Analyzing current paths and magnetic fields.

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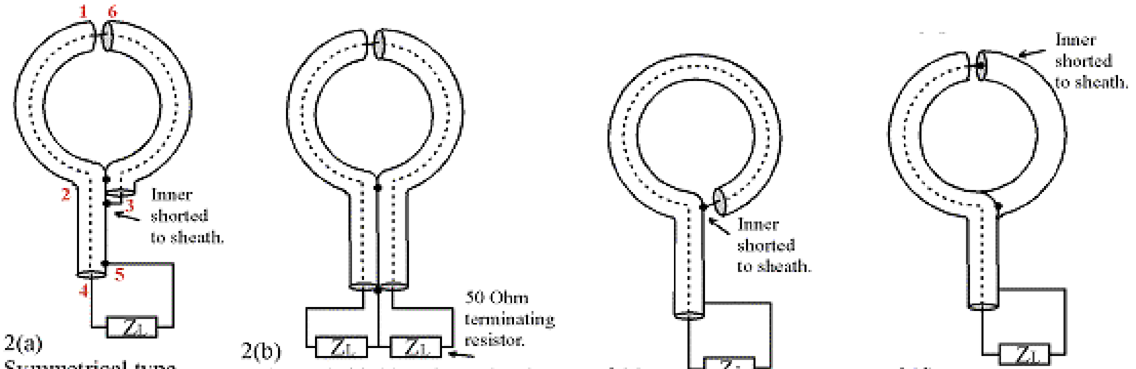
Introduction.

This experiment demonstration applies elements of two experiments from Volume 1 of the IEEE EMC Soc. Education Manual, ("Noise Measurement by Induction" and "The effect of circuit impedance on field-coupled crosstalk"), to investigate effects on various circuits and structures. The probing method enables the level, position and relative direction of signal and return currents to be determined and visualised. A variety of probe types may be utilized, each having their own characteristics and advantages.

Various magnetic field sensing probes.

Coaxial shielded loops.

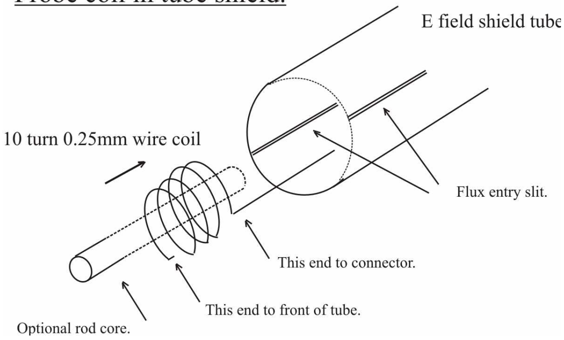
Various configurations may be formed with coaxial cable or semi-rigid coax. Four basic types are shown. (A moebius version of the balanced termination type 2b may also be constructed which uses a balun).



2(a) Symmetrical type, central gap.
2(b) Balanced shield and termination, central gap.
2(c) Unbalanced, gap at neck.
2(d) King type, central gap.

For further information on this type of probe refer to: "Probing the magnetic field probe", by R. C. Ediss, published in EMC & Compliance Journal Issue 47 July 2003.

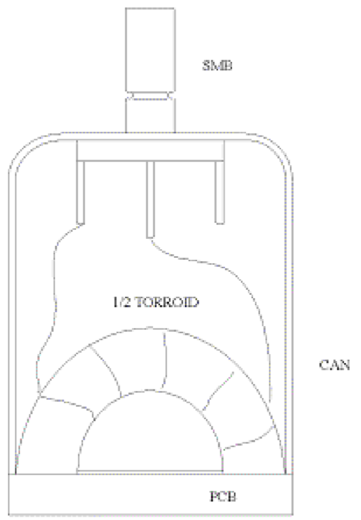
Probe coil in tube shield.



These are small air or ferrite rod cored coils with a surrounding electric field shielding tube. The shield may have two "flux entry" cuts on opposite sides of the shield.

"C"-core with coil.

The basic construction of small magnetic field sensing probes is shown below. They are made from a torroid core, ground with aluminium oxide paper to form a half circle. A number of turns of insulated wire are applied, which form a secondary winding of a current transformer when the probe is used on a conductor. The high permeability torroid material attracts, concentrates the magnetic field and increases sensitivity. The assembly may be shielded against electric fields with a metal can provided the two ends of the half-torroid are not enclosed. It's useful to mark the winding orientation for reference. A "horseshoe" probe of this shape will record a maximum when its longest axis is placed across the direction of current, in line with the magnetic flux produced. When held upright the vertical components entering at each end of the half-torroid tend to cancel and horizontally polarized field will be sensed. When held on its side horizontal components tend to cancel and vertically polarized field will be sensed. The sensitivity of the probe will vary with frequency. There is a sensitivity variation above and below a corner frequency which is dependent on the number of coil turns and probe inductance which forms a low pass LR filter with the 50 Ohm measurement instrument impedance. (See Appendix B). Up to 14 turns of 0.315 mm wire can be applied to this size of half torroid, however the interwinding self-capacitance has an influence on high frequency performance with more than approximately 5 turns.

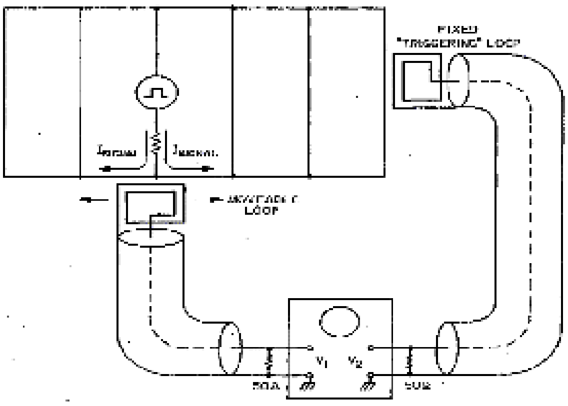


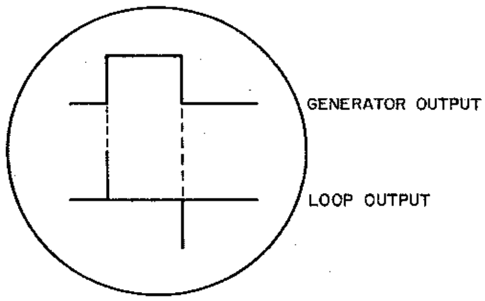
"C" core magnetic field sensing probe.
Winding *n* turns of 0.315 mm dia. Cu wire
Suggested materials for ½ torroid:
Ferroxcube ferrite, 4C65 & 3F3 TC6.3/2.5
Micrometals iron powder, T25-17

The initial circuit to be investigated, from the "Noise Measurement by Induction" experiment.

The characteristics of the induced voltage in the sensing probe are dependent on several factors as detailed in the original notes but most importantly; the polarity of the induced voltage has a dependence on the relative direction of circuit current. The points detailed in Appendix A, which relate to this statement, should be considered.

Refer to the circuit below on page 3. A 1 MHz 4V p-p input square wave signal is applied. As the probe passes the branch and the relative direction of circuit current changes, the voltage induced in the probe reverses polarity. So you can "see" the current divide. This method of determination of relative direction of current can be used to investigate signal and return current paths and effects on circuit structures.



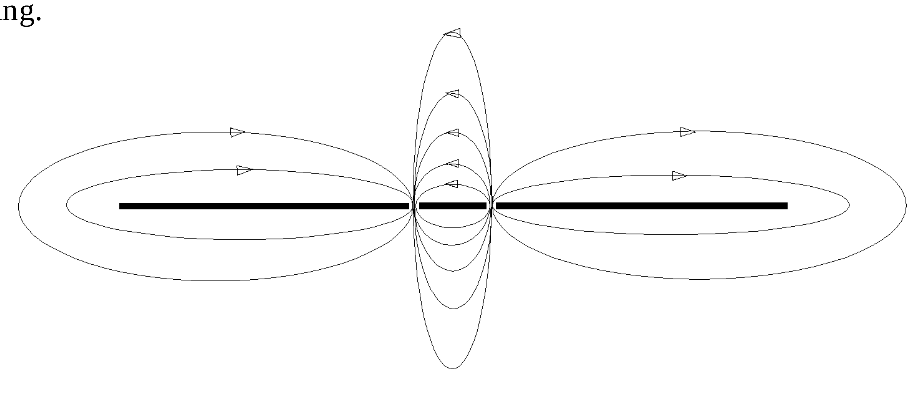


Instead of a fixed triggering loop as shown above, a resistive splitter is used from the generator output which enables an input waveform to be displayed on channel A of the scope. At the signal edge a pulse is induced in the probe as shown below.

Investigating current paths on PCB test pieces.

Coplanar and microstrip structures are investigated. The input signal is applied to PCB traces which have a characteristic impedance of 50 Ohms, terminated with 50 Ohms and the waveform is viewed on channel A.

With a coplanar transmission line on single-sided PCB, if the probe is placed to sense horizontally polarized field on the active line, a pulse is observed on channel B. When the probe is moved immediately to the right or left onto the ground, a reverse polarity pulse is then induced. **This reversal of polarity shows a relative difference in the direction of magnetic flux which is from the return current.** The return current wants to follow the path of least inductance which occurs due to mutual coupling closest to the signal line. Cancellation between opposing fields occurs due to the mutual coupling.

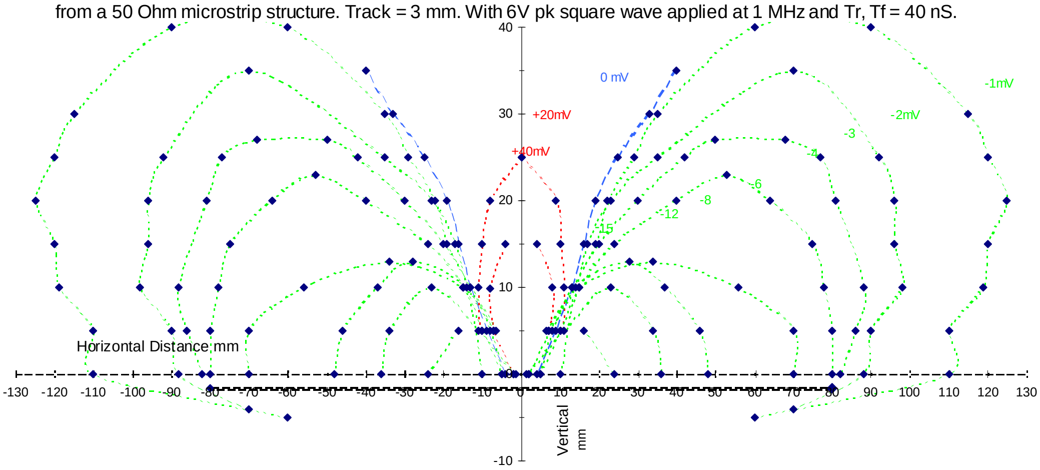


Typical magnetic field around coplanar trace structure.

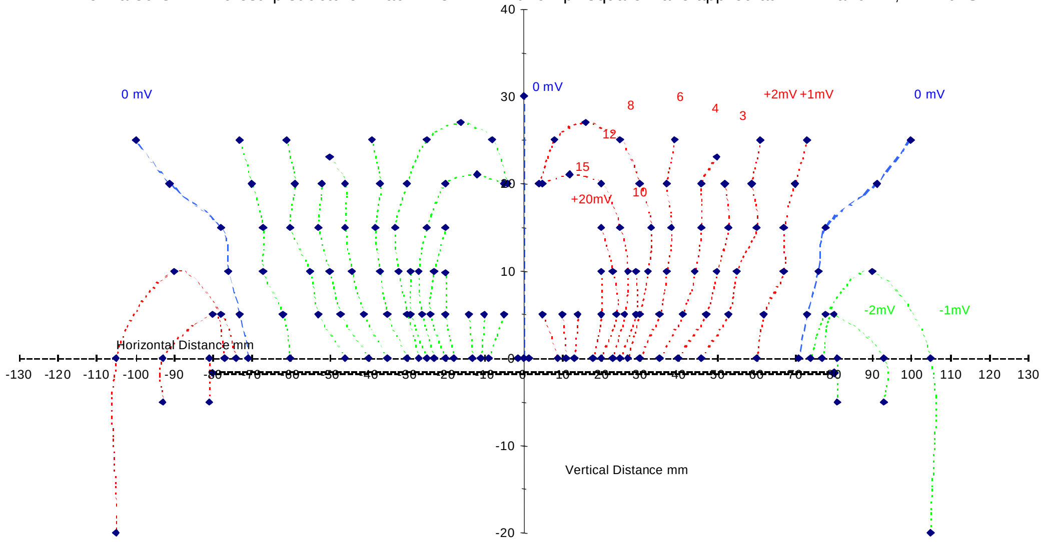
If the probe is traversed along the edge of the ground closest to the signal trace, a consistent voltage level is induced in it. But if a cut is introduced into the ground, which prevents the return current following the signal line path, all of the return current can then be seen to be forced away from the signal line. This additional path will cause an unwanted increase in the inductive characteristics of the ground. A voltage is then introduced [V=Ldi/dt], which drives common-mode radiation as described by the current driven common-mode model.

The effects with a microstrip structure are a little more complex. With the probe sensing horizontally polarized components on the signal line, a pulse is again observed on channel B. On the top surface of the PCB ground to the left and right of the signal trace, a reverse polarity pulse is then observed, which is from the resultant flux of signal AND image return current paths. The return current flows preferentially on the lowest inductance image ground route, which is induced, and occurs due to mutual coupling under and in close proximity to the signal trace. The sensed magnetic flux reduces towards the outside of the finite ground plane. The profile of the voltage induced in the probe can be mapped and is shown below. At the edge of the PCB, it can be seen from the horizontal and vertical components, that a small amount of flux wraps around the PCB.

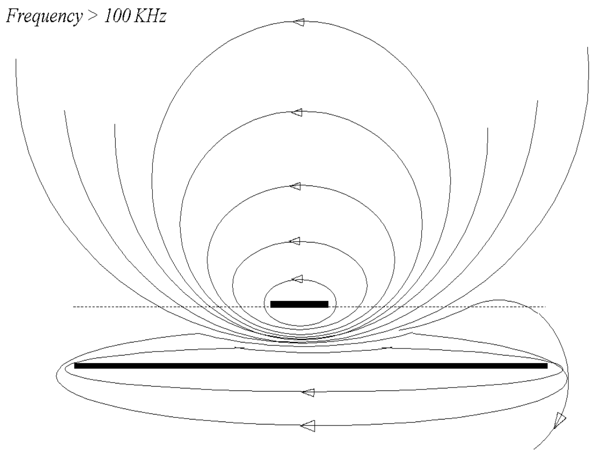
Contours of pulse voltage level induced in a horizontally polarized probe (with +30 dB amplifier) at fixed sensing positions from a 50 Ohm microstrip structure. Track = 3 mm. With 6V pk square wave applied at 1 MHz and Tr, Tf = 40 nS.



Contours of pulse voltage level induced in a vertically polarized probe (with +30 dB amplifier) at fixed sensing positions from a 50 Ohm microstrip structure. Track = 3 mm. With 6V pk square wave applied at 1 MHz and Tr,Tf = 40nS



Typical magnetic field around microstrip trace and finite plane.

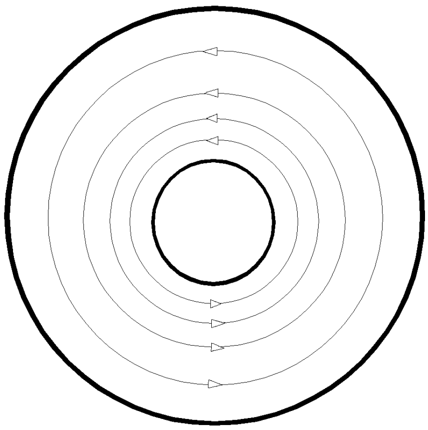


Only a small amount of "lost" flux wraps around the PCB. Because of mutual coupling and the skin effect there is in fact little sensed on the bottom surface of the ground, apart from the low frequencies under the signal line, which penetrate through the copper. With a cut in the ground under the microstrip line, again the return current can be traced over a path, which increases the ground inductive characteristic and produces an unwanted voltage. I am applying a 1MHz square wave with a wide spectral content. There is an effect on the return current path, which is dependent on frequency. Below about 100 KHz the return current will not follow the path of least inductance but switches to the path of least resistance.

Coaxial cable.

The microstrip PCB has a finite groundplane. A length of 4"coaxial cable with a solid shield helps to illustrate the effect of an infinite ground plane. The input signal is applied to the cable that has a characteristic impedance of 50 Ohms and is terminated in 50 Ohms.
If the probe is placed on the hollow signal line internal surface nothing is sensed because mutual coupling and the skin effect causes the signal current to flow on the outside surface of the signal line. If the induced voltage from the magnetic flux is sensed, it is the same polarity all the way across the gap between signal line and shield. In this case a particular return current position cannot be sensed because the solid coax shield is effectively a wrapped around infinite "ground plane". No external flux wraps around it that may be sensed, therefore the return path has no partial inductance.

Typical magnetic field within solid shield coaxial cable.

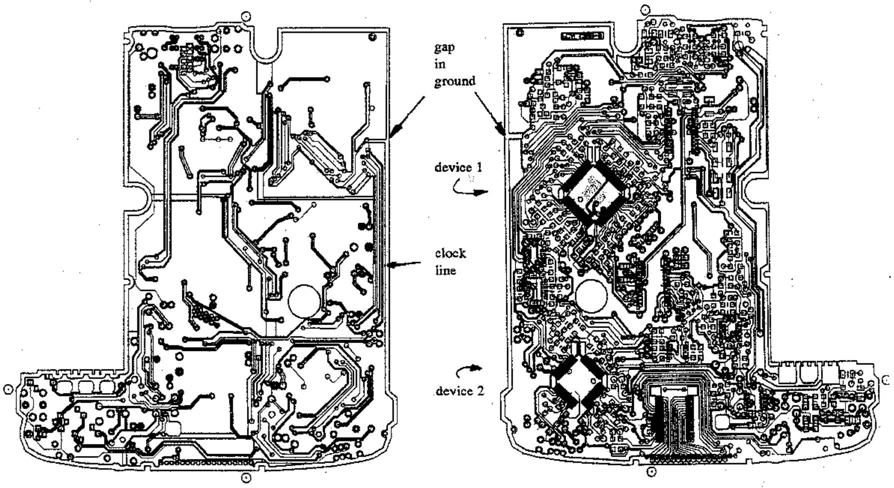


A real circuit.

A gap in the ground layer of a portable CD player PCB, prevented clock return currents returning to the source device over a path that was in close proximity and mutually coupled to the signal line. A voltage gradient then produced common-mode emissions from the phones connection.

A simplification of the circuit uses a 10 MHz square wave oscillator, a logic device as a source and another as a load. The ground plane has a cut in it which can be bridged with a switch.

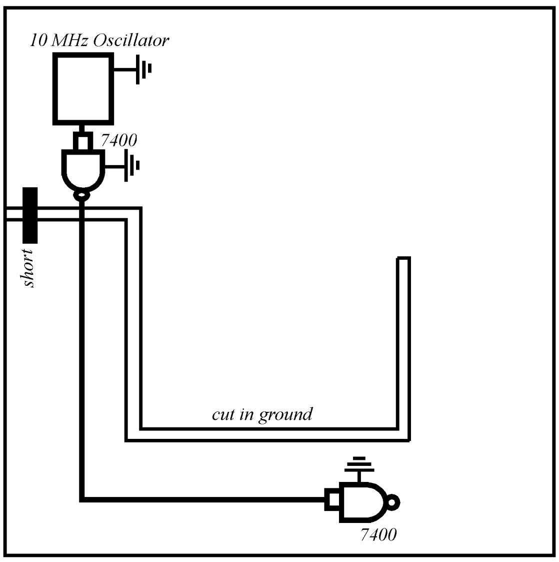
Two sensing probes are used. The “triggering” one on the clock line is connected to channel A and a pulse is displayed from the signal edge. The searching probe, with the same orientation, can be used to trace the reverse polarity pulse from the return current. With the switch open the preferred return route follows the cut; with the switch closed there is little excitation of the ground. The difference in ground voltage with the switch open and closed can be measured with a scope probe.



HP7000 CD player PCB12880 both sides.

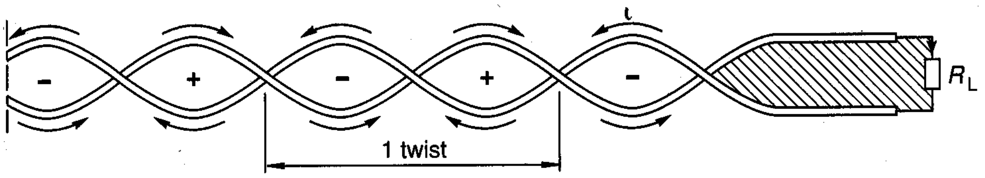
Gap in ground prevents correct return current flow.

SIMPLIFIED LAYOUT



Investigating twisted pair cable.

The input signal is applied to an open-spaced twisted conductor pair, which is terminated in 50 Ohms and this waveform is viewed on Channel A. If the probe is placed at the same position on alternate loops a polarity reversal is observed on Channel B.



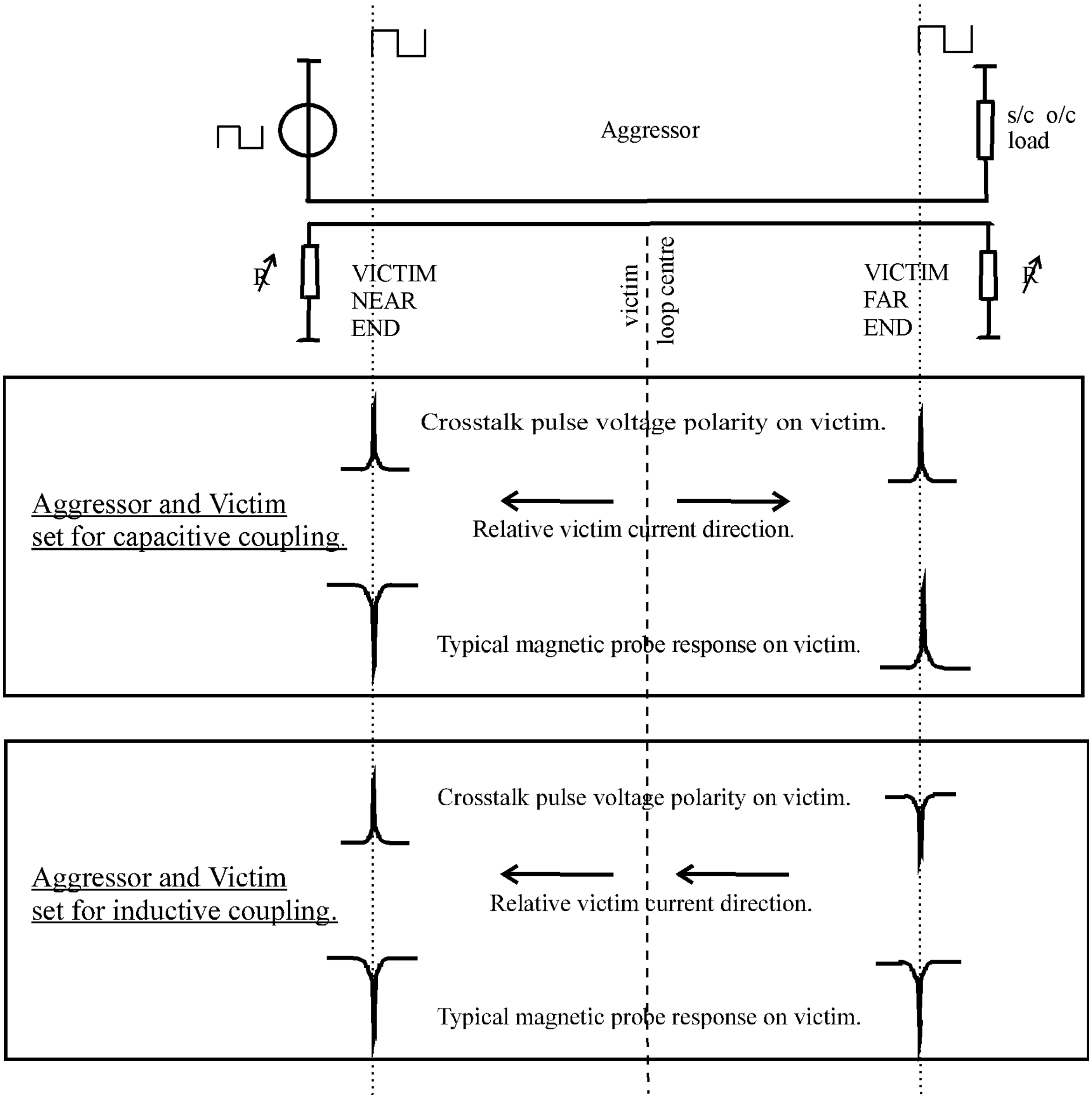
Each twist consists of two loops with reversed current direction and field polarity, which therefore tend to cancel, resulting in reduced net emission. Immunity is also improved because the net induced voltage decreases due to the induced voltage in adjacent loops tending to cancel.

A crosstalk demonstrator PCB.

A U shaped source trace may be arranged by s/c and o/c termination to provide either inductive magnetic fields (low wave impedance) or capacitive electric fields (high wave impedance). The impedance of an adjacent victim trace may also be varied with variable resistors to be low or high. The relative polarity of the coupled signal sensed at either end of the victim may be observed.
Refer to the victim signal attributes summary diagram that follows on page 8.
With inductive magnetic coupling, the polarity and direction of the induced voltage sensed with the magnetic field probe at either end of the victim is the same. It is dependant on the relative direction of source current and is determined by Lenz's Law.
With capacitive coupling there is no such directional association with source and victim signals, and the voltage sensed at either end of the victim differs in polarity. The victim current just flows away from the coupling point, hence the opposite circuit current directions.

The effectiveness of a shorted turn.

The inductive magnetic coupling effect may be minimised. A short-circuit loop running parallel to a victim or sensing pick-up loop, is called a shorted turn, as it acts like a shorted one-turn low impedance secondary of a transformer. When cut by the changing source magnetic flux the shorted turn will have eddy currents induced in it. These currents cause a changing magnetic nulling field, which opposes the changing source field polarity and cancels it. This is sometimes referred to as "Active Shielding" and the energy is converted to heat in the shorted turn.

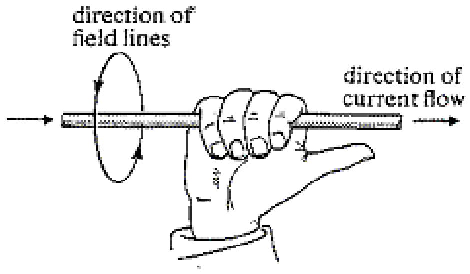


Inductive & Capacitive coupling - Victim signal attributes.

Note: The polarity of all pulses sensed with the magnetic field probe will reverse if its orientention is reversed.

Appendix A. Theory associated with induced voltage.

i) The circuit signal current has an associated magnetic flux, with direction given by **The Right Hand Method or Rule** as detailed below.



By using your right hand to 'grip' a current-carrying conductor, you can work out the direction of the magnetic field. When your thumb points in the direction of current flow, your fingers indicate the direction of the magnetic field.

ii) The signal edge induces a voltage in the probe as described by **Faradays Law**. *The magnitude of the e.m.f. in a circuit is related to the rate of change of magnetic flux through the circuit.* The open circuit voltage is also dependent on the number of turns and the mutual coupling.

$$e.m.f. = \frac{d\Phi}{dt}$$

Where Phi, Φ is the magnetic flux.

Plus the voltage induced in the pickup loop is:

$$V_{induced} = N M \frac{di}{dt}$$

Where i is the current in the signal path,
N is the number of turns,
M is the mutual inductance between pickup loop and circuit.

iii) The polarity of the induced voltage is dependant the relative direction of circuit current and is determined by **Lenz's Law.** *Whenever a change of some kind causes an induced current, the direction in which that current flows is such as to produce effects that oppose the change that caused the current.* Hence: The direction of the induced current must be such as to oppose the changing flux that causes it.

Appendix B. Probe characteristics. **Actual "C"-core Probe Transfer Impedance with ½ toroid.**

Using: Zt(dB referenced to 1 Ohm) = V(dBuV) – I (dBuA)
so for circuit current in dBuA, I(dBuA) = V(dBuV measured) – Zt(dBOhms off plot)