SILENT

Practical Probing Techniques for EMC Troubleshooting

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Instructor Biography

Lee Hill is Founding Partner of SILENT Solutions LLC, an independent electromagnetic compatibility (EMC) and RF design firm he established in 1992. Besides providing EMC design review and troubleshooting services, Lee is also a member of adjunct faculty at Worcester Polytechnic Institute (WPI) where he teaches graduate courses in EMC. He is also an EMC class instructor at the University of Oxford (England), and for the IEEE EMC Society's annual Global University program and EMC Fundamentals workshop. In past years Lee was also an EMC course instructor for UC Berkeley Extension as well for Hewlett Packard and Agilent Technologies. Previously Lee was Principal EMC and Systems Engineer at Digital Equipment Corporation's Workstation Systems Engineering Group in Palo Alto, CA. In 2017 Lee founded SILENT Solutions GmbH in Munich, Germany.

Lee received the Master of Science Degree in Electrical Engineering & Electromagnetics with highest honors from the University of Missouri-Rolla, (now Missouri University of Science and Technology). He is an inventor of three US patents for EMI control in electronic systems, and provides expert witness services for patent litigation.

In the past fifteen years he has been a frequent featured speaker at IEEE EMC Society fundraising events in cities throughout the US including Santa Clara, Seattle, Portland, Chicago, Milwaukee, Dallas/Fort Worth and Detroit. He has also provided technical presentations to Society chapters in Los Angeles, San Diego, Santa Clara, Boston, Austin, Colorado Springs, Pittsburgh, and Orange County, CA. He served a term as an IEEE EMC Society Distinguished Lecturer from 1994-1996.

Lee has over twenty-five years of experience in the EMC design and retrofit of complex electronic systems. He has been teaching short courses on EMC design and troubleshooting for twenty years. Lee consults and teaches worldwide, and has presented classes in Taiwan, Singapore, Mexico, Norway, Canada, South Korea, France, Germany and United Kingdom. He has completed a three-year term on the Editorial Review Board of Printed Circuit Design Magazine.. He is an avid father, runner, motorcyclist, table tennis player and Amateur Radio operator, and has served as an officer on the board of directors of several non-profits.

Lee is past member of the IEEE EMC Society Board of Directors (2004-2007). From 1999-2006 he chaired the IEEE EMC Society's Distinguished Lecturer Program, and served as Co-Technical Chair of the 2003 IEEE Symposium on EMC in Boston, MA.
In 1999 Lee received a Certificate of Appreciation from the EMC Society for significant contributions to education through his annual participation in the Demonstrations and Experiments portion of annual IEEE EMC Symposia.

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Outline

PART 1: Probing Tools

- Why are we using probes?
- Why CURRENT is important in typical regulatory noise problems
- Key PASSIVE Probe Characteristics
- Voltage Probes
- Clamp-on Current Probes
- Magnetic Field Probes
- Electric Field Probes
- Self-contained Immunity Generator “active probes”
- Our Favorite Tools

Special Thanks to Dr. Tom Van Doren, Professor Emeritus,
Electrical and Computer Engineering Department,
Missouri University of Science & Technology, for permission to use
portions of his original source material contained in this section

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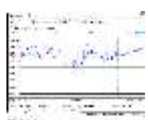
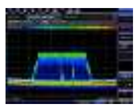
WHY Do We Use PROBES?

Pass a “stupid EMI test” or fix a problem
that causes EMC regulatory test failure



Understand or fix a “functional” noise problem

Characterize an environment



Characterize a device

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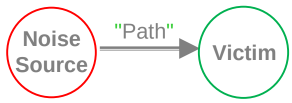
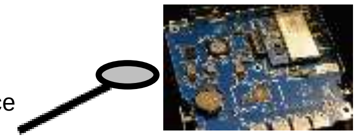
WHAT Are We Trying To Do With A Probe?

Every noise problem is source – path – victim



USE PROBES TO:

LISTEN / FIND / MEASURE
a noise quantity FROM an existing source



INDUCE / REPRODUCE
a noise quantity INTO an existing victim

Some probes are good at doing both, some probes are good for only one.

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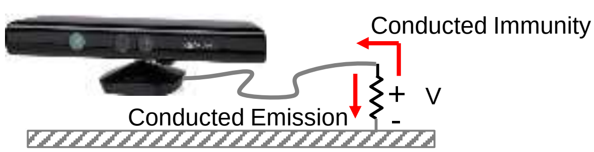
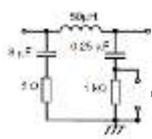
Most "Conducted" Noise Problems Can Be Understood by Locating the Path of the Responsible Noise Current



Conducted EMISSIONS

EUT Noise Current



Measured Noise Voltage

Conducted IMMUNITY

Current driven into EUT

Noise Generator Current

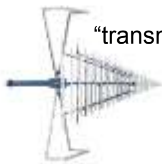
Most "Radiated" Noise Problems Can Be Understood by Locating the Path of the Antenna (noise) Current

Radiated Immunity

Radiated Emission

Radiated EMISSIONS

Current
di/dt

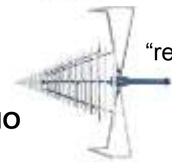


"transmitting"

Radio Wave
E,H

Radiated IMMUNITY

Current
di/dt



"receiving"

Radio Wave
E,H

DEMO

What Makes a Good EMC Probe?

Bandwidth: F_1 < Frequency < F_2

Sensitivity (Listening), Efficiency (Injecting)

Less preamplifier gain (listening)
Less power amplifier gain (injecting)

Ruggedness

Usually the difference between purchased and homemade

Impedance Loading (of circuit under test)

Does the probe disturb the (I,V) quantity being measured?

Field Perturbation

Does the probe disturb the field quantity being measured?

Impedance Balance

When trying to measure Idm or Vdm, does Icm increase?

Repeatable Positioning

Same location = same E,H, same V,I

Cost, Calibration

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What Should We Try to Measure with Our Probe?

Coupling Mechanism	Quantity Measured	Measuring Process
Conducted	Voltage (V)	Resistive Divider + Amplifier
	Current (I)	Resistive Shunt (I=V/R)
		Magnetic Coupling (Xfrmr)
Near Field	Magnetic Field (H)	Magnetic Coupling $V = M di/dt \propto dH/dt$
	Electric Field (E)	Displacement Current $I = C dV/dt \propto dE/dt$
Far Field	EM Wave (E,H)	Antenna $V_{out} = AF \times \lvert E \rvert$

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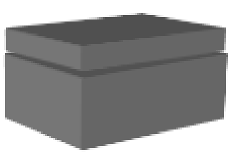
Passive Voltage Probes (Listening to locate sources)

Radiated emissions

Measure voltage across seams or apertures of conductive chassis
Measure voltage between connector pin and conductive chassis



- Radiated or conducted emissions or self-interference
- Finding circuit nodes with "Bonus Noise" (Unexpected RF sources)
- Radiated emissions or self-interference in radio / "wireless" receivers

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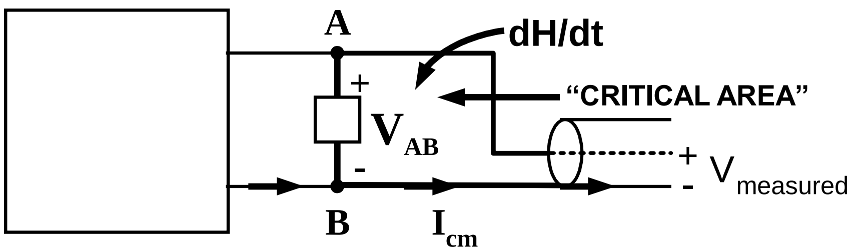
Problems with Passive Voltage Probes (Listening)

Sources of Measurement Error:



$$|V_{measured}| = V_{AB} \pm \omega_1 M I_{CM} \pm \omega_2 \iint H \cdot ds$$

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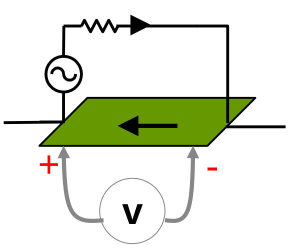
You Can't Measure "Noisy Grouvd" or "Ground Plane Inductance or Voltage", or Voltage near Big $\bar{H}$

Sources of Measurement Error:



V depends on location of wires
and amount of flux wrapping the plane

"Critical Area"
is obvious
DEMO

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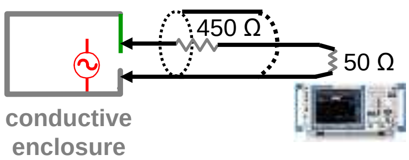
Passive, Unbalanced 10x Voltage Probes

(Listening to locate noise sources)

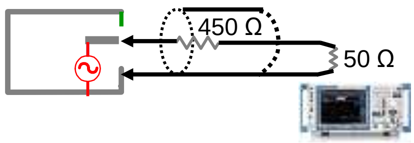
Radiated emissions

- Measure voltage across seams or apertures of conductive chassis
- Measure voltage between connector pin and conductive chassis

Aperture



Connector Pin



Measuring voltage difference across many different seams or pins might identify the location of a dominant energy leakage

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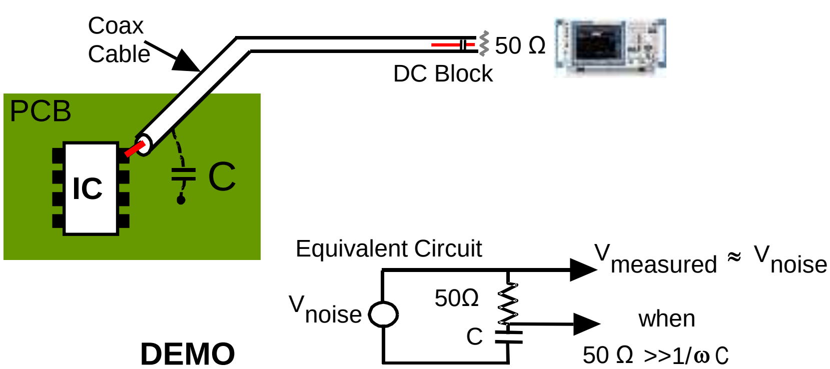
Passive “1 Terminal” Voltage Probes (Listening)

Radiated Emissions or E field (dv/dt) Source:

Finding Circuit Nodes with “Bonus Noise” (Unexpected RF sources)
E field (dv/dt) source – cause of radiated emissions if coupled to an antenna



DEMO

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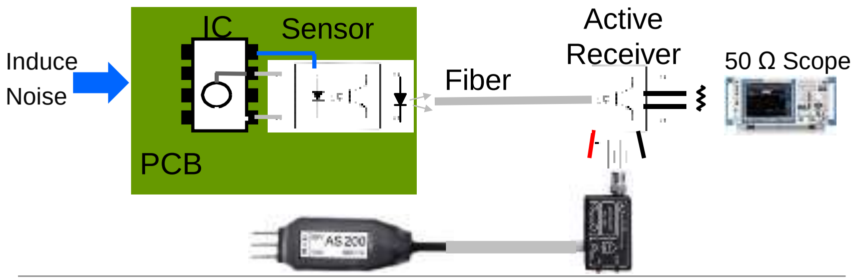
Active Voltage Probes (Listening to SIGNAL during NOISE Event)

Fiber optic analog or digital signal detector, hardened against RF, monitors critical EUT signal via fiber to active receiver.

For use during conducted immunity or radiated immunity or ESD tests. Measure health of intended signals with isolated sensor to avoid RF coupling via measurement wires.



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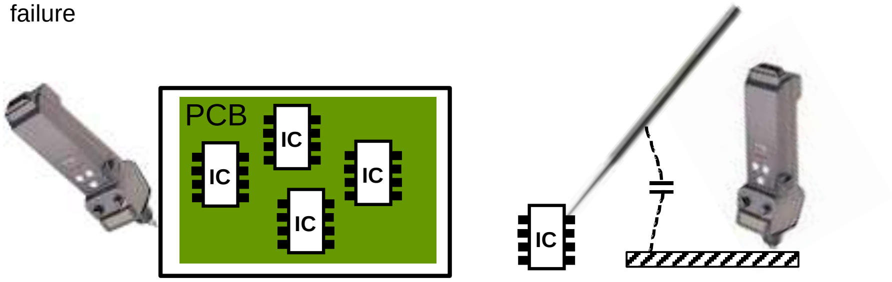
Active Noise Probes (Generators) To Locate Victim Circuits Sensitive to ESD. EFT, Rad. Immun.

“Manual Injection” methods can be tricky / ineffective

Which IC / trace causes system ESD failure?

Identifying the precise location of victim circuits that cause system level ESD failure



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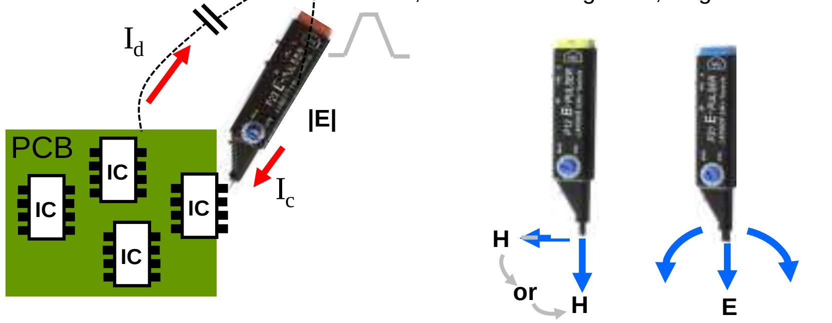
Active Noise Probes (Generators) To Locate Victim Circuits Sensitive to ESD. EFT, Rad. Immun.

Identifying the precise location of victim circuits that cause system level ESD failure

1.2 kV, 1.8 nS min. edgetime, single or 5 kHz



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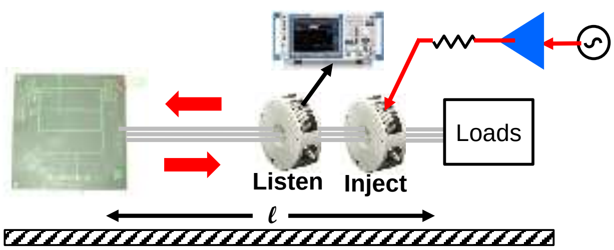
Passive Current Probes - Listening for CE or RE, Injecting for CI or “Simulated” RI



Net current Enclosed = $\oint \mathbf{H} \bullet dl = \underbrace{\oint \mathbf{J} \bullet \mathbf{dS}}_{\text{conduction}} + \cancel{\underbrace{\frac{d}{dt}\int \mathbf{D} \bullet \mathbf{dS}}_{\text{displacement}}}$

Probe with Electric Field shield makes this term = 0

Shielded – We only want to detect dH/dt and thus the current (listening)

We only want to deliver i(t) (injecting)

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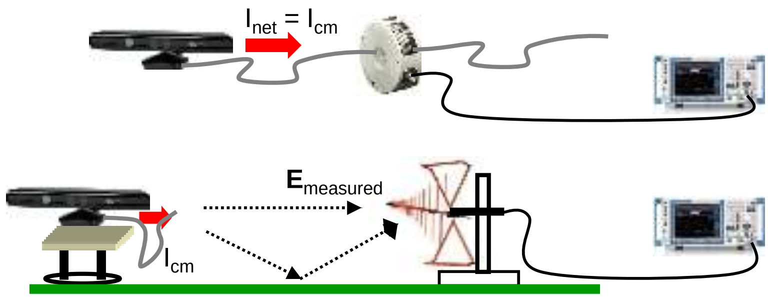
Passive Current Probes (Listening for RE)



Under far field conditions, at a distance of R meters from a $\lambda/2$ dipole

$E = \frac{60\,I}{R}$ where I = current (A) at center of dipole

$I < \frac{R\,|Emax|}{60} = \frac{(10m)(100\,\mu V/m)}{60\,\Omega}$ / 2 ~ 8 μA (EN 55032 @ 10m)

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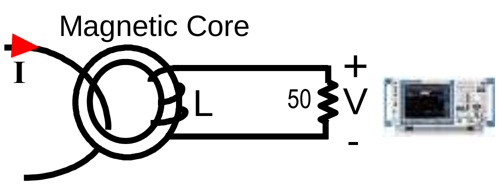
Passive Current Probes (Listening for CE or RE)



$| I | = | V | / | Z_T |$ $V_{dB} = I_{dB} + Z_{T\ dB}$

For listening to noise current, we want a “sensitive” probe that delivers max V for a given I_{noise} so we want Z_T to be ___.

Do you like 0 dBΩ probe?

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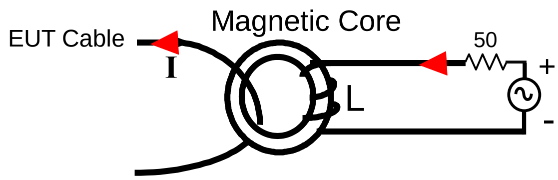
Passive Current Probes - Injecting CI or “Simulated” RI

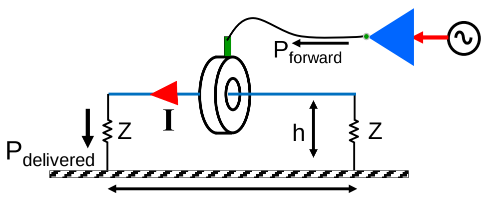


For a given available RF power output, we want a probe that delivers maximum current I

“Insertion Loss” Calibration

10 Log ($P_{forward}$ / $P_{delivered}$)

<u>SMALL Insertion Loss = Good</u>



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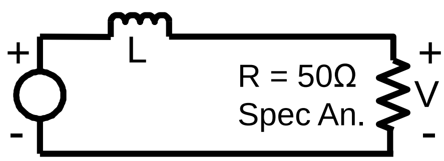
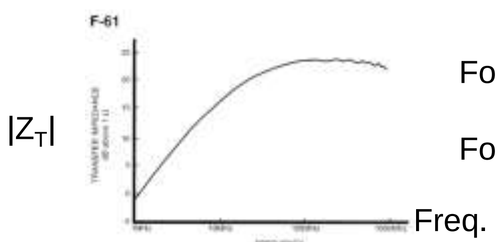
Passive Current Probes for Listening – Equivalent Circuit



$$|V| = \frac{\omega M R I}{\sqrt{R^2 + (\omega L)^2}} = I|Z_T|$$



For $\omega L \ll R$, $|Z_T| = \omega M$

For $\omega L \gg R$, $|Z_T| = MR/L$

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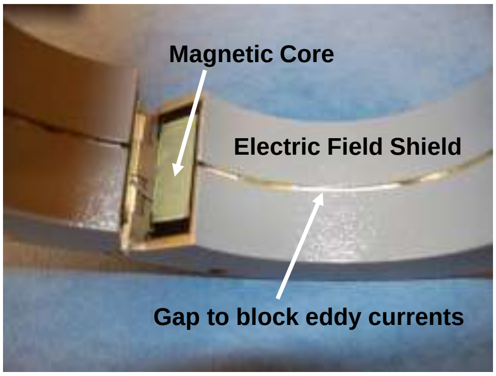
Passive Current Probes – Electric Field Shielding



The wire under test can capacitively couple to the Probe winding through the slot This is usually minor at F< ~ 400 MHz.

Some people use a foam “donut” to prevent cables from getting very close to the gap and causing loading and measurement repeatability problems.

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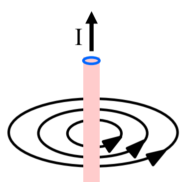
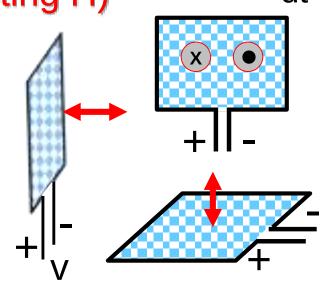
Passive Magnetic H Field Probes (Listening for CE or RE, or Injecting H)

$$V \propto \frac{dH}{dt}$$

$$\oint \mathbf{H} \bullet dl = \underbrace{\oint \mathbf{J} \bullet \mathbf{dS}}_{\text{conduction}}$$





We can use a simple loop probe to:

1) Detect the relative amplitude AND direction of time-changing current (nice if it’s calibrated)

2) Detect the relative amplitude of a time changing magnetic field e.g., if we’re failing a magnetic field emissions test or looking for “leaky” inductive components. **DEMO**

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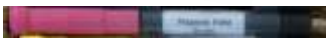
Passive Magnetic Field Probes

We measuring **B**, to find **I**
(magnitude & direction)
Where is the magnetic flux?

Large probes for large objects – cables, connectors, enclosures

1 cm (and larger) loops



> 1 cm aperture

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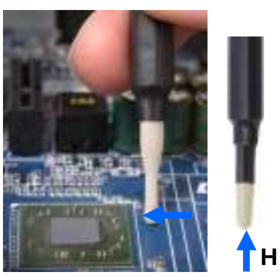
Passive & Active Magnetic Field Probes

Small probes for small objects – PCBs, ICs, PCB traces, PCB vias

Passive
Calibrated. 1 GHz ≤ F ≤ 10 GHz
Resolution ~ 1 to 2 mm



Active: These can localize noise to a via or BGA bump.
Calibrated. 100 MHz ≤ F ≤ 6 GHz
Resolution ~ 200 um

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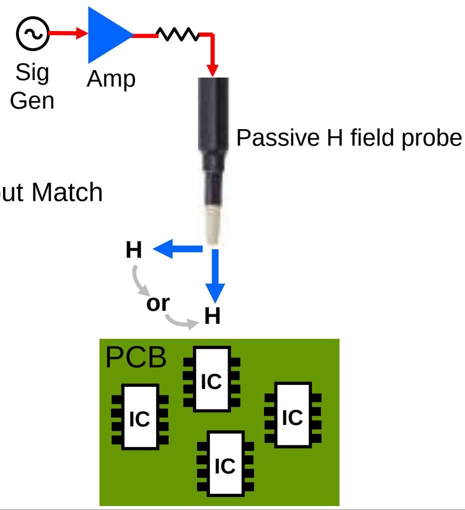
Use Passive H field Probes for Immunity Troubleshooting

Some Vendors Categorize
Max Forward Power and Input Match



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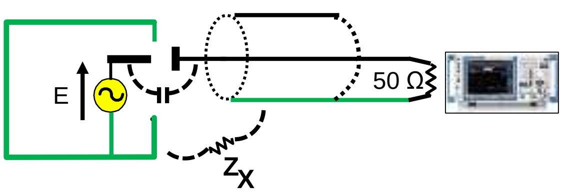
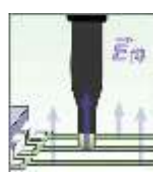
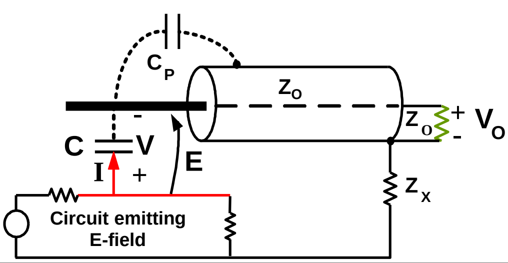
Passive E field Probes – Where's the Current Loop?







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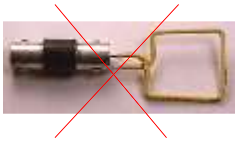
Pitfalls of Homemade Probes

H field loop probes and current probes must be shielded, otherwise;

- Confusing measurement results
  - May interact with human's capacitance
  - May interact with E, dv/dt of circuit under test
- Poor spatial resolution – It's tough to make really tiny, shielded, homemade H-field probes.



Homemade probes are often uncalibrated

- Difficult to distinguish between "interesting" and "important" when multiple sources exist.
- Large bandwidth of commercial probes is difficult to duplicate

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Common Mistakes When Using EMC Probes

Using too much (preamplifier) gain with 1cm or larger H-field loop probes.

Using homemade H field probes with poor E field shielding

Trying to fix radiated emissions problems by measuring and "fixing" z near H and E fields from PCBs, instead of measuring I_{cm} from cables and V_{cm} along enclosure seams

Trying to measure voltages between different "GNDs"
with large measurement loop area
in area with large dB/dt

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Where to Buy the Tools

Places to buy the tools that SILENT uses:

Real-Time EMC Spectrum Analyzers and Test Receivers
Rohde & Schwarz www.rohde-schwarz.com

Handheld E & H Probes, Noise Generators
Langer EMV-Technik www.langer-emv.com
Van Doren Company www.emc-education.com

Clamp-on Current Probes
Fischer Custom Communications www.fischercc.com

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Upcoming EMC Education from SILENT

For more EMC education with theory, applications, and live demos:

University of Oxford, England
Advanced Product Design & Troubleshooting for EMC June 18+19
Advanced PCB Design for EMC. June 18+20
Mechanical Design for EMC June 18+21

Dresden, Germany
Advanced PCB Design for EMC April 17-18
Mechanical Design for EMC April 17,19

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Favorite Passive Current Probes

Fischer F-61
Listening
1 MHz ≤ F ≤ 1 GHz

Fischer F-16
Listening
10 Hz ≤ F ≤ 70 MHz

Fischer F-130x
Injection
10 kHz ≤ F ≤ 400 MHz

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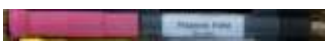
Favorite Passive Near Field E + H Probes



Van Doren Company
MFH-23
MLF-11
40 MHz ≤ F ≤ 400 MHz
3 kHz ≤ F ≤ 300 kHz

ETS-Lindgren
1 and 3 cm loop probes
F ≤ 1.5 or 2.3 GHz

Langer EMV-Technik
RF-R400-1
RF-E 02
RF-E-10
RF-U 2.5-2
RF-B 3-2
F ≤ 6 GHz
Best Spatial Resolution

Rohde & Schwarz
HZ-15 Probe Set

Probing of Systems / Cables

Probing of PCBs/ ICs

Favorite “Active” E + H Probes

All Made By Langer EMV-Technik

“Pulsers”: P1 set, P23
Noise Generators

MFA Active H Field Probes
For Listening