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THE 11940A CLOSE FIELD PROBE: Characteristics and Application to EMI Troubleshooting

SIGNAL ANALYSIS DIVISION

AUTHOR:
MARK TERRIEN

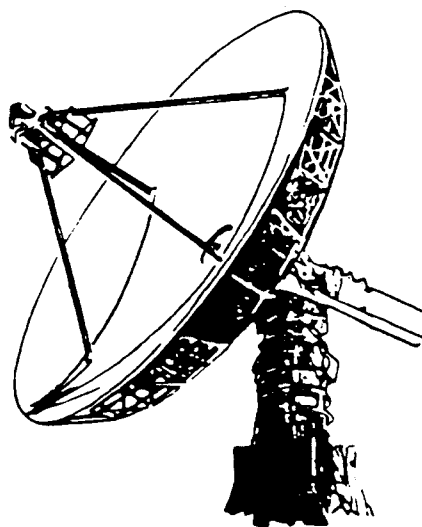


11940-90004

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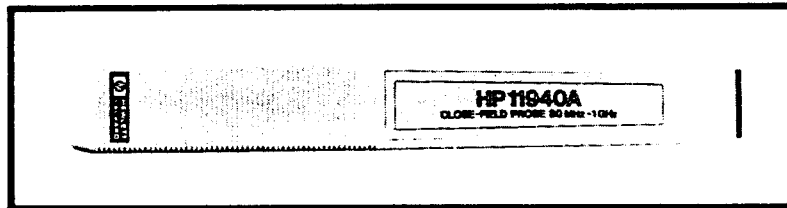
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ABSTRACT: This paper discusses the theory of operation and RF characteristics of the HP 11940A and addresses its application to several EMI troubleshooting situations. Radiated and susceptibility problems are covered with a general discussion and several specific applications are presented.

AUTHOR: Mark Terrien, R & D Engineer, HP Signal Analysis Division, Rohnert Park, CA. BS in Physics, University of Wisconsin (Milwaukee), 1978; MSEE, University of Wisconsin (Madison), 1980. Joined HP Technology Center, Santa Rosa, in 1980 and worked for three years on characterization of microwave components. Now involved in development of EMI measurement equipment in Signal Analysis R & D Lab.



- Hand-held Magnetic Antenna
- Broadband 30 MHz - 1 GHz
- Calibrated

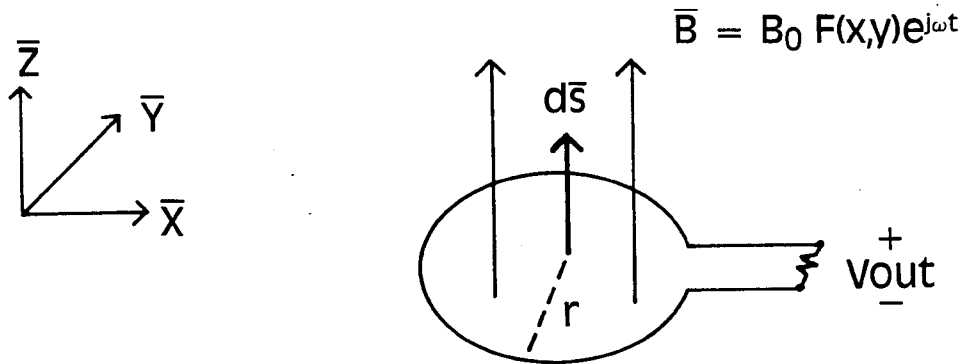
The HP 11940A Close-Field Probe is a broadband magnetic field sensor designed for EMI troubleshooting. It can be used in a variety of design lab, production line, and quality assurance applications with all of the HP spectrum analyzers that cover the 30 MHz to 1 GHz band.

OUTLINE

- Operating Principals
- Product Benefits
- Uses
 - Locating Radiation
and Susceptibility Problems
- Special Applications

This talk will first cover operating principles and benefits of the HP 11940A, and then discuss general usage of the unit in several specific measurement applications.

THEORY OF OPERATION



$$V_{out} = -\frac{\partial}{\partial t} \int_{\text{surface}} \bar{B} \cdot d\bar{s}$$

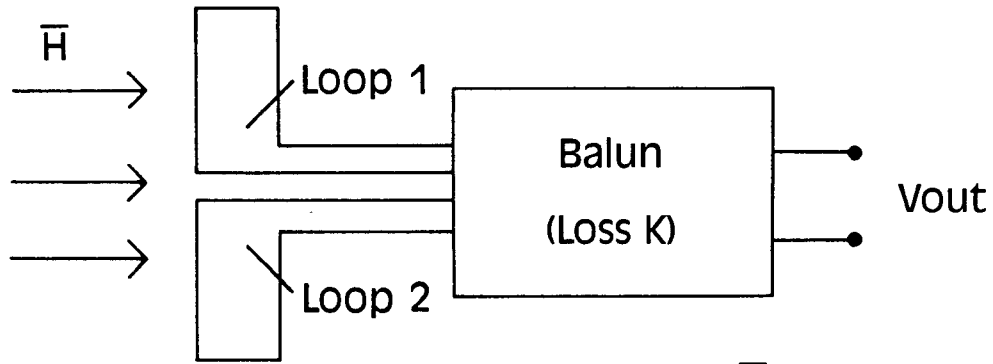
if $|\bar{B}|$ is Uniform Over S

$$V_{out} \rightarrow \omega S |\bar{B}| = \omega \mu S |H|$$

The design of the 11940A is based on Faraday's induction law: the output voltage of a single turn loop is proportional to the time rate of change of the total magnetic flux passing through the loop. The total flux can be evaluated if we assume that the flux density is uniform over the loop area. If we also know the time derivative of the flux, we can then calculate the output voltage of the loop. See References 1 and 2.

The maximum loop dimension of the 11940A was designed to be less than one-tenth of one wavelength at 1 GHz; this constraint limits the variation of the magnetic field over the loop and allows calibration. It also limits the cross-sectional area of the loop and, therefore, the sensitivity of the probe.

11940A BLOCK DIAGRAM

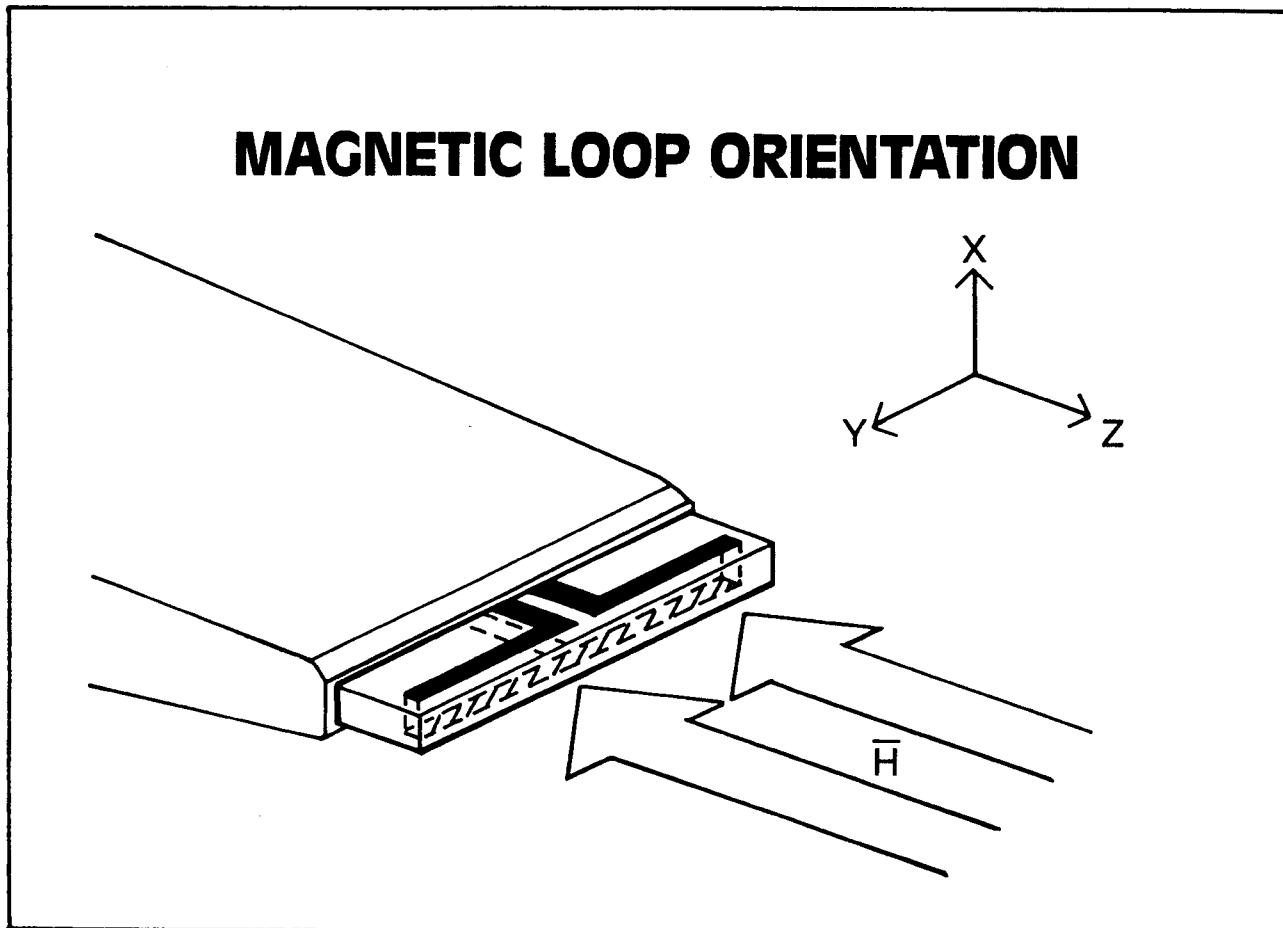


$$V_{out} = K\omega\mu_0 S |\bar{H}|$$

$$\left| \frac{\bar{H}}{V_{out}} \right| = \frac{1}{K\omega\mu_0 S} \text{ dB} \left[\frac{\frac{\mu\text{A}}{\text{m}}}{\mu\text{V}} \right] = \text{Antenna Factor (AF)}$$

The 11940A consists of two single turn loops feeding a balun structure. The balun structure improves the performance of the probe but introduces additional losses. These losses are taken into account in the relationship between the CW magnetic field intensity at the probe tip and the output voltage. This relationship is called the antenna factor (AF) of the probe.

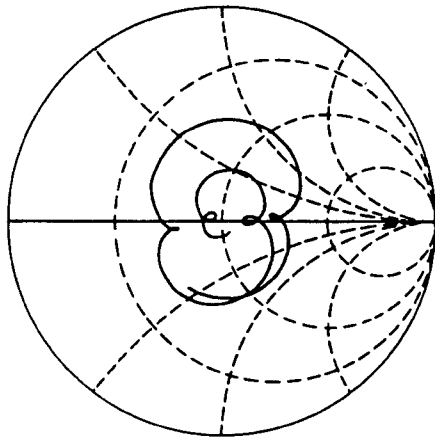
MAGNETIC LOOP ORIENTATION



The sketch shown above displays the probe loop orientation. The loop is in the X-Y plane. Maximum coupling is achieved when the incident magnetic field is Z-directed. The loop cannot be seen on production units because it is covered with a dielectric insulation material that acts as a boundary to prevent the metal loop traces from shorting to the DUT. This material will withstand 1000V. Exercise caution when probing near high potentials.

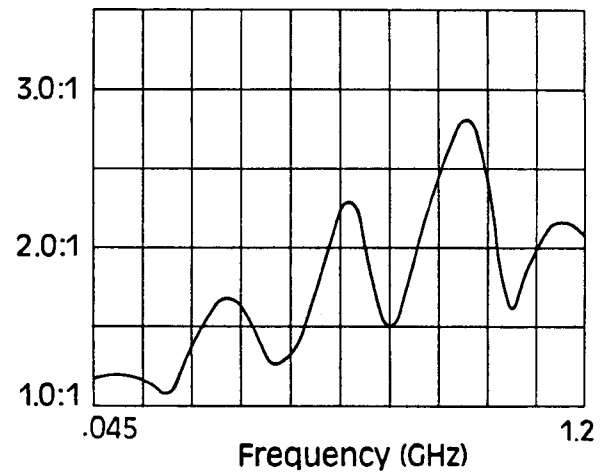
REFLECTION CHARACTERISTICS

S11



START .045 GHz
STOP 1.2 GHz

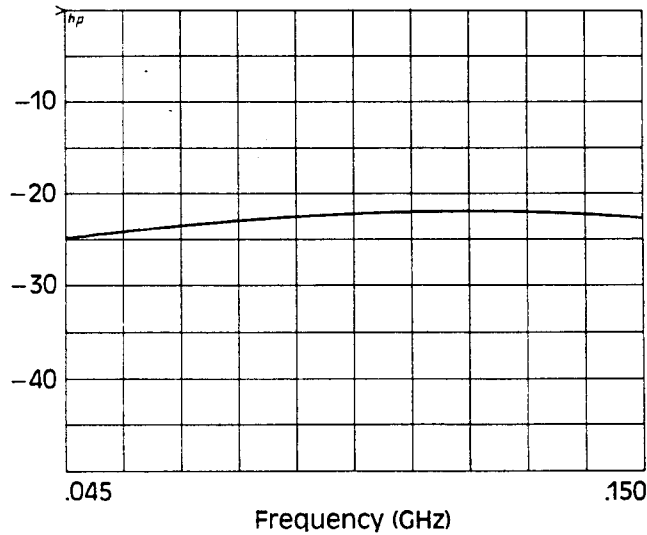
VSWR



The 11940A is a reciprocal device; it can be used to source and sense magnetic fields. This probe has a nominal input impedance of 50 ohms.

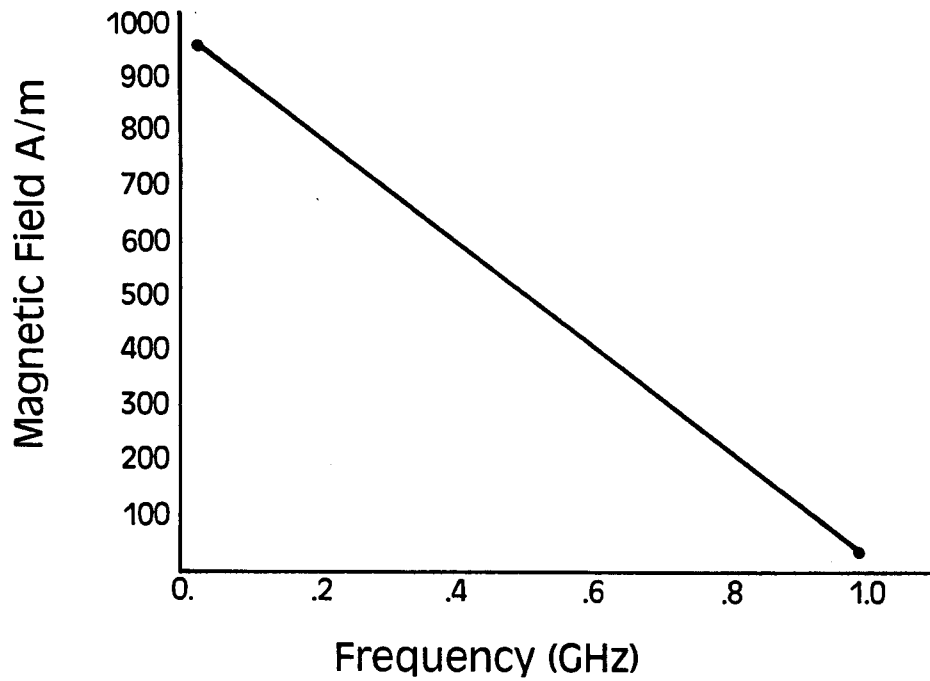
OPERATION VERIFICATION: Measure HP 11940A Return Loss

S11



Measurement of the 11940A antenna factors requires extensive fixturing. Internal damage can be detected in the field by making a measurement of the return loss at lower frequencies. Typically the return loss is better than 18 dB below 100 MHz. Any internal damage to the unit will degrade the return loss of the probe significantly. The procedure for making this measurement is given in the 11940A Operation Note. If damage is done to only one loop or its circuitry, significant sensitivity to handling and cabling will be observed.

MAXIMUM CONTINUOUS MAGNETIC FIELD STRENGTH



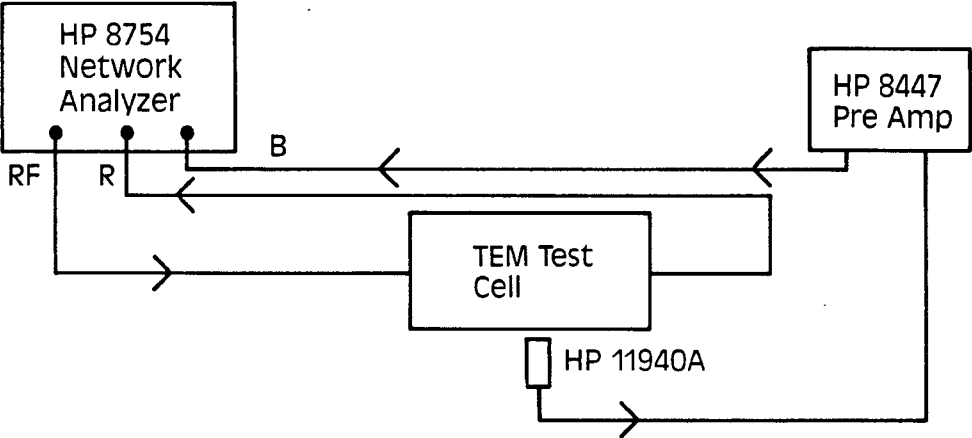
Maximum measurable field amplitude is limited by the power dissipation capabilities of the internal impedance-matching elements. Continuous measurement of signals larger than those given above will cause overheating and eventual failure of circuit components.

BENEFITS

- Calibrated
- Minimal Mutual Coupling
- Reduced Sensitivity to Electric Fields
- Convenient Geometry
- Localized Source

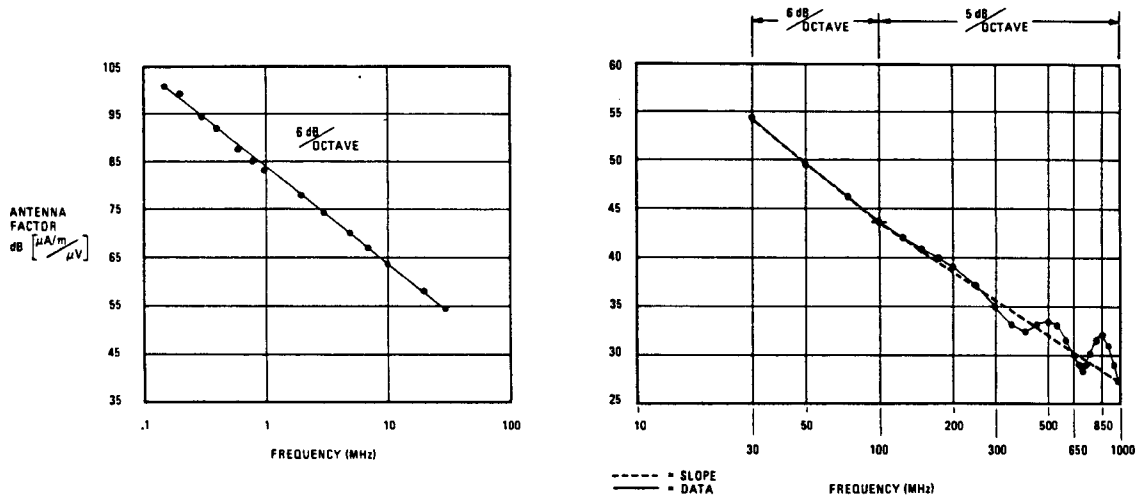
INDIVIDUAL ANTENNA FACTORS

FREQ MHz	30	100	500	850	1k	SER	MADE IN USA
ANT FCTR dB ($\frac{\mu A/m}{\mu V}$)	55	44	35	31	27	0000000000	



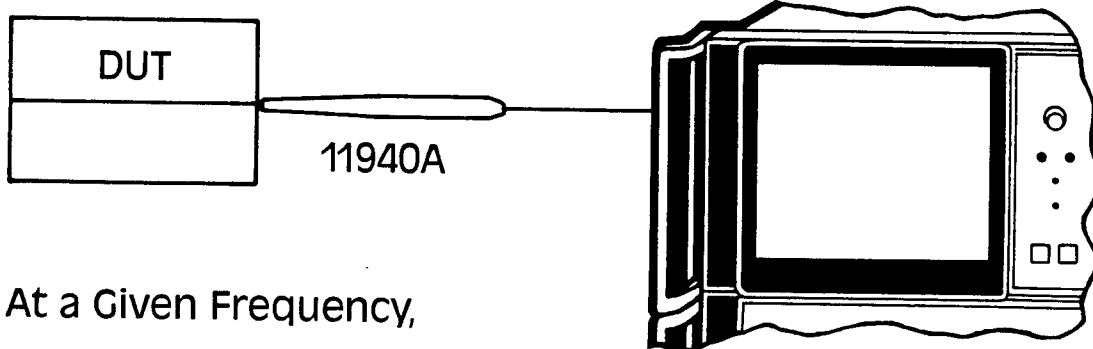
The antenna factors of each probe are measured to within ± 2 dB with a CW signal in a 377-ohm field impedance utilizing a specially-designed coaxial test fixture. This measurement individually characterizes the internal circuit losses of each probe. These AFs are listed on the side of each probe.

ANTENNA FACTORS



The antenna factors of each 11940A are measured at five frequencies over a range of 30 MHz to 1 GHz. The balun works over this range providing electric field rejection. The 11940A works below 30 MHz and above 1 GHz but without the rejection provided by the balun. The curves above give the AF of the probe from 150 kHz to 1 GHz.

APPLICATION OF ANTENNA FACTORS



At a Given Frequency,

$$H \left(\text{dB} \frac{\mu\text{A}}{\text{m}} \right) = \text{AF} + \text{VSA} (\text{dB} \mu\text{V}) + K$$

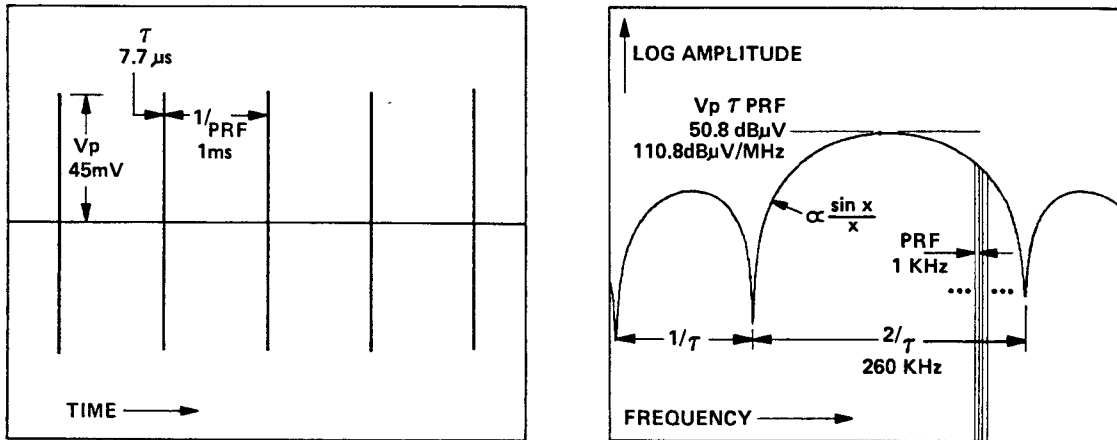
$$E \left(\text{dB} \frac{\mu\text{V}}{\text{m}} \right) = \text{AF} + \text{VSA} (\text{dB} \mu\text{V}) + K + 51.5$$

$$S \left(\text{dB} \frac{\text{mW}}{\text{cm}^2} \right) = \text{AF} + \text{VSA} (\text{dB} \mu\text{V}) + K - 104.3$$

Assumes
377 Ω
Field
Impedance

Measurement of a radiated CW magnetic field is accomplished by adding the measured output voltage in dBuV at a given frequency to the associated AF. Any gain or loss between the analyzer and the probe must be taken into account. [K is positive for loss, negative for gain.] The analyzer should be used in spectral line mode to accurately determine field intensities. Equivalent plane wave electric field intensities and power densities can be calculated from the magnetic field measurements by assuming a 377-ohm field impedance.

APPLICATION OF ANTENNA FACTORS: MEASURING IMPULSIVE SIGNALS



The AF of the 11940A may be applied to the spectral components of impulsive and modulated signals as long as these signals are viewed in the spectral domain. Reconstruction of the original impulsive or modulated signal is usually not possible due to band-limiting by the radiating structure. Amplitude information of the individual spectral components usually cannot be directly related to amplitude of internal pulsed RF signals, but spectral frequency and null spacing can be related to properties of the modulation.

MUTUAL COUPLING

1. Coupling Between the Source and the Sensor Alters the Existing Source Current Distribution
2. Magnitude of Coupling is a Function of the Entire System: Source, Sensor, Cabling and Operator
3. Mutual Coupling is Unique to Each System

Placing any sense probe in close proximity to a radiator can alter the source current distribution. In most cases the source will "see" the probe and the other elements of the measurement system, including the operator, through mutual coupling. As the word "mutual" implies, the coupling between a given source and sensor depends on the characteristics of each and is therefore unique to each system. Closed-form solutions for the magnitude of the source disturbance are possible only for relatively simple systems, but general characteristics of the interactions between the 11940A and different types of radiators can be determined.

MUTUAL COUPLING (cont.)

4. Type of Coupling is Dependent on Source Type and Geometry
 - a. Low Impedance Source:
Magnetic Coupling Through Mutual Impedance —
Induced Current in the Sensor Re-Radiates and
Reduces the Total Flux of the Source
(eg. slot radiator).
 - b. High Impedance Source:
Electric Coupling Through Mutual Capacitance —
Presence of Sensors Alters Source Capacitance and
Changes Local Source Current Distribution
(eg. electric dipole).

The impedance and the geometry of the source affect the nature of the mutual coupling. Low-impedance sources (e.g., slot space radiators) are altered by re-radiated magnetic fields while high-impedance sources (e.g., electric dipole) are disturbed by increased localized capacitance due to the presence of the sensor. Magnetically-induced currents in the 11940A loops re-radiate 180 degrees out of phase with the source fields and reduce the flux of the low-impedance source. The presence of the 11940A near a high-impedance source increases the capacitance of the source and changes the magnitude of the current at the point of interaction.

The design of the 11940A rejects stray signals that are normally coupled to a sense probe due to interaction between the source and the measurement system, but does not eliminate this interaction. As a result, the antenna factors that relate flux density through the loops to output voltage remain valid, but the presence of the loops near the source can change the magnitude of the source flux density.

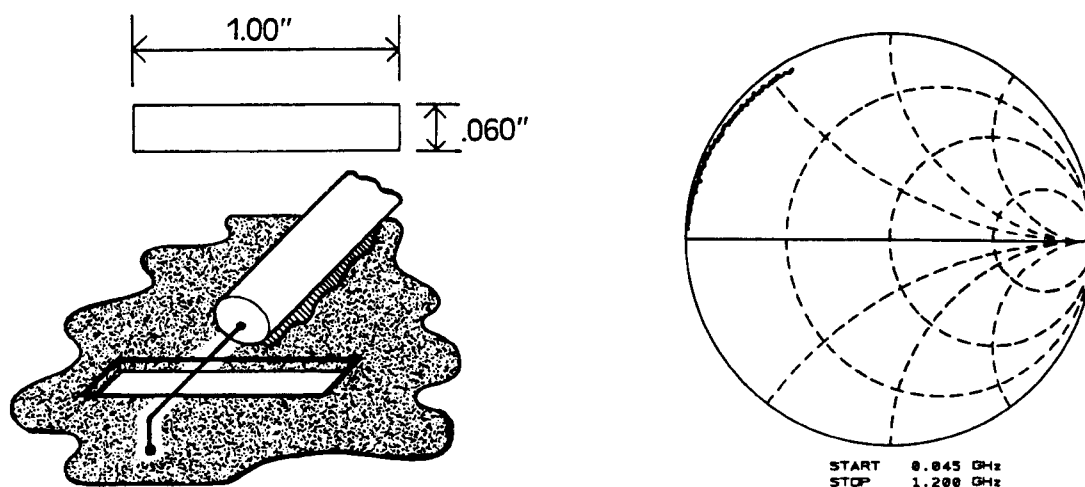
MUTUAL COUPLING (cont.)

How to Determine the Magnitude of the Effects the HP 11940A has on Current Distributions if Each Case is Unique?

Measure Impedance Variations Due to the HP 11940A of Best Case and Worst Case Examples. Impedance Variations Directly Reflect Changes in the Source Current Distributions.

Source current changes due to the presence of the 11940A can be monitored by measuring the changes in the source impedance with a network analyzer. An examination of worst-case variations for low- and high-impedance radiators will provide an understanding of the range of variation relative to the radiator impedances.

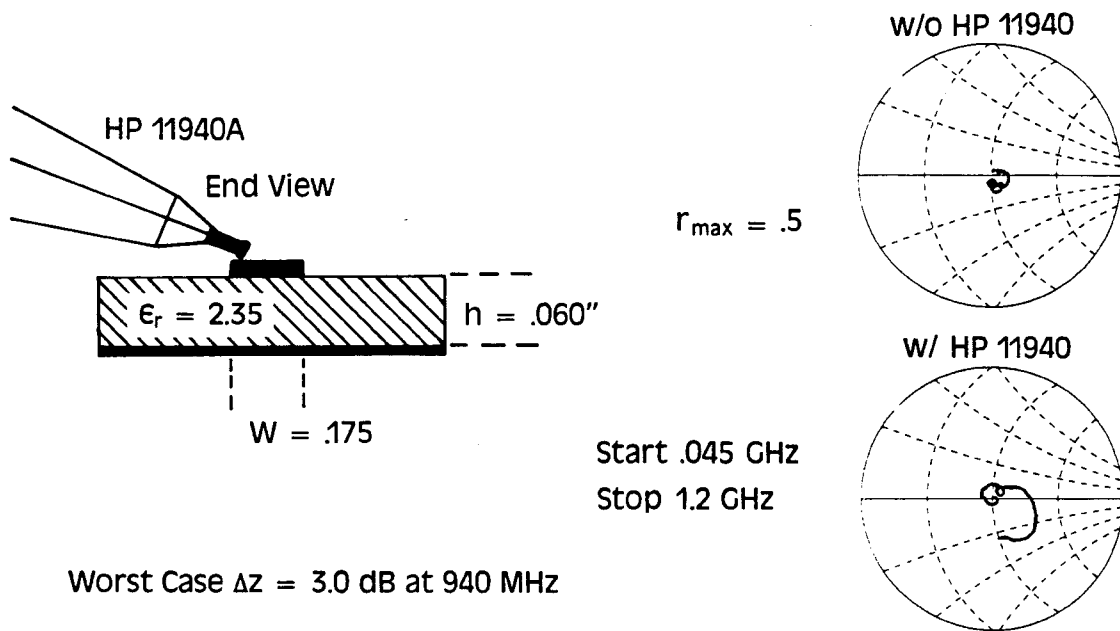
EXAMPLE: LOW IMPEDANCE APERTURE RADIATOR



Worst Case $\Delta z = 1.2\%$ at 1 GHz

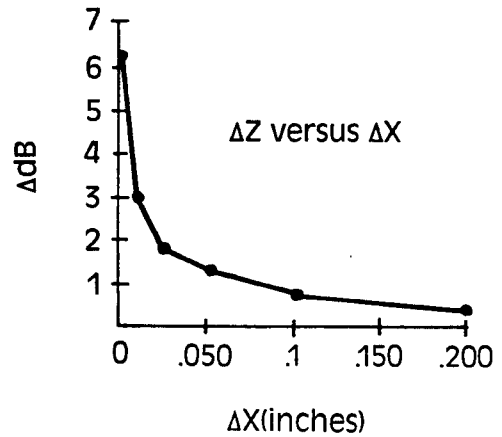
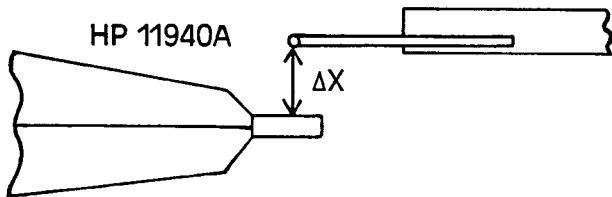
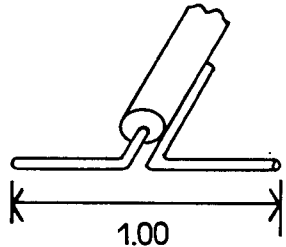
The inductance change of a 3.78 nH aperture radiator due to the presence of an 11940A was monitored using a network analyzer. The inductance was measured with and without the probe maximally coupled to the aperture. The geometry of the aperture was equivalent to that of the 11940A loops (.060" x 1.00"). The aperture inductance was reduced by 1.2%, or .1 dB, due to the re-radiated magnetic field from the 11940A.

EXAMPLE: 50 Ω MICROSTRIP TRANSMISSION LINE



The center conductor of a 50-ohm microstrip line was probed to determine the effects the 11940A had on the measured line impedance. The relative dielectric constant of the support material was kept low (2.35) to maximize the field in the air above the line. The insulated tip of the 11940A was placed in contact with the center conductor and the maximum impedance shift was monitored with an HP 8510 network analyzer. The worst-case impedance change of 3 dB occurred at 940 MHz.

EXAMPLE: HIGH IMPEDANCE DIPOLE ANTENNA



Worst Case ΔZ is 6 dB with Direct Contact at 957 MHz

Strong capacitive coupling between a small 1" unbalanced dipole antenna and the 11940A resulted in the largest observed variations in source impedance. The greatest variation occurred when the 11940A was in direct contact with the dipole conductors. This variation decreased rapidly as the probe was moved away from the radiator. (At .025" spacing, the impedance change is only 2 dB.) The actual conductors on most high-impedance radiators found on equipment (e.g., power and computer cabling) are not accessible because they are insulated with .020" to .050" of dielectric material to avoid shorting.

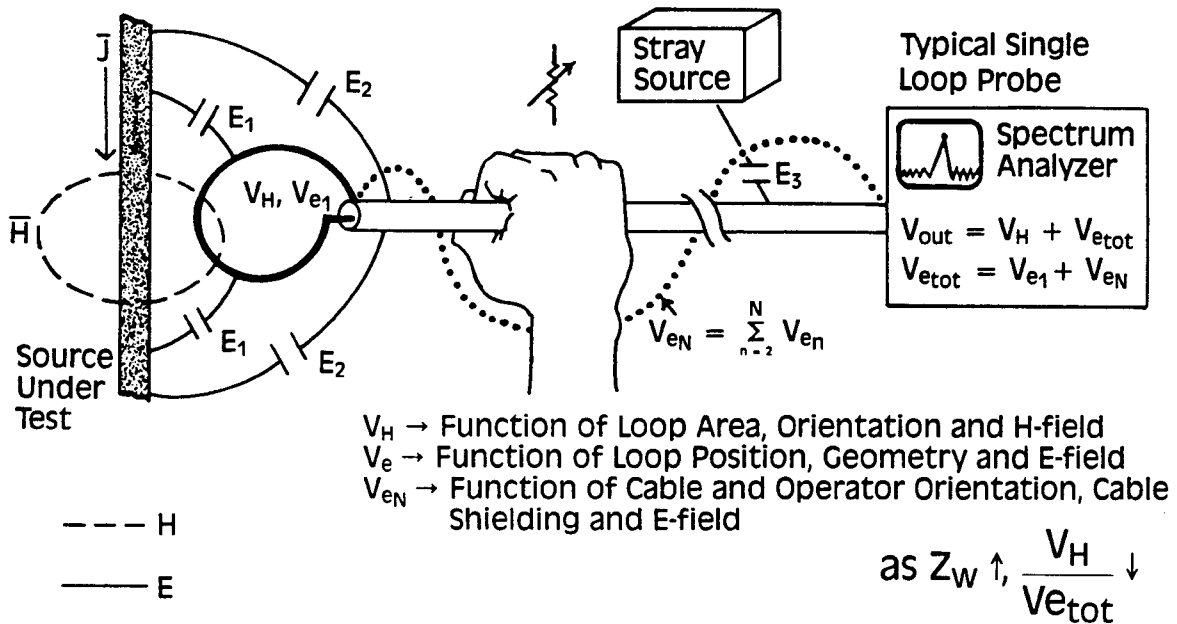
CONCLUSIONS

1. Mutual Inductance Between the HP 11940A and a Low Impedance Source is Low and the Presence of the Probe does not Significantly Affect the Source Current Distribution.
2. Mutual Capacitance Between the HP 11940A and a High Impedance Source can be Significant and is a Strong Function of Spacing. Direct Contact Between the Probe and the Current-Carrying Surface Should be Avoided for Best Accuracy.

The presence of the HP 11940A will not significantly disturb the fields of low-impedance sources. Physical contact between the probe and the actual current-carrying surface of a high-impedance source will affect the localized current distribution. However, most high-impedance sources (such as RF or computer cabling) have an insulation layer over the current-carrying surface to prevent shorting. In this case the disturbance will be in the 1--2 dB range.

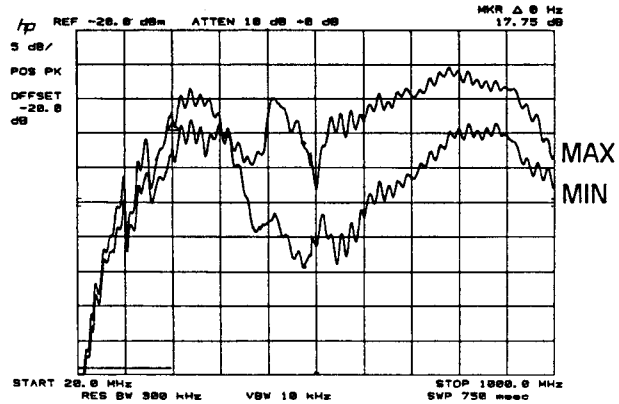
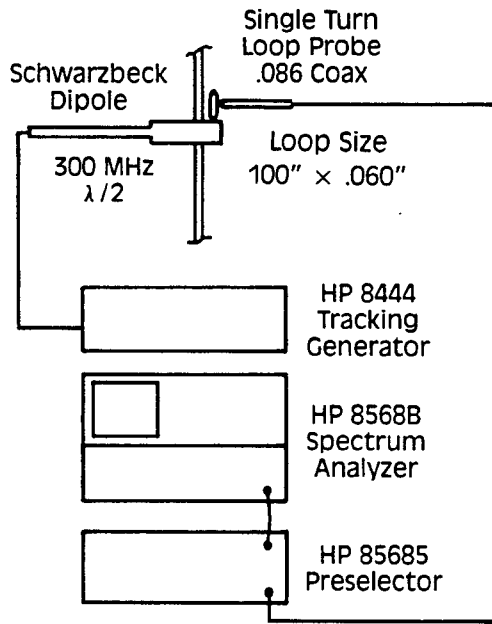
MEASUREMENT REPEATABILITY

... Induced voltage on Probe Cable Shielding



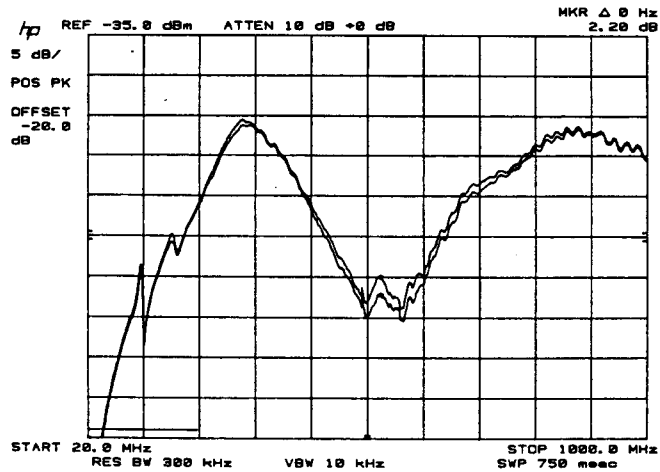
Measurement repeatability is a major problem facing the engineer doing EMI troubleshooting. Comparative field strength measurements require a high degree of antenna insensitivity to the environment in order to provide correct information to the designer. Measurement repeatability is dependent on antenna design, cabling type and layout, measurement technique, and field impedance. Field impedance is defined as the ratio of the electric field to the magnetic field. The output voltage of a single turn unbalanced loop probe is the vector sum of the desired magnetically-induced component and the stray electrically-induced component. For a given probe placement, the output voltage varies as the magnitude and phase of the stray components change relative to each other and to V_H . The operator acts as a variable impedance to the cabling voltage. The ratio of V_H/V_{etot} decreases as the wave impedance increases and the variations in V_{out} become more pronounced. V_{etot} is also affected by cable shielding quality and connector type.

EXAMPLE: OUTPUT VARIATION OF A SINGLE LOOP PROBE



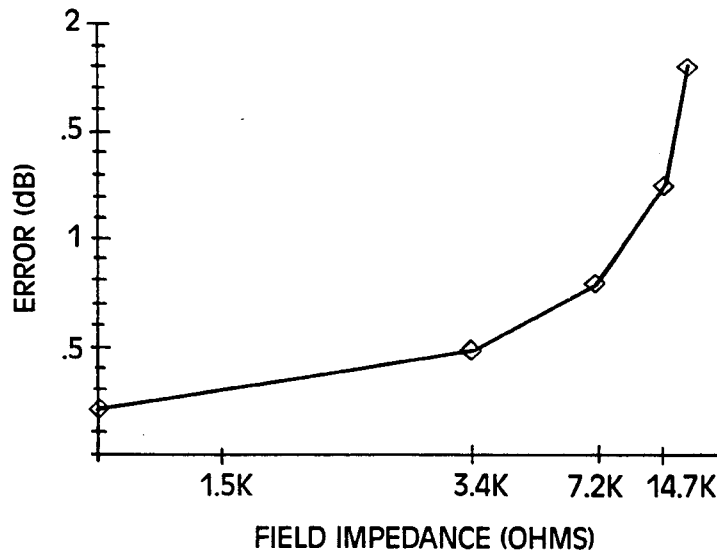
The curves above show the variation in output voltage of a single loop probe as a function of handling and cable position. The upper trace is the maximum value and the lower trace the minimum value of the coupled signal at a given frequency. The source used was a 300 MHz half-wave tuned Schwarzbeck dipole. The position of the single loop probe (1" x .060") relative to the antenna was fixed; only hand and cable positions were changed. By sweeping the dipole from 20 to 1000 MHz and measuring near the feed point of the dipole, we can observe the effects of stray capacitive coupling and varying field impedance on the probe output voltage. The actual field impedance is unknown, but it is related to and larger than the input impedance of the source antenna. The variations are much higher at a high field impedance (600 MHz) than at a low field impedance (300 MHz).

EXAMPLE: OUTPUT VARIATION OF HP 11940A



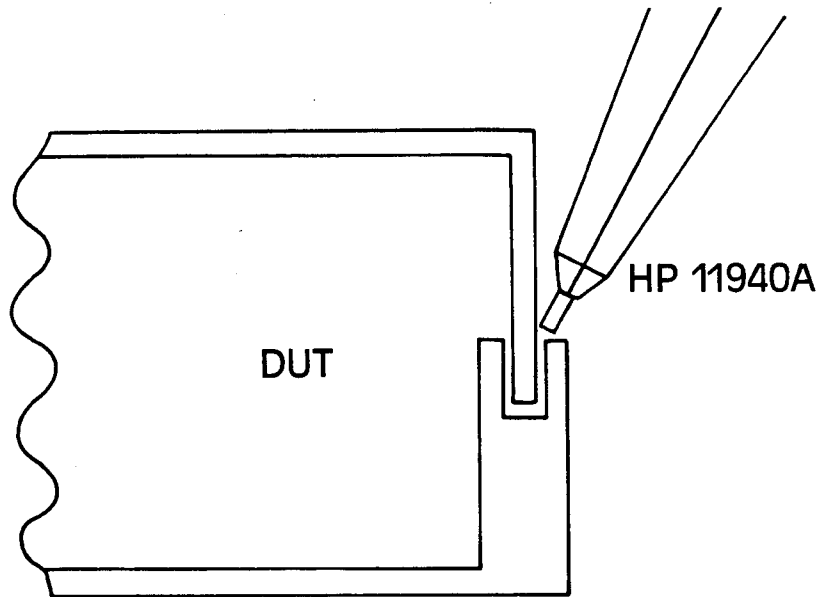
The variation in the output voltage of the 11940A is considerably less than the single loop probe when making the same measurement. Here again, the 11940A was fixed in place relative to the Schwarzbeck dipole: the only variation was hand position and cable placement. The largest output variation was seen with high field impedances near the full wave resonance frequency of the dipole (500--600 MHz).

HP 11940 ERROR VS. FIELD IMPEDANCE AT 30 MHz (typical)



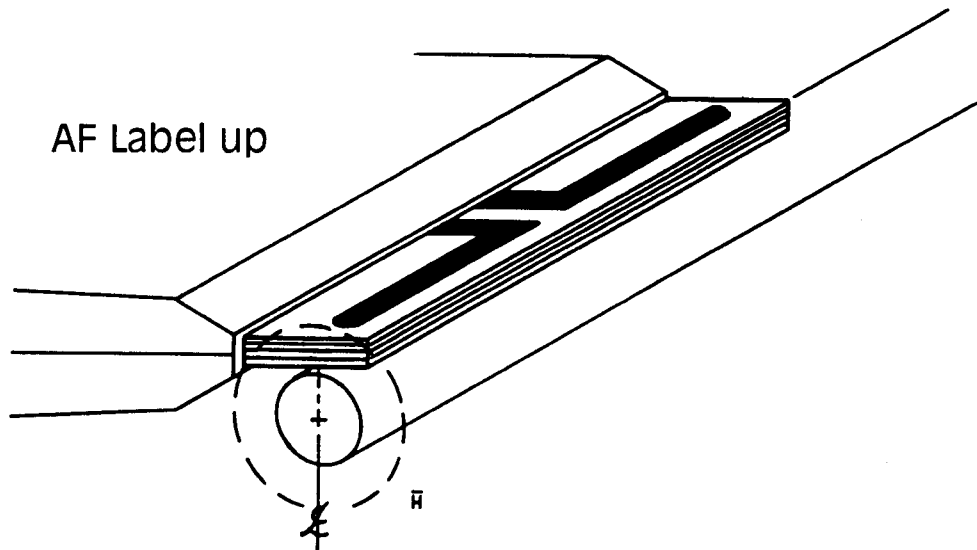
Electrically-induced error signals add vectorially to the magnetically-induced voltage in the 11940A. One method of defining this error voltage is to measure the difference in the probe output voltage for a 180-degree phase reversal in the magnetic field. For one orientation the output voltage consists of $|V_h + V_e|$, and for the other orientation the output voltage consists of $|-V_h + V_e|$. The difference between these two measurements is defined to be the probe error voltage. The data above displays the measured error voltage at 30 MHz as a function of field impedance. For this measurement the probe loops were placed in an electromagnetic field of a coaxial TEM cell. The field impedance was determined from a measurement of the return loss of the chamber. The 180-degree magnetic field reversal relative to the electric field was achieved by measuring fields on opposite sides of the center conductor but at the same radial distance. The loop orientation relative to the center conductor was the same for both measurements. Measured error voltages for field impedances ≤ 377 ohm were less than .2 dB, due mainly to probe placement repeatability and TEM manufacturing tolerances. The cabling was not in the field during these measurements. This work is described in Reference 6.

MEASURING RADIATING APERTURES



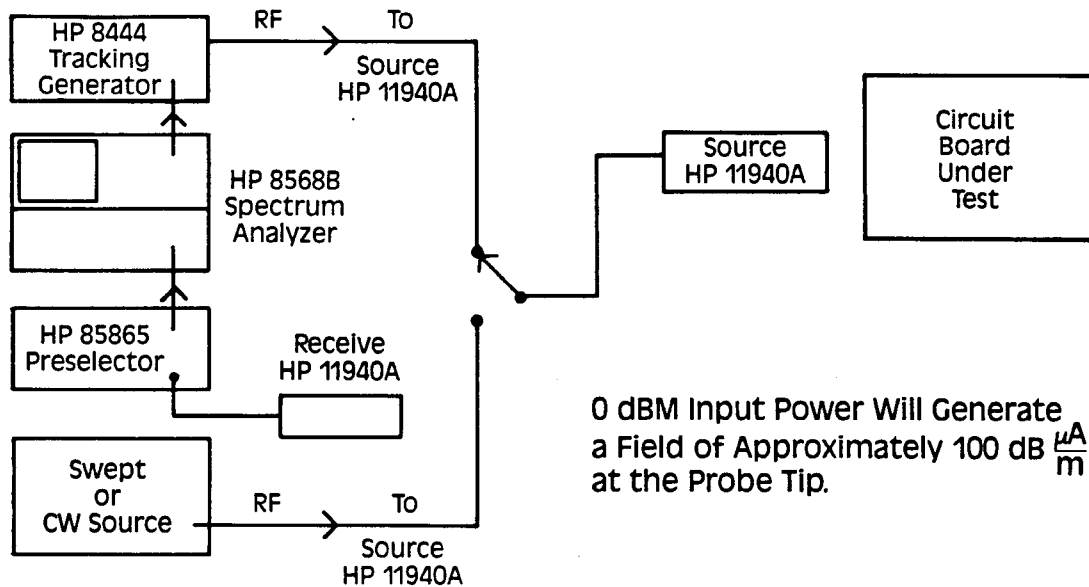
The 11940A is designed to be held in very close proximity to a radiator. The small loop geometry facilitates the location of radiating "hot spots". With this tool, the design or production engineer can quickly locate areas requiring extra shielding. When measuring apertures such as enclosure seams and cooling slots, the long dimension of the probe is to be oriented along the long dimension of the radiator and rotated about the loop edge until maximum coupling is achieved.

CABLING MEASUREMENTS



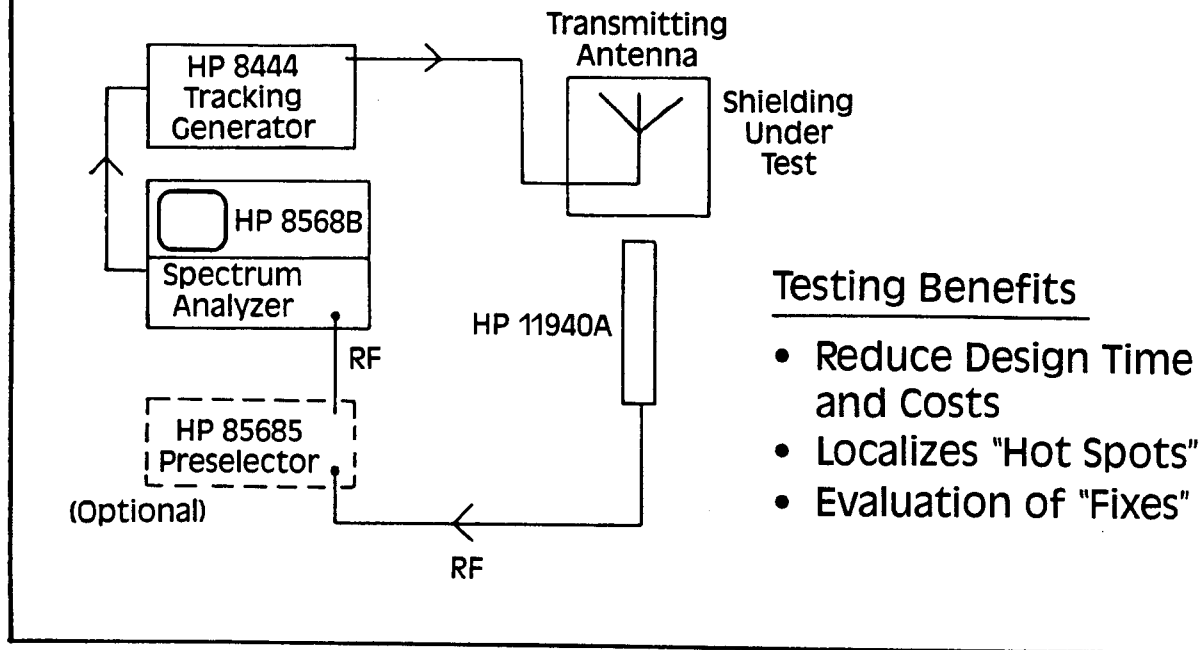
Linearly-oriented common-mode current distributions that exist on single- or multi-conductor cables have strong circumferentially-oriented magnetic field components. The loops of the 11940A should be oriented in the r - z plane to measure this field. These structures should be measured with the antenna factor label facing away from the cable under test. Slight variations in output voltage (1 to 2 dB) will be observed between the two probe orientations when measuring fields with a very high spatial gradient, due to circuitry differences on each side of the 11940A. Caution should be exercised when analyzing the measurements of the close field of structures that carry both differential- and common-mode currents. The field very near the radiator contains components of both types of current; the field of the differential mode is not completely cancelled.

LOCATING SUSCEPTIBLE COMPONENTS WITH LOCALIZED SIGNAL INJECTION



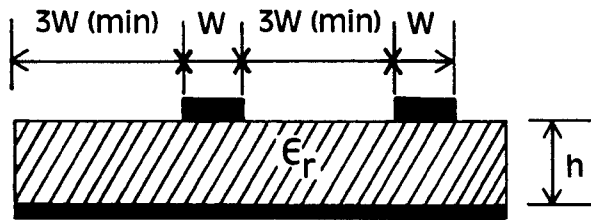
The 11940A can be used as a localized magnetic field source for component-level susceptibility testing. A magnetic field can be generated at the probe loop by injecting current in the SMA connector with either a swept or a CW source. Susceptible areas are located by observing changes in the DUT parameter of interest. Certain types of testing can be done with a tracking generator as a source and a spectrum analyzer as a receiver. Monitoring the DUT response can be done with several techniques. The output of some types of circuitry can be observed directly with a spectrum analyzer. Other circuits can be monitored with a second HP 11940A connected to the analyzer.

TEST SHIELDING EARLY IN THE DESIGN CYCLE



EMI compliance testing is typically performed during the latter stages of the design cycle—a time when design modifications can be expensive and can cause considerable delays in the completion of a project. The system shown above can be used to evaluate initial mechanical designs. The radiator in this system is not the actual system circuitry. A transmitting antenna is used in place of the circuitry. This antenna is driven with a tracking generator. Tracking generators make ideal sources for this work because they provide an output signal that tracks the tuning of the spectrum analyzer LO, thus providing a wide dynamic measurement range. With this system, hot spots in initial designs can be located and fixes for these areas can be evaluated. References 3 and 4 discuss this type of testing.

MICROSTRIP TRANSMITTING ANTENNA



Design Example

$$\begin{aligned}\epsilon_r &= 2.35 \\ W &= .150 \\ h &= .070 \\ Z_0 &= 50 \Omega\end{aligned}$$

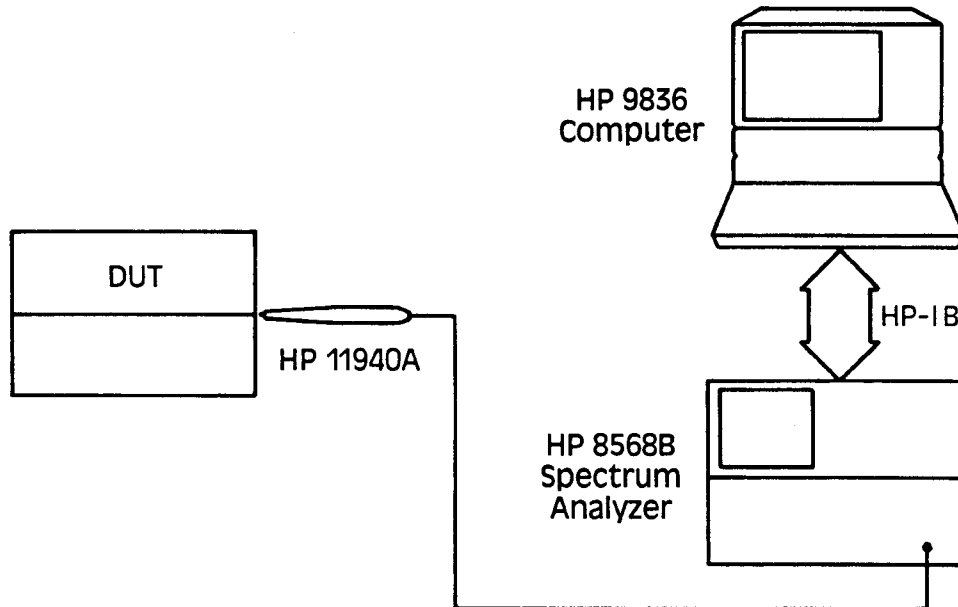
Spacing Between Line and Board
Edge or Another Trace = 3W Minimum
to Ensure 50 ohms

A microstrip transmission line is a waveguiding structure consisting of a planar center conductor suspended above a ground plane. The impedance of the line is determined by three parameters: the width of the planar center conductor, W ; the conductor's height above ground plane, h ; and the dielectric constant of the support material. This structure features:

1. broadband, repeatable, characteristic impedance--insensitive to external surroundings;
2. easy, inexpensive construction;
3. size flexibility;
4. readily-available design curves (see References 7, 8);
5. good power-handling capability;
6. low radiation efficiency.

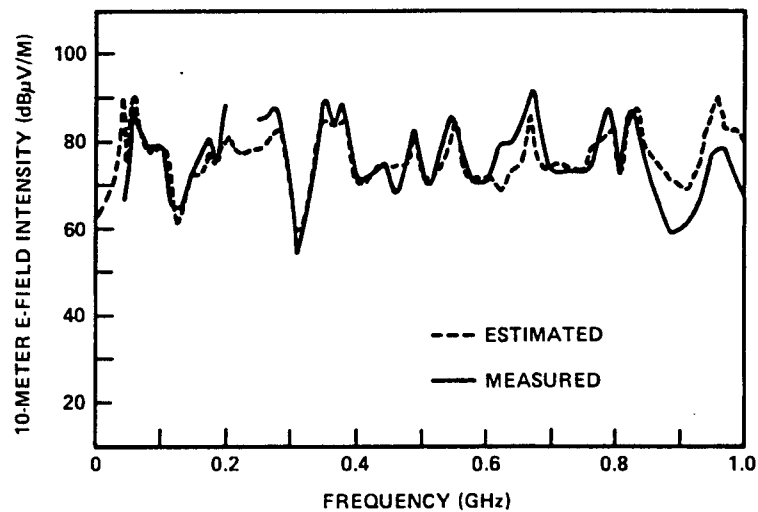
Radiation efficiency is improved by minimizing the material's dielectric constant.

IDENTIFYING RADIATED FREQUENCIES



The 11940A can be used to catalog "suspect" frequencies radiated from a given DUT to facilitate open-site testing. Cataloging possible problem frequencies prior to open-field testing reduces site time requirements.

MODELLING RADIATED FIELDS



Relationships between measured near-field and estimated far-field amplitudes can be generated. This field modeling can range in complexity from observed comparisons between measured near- and far-field data to actual computer algorithms that predict the radiated far-field amplitudes from measured near-field data. The curves above compare actual measured far-field amplitudes to estimated amplitudes generated from laboratory measurements using computer algorithms. The known antenna factors of the 11940A make these estimations possible. Reference 5 discusses this modeling work.

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