Electromagnetic Emission from ‘Dielectric’ Optical Fiber Cables

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Outline

- Introduction
- Review of enclosure design rules
- Early emissions failures
- Proposed model
- Experimental Verification
  - Verify dipole radiation pattern
  - Verify driving source of dipole
  - Role of ground pins
- Conclusions

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Electromagnetic Compliance (EMC)

- Nearly all equipment introduced into commerce must meet government Electromagnetic Compliance (EMC) regulations: FCC in the USA, IEC in Europe, Nemko in Scandinavia…
- Early optical fiber networking equipment - telecom apps:
  - Lower data rates (at first), installed and operated by trained personnel
  - Engineered installations, controlled access to equipment
  - Telecom typically FCC “Class A” requirement for RF emissions
- In 1990s networking technology proliferates - datacom apps:
  - Technology progressed to gigabit rates by the time low costs achieved
  - Plug-and-play installations, consumer and office environment
  - Datacom typically FCC “Class B” (more restrictive) for RF emissions
- EMI FAILURES IN EARLY DATACOM SYSTEMS
- In 2000s convergence and harmonization of requirements

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Example: Point-to-Point Datacom Network

- Mass storage physically decoupled from CPU
- Tower, desktop, rack-mount, or “pizza-box” enclosures
- Enclosures always electrically shielded with limited apertures
- Optical fiber is medium of choice for high-speed data links
- Host adapter card (HAC) using e.g. PCI, ISA, S-Bus interface
- Interface with optical fiber via optical module on HAC
- Fiber-optic receptacle/connector protrudes through panel

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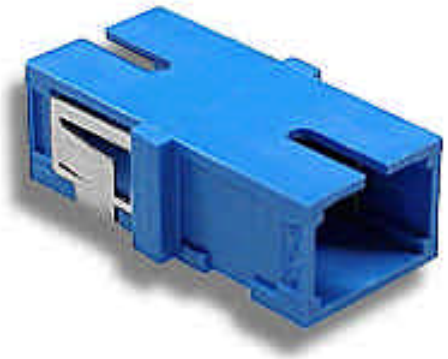
Fiber-Optic Connectors and Receptacles

- Many types of fiber-optic connectors are in use
- Examples below are used in Telecom and Datacom



Simplex-SC

Duplex-SC

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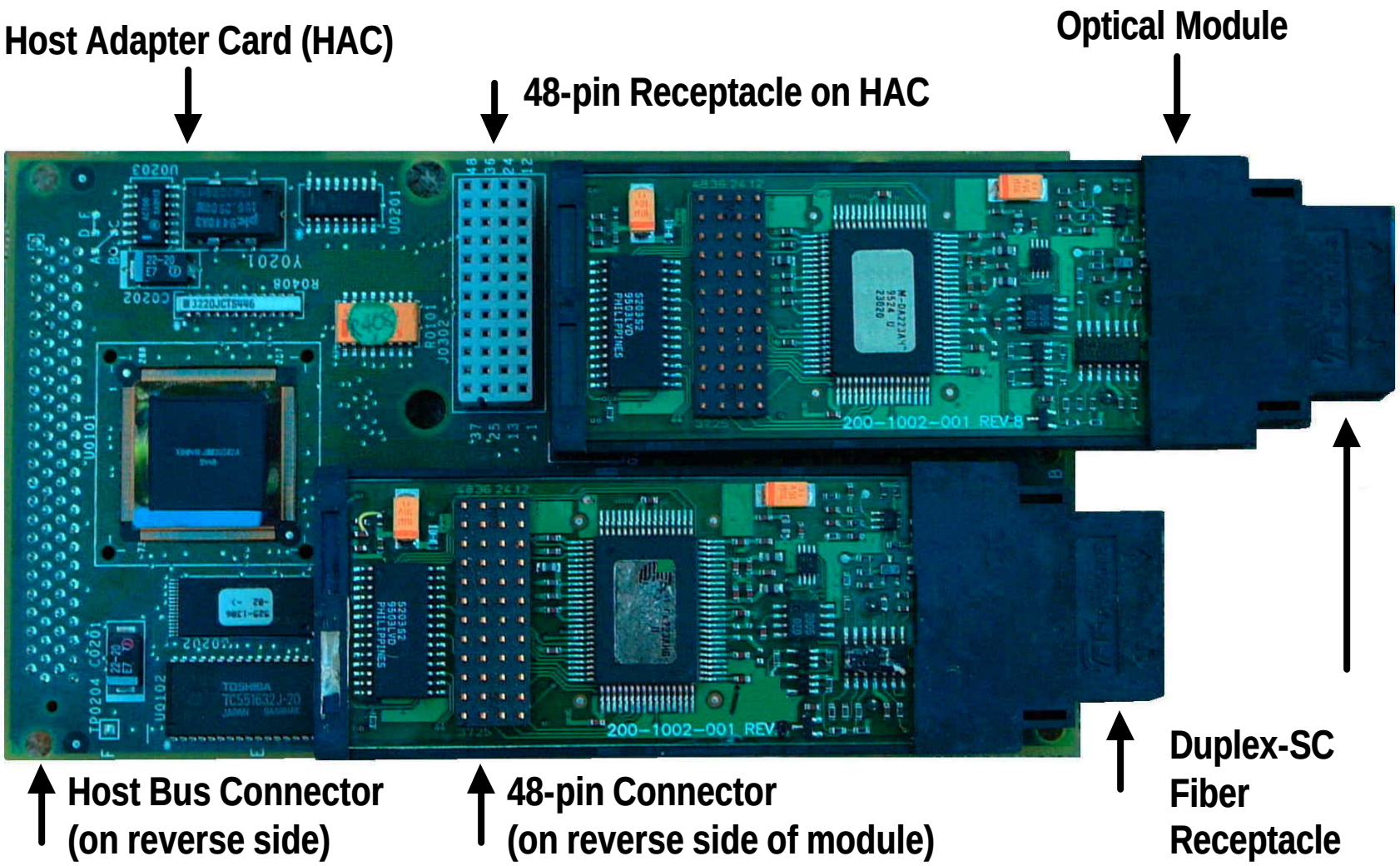
Photograph of HAC with optical modules

Enclosure not shown



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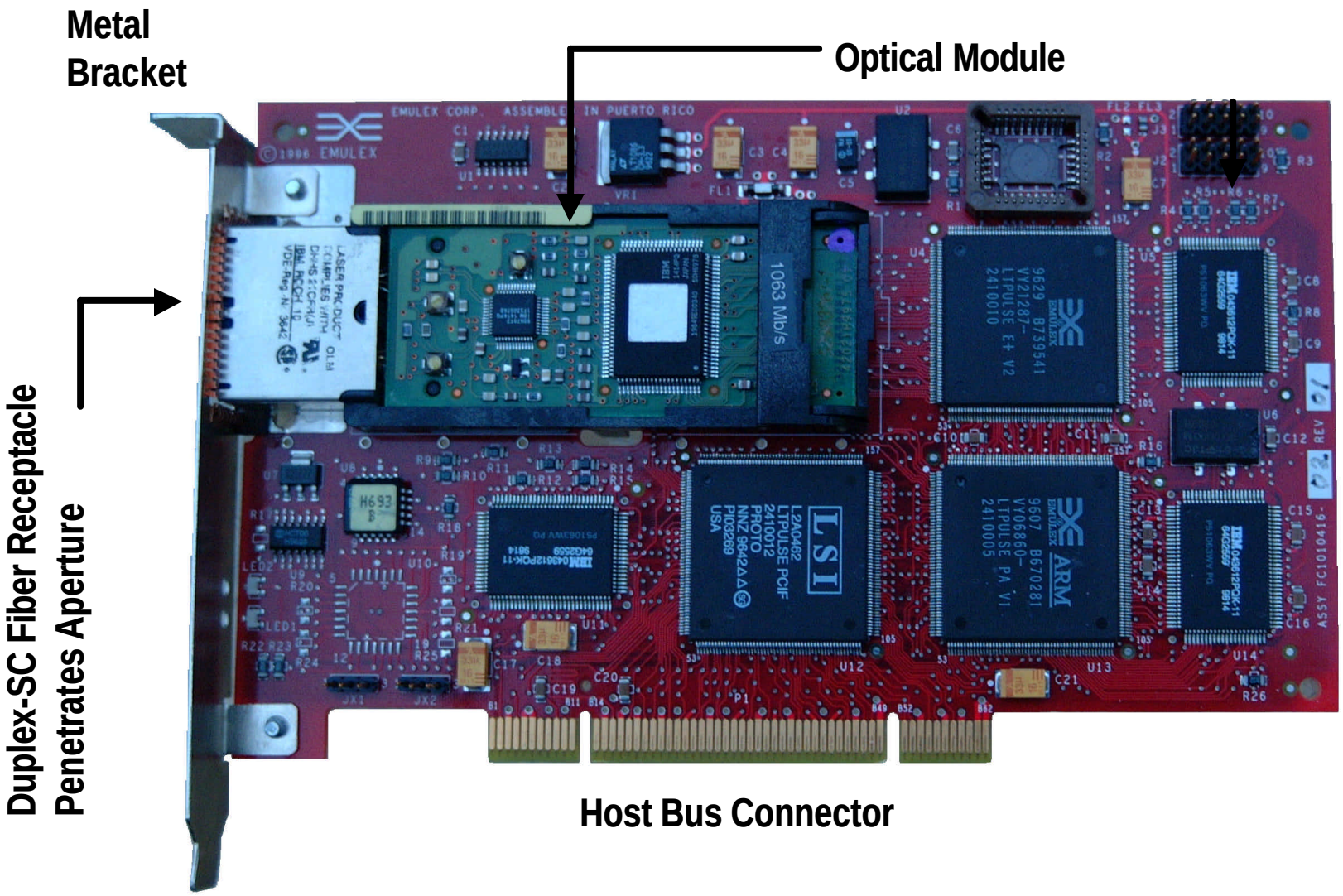
Photograph of HAC with optical module



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Review of Design Rules

And the shielding of apertures

Enclosure Design Rules

- EMC rules consider the 5th harmonic of the max frequency
- RF energy is inside enclosure, which must be “RF tight”
  - Usually metal enclosure acts as shield
  - Conductive polymers or plastic with conductive coating
  - Minimum requirements on shield thickness and conductivity
- Carefully control seams, louvers, backpanels, and other sources of RF emission “leakage” from enclosure
  - Rigorous and robust mechanical design
  - RF gaskets to maintain shield integrity
- Particular attention is paid to connector feedthroughs and apertures for ventilation, indicator lights, and displays
  - Limit number of apertures in shield
  - Limit maximum size of apertures in shield

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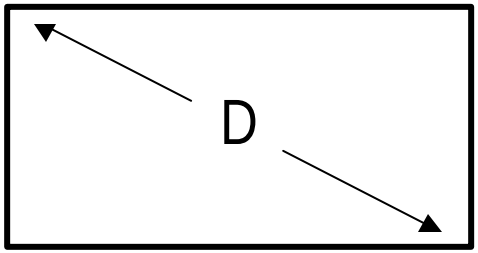
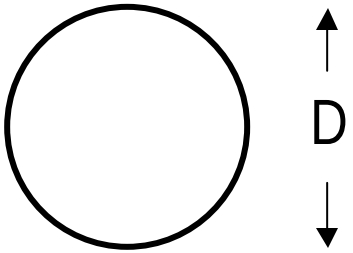
Apertures in an Ideal Enclosure





- For RF of wavelength Λ, in general apertures smaller than a *half-wavelength* will not radiate RF
- The aperture is said to be "cut off" for $\Lambda > \Lambda_c$ i.e. for RF frequencies below a critical value called f_c
- For $f < f_c$, only evanescent (bound) solutions to Maxwells' equations exist. Evanescent field amplitude decays exponentially within a few mm
- Assumes air; neglects waveguide and other effects

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RF Cutoff Frequency Calculation for an Ideal Enclosure with an Aperture of size D

- The cutoff wavelength Λ_c may be found by setting

  $$D = \Lambda_c / 2$$

  $$\Rightarrow \quad \Lambda_c = 2D$$

- substituting

  $$\Lambda \equiv c / f \qquad \text{where } c \cong 3 \times 10^8 \text{ m/sec}$$

- yields the cutoff frequency f_c of an air-filled aperture

  $$f_c = c / \Lambda_c = c / 2D$$

- Example: duplex-SC fiber aperture (D = 28 mm)

  $$f_c \approx 5.4 \text{ GHz}$$

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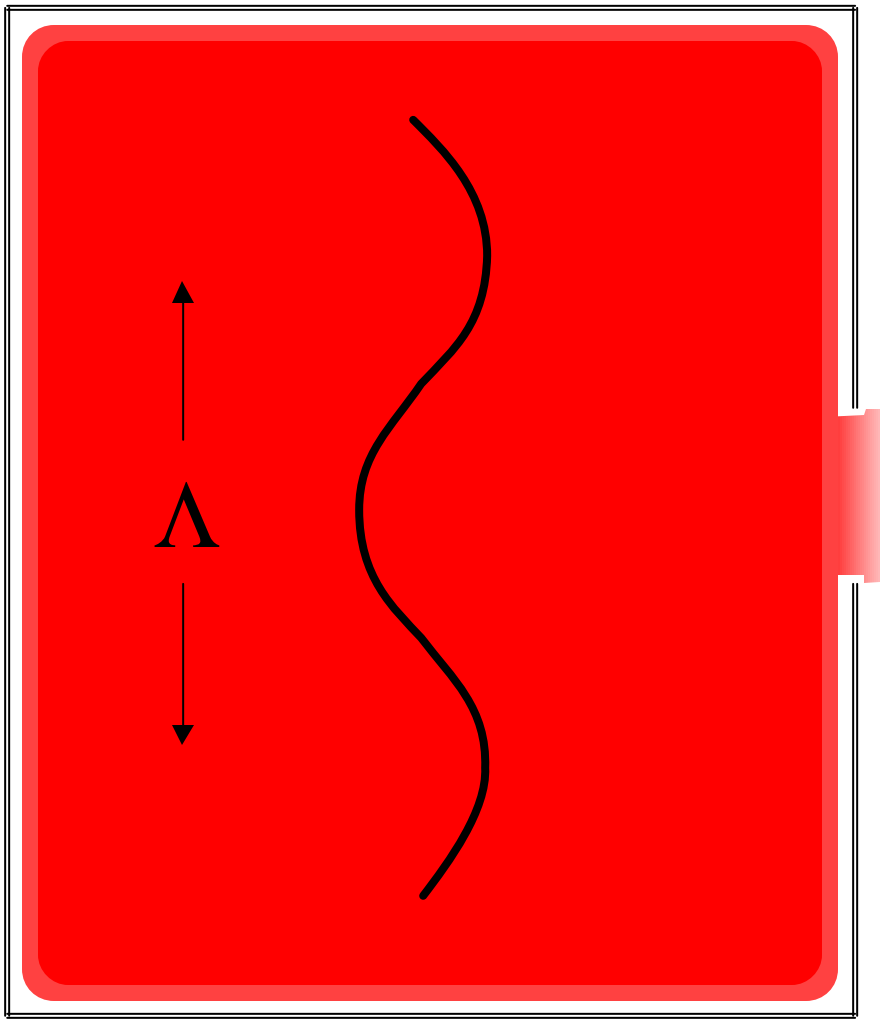
Low Frequency Inside Ideal Enclosure



$\Lambda > 2D$

$f < f_c$

EMC
PASS

Evanescent
(bound) Field

No Radiated Field

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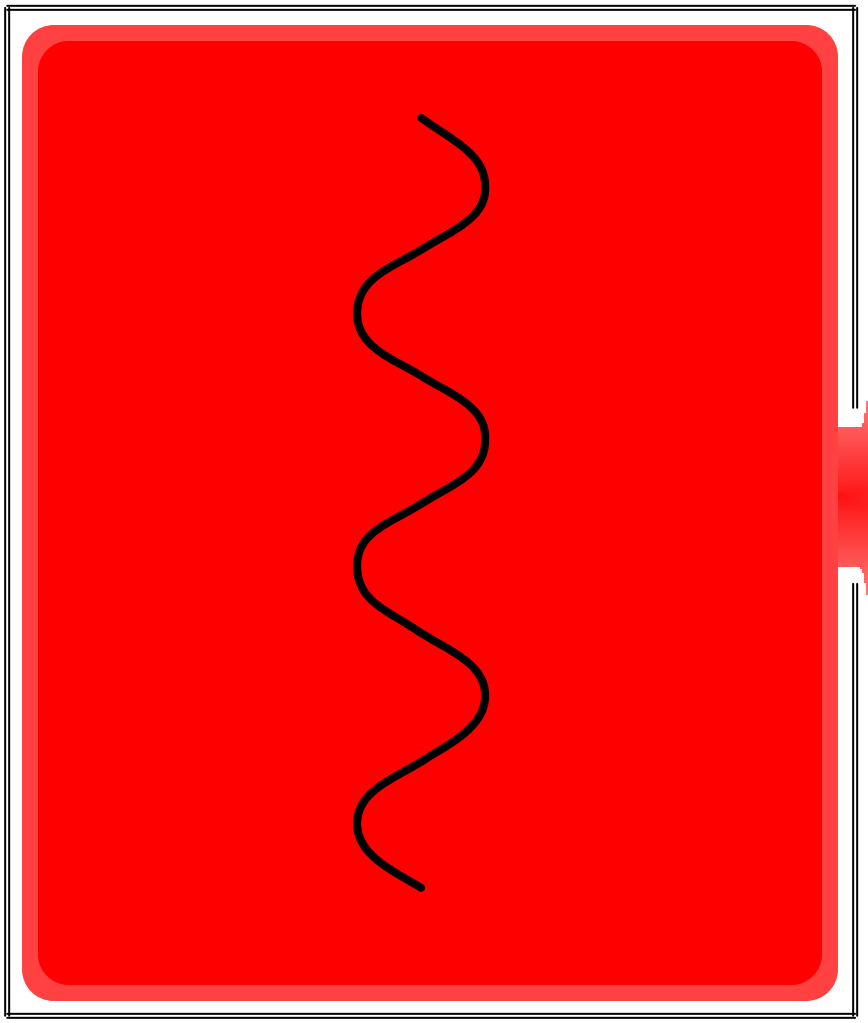
High Frequency Inside Ideal Enclosure



$\Lambda < 2D$

EMC
FAIL

Radiated Field

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Cutoff Frequency for Various Apertures

Fiber Connector	**Aperture Size D**	**Calculated f_c**
Duplex-SC	28 mm	5.4 GHz
Simplex-SC *	14 mm	10.7 GHz
MT-RJ	11 mm	14 GHz
2x SC Ferrule	5.0 mm	30 GHz
2x LC Ferrule	2.5 mm	60 GHz

* Or duplex-SC with conductive septum

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Early Assumptions/Conventional Wisdom

- Optical fiber is a dielectric waveguide
  - Unperturbed fiber has no radiating optical modes, once EMD achieved
  - No RF emissions, even if light is modulated at high frequency
- Optical fiber cable is a dielectric
  - Fiber itself is made of glass
  - Cables used aramid fiber and polymer construction
  - Electrical isolation between equipment means no ground loops
  - Non-metallic cables exempt from conducted immunity EMC testing
- Several advantages over other communication technologies
  - Zero RF emissions
  - Easier to pass EMC regulatory hurdles
  - Immune to RF interference and ESD
  - Very secure and tap-resistant

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Example: Gigabit Ethernet

- IEEE 802.3 Gigabit Ethernet 1.25 Gigabits/sec serial
- Maximum frequency (neglecting other sources) arises from a 101010… data pattern

$$f = 1250 \text{ Mbps} / 2 = 625 \text{ MHz}$$

- FCC requires testing of 5^{th} harmonic of this signal

$$f = 5 \times 626 \text{ MHz} = 3.125 \text{ GHz}$$

- Air-filled duplex-SC aperture (D = 28 mm diagonal)
  - Cutoff frequency $f_c \approx 5.4$ GHz
  - Aperture is sufficiently small to contain 3.125 GHz
  - Margin: aperture will contain 8^{th} harmonic (5 GHz)

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Early Regulatory Failures

In normally RF-tight enclosures

Early Regulatory Failures

- Early adopters of optical fiber technology often used HAC “daughtercards” to upgrade existing system chassis
- These systems chassis were production items that had already undertaken EMC testing, and had passed with wide margin
- In the early 1990s, when fiber optic networking HACs were installed, formerly RF-tight products failed radiated emission in the 3 GHz range
- Equipment could not ship, causing consternation and delay
- Initially, individual vendors developed ad-hoc methods (usually involving more shielding) to pass EMC
- Eventually, multi-source agreements (MSAs) standardized
- WHY WERE THERE EMC FAILURES ??

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Open Air Test Site (OATS) for Testing

Control room not shown

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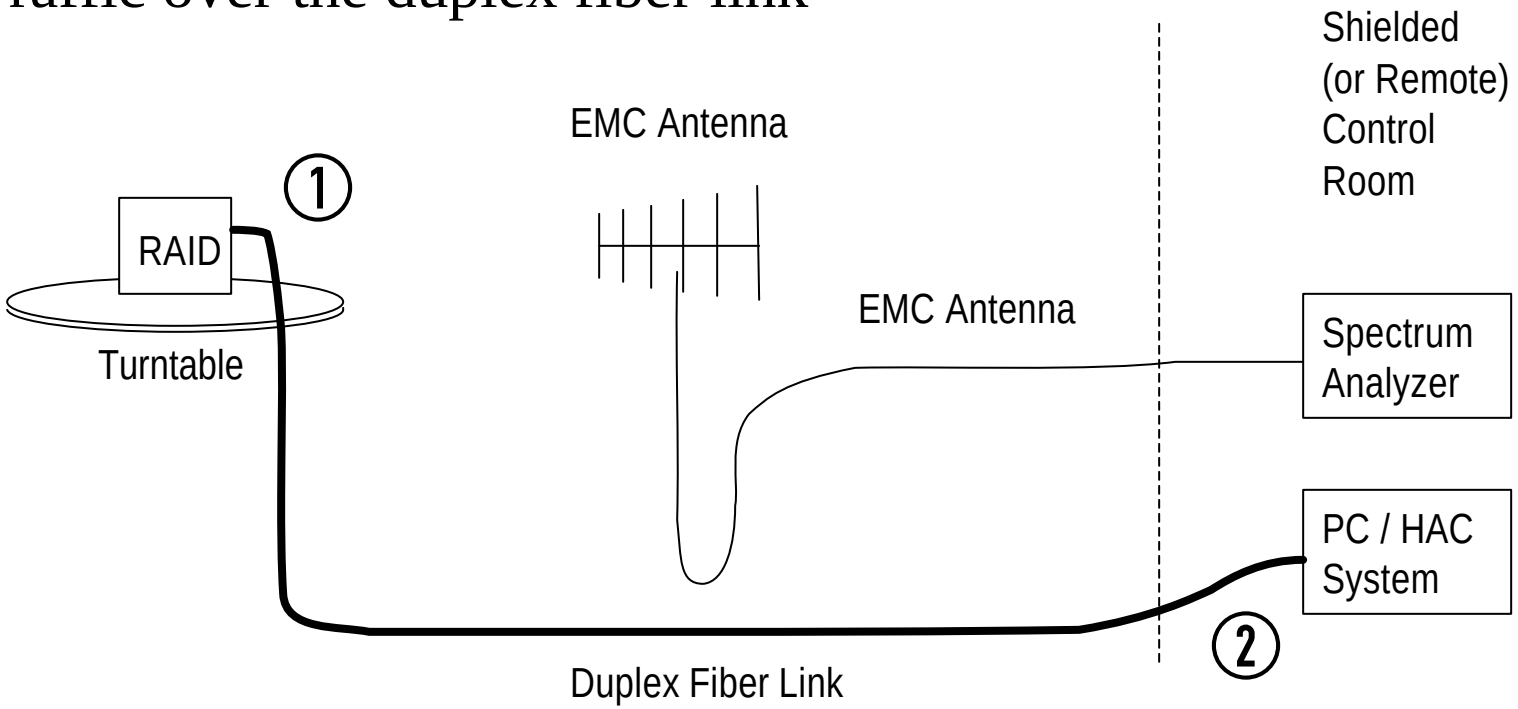
Courtesy UL

EMC Test Setup for Radiated Emission

- “Engineering scans” done, not formal EMC testing
- Follow EMC test protocols
- Carefully calibrated test equipment
- Traffic over the duplex fiber link



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Observations and Serendipity

- Fiber connected at ① (on turntable) and ② (outside OATS)
  - Observed high RF emissions
- Unplugged connector ①, observed low RF emissions
  - No traffic. Observed low (baseline) RF emissions
- Reinstalled connector ①, traffic reestablished
- Unplugged connector ② (outside OATS)
  - No traffic. Observed high RF emissions
  - RF emissions should be the same for unplugging either connector
- Accidental observation of emission while connector ① was unplugged from the RAID system duplex-SC receptacle
  - Observed high RF emissions when metal screwdriver near aperture
  - RF emissions dropped to baseline when screwdriver was withdrawn
- Deconstructed several optical fiber connectors

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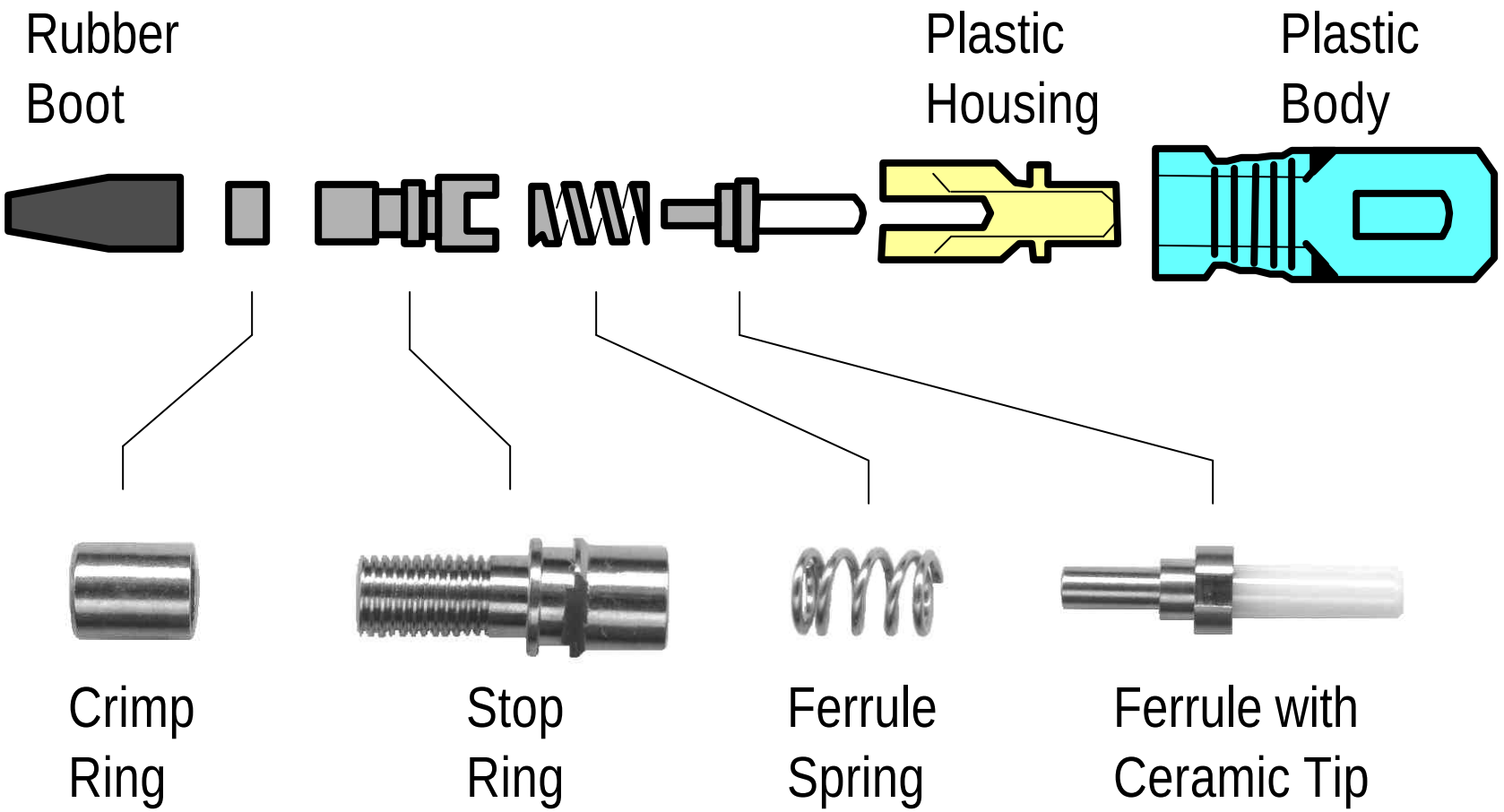
Exploded View of SC Connector



TYPICAL CONDUCTIVE PARTS

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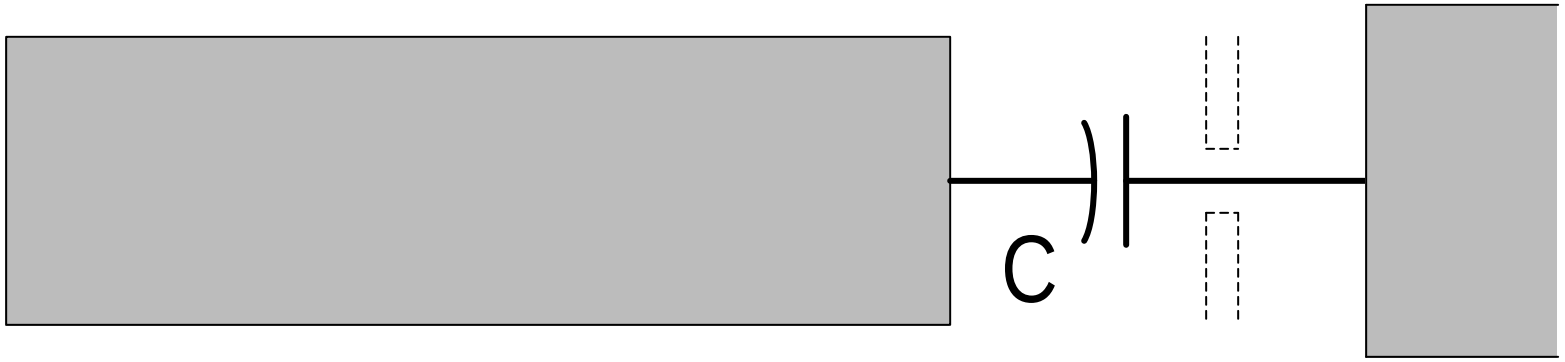
Proposed Model

Small conductive parts in fiber-optic connectors cause RF emission failures

Proposed Equivalent Circuit for Model

- Shield and aperture shown by phantom lines

= Metallic body with parasitic capacitance C to inside shield



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Magnitude of Capacitance

- At high frequencies a 1 pF capacitance is low impedance

$$Z = \frac{1}{2\pi f C} \angle -90° \approx -16\,j \text{ ohms at 10 GHz}$$

- Optical connectors that have finite capacitance to within the enclosure may be easily driven by potential differences V

$$I = V / Z$$

- For example, a 28 mm × 12 mm parallel plate capacitor separated by 1mm air gap results in 3 pF capacitance
- Assume there will be some finite capacitance to within chassis
- There will also be capacitance to the chassis itself (ignore)

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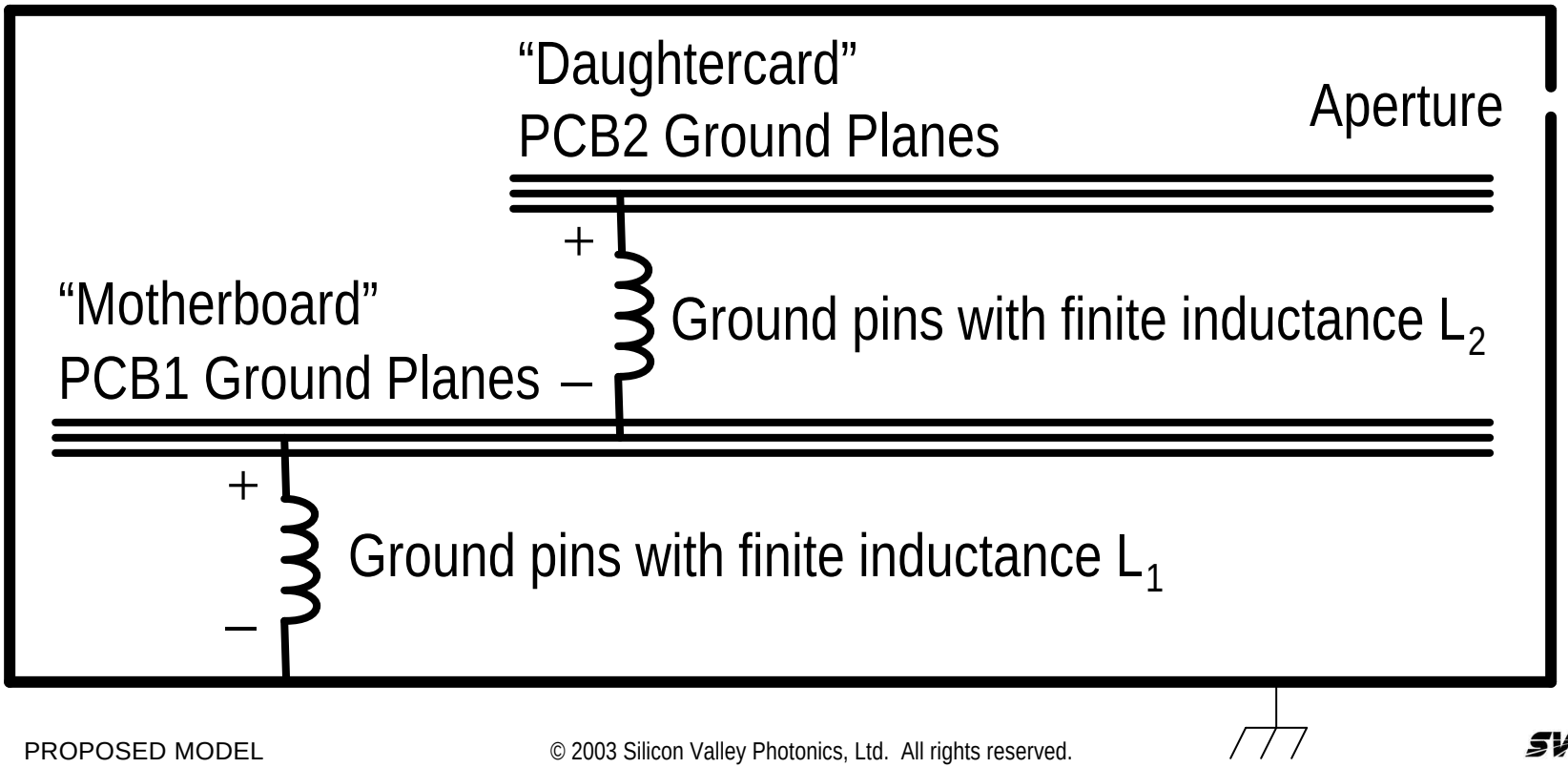
Where does driving voltage come from?

- Propose V potential across parasitic inductances
- PCB-to-PCB connectors, e.g. optical module on HAC
- Finite impedance between ground planes in PCB stack



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Magnitude of Inductance

- All electrical connectors have parasitic inductance.
- At high frequencies, a 1 nH inductance presents impedance

$$Z = 2\pi f L \angle 90° \approx +63\,j \text{ ohms at 10 GHz}$$

- Connector parasitic inductance needs to be minimized in high-speed PCB-to-PCB electrical interconnect
- Parasitic inductance will generate a voltage difference proportional to the current passing through the connector

$$V = Z I$$

- For example, groundplane-to-groundplane
  - Ground is no longer homogeneous
  - Transient voltage differences between ground planes in PCB stack
  - Well-understood, and commonly called “ground bounce”

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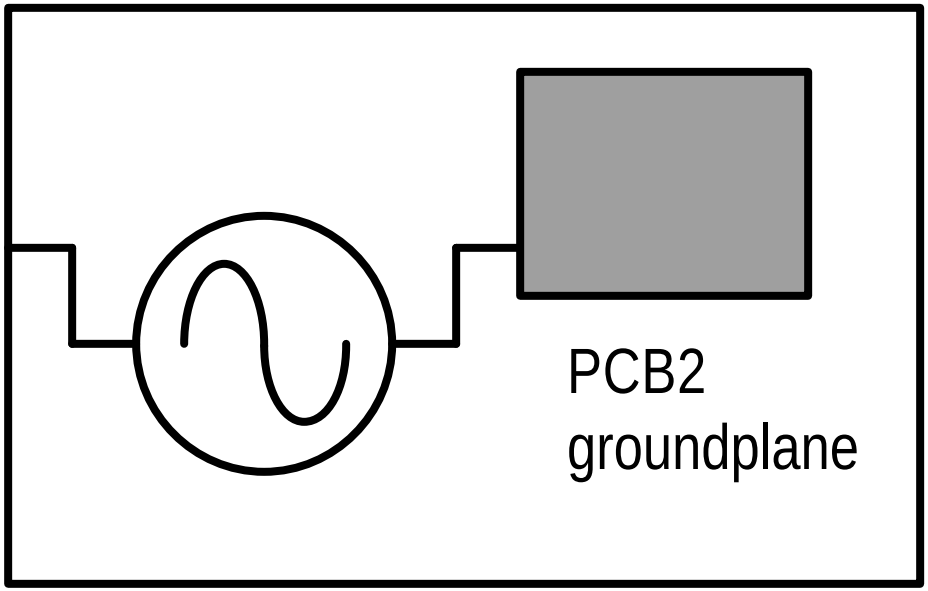
Ideal Enclosure with RF Voltage Source

- Replace voltage across parasitic inductance with a Thévenin-equivalent voltage source of the correct amplitude, impedance, phase, frequency, etc.
- Assume motherboard is well-grounded to chassis



100%
Shielded

No Dipole
=
No Fields

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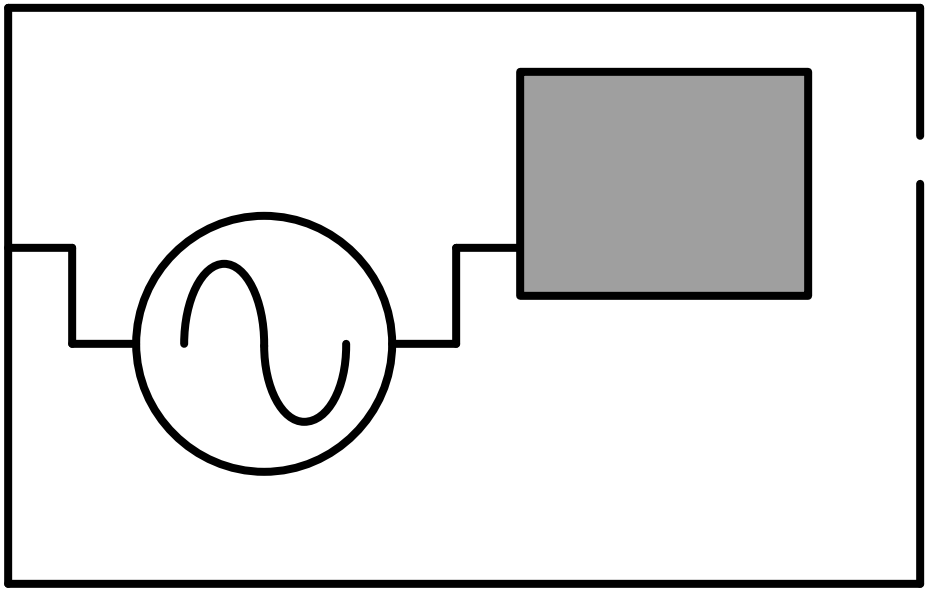
Enclosure with Aperture in Cutoff Regime

- For $f < f_c$, there is no radiated emission
- For $f < f_c$, there is only evanescent (bound) field within a few millimeters of the aperture
- There is no radiated solution to Maxwell's equations



Evanescent
Field Only

No Radiated
RF Emission

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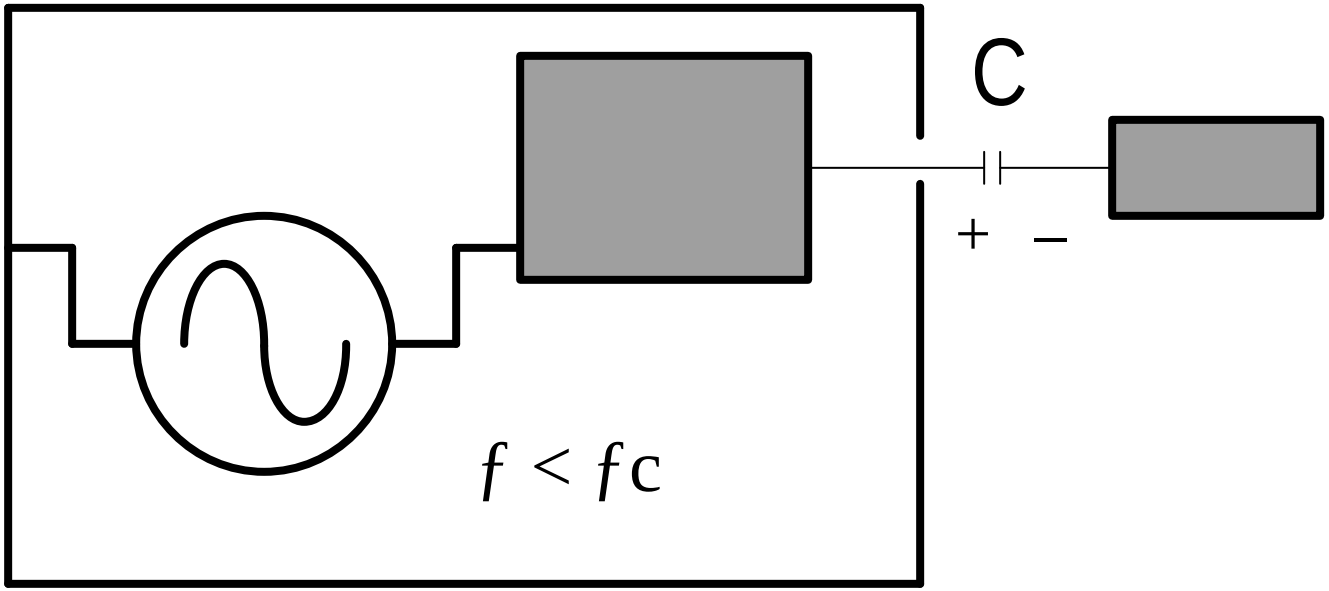
Enclosure with Metallic Body Near Aperture

- Assume a finite parasitic capacitance C exists via the aperture, between the interior ground plane to the exterior metallic body
- High-frequency currents through C induces potential



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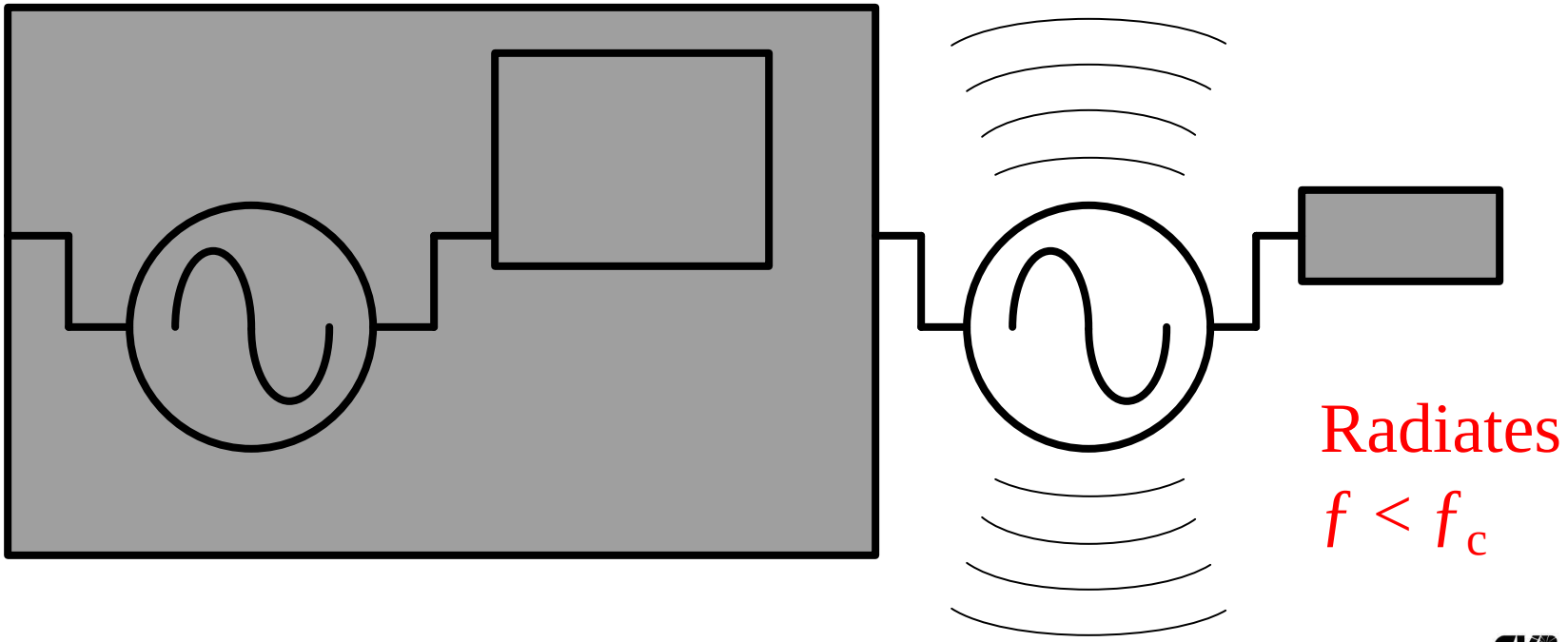
Resultant Equivalent Circuit

- Replace voltage across parasitic capacitance with Thévenin-equivalent voltage source as before
- The proposed model is that a new dipole is created between the chassis and the external metallic body



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Experiments

Three tests to validate hypothesis

Experimental Overview

- Demonstrate that the proposed model qualitatively explains failure mechanism
- Constructed a battery-powered enclosure with ground plane stack and internal RF source
- Measure electromagnetic emissions at EMC test site
  - Maximum emissions, with respect to angle and elevation
  - Emission measurement accuracy ± 4 dB
- Introduce external metallic body near aperture
- Verify RF emission for $f < f_c$ condition
- Verify ultimate source of driving voltage

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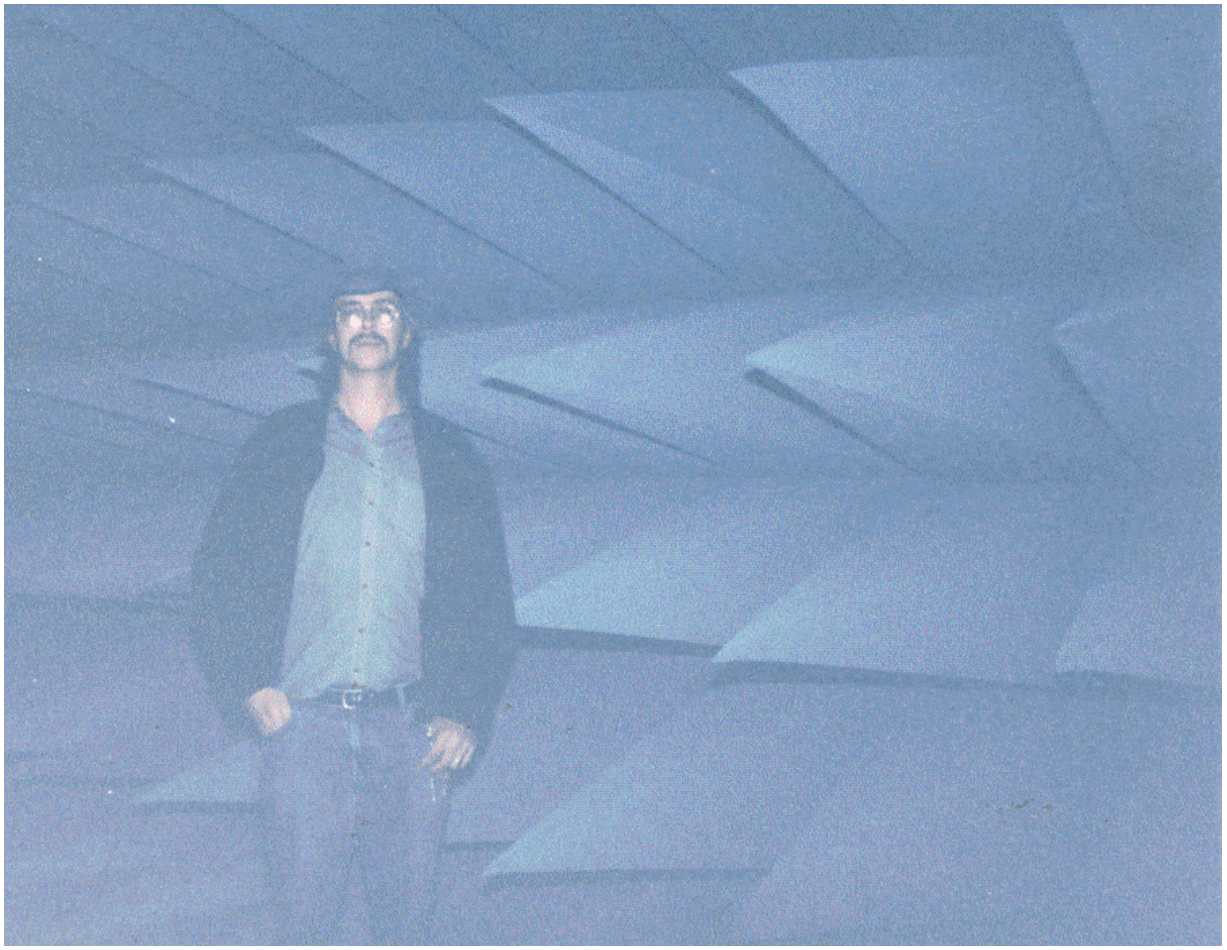
Inside 10 meter Semi-Anechoic Chamber



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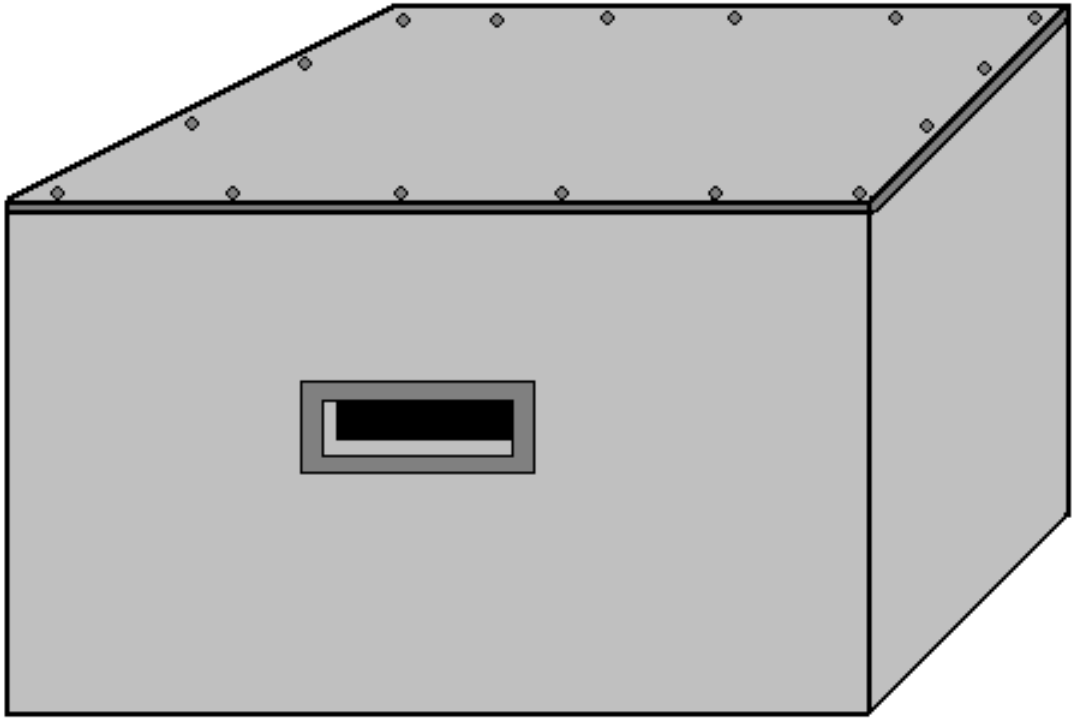
Experimental Test Enclosure

- Attempt to simulate computer system with aperture
- 20 cm × 30 cm × 28 cm Bud™ box
- RF gasket and many screws to seal the cover



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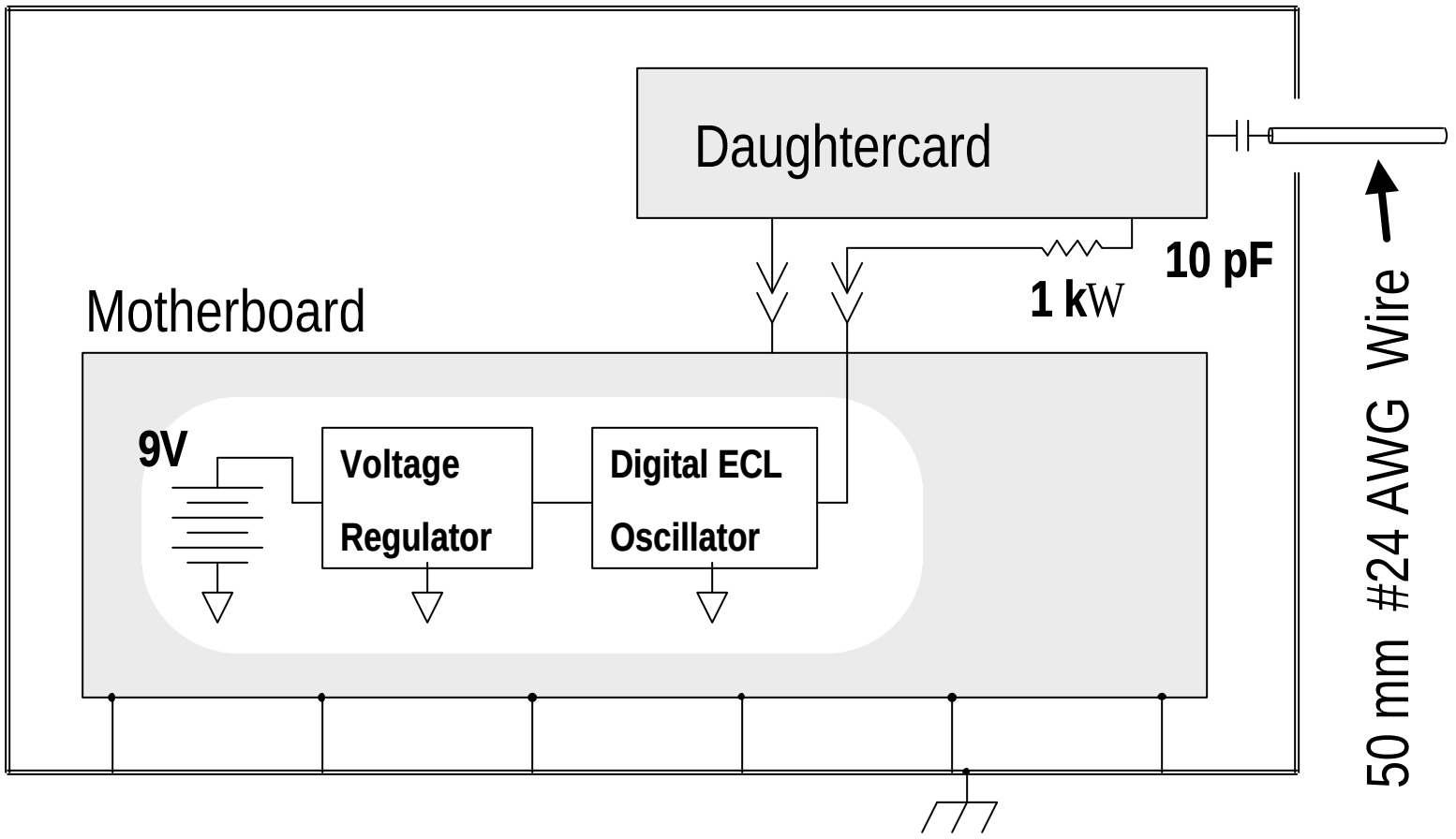
Schematic of RF-Generating Circuit



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Experimental Details

- RF-tight enclosure with 28 mm × 12 mm aperture
- Motherboard ground plane has multiple low-impedance connections to the chassis, neglect L_1
- Battery-powered RF energy source on motherboard
  - Ecliptec 160 MHz ECL oscillator
  - 1.1 nsec rise/fall times (f components slightly below 1 GHz)
- Daughtercard connected via 48-pin PCB-to-PCB connector
  - 1 signal pin and 1 ground pin
- 1 kΩ mismatched load (to maximize RF) on daughtercard
- External metallic body simulated by 50 mm of #24 AWG wire
- 10 pF coupling capacitor between external metallic body and daughtercard ground plane

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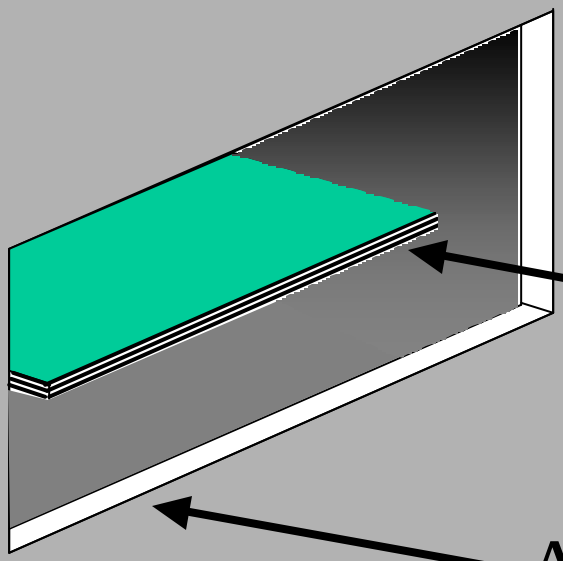
Experiment #1

Confirmation of dipole model

Experiment 1A - Aperture Only



Edge of Daughtercard
28 mm from Aperture

Aperture in Front Panel
28 mm × 12 mm

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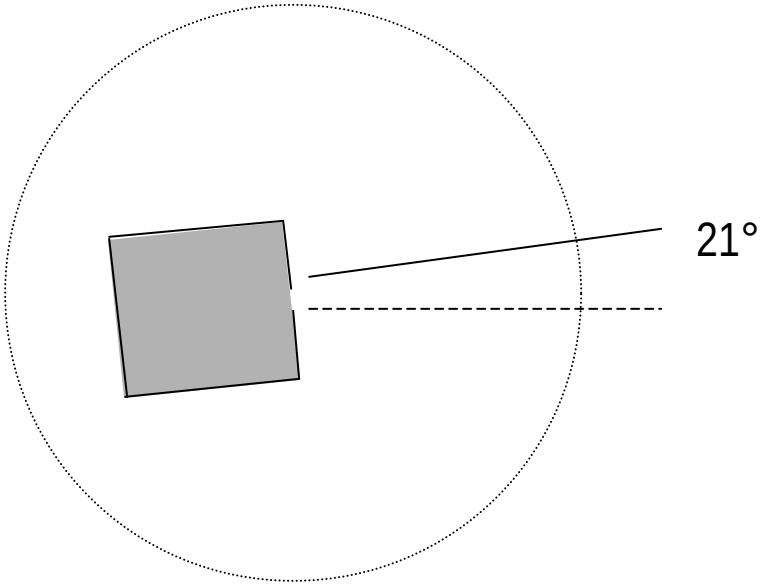
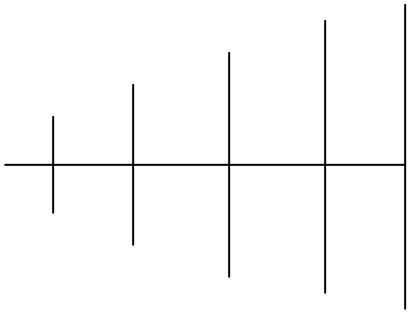
1A - RF Emissions from Aperture Only





- Place test box on turntable and rotate for maximum emissions
  - Angle = 21° Vertical offset = 0
- Demonstrates enclosure is RF-tight, aperture is in cutoff regime
  - Very Low far-field RF emissions from open aperture
  - RF Emission = 26.4 dBuV/m at 957.5 MHz
    (20 dB margin below FCC Class A)
- Evanescent RF could be detected with near-field probe

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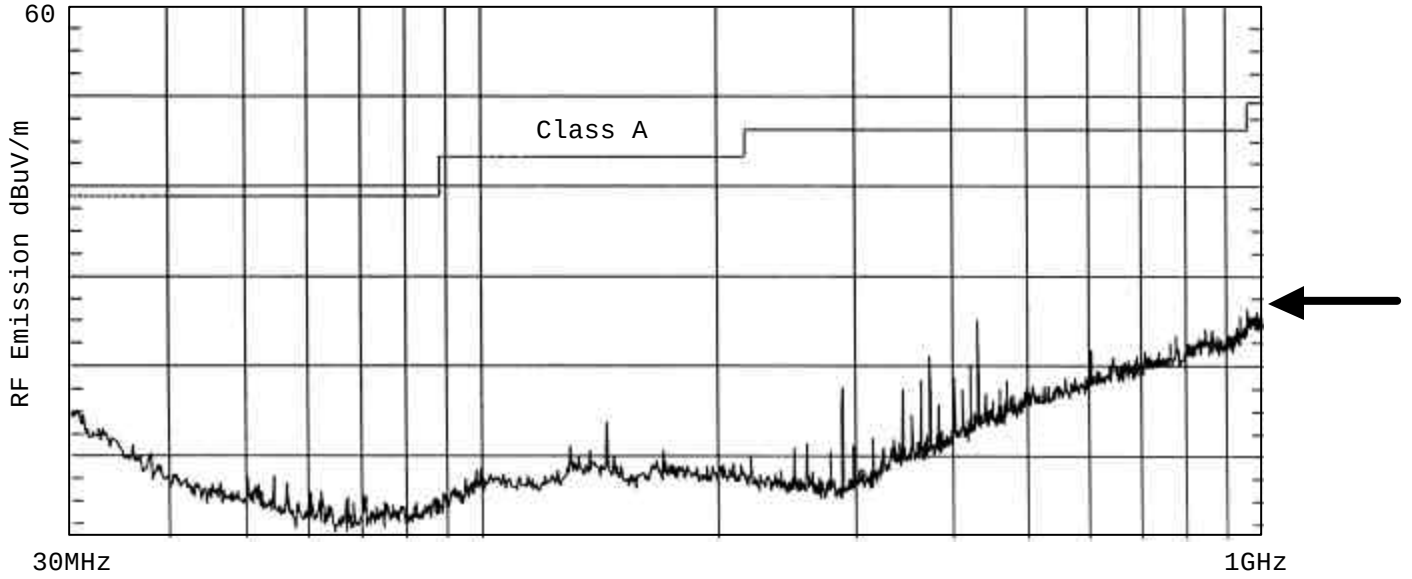
1A - RF Emission as a Function of *f*

- Baseline Measurement – No External Metallic Body
- Aperture in cutoff mode for < 1 GHz, low emissions



Freq Mhz	PK Level	QP Limit	Delta	Angle	Height	Polar	TCF	Probe CF	Coax CF	Preamp CF
957.5	26.36	46.4	-20	21	102	0	6.92	25.2	6.4	24.7
936.25	25.55	46.4	-20.8	21	102	0	5.79	24.1	6.08	24.4
431	25.16	46.4	-21.2	21	102	1	-4.84	15.8	3.84	24.5
846.25	24.26	46.4	-22.1	21	102	1	5.46	23.8	6.08	24.4
907.5	23.57	46.4	-22.8	21	102	0	4.77	23.4	5.76	24.4
775	23.38	46.4	-23	21	102	0	3.3	22.3	5.44	24.4
831.25	23.31	46.4	-23.1	21	102	1	4.83	23.8	5.76	24.7
997.5	25.67	49.5	-23.8	21	102	0	7.19	25.2	6.4	24.4
30.525	15.14	39	-23.9	21	102	1	-5.26	18.9	0.96	25.1
602.5	21.75	46.4	-24.7	21	102	1	0.706	20	5.12	24.4
707.5	21.71	46.4	-24.7	21	102	1	1.95	21.5	5.12	24.7
737.5	21.7	46.4	-24.7	21	102	0	2.9	21.9	5.44	24.4
373.5	21.12	46.4	-25.3	21	102	1	-7.6	13.4	1.52	24.5
643.75	21.1	46.4	-25.3	21	102	1	1.98	21.3	5.12	24.4

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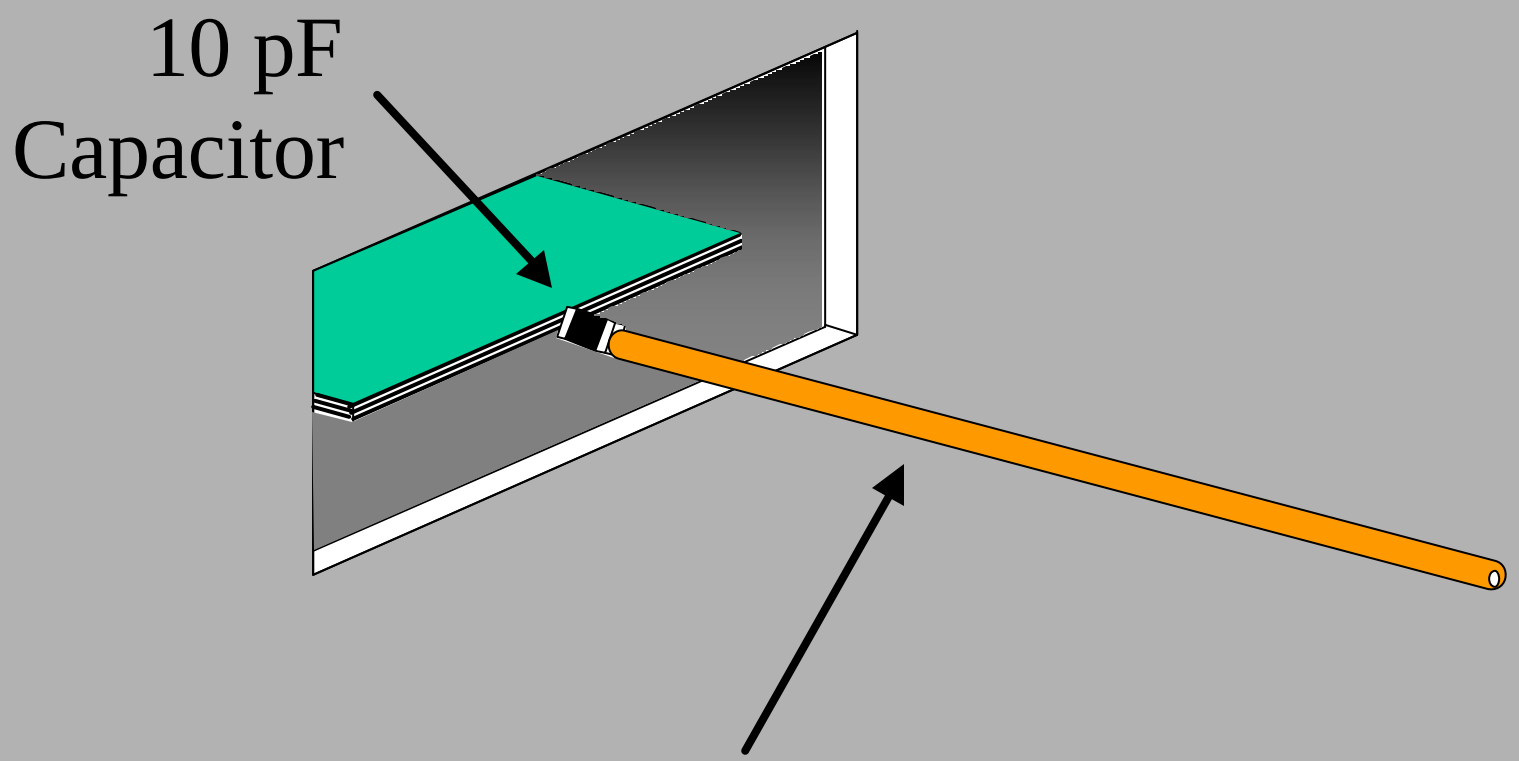
Experiment 1B – Wire and Capacitor



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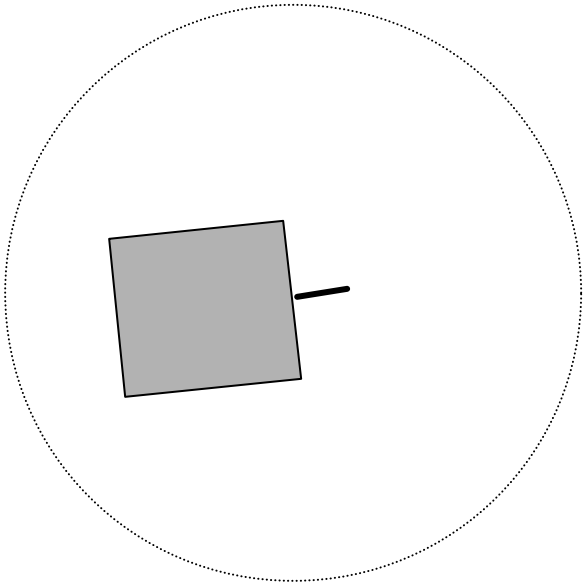
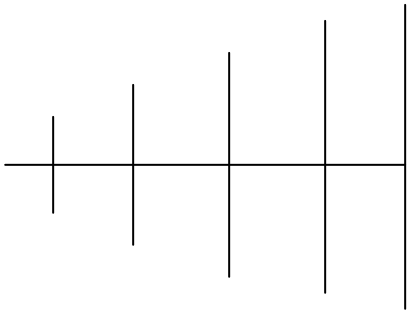
1B - Ext Metallic Body with Coupling Cap





- Added 50mm long #24 AWG wire and 10 pF coupling cap
- Carefully reposition box on turntable, do not change angle
  - Angle = 21° Vertical offset = 0
- Slight, in RF emissions above experimental noise floor
  - RF Emission = 26. 0 dBuV/m at 952.5 MHz
    (20.4 dB margin below FCC Class A)

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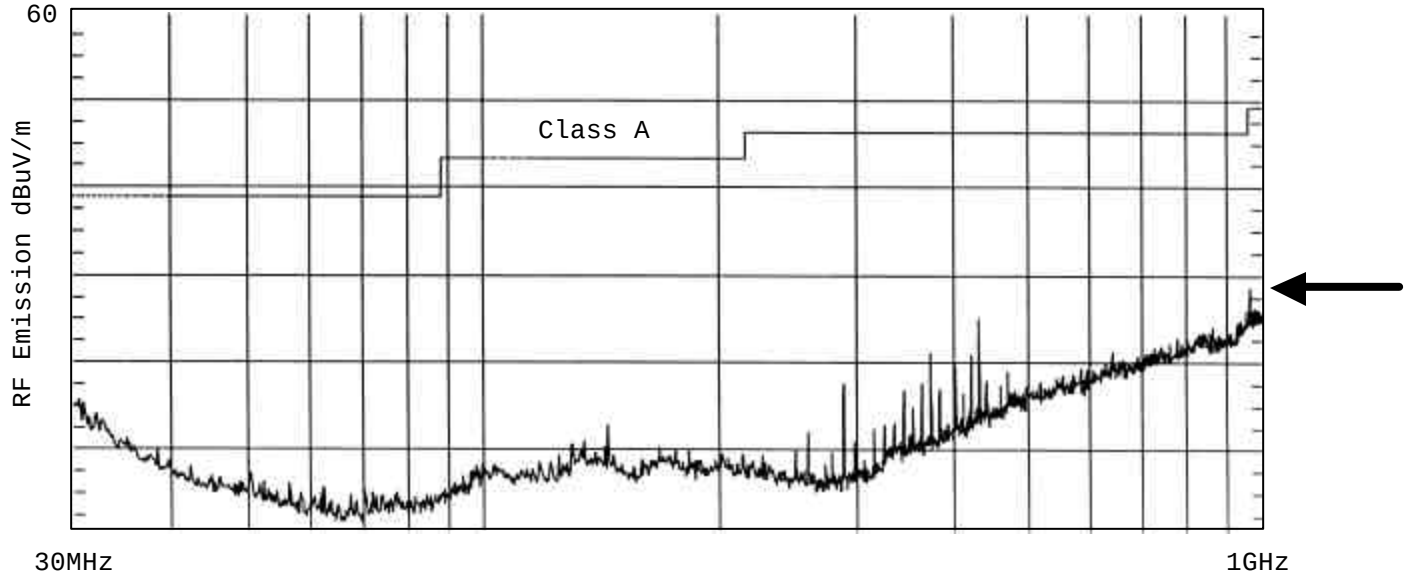
1B - RF Emission as a Function of *f*

- Ext Metallic body and 10 pF capacitor present
- Some RF emission noted at 961 MHz



Freq MHz	PK Level	QP Limit	Delta	Angle	Height	Polar	TCF	Probe CF	Coax CF	Preamp CF
952.5	26.01	46.4	-20.4	21	102	1	6.89	24.9	6.4	24.4
962.5	28.82	49.5	-20.7	21	102	1	7.46	25.5	6.4	24.4
431	25.16	46.4	-21.2	21	102	1	-4.84	15.8	3.84	24.5
862.5	24.14	46.4	-22.3	21	102	0	4.7	23.3	5.76	24.4
911.25	23.59	46.4	-22.8	21	102	0	5.11	23.4	6.08	24.4
827.5	23.47	46.4	-22.9	21	102	1	4.99	23.6	5.76	24.4
30.525	15.78	39	-23.2	21	102	0	-5.26	18.9	0.96	25.1
777.5	22.98	46.4	-23.4	21	102	1	3.54	22.2	5.76	24.4
1000	25.81	49.5	-23.7	21	102	1	6.69	24.7	6.4	24.4
741.25	21.92	46.4	-24.5	21	102	0	2.48	21.8	5.44	24.7
641.25	21.39	46.4	-25	21	102	0	1.63	21.2	5.12	24.7
711.25	21.17	46.4	-25.2	21	102	1	2.37	21.7	5.12	24.4
373	21.14	46.4	-25.3	21	102	1	-7.58	13.4	3.52	24.5
421	21.05	46.4	-25.3	21	102	1	-5.75	15.2	3.84	24.8

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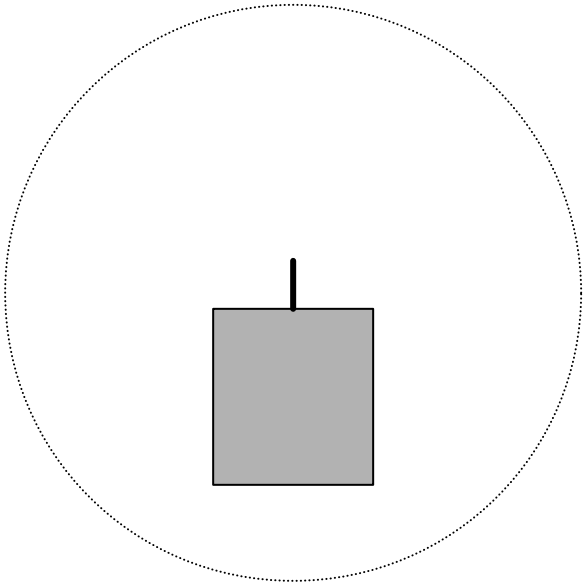
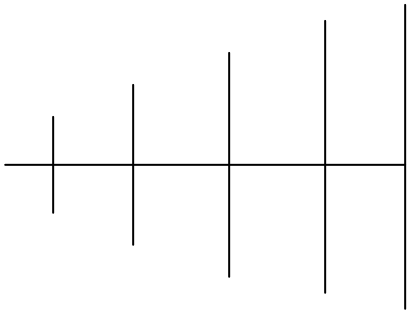
1C – Optimize Angle and Vertical Offset





- Rotate turntable to achieve maximum emissions
  - Angle = 89° Vertical offset = 0
- Classic dipole radiation pattern noted during rotation
- Large increase in RF Emissions
  - RF Emission = 41.0 dBuV/m at 961.25 MHz
    (8.5 dB margin below FCC Class A)

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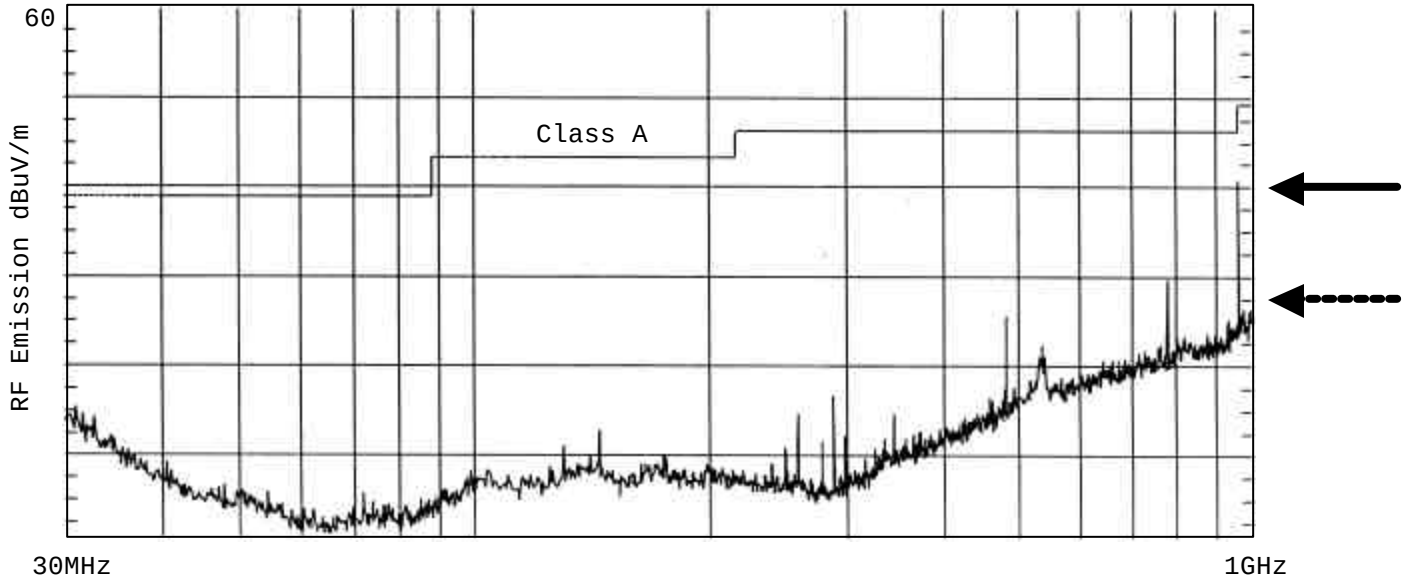
1C - RF Emission as a Function of *f*

- After rotating to find maximum emissions at 89°
- Large increase in 961 MHz and other emissions



Freq Mhz	PK Level	QP Limit	Delta	Angle	Height	Polar	TCF	Probe CF	Coax CF	Preamp CF
961.25	40.99	49.5	-8.51	89	102	1	6.83	25.1	6.08	24.4
777.5	29.7	46.4	-16.7	89	102	1	3.54	22.2	5.76	24.4
481	25.59	46.4	-20.8	89	102	1	-2.81	17.5	4.16	24.5
932.5	25.32	46.4	-21.1	89	102	1	5.24	23.9	5.76	24.4
877.5	23.8	46.4	-22.6	89	102	1	5.32	23.3	6.08	24.1
818.75	23.34	46.4	-23.1	89	102	1	4.54	23.5	5.76	24.7
873.75	23.14	46.4	-23.3	89	102	1	4.66	23.3	6.08	24.7
30.875	15.53	39	-23.5	89	102	1	-5.51	18.7	0.96	25.1
998.75	25.58	49.5	-23.9	89	102	1	7.1	24.8	6.72	24.4
536.25	22.45	46.4	-24	89	102	1	-1.47	18.8	4.48	24.7
726.25	21.87	46.4	-24.5	89	102	1	2.75	21.7	5.44	24.4
713.75	21.5	46.4	-24.9	89	102	1	2.38	21.7	5.12	24.4
642.5	20.77	46.4	-25.6	89	102	1	1.97	21.2	5.12	24.4
633.75	19.69	46.4	-26.7	89	102	1	1.53	21.1	4.8	24.4

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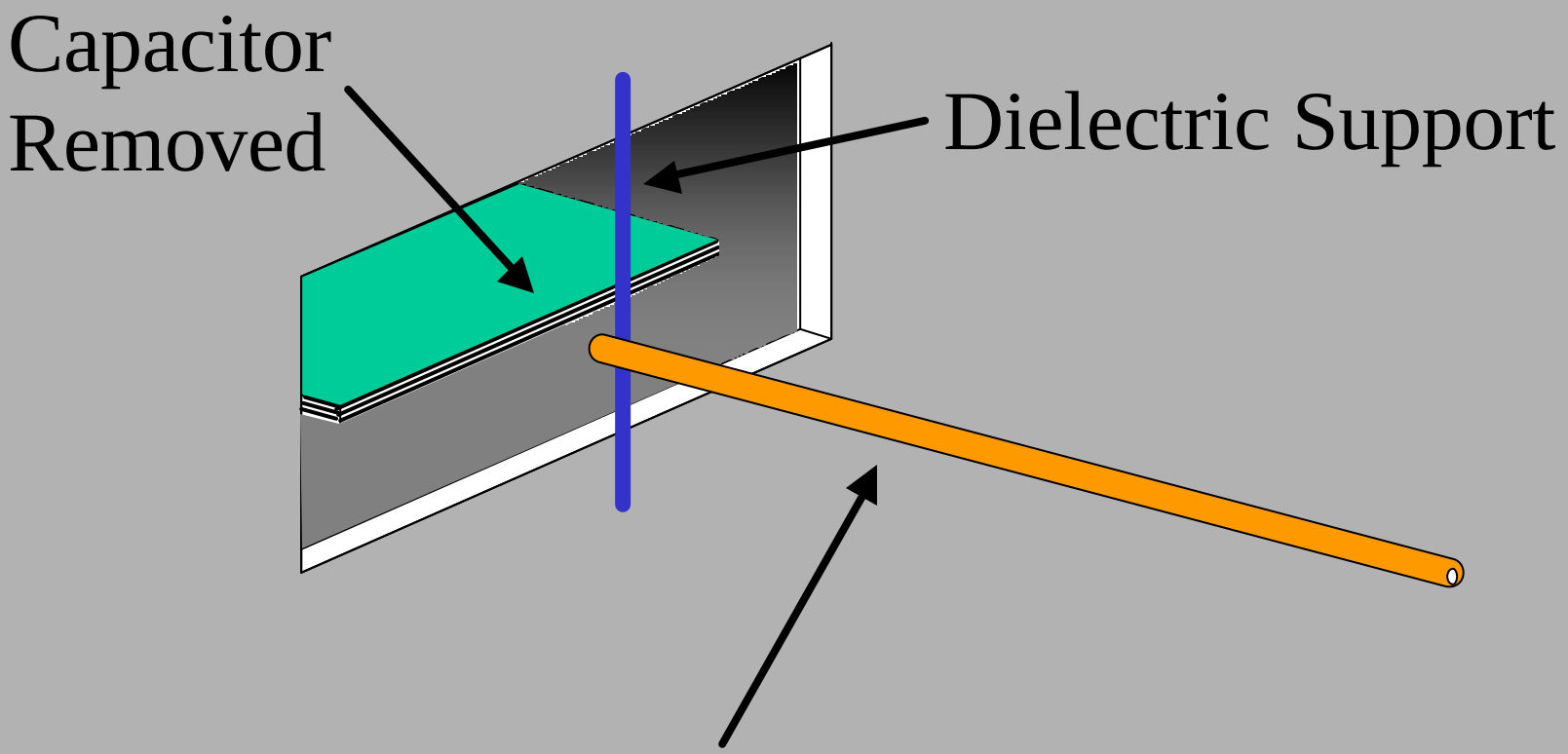
Experiment 1D – Wire Only



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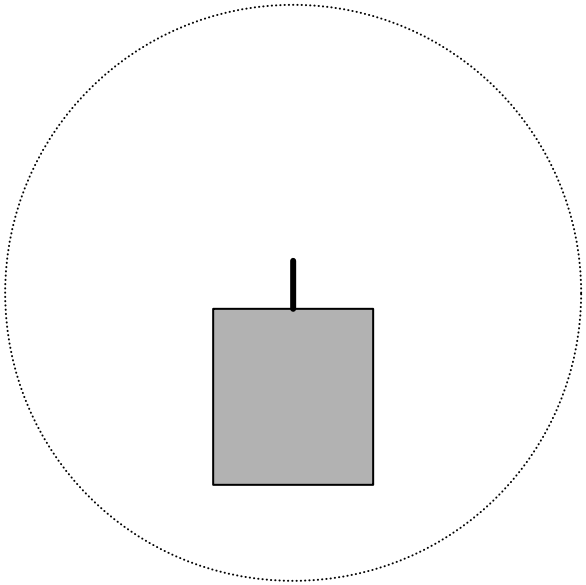
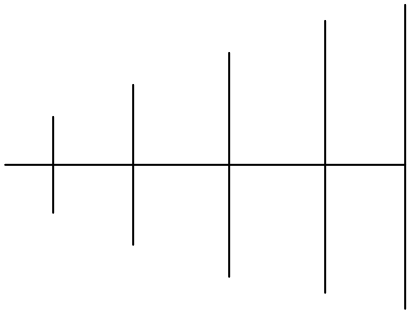
1D - External Metallic Body Only





- Remove 10 pF capacitor and reposition wire in place
- Carefully return system to position of maximum emissions.
  - Angle = 89° Vertical offset = 0
- RF Emission observed to drop to slightly above baseline
  - RF Emission = 29.0 dBuV/m at 961.25 MHz

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Experiment #1 Summary

No.	Angle	Cap	Wire	MHz	dBuV/m
1A	22°	No	No	957	26.4
1B	22°	10 pF	Yes	952	26.0
1C	89°	10 pF	Yes	961	41.0
1D	89°	No	Yes	961	29.0

- Dipole model is confirmed, maximum near 90°
- Emission is strongly dependent on capacitance

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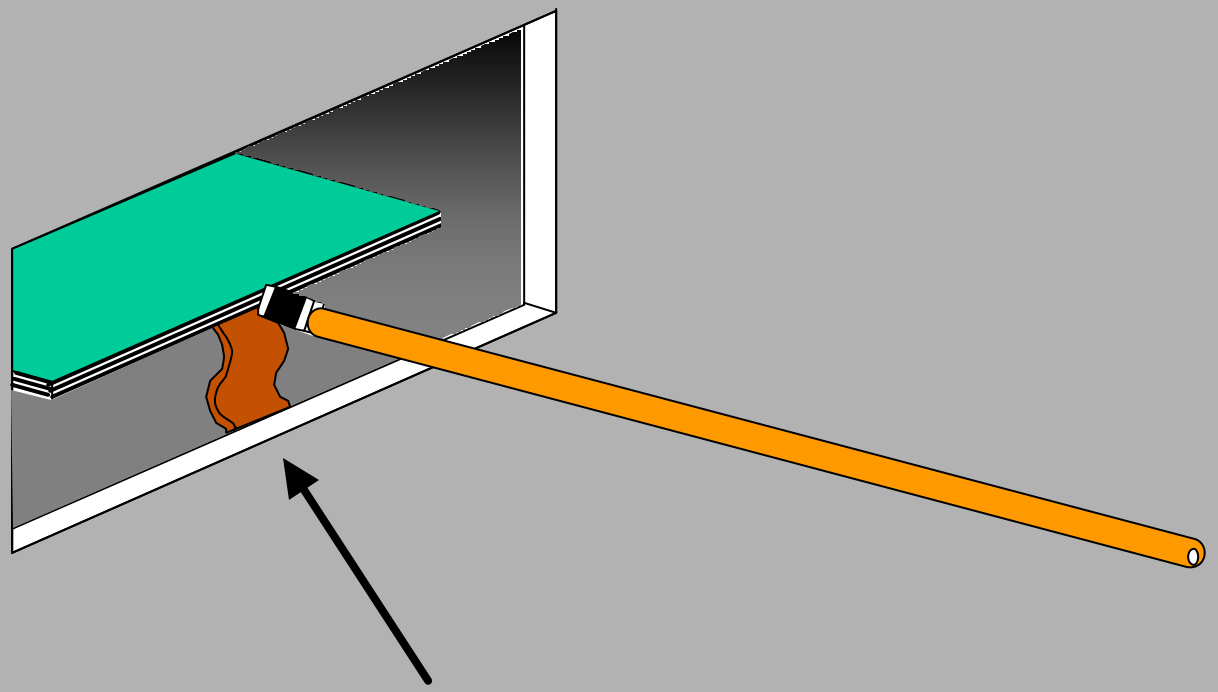
Experiment #2

Confirmation of voltage source

Experiment 2B – Shorting PCB to Chassis



Copper Tape Soldered from Chassis
To Daughtercard Groundplane

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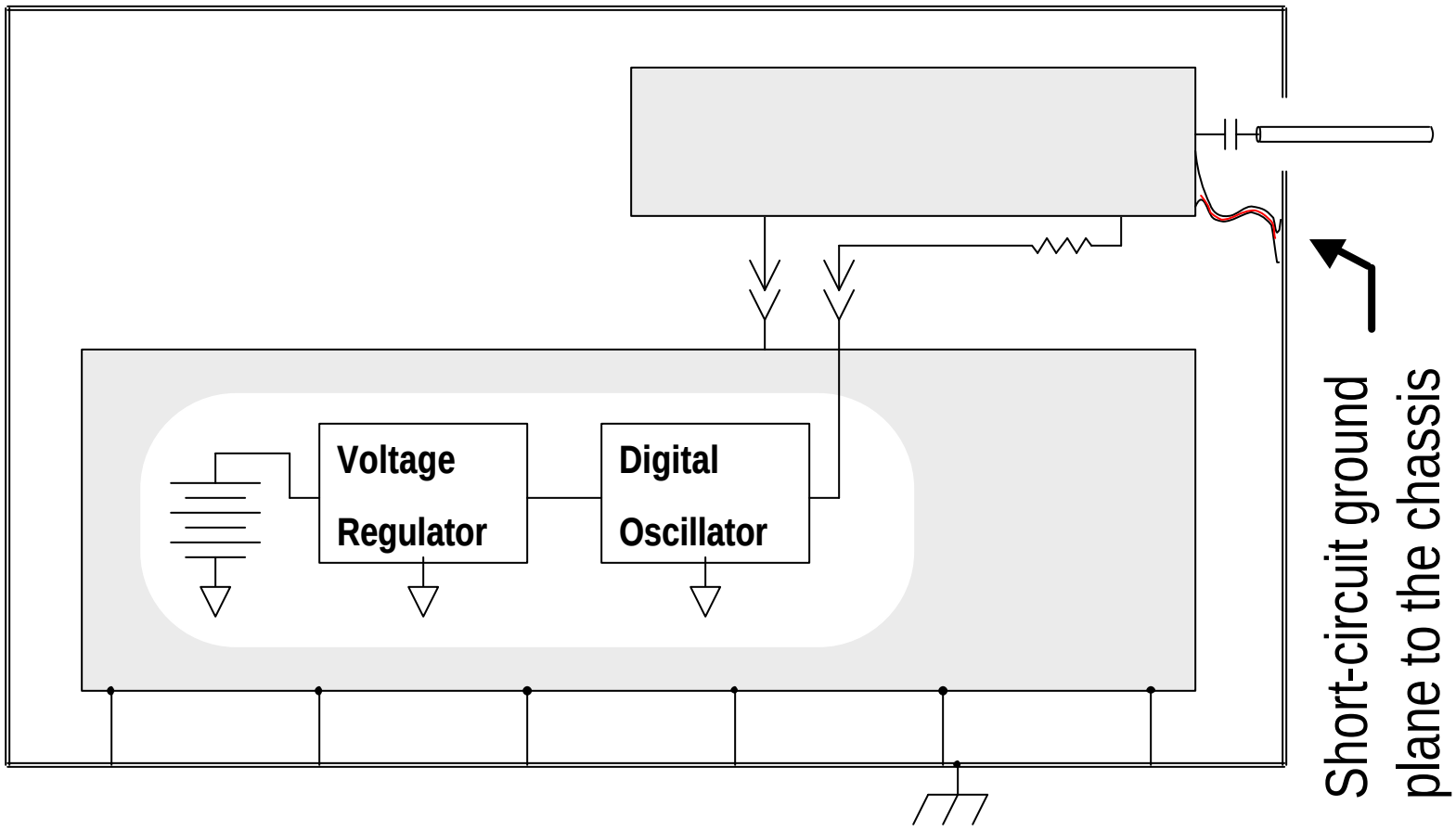
Experiment 2:
Confirm Driving Source



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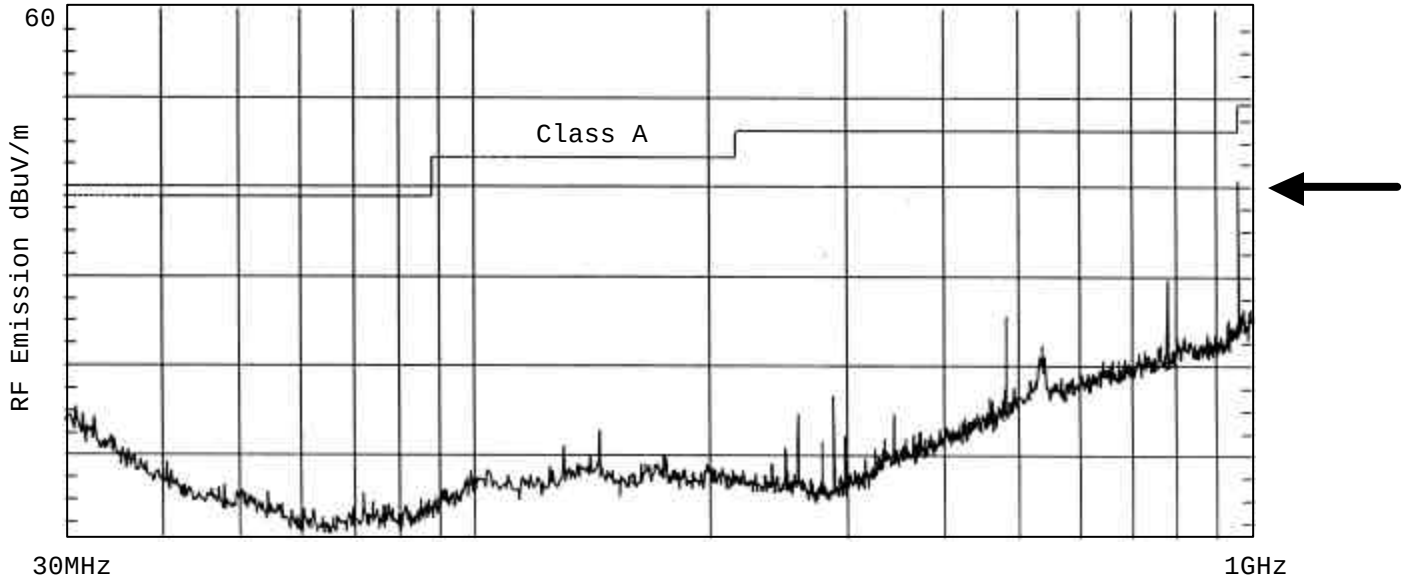
2A - RF Emission as a Function of *f*

- Repeat of 1C data at 98° - Ground pin only, no tape
- Note strong emissions at 961 MHz



Freq Mhz	PK Level	QP Limit	Delta	Angle	Height	Polar	TCF	Probe CF	Coax CF	Preamp CF
961.25	40.99	49.5	-8.51	89	102	1	6.83	25.1	6.08	24.4
777.5	29.7	46.4	-16.7	89	102	1	3.54	22.2	5.76	24.4
481	25.59	46.4	-20.8	89	102	1	-2.81	17.5	4.16	24.5
932.5	25.32	46.4	-21.1	89	102	1	5.24	23.9	5.76	24.4
877.5	23.8	46.4	-22.6	89	102	1	5.32	23.3	6.08	24.1
818.75	23.34	46.4	-23.1	89	102	1	4.54	23.5	5.76	24.7
873.75	23.14	46.4	-23.3	89	102	1	4.66	23.3	6.08	24.7
30.875	15.53	39	-23.5	89	102	1	-5.51	18.7	0.96	25.1
998.75	25.58	49.5	-23.9	89	102	1	7.1	24.8	6.72	24.4
536.25	22.45	46.4	-24	89	102	1	-1.47	18.8	4.48	24.7
726.25	21.87	46.4	-24.5	89	102	1	2.75	21.7	5.44	24.4
713.75	21.5	46.4	-24.9	89	102	1	2.38	21.7	5.12	24.4
642.5	20.77	46.4	-25.6	89	102	1	1.97	21.2	5.12	24.4
633.75	19.69	46.4	-26.7	89	102	1	1.53	21.1	4.8	24.4

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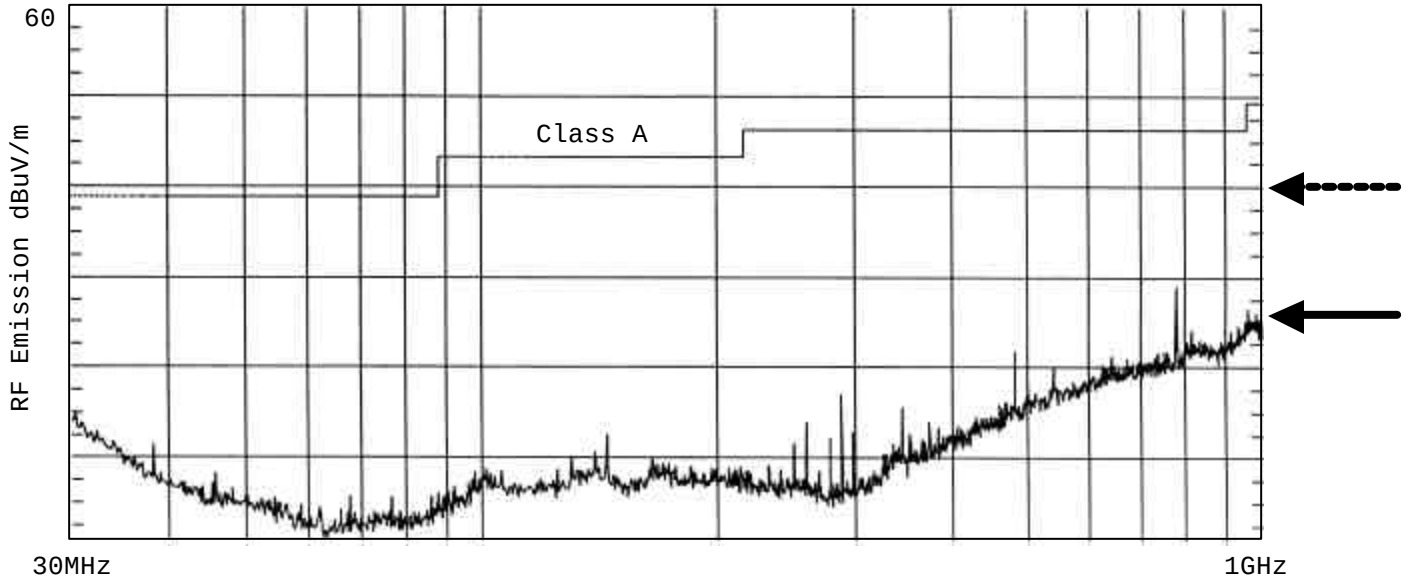
2B - RF Emission as a Function of *f*

- Daughtercard ground plane shorted to chassis
- 961 MHz line has been reduced below noise level



Freq Mhz	PK Level	QP Limit	Delta	Angle	Height	Polar	TCF	Probe CF	Coax CF	Preamp CF
777.5	29.06	46.4	-17.3	89	102	1	3.54	22.2	5.76	24.4
953.75	25.21	46.4	-21.2	89	102	1	6.73	25	6.4	24.7
957.5	25.08	46.4	-21.3	89	102	1	6.92	25.2	6.4	24.7
813.75	24.13	46.4	-22.3	89	102	1	4.37	23.3	5.44	24.4
915	24.11	46.4	-22.3	89	102	1	5.31	23.6	6.08	24.4
850	22.97	46.4	-23.4	89	102	1	4.81	23.8	5.76	24.7
30.35	14.91	39	-24.1	89	102	1	-5.17	19	0.96	25.1
751.25	21.88	46.4	-24.5	89	102	1	3.08	22	5.44	24.4
998.75	24.94	49.5	-24.6	89	102	1	7.1	24.8	6.72	24.4
481	21.75	46.4	-24.6	89	102	1	-2.81	17.5	4.16	24.5
641.25	21.39	46.4	-25	89	102	1	1.63	21.2	5.12	24.7
697.5	20.69	46.4	-25.7	89	102	1	1.89	21.5	5.12	24.7
623.75	20.34	46.4	-26.1	89	102	1	1.22	20.8	4.8	24.4
538.75	19.92	46.4	-26.5	89	102	1	-1.12	18.8	4.48	24.4

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Experiment #2 Summary

No.	Angle	Cap	Wire	Shorted	MHz	dBuV/m
2A	89°	10 pF	Yes	No	961	41.0
2B	89°	10 pF	Yes	Yes	961	< 25 *

* measurement limited

- High frequency voltage on daughtercard groundplane is driving the external metallic body via the capacitor
- Implicates metal parts in fiber optic connectors

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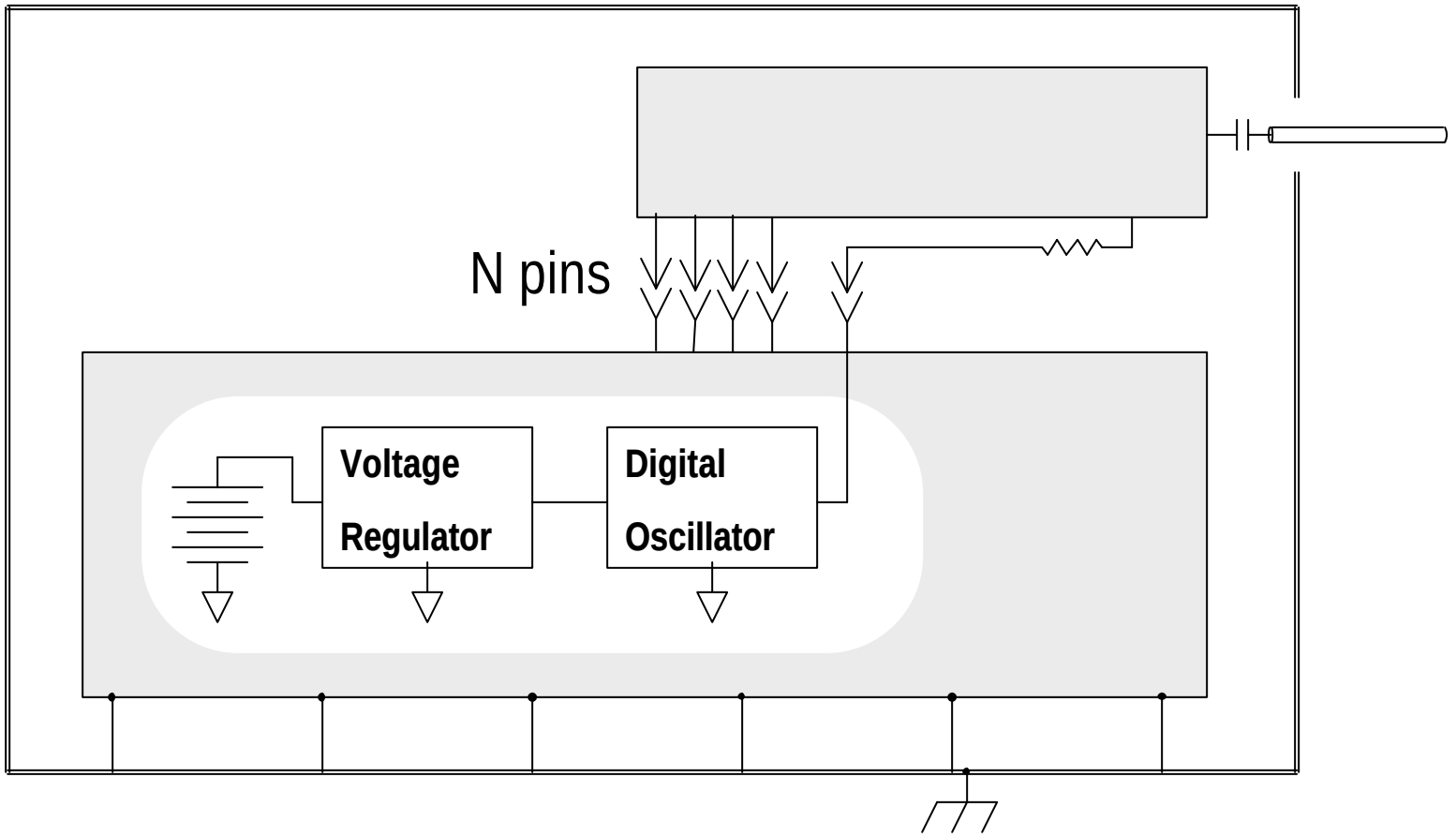
Experiment #3

Role of ground pins as ultimate driving source

Experiment 3 - Ground Pin Dependence

- Repeat Experiment 1C with more than one ground pin



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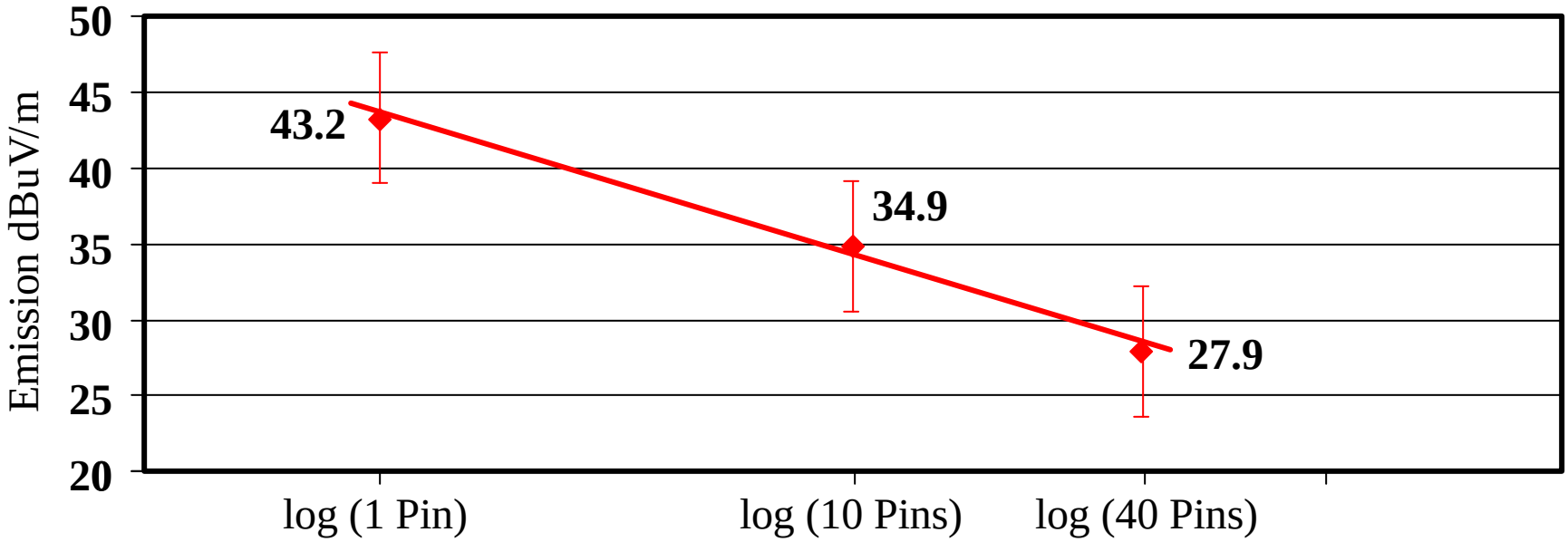
Maximum RF Emission Values

No.	Signal Pins	Gnd Pins N	MHz	dBuV/m
3A	1	1	961	43.2
3B	1	10	961	34.9
3C	1	40	961	27.9



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Experiment #3 Summary

- Parasitic inductance in PCB-to-PCB connectors generates high-frequency potential differences between the daughtercard's groundplane and chassis
- More ground pins correlate with lower amplitude
  - 8dB reduction for 10 ground pins
  - 15 dB reduction for ground 40 pins
- Relationship of RF emissions with respect to N is nonlinear, due to self-inductance, mutual-inductance, and geometric effects
- Problem exacerbated by multiple PCBs and the isolation of "logic ground" from "chassis ground"

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Conclusions

The adoption of higher data rates and new technologies can often expose previously hidden non-idealities

Conclusions

- Previously ignored, small metallic parts within optical fiber connectors caused EMC failures in otherwise RF-tight chassis for $f < f_c$
- RF emission is caused by parasitic capacitive coupling of metallic connector parts, via the aperture, to within the otherwise RF-tight chassis
- High-frequency perturbations on daughtercard groundplane, shield, or PCB traces near the aperture provides driving via the parasitic capacitance
- This new, asymmetric, dipole radiates below f_c
- PCB-to-PCB connector inductance implicated

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Some Design Practices

- Make apertures as small as physically possible
  - Higher cutoff frequency
  - Reduces parasitic capacitance
- Use conductive septum to divide duplex-SC aperture
- Use conductive dust cover or “trap door” on apertures
- Arrayed apertures will reduce effectiveness
- Limit the amount of conductive materials used in fiber-optic connectors, and anywhere near aperture
- Know your fiber optic cable supplier, and if necessary, specify connectors made from nonconductors
- All optical devices need to be evaluated with the system
- Do not underestimate the mechanical precision required to maintain low-impedance grounding with PCB stacks

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Some More Design Practices

- Use numerous ground pins and auxiliary grounding
  - Reduces high-frequency potential differences
  - Better PCB-to-PCB signal integrity
- V_{cc} plane(s) should have ultra-low Z to many GHz
- Shield or isolate high-frequency pads or current loops
- Do not route high-frequency transmission lines on surface
- Control and minimize area of high-frequency current loops
- Follow IC manufacturer's bypassing instructions
- Minimize daughtercard exposure to aperture
  - Minimize surface area near the aperture
  - Maximize distance to the aperture
- Frontside/backside optical module shielding techniques
- Care should be exercised when isolating logic/chassis ground

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Acknowledgements and References

- Acknowledgements
  - Fujikura Technology America Corporation
  - Underwriters Laboratory (formerly C&C Labs)
  - BABT Corporation (formerly Rolm Electronics)
  - Silent Solutions, Alcoa-Fujikura, Emulex, Sun Micro
  - San Francisco State University
  - San Jose State University

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  - K. Masterson, NIST Technical Note #1383 (1997)
  - M. Robinson, IEEE Trans Electromag Compat, V40, N3

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