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Measurement of leakage signal in radio frequency or microwave systems

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Vitawat Sittakul[1], Sarinya Pasakawee[2] ✉

[1]*Department of Electronics Engineering Technology, King Mongkut's Institute of North Bangkok, Bangkok, Thailand*
[2]*National Institute of Metrology (Thailand), Klongluang, Pathumthani, Thailand*
✉ *E-mail: sarinya@nimt.or.th*

Abstract: This study proposes a setup configuration for leakage signal measurement in a radio frequency or microwave system. The leakage signal usually influences on such a system and basically is defined as a source of uncertainties. In this configuration, a programmable attenuator is used as the device under test (DUT) in the system to fully study the leakage signal effects. The DUT is initially characterised in terms of phase as a function of attenuation before used to represent any electronic device with a specific insertion loss and frequency. Then, the amplitude and phase of the leakage signal are found and compared with the mathematical model to confirm the obtained results. Finally, the maximum amplitude deviation of the leakage signal is found and used to calculate as a limit of leakage error.

1 Introduction

There are many electrical devices in radio frequency (RF) and microwave systems such as mobile phones, digital television boxes, cable televisions, satellite systems, wireless local area network access points and radar systems. In these systems, the signal frequencies are very high (>10 MHz) and it is very difficult to precisely measure the electrical quantities (amplitudes and phases) without their uncertainties. According to [1], the uncertainties are classified based on type A and type B contributions. The type A uncertainty is calculated from statistical distribution of quantity values from series of measurement and can be characterised by standard deviations. The type B uncertainty can also be characterised by standard deviations, evaluated from probability density functions based on experience or other information.

As for RF or microwave measurement system, there are many sources of type B uncertainties: reference standards, mismatch, system linearity, connector repeatability, stability, resolution, non-linearity and leakage [2, 3]. However, very little research has studied the leakage [4–6] and hence this paper focuses on this effect. At high frequencies, the signals do not only propagate in transmission lines, circuit boards or cables but also in the air or device surfaces, known as leakage signals. Particularly, for low attenuation measurements (≤60 dB), the commercial 2-port RF instrument such as a network analyser, can be used to find these quantities.

However, for high attenuation measurements (>60 dB), the leakage signals contribute more significant errors. Many sources of leakage are found in such systems and many methods are used to minimise these leakage effects such as using short cables, interconnecting between the instruments, using aluminium foil, adhesive copper tape and wire wool [4]. Unfortunately, the effects of leakage signal depend on both signal level and phase and they cannot be easily detected. Therefore, in order to accurately measure the wanted signals, their effects have to be understood and taken into account.

To investigate the leakage effects, some techniques have been carried out [4–6]. Here, the attenuators with different attenuation values can be applied in the systems to increase or decrease the leakage signals. Then, the effects of leakage signals as a function of attenuation values can be measured.

As shown in Figs. 1 and 2, it is an attenuation measurement system using the voltage ratio principle as described in [5–8] to investigate the leakage effects [4]. In such a system, the RF or microwave signal frequency is down converted by mixing with a local oscillator to be a low frequency at 10 kHz. Then, the signal level is amplified by an intermediate frequency (IF) amplifier and measured by a commercial digital multimeter. The phase detector is used to compare the different phases between the measured signal and the 5 kHz reference signal. The variable attenuator is used as the device under test (DUT) in the system to adjust the attenuation of the system. The DUT can be used to simulate any electronic device with a specific insertion loss and frequency.

Each unit, connection and cable presents sources of signal leakage and the leakage effects are predicted according to the mathematical model. However, the phases of the leakage signals cannot be changed in such system, and therefore the leakage effects as a function of phase cannot be measured. Recently, a configuration to measure the leakage in broadband RF and microwave systems is demonstrated in Fig. 3 [5, 6] using IF substitution technique as described in [7, 8].

In this configuration, the different phases of the leakage signals can be changed through a set of delay lines, relative to the input signal and the leakage effects as a function of attenuation and phase. However, the use of delay lines has some disadvantages; their phases are fixed at a specific frequency and cannot be tuned. Thus, in this paper, a new attenuation measurement system is presented where the delay lines are replaced by the uses of a phase shifter and a network analyser. A phase shifter is used to change the phase of the leakage signal and the phase is then confirmed by the network analyser. With this scenario, it is possible to precisely measure the leakage signal and its information can be used to calculate as a limit of leakage error.

This paper is organised as follows: Section 2 describes the theory and mathematical model of leakage signal. Section 3 shows the DUT characterisation and Section 4 explains the experimental setup. In Section 5, the experimental results are compared with the mathematical model to confirm the obtained results and the limit of the leakage error can be found.

2 Theory

In any RF or microwave system, the total measurement signal through the DUT at receiver (E_R) can be found from the sum of wanted signal (E_A) through the DUT at the receiver and the

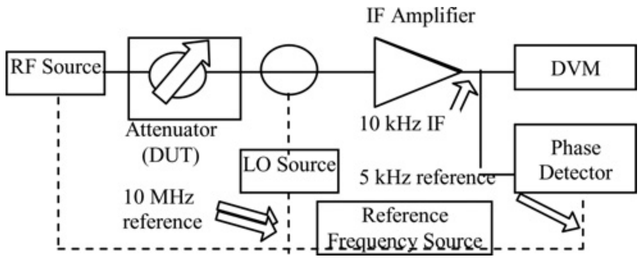

Fig. 1 *Typical attenuation measurement system [4]*

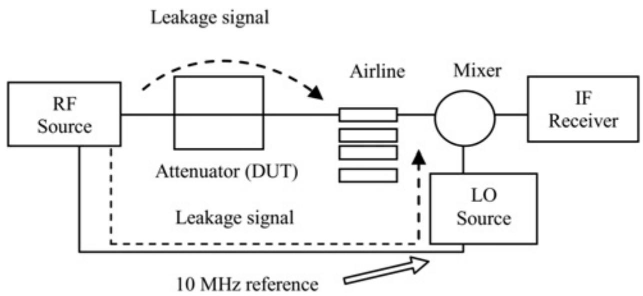

Fig. 2 *Simple attenuation measurement system [5, 6]*

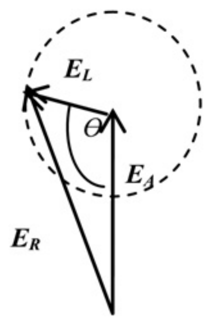

Fig. 3 *Leakage signal of DUT*

leakage signal (E_L) as shown in Fig. 4. E_L are any signals that propagate through undesired paths to reach the receiver. The resultant amplitude at the receiver through the DUT is given by [5, 6]

$$E_R = \left\{E_A^2 + E_L^2 + 2E_A E_L \cos\theta\right\}^{1/2} \quad (1)$$

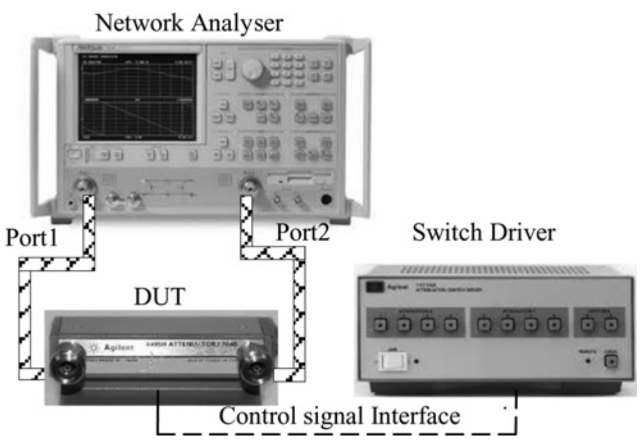

Fig. 4 *DUT characterisation setup diagram*

where θ is the phase between E_A and E_L. During the measurement, the amplitude of the input signal (E_G) is put through the DUT and it causes E_L with an uncertainty. In the attenuation measurement, the leakage uncertainty (δA_L) is given by

$$\delta A_L = 20\log_{10}\frac{E_G}{E_R} - 20\log_{10}\frac{E_G}{E_A} \quad (2)$$

$$= 20\log_{10}\left\{1 + \left(\frac{E_L}{E_A}\right)^2 + 2\frac{E_L}{E_A}\cos\theta\right\}^{-1/2} \quad (3)$$

From (3), the leakage uncertainty or δA_L can be reached maximum/minimum when $\cos\theta = \pm 1$ and this maximum leakage uncertainty can be simplified to

$$\Delta A_L = 20\log_{10}\left(1 \pm \frac{E_L}{E_A}\right)^{-1} \quad (4)$$

E_L and E_A can be re-written in terms of attenuations A_L and A_A in decibels (dB) as $E_L/E_A = 10^{-(A_L-A_A)/20}$ and (4) becomes

$$\Delta A_L = 20\log_{10}\left(1 \pm 10^{-(A_L-A_A)/20}\right)^{-1} \quad (5)$$

As can be seen in Section 5, the expression (5) can be experimentally found by subtracting the maximum δA_L by the minimum δA_L and they occur when $\cos\theta = \pm 1$. In practice, the leakage signal is significantly lower than the wanted signal and it is possible to apply the mathematical approximation of ($e^x = 1 + x$) to (5). The expression in (5) can be simplified to

$$\Delta A_L = 20\log_{10}\left(e^{-10^{-(A_L-A_A)/20}}\right) \quad (6)$$

$$\Delta A_L = -10^{-(A_L-A_A)/20} \times 20\log_{10}(e) \quad (7)$$

$$\Delta A_L = \pm 8.686\left(10^{-(A_L-A_A)/20}\right) \quad (8)$$

3 DUT characterisation

The programmable attenuator (Agilent 8496H) is used as the DUT. It is very important to check whether the change in the attenuation of DUT (A_{DUT}) significantly affects its phase. Therefore, the DUT has to be characterised in terms of phase as a function of attenuation as shown in Fig. 4.

Fig. 4 shows the setup for DUT characterisation. The two ports of the DUT are connected to ports 1 and 2 of the 40 MHz–20 GHz network analyser (Anritsu 37347C) to measure the phase of $S21$ parameter. The attenuation of DUT can be adjusted and controlled via the switch driver (Agilent 11713A) by pressing the switches (numbers 1–4). Initially, all switches are turned off to a reference of 0 dB attenuation and 0° phase reference. Then, the attenuation

Table 1 Phase shift due to A_{DUT} at 5, 12 and 18 GHz

Switch number	Attenuation value (A_{DUT}), dB	Phase shift (5 GHz), deg	Phase shift (12 GHz), deg	Phase shift (18 GHz), deg
–	0	0	0	0
1	10	−7.2	−16.6	−26.3
2	20	−4.5	−10	−15.5
1 + 2	30	−11.7	−26.6	−41.8
3	40	4.5	14.4	36.7
1 + 3	50	−2.7	−2.2	10.4
2 + 3	60	0	4.4	21.2
1 + 2 + 3	70	−7.2	−12.2	−5.1
3 + 4	80	8.8	28.1	72.5

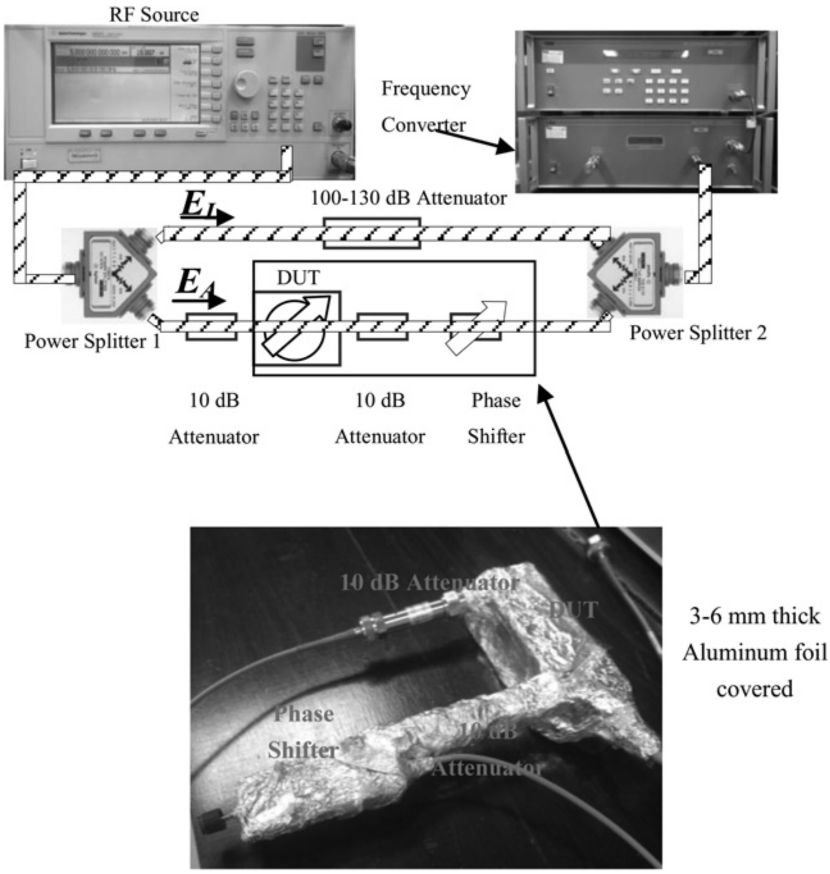

Fig. 5 *Leakage measurement system*

value is adjusted by pressing the switches and the phase shifts at frequencies of 5, 12 and 18 GHz are recorded in Table 1.

It can be seen that the change in attenuation of the DUT affects the phase. This is because the built-in attenuators are inter-connected and hence the electrical length increases. At higher frequencies, the change in electrical length significantly affects the phase shift due to the smaller wavelength. At 5, 12 and 18 GHz, the phase shifts are about ±10°, ±30° and ±70°, respectively. This data will be used to compensate the measured phase of the phase shifter at different attenuation values and frequencies for the next sections.

4 Experimental setup

Practically, E_L is very difficult to measure since it always propagates in the same path with E_A and both signals are combined as E_R. This makes it impossible to measure E_L while addressing the uncertainty due to E_L. To measure the leakage signal, a setup specifically designed to measure E_L is now proposed in Fig. 5. As shown in Fig. 5, the signal generator 250 kHz–20 GHz (Agilent E8257C) is used as the RF source and the DC-18 GHz power splitters 1 and 2 (Agilent 1167A) are used to split and combine the signal in the

Table 2 Experimental results of A_A at 5 GHz and 90°

Set A_{DUT}, dB	Read value	#1	#2	#3	Average value, dB	10 dB step linearity, dB
10	P_i, dBm	−20.686	−20.688	−20.688	—	—
	P_f, dBm	−30.719	−30.713	−30.712	—	—
	A, dB	10.033	10.025	10.024	10.027	10.027
20	P_i, dBm	−20.675	−20.678	−20.675	—	—
	P_f, dBm	−40.793	−40.789	−40.791	—	—
	A, dB	20.118	20.111	20.116	20.115	10.088
30	P_i, dBm	−20.673	−20.671	−20.668	—	—
	P_f, dBm	−50.824	−50.827	−50.826	—	—
	A, dB	30.151	30.156	30.158	30.155	10.040
40	P_i, dBm	−20.669	−20.668	−20.663	—	—
	P_f, dBm	−60.902	−60.899	−60.896	—	—
	A, dB	40.233	40.231	40.233	40.232	10.077
50	P_i, dBm	−20.655	−20.654	−20.657	—	—
	P_f, dBm	−71.02	−71.028	−71.03	—	—
	A, dB	50.365	50.374	50.373	50.371	10.138
60	P_i, dBm	−20.777	−20.778	−20.775	—	—
	P_f, dBm	−81.513	−81.512	−81.514	—	—
	A, dB	60.736	60.734	60.739	60.736	10.366
70	P_i, dBm	−20.77	−20.769	−20.77	—	—
	P_f, dBm	−92.324	−92.343	−92.321	—	—
	A, dB	71.554	71.574	71.551	71.560	10.823
80	P_i, dBm	−20.771	−20.772	−20.771	—	—
	P_f, dBm	−105.11	−105.24	−105.17	—	—
	A, dB	84.338	84.464	84.402	84.401	12.842

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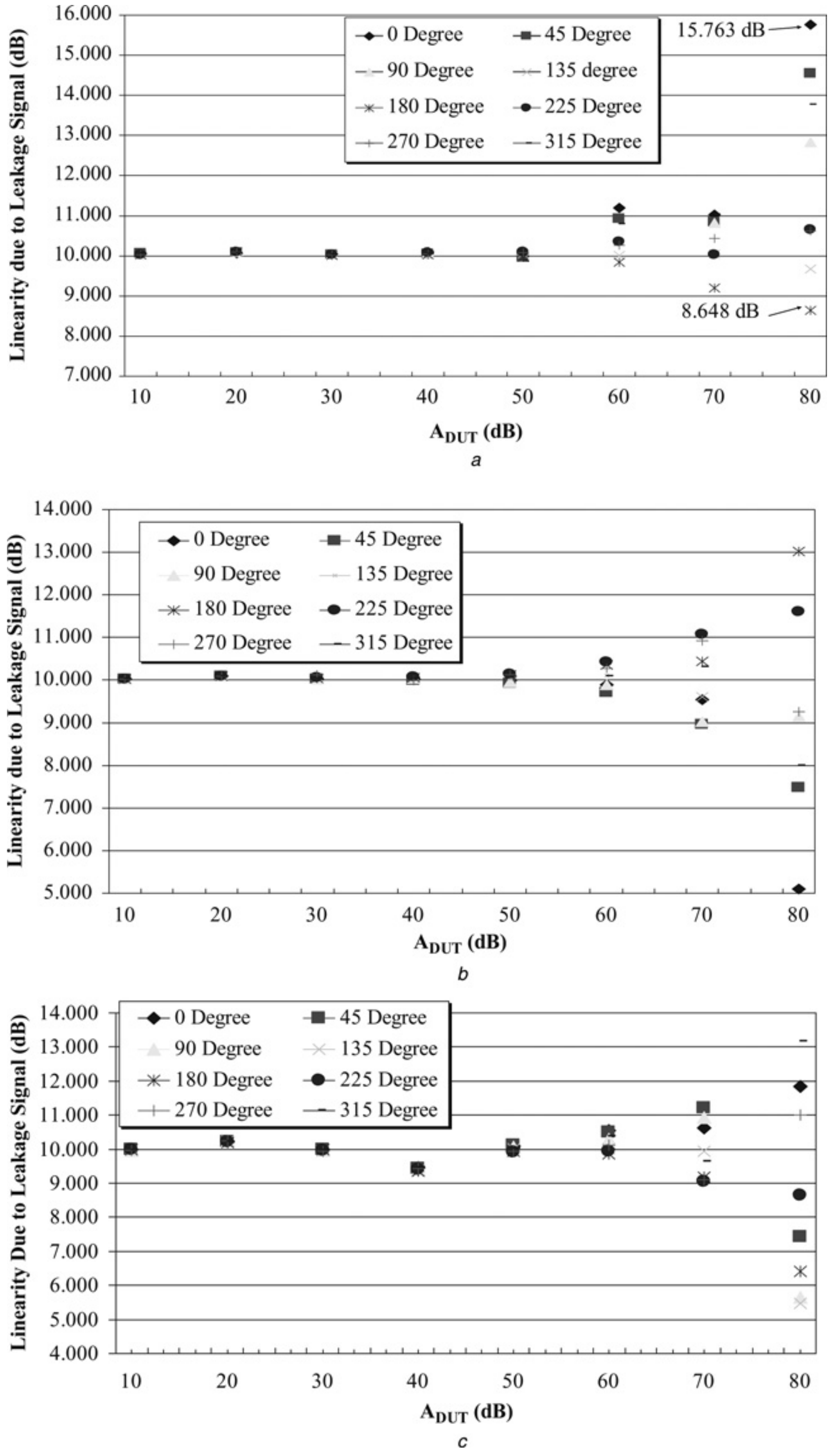

Fig. 6 *10 dB step linearity at different phases at*

a 5 GHz
b 12 GHz
c 18 GHz

upper and lower paths. The 100–130 dB attenuator (DC-18 GHz) can be obtained by cascading the fixed attenuators and it is installed in the upper path. The fixed attenuators comprise the three of 10 dB attenuators (Weinschel Corp model 44-40), 60 dB attenuator (Weinschel Corp model 44-40) and 40 dB attenuator (Weinschel Corp model 44-60), respectively.

The upper path simulates the case where most of E_A is blocked by the attenuator and only E_L can pass through. Consequently, most of E_A only passed through the lower path. The lower path is composed of two of 10 dB attenuators, the DUT and the phase shifter, whereas the E_L in this lower path is relatively small and can be omitted (compared with E_A). Therefore, with this configuration, E_L and E_A are theoretically separated into two paths. According to (6), A_L is the total attenuation of the upper path and it can be adjusted between 100 and 130 dB by inserting or removing the fixed attenuators. A_A is the total attenuation in the lower path and it can be adjusted via the DUT. Finally, at power splitter 2, the signals E_L and E_A are combined and down converted to the IF and monitored by the frequency converter (TEGAM 8852) and IF receiver (model TEGAM VM7), respectively.

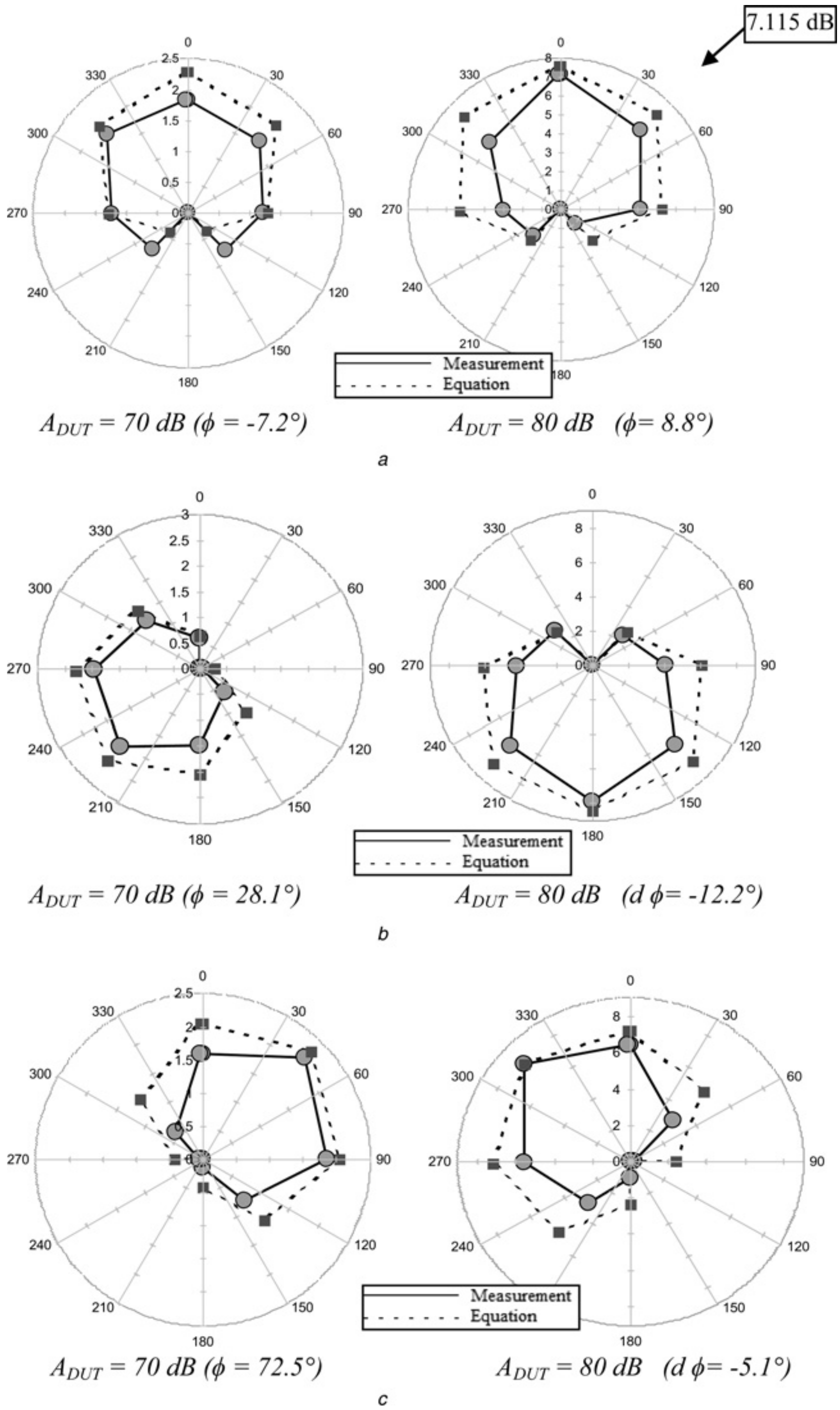

Fig. 7 *Normalised leakage amplitude of A_{DUT} = 70 and 80 dB at frequencies of 5, 12 and 18 GHz*

a At 5 GHz
b At 12 GHz
c At 18 GHz

It has to be noted here that the 3–6 mm thick aluminium foil is used to cover the DUT, 10 dB attenuator and the phase shifter to eliminate the leakage signal between them as much as possible [4]. Moreover, two 10 dB attenuators (Weinschel Corp model 44-10) with a voltage standing wave ratio of 1.25 in the lower path are inserted to improve the impedance mismatch between each device. Without the use of two 10 dB attenuators, the impedance mismatch might be very high and overshadow the leakage effects.

To obtain the experimental results, a sinusoidal wave with amplitude of 25 dBm at 5 GHz generated from the RF source is fed to the power splitter 1. The phase of the 2-port phase shifter is set between 0° and 360° using the 40 MHz–20 GHz network analyser (Anritsu 37347C) for validation before inserting it to the setup. Now A_A can be adjusted by varying the attenuation of the DUT (A_{DUT}) from 10 to 80 dB at a fixed value of A_L 110 dB and the IF signal at the receiver is monitored and recorded as shown in Fig. 4. It can be noted that the A_A can only be set between ∼30 and 100 dB. This is because there are two of 10 dB fixed attenuators inserted (∼20 dB) and the noise floor of the frequency converter is ∼110 dBm.

Finally, as shown in Fig. 5, A_L of the fixed attenuation is varied from 100 to 130 dB at a fixed value of A_A 100 dB (A_L can be selected by cascading any set of the fixed attenuators of the three

Table 3 Effects of leakage on the measured signal

A_L, dB	A_{DUT}, dB	A_A, dB	A_L–A_A, dB	Maximum leakage calculated ΔA_L, dB	Maximum leakage measured ΔA_L, dB
Effects of leakage on the measured signal at 5 GHz					
110	80	80 + 22.3	7.7	±3.81	±3.56
110	70	70 + 22.3	17.7	±1.14	±0.91
110	60	60 + 22.3	27.7	±0.36	±0.44
110	50	50 + 22.3	37.7	±0.11	±0.07
110	40	40 + 22.3	47.7	±0.04	±0.02
110	30	30 + 22.3	57.7	±0.01	±0.001
110	20	20 + 22.3	67.7	±0.004	±0.005
110	10	10 + 22.3	77.7	±0.001	±0.005
Effects of leakage on the measured signal at 12 GHz					
110	80	80 + 23.1	6.9	±4.23	±3.96
110	70	70 + 23.1	16.9	±1.23	±1.05
110	60	60 + 23.1	26.9	±0.39	±0.36
110	50	50 + 23.1	36.9	±0.12	±0.11
110	40	40 + 23.1	46.9	±0.04	±0.04
110	30	30 + 23.1	56.9	±0.01	±0.04
110	20	20 + 23.1	66.9	±0.00	±0.02
110	10	10 + 23.1	76.9	±0.001	±0.01
Effects of leakage on the measured signal at 18 GHz					
110	80	80 + 23.0	7.0	±3.86	±3.85
110	70	70 + 23.0	17.0	±1.15	±1.08
110	60	60 + 23.0	27.0	±0.39	±0.34
110	50	50 + 23.0	37.0	±0.12	±0.11
110	40	40 + 23.0	47.0	±0.04	±0.05
110	30	30 + 23.0	57.0	±0.01	±0.03
110	20	20 + 23.0	67.0	±0.004	±0.027
110	10	10 + 23.0	77.0	±0.001	±0.018

10 dB attenuators in the upper path of the system) and the IF signal at the receiver is monitored and recorded.

5 Experimental results

5.1 Experimental results ($A_A \simeq 30$ to 100 dB, $A_L = 110$ dB)

By setting the RF source at 5 GHz and the phase of the phase shifter at 90°, A_{DUT} can be measured by subtracting the initial power value (P_i) by the final power value (P_f) of IF power (in dB) at the receiver. The experimental results are shown in Table 2.

Table 2 shows the average read values of A_{DUT} at different attenuations for three measurements. Then, the 10 dB step linearity of the attenuator is extracted by subtracting the current measured value by the previous measured value. For example, at the A_{DUT} setting of 20 dB, the 10 dB step linearity is calculated by 20.115–10.027 = 10.088 dB. It can be seen that the average values are slightly different from the setting values – this might be because of the manufacturing process error and measurement errors. The former error can be corrected by offset compensation whereby the latter has to be minimised by improving the measurement system and realised as the uncertainty of the system. To find the uncertainty, the measurement is repeated at different phases from 0° to 360° at a frequency of 5 GHz and the graph of 10 dB step linearity as a function of attenuation is plotted and shown in Fig. 6*a*.

However, to understand more the effects of the leakage effects at different frequencies, the same measurement has been repeated for the frequencies of 12 and 18 GHz, respectively, and the results are shown in Figs. 6*b* and *c*.

Fig. 6 shows the graphs of 10 dB step linearity as a function of attenuation at 5, 12 and 18 GHz, respectively. It can be seen that the 10 dB step linearity is linear (close to ∼10 ± 0.5 dB) at the A_{DUT} lower than 60 dB for all frequencies. This explains that at the A_{DUT} lower than 60 dB, the wanted signal dominates the leakage signal in amplitude as a result of $\Delta A_L \simeq 0$. As the A_{DUT} is

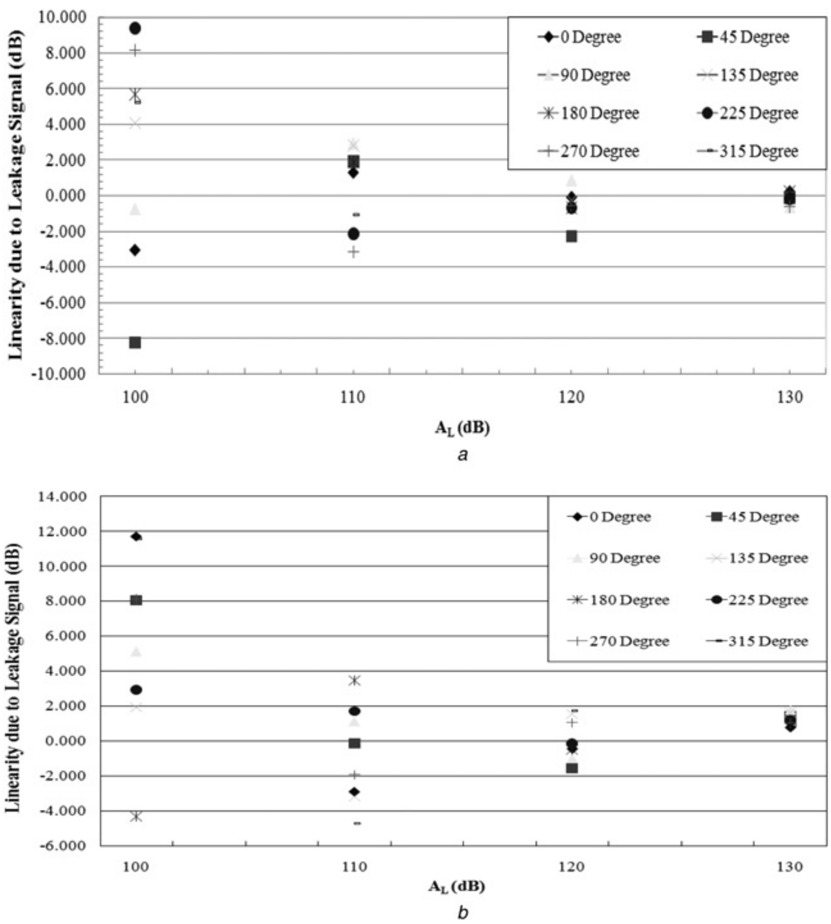

Fig. 8 *10 dB step linearity at different phases at*
a 5 GHz
b 18 GHz

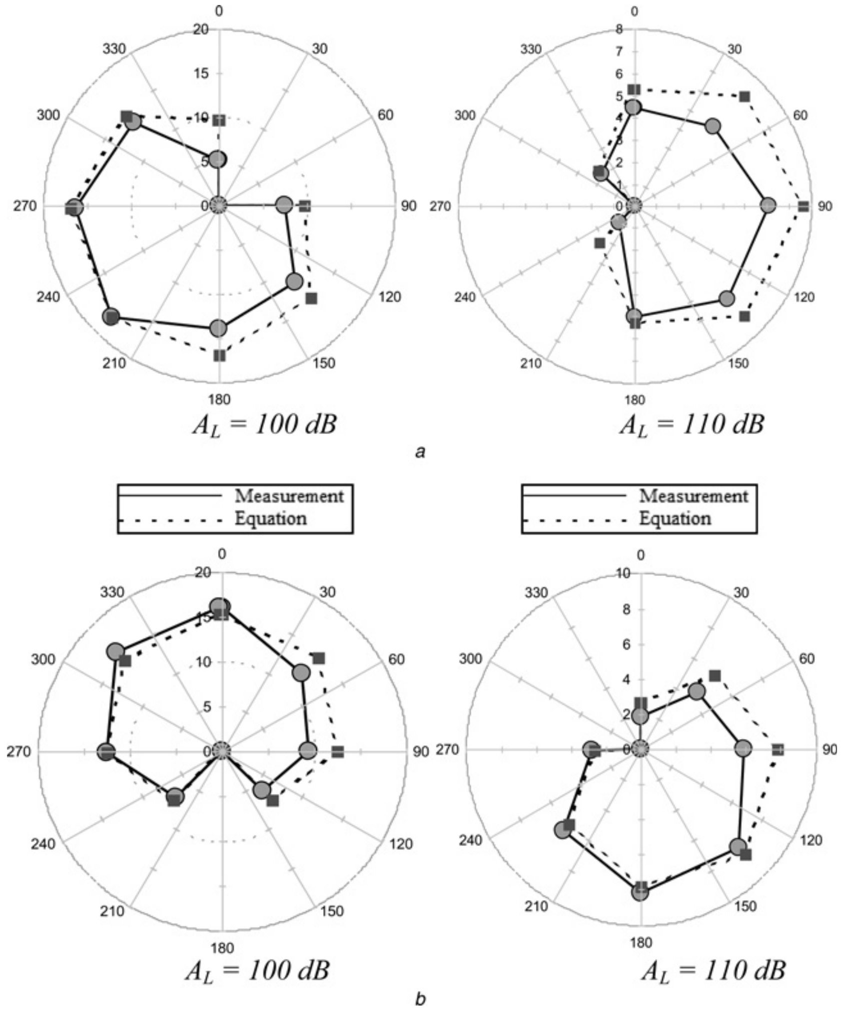

Fig. 9 *Normalised leakage amplitude of A_L = 100 and 110 dB at frequencies of 5 and 18 GHz*

a At 5 GHz
b At 18 GHz

higher than 60 dB, the deviation of leakage signals becomes larger and it can be approximated as ΔA_L.

In addition, the leakage effects are different for each phase. This can be explained by (1) where the change in phase affects the overall measurement signal at the receiver. Since the ΔA_L becomes large while A_{DUT} is higher than 60 dB, it is now possible to extract δA_L versus phases as a function of $A_{DUT} = 70$ and 80 dB at 5, 12 and 18 GHz as can be seen in Fig. 7.

Fig. 7 shows the normalised leakage amplitude ($\overline{\delta A_L}$) of A_{DUT} = 70 and 80 dB at frequencies of 5, 12 and 18 GHz, respectively. The $\overline{\delta A_L}$ is normalised by subtracting the maximum value by minimum value of δA_L (as stated in Section 2) to easily plot in the polar graphs and obtain the maximum leakage uncertainty. The (ΔA_L) of $A_{DUT} = 80$ dB at 5 GHz and 0°, for example, can be found by subtracting the maximum of δA_L at 0° by the minimum of δA_L at 180° as shown in Fig. 6*a* = 15.763–8.648 = 7.115 dB and this value (7.115 dB) is plotted in Fig. 7*a* at the phase of 0°. It can be seen that there is a phase shift ($\Delta\phi$) between the polar graphs of $A_{DUT} = 70$ and 80 dB at each frequency (The maximum amplitudes do not occur at the same phase.). $\Delta\phi$ at 5, 12 and 18 GHz can be visually measured in the range of 10°, 45° and 90°, respectively. This is due to the DUT characteristic. As shown in Table 1, the ϕ(s) of A_{DUT} 70 and 80 dB are −7.2° and 8.8°, respectively, and therefore the $\Delta\phi = -7.2° – 8.8° = 16°$.

Similarly, the $\Delta\phi$ (s) of A_{DUT} at 12 and 18 GHz can be calculated as (28.1° + 12.2° = 40.3°) and (72.5° + 5.1° = 77.6°), respectively. The errors here come from the low graph resolutions due to only eight sampling points being used (0°, 45°, 90°, 135°, 180°, 225°, 270° and 315°). Then, the results of mathematical model in (3) where $E_L/E_A = 10^{-(A_L - A_A)/20}$ are plotted in dash line and compared in the same graphs. It has to be noted here that (8) shall not be used here since A_L is close to A_A at $A_{DUT} = 80$ dB. A_A is the attenuation loss in dB of the lower path of Fig. 5 and it is the sum of the attenuation of DUT, the attenuation losses of the two of 10 dB attenuators and phase shifter. The attenuation losses of the two 10 dB attenuators and phase shifter are measured by the network analyser at 5, 12 and 18 GHz to be 22.3, 23.1 and 23.0 dB, respectively. For example, the A_A at $A_{DUT} = 80$ dB at 5 GHz is 80 dB + 22.3 dB = 102.3 dB. With these results, it is possible to compare the maximum leakages of the measurement with the theory. The maximum leakage of the measurement at $A_{DUT} = 80$ dB at 5 GHz, the maximum amplitude of the leakage signal is found to be 7.115 dB and it can be re-written in terms of maximum leakage measured or limit of leakage error (ΔA_L) as ±3.56 dB. Owing to the rectangular probability distribution [2], the divisor is equal to $\sqrt{3}$ and the uncertainty contribution of leakage (Type B) can be calculated to be $3.56/\sqrt{3} = 2.1$ dB.

Similarly, all the maximum amplitudes can be found at each A_{DUT} and frequency as shown in Table 3 but the uncertainty contributions of leakage will not be calculated and shown here. Table 3 shows the maximum leakages from the measurement, compared with the theory in (3). It can be seen that the measured maximum leakage is logarithmically proportional to ($A_L - A_A$) as expected. The comparison results agree well in shapes and amplitudes with the theory with some deviations. The deviations here might be due to the accuracy of attenuators, statistical errors in measurement and

Table 4 Effects of leakage on the measured signal

A_L, dB	A_A, dB	$A_L - A_A$, dB	Maximum leakage calculated ΔA_L, dB	Maximum leakage measured ΔA_L, dB
Effects of leakage on the measured signal at 5 GHz				
100	80 + 22.3	−2.30	±8.81	±8.81
110	80 + 22.3	7.70	±3.81	±3.05
120	80 + 22.3	17.7	±1.14	±1.58
130	80 + 22.3	27.7	±0.36	±0.44
Effects of leakage on the measured signal at 18 GHz				
100	80 + 23.0	−3.00	±7.67	±8.02
110	80 + 23.0	7.00	±4.17	±4.09
120	80 + 23.0	17.00	±1.24	±1.65
130	80 + 23.0	2700	±0.39	±0.50

mismatch errors [9, 10]. In addition, these results are consistent with [5]. For instance, $\Delta A_L(s)$ in [5] from calculation and measurement at $(A_L - A_A) = 50$ dB are 0.03 and 0.02 dB, respectively. These values are on the same order (≃0.02–0.04 dB) as those shown in Table 3 at $(A_L - A_A) \simeq 50$ dB.

5.2 Experimental results ($A_L = 100$ to 130 dB, $A_A \simeq 100$ dB)

In section *A*, the experiment setup as shown in Fig. 5 is performed where A_L is fixed and A_A is varied. In this section, the A_A is now fixed and A_L is varied by inserting or removing the 10 dB fixed attenuators (from 100 to 130 dB). This is to confirm that varying the attenuation of the upper path (A_L) also affects the leakage signal. The same experiment as shown in section *A* is now performed at 5 and 18 GHz but now A_A is fixed and A_L is varied. The results of 10 dB step linearity as a function of A_L can be seen in Fig. 8.

Fig. 8 shows the 10 dB step linearity as a function of A_L at different phases. The results are similar to that of Fig. 6 but with an inverse *x*-axis. This is due to the fact that the symbol sign of A_L and A_A are opposite. It can be seen that the leakage effects dominate other effects at A_L more than 120 dB.

Similarly to section *A*, the polar graphs can be plotted as shown in Fig. 9 by extracting the data from Fig. 8. Taking (3), it is possible to calculate δA_L and plot as a function of phase. The calculated results are now plotted and compared with the measurement results (in dash line) as shown in Fig. 9.

As can be seen in Fig. 9, the calculated results from (3) are close to the measurement results in both the amplitudes and phases. There are phase shifts ($\Delta\phi$) between the results of $A_L = 100$ and 110 dB at the same frequency. This is due to that the electrical lengths are changed when inserting or removing the 10 dB fixed attenuators from the upper path and it is already stated in section *A*. Now $\Delta A_L(s)$ are extracted from Fig. 8 and compared with (3) and shown in Table 4.

Table 4 shows ΔA_L from the measurement, compared with the theory in (3). Similarly, A_A is the attenuation of the lower path in dB and it has to include the attenuation of the two 10 dB attenuators and the phase shifter. The attenuation losses of the two 10 dB attenuators are already measured by the network analyser in section *A* at 5 and 18 GHz to be 22.3 and 23.0 dB, respectively. Therefore, A_A are (80 + 22.3 = 102.3 dB) and (80 + 23 = 103 dB) at 5 and 12 GHz, respectively. It can be seen that the measured maximum leakage is also logarithmically proportional to $(A_L - A_A)$ as expected. These values agree well with the calculated maximum leakage by (3) with some deviations due to the accuracy of attenuators, statistical errors in measurement and mismatch errors [9, 10].

6 Conclusion

A new configuration of leakage signal measurement using a phase shifter and network analyser is proposed. With this technique, it is possible to precisely adjust the phase between E_A and E_L and validate it with the network analyser. By using a variable attenuator as the DUT, it is possible to investigate the leakage signals in terms of amplitude and phase at each frequency. The polar graphs of leakage amplitudes and phases for $A_{DUT} = 70$ and 80 dB (at 5, 12 and 18 GHz) and $A_L = 100$ and 110 dB (at 5 and 18 GHz) can be successfully plotted and compared with the theory. The maximum amplitude deviation of the leakage signals at each frequency can be used as a limit of leakage error and they agree well with the theory as can be seen in Tables 3 and 4. The errors from the measurement here may be due to the accuracy of attenuators, statistical errors in measurement and mismatch errors.

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