IMPROVEMENTS TO THE DETECTION AND ELIMINATION OF LEAKAGE IN THE NATIONAL ATTENUATION MEASUREMENT FACILITY

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Introduction

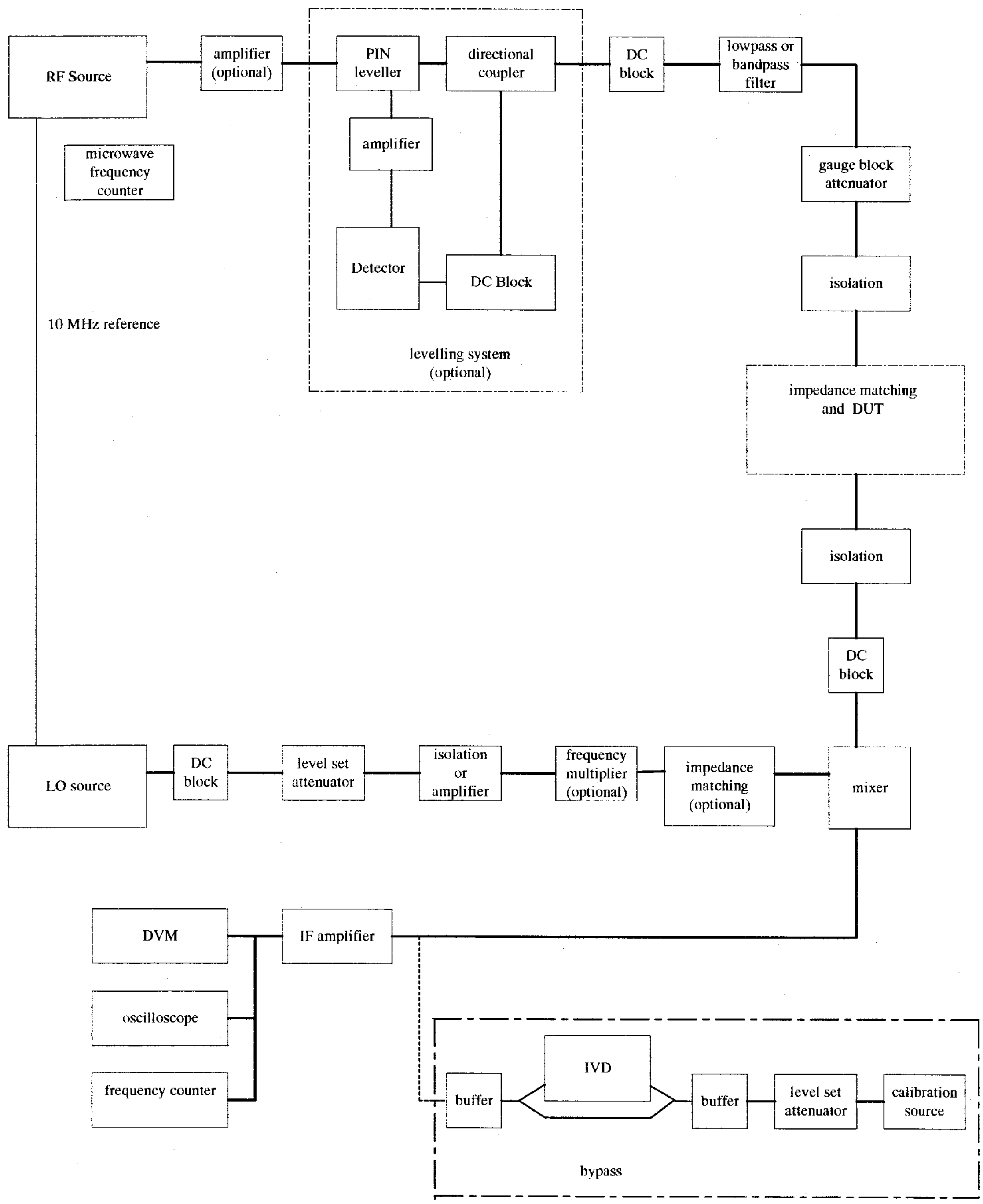
NPL is continually working to improve its measurement capability. In the RF and Microwave attenuation area we have seen an increased demand for high attenuation measurements over 80 dB. While there are many contributions to attenuation measurement uncertainties, leakage has always been one of the major limiting factors in the uncertainty of very high attenuation measurement.

Any signal reaching the detector in an attenuation measurement system, other than through the correct path which includes the device under test, can be considered as a leakage signal. This paper covers some of the techniques being employed to detect and reduce leakage in the current attenuation systems.

Typical Attenuation Measurement System

A typical Voltage Ratio Attenuation Measurement System is shown in figure 1. In these systems the RF or microwave signal is passed through a gauge block attenuator and the device under test before being down converted to a low frequency. In our systems this lower frequency is either 10 kHz or 50 kHz. It is measured by a commercial AC digital voltmeter, previously calibrated using a stable low frequency source and an inductive voltage divider, the latter being the attenuation standard. As can be seen from the diagram there are a considerable number of individual components, all of which need to be interconnected. Each unit and interconnection, and even power or control lead, presents a potential source of leakage. Consequently there can actually be many leakage paths, all of which must be eliminated. Further details of these systems can be found in references 1 and 2.

Figure 1: Voltage Ratio - General System Diagram



As can be seen from Table 1 the high dynamic range and frequency coverage of the NPL systems means that we have to address leakage under many different conditions.

Table 1: Typical NPL Attenuation Capability

Frequency Range	**Attenuation Range**	**Estimated uncertainty (95% confidence level)**	**Transmission Media**
			50 Ω Coaxial Line
10 kHz, 50 kHz	0 dB to 90 dB	(0.0006 dB / 10 dB) + 0.0006 dB	
0.5 MHz to 100 MHz	0 dB to 100 dB	(0.0006 dB / 10 dB) + 0.0006 dB	Supported Connectors: GR900, N, Precision N, GPC-7, GPC-3.5, 2.92, 2.4
	100 dB to 120 dB	(0.0008 dB / 10 dB)	
	120 dB to 130 dB	(0.001 dB / 10 dB) + 0.01 dB	
0.1 GHz to 18.0 GHz	0 dB to 100 dB	(0.0006 dB / 10 dB) + 0.0006 dB	
18.0 GHz to 26.5 GHz	0 dB to 80 dB	(0.0006 dB / 10 dB) + 0.0006 dB	
26.5 GHz to 40.0 GHz	0 dB to 80 dB	(0.0006 dB / 10 dB) + 0.0006 dB	
40.0 GHz to 50.0 GHz	0 dB to 70 dB	(0.0006 dB / 10 dB) + 0.0006 dB	
			Rectangular Waveguide
2.4 to 3.95 GHz	0 dB to 90 dB	(0.0006 dB / 10 dB) + 0.0006 dB	WG10
3.3 to 4.9 GHz			WG11A
3.95 to 5.85 GHz			WG12
5.85 to 8.2 GHz			WG14
7.5 to 10.0 GHz			WG15
8.2 to 12.4 GHz			WG16
10.0 to 15.0 GHz			WG17
12.4 to 18.0 GHz			WG18
18.0 GHz to 26.5 GHz	0 dB to 80 dB	(0.0006 dB / 10 dB) + 0.0006 dB	WG20
26.5 GHz to 40.0 GHz			WG22
33.3 GHz to 50.0 GHz	0 dB to 70 dB	(0.0006 dB / 10 dB) + 0.001 dB	WG23
50.0 GHz to 75.0 GHz	0 dB to 60 dB	(0.001 dB / 10 dB) + 0.001 dB	WG25
75.0 GHz to 110.0 GHz	0 dB to 50 dB	(0.001 dB / 10 dB) + 0.001 dB	WG27

The dynamic range of the systems depends on a combination of factors including the available source power, the noise generated by the RF or microwave mixers used to convert the RF or microwave signal to that of the attenuation standard and the sensitivity of the final detector to the unwanted noise. Generally the dynamic range is not limited by the leakage itself, but this becomes one of the major uncertainty contributions.

Uncertainty due to leakage

An expression for the effects of the leakage signal is derived in Chapter 2 of Reference 3. The resultant amplitude at the receiver due to the paths through the device under test and the leakage path is given by:-

$$E_R = 20\log_{10}(E_A^2 + E_L^2 + 2E_A E_L \cos\phi)^{1/2}$$

Where E_A and E_L are the signals at the receiver via the device and the leakage paths respectively with a phase difference ϕ between them. The phase can take on any value, depending upon the path differences, and the upper and lower limits of the leakage occur when $\cos \phi = \pm 1$. In practice the phase of the leakage relative to the wanted signal is very difficult to measure and probably alters during the course of the measurement due to changing physical layouts etc. Provided that the leakage is considerably less than the signal path the expression for the upper and lower limits of the attenuation error due to the leakage path reduces to:-

$$\Delta A_L \approx \pm 8.686\{10^{-(A_L - A_A)/20}\}$$

Thus the effect of leakage depends only on the relative signal levels. This is a Type B (systematic) uncertainty with the quoted maximum errors being considered as a rectangular distribution. Thus the standard leakage uncertainty contribution is obtained by dividing the maximum error, ΔA_L by $\sqrt{3}$.

The following table lists the standard uncertainty as a function of the signal to leakage path. To obtain an uncertainty contribution of about 0.001 dB (at 95% CL) requires that the leakage must be at least 75 dB below the signal level. For comparison, at NPL, a good (ie well matched and repeatable) 100 dB attenuator can be measured with a total uncertainty of 0.007 dB (95% CL). As can be seen from the following table, the effect of leakage is comparatively insignificant at lower attenuation value, but increases exponentially and will dominates the budget for the higher attenuations.

Table 2: The effects of leakage on the measured signal

Leakage Attenuation - Signal Path Attenuation (A_L - A_A) (dB)	Standard Leakage Uncertainty (dB)
90	0.00014
70	0.0014
50	0.014
30	0.14

Detecting Leakage

Several alternative techniques have been employed to detect the system leakage, either directly or indirectly. One of the least efficient is to repeatedly measure a known attenuator while making minor changes to the system. Generally 'hunting' for leaks with a small wire loop or horn antenna connected to a spectrum analyser or receiver fails due to the lack of sensitivity or positional resolution to identify the leakage source. Additional detectors connected directly to the measurement systems specifically to measure leakage have proved to be more successful. However care must be exercised as the additional components (usually extra amplifiers followed by power sensors) frequently cause an increase in the leakage - occasionally swamping the signal they are there to detect.

Normally the leakage investigation is made with either loads or short circuits connected in place of the DUT, however even well made loads have been known to radiate, abet at a low level. Leakage checks must be made with the gauge block attenuator in both its maximum and minimum settings if a realistic leakage estimate is to be made.

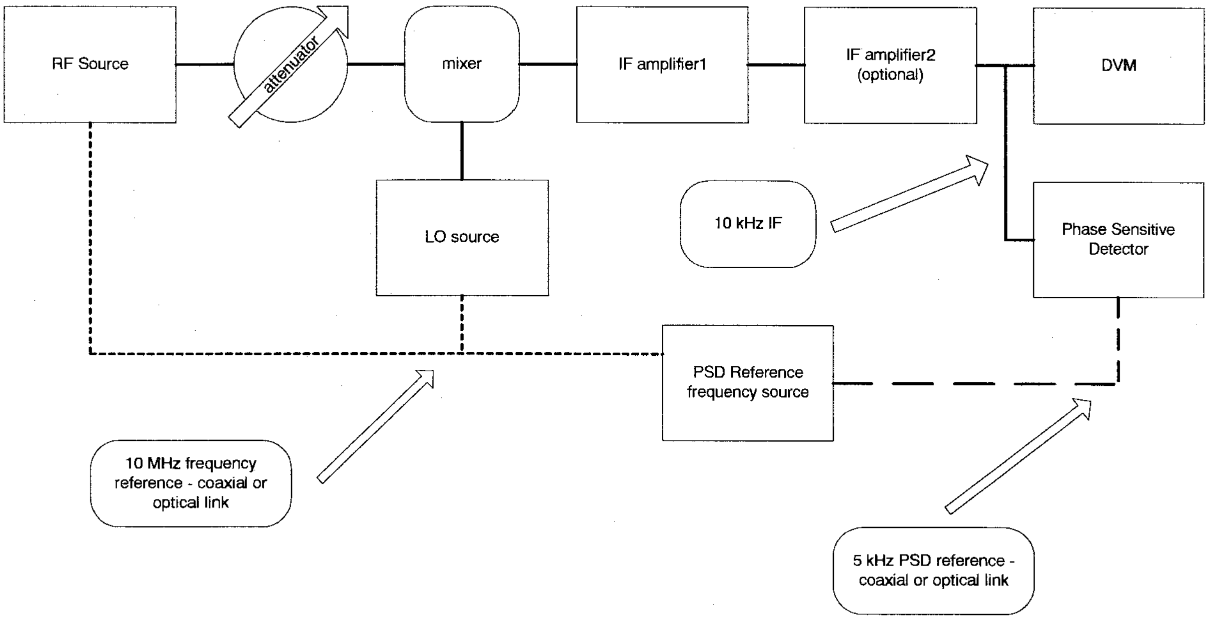
The Phase Sensitive Detector

The most effective device we have found for assessing leakage is a phase sensitive detector (PSD). PSDs, sometimes called lock in amplifiers, can be considered as vector voltmeters measuring the amplitude and phase of signals having a coherent phase relative to a reference signal. As they are comparatively insensitive to signals that are not phase related to the reference (ie noise) they are ideal for measuring small signals in the presence of other, larger random, signals. The instruments we use, when connected into the attenuation systems, and operated at high gain settings, can reliably detect signal at the –150 to –170 dBm level. As the detected signal is displayed as relative amplitude and phase they offer a very powerful tool in detecting the source of leakage. As the phase of the leakage signal can easily be changed by altering the electrical length of leakage path, for example by placing a hand close to the system, the leakage source can easily be discovered.

In making leakage assessments the PSD does not require calibration, just an initial reference level. This can be achieved by placing the DUT and the GB to a high attenuation and relating the normal DVM reading to the PSD displayed amplitude. For the purposed of assessing leakage the IF amplifier (which will have its gain increased) and the PSD can be assumed to be sufficiently linear for reliably estimating the leakage signal.

The principal disadvantage of the PSD is that it requires a reference input. With most detectors this is at the same frequency as the signal being measured. With our microwave systems the reference is commonly derived from a third synthesiser with its reference frequency locked to the other RF sources. These additional components, plus a large signal at the IF frequency can be an additional source of leakage, frequently greater than the leakage under investigation. One solution to this problem is to lock the PSD not to a reference at the IF frequency but to one at half this, and use the ability of many modern PSDs to measure the harmonics of the reference. As we commonly use a 5 kHz reference for a 10 kHz signal the method is referred to as f/2 locking. There is of course a requirement that all the synthesisers are capable of phase locking their output to the 10 MHz reference signal if stable operation is to be obtained.

Figure 2: Simplified PSD system – 190 dB range



How do you reduce leakage?

Most of the sources of leakage can be addressed through good electrical and mechanical design and assembly. Using the shortest cable or interconnect runs, particularly at high signal level points of the system, is highly effective. Checking that all connectors are correctly torqued, and that they remain tight is equally important. By mechanically supporting components the strain on connectors can be reduced, substantially reducing the possibility of connectors twisting and then undoing themselves. At NPL we frequently resort to using aluminium foil, adhesive copper tape and wire wool (contained in plastic bags) for maintaining an effective screen. However such methods must be applied judiciously as it is possible to short out the DC blocks placed in the systems to prevent circulating earth currents.

Where the expense can be justified, we have manufactured aluminium cases for equipment that is particularly prone to leakage. These cases are constructed from 3 to 6 mm thick aluminium alloy plate with five of the six sides welded together. The lid is then bolted down to a machined flat surface to complete the screening. Adding these boxes to our commercial automated 1.8 –18 GHz coaxial tuners improved their leakage performance by over 25 dB.

Optical isolators

The RF source, local oscillator and phase sensitive detector all require to be locked to a common frequency reference. The coaxial interconnections create unwanted signal paths. In our 0.5 - 100 MHz attenuator calibrator, the RF sources have proved to be so stable that no frequency reference link is necessary. Removing this link improved the leakage from -180 to over -190 dBc, indicating that the signal frequency was leaking through the 10 MHz reference cable. This is a significant improvement as the potential dynamic range of this system can approach 160 dB.

To provide similar levels of leakage performance on our other systems optical isolators have been investigated to transfer the 10 MHz synthesiser frequency reference and the 10 or 50 kHz PSD reference signals. The technique was successfully pioneered by F L Warner in the NPL 0.5 –100 MHz attenuator calibrator, however he confined the optical path to just the 10 kHz PSD reference signal. The transmitter unit is a TTL input buffer driving a light emitting diode coupled to an optical fibre. This optical fibre provides complete electrical isolation (if the path via the mains power supplies is neglected). The receiver is a photodiode followed by a suitable amplifier. For the 10 MHz detector, it has been found necessary to follow the amplifier with a comparator to give a 'clean' signal suitable for locking a synthesised signal generator. For best isolation these amplifiers are fed from 'floating' power supplies.

While not directly relevant to the reduction of RF leakage, careful design of the cable runs and the use of DC / low frequency blocks and attention to the earthing of individual items of equipment can eliminate the problems associated with circulating earth currents. Circulating earth currents cause ohmic losses in the outer conductors of coaxial cables. This gives rise to leakage effects in that currents are set up between connected items at different RF potentials, these currents having amplitude and phase relationships to the RF signal.

System Performance

The phase sensitive detection for the detection of leakage has been in use for some time on low lowest frequency system, which incorporates a custom built PSD with the detector reference supplied via an optical fibre link. The lowest recorded leakage on this system has been 193 dB.

Commercial PSDs, both analogue and digital, are now routinely used on our 0.1 to 18 GHz systems with the PSD reference being supplied by a dedicated low frequency synthesiser locked to the main 10 MHz reference. This enables the PSD reference to be different from the signal frequency. After paying considerable attention to the screening and interconnection of the individual system components leakage levels of 170 dB are obtained on a regular basis. This is 70 dB below our normal working range. However, at discrete frequencies the apparent leakage is 'only' –150 dBc due to unwanted spurious emissions from the system LO source. For example we have found that synthesisers operating at 1.000010 GHz (1 GHz + 10 kHz) often have a 1 GHz component present at about –150 dBc. However at 1.000008 GHz (1 GHz + 8 kHz) the spurious 1GHz signal is below –170 dBc.

Other sources such as PCs and data networks within the laboratories can also cause interference. Many of these 'external' signals are derived from moderately stable oscillators and can be seen to be slowly drifting in and out of phase with the wanted signal.

Over 18 GHz the technique proves slightly less effective due to the need to provide a phase stable reference to the PSD. While this can, in part, be reduced by using the PSD in 'amplitude / phase' output mode (as opposed to the in phase and quadrature display), jumps and rapid changes of relative phase between the 10 MHz reference and the synthesised RF output are difficult to distinguish from changes in leakage. Some microwave synthesisers are generally better in this respect than others and the technique has proved capable of use to 40 GHz.

This locking problem can be eliminated by using a dual channel system with two RF mixers fed from a common LO. One mixer provides the reference signal for the PSD by downconverting an RF signal taken before the gauge block and DUT. The second mixer follows the DUT in the normal way. However, as the reference signal is at the IF frequency, leakage becomes a problem and so the technique is commonly only used over a lower dynamic range. Having a reference signal at the IF also permits the direct measurement of phase changes by connecting a phase meter between the two (IF) channels.

Other Applications 1: Series Substitution Attenuation Measurements

Series substitution is a technique where the value of an unknown attenuator is compared directly against a known 'infinitely' variable attenuator connected in series. The known attenuator can be operated at the same frequency as the unknown device but it is more commonly positioned after a mixer and operated at a lower frequency. Rather than directly calibrating the detector (as with the Voltage Ratio technique), the detector is only used to indicate that, after inserting the unknown device, the known attenuator has been adjusted to restore the original detected signal level. PSDs are suitable as detectors in this application as they are highly immune to noise. To improve the resolution it is common practice to compare a PSD analogue output to a stable voltage using a millivoltmeter.

Other Applications 2: Leakage Cancellation

As leakage is a vector quantity it is necessary to establish both the magnitude and relative phase of the 'real' and leakage signals if any sort of numerical correction can be applied. While in principle it would be possible to use a phase sensitive detector to make these measurements and then apply a correction, in practice the leakage signal is both at a very low level, which makes accurate determination of phase difficult, and it is also not constant, being dependant on the DUT setting. This makes it impractical to perform a real time correction for low level leakage signals.

Summary

Phase sensitive detection has proved to be a very successful tool for detecting unwanted leakage signals. By generating a reference signal for the PSD at a sub-harmonic of the (IF) signal frequency many of the problems associated with the presence of additional large signals at the measurement frequency can be avoided. The system has potentially a detection level below –170 dBm, which when combined with a 20 dBm RF or microwave source gives a leakage measurement range in excess of 190 dB.

By taking care with the design and assembly of the attenuation facilities, leakage levels of 190 dB have been obtained on the 10 – 100 MHz system and leakages of 170 dB can regularly be obtained up to 18 GHz.

Acknowledgements

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References

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2. Microwave Attenuation Measurement, F L Warner IEE Monograph Series 19, Peter Peregrinus Ltd. 1977 ISBN:0 901223.