TI Technology Days 2010

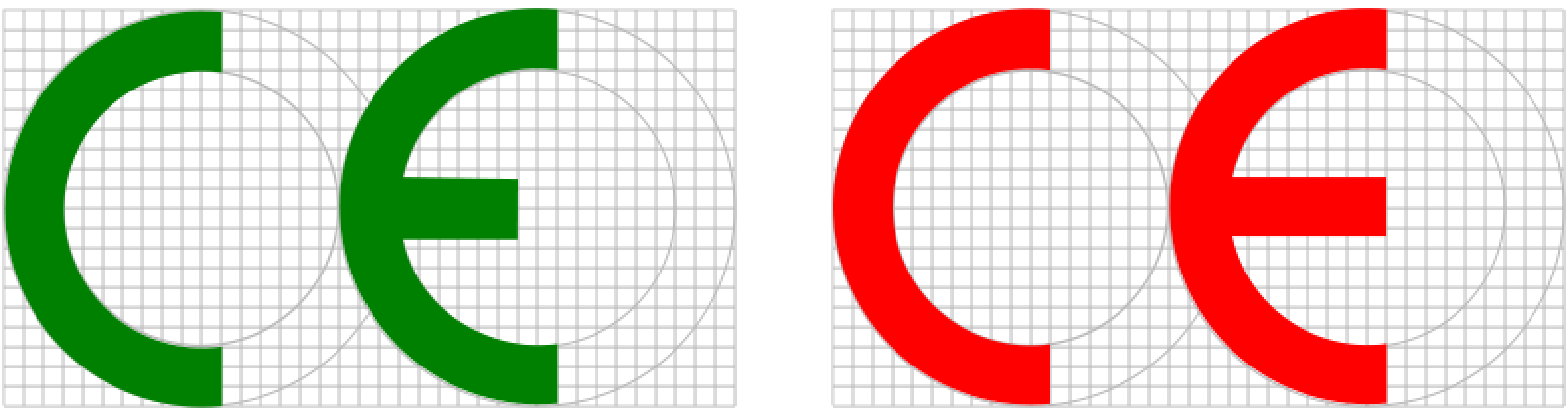
EMV in Theorie und Praxis fuer Jedermann

Josef Warta

AGENDA

- Rechtsgrundlagen
- Theorie
- Praktische Tipps

CE Kennzeichnung



http://www.ce-richtlinien.eu/index.html

CE Richtlinien

fuer unterschiedliche Anwendungsgebiete, z.B.

- Spielzeug-Richtlinie 2009/48/EG
- Aktive implantierbare medizinische Geräte 90/385/EWG
- Richtlinie 2004/108/EG:
  Elektromagnetische Verträglichkeit von Elektro- und Elektronikprodukten – EMV
- Niederspannungsrichtlinie 2006/95/EG
- Telekommunikations-Richtlinie 1999/5/EG
- .
- .
- .

RICHTLINIE 2004/108/EG DES EUROPÄISCHEN PARLAMENTS UND DES RATES

vom 15. Dezember 2004

zur Angleichung der Rechtsvorschriften der Mitgliedstaaten über die elektromagnetische Verträglichkeit

und zur Aufhebung der Richtlinie 89/336/EWG

"…die Fähigkeit eines Apparates, einer Anlage oder eines Systems, in der elektromagnetischen Umwelt zufriedenstellend zu arbeiten, ohne dabei selbst elektromagnetische Störungen zu verursachen, die für alle in dieser Umwelt vorhandenen Apparate, Anlagen oder Systeme unannehmbar wären."

Weitere Links:

- Gesetz über die elektromagnetische Verträglichkeit von Betriebsmitteln (EMVG)
- Harmonisierte Normen (z.B. Fachgrundnormen EN-61000-6, Produktenormen EN-61326, Pruefnormen EN-61004-4,….)

Begriffsdefinition

Kopplungsmechanismen

- Galvanische Kopplung
- Kapazitive Kopplung
- Induktive Kopplung
- Strahlungskopplung

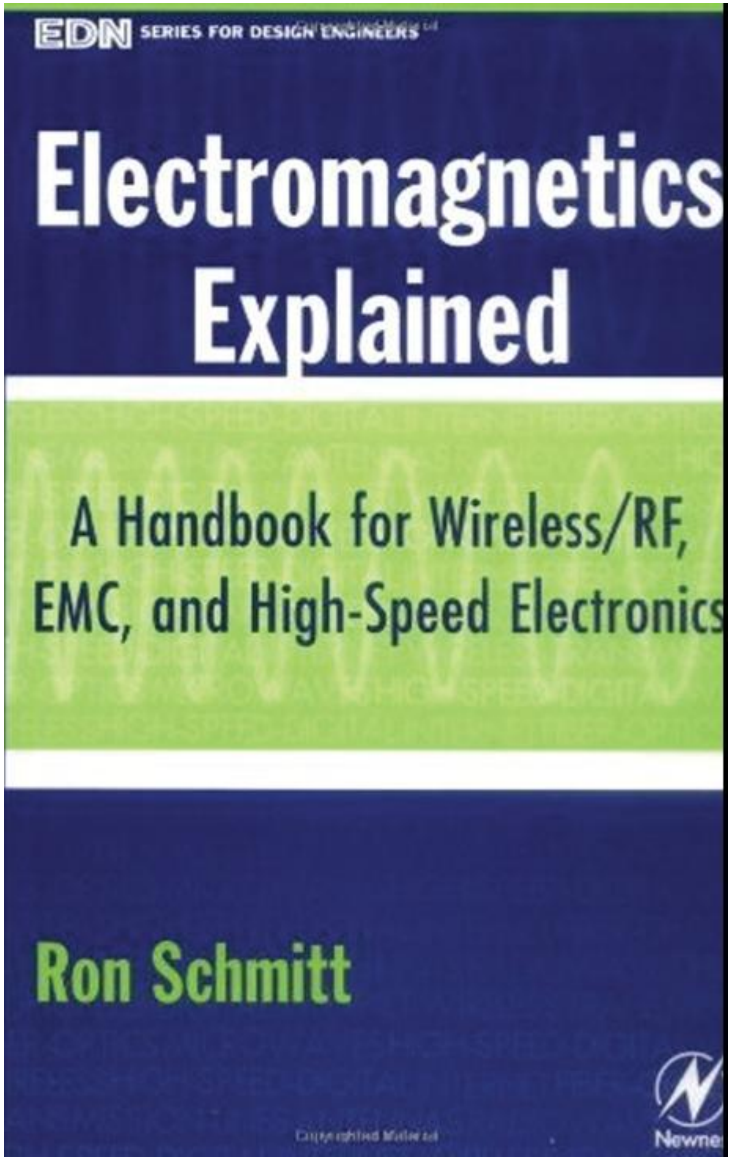
Arten von Störungen

- **leitungsgebundenen Störungen** werden von der Störquelle direkt über Versorgungs- oder Signalleitungen zur Störsenke übertragen.
- **feldgebundenen Störungen** werden zum Beispiel als elektromagnetisches Feld auf die Störsenke übertragen und dort beispielsweise von einem als Antenne fungierenden Leiter empfangen. Auch kapazitive und induktive Beeinflussungen elektrischer bzw. magnetischer Felder werden als feldgebundene Störungen bezeichnet.

Theorie

Die elektromagnetische Welle

Grundlagen: Electromagnetics



Elektromagnetisches Spektrum

$$\lambda = \frac{c}{f} \qquad \lambda' = \frac{\lambda_0}{\sqrt{\mu_r \varepsilon_r}} = \frac{c}{f}\frac{1}{\sqrt{\mu_r \varepsilon_r}}$$

$$T = \frac{1}{f}$$

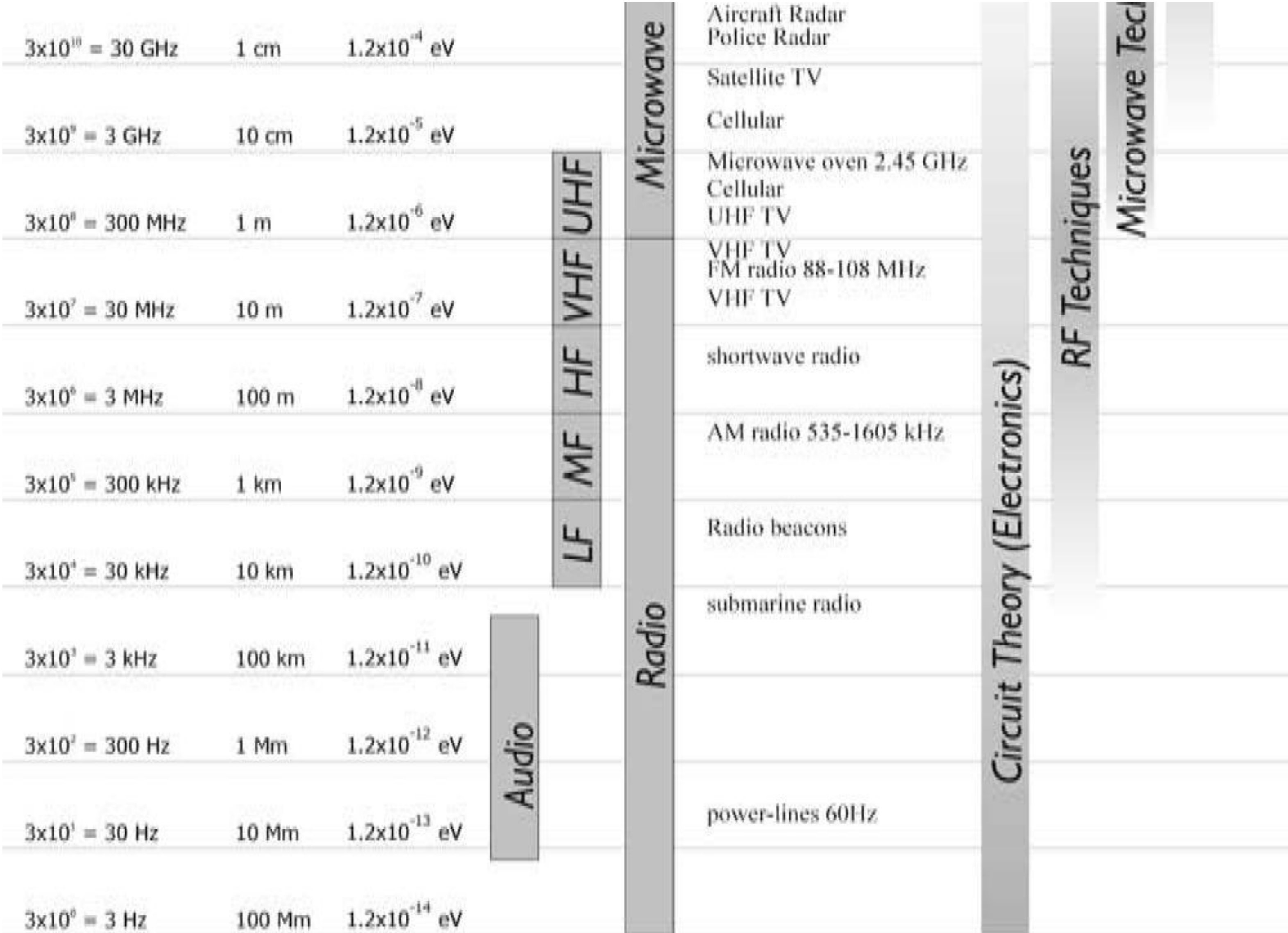
$$E = h \times f$$

$$\text{Electrical length} = \frac{L}{\lambda}$$

Permittivität *ε* (*dielektrische Leitfähigkeit*, gibt die Durchlässigkeit eines Materials für elektrische Felder an)

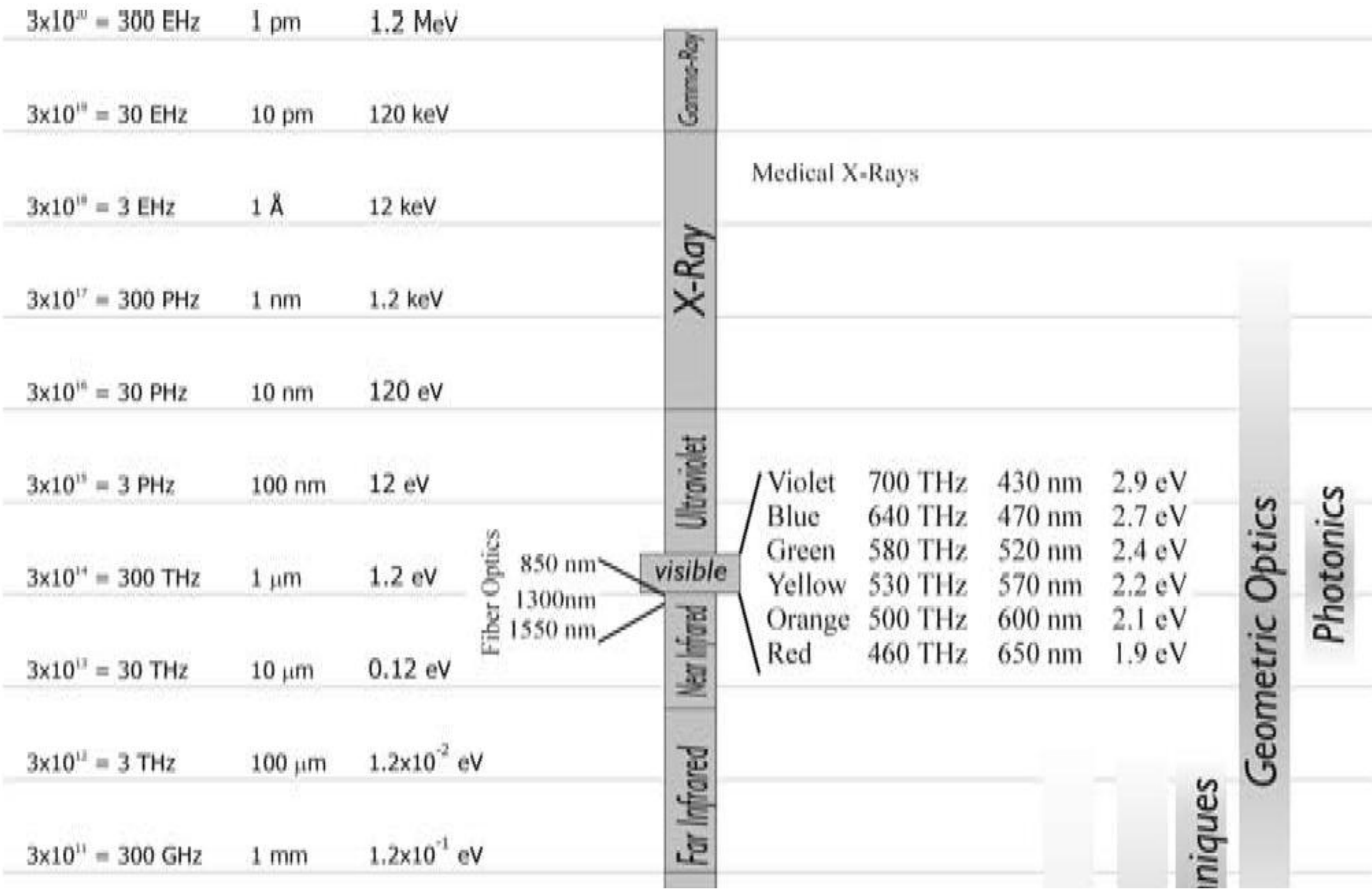
Permeabilität *μ* (*magnetische Leitfähigkeit* bestimmt die Durchlässigkeit von Materie für magnetische Felder)

Elektromagnetisches Spektrum (1)



(Quelle: Electromagnetics explained)

Elektromagnetisches Spektrum (2)



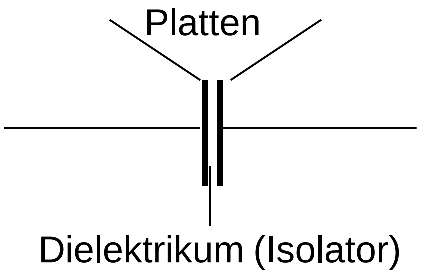
(Quelle: Electromagnetics explained)

Elektrisches Feld - Kondensator

Grundeigenschaft: Speicherfähigkeit von elektrischen Ladungen (elektrisches Feld) - **Kapazität C**.

Kapazität allgemein:

$$C = \frac{Q}{U}$$



Kapazität Plattenkondensator:

$$C = \varepsilon \frac{A}{d}$$

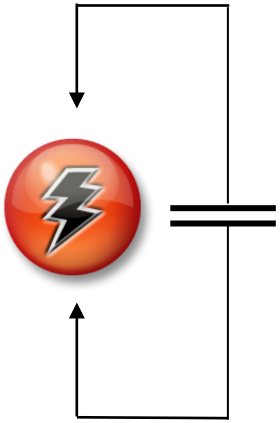
Einheit: $[C] = \frac{1As}{V} = 1F$

Abgewandelte Einheiten: 1F = $10^6\mu$F = 10^9nF = 10^{12}pF

Strom-Spannungs-Beziehung: $$i = C \cdot \frac{du}{dt}$$

(Quelle: Uni Muenster, IVV4Naturwissenschaften)

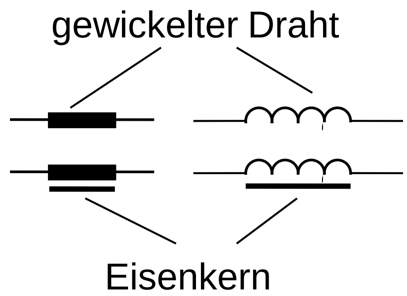
Elektrisches Feld - Kondensator



Magnetisches Feld / Spule

Grundeigenschaft: Zeitlich begrenzte Speicherfähigkeit des magnetischen Feldes - **Induktivität L**.

Induktivität allgemein: $$L = \frac{N \cdot \phi}{I}$$



Induktivität der Spule: $$L = \frac{\mu_0 \cdot \mu_r \cdot N^2 \cdot A}{l}$$

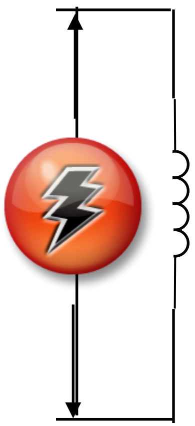
Einheit: $$[L] = \frac{1Vs}{A} = 1H$$

Abgewandelte Einheiten: $1H = 10^3 mH = 10^6 \mu H$

Strom-Spannungs-Beziehung: $$u = L \bullet \frac{di}{dt}$$

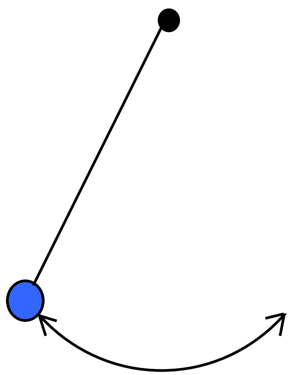
(Quelle: Uni Muenster, IVV4Naturwissenschaften)

Magnetisches Feld / Spule

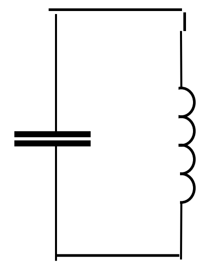


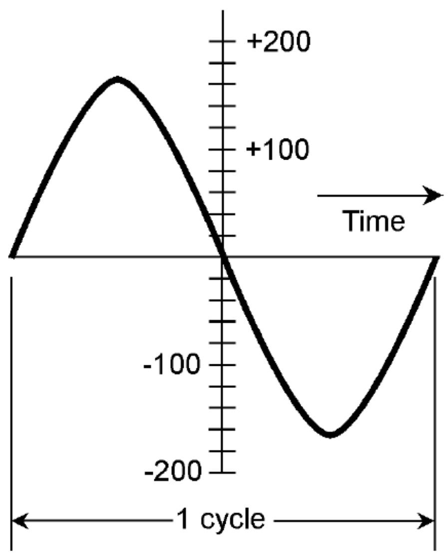
Elektro-Magnetischer Wechsel

Mechanische Modell
“Pendel”

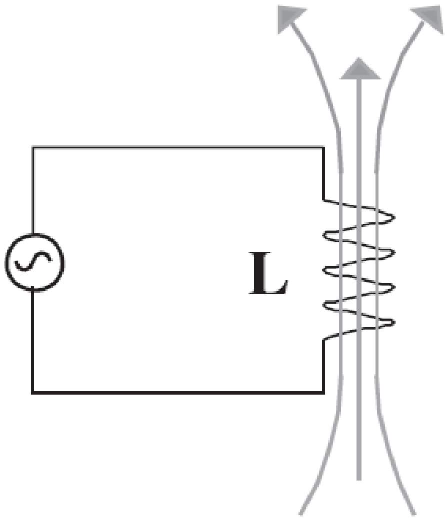


Elektrisches Modell
“Schwingkreis”



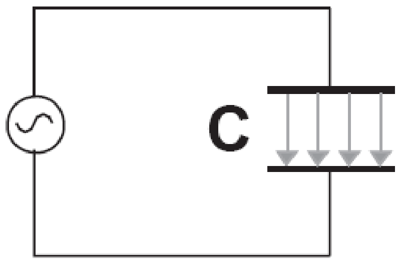


Nah-Strahlung
Induktiv



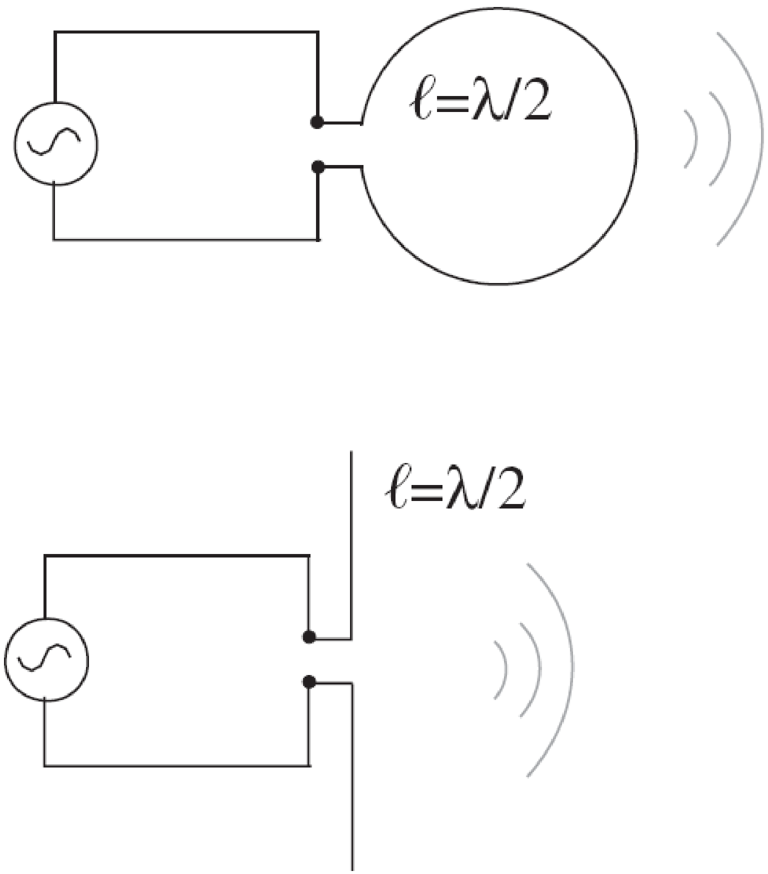
(Quelle: Electromagnetics explained)

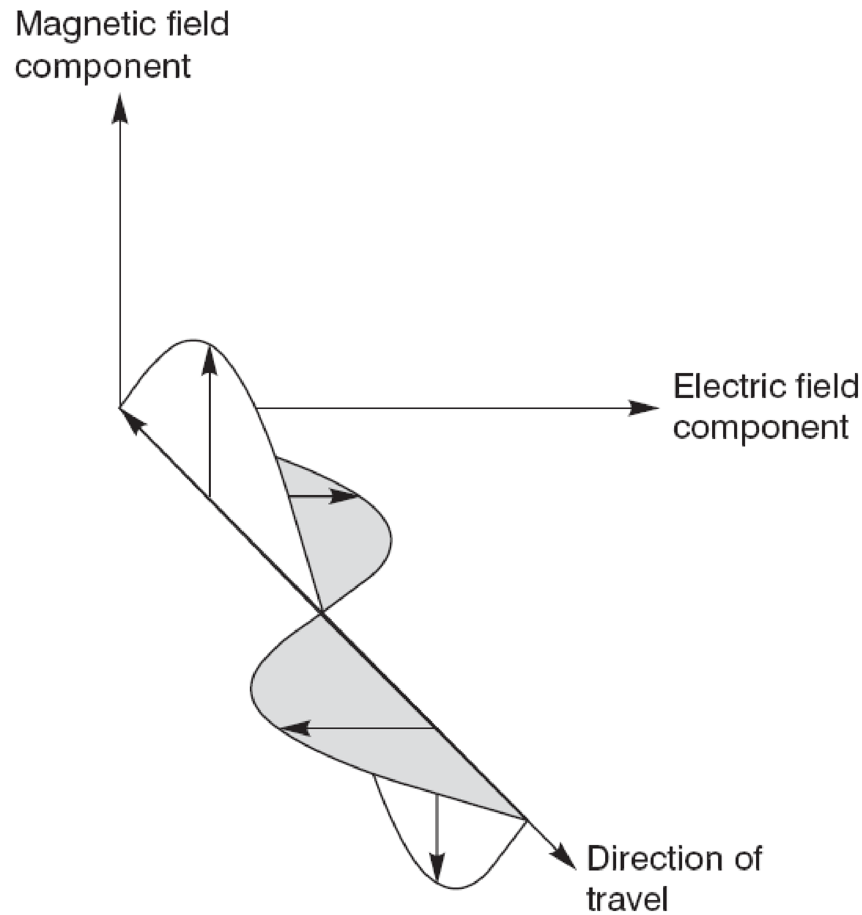
Nah-Strahlung
Kapazitiv



(Quelle: Electromagnetics explained)

Fern-Strahlung





(Quelle: Electromagnetics explained)

Nah/Fern-Strahlung

	Near (Reactive) Field	*Far (Radiated) Field*
Carrier of Force	Virtual photon	Photon
Energy	Stores energy. Can transfer energy via inductive or capacitive coupling.	Propagates (radiates) energy.
Longevity	Extinguishes when source power is turned off.	Propagates until absorbed.
Interaction	Act of measuring field or receiving power from field causes changes in voltages/currents in source circuit.	Act of measuring field or receiving power from field has no effect on source.
Shape of Field	Completely dependent on source circuit.	Spherical waves. At very long distances, field takes shape of plane waves.
Wave impedance	Depends on source circuit and medium.	Depends solely on propagation medium ($\eta = 120\pi \cong 377\,\Omega$ in free space).
Guiding	Energy can be transported and guided using a transmission line.	Energy can be transported and guided using a wave guide.

(Quelle: Electromagnetics explained)

Maxwellsche Gleichungen elektromagnetischer Felder und Wellen

Maxwellsche Gleichungen

Differentialform

$$\nabla \times \underline{\mathbf{E}}(\underline{\mathbf{R}},t) = -\frac{\partial}{\partial t}\underline{\mathbf{B}}(\underline{\mathbf{R}},t) - \underline{\mathbf{J}}_{\mathrm{m}}(\underline{\mathbf{R}},t)$$

$$\nabla \times \underline{\mathbf{H}}(\underline{\mathbf{R}},t) = \frac{\partial}{\partial t}\underline{\mathbf{D}}(\underline{\mathbf{R}},t) + \underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t)$$

$$\nabla \cdot \underline{\mathbf{D}}(\underline{\mathbf{R}},t) = \rho_{\mathrm{e}}(\underline{\mathbf{R}},t)$$

$$\nabla \cdot \underline{\mathbf{B}}(\underline{\mathbf{R}},t) = \rho_{\mathrm{m}}(\underline{\mathbf{R}},t)$$

Integralform

$$\oint_{C=\partial S} \underline{\mathbf{E}}(\underline{\mathbf{R}},t) \cdot \underline{\mathbf{dR}} = -\iint_S \frac{\partial}{\partial t}\underline{\mathbf{B}}(\underline{\mathbf{R}},t) \cdot \underline{\mathbf{dS}} - \iint_S \underline{\mathbf{J}}_{\mathrm{m}}(\underline{\mathbf{R}},t) \cdot \underline{\mathbf{dS}}$$

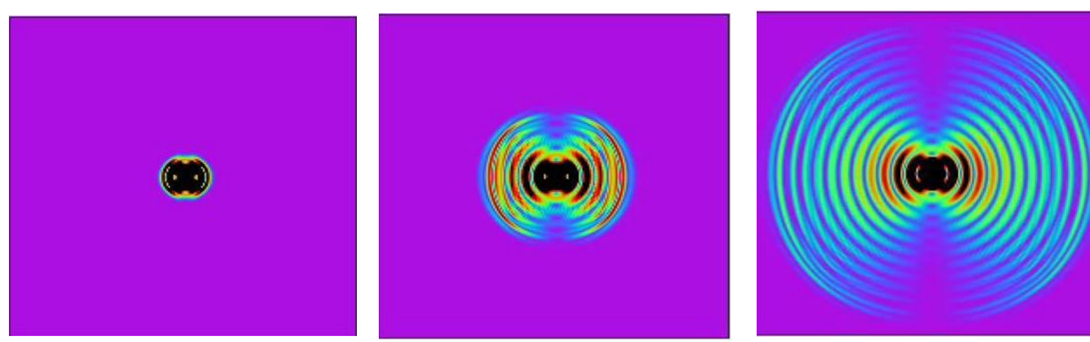
$$\oint_{C=\partial S} \underline{\mathbf{H}}(\underline{\mathbf{R}},t) \cdot \underline{\mathbf{dR}} = \iint_S \frac{\partial}{\partial t}\underline{\mathbf{D}}(\underline{\mathbf{R}},t) \cdot \underline{\mathbf{dS}} + \iint_S \underline{\mathbf{J}}_{\mathrm{e}}(\underline{\mathbf{R}},t) \cdot \underline{\mathbf{dS}}$$

$$\oiint_{S=\partial V} \underline{\mathbf{D}}(\underline{\mathbf{R}},t) \cdot \underline{\mathbf{dS}} = \iiint_V \rho_{\mathrm{e}}(\underline{\mathbf{R}},t)\,\mathrm{d}V$$

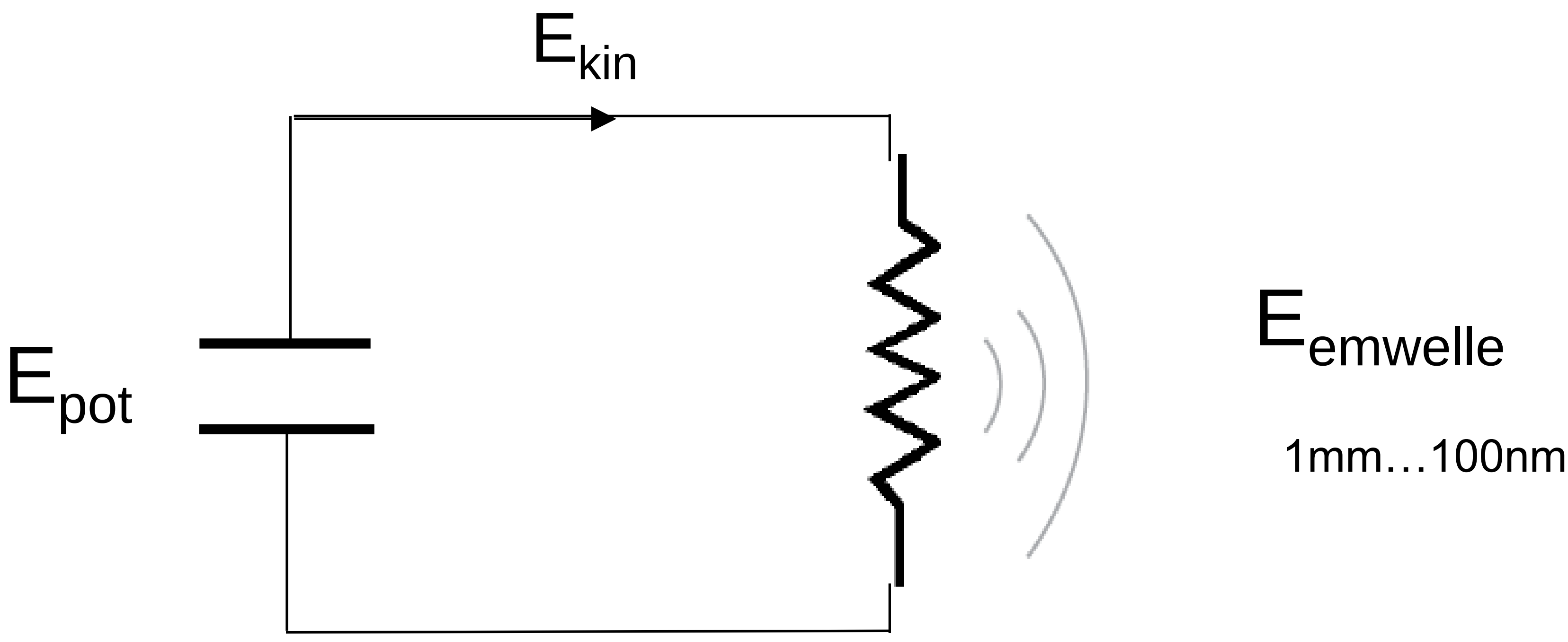
$$\oiint_{S=\partial V} \underline{\mathbf{B}}(\underline{\mathbf{R}},t) \cdot \underline{\mathbf{dS}} = \iiint_V \rho_{\mathrm{m}}(\underline{\mathbf{R}},t)\,\mathrm{d}V$$

Wasseroberflächenwellen

Hertzscher Dipol: EM Wellen



Energieumwandlung



Spektrum

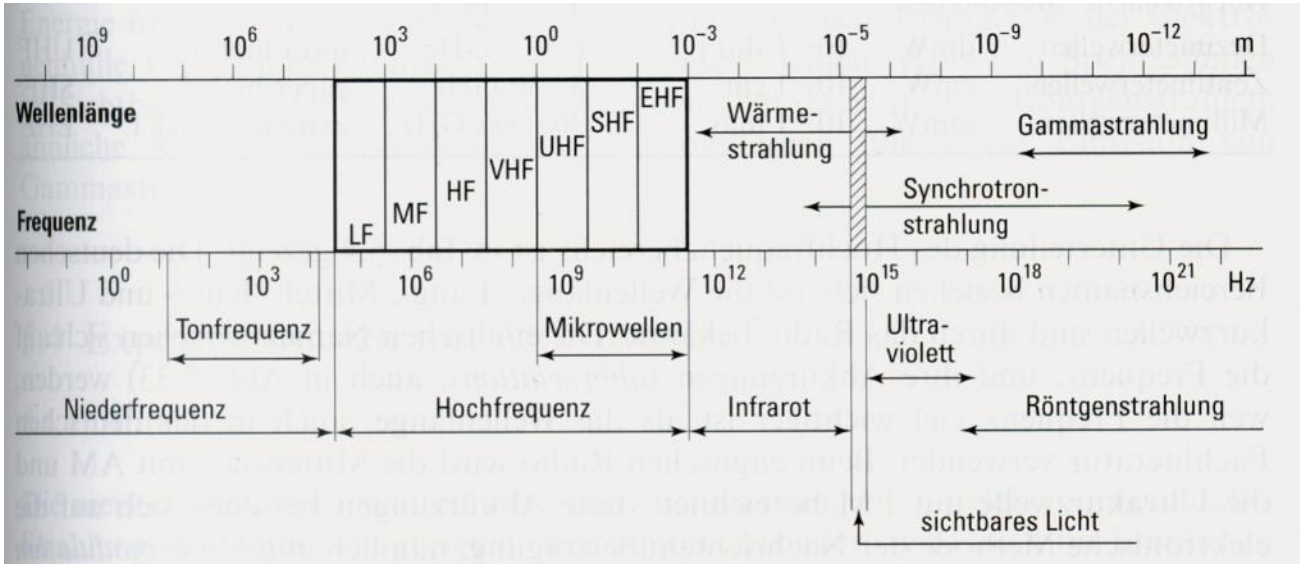
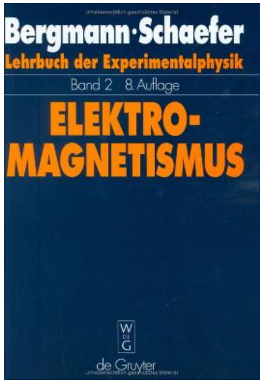


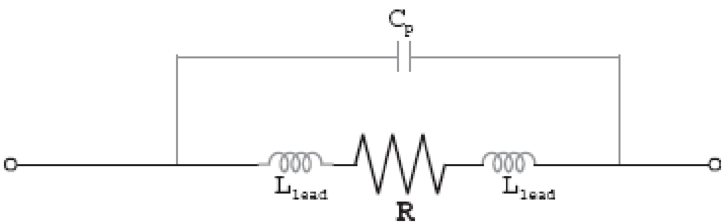
Abb. 5.33 Das Spektrum elektromagnetischer Schwingungen und Wellen.

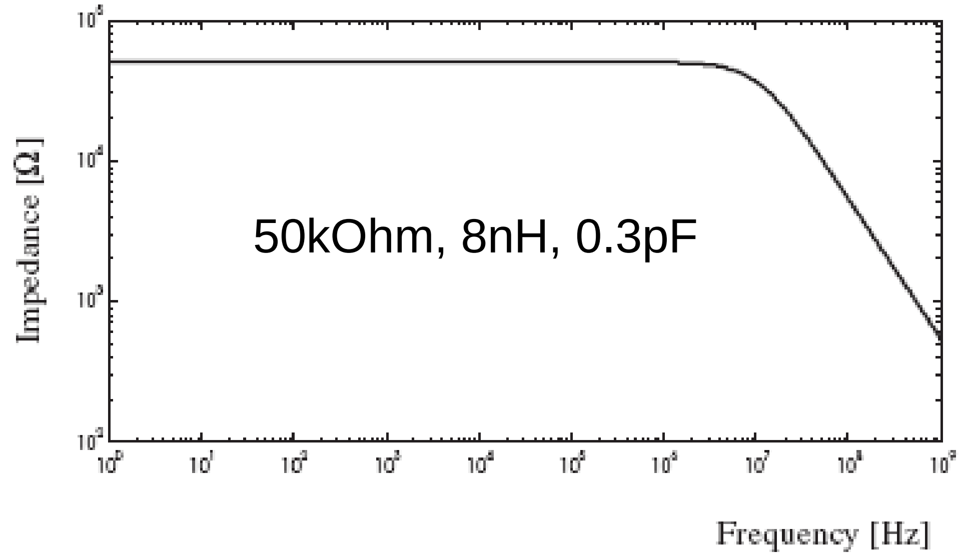


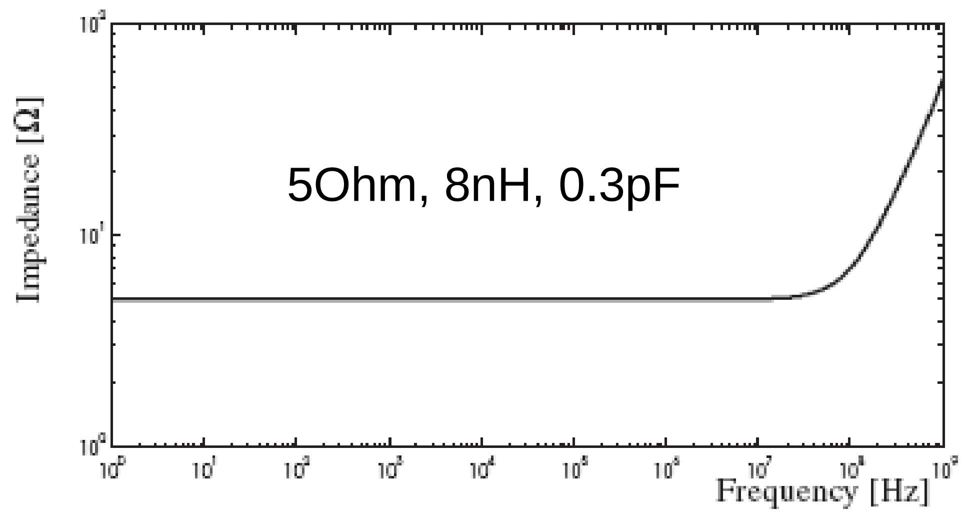
Bergmann-Schaefer,
Band 2
Elektromagnetismus
S. 323

‘Versteckte’ Bauelemente

Realer Widerstand

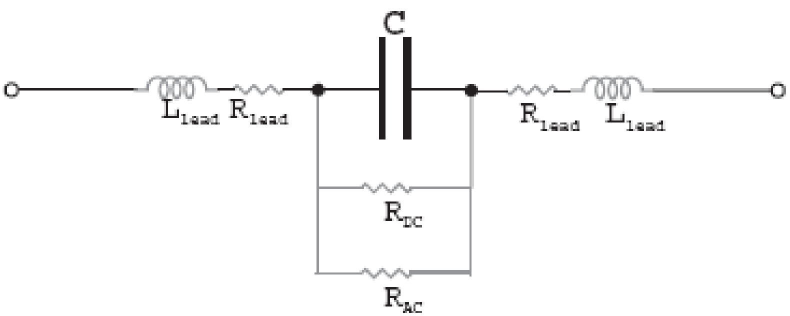


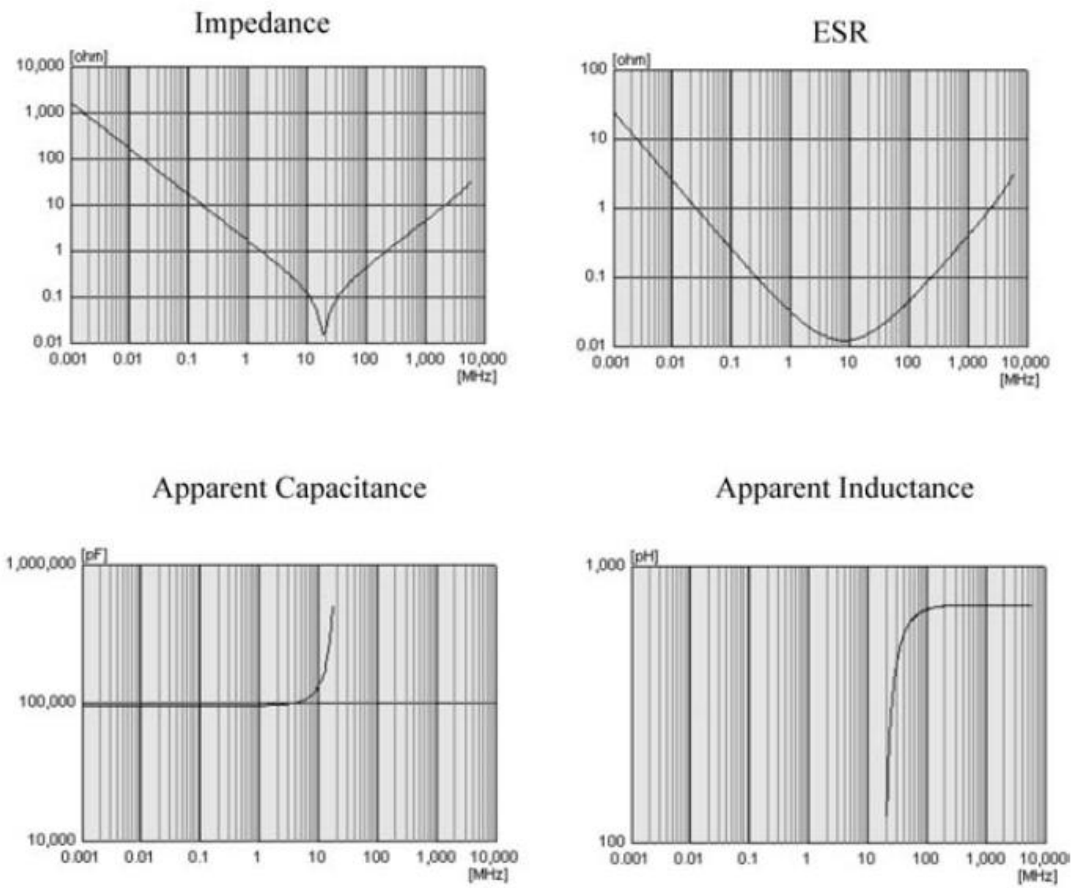




‘Versteckte’ Bauelemente

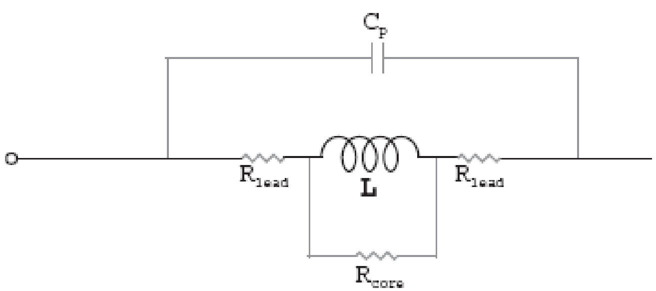
Realer Kondensator

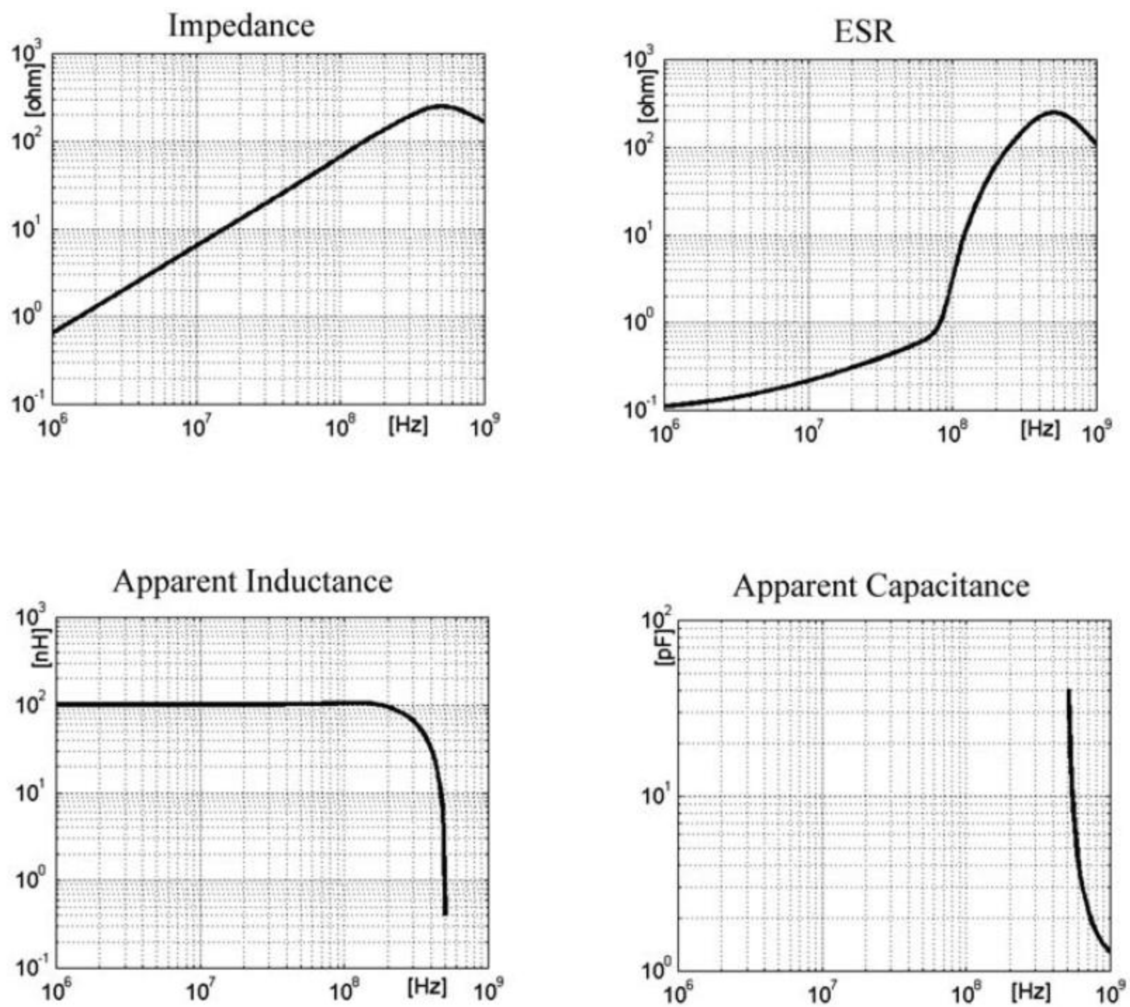




‘Versteckte’ Bauelemente

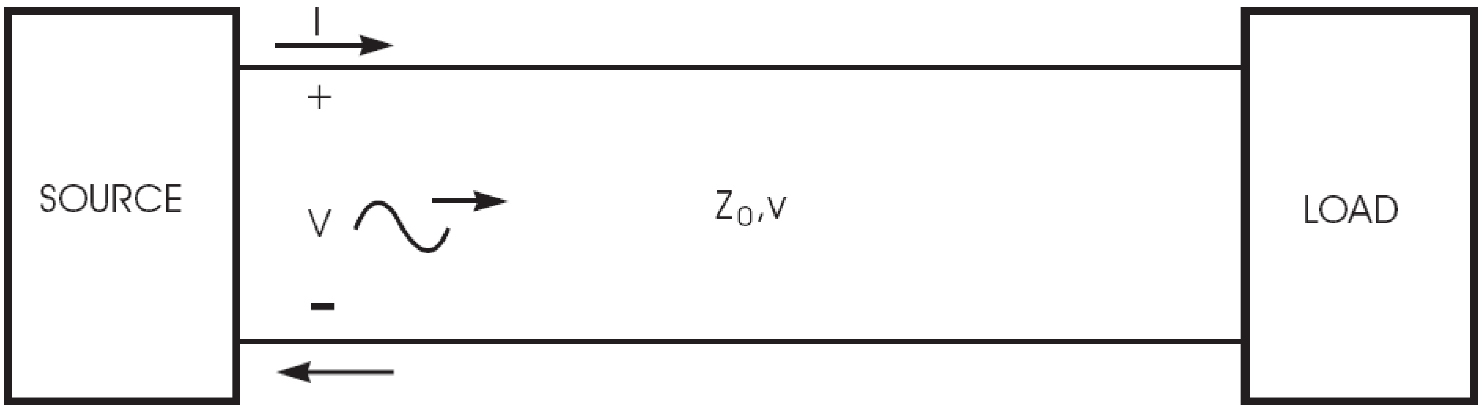
Reale Spule





Signalleitung

Signalleitung



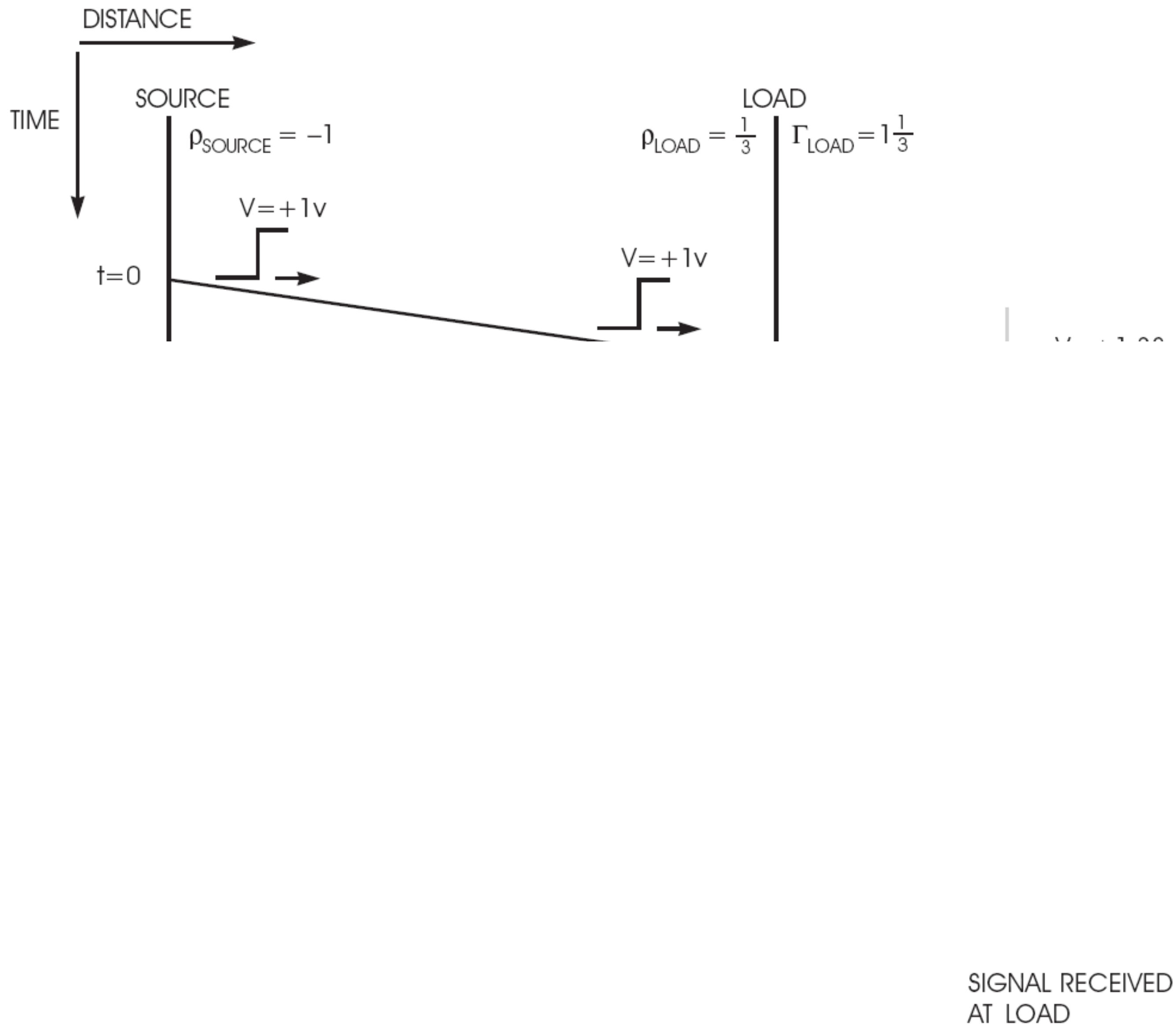
$$Z_o \cong \frac{60}{\sqrt{\varepsilon_r}} \ln\left[\frac{D}{d}\right]$$

$$v = \sqrt{\frac{1}{\varepsilon\mu}}$$

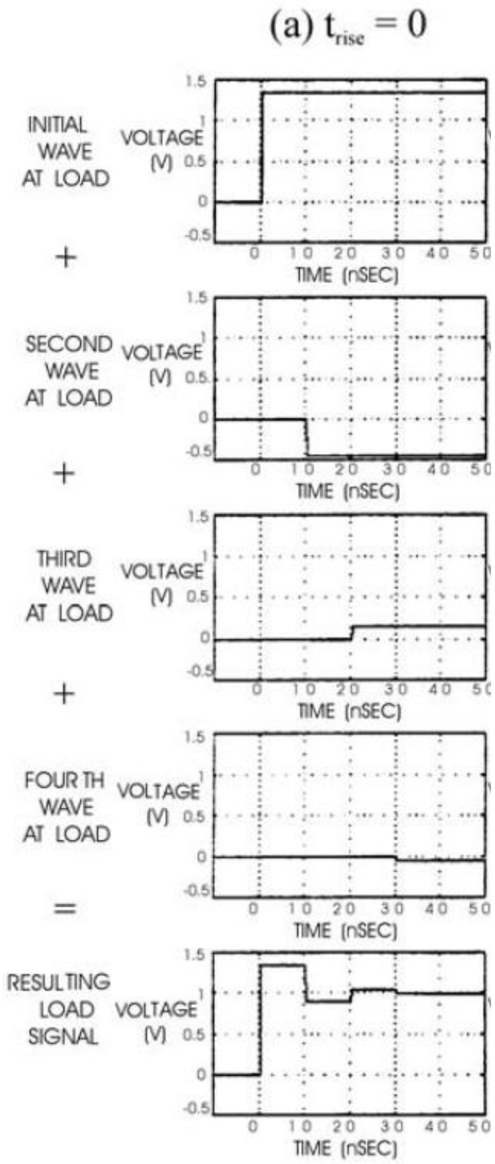
$$Z_o = \sqrt{\frac{L}{C}}$$

$$v = \sqrt{\frac{1}{LC}}$$

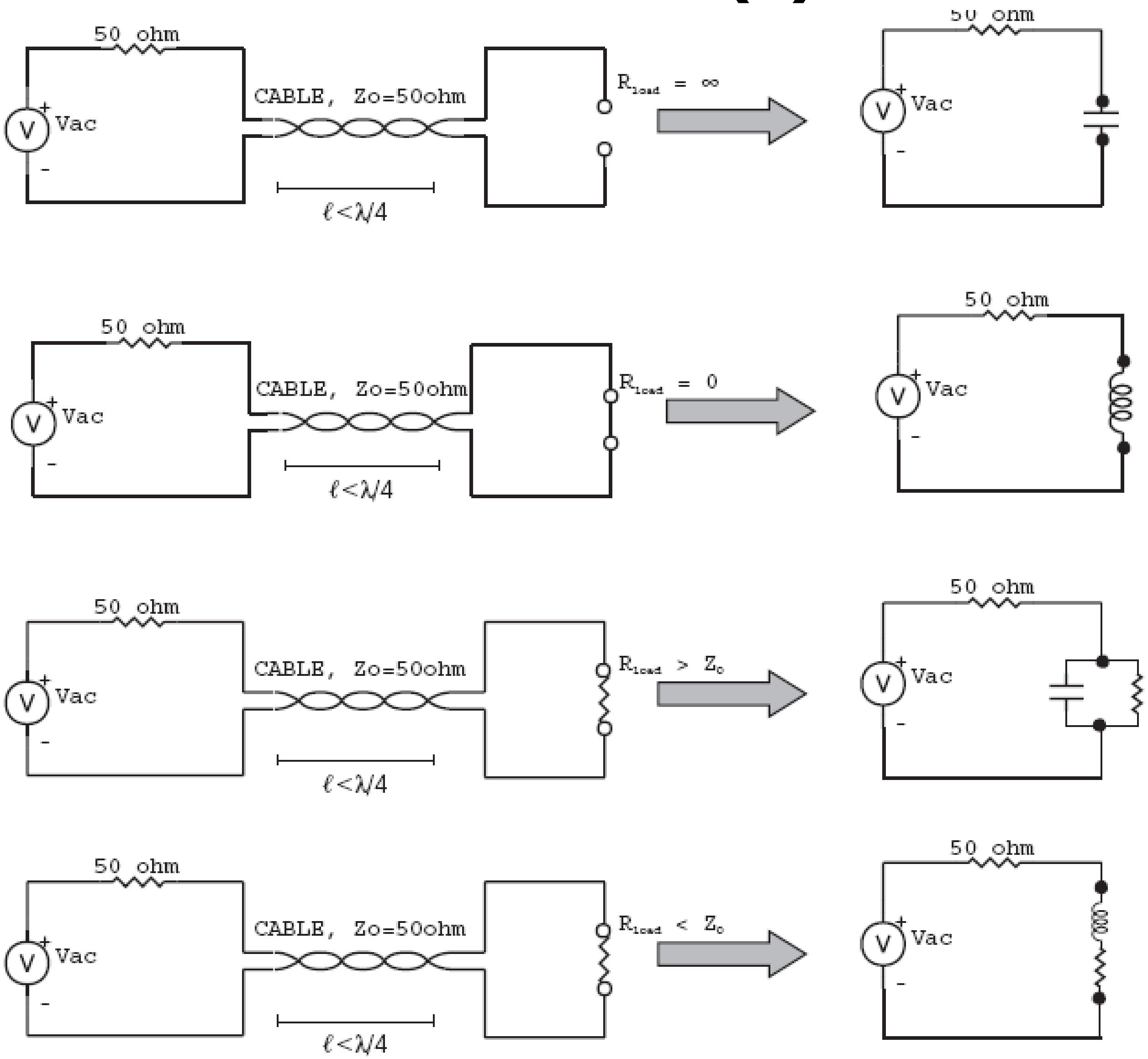
Reflektion


DISTANCE
TIME
SOURCE
LOAD
$\rho_{SOURCE} = -1$
$\rho_{LOAD} = \frac{1}{3}$
$\Gamma_{LOAD} = 1\frac{1}{3}$
V=+1v
t=0
V=+1v
SIGNAL RECEIVED
AT LOAD

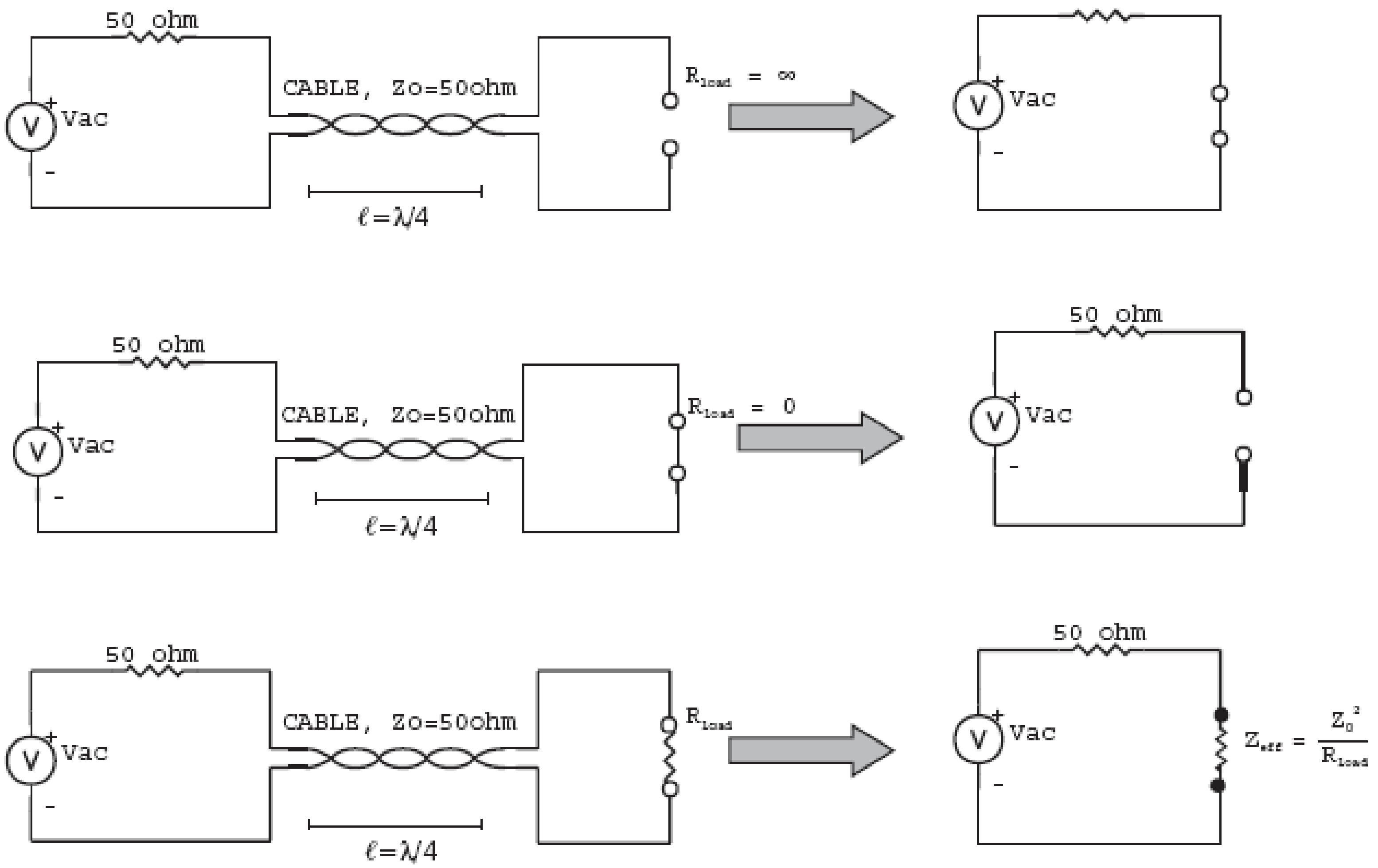
Reflektion (2)



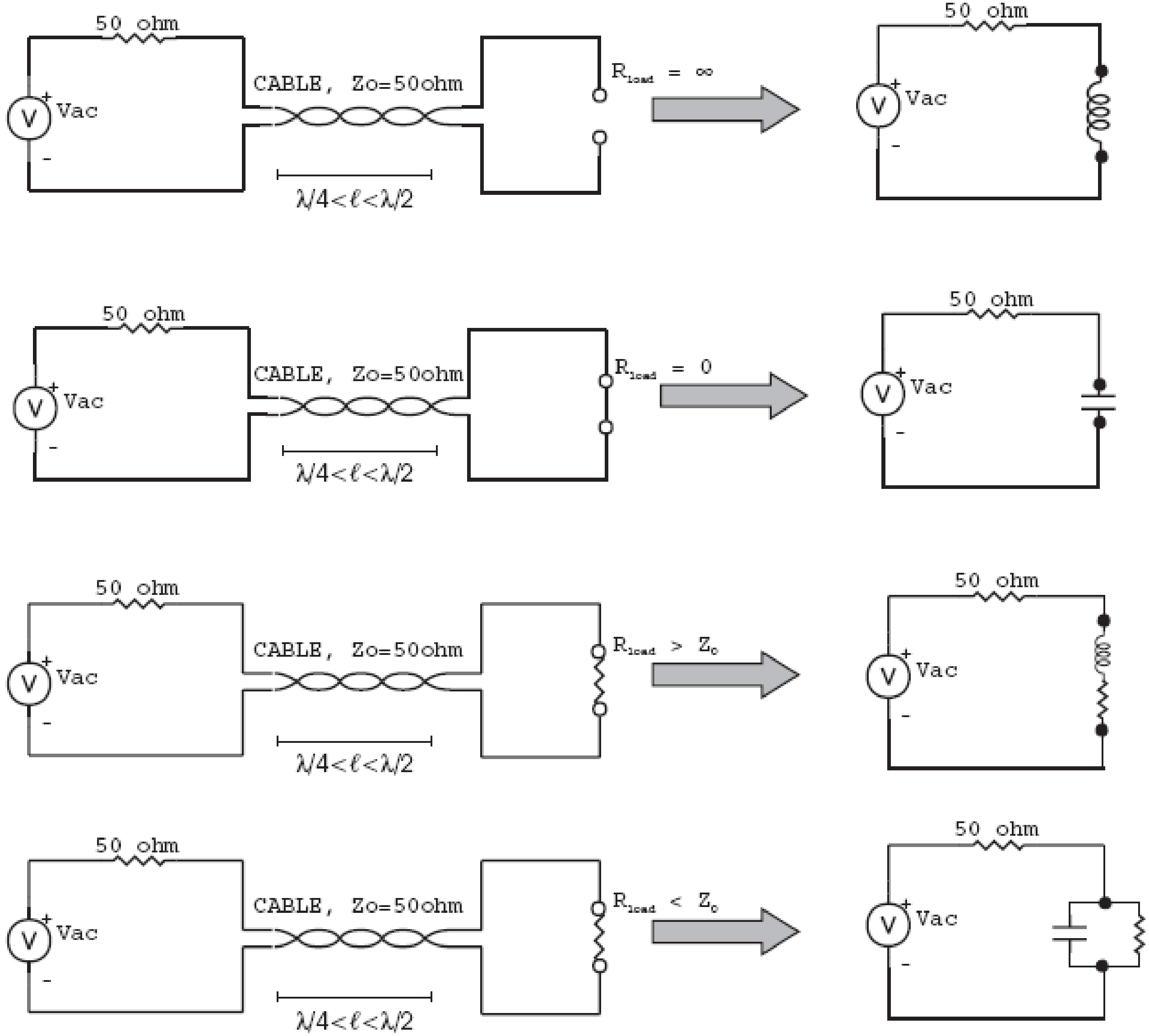
Reflektion (3)



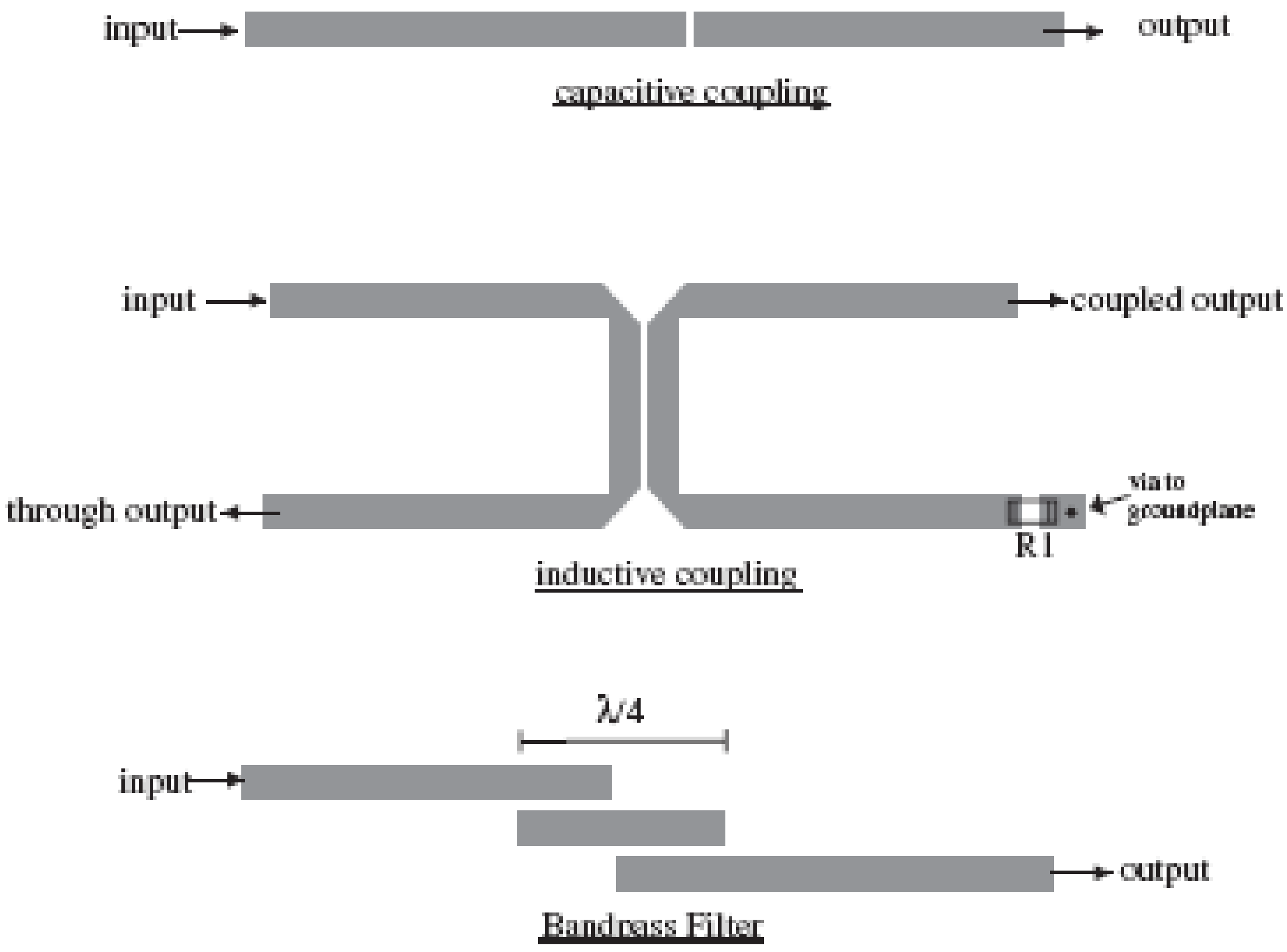
Reflektion (4)



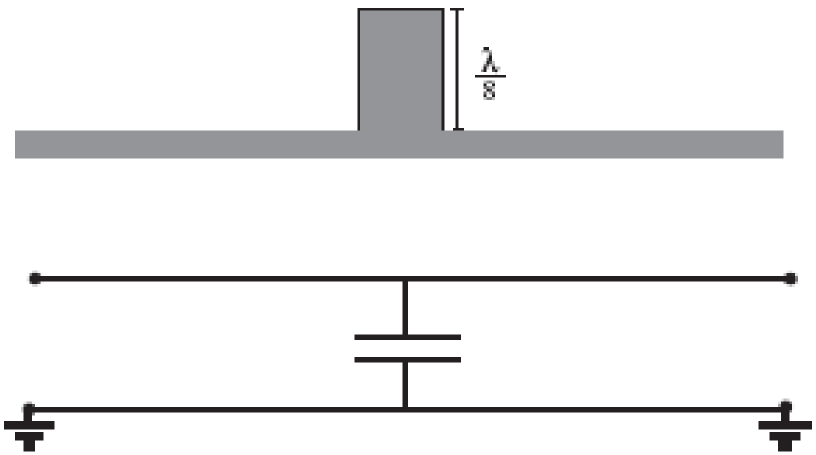
Reflektion (5)

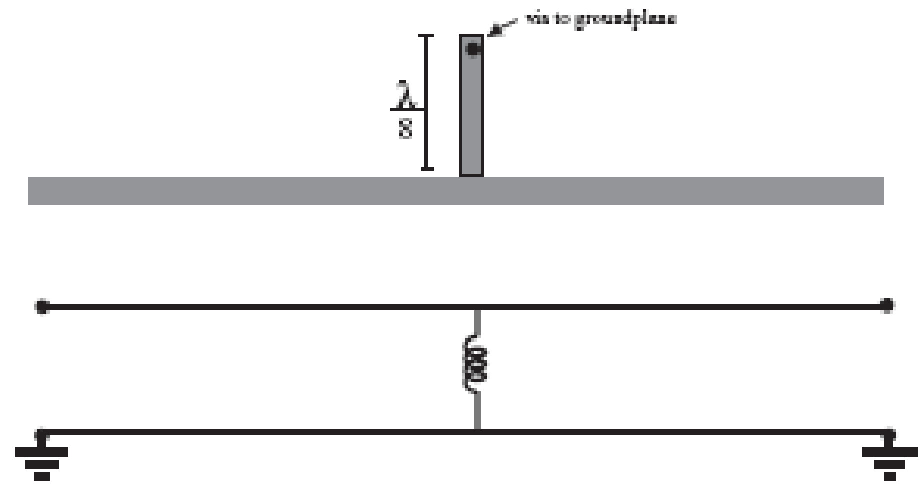


Microstrip Transmission Lines

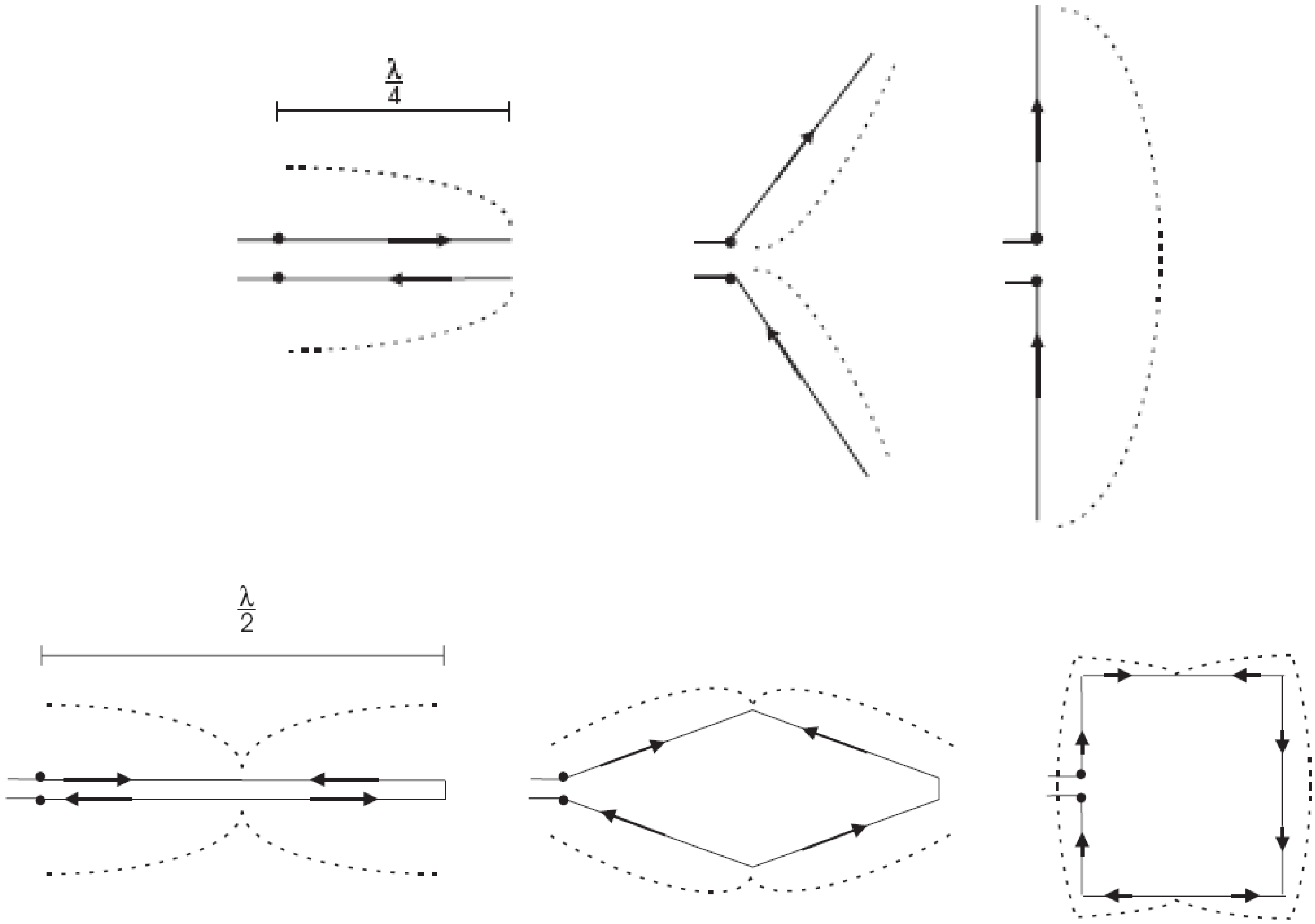


Microstrip Transmission Lines





Antennen



Praktische Tipps zu EMV

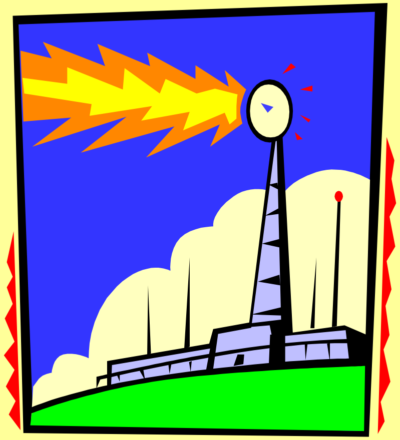
EMI – RFI

EMI – Electromagnetic Interference

RFI – Radio frequency Interference

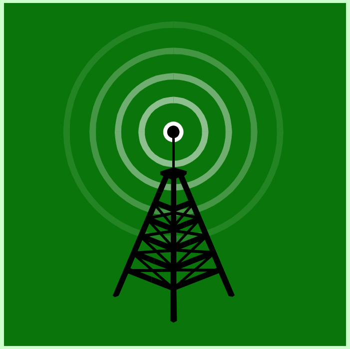
Why are EMI and RFI a concern?

- RF Spectrum pollution
- Compatibility within circuits
- System disturbance or malfunction
- Damage and liability
- Regulation conformance

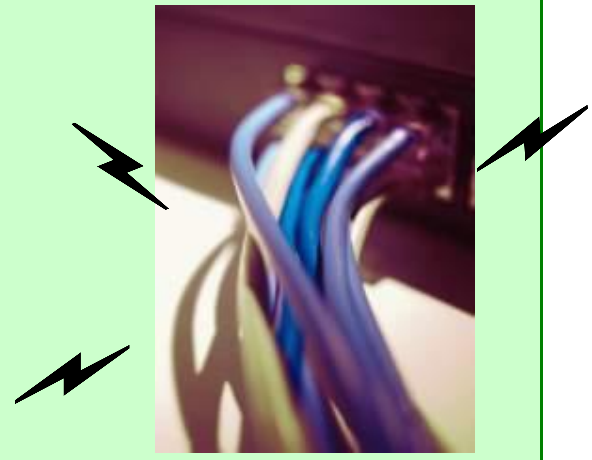


EMI or RFI?

Both are sources of radio frequency (RF) disturbance



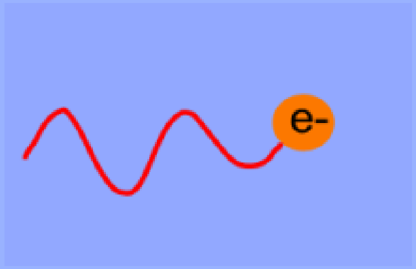
- EMI – electromagnetic interference
  - Often a broadband RF source
- RFI – radio frequency interference
  - Often a narrowband RF source



- Terms are often used interchangeably

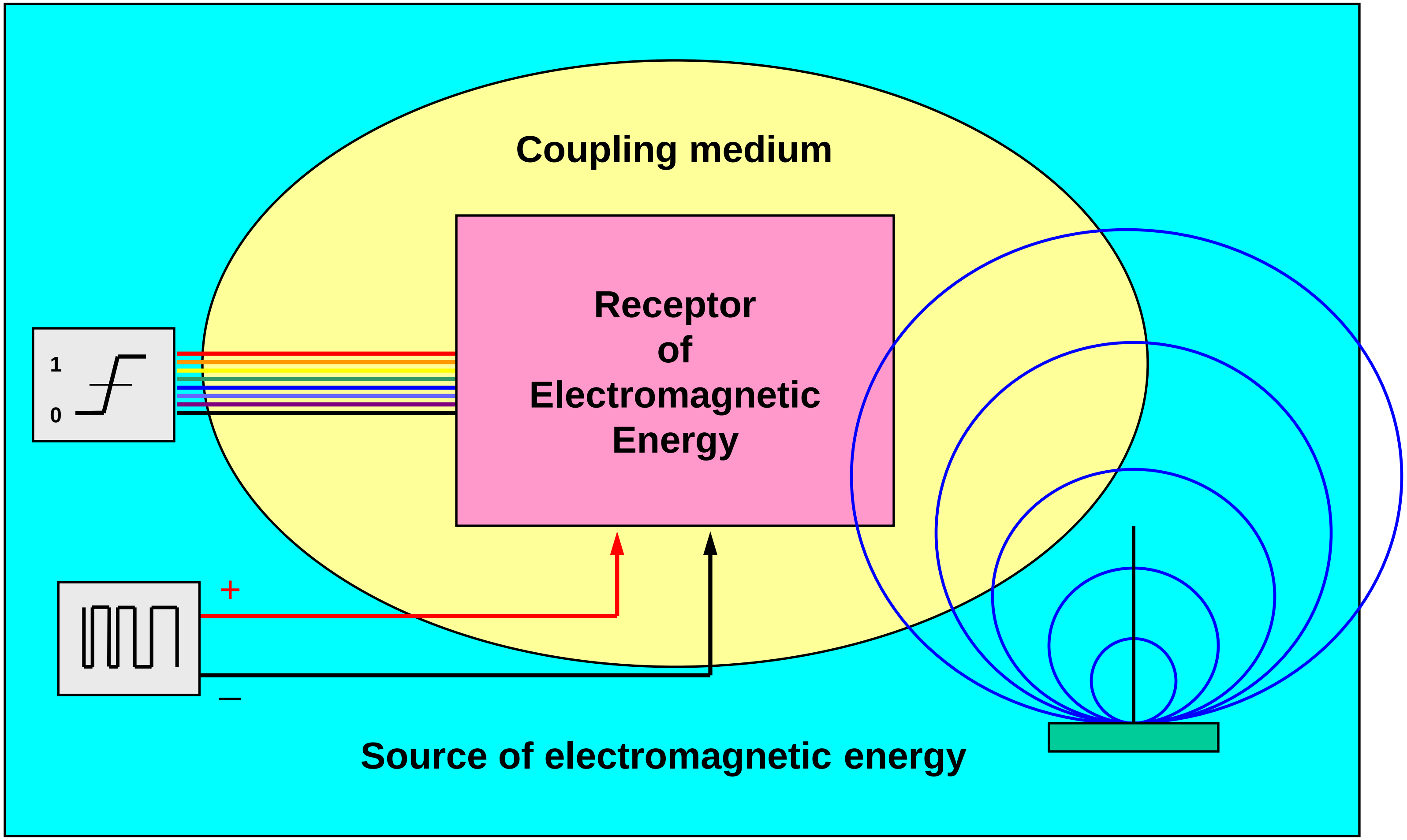
Fields – EMI can propagate by one or more types

- Electric Field (E) – Force created by uneven charge distribution
- Magnetic Induction Field (H) – Force created by moving charges
- Electromagnetic Field – Created whenever charges are accelerated

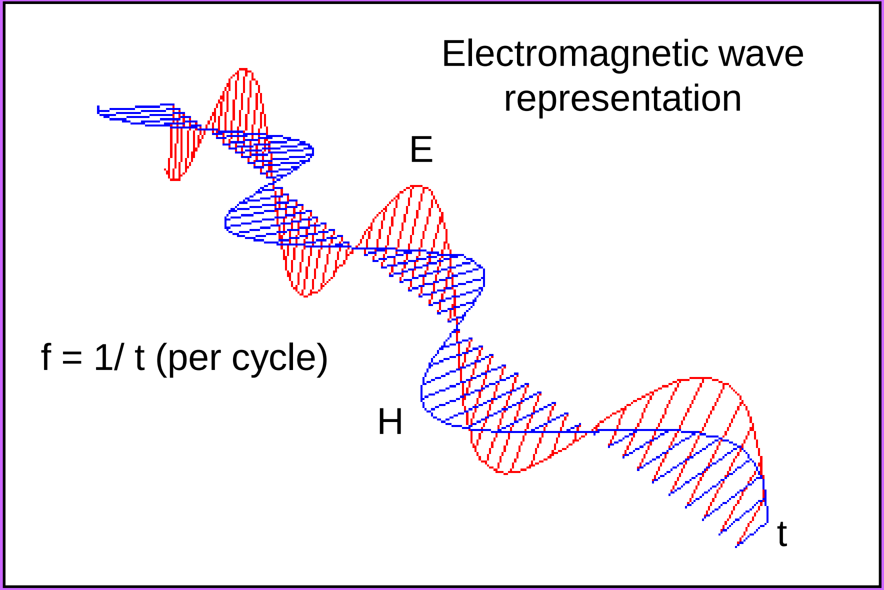


Source http://www.w8ji.com/radiation_and_fields.htm

The necessary elements for EMI



Source of Electromagnetic Energy



RF generating sources

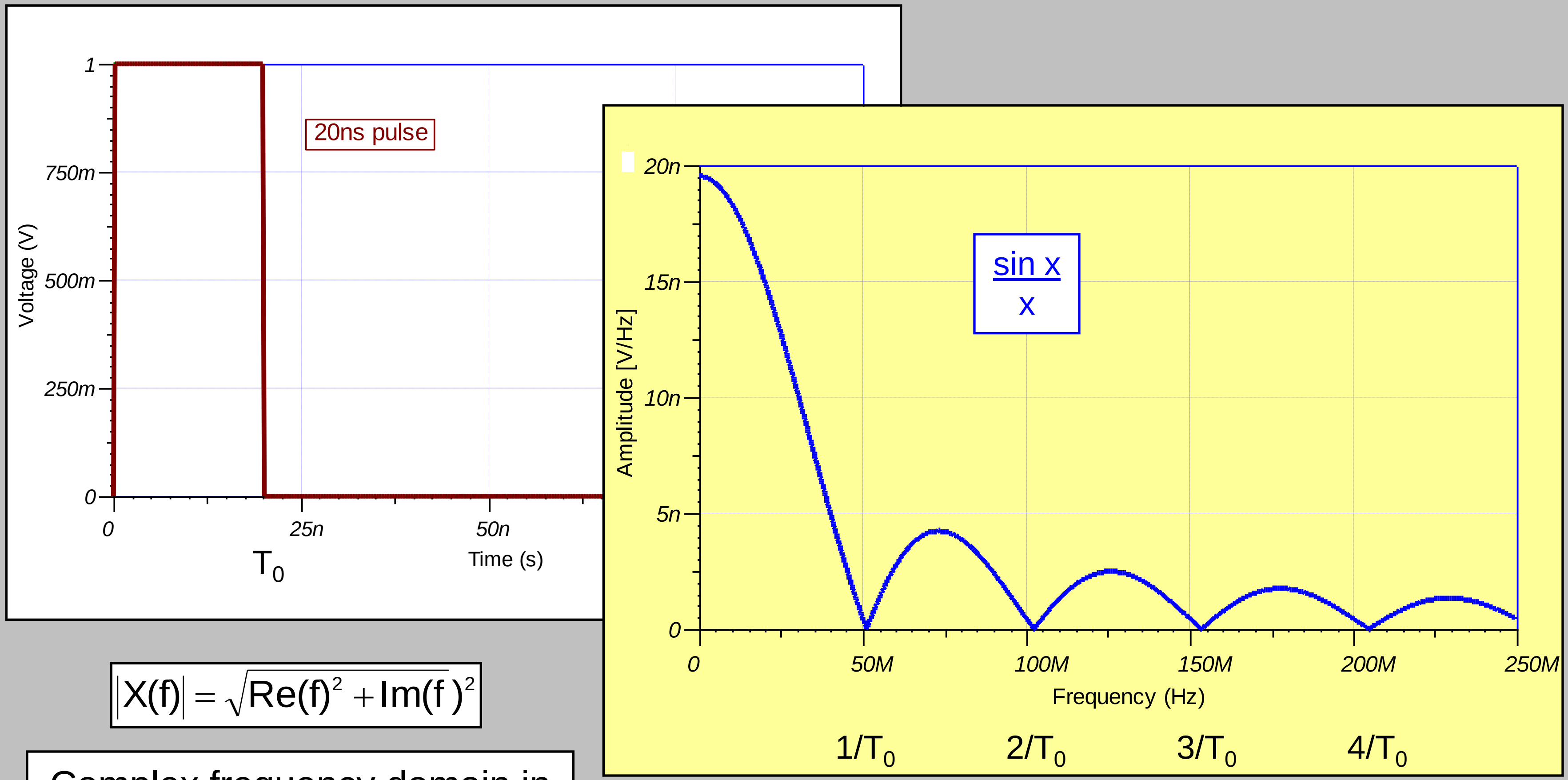
Intentional radiators

- cell phones
- transmitters & transceivers
- wireless routers, peripherals

Unintentional radiators

- System clocks & oscillators
- Processors & logic circuits
- Switching power supplies
- Switching amplifiers (class D)
- Electromechanical devices
- Electrical power line services

How radio frequency energy comes about in circuitry



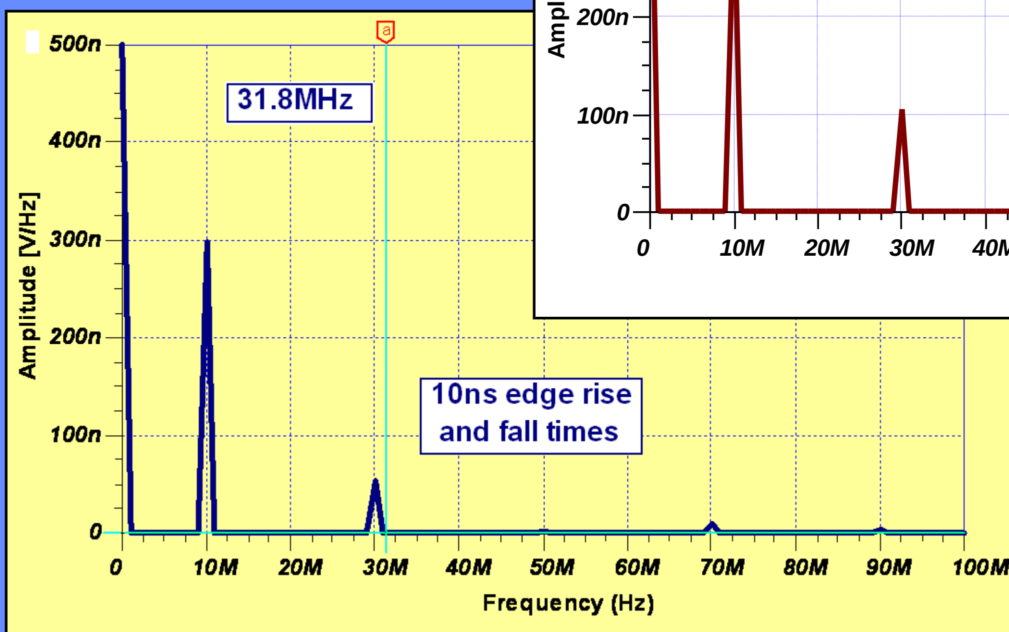
$$|X(f)| = \sqrt{Re(f)^2 + Im(f)^2}$$

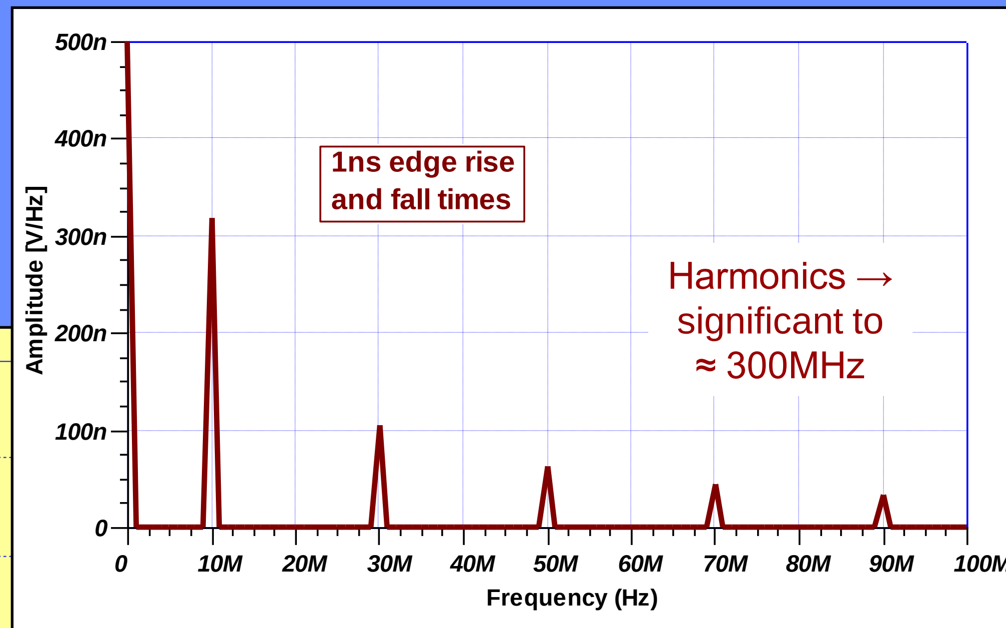
Complex frequency domain in Polar form

It’s all about edge rates

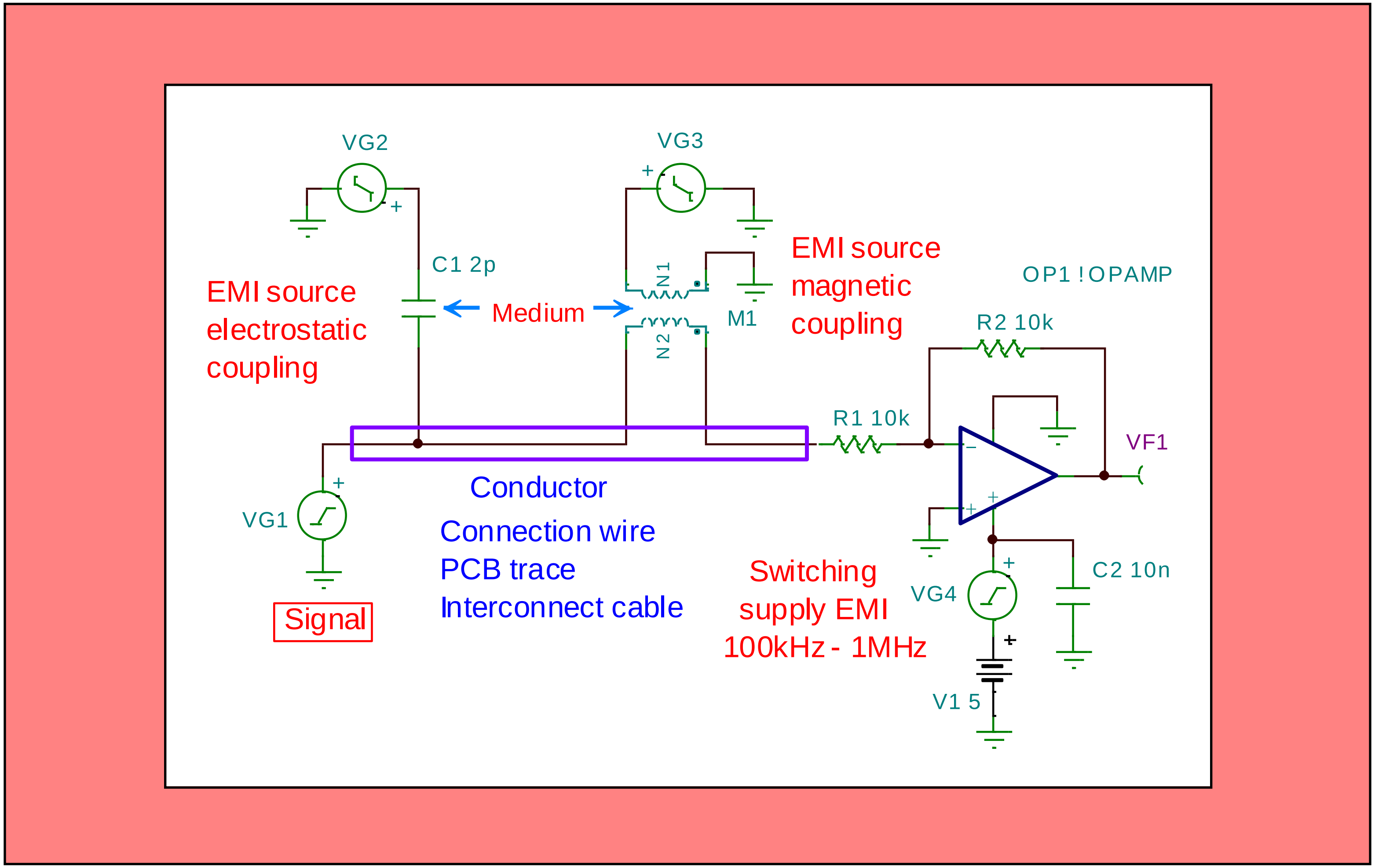
A rule of thumb for digital signals and transients

$$f_{\max} = (\pi * t_{rise})^{-1}$$

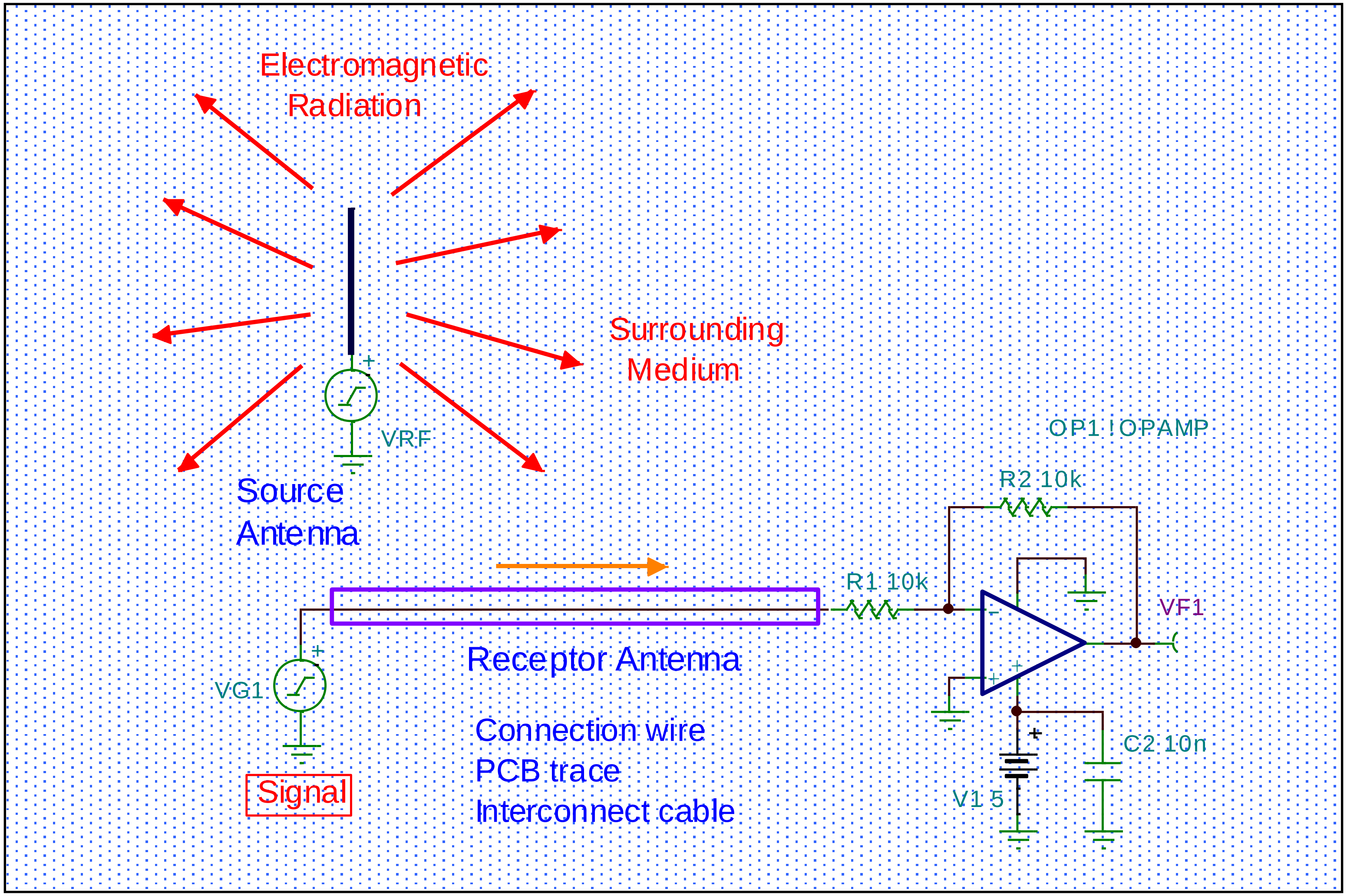




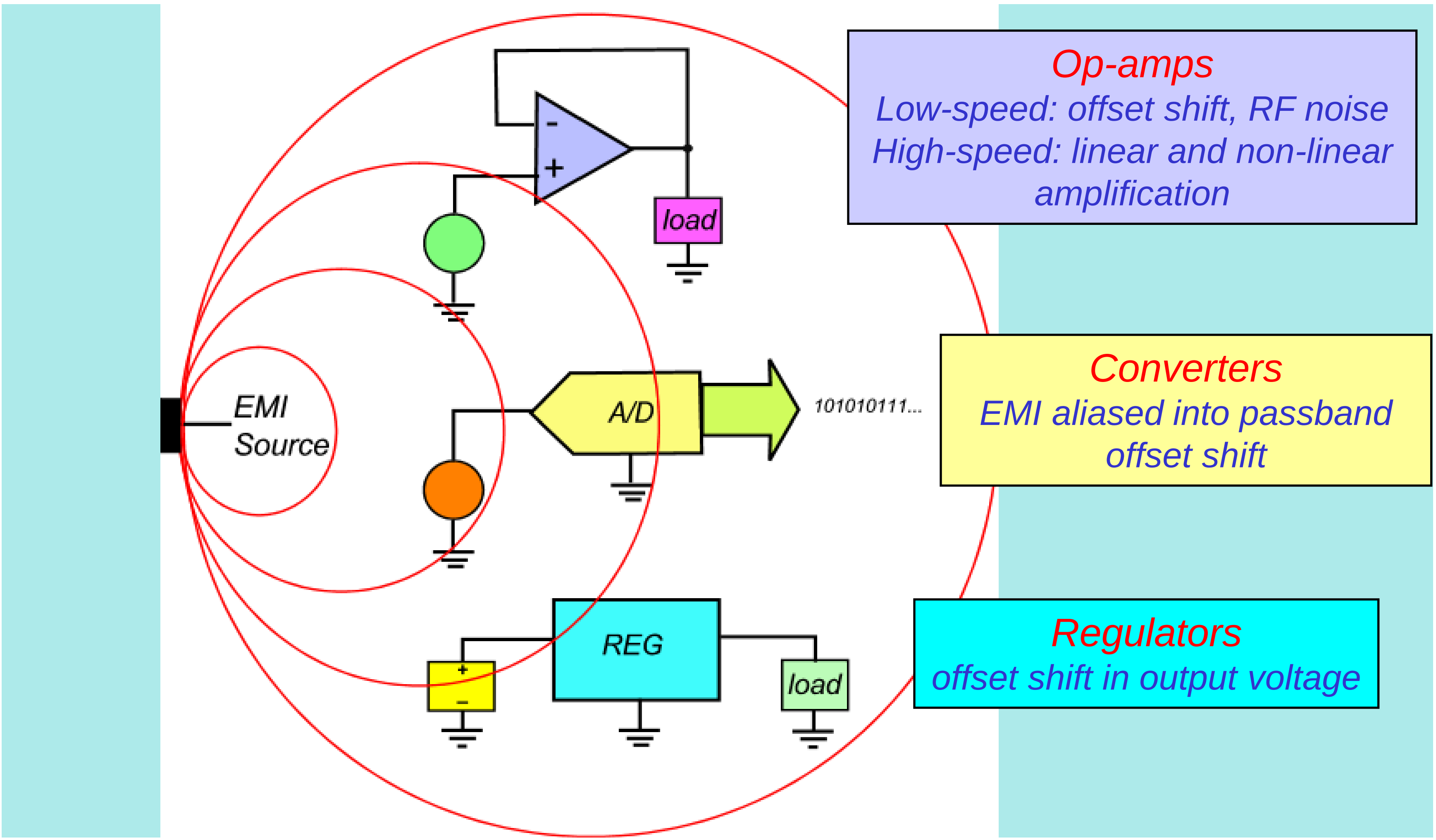
Coupling Medium: Conducted Emissions



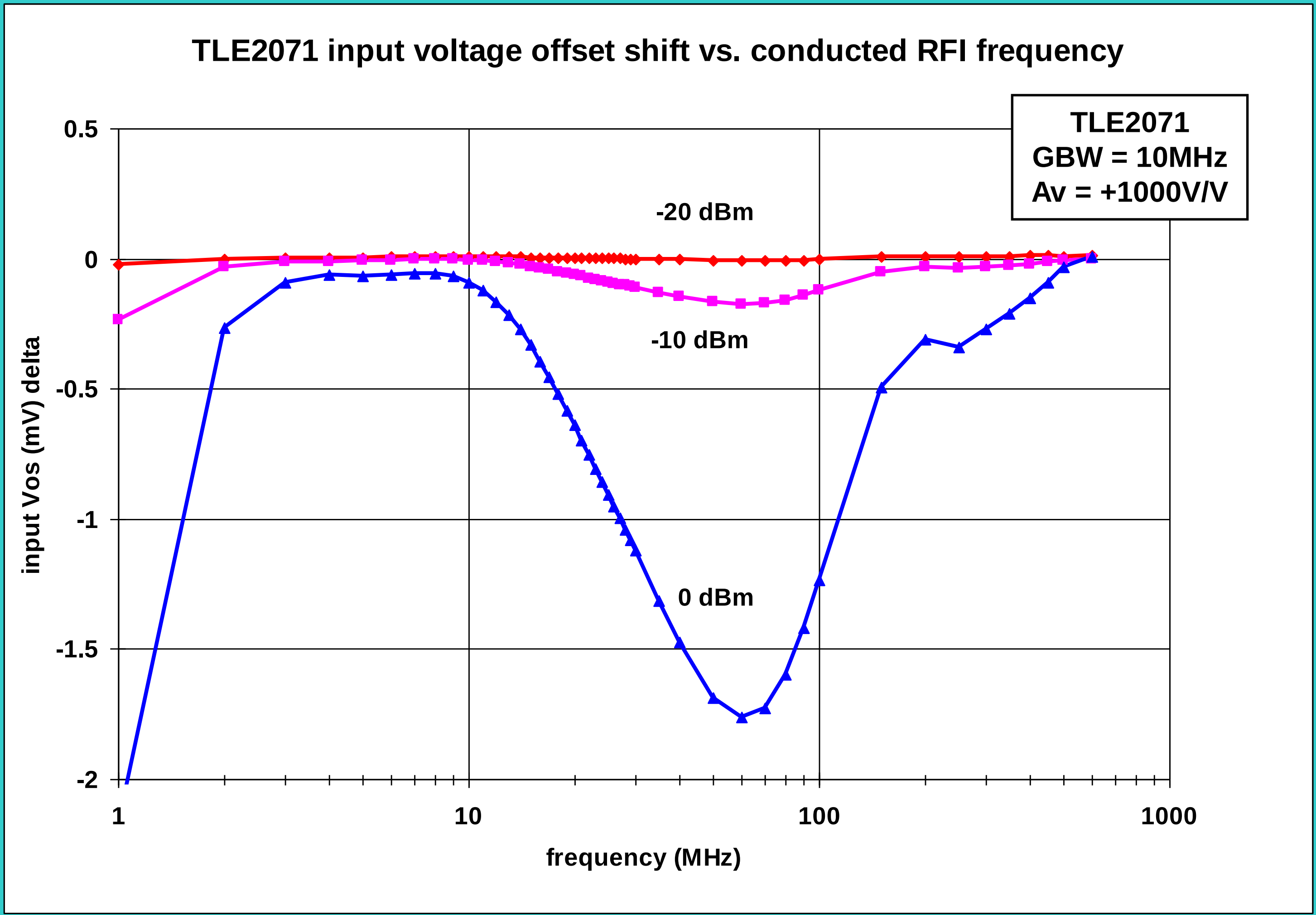
Coupling Medium: Radiated Emissions



Analog receptors: electromagnetic energy



Conducted EMI and its effect on an op-amp's voltage offset



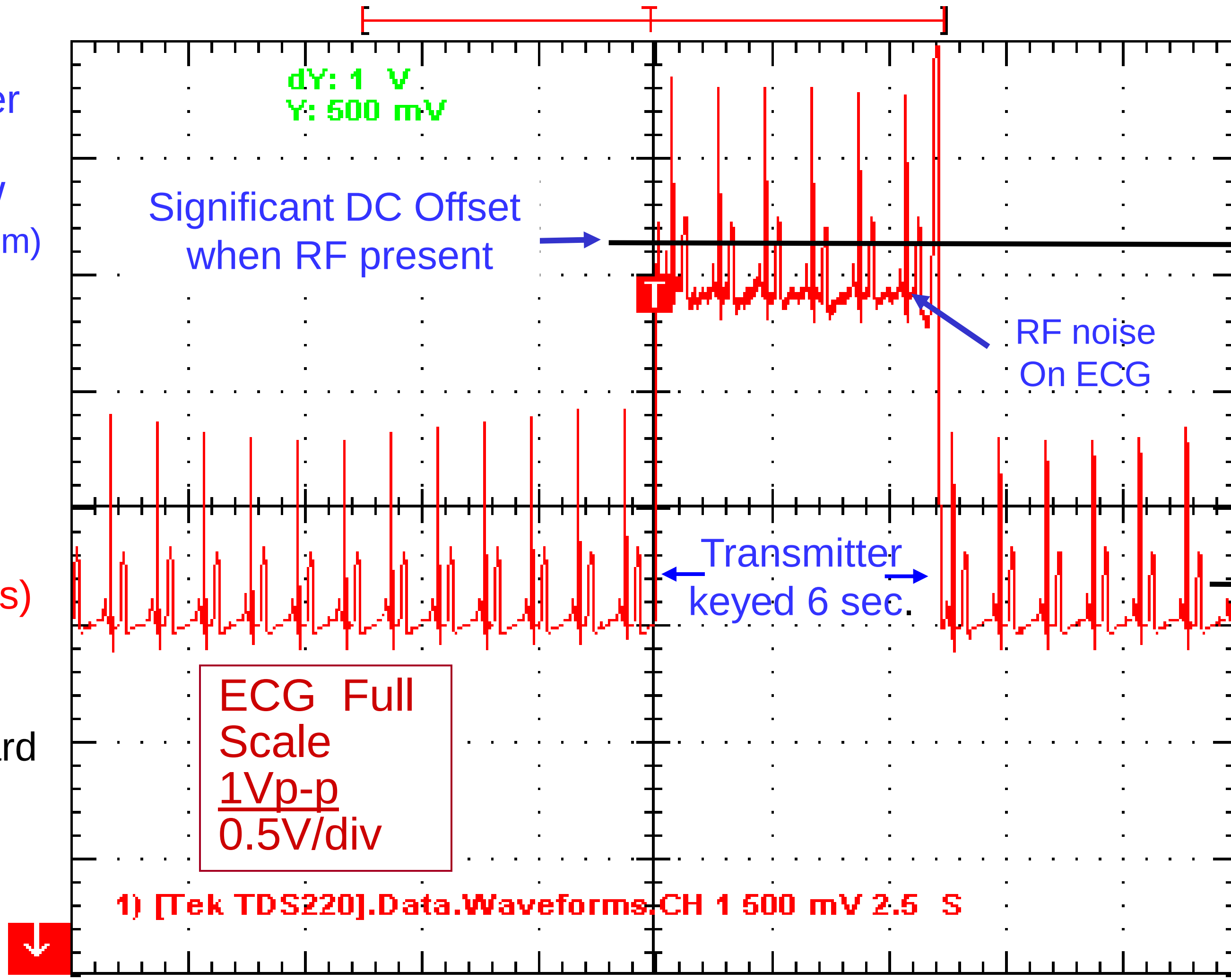
Radiated RFI and its effect on an ECG simulator

($V_{in} \approx 1mV_{p\text{-}p}$ G = 2500V/V)

Transmitter
470MHz
P_{out} 0.5W
d ≈1.5 ft (46cm)

Single
Supply
CMOS
INA326
OPA335(s)

Fly wire
Proto board



+4.0V offset RF present

Δ1.5V

Due to RFI

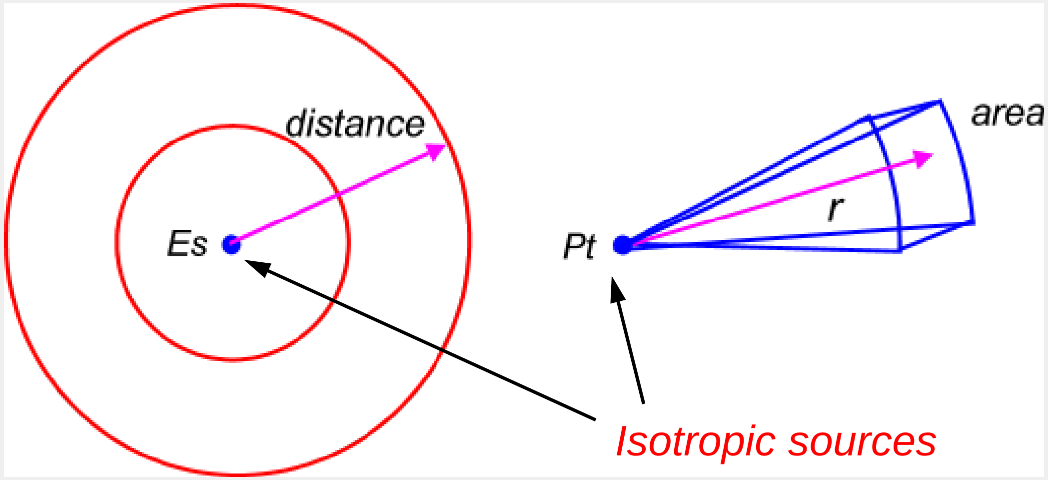
+2.5V offset normal

EMI slide
Information
by John Brown

Electric-Field Strength, Power Density

EMI - electric-field strength units

Communications - power density units



$E\ (V/m) = 61.4\ [P(mW)\ /\ cm^2\ ]^{1/2}$

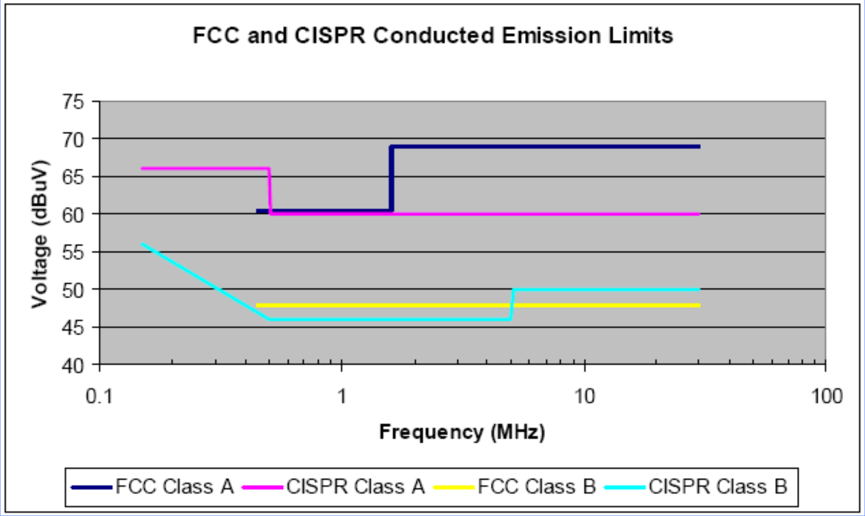
For free space Z =377Ω

$P_d = P_t\ /\ 4\pi \cdot r^2 \quad (W/m^2 \text{ or } mW/cm^2)$

100V/m = 2.65mW/cm²	**10mW/cm² = 194V/m**
10V/m = 26uW/cm²	**1mW/cm² = 61V/m**
1V/m = 0.26uW/cm²	**0.1mW/cm² =1.9V/m**

Emission Source Limits

Conducted Emissions - 10kHz to 30MHz

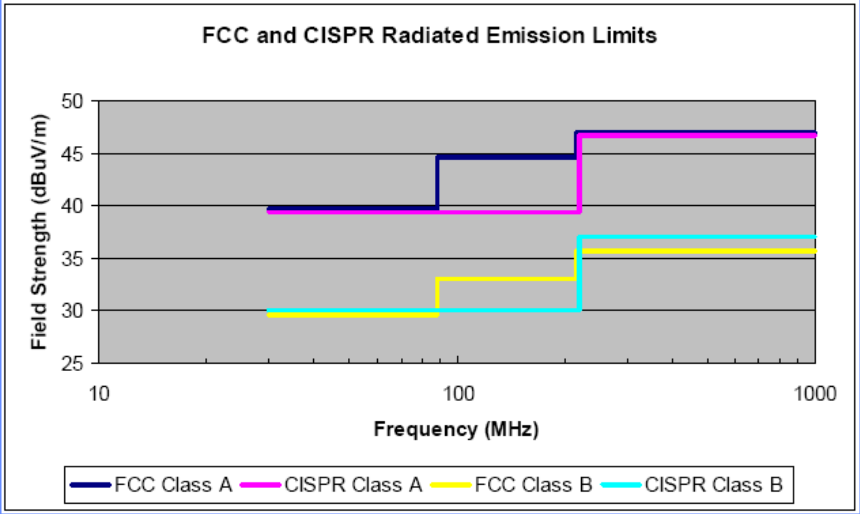


Freq (MHz)	Class A dBuV	Class B dBuV
0.45 - 1.6	60	48
1.6 - 30	69.5	48

Sources: SynQor app. note 00-08-02 Rev. 04
& www.cclab.com/engnotes/eng290.htm

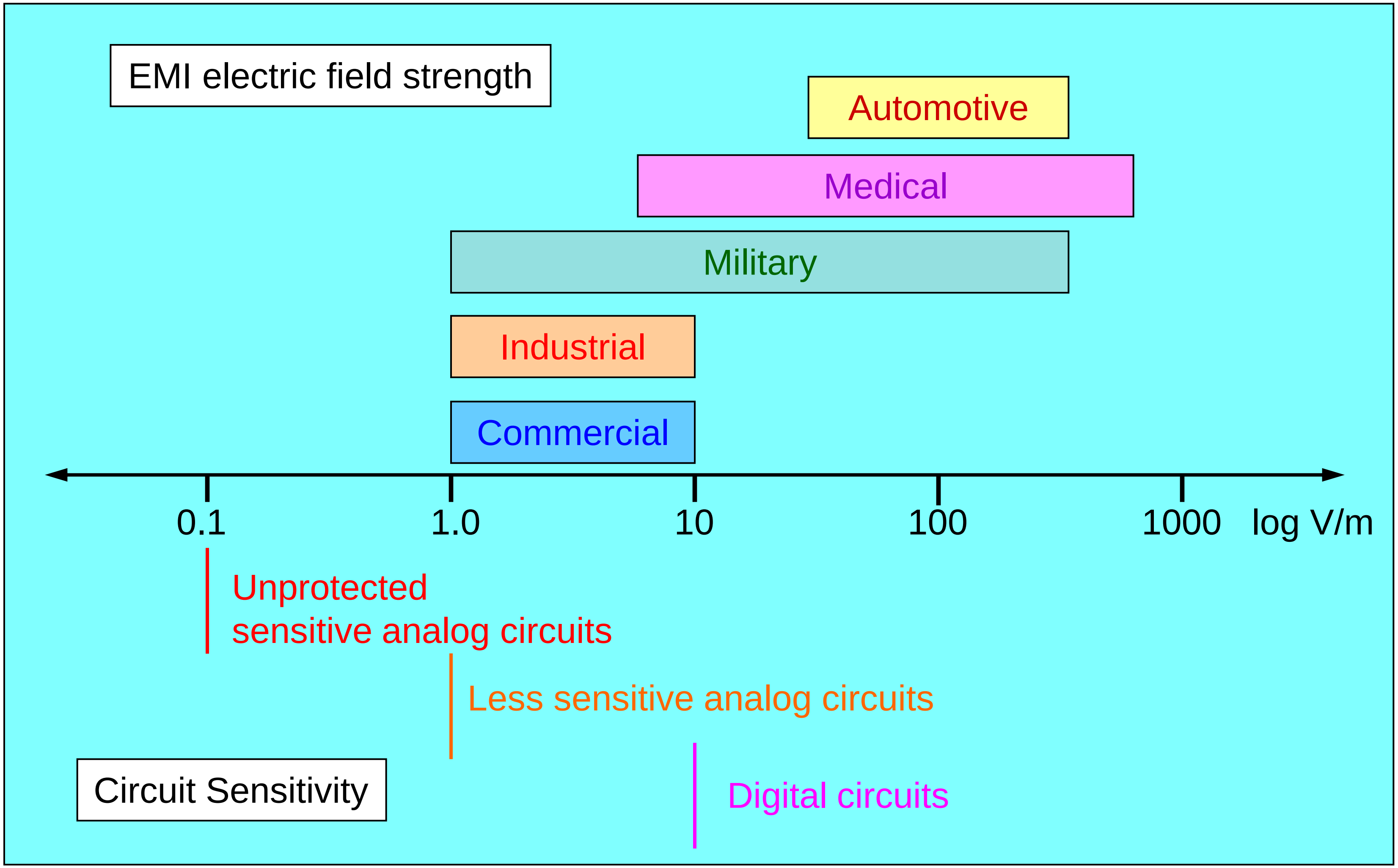
Radiated Emissions - 30MHz to 1GHz

measurement distance 10m



Freq (MHz)	Class A dBuV/m	Class B dBuV/m
30 - 80	39	29.5
88 - 216	43.5	33
216 - 960	46.4	35.6
960 - 1000	49.5	43.5

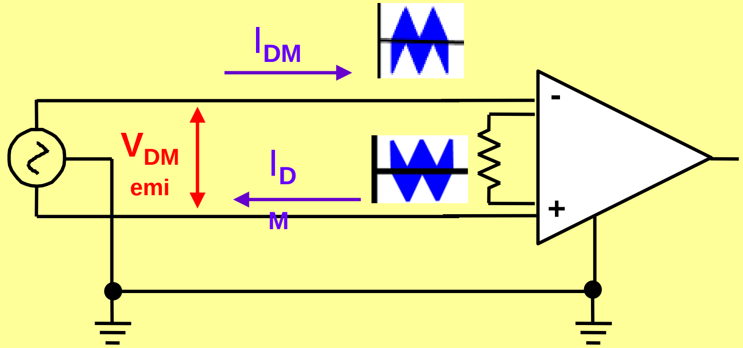
Typical RF field levels



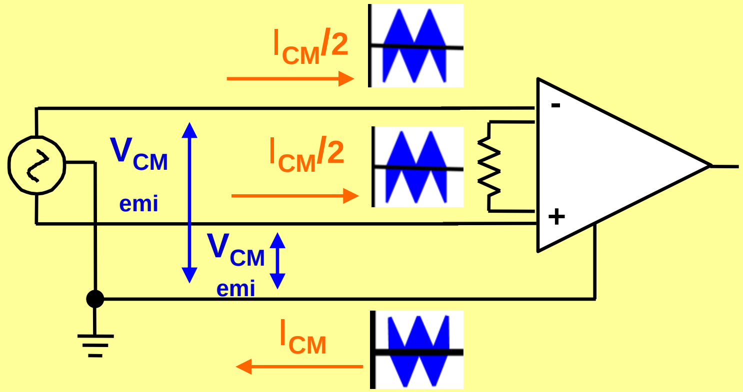
Differential and Common-mode EMI

Common-mode interference is most frequently encountered

Differential-mode EMI dominates f < 1MHz Often results through conduction



Differential-mode EMI produces a voltage difference between the inputs



Common-mode EMI dominates f > 1MHz Often originates as radiation

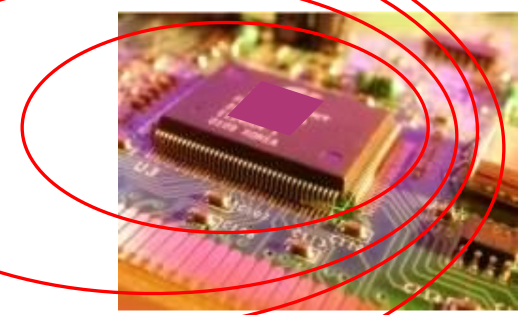
Common-mode EMI produces the same voltage on each input with respect to ground

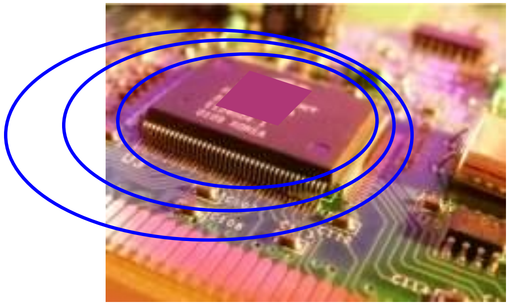
Taming the EMI environment

- Minimize EMI radiation at source

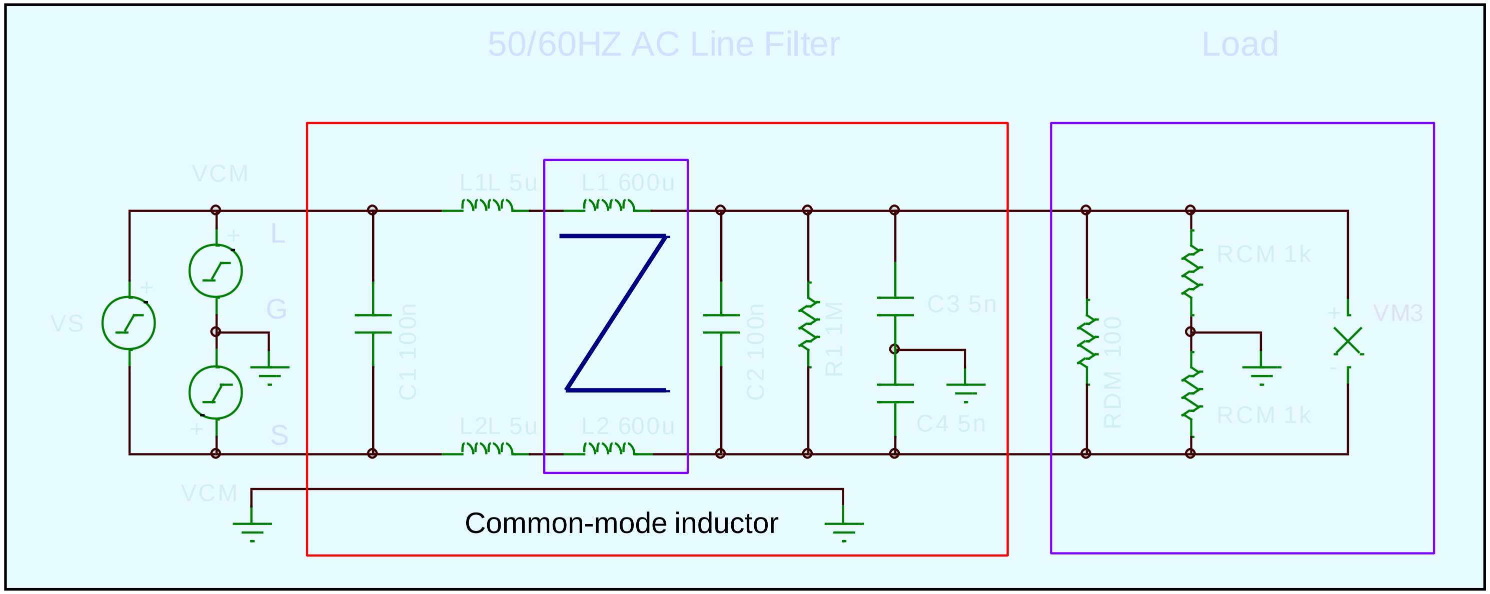
- Minimize coupling medium’s effectiveness

- Minimize receptor susceptibility to EMI





An AC line filter for conducted EMI

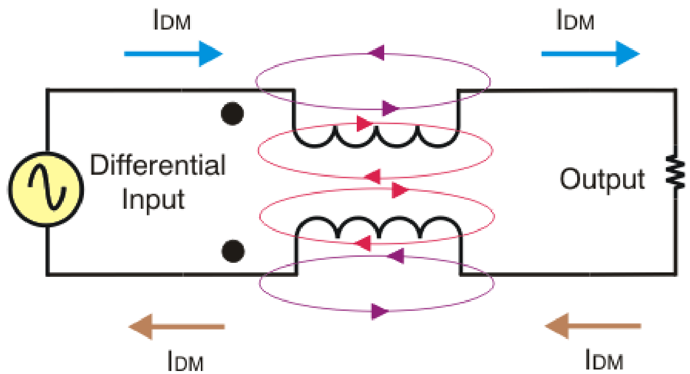


Mode	150kHz	500kHz	1MHz	5MHz	10MHz	20MHz	30MHz	
Common	6	20	28	42	45	45	48	dB
Differential	10	13	30	50	50	40	40	dB

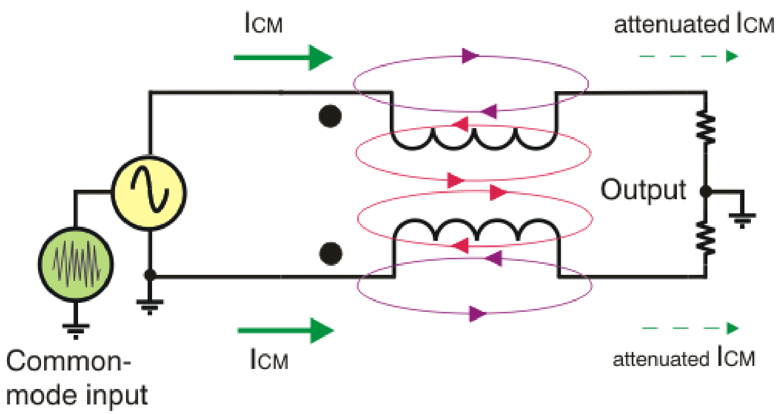
Attenuation characteristics for AC line filter (SAE GA1B-10)

The common-mode transformer

An effective common-mode filter

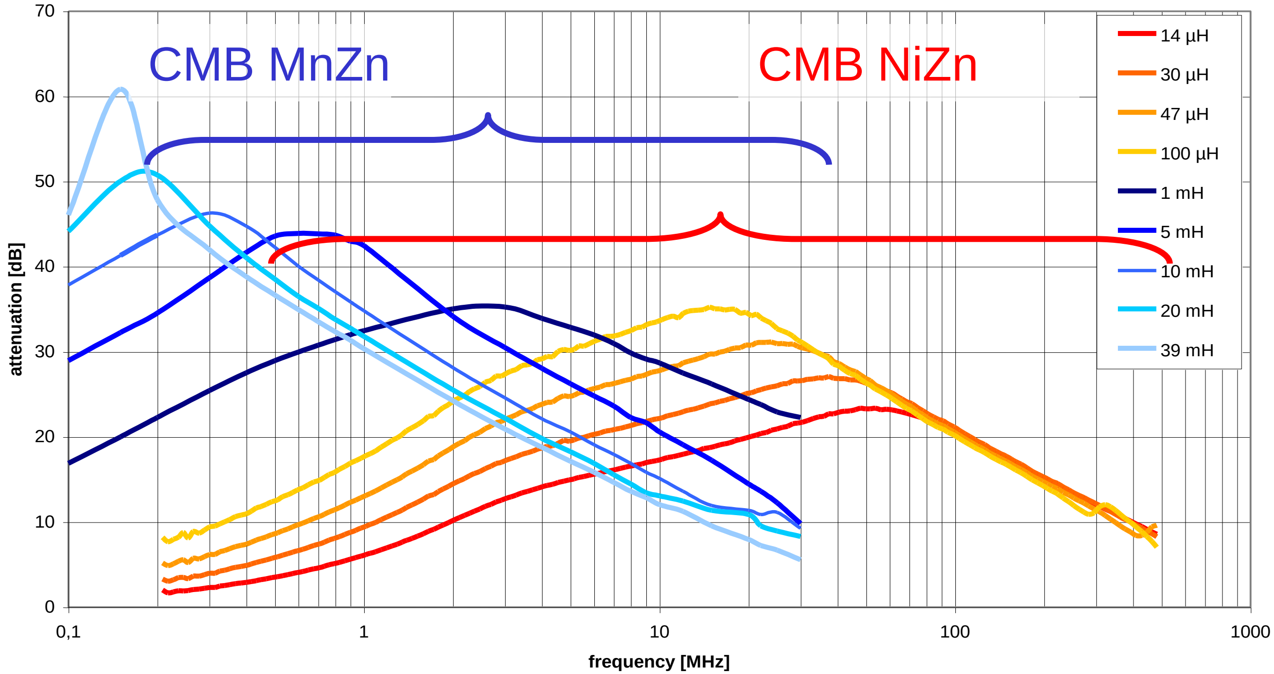


Opposing Fields - No voltage induced in either winding



Aiding Fields - Common-mode current sees full impedance of windings

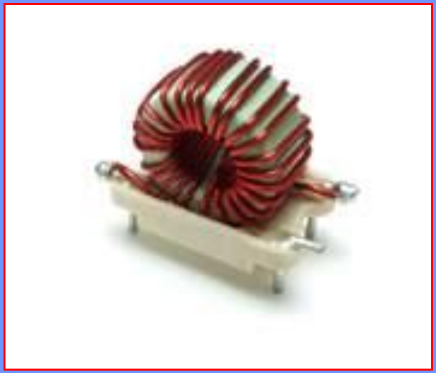
Stromkompensierte Drosseln (Wuerth)



An AC line filter for conducted EMI

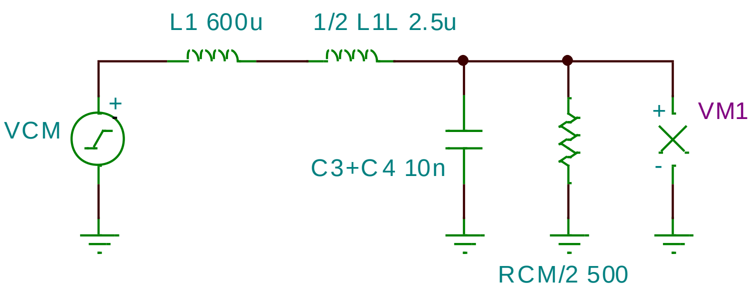
Common mode inductor

Torroid coil for DM inductor



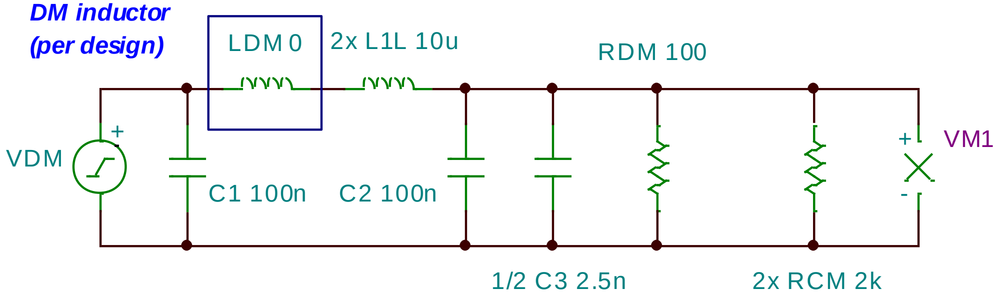
Examples from CWS - Coil Winding Services

Common mode model

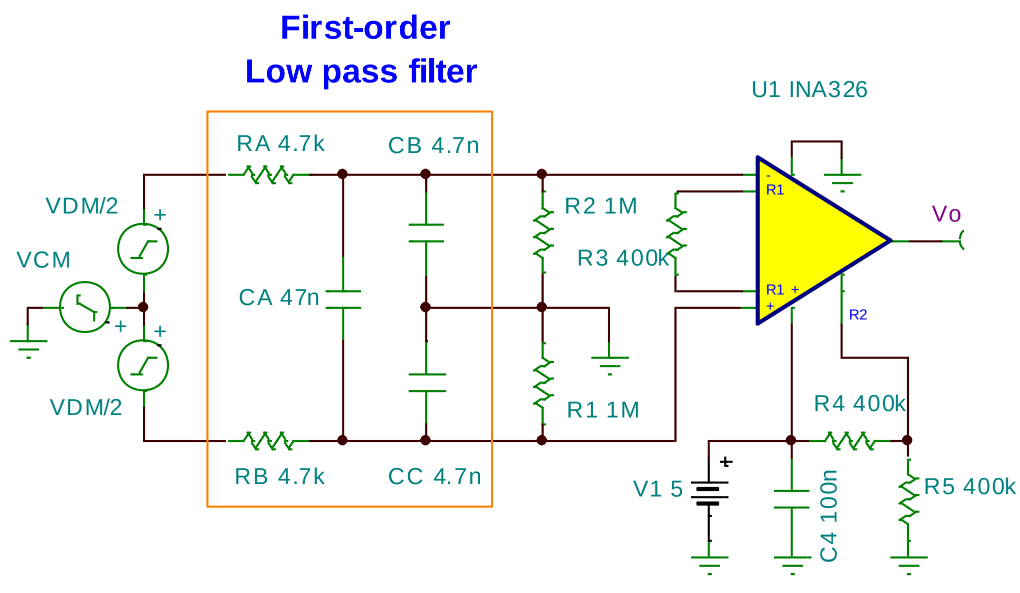


Differential mode model

DM inductor (per design)



Input RC filtering as applied to an instrumentation amplifier



Differential Mode

$f_{-3dB} = [2\pi(R_A + R_B)(C_A + C_B/2)]^{-1}$

let $R_B = R_A$ and $C_C = C_B$

$f_{-3dB} = 343\text{Hz}$

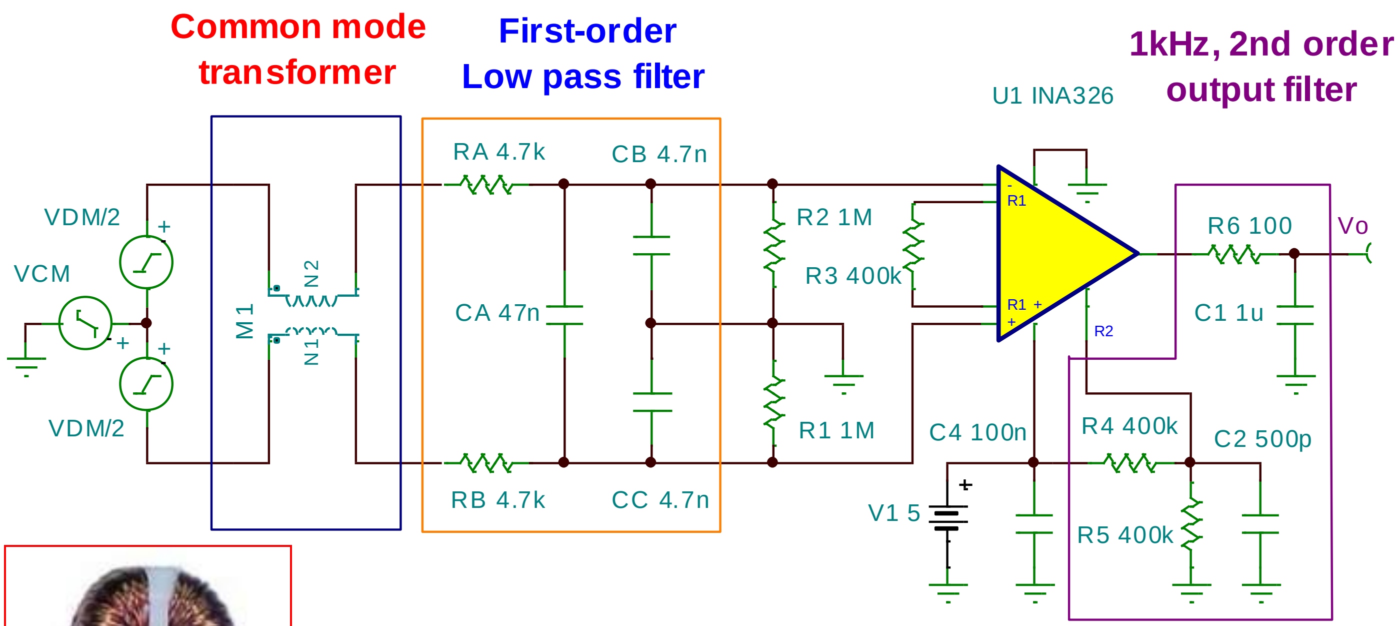
Common Mode

$f_{-3dB} = [2\pi \cdot R_A \cdot C_B)]^{-1}$

let $R_B = R_A$ and $C_C = C_B$

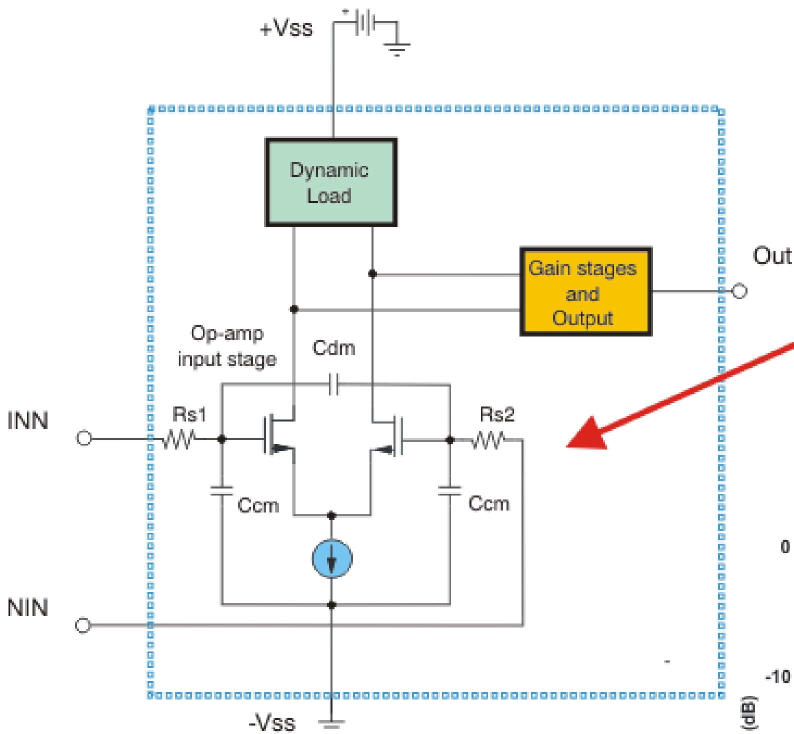
$f_{-3dB} = 7.2\text{kHz}$

Adding a common-mode transformer at low frequencies

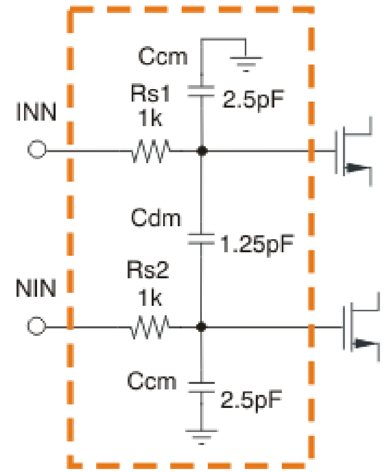


Newer Op-amps have EMI filtering

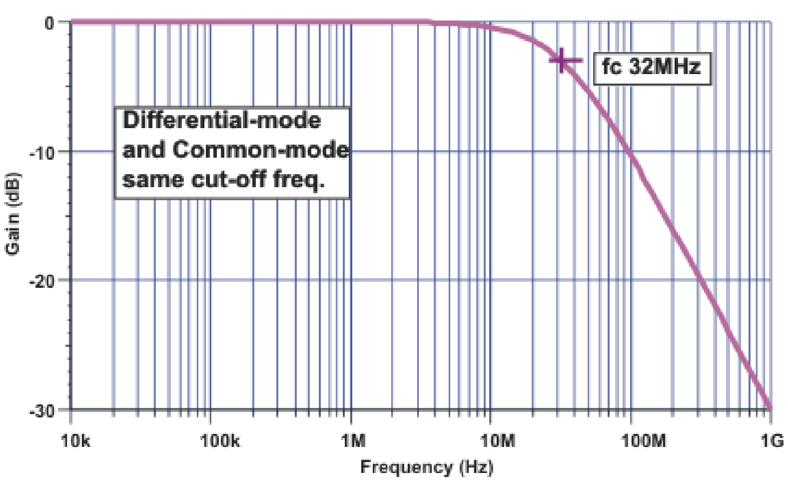
Simplified CMOS Op-amp



Built-in input EMI Filter

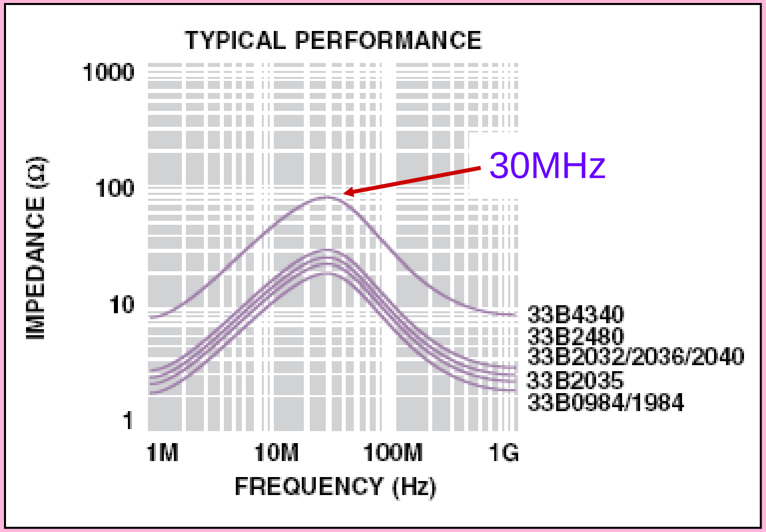


Filter response



Ferrites for EMI suppression

Ferrite surrounding the cable actually forms a common-mode transformer

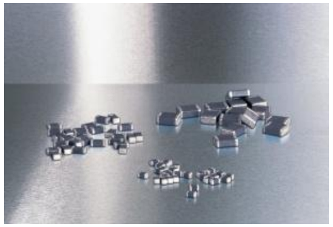


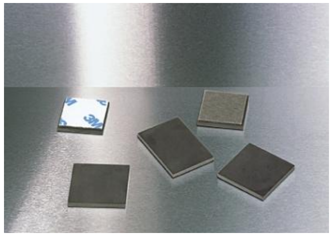
Impedance of wire passing through Wuerth ribbon cable ferrite

Was ist ein EMV-Ferrit?

…technisch gesehen:

→ gesintertes Ferritmaterial um einen Draht





<u>Anwendung als:</u>

- HF-Absorber
- frequenzabhängiger Filter

<u>Bauformen:</u>

Klappferrit

Ferrithülsen / -ringe

Blockkerne

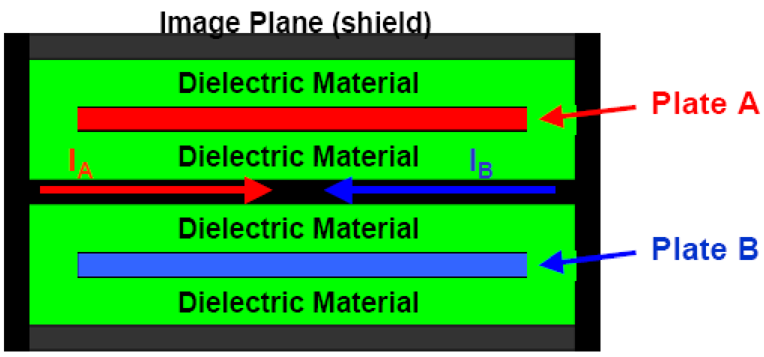
Ferritplatten

SMD-Ferrite

Ferritperlen

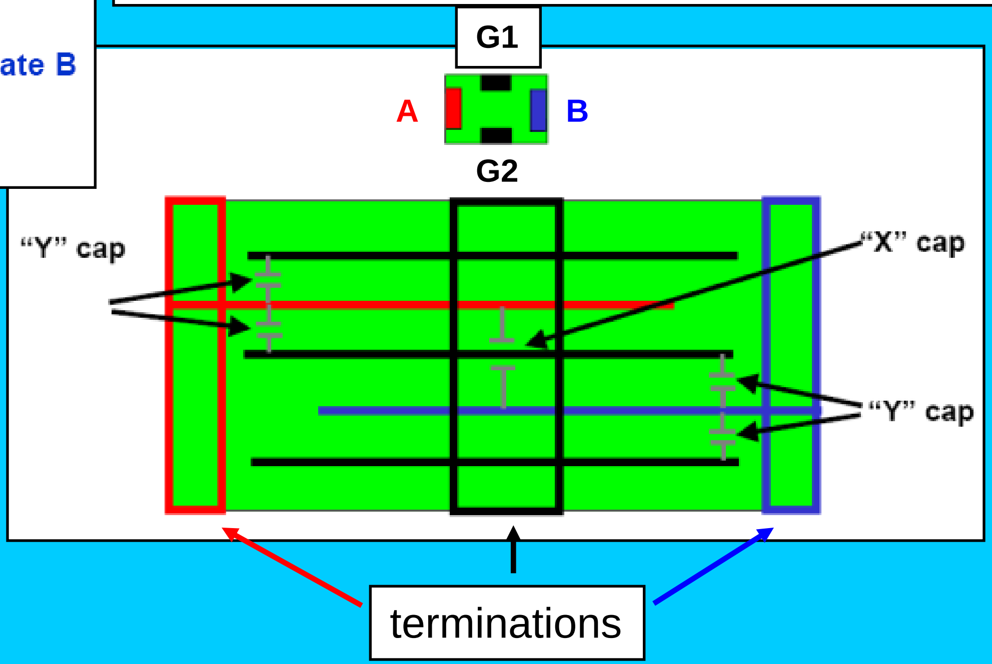
X2Y Capacitor Architecture

X2Y Architecture



The X2Y capacitor:
1 “X” capacitor, 2 “Y” capacitors

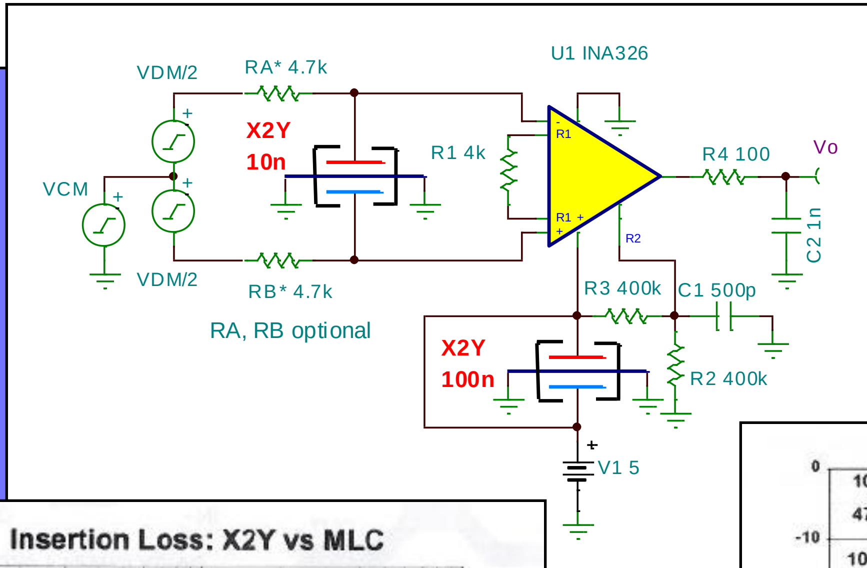
Simultaneous common-mode and differential-mode filtering



Cx = ½ Cy

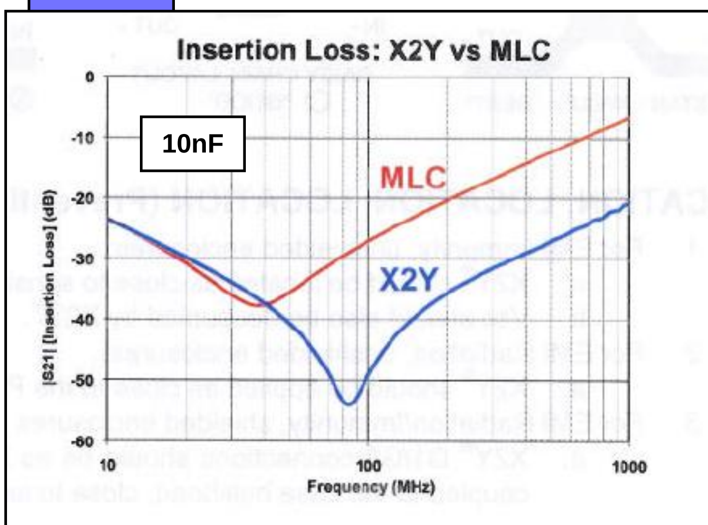
From Yageo.com website

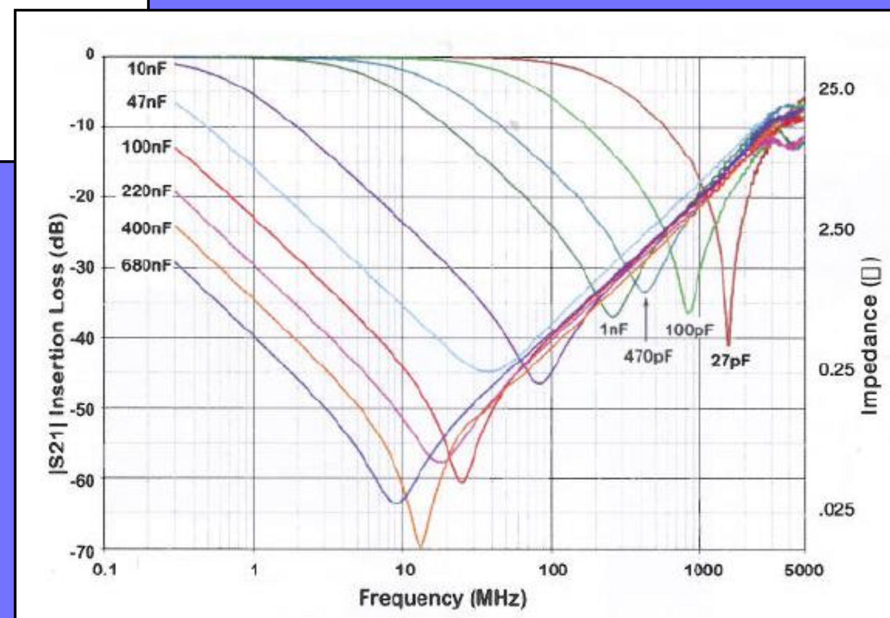
The X2Y® Capacitor



X2Y® Filter & Decoupling Capacitors

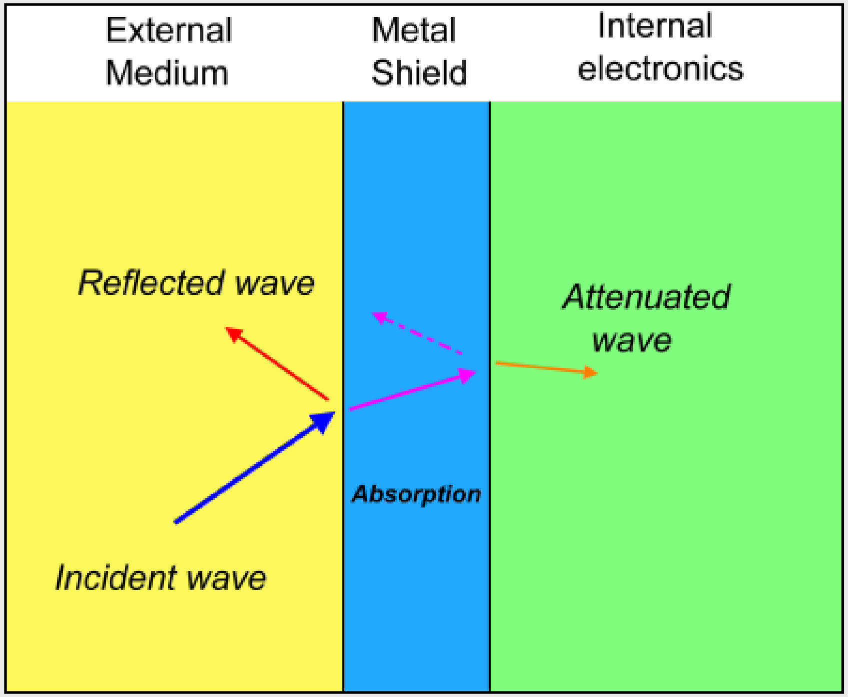
Input filtering s21
Signal-to-Ground





Shielding & Screening

Minimizing the medium's effectiveness



Derived from: *EDN – The Designer's Guide to Electromagnetic Compatibility*

Shielding Effectiveness *(S.E.)* of enclosed material

<u>Emission Suppression</u>

$\text{S.E}_{\mathbf{dB\ (Em.\ Supp.)}} \approx \text{A}_{\mathbf{dB}}$

<u>Susceptibility</u>

$\text{S.E}_{\mathbf{dB\ (Sus.)}} \approx \text{A}_{\mathbf{dB}} + \text{R}_{\mathbf{dB\ (appropriate)}}$

where: A: absorption loss in dB
R: reflection loss in dB

From: COTS Journal, *January 2004 – "Design Considerations In Building Shielded Enclosures."*

Shielding & Screening

Minimizing medium's effectiveness

Metal Shielding

Magnetic field   f < 20kHz

Ferrous metals

- steel
- Mu-metal – nickel, iron

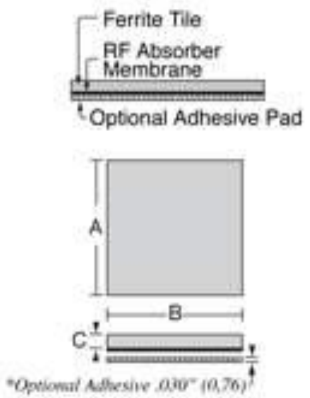
RF fields   10kHz < f < 1GHz

Non-ferrous metals

- Al foil I_{Loss} > 90dB
- Cu, Ni I_{Loss} 40-60dB
- Vacuum plating
  I_{Loss} > 80dB
- Electroless deposition
  I_{Loss} > 80dB

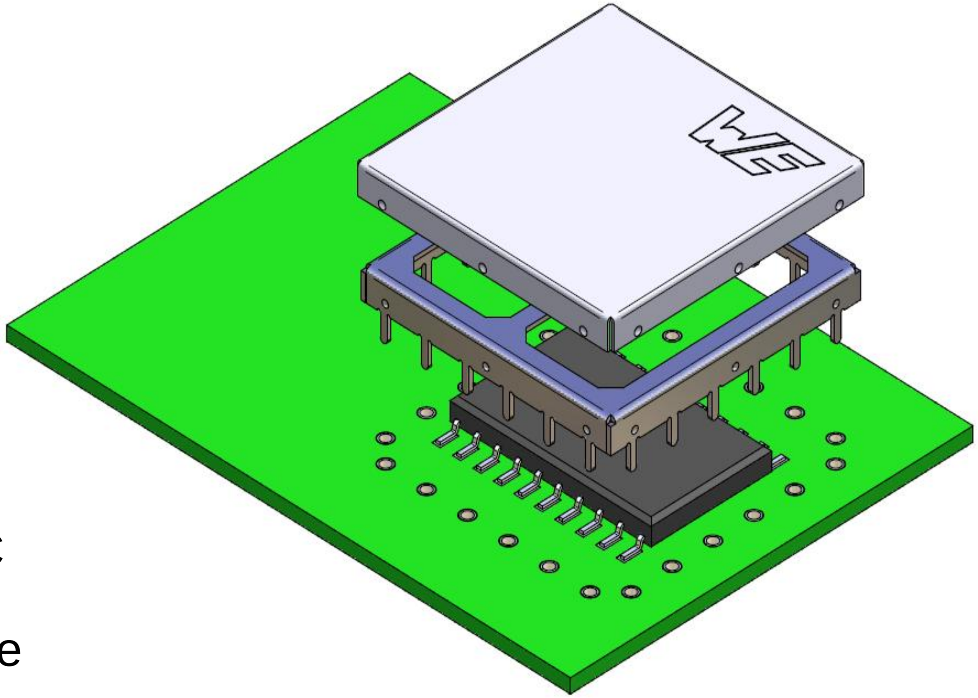
From: EDN EMI/EMC guide

Ferrite shield



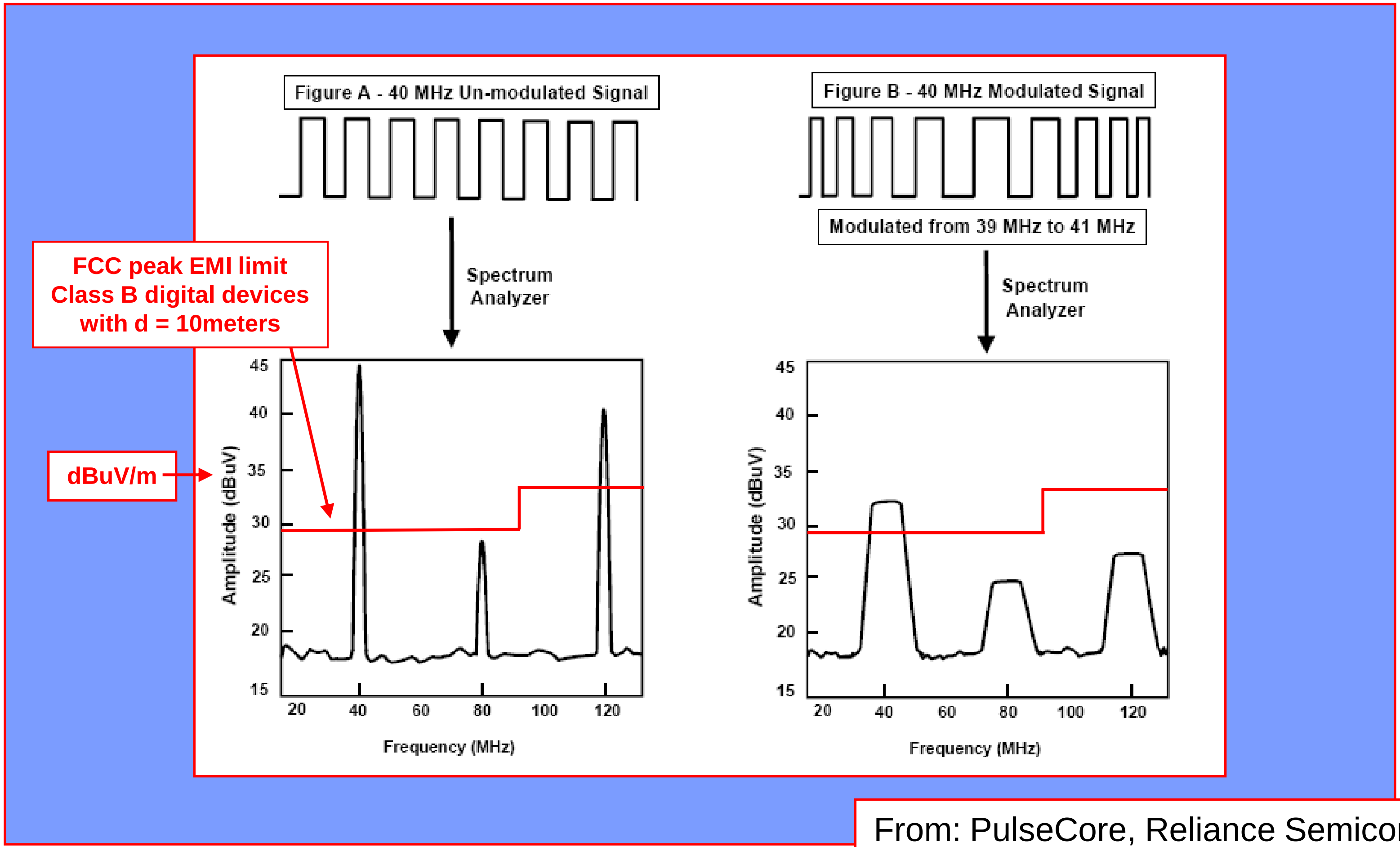
RF absorber shield

EMC Shielding Cabinet WE-SHC



- Applications are:
  - Oscillators
  - RF output stages
  - RF input & amplifier stages
  - EMC sensitive
- Overview of the materials WE-SHC
  - Diefferent materials are available
  - Tinplate is the standard material which we use for WE-SHC
- All materials can be lacquered, in particular in black for better thermal dissipation.

Frequency spreading of the system clock



From: PulseCore, Reliance Semiconductor

a Loop – the path current follows

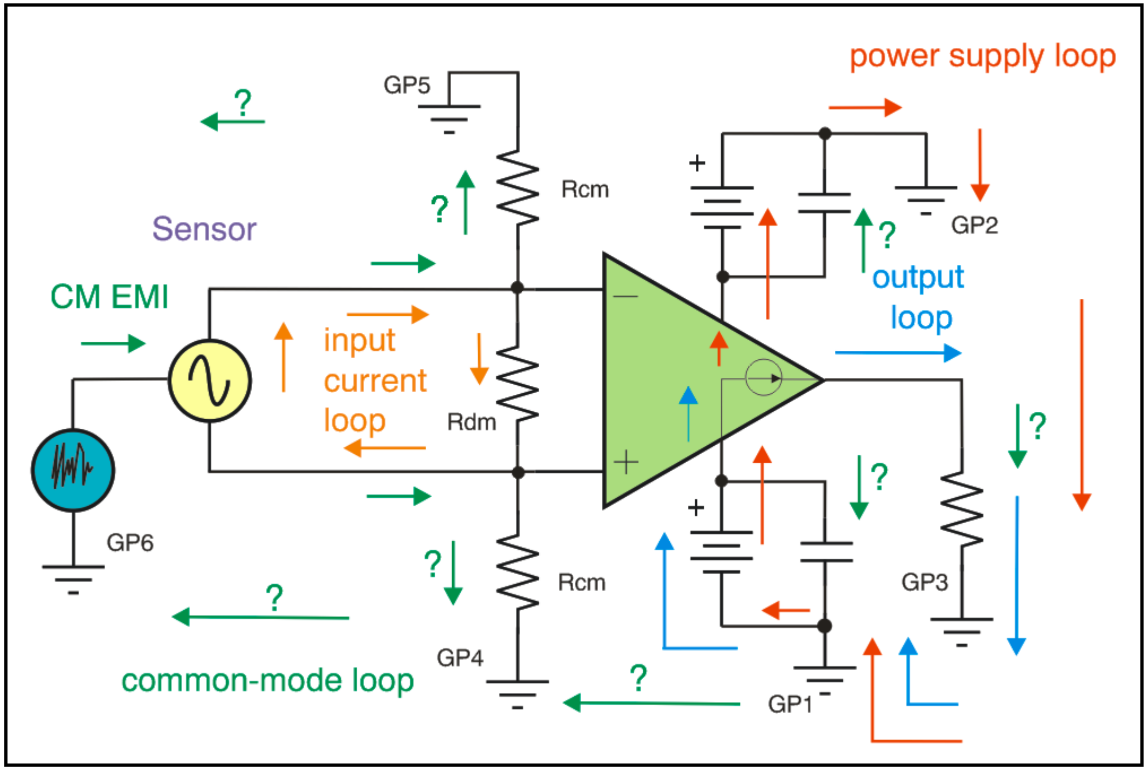
Loops

- Introduces unintended inductance in the current path where:

  $V_L = L\ di/dt$

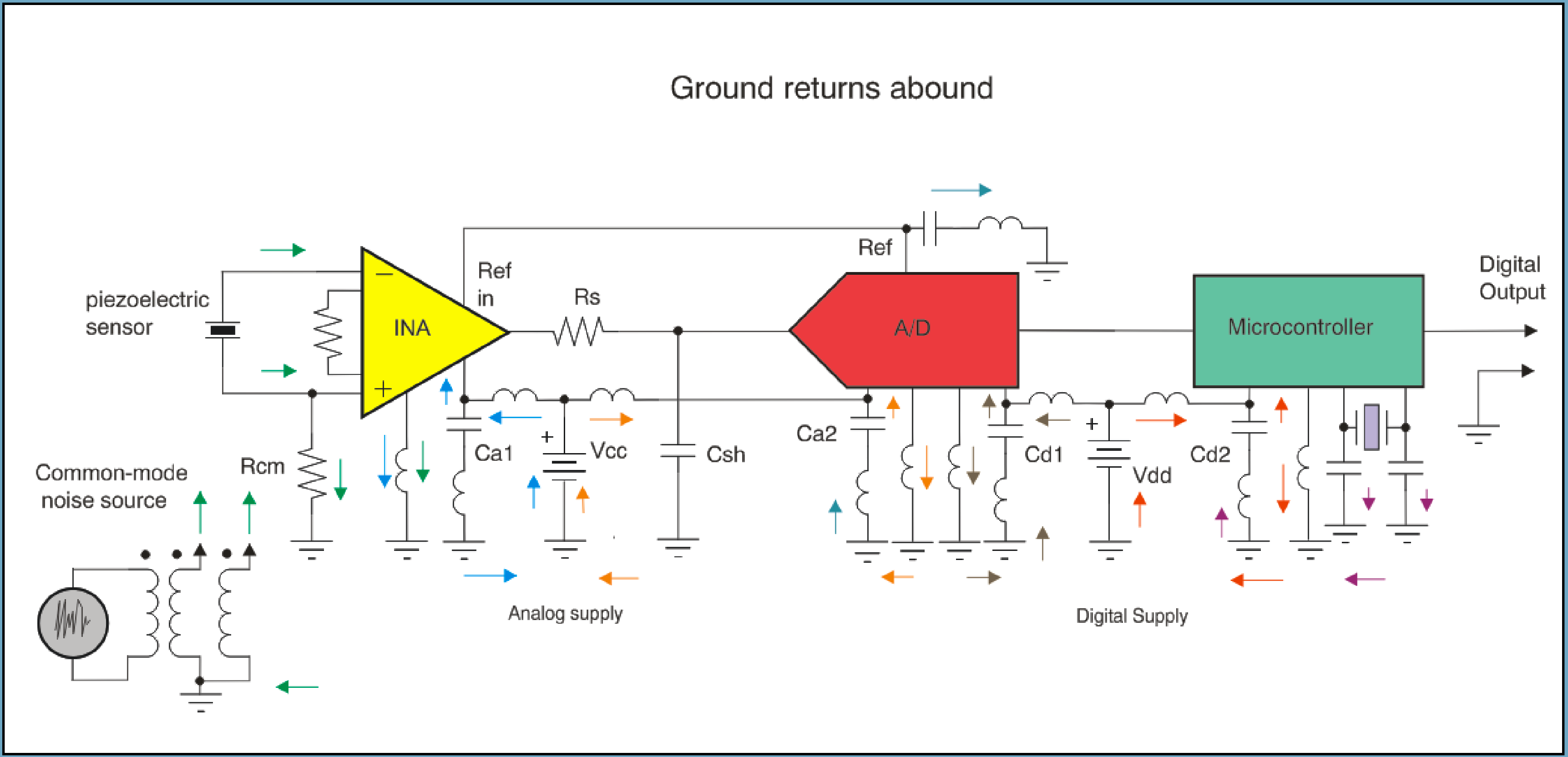
- May result in multiple AC signals sharing a current path
- May become a loop antenna that couples EMI/RFI

The common-mode return loop may be difficult to predict



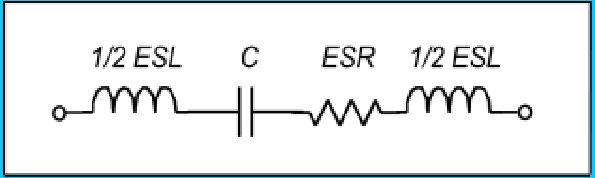
The ground return environment may be very complex

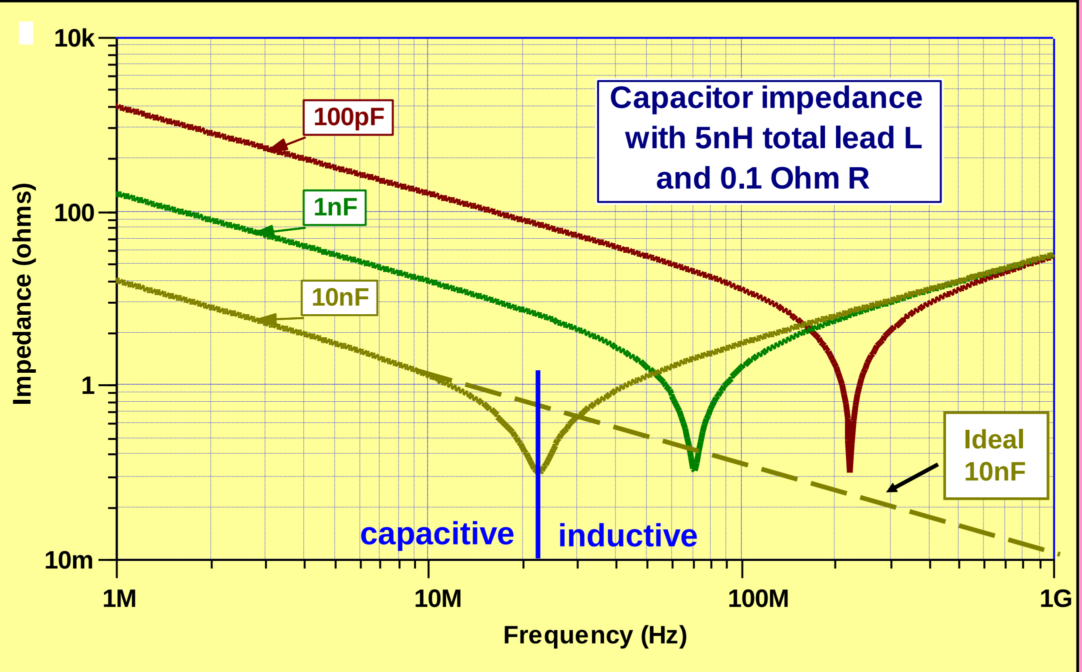
Current paths must be carefully considered to avoid long loops



Non-ideal passive components in the RF and EMI realms

Non-ideal Capacitor model





Other passives at RF

Conductors

- *skin effect*
- *inductance*
- *capacitance*

Inductors

- *resonance at f_r*
- *X_c above f_r*

PC board traces

- *ground loops*
- *traces and planes become monopole or loop antennas*

Use the correct capacitor to help minimize EMI

Capacitors

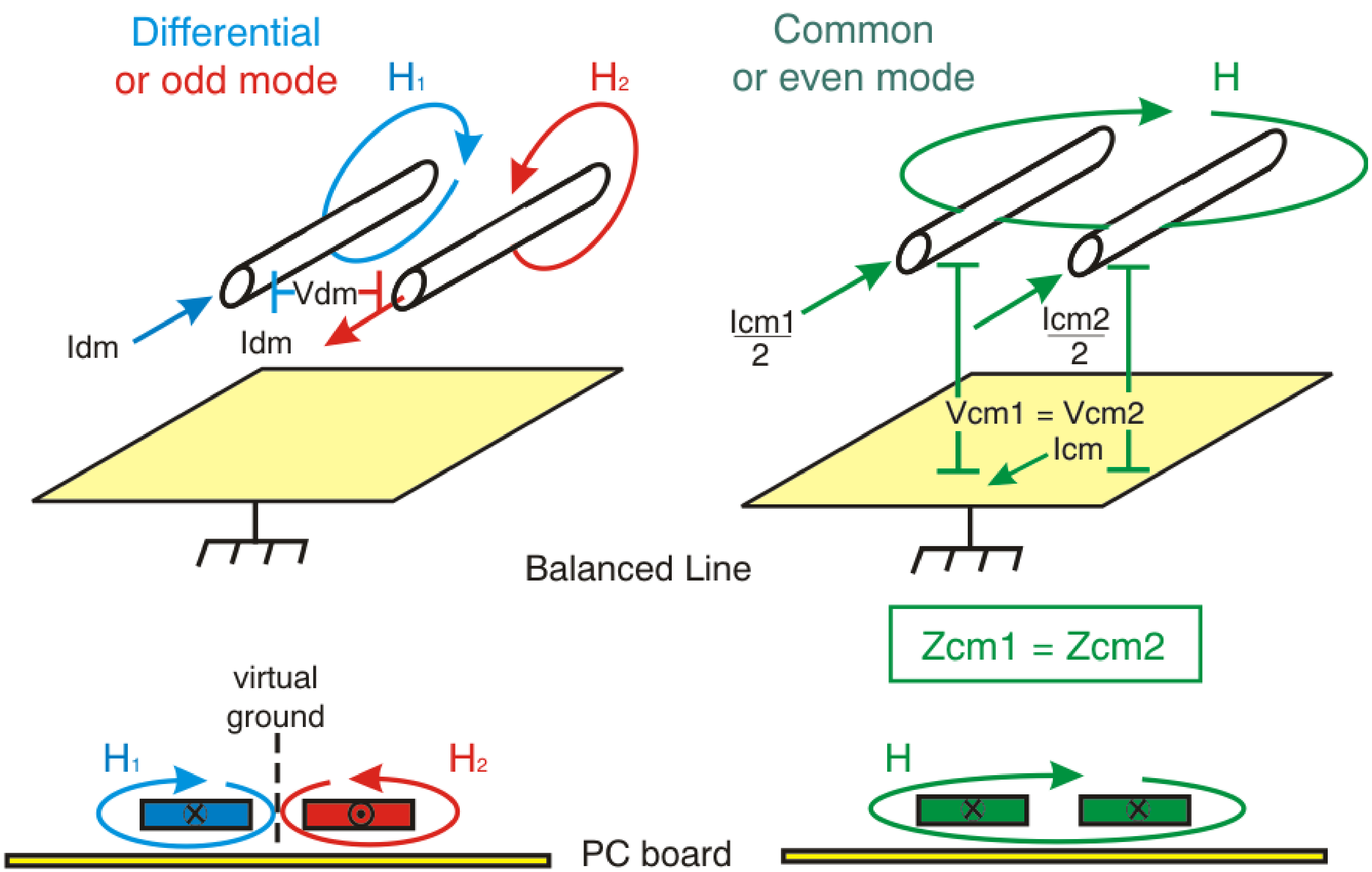
- Decoupling capacitors serve as charge reservoirs supplying transient current demands
- Decoupling capacitors must have low self-inductance and have low inductance circuit paths
- Distribute decoupling capacitors among pins having the same function; +Vdd, etc
- Use the correct capacitor type for the frequency range

Capacitor type	Maximum useable frequency*
aluminum	100kHz
tantalum	1MHz
plastic film	10MHz
silvered mica	500MHz
leaded ceramic	> 500MHz
surface mount ceramic	> 1GHz
surface mount glass, porcelain	>1GHz
PCB embedded ceramic	1GHz +

*much dependent on total inductance

Balance helps limit CM EMI response

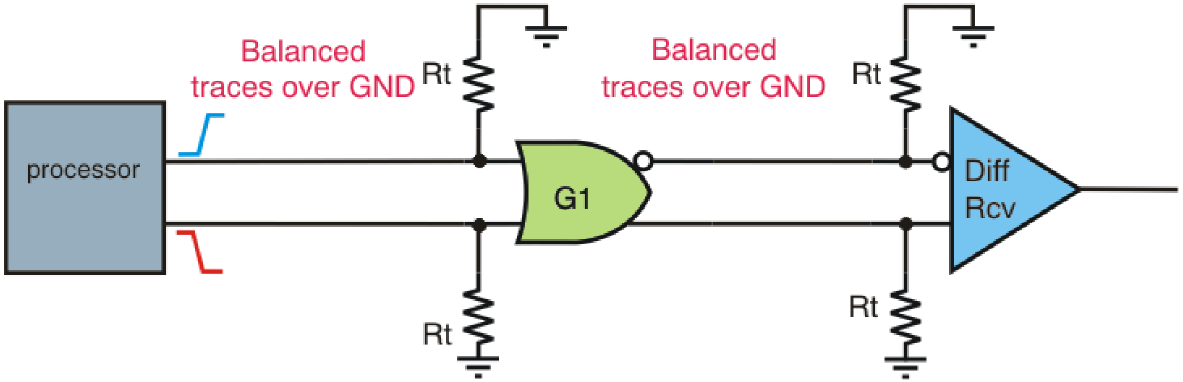
Balance helps prevent common-mode EMI from being converted to differential-mode EMI



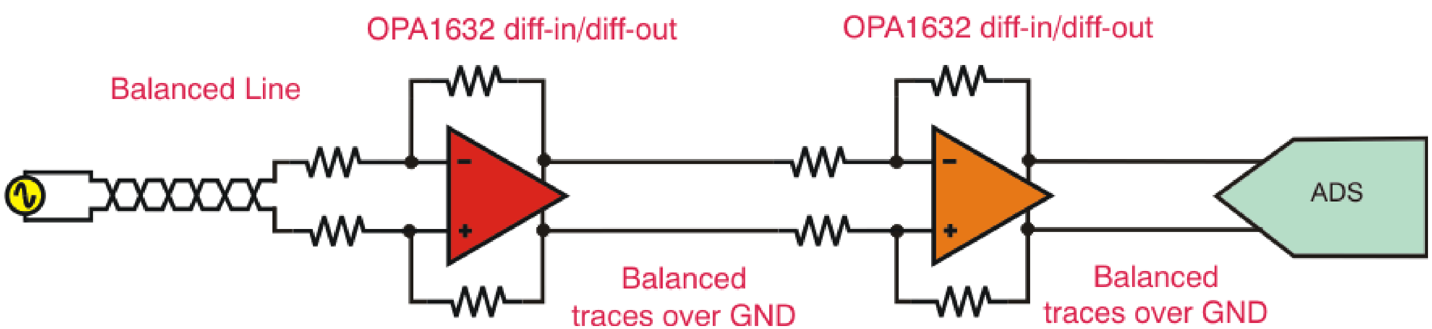
Balanced analog and digital circuit

(common-mode signals not welcome!)

Balanced digital logic: LVDS, PECL, HSTL

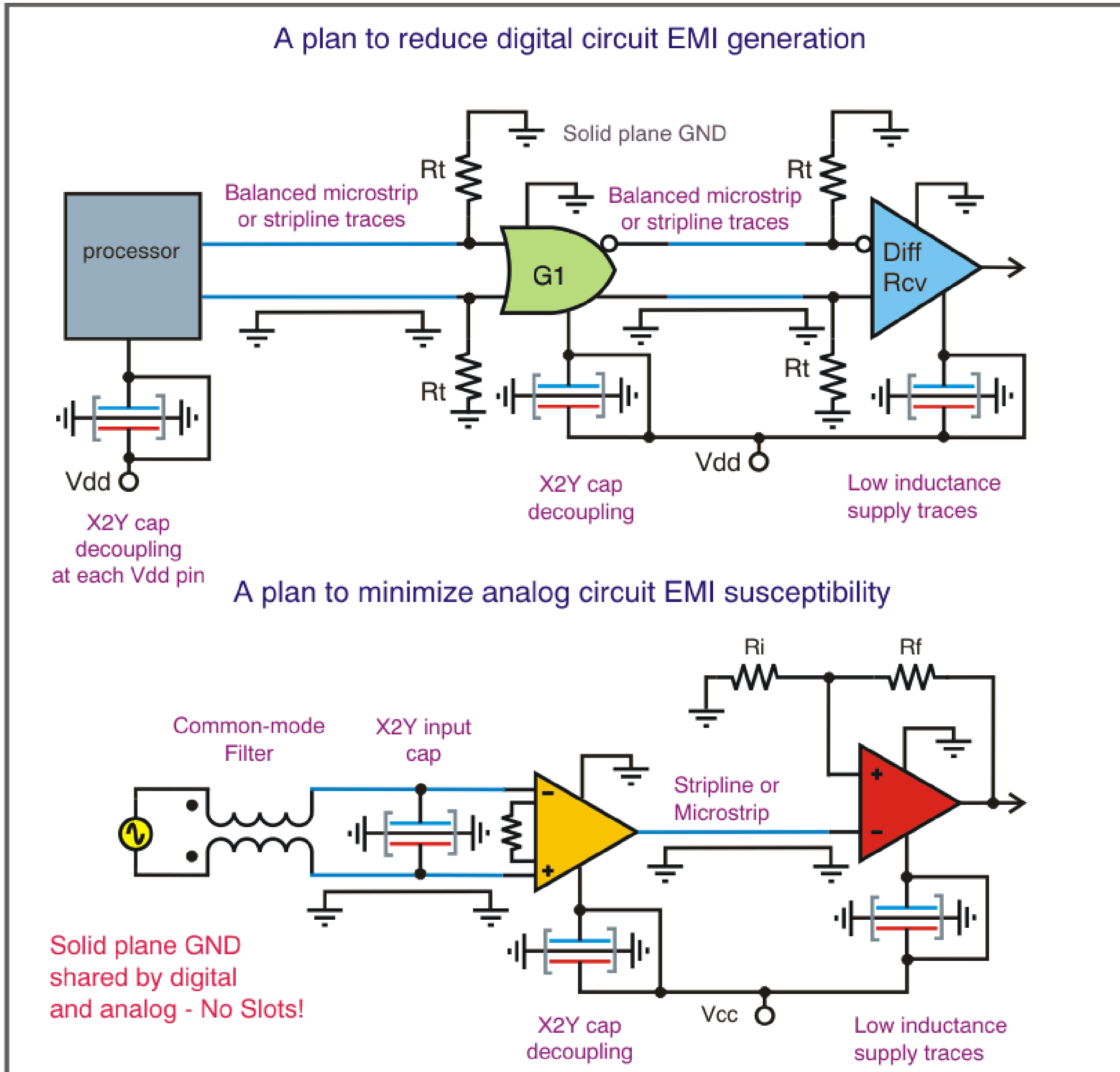


Balanced differential analog circuitry



Circuit techniques to minimize EMI

- Strive for a zero impedance ground
- Design for a differential signal environment, both logic and analog
- Minimize PCB loops that act as EMI antennas
- Use X2Y capacitors for filtering and decoupling
- Make use of common-mode transformers
- Use balanced lines and traces

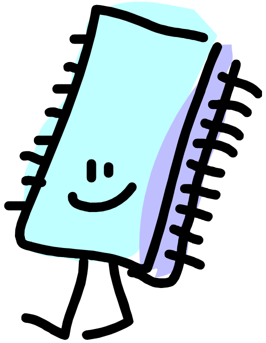


PCB layout tips to minimize EMI

- Minimize path inductance - especially ground
- Use a continuous ground plane - without slots!
- Partition potential EMI sources on one end of board, receptors on the other end
- Utilize true differential signals and paths when possible
- Use microstrip and stripline traces between circuits
- Use terminated transmission lines for high-speed and wide-band signals
- Fill open areas on signal plane with ground

In Conclusion EMI/RFI

- May constitute an operational, liability or regulatory concern
- Is best confronted at the onset of a design
- Requires a source, medium and receptor
- Propagates by conduction and/or radiation
- May require one or more reduction techniques
  - striving for a near-zero impedance ground
  - effective decoupling
  - minimizing circuit loops and loop areas
  - shielding > cables and metal cabinets
  - filtering > RC, LC and CM/DM transformers
  - balanced logic and/or analog circuits



A Happy IC - EMI Free!