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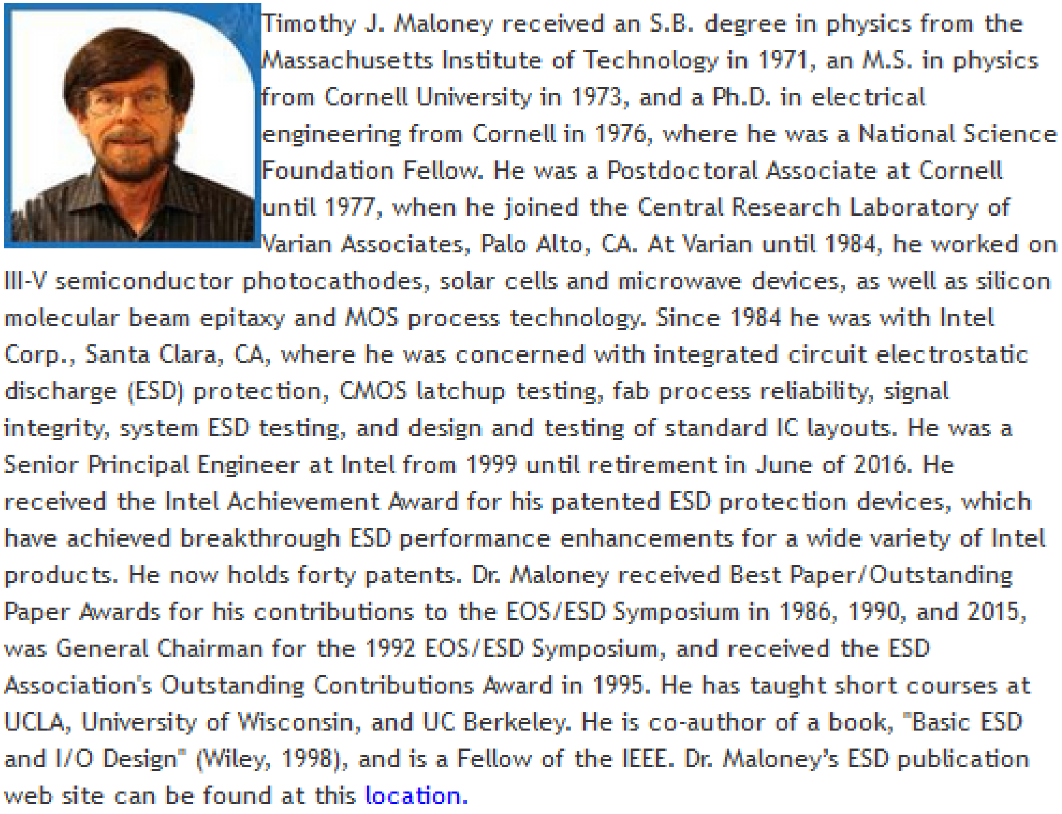
Title : The case for measurement and analysis of ESD fields in semi-conductor manufacturing

Guest Speaker : Timothy Maloney

Abstract: A destructive Charged Device Model electrostatic discharge event can happen in semiconductor manufacturing and should be detectable from radiation that results from collapse of an electric dipole. The analytically describable radiation field pulse of CDM can be readily produced with a new instrument (CDM Event Simulator or CDMES) that creates dipole collapse at will. A coaxial monopole E-field antenna's transfer function gives the antenna signal in near-field, and experiments compare well with theory. These and other instruments for CDM ESD monitoring and process control are described in a newly-issued patent, reviewed here.



Timothy J. Maloney received an S.B. degree in physics from the Massachusetts Institute of Technology in 1971, an M.S. in physics from Cornell University in 1973, and a Ph.D. in electrical engineering from Cornell in 1976, where he was a National Science Foundation Fellow. He was a Postdoctoral Associate at Cornell until 1977, when he joined the Central Research Laboratory of Varian Associates, Palo Alto, CA. At Varian until 1984, he worked on III-V semiconductor photocathodes, solar cells and microwave devices, as well as silicon molecular beam epitaxy and MOS process technology. Since 1984 he was with Intel Corp., Santa Clara, CA, where he was concerned with integrated circuit electrostatic discharge (ESD) protection, CMOS latchup testing, fab process reliability, signal integrity, system ESD testing, and design and testing of standard IC layouts. He was a Senior Principal Engineer at Intel from 1999 until retirement in June of 2016. He received the Intel Achievement Award for his patented ESD protection devices, which have achieved breakthrough ESD performance enhancements for a wide variety of Intel products. He now holds forty patents. Dr. Maloney received Best Paper/Outstanding Paper Awards for his contributions to the EOS/ESD Symposium in 1986, 1990, and 2015, was General Chairman for the 1992 EOS/ESD Symposium, and received the ESD Association's Outstanding Contributions Award in 1995. He has taught short courses at UCLA, University of Wisconsin, and UC Berkeley. He is co-author of a book, "Basic ESD and I/O Design" (Wiley, 1998), and is a Fellow of the IEEE. Dr. Maloney's ESD publication web site can be found at this location.

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2018 IEEE SYMPOSIUM ON ELECTROMAGNETIC COMPATIBILITY, SIGNAL AND POWER INTEGRITY
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The Case for Measurement and Analysis of ESD Fields in Semiconductor Manufacturing

Timothy J. Maloney

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CAI

Outline

- Charged Device Model (CDM) event in manufacturing and *in situ* event monitoring

- Antenna and detector arrangement in factory
    - Create CDM events at will with the CDMES (event simulator) and use the antenna and detector in place
    - Calibrate the detector with a reproducible antenna-like pulse

- Present theory of
    - CDM fields
    - Resulting antenna pulse
    - Synthesis of artificial antenna pulse

- Considerations for adopting the technology

Analytical Features (see Refs.)

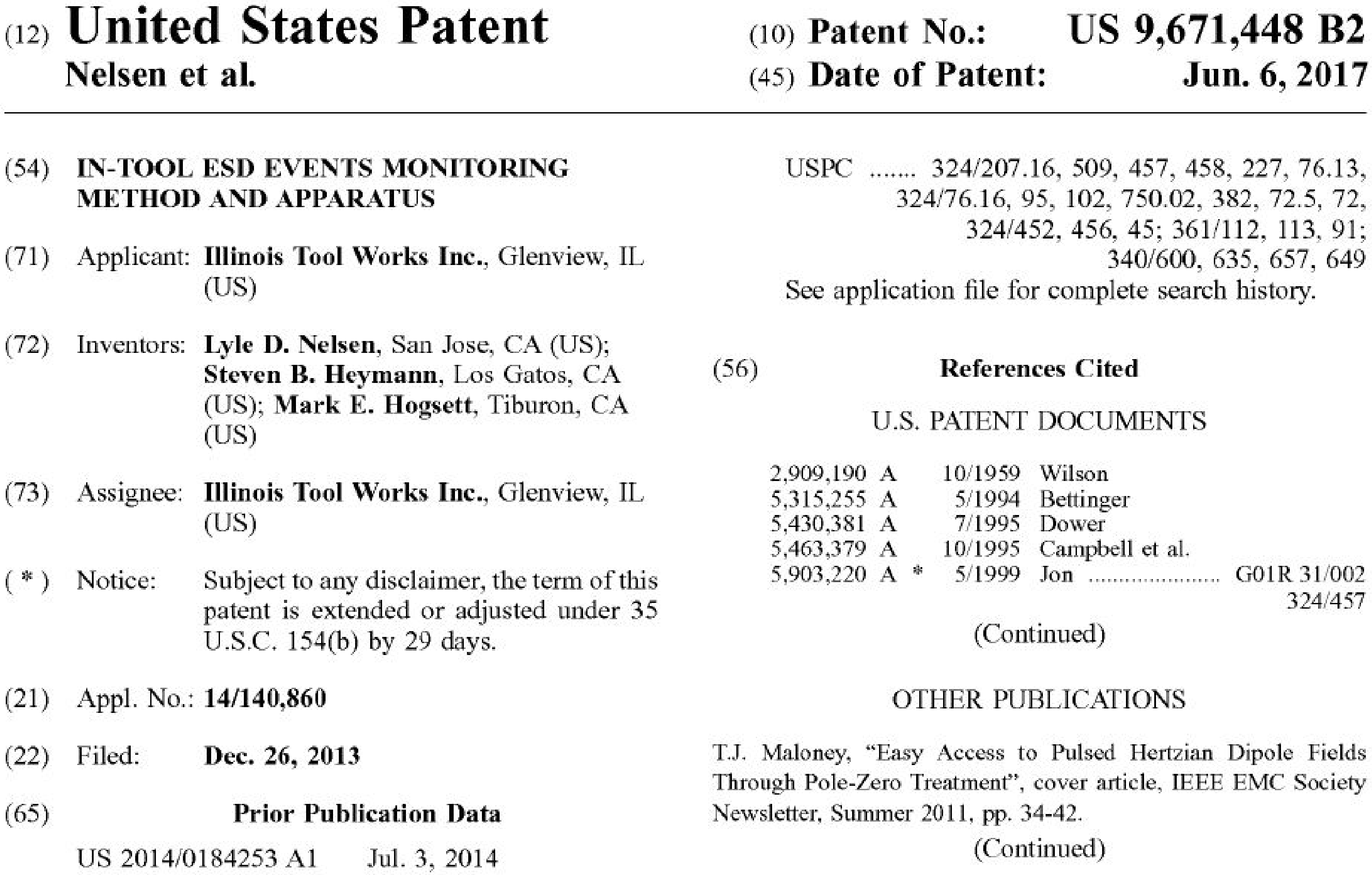
- CDM as a 2-pole circuit
    - Add spark rise time
    - Map to time domain with Inverse Laplace Transform

- CDM as a source of dipole radiation, CDM Event Simulator
    - Detect with monopole antenna
    - s-domain expressions for everything from CDM current source to antenna signal on scope

- Experimental results on antenna signal, agreement with theory

- Artificial antenna signals with “monocycle” pulser
    - Theory and experiment, compared favorably
    - Calibration of MiniPulse detector with monocycle pulser

Related Recent Patent



(12) **United States Patent**

Nelsen et al.

(10) **Patent No.:** **US 9,671,448 B2**

(45) **Date of Patent:** **Jun. 6, 2017**

(54) **IN-TOOL ESD EVENTS MONITORING METHOD AND APPARATUS**

(71) Applicant: **Illinois Tool Works Inc.**, Glenview, IL (US)

(72) Inventors: **Lyle D. Nelsen**, San Jose, CA (US); **Steven B. Heymann**, Los Gatos, CA (US); **Mark E. Hogsett**, Tiburon, CA (US)

(73) Assignee: **Illinois Tool Works Inc.**, Glenview, IL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 29 days.

(21) Appl. No.: **14/140,860**

(22) Filed: **Dec. 26, 2013**

(65) **Prior Publication Data**

US 2014/0184253 A1 Jul. 3, 2014

USPC 324/207.16, 509, 457, 458, 227, 76.13, 324/76.16, 95, 102, 750.02, 382, 72.5, 72, 324/452, 456, 45; 361/112, 113, 91; 340/600, 635, 657, 649

See application file for complete search history.

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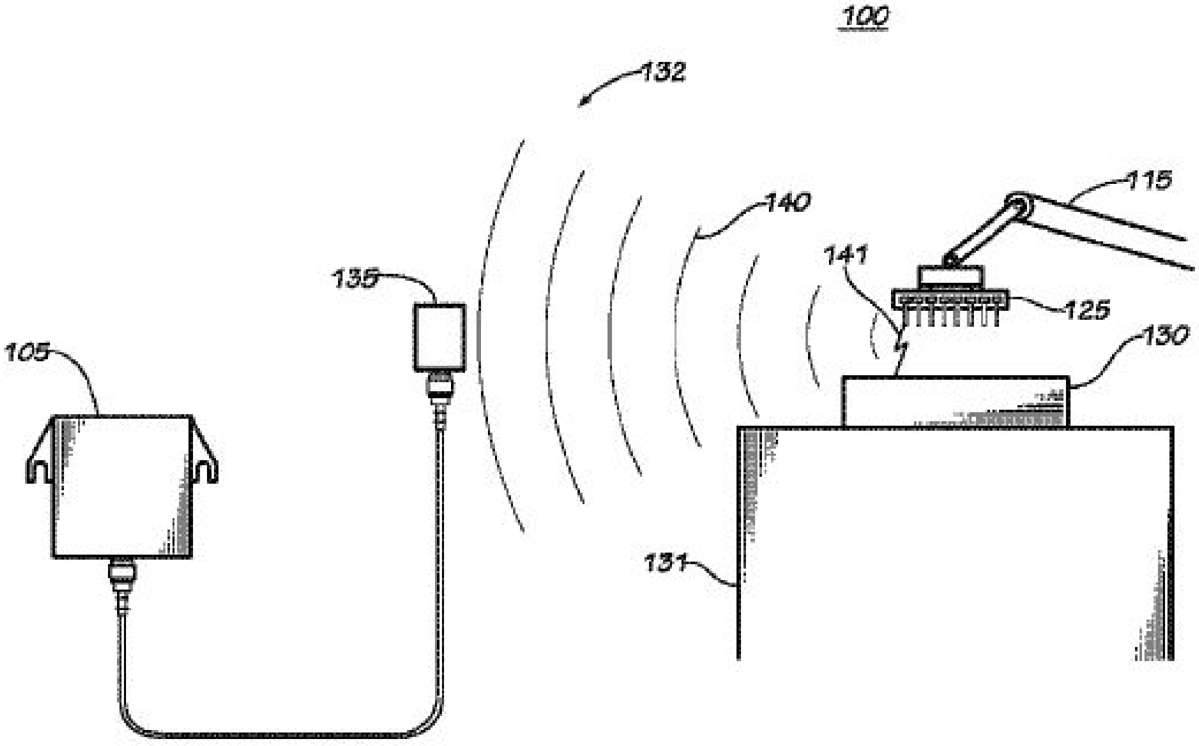
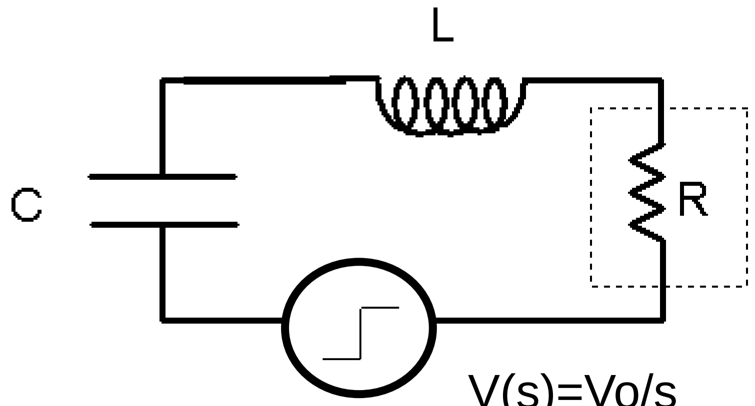
(Continued)

CDM Event and Field Detection



From US Patent 9,671,448 (2017)

Simplified CDM Network



V(s)=Vo/s

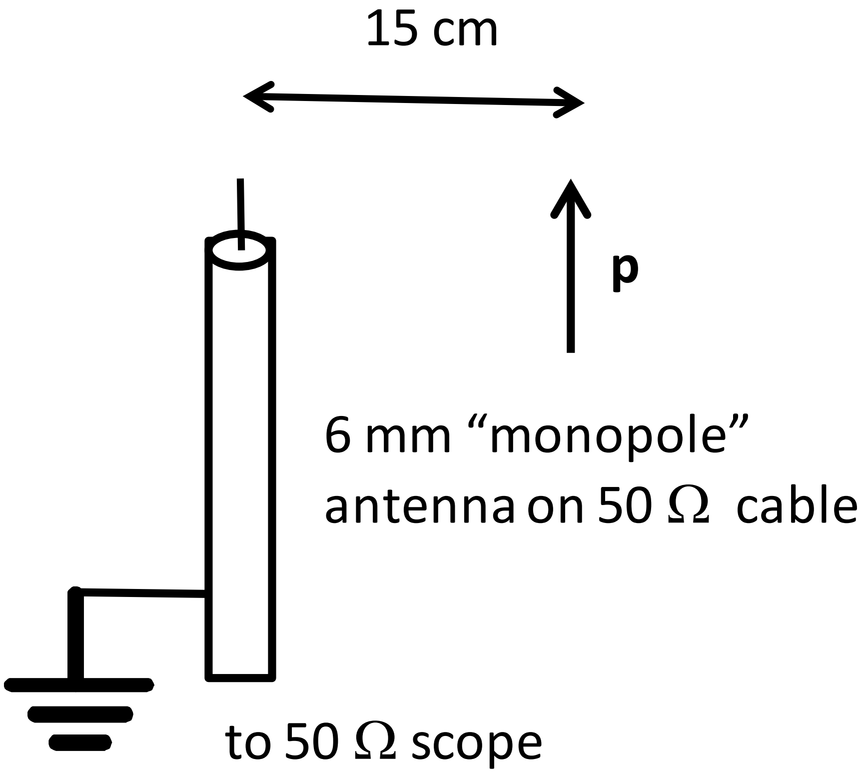
$$Y(s) = \frac{Cs}{1 + RCs + LCs^2}$$

$$I(s) = V(s)Y(s) = \frac{CV_0}{1 + RCs + LCs^2}$$

Examine step response of this network

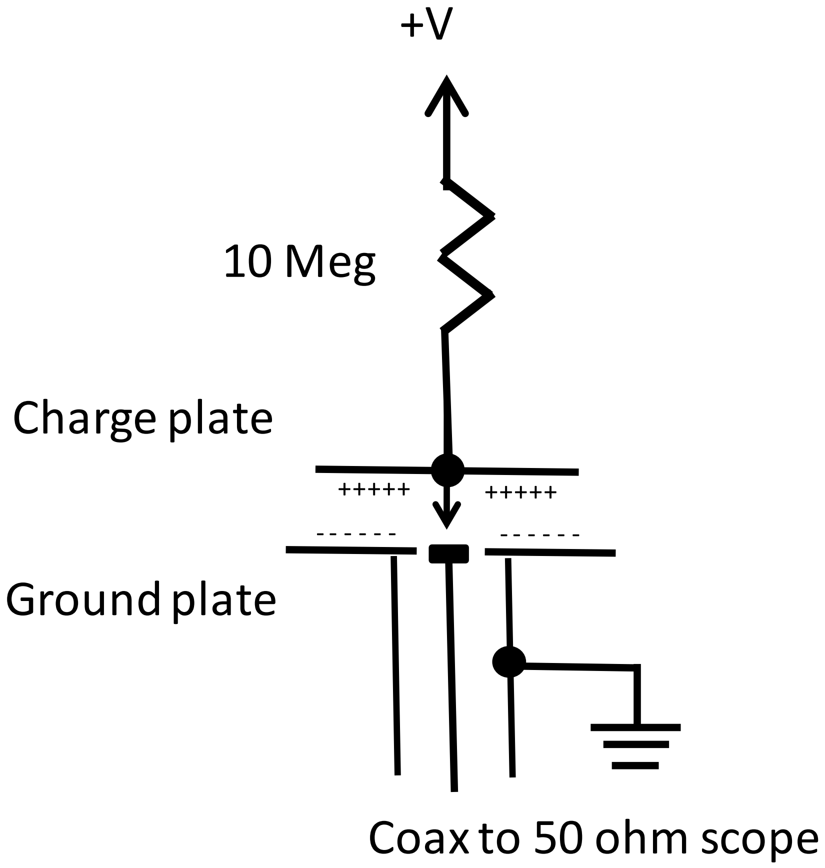
R is spark resistance, ~25-60 ohms

CDM dipole radiation, monopole antenna



Experimental arrangement of CDM electric dipole initial source **p** and 6 mm coaxial antenna.

CDM Event Simulator (CDMES)



CDM pulse generator. Charge plate probe hits pedestal and dipole collapses, with current pulse and dipole radiation.

Simco-ITW CDMES Model

7” long. Voltage cable and signal coax cable shown.

Described in US Patent 9,671,448 (2017)

Field Detection with CDMES

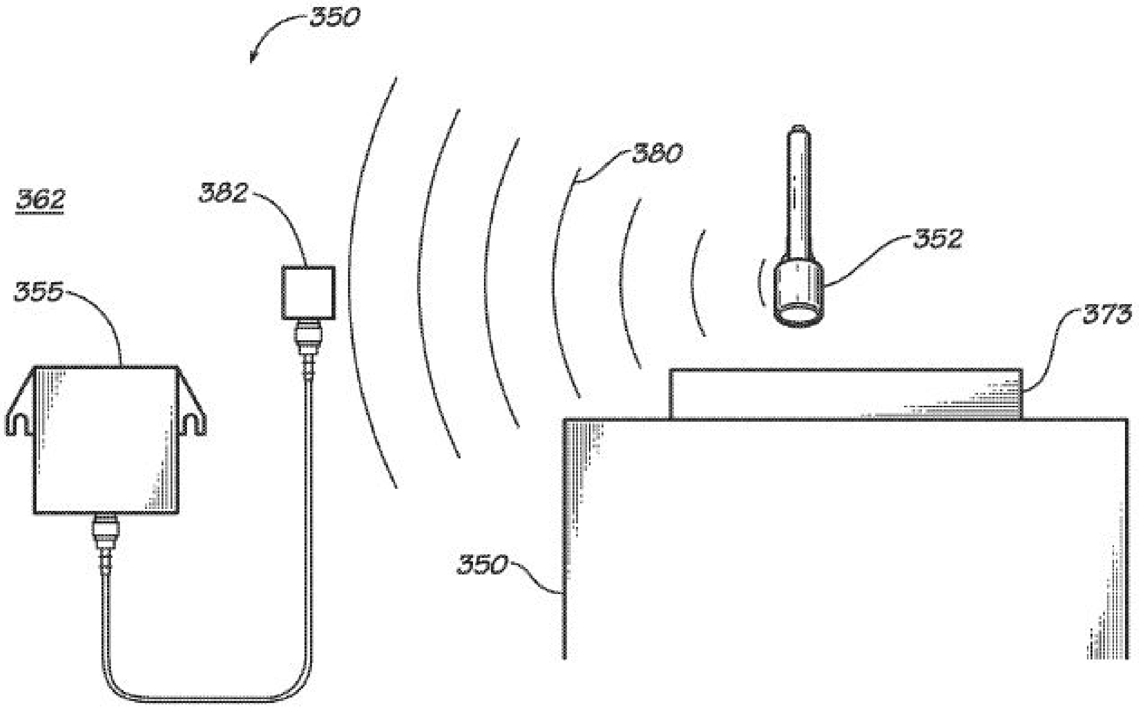
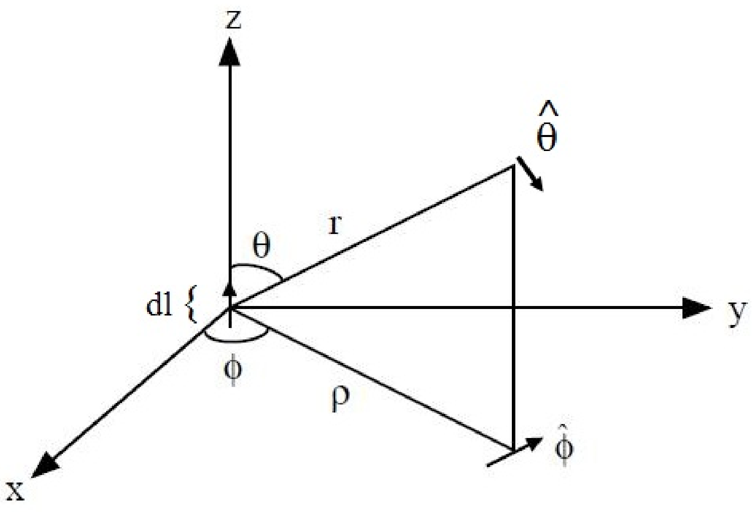


FIG. 3b

From US Patent 9,671,448 (2017)

Electric Dipole “equatorial” field



$$E_\theta(t) = \frac{\sin\theta}{4\pi\varepsilon_0}\left(\frac{[\ddot{p}]}{c^2 r} + \frac{[\dot{p}]}{c r^2} + \frac{[p]}{r^3}\right)$$

sinθ=1 at equator

$$p = Q(t)\cdot dl$$

$$i(t) = \frac{dQ(t)}{dt};\left[I(s) = sQ(s)\right]$$

$$\dot{p} = i(t)\cdot dl$$

$$\ddot{p} = \frac{di(t)}{dt}\cdot dl$$

$\boxed{s=\sigma+j\omega}$

In the s-domain, sinθ=1:

$$\boxed{E_\theta(s) = \frac{I(s)}{4\pi\varepsilon_0 s r^3} dl\cdot(1 + s\tau + s^2\tau^2), \tau = \frac{r}{c}}$$

Convert to practical units

More in Ref. 5

Dipole E-field, sinθ=1

s=σ+jω

But we know that $I(s)=\dfrac{CV_0}{1+RCs+LCs^2}$

So $E_\theta(s)=\dfrac{CV_0\cdot dl}{4\pi\varepsilon_0 sr^3}\cdot\dfrac{(1+s\tau+s^2\tau^2)}{1+RCs+LCs^2}$

Solve in time domain with inverse Laplace Transform;
pole-zero expansion in natural frequencies

current

-0.496 A max

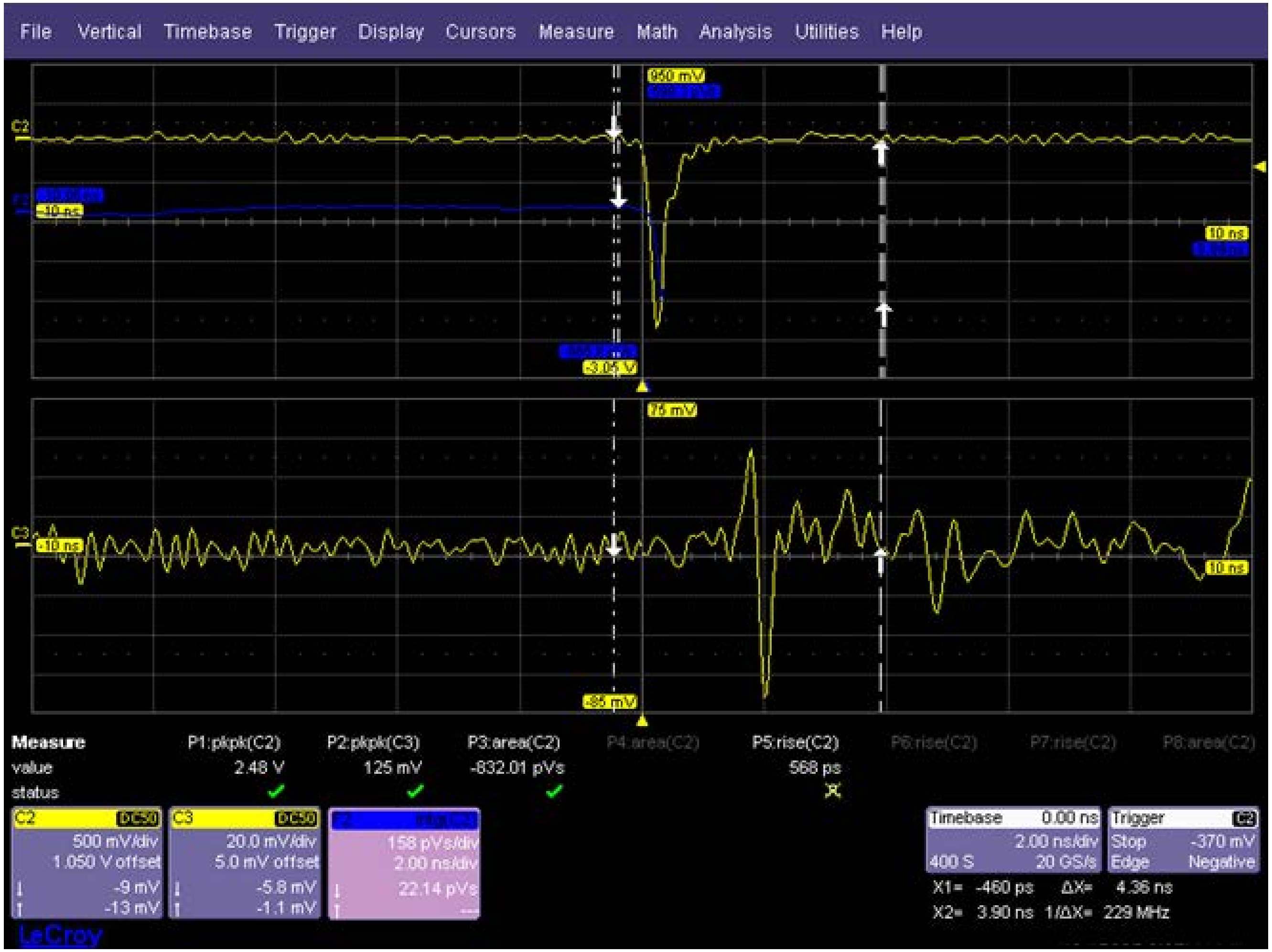
-166.4 pC

antenna, 15 cm

125 mV =Vp-p

1.664 pF

-100V pulse



Measure	P1:pkpk(C2)	P2:pkpk(C3)	P3:area(C2)	P4:area(C2)	P5:rise(C2)	P6:rise(C2)	P7:rise(C2)	P8:area(C2)
value	2.48 V	125 mV	-832.01 pVs		568 ps			
status	✓	✓	✓		☒			

C2 DC50: 500 mV/div, 1.050 V offset, ↓ -9 mV, ↑ -13 mV

C3 DC50: 20.0 mV/div, 5.0 mV offset, ↓ -5.8 mV, ↑ -1.1 mV

F2: 158 pVs/div, 2.00 ns/div, ↓ 22.14 pVs, ↑ ---

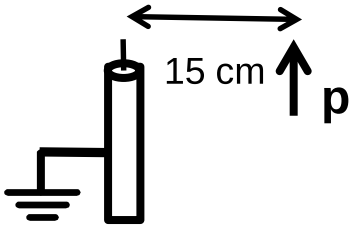
Timebase 0.00 ns: 2.00 ns/div, 400 S, 20 GS/s

Trigger C2: Stop -370 mV, Edge Negative

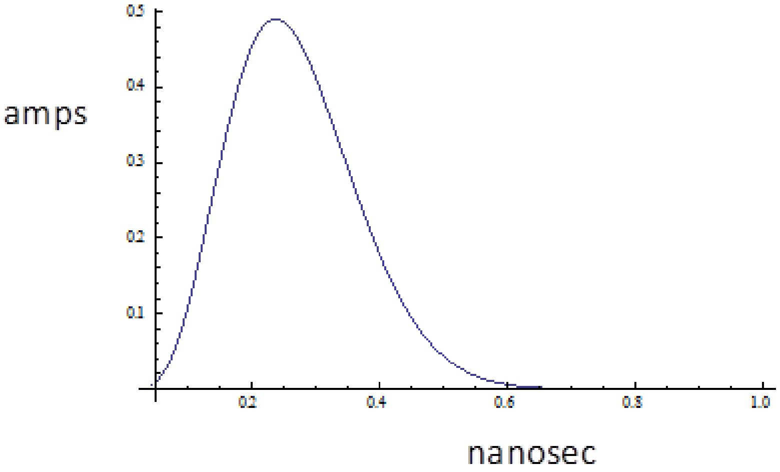
X1= -460 ps ΔX= 4.36 ns

X2= 3.90 ns 1/ΔX= 229 MHz

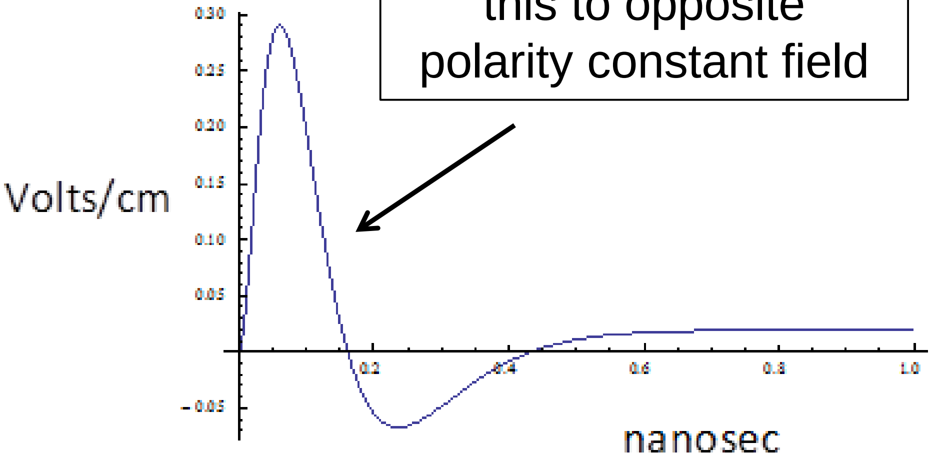
Measured current (top) and antenna response (bottom) to E-field at 15 cm, using artificial CDM source; 2 nsec/division



Calculated current and field



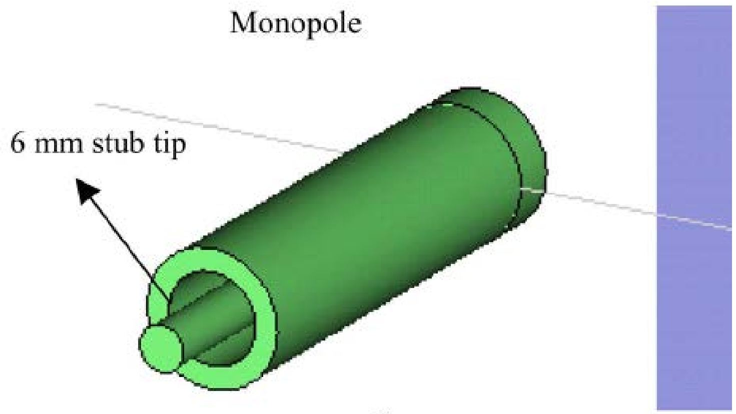
Calculated CDM current pulse, 1 nsec full scale.



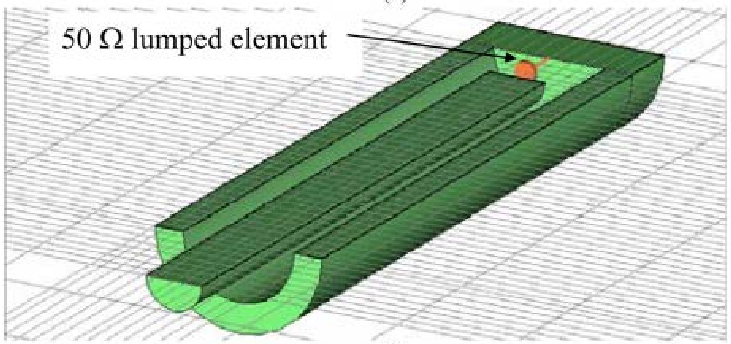
Collapsing field adds this to opposite polarity constant field

E-field pulse E_θ at 15 cm from CDM current source; 1 nsec full scale.

Antenna Transfer Function



(a)



(b)

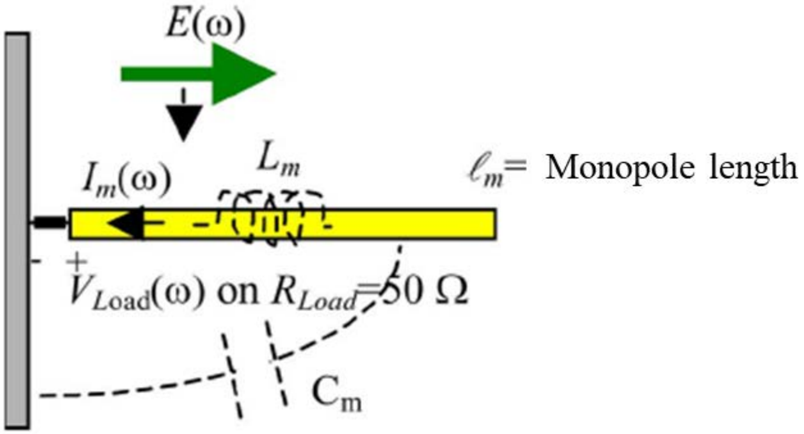


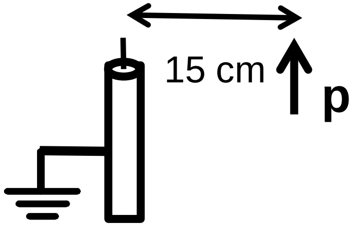
Fig. 13. Schematic representation of the E-field monopole probe.

By simple manipulations on (10), the E-field probe transfer function is derived as

$$T_E(\omega) = \frac{V_{\text{load}}(\omega)}{E(\omega)} = \frac{\ell_m}{j\omega\frac{L_m}{R_{\text{load}}} + \frac{1}{j\omega C_m R_{\text{load}}} + 1}. \qquad (11)$$

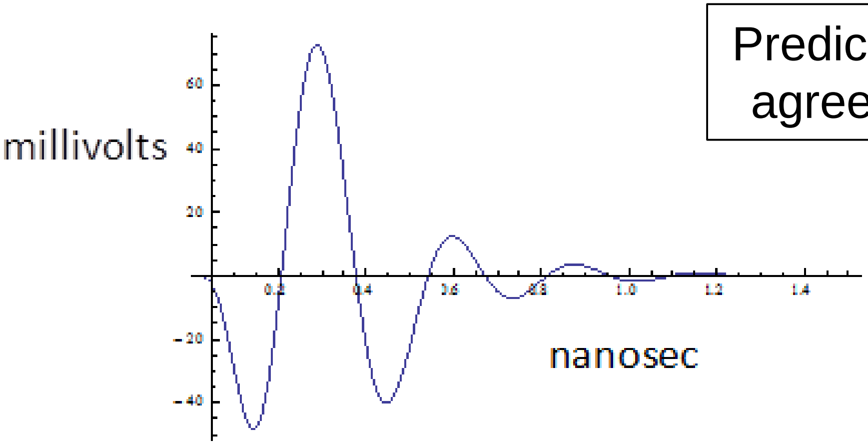
From Caniggia and Maradei, 2007

Transfer function in terms of initial dipole source **p**



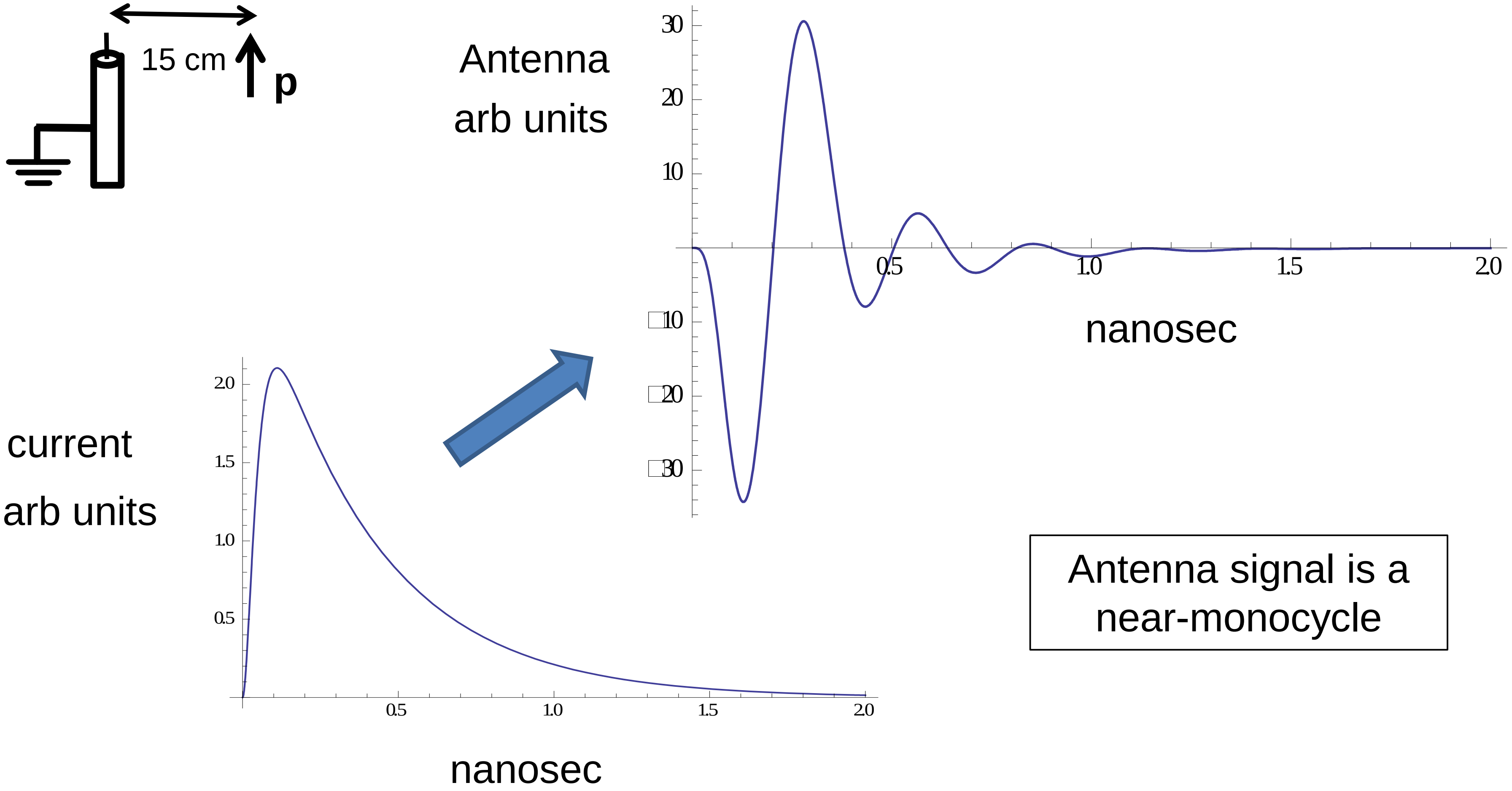
$$\frac{V_m(s)}{E_{-z}(s)} = -\frac{l_m Z_0 C_m s}{1 + Z_0 C_m s + L_m C_m s^2}$$

Predicted antenna signal. Good agreement with measurement.



Calculated antenna response to E-field,15 cm from CDM source, 1.5 nsec full scale

Adjust the current function just a little and…



Antenna signal is a near-monocycle

Measurement Uncertainties

- Dipole length dl is not precisely known for each zap
  - Yet every field in the theory is proportional to dl

- Finite source size, spark timing, surrounding metal all affect fields

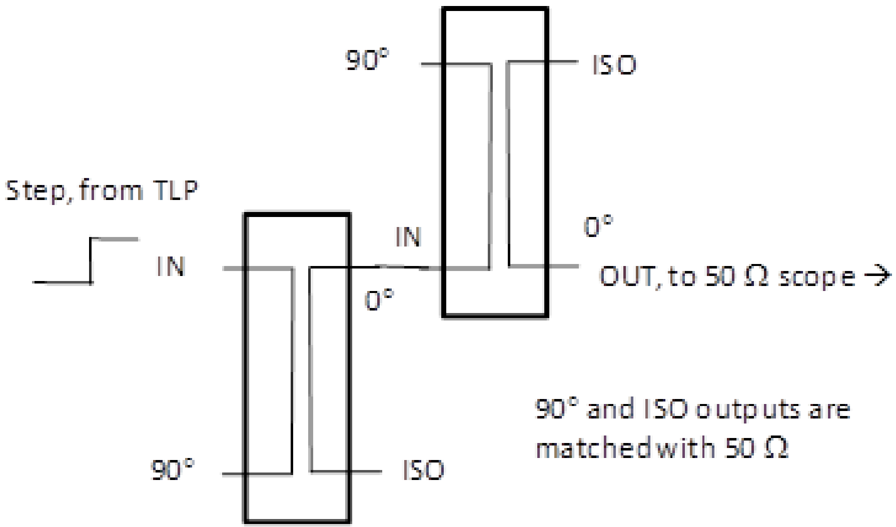
- Antenna properties, particularly effective capacitance

- Discharges can be fragmented (spark shower) and spread over short times, meaning weaker device event but confusing signal
  - But worst-case discharges are crisp dipole collapses

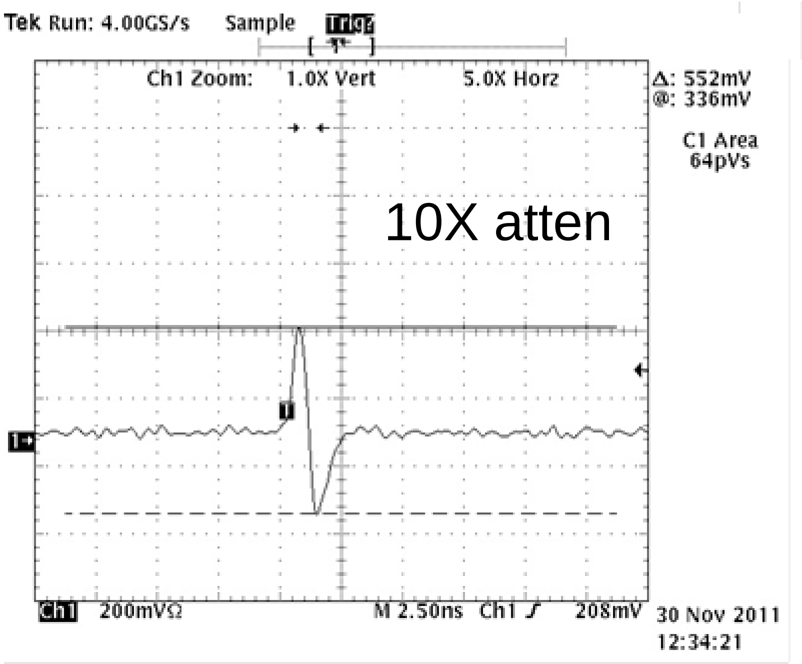
- We ultimately care about stress felt by the device, not the field. So we must ask, how <u>lousy</u> can the radiation efficiency be?
  - If it’s lousy enough, there’s a weak signal and a strong CDM event; not good

- Despite all this, theory and experiment agreed pretty well

Artificial antenna pulses

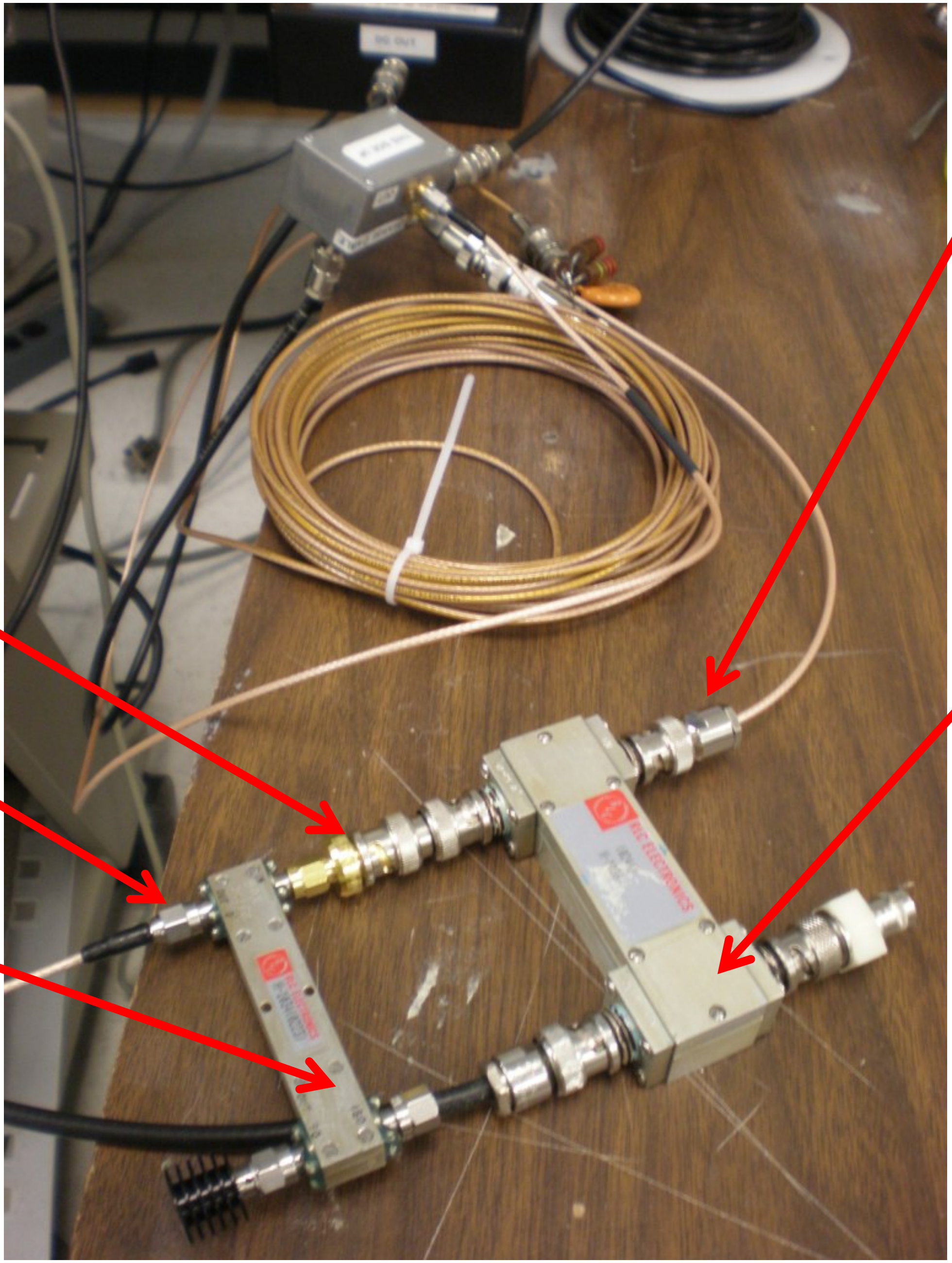


TLP-based setup with two quarter-wave 3 dB couplers, aimed at producing a monocycle pulse.



Monocycle pulse output at 50V line charge, 2.5 nsec/division. Vp-p=5.52 V

Monocycle pulser hardware



TLP in

Coupler 1 to Coupler 2

Coupler 1

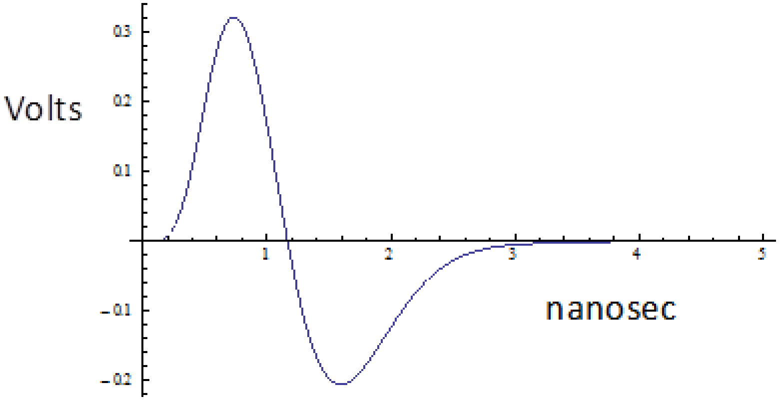
OUT, to scope

Coupler 2

Approximate solution, monocycle

$$\frac{V_m(s)}{V_1(s)} = \frac{k_1 k_2 t_{01} t_{02} s^2}{k_1' k_2' \left[1 + s\left[\frac{t_{01}}{k_1'} + \frac{t_{02}}{k_2'} \right] + s^2 \left[\frac{t_{01} t_{02}}{k_1' k_2'} + \frac{t_{01}^2 + t_{02}^2}{3} \right] + \cdots \right]}.$$

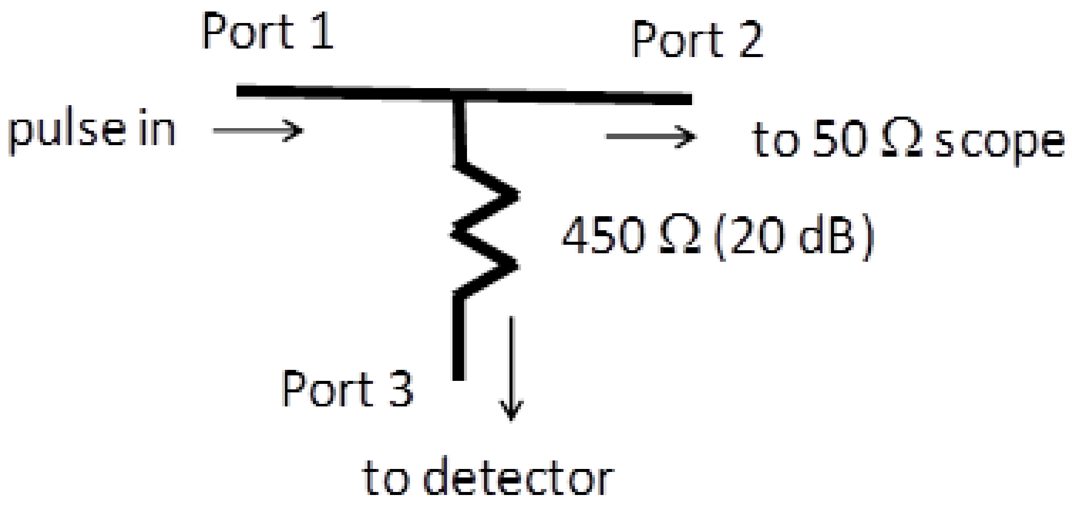
i.e., close to a double derivative



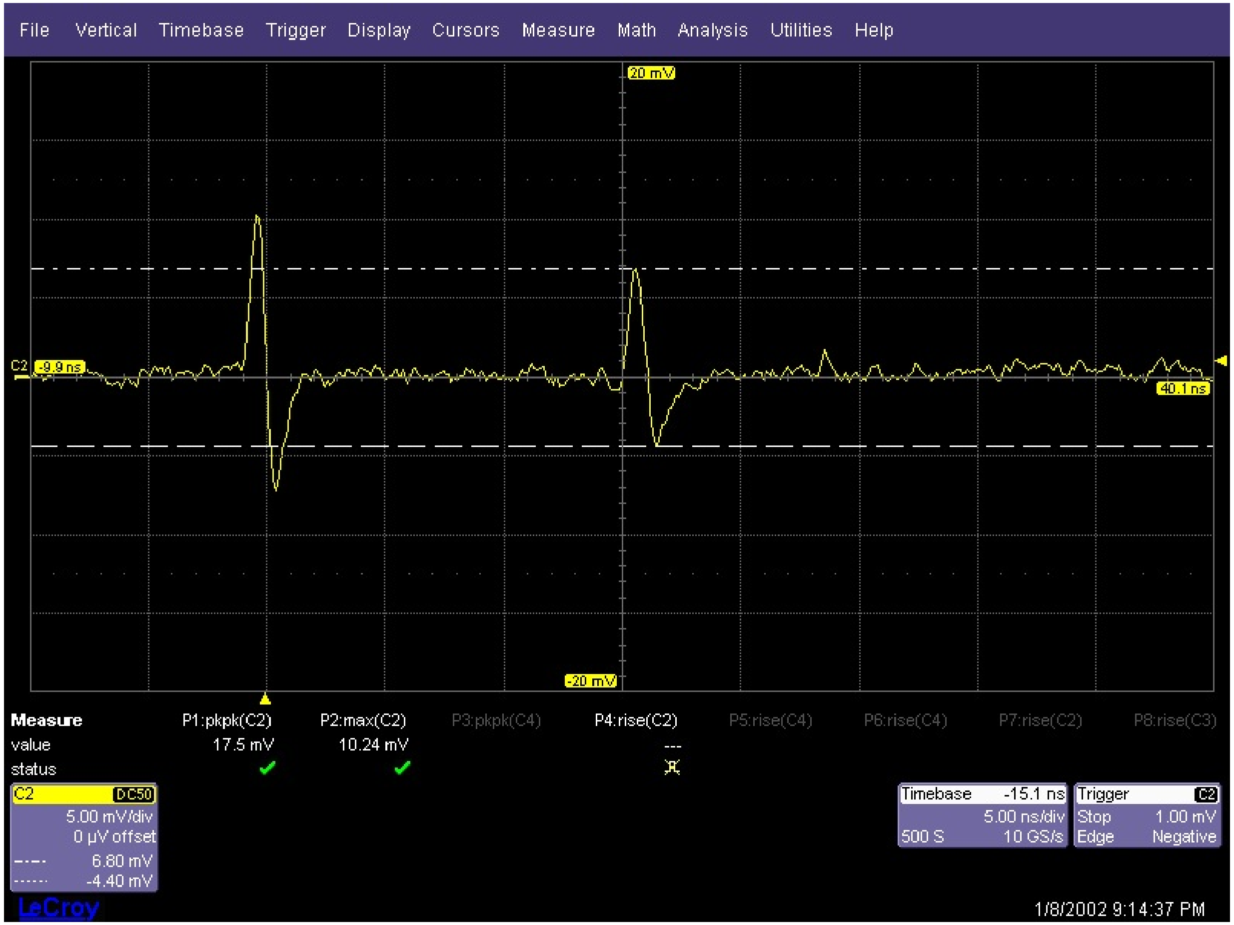
Allows accurate design with easy calculation.

- Predicted monocycle signal using 2-pole approximations
- 5 nsec full scale
- Peak heights, ratios, pulse shape and time scale are all close to measured data.
- See 2012, 2013 references

Calibration Example



Simco-ITW MiniPulse is detector. Must have z-mismatch to simulate actual antenna (a near-open circuit). Input of MiniPulse is not matched (see next slide)



Measure	P1:pkpk(C2)	P2:max(C2)	P3:pkpk(C4)	P4:rise(C2)	P5:rise(C4)	P6:rise(C4)	P7:rise(C2)	P8:rise(C3)
value	17.5 mV	10.24 mV		---				
status	✓	✓		⧗				

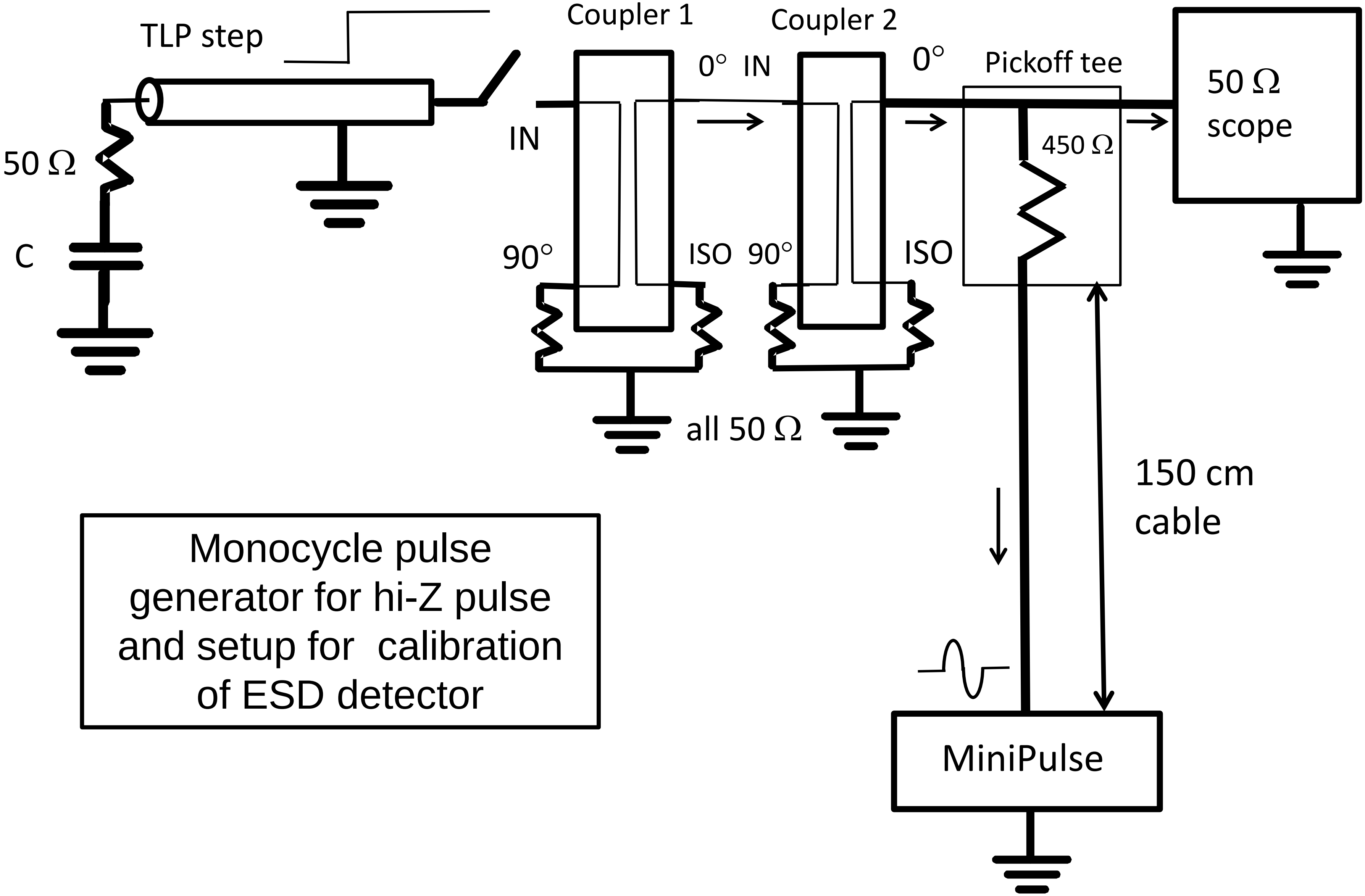
C2 DC50
5.00 mV/div
0 µV offset
-·-·- 6.80 mV
------ -4.40 mV

Timebase -15.1 ns
5.00 ns/div
500 S 10 GS/s

Trigger C2
Stop 1.00 mV
Edge Negative

1/8/2002 9:14:37 PM

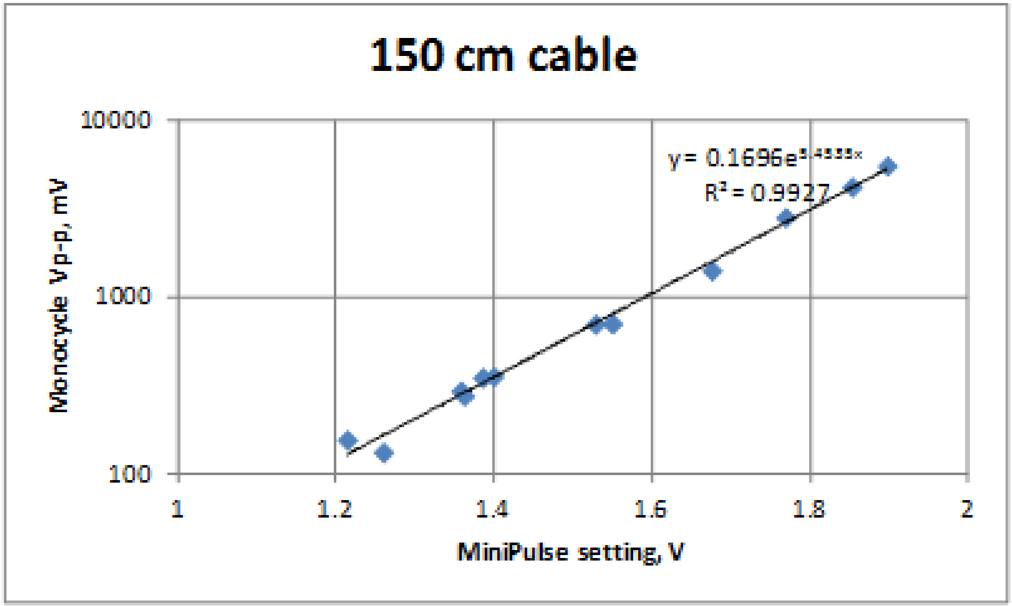
Monocycle pulse (left, 175 mV=Vp-p) and its reflection from ESD event detector (right, 112 mV) after transit of 150 cm cable (15 nsec).



Monocycle pulse generator for hi-Z pulse and setup for calibration of ESD detector

MiniPulse electronics described in US Patent 9,671,448 (2017)

MiniPulse calibration



Vp-p sensitive, as hoped. Log amp in MiniPulse is in evidence.

Monocycle pulse peak-to-peak voltage (Vp-p) magnitude vs. threshold setting of MiniPulse event detector, semi-log plot. Excellent agreement with exponential fit (422 mV/decade).

Comments on First Five Years of Usage

- Heavy use of CDMES for *in situ* electrostatic event creation

- MiniPulse is a compact substitute for a scope but improved versions are possible
    - Hi-pass input filter and log amp are its most important features at present

- Field-detection tools are used for troubleshooting and maintenance, more than continuous *in situ* monitoring of process
    - Managers will decide usage level, based on cost
    - Consider in context of history of ESD-related factory tools, e.g., GPS-like location of ESD event (1990s), developed but not routinely used.

Conclusions

- How *in situ* event monitoring in manufacturing works, using antenna and detector arrangement
  - Also create CDM events at will with the CDMES (event simulator) and use the antenna and detector in place
  - Calibrate the detector with a reproducible antenna-like pulse

- Tools were developed along with the theory of
  - CDM and CDMES fields
  - Resulting antenna pulse
  - Synthesis of artificial antenna pulse

- Measurement uncertainties
  - Dipole length, device stress vs. field strength, etc.

- Considerations for adopting the technology

- TJM ESD publications (this one is emc18):

  See https://sites.google.com/site/esdpubs/documents

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