Traceability of the WBCO Standard Attenuator by Comparing With A Inductive Voltage Dividers

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Abstract. A measurement system for the traceability of attenuation of a Waveguide Below Cut-Off attenuator standard (WBCO) is presented. This system consists of calibrating a lock-in amplifier at 10 kHz by frequency substitution using a WBCO at 30 MHz and a Inductive Voltage Dividers IVD as primary standards at 10 kHz. The new systems allows the establishement of a new traceability scheme at LNE, the French National Metrology Institue, The paper hereby describes the measurement method, and details the associated measurement model. Then a validation method is presented and the results are discussed. .

1 Introduction

Attenuation is a key quantity in the field of high-frequency electrical metrology, as it affects many other key quantities in the high frequency domain, such as power, voltage, and reflection coefficients. It also has great importance in electronic system design due to its significant influence on system performance. The increasing demand for higher accuracy in measuring this electrical parameter has driven the development of precise measurement systems. In our laboratory, a Waveguide Below Cut-Off attenuator, (WBCO) serves as a primary standard at 30 MHz. The traceability to dimensional quantities makes it a very good attenuation standard, however, it suffers from several drawbacks due to its non-dissipative nature, as it reflects varying amounts of energy rather than absorbing it as the attenuation is varied, which leads to a limited range of achievable attenuation.

To correct the errors related to these physical phenomena and to establish the traceability of the WBCO to an even more accurate standard, we have devised a system to compare the voltage ratios obtained from the WBCO at 30 MHz standard and an inductive voltage divider (IVD) at 10 kHz using a serial mode substitution method [1]. The latter will also provide a more common attenuation standard, ensuring the mitigation of failure of any of both equipements. The voltage division obtained by the IVD can be realized with errors considerably less than 1 part per million of V, and such units find wide use as standards of voltage ratio in the discipline of electrical measurements.

Measurement uncertainty analysis of the broadband system has been conducted [3,4,5,6 and 7]. The expanded systematic measurement uncertainty (k=2) is estimated to be 0.002–0.02 dB for a 0–50 dB variable attenuator at 30 MHz. These systems have been used as the French national standard for microwave attenuation measurement.

2 Measurement method

The system below presents the measurement setup used for the calibration of the WBCO using an IVD.

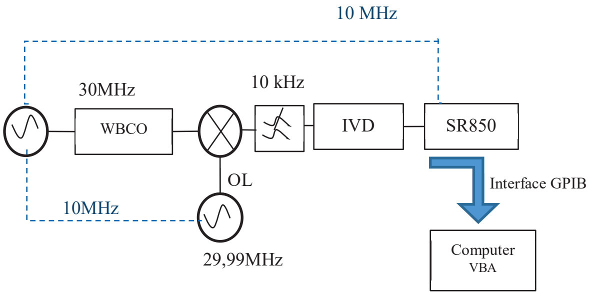

Figure 1: Measurement set up for calibrate the waveguide below cut-off attenuator using a reference inductive voltage divider

The RS850 lock-in amplifier is used to measure attenuation by monitoring voltage variation. The objective is to compare the WBCO attenuation with the reference attenuation obtained through voltage variation using the VDI.

The attenuation is calculated using the following formulas:

$$A_{dB}^{WBCO} = 20.\log_{10}\left(\frac{V_0}{V_1}\right) \qquad (1)$$

and

$$A_{dB}^{IVD} = 20.\log_{10}\left(\frac{V_0}{V_1}\right) \qquad (2)$$

where V_0 is the measured voltage at the reference position and V_1 is the voltage measured at the desired position of attenuation in dB.

2.1 Measurement Uncertainty Analysis

The uncertainties related to the different parameters are:

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$$u^2(A) = \left(\frac{\partial A}{\partial V_0}\right)^2 . u^2(V_0) + \left(\frac{\partial A}{\partial V_1}\right)^2 . u^2(V_1) \qquad (3)$$

The attenuation A is in linear scale, is expressed by the following relation:

$$A = \frac{V_0}{V_1} \qquad (4)$$

The relative uncertainty is given by:

$$\frac{u^2(A)}{A^2} = \left(\frac{\partial A}{\partial V_0}\right)^2 . \frac{u^2(V_0)}{A^2} + \left(\frac{\partial A}{\partial V_1}\right)^2 . \frac{u^2(V_1)}{A^2} \qquad (5)$$

$$\frac{u^2(A)}{A^2} = 1.\frac{u^2(V_0)}{V_0^2} + 1.\frac{u^2(V_1)}{V_1^2} \qquad (6)$$

The uncertainty budget for this model is presented below:

a) DUT repeatability

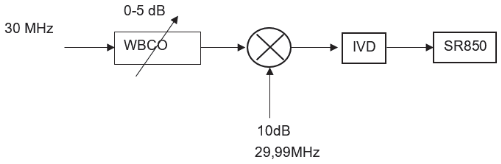
The repeatability of the WBCO attenuation measurements A1 and the inductive voltage divider A2 are statistically estimated during the measurements.

The repeatability of the WBCO attenuation measurements varies between 0.001dB and 0.003 dB. And the repeatability of the DVI attenuation measurements varies between 0.001 dB and 0.009 dB.

b) Mixer's nonlinearity

The mixer's and receiver nonlinearities are also characterized using a step attenuator by varying the source power and the step attenuator by 5dB.
By calculating the deviation (A-A$_{ref}$):

1) We vary the generator power by AdB
2) Then we vary the step attenuator by Aref
3) The diviation is calculated as (A-Aref)



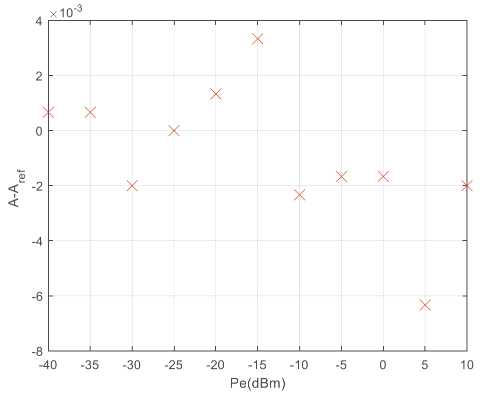


Figure 2: Non-Linearity of the system mixer and lock-in amplifier according to the power level

c) Mismatch uncertainty

The errors in the measurement of standard attenuation due to mismatch and the connector deficiencies have been analysed [1]
In the case of the step attenuator or variable attenuator, two setting values would be considered at each measurement frequency, one the initial value i.e 0 dB and the final value, the attenuation level to be measured.

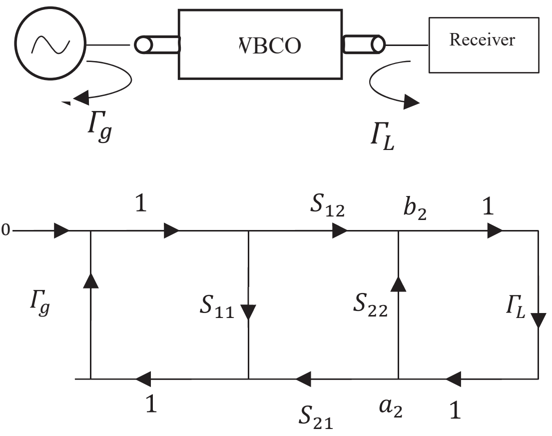


Figure 3: Modelling of the variable attenuator

So each attenuation value can be considered as one tow port attenuator is replaced by second two port attenuator, and mismatch for the step attenuator error (MSA) for incremental attenuation is given by [2]

$$MSA(dB) = 20\log\left(\frac{(1-\Gamma_G S_{11})(1-\Gamma_L S_{22})-\Gamma_G\Gamma_L S_{21}S_{12}}{(1-\Gamma_G S'_{11})(1-\Gamma_L S'_{22})-\Gamma_G\Gamma_L S'_{21}S'_{12}}\right) \qquad (7)$$

Where :
Γ_G : effective source port match ;
Γ_L : effective load match ;
$S_{11}, S_{12}, S_{21}, S_{22}$: Scattering coefficientes of the attenuator (at the attenuation level) ;
$S'_{11}, S'_{12}, S'_{21}, S'_{22}$: Scattering coefficientes of the two port device at the initial state 0 dB.

The S-parameters of the variable attenuator were measured, and the MSA was calculated for different attenuation positions.

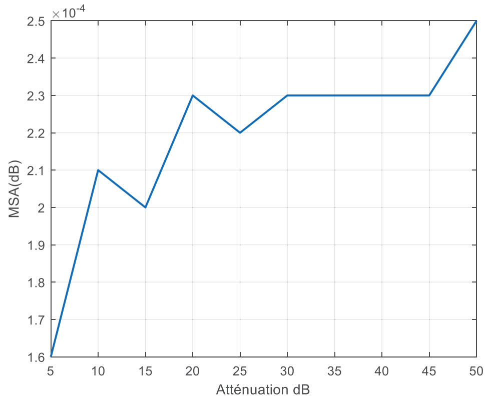


Figure 4: Variation of the MSA as a Function of Different Positions of attenuation

Figure 4 shows the variation of the measured MSA (dB) as a function of different positions of the attenuator.
To reduce the mismatch error, we have placed a fixed 10 dB attenuator pad.

d) Lock-in-detector fluctuation and noise

The noise of the lock-in amplifier was determined experimentally by calculating the standard deviation of the voltage variation as a function of time.

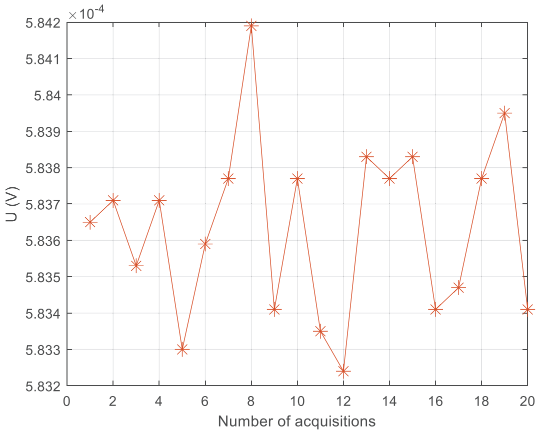


Figure 5: Measurement of the noise of the lock-in amplifier.

The error due to noise and fluctuation of the lock-in amplifier can be modeled using the following formula

$$e_n = 20\log_{10}\left(\frac{(D_2+\varepsilon)D_1}{(D_1-\varepsilon)D_2}\right) \qquad (8)$$

Where:
D_1 and D_2: denotes the IVD ratio before and after the attenuation is changed, and ε represent the absolute error shown in the Figure 3.
To reduce this error, the data acquisition is automated for each measurement using a VBA program.
For each measurement, 30 acquisition were collected, and the average value was calculated to determine D_1 and D_2.
The noise is also present in the repeatability of the A1 and A2 measurements.

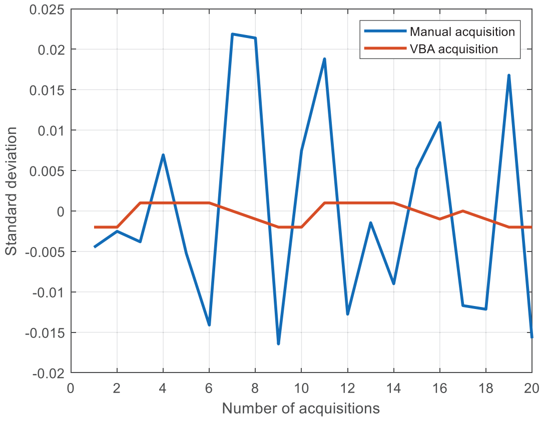


Figure 6: The effect of the automatic program and the number of acquisitions on the measurement results.

This figure illustrates the effect of noise, which is significant when the program uses a single acquisition. The standard deviation of the measurements becomes less than 0.005 dB when 30 automatic acquisitions are taken.

e) Leakage error

Receiver noise and leakage error are negligible for measurement of attenuation below 70 dB.

f) Uncertainty budget

Uncertainty Component		5dB	10dB	15dB	20dB
Repeatability IVD	/1	0.001	0.000	0.001	0.000
Repeatability WBCO	/1	0.001	0.001	0.001	0.001
IVD error	/2	1.01E-08	1.01E-08	1.01E-08	1.01E-08
Mismatch error	/√2	1.16E-04	1.49E-04	1.45E-04	1.65E-04
Receiver Noise	/2√3	5.19E-06	5.19E-06	5.19E-06	5.19E-06
U (k=2)		0.002	0.003	0.002	0.002
Uncertainty Component		25dB	30dB	35dB	40dB
Repeatability IVD	/1	0.001	0.002	0.001	0.001
Repeatability WBCO	/1	0.001	0.001	0.003	0.005
IVD error	/2	1.01E-08	1.01E-08	1.01E-08	1.01E-08
Mismatch error	/√2	1.56E-04	1.61E-04	1.63E-04	1.63E-04
Receiver Noise	/2√3	5.19E-06	5.19E-06	5.19E-06	5.19E-06
U (k=2)		0.003	0.005	0.007	0.010
Uncertainty Component		45dB	50dB		
Repeatability IVD	/1	0.001	0.003		
Repeatability WBCO	/1	0.005	0.009		
IVD error	/2	1.01E-08	1.01E-08		
Mismatch error	/√2	1.65E-04	1.78E-04		
Receiver Noise	/2√3	5.19E-06	5.19E-06		
U (k=2)		0.010	0.020		

3 Validation

To validate our measurement system, we compare the measured values of two fixed attenuators, calibrated by an external laboratory and then measured by our system using a lock-in amplifier.

To evaluate the two results, we calculated the normalized deviation using the following formula:

$$E_n = \frac{|X_1 - X_2|}{\sqrt{U_1^2 + U_2^2}} \qquad (9)$$

Table 1. Measurement results for the two attenuators using our measurement system.

Attenuator 50 dB	LNE results			
	Measured value		Calibration uncertainty.	
(1)	49,843	dB	0,020	dB
(2)	49,943	dB	0,020	dB

Table 2. External laboratory measurement.

Attenuator 50 dB	Reference results			
	Measured value		Calibration uncertainty.	
(1)	49,841	dB	0,023	dB
(2)	49,936	dB	0,023	dB

The normalized deviation for the measurements of attenuator 1 is equal to 0.05 and for the attenuator 2 equal to 0.24.

The normalized deviations for the two attenuators are less than 0.5, which demonstrates the reliability of our measurement and measurement system.

4 Conclusion

We have developed a precise microwave Attenuation measurement system for calibrating a national standard waveguide below cut-off (WBCO) at 30 MHz. This measurement standard is traceable to an inductive voltage divider (IVD) operating at 10 kHz. A detailed measurement uncertainty analysis has been developed to characterize the performance of the proposed method.

This system have been used as the French national standards for attenuation measurement at microwave and millimeter wave frequency.

The next work will concentrate on enhancing our measurement system to attain higher attenuation levels, reaching up to approximately 120 dB.

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