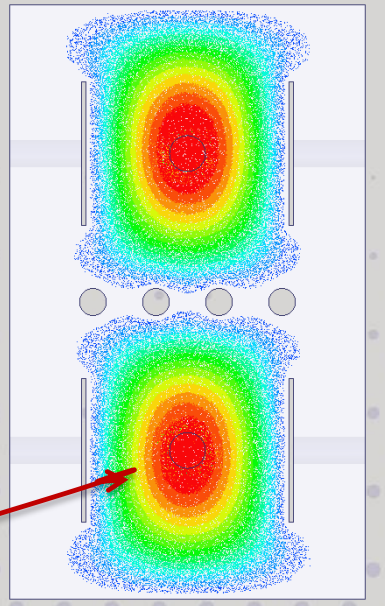
Patents Pending

Waveguide TE_{101} Cavity

2 Post Coupled Resonators

CH40





Resonant frequency

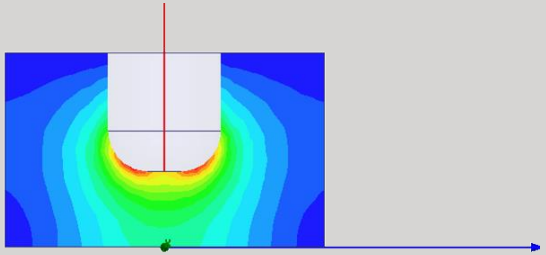
$$f_r = \frac{c}{2\pi}\sqrt{\left(\frac{m\pi}{1.02a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{p\pi}{l}\right)^2} \quad GHz$$

Helpful for re-tuning

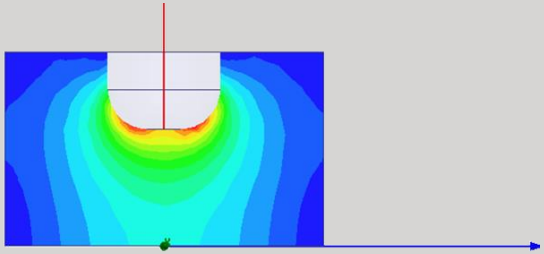
Increased E field density for higher channels

Revisit Peak Power

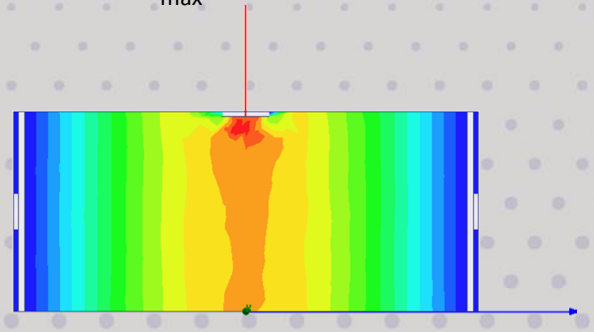
Peak Power Comparison



CH14
$E_{norm,i}$ = 623V/m
P_{max} = 243 kW

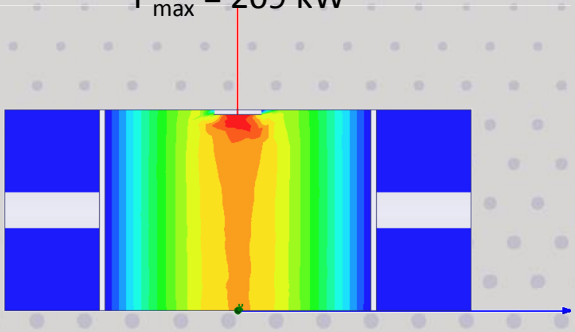


CH40
$E_{norm,i}$ = 673 V/m
P_{max} = 209 kW



CH14
$E_{norm,i}$ = 220 V/m
P_{max} = 1952kW

x 8



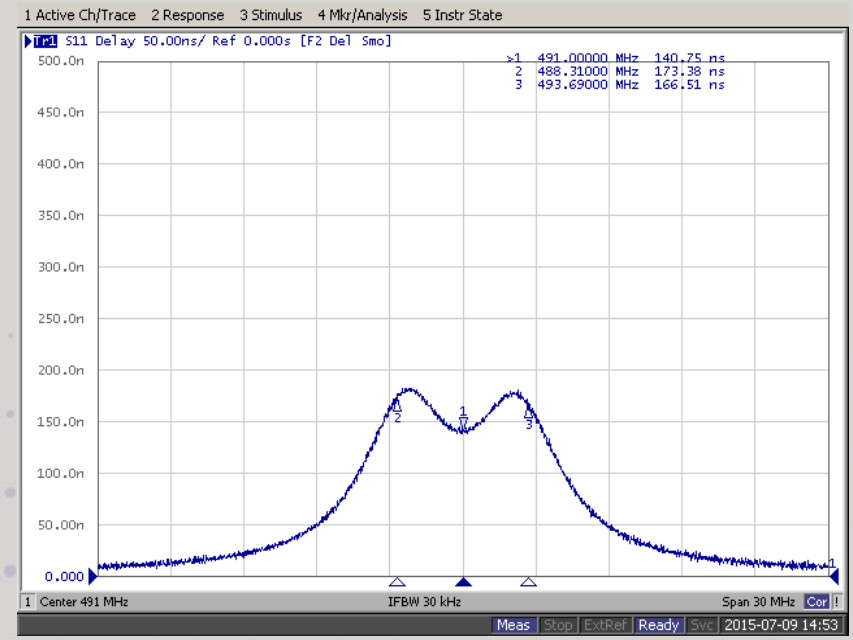
CH40
$E_{norm,i}$ = 283V/m
P_{max} = 1253 kW

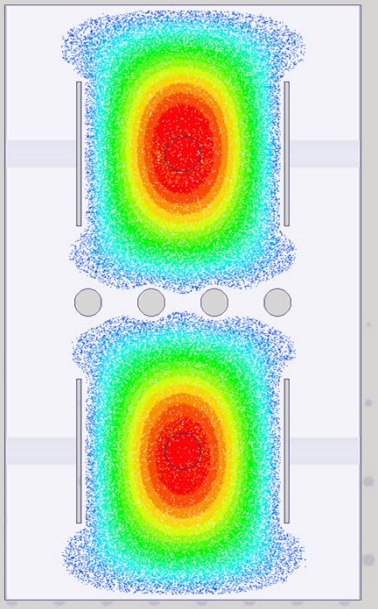
x 6

Waveguide, Greater Peak Power Handling

Waveguide TE_{101} Cavity

2 Post Coupled Resonators





Coupling b/w two resonators is the displacement of the resonant frequencies: Δf

Normalized coupling co-efficient b/w resonators *i* and *j*: $M_{i,j} = \frac{\Delta f}{bw_r}$

Constant coupling with frequency is desired for easy tune-ability

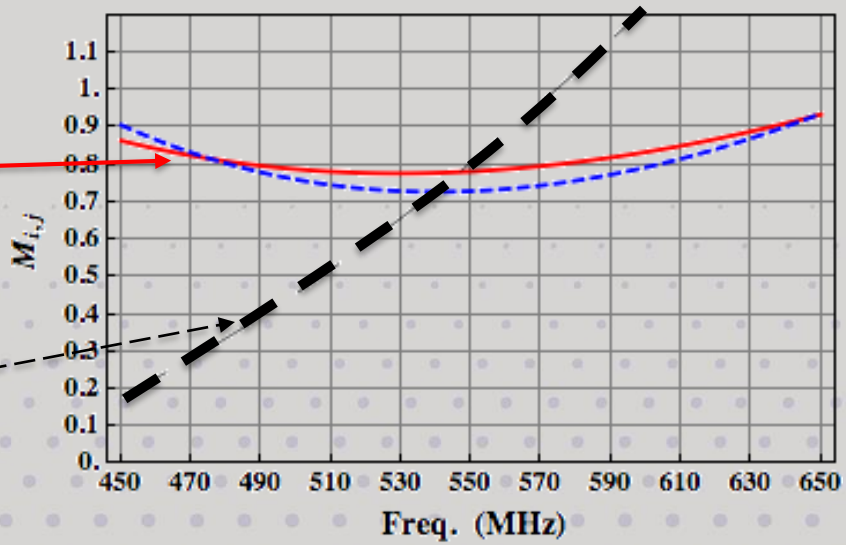
Waveguide Cavity Coupling

2 Post Coupled Resonators

Tunable waveguide coupling is relatively constant since variation in $\frac{\lambda_g}{\lambda}$ is reduced by changing "a" dimension.

Waveguide coupling increases significantly with frequency due to large variation in $\frac{\lambda_g}{\lambda}$.

Coupling Variation with Frequency

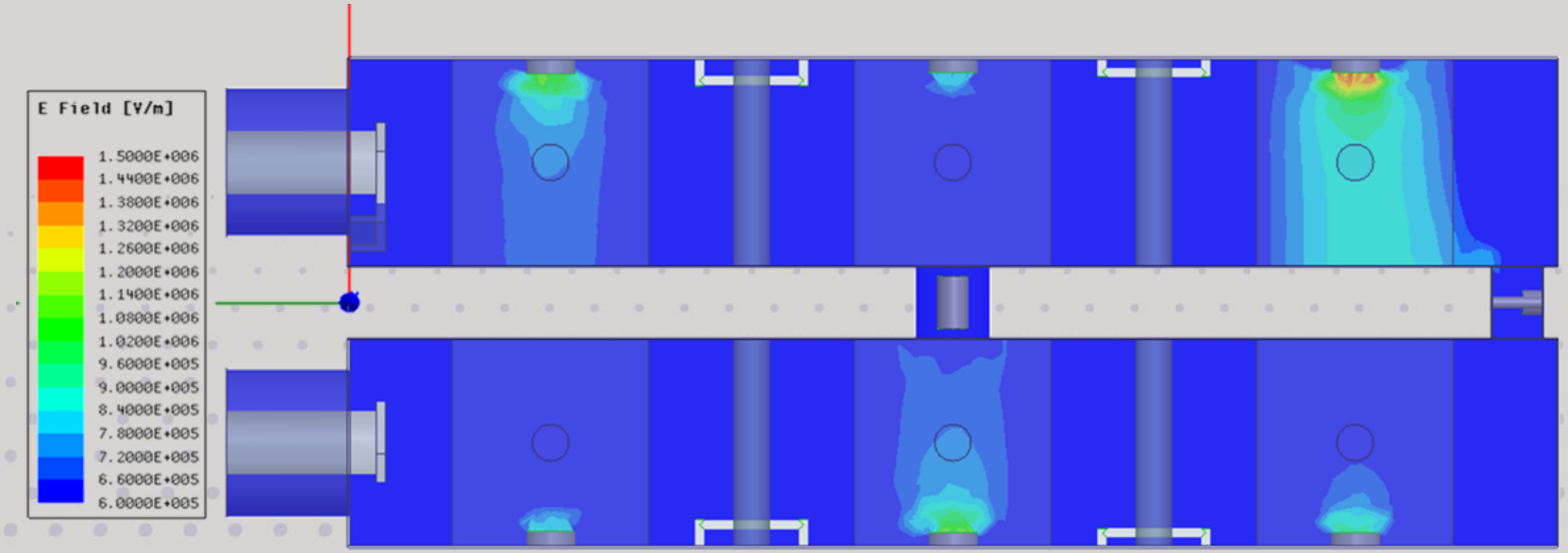


- - - - WR1500 waveguide

- - - - Tunable TE_{10}

——— Tunable TE_{10} , Optimized

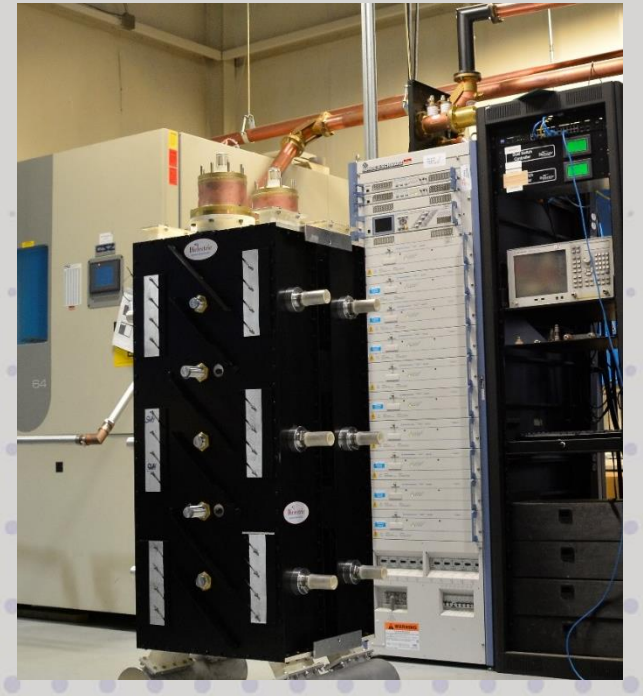
Tunable Waveguide Filter



Tunable Waveguide Filter

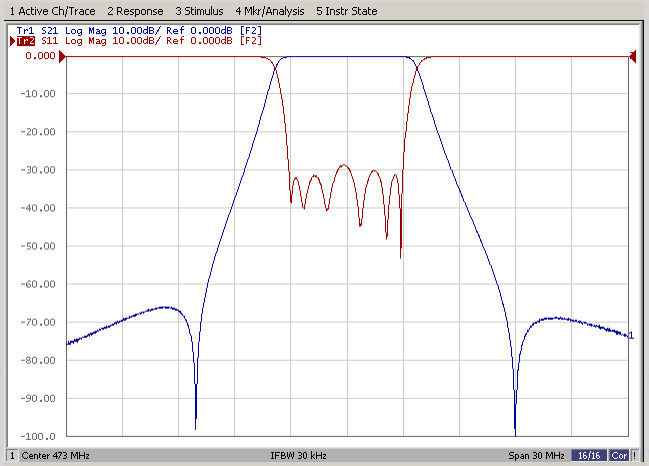
Test Results

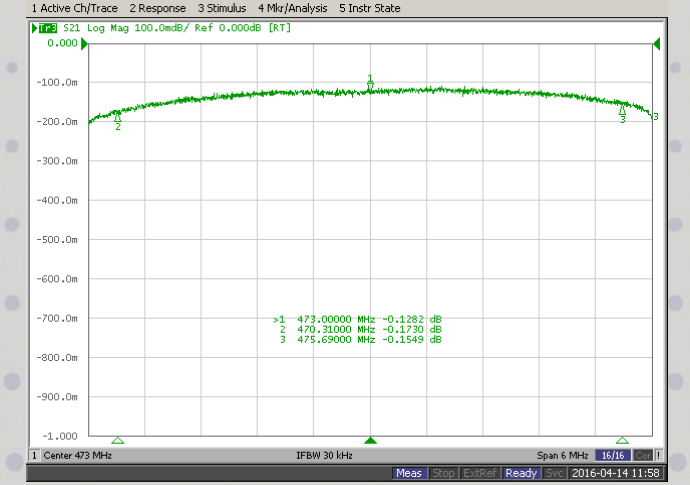
Patents Pending



CH14

Loss	
f_0	.12 dB
Int.	.13 dB
Eff.	97.1 %

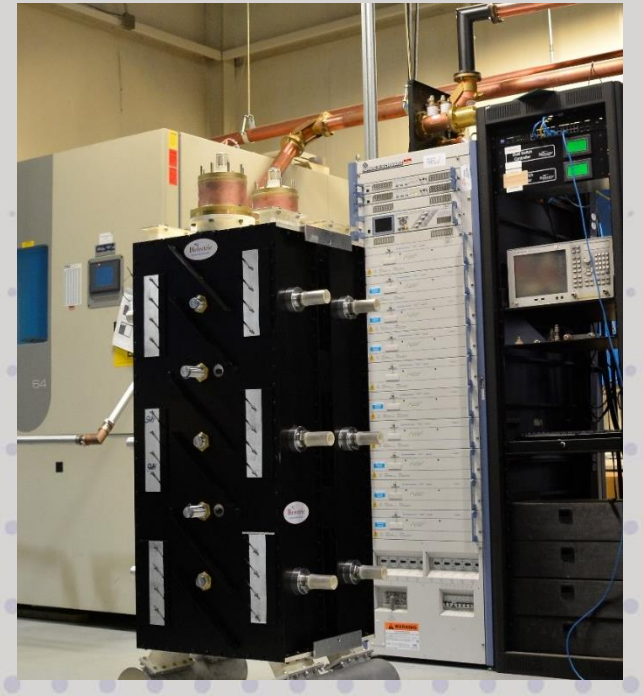




Tunable Waveguide Filter

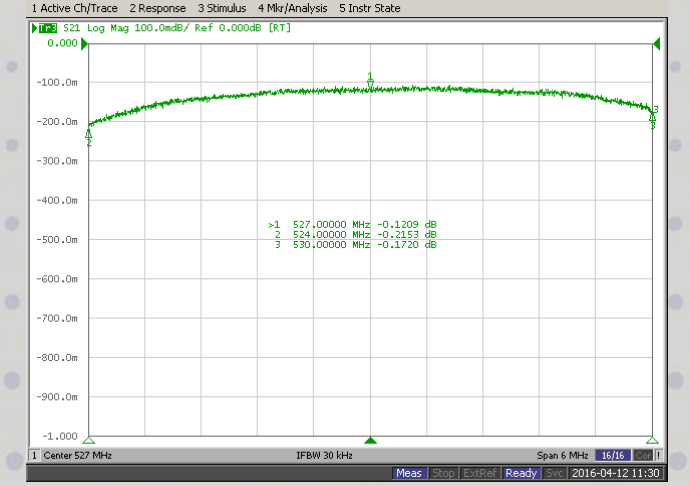
Test Results

Patents Pending



CH23

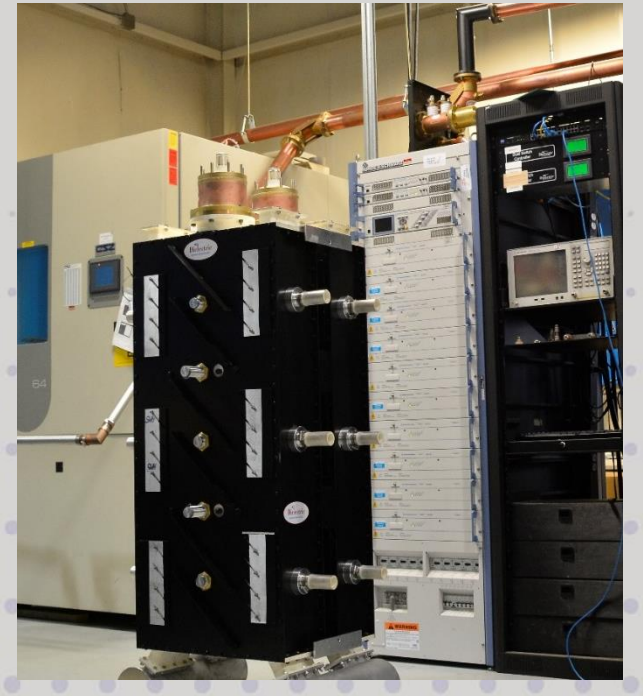
Loss	
f_0	.12 dB
Int.	.13 dB
Eff.	97.1 %



Tunable Waveguide Filter

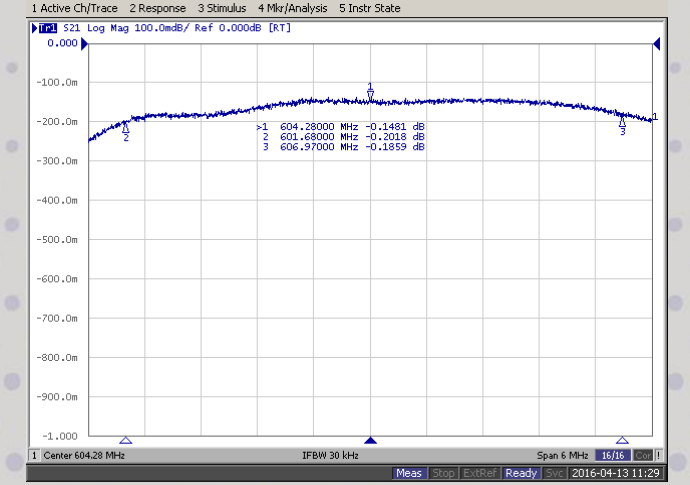
Test Results

Patents Pending



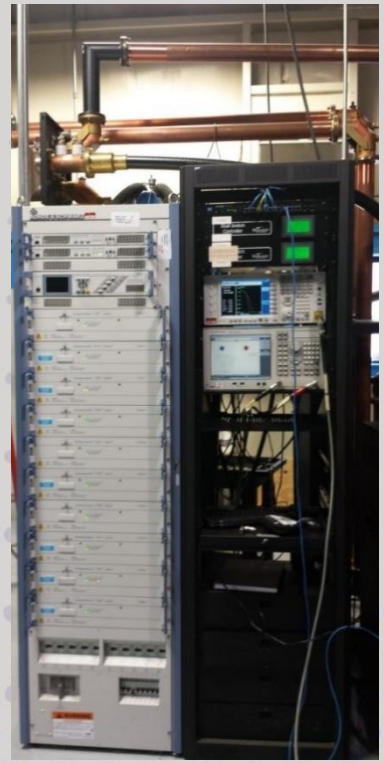
CH36

Loss	
f_0	.147 dB
Int.	.157 dB
Eff.	96.4 %



Filter Power Testing

Rohde & Schwarz
9 kW solid state
6 MHz DVB-T Exciter

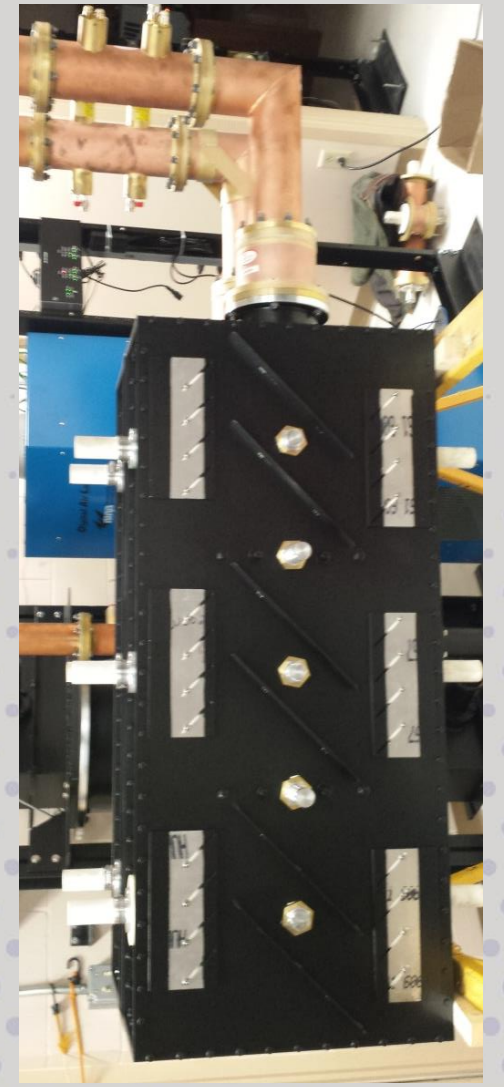


WPFO
Comark 40 kW, 2 Tube
FLO Exciter

30kW Tunable Waveguide Filter

Patents Pending

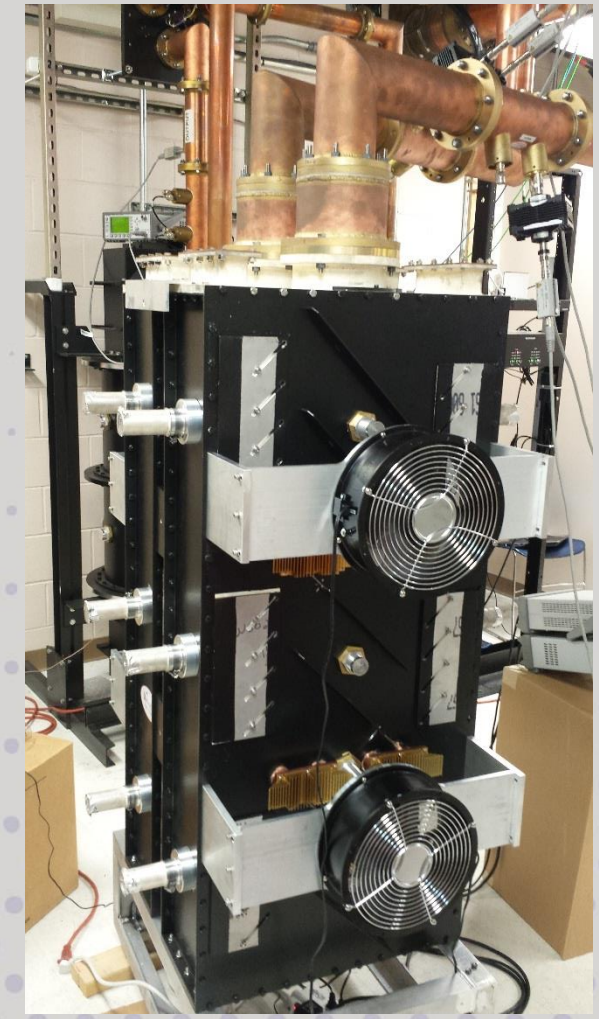
- 6 or 8 Poles
- Convection Cooled
- Coaxial or Waveguide Ports
- Tunable 14-36
- Insertion loss 0.12 -.15dB max, mid-band
- 32” x 23” x 55” (81 cm x 59 cm x 150 cm)
- 430lbs (195kg)



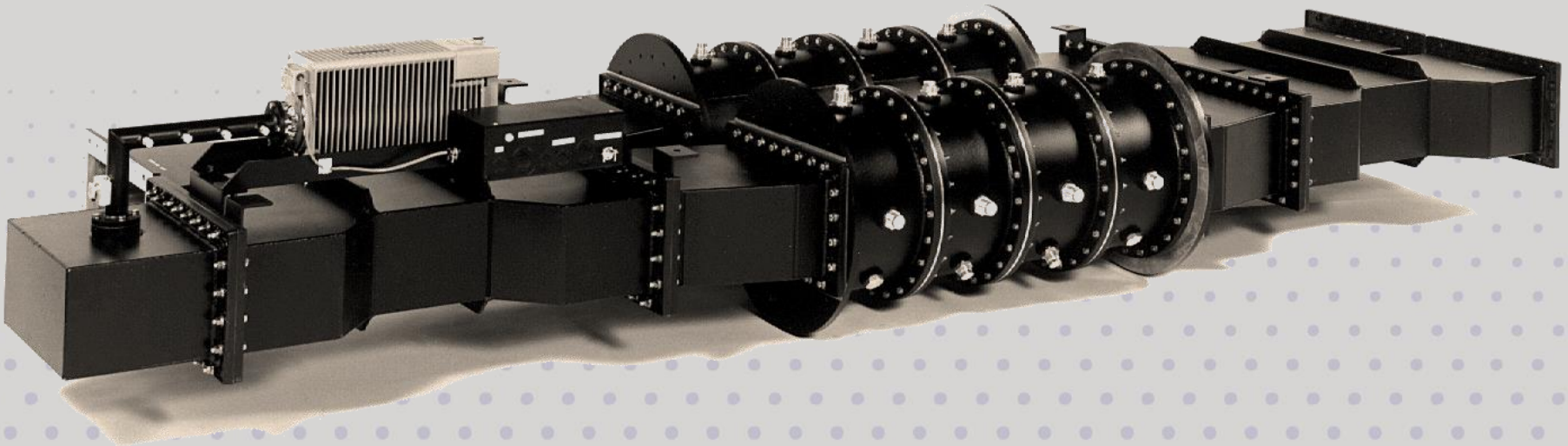
60kW Tunable Waveguide Filter

Patents Pending

- Forced Air Cooling
- 2.4 kW dissipated @ 60 kW
  (0.682 Tons of AC)



Bullet Proof Waveguide Filter



Cylindrical Waveguide has exceptional peak power handling

THANKS FOR YOUR TIME!
ANY QUESTIONS?

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