PRECISION RF/MW MEASUREMENT TECHNIQUES AND STANDARDS AT NMIJ/AISTA BROADBAND ATTENUATION MEASUREMENT SYSTEM

TEKNIK DAN STANDAR PENGUKURAN RF/MW PRESISI PADA NMIJ/AIST SUATU SISTEM PENGUKURAN ATENUASI RENTANG FREKUENSI LEBAR

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ABSTRACT
An accurate-broadband attenuation measurement system was established at National Metrology Institute of Japan (NMIJ/AIST) to renew the Japan national standard of attenuation. The system works on the principle of intermediate frequency (IF) substitution technique using a calibrated resistive step-attenuator assembly as an IF reference standard. The standard is traceable to the voltage ratio of the inductive voltage divider (IVD) at frequency of 1 kHz. Some unique measurement techniques for achieving highly accurate measurements are presented and discussed in detail. The measurement capability of the system is 0 to 110 dB in the frequency range of 10 MHz to 50 GHz with the expanded uncertainties are from 0.002 dB to 0.068 dB.

Keywords: radio frequency; microwave; power; attenuation; impedance; noise; measurement; standard; uncertainty.

ABSTRAK
Telah dibangun sistem pengukuran atenuasi rentang frekuensi lebar yang akurat di Lembaga Metrologi Nasional Jepang (NMIJ/AIST) untuk memperbarui standar nasional Jepang untuk atenuasi. Sistem tersebut bekerja berdasarkan prinsip teknik substitusi dari frekuensi menengah menggunakan perangkat step attenuator yang terkalibrasi sebagai standar acuan atenuasi frekuensi menengah. Standar tersebut tertelusur ke perbandingan tegangan dari pembagi tegangan induktif pada frekuensi 1 kHz. Beberapa teknik pengukuran yang khas untuk mendapatkan pengukuran yang sangat akurat disajikan dan didiskusikan secara lengkap. Kemampuan pengukuran dari sistem adalah 0 sampai dengan 110 dB dalam rentang frekuensi 10 MHz – 50 GHz dengan ketidakpastian bentangan 0,002 dB – 0,068 dB.
1. INTRODUCTION

With the rapid progress in electronics and communication devices using radio frequency and microwaves (RF/MW) such as microwave ovens, mobile phones, magnetic resonance imaging systems etc., high reliability measurements and standards of electromagnetic waves has become mandatory to address some key issues such as the effects of electromagnetic exposure on the human body and electromagnetic interference etc., in addition to ensuring the performance of the devices themselves.

In an AC/DC low frequency circuit, voltage, current and resistance, are known as the fundamental measurement quantities. However, at higher frequencies i.e., radio frequency and microwave (RF/MW) circuits, since the wavelength of the signal is almost equal to or shorter than the dimension of the object to be measured, theory of electromagnetic wave propagation should be implemented, and then in the RF/MW circuits, power, noise, attenuation and impedance are usually used as the fundamental measurement quantities. National Metrology Institute of Japan (NMIJ/AIST) is responsible for establishment of the Japan national physical primary standards, in this case are RF power, noise, attenuation and impedance standards as mentioned above. However, for use in the measurements, calibrations and evaluations of the recent RF/MW electronic devices, RF standards having high accuracy, broadband and high dynamic range are required. Moreover, from the viewpoint of improvement of measurement accuracy and efficiency, automation of the measurement systems is also required.

This paper describes the newly developed precision and broadband RF attenuation measurement system which is used to replace the former Japan national standard of attenuation. The system works in the frequency range of 10 MHz to 50 GHz with the measurement capability up to 110 dB. The characteristics of the system and some of the unique measurement techniques that have been developed for achieving highly accurate results are discussed in detail as follows.

2. BASIC PRINCIPLE

a. Definition of Attenuation

Attenuation is defined as the ratio of power absorbed by the load $P_1$ without
the under test (DUT) in the line to the power absorbed by the load $P_2$ with the DUT inserted in the line when the source and load are perfectly matched to the line impedance (i.e., there is no reflected signal occurs in the circuit) (Warner, 1977).

Attenuation $A$ is given in decibels by

$$A = -10\log_{10} \frac{P_2}{P_1} = -20\log_{10} |S_{21}| \quad ...[1]$$

where $S_{21}$ is a scattering (transmission) coefficient of the DUT. When a variable attenuator as the DUT is moved from its zero (i) position to any other setting (f), the change in attenuation that occurs is called the incremental attenuation $\Delta A$, and is given in decibels by

$$\Delta A = -10\log_{10} \frac{P_2}{P_1} = -20\log_{10} \left| \frac{S_{21}^f}{S_{21}^i} \right| \quad ...[2]$$

b. Measurement Methods

Many different methods of measuring attenuation have been developed over the years including the power ratio (Coster, 1995), voltage ratio, audio frequency substitution (Warner, 1990), IF substitution (Weinert and Weinschel, 1976) and RF substitution (Larson and Campbell, 1971). However, the IF substitution method has been the most widely used, since it gives high accuracy, broadband and large dynamic properties to the measurement system.

In such the system, the RF attenuation is converted into an IF attenuation by using the linearity properties of the heterodyne detection, then it is compared with the standard attenuator working at the IF (Warner, 1977).

At NMIJ/AIST, an accurate ‘RF/MW Attenuation Calibration System’ operated in the frequency range of 10 MHz to 50 GHz has been developed and used as a national standard of attenuation (Widarta, 2004 and 2008, Widarta and Katou, 2014). The system works on principle of IF substitution technique by employing a resistive step attenuators assembly as an IF reference standard and a general-purpose receiver as a sensitive level detector. The traceability of the system is simply ensured by calibrating the IF reference standard using the originally developed ‘Precision IF Attenuation Measurement System’, based on the voltage ratio of the IVD (Widarta, et al, 2003). The ‘Broadband Mismatch Correction Technique’ has been developed for minimizing the influence of impedance mismatch as in (Widarta, 2010 and 2011) and the ‘Double-step Measurement Technique’ has also been developed for reducing the influence of noise on high attenuation calibrations (Widarta, 2012).

| 75 |
3. CALIBRATION SYSTEM

a. RF/MW Attenuation Calibration System

Figure 1 shows the block diagram of RF/MW attenuation measurement system works in the frequency range of 10 MHz to 50 GHz developed in NMIJ/AIST. The RF signal sources passes through the DUT and mixed with local signal at the mixer to produce a 30-MHz IF signal where the amplitude is proportional to the RF amplitude. The RF attenuation after converting to the IF attenuation is compared with the IF attenuation of the IF standard attenuator using the IF receiver which acted as a sensitive level comparator. The power level difference of the signals which enters the receiver is kept for less than 1 dB by adjusting the IF standard attenuator before and after setting of the DUT.

Letting the attenuation of the standard attenuator is $Std$ and the power level displayed at the receiver be $D_i$ [dBm] at initial setting and be $D_f$ [dBm] at final setting, respectively, then the attenuation value $A$ of the DUT is determined in decibel by

$$A = Std + (D_i - D_f) \quad [3]$$

Two coaxial resistive step attenuators, i.e. 11 dB in 1 dB steps and 90 dB in 10 dB steps, fitted with 40 dB isolators on each port are assembled in series and applied as a set of an IF standard attenuator. The assembly then has an attenuation range of 101 dB with the increment resolution of 1 dB. Each attenuator is calibrated at each step at frequency of 30 MHz using the ‘Precision IF Attenuation Calibration System’ describes in the next subsection. The isolators are used to keep the calibration values from mismatch uncertainty effects. The non-calibrated attenuation which consists of the combination steps of these attenuators is obtained easily by totaling the calibrated attenuation steps. For instance, attenuation of 25 dB is found by adding up the calibrated attenuation step of 5 dB of the first attenuator and the 20 dB of the second attenuator, respectively.
As mentioned above, the receiver is used to detect the power level differences of the last signals for less than 1 dB. Therefore, extremely high linearity and high ‘gain blocks' repeatability properties are unnecessary, and hence a general purpose receiver, such as a measuring receiver, spectrum analyzer, level meter etc., is suitable applied to the system. In this system, a programmable general-purposed receiver with the digital display resolution of 0.001 dB is used. As for RF section, it consists of an RF/MW signal source and a local signal source and a double-balanced mixer. The signal sources are synthesized generators which are locked to the same 10 MHz reference frequency oscillator to maintain the frequency difference of the sources. This frequency reference is also fed to the receiver. The matching pads are used to minimize the mismatch uncertainties.

b. Precision IF Attenuation Measurement System
Traceability route of the ‘RF/MW attenuation calibration system’ described above, is ensured by performing periodic calibration to the IF attenuation reference standard assembly using the originally developed ‘Precision IF Attenuation Calibration System’ based on the voltage ratio of the inductive voltage divider (IVD), which the voltage ratio is traceable to the Japan national standard of low frequency voltage ratio.
Fig. 2. Block diagram of precision IF attenuation calibration system based on the dual-channel IF substitution technique using IVD as a reference standard.

Figure 2 shows a block diagram of the system constructed system consists of 30-MHz section and a 1-kHz null-balance receiver which employs a programmable IVD as a reference standard. The signal from the 30 MHz source is divided into measuring and reference signals by a directional coupler. The measuring signal passes through the IF reference standard assembly as the DUT, and is mixed with local signal at the main mixer to produce a 1 kHz IF measuring signal, where the amplitude is proportional to the 30 MHz signal amplitude. The signal is then applied to the signal input of the receiver. The reference signal is led to the reference mixer to produce 1 kHz IF reference signal, and then, it is applied to the reference input of the receiver. At the receiver, the measuring and the reference signals are kept balanced by adjusting the IVD and of the DUT. A lock-in amplifier is used as a null detector. Letting the IVD values at the initial and final settings be $R_i$ and $R_f$, respectively, then the incremental attenuation value $\Delta A$, is determined in decibels by

$$\Delta A = -20 \log_{10} \left| \frac{R_i}{R_f} \right| \quad \text{[4]}$$

c. Broadband Mismatch Correction Technique.

The mismatch occurs if the measurement is carried out without the source and the load being perfectly matched to the line impedance. To diminish the effects of the mismatch, RF tuners are usually used, and a precise match of the source and the load to the line impedance is possible. It provides the smallest mismatch uncertainty if carefully executed but has to be carried out anew when changing the measure-
ment frequency. At NMIJ a practical technique by applying the mismatch loss correction has been developed to diminish the effects of the mismatch.

When an attenuation measurement is carried out without the source and load being perfectly matched there will be an error in the result, i.e. mismatch loss error \( M_l \). \( M_l \) is expressed in decibels by

\[
M_l = -10 \log_{10} \left( \frac{|1 - \Gamma_G \Gamma_L|}{|1 - S_{11} \Gamma_G(1 - S_{22} \Gamma_L) - S_{21} S_{12} \Gamma_G \Gamma_L|} \right)
\] ............................... [5]

where \( \Gamma_G \) and \( \Gamma_L \) are the source and load reflection coefficients, respectively. \( S_{ij} \) denotes the scattering coefficient of the DUT. Using the vector network analyzer, all the independent variables in (5) are able to be known, and then \( M_l \) can be found precisely, and then it can be used as a correction factor of mismatch error.

To determine the standard uncertainty \( u(M_l) \) of \( M_l \), the law of error propagation is may be implemented (ISO, 1993). However, since the equation form of (5) is complicated and all of the parameters are the complex numbers, the solutions are not easily obtained. Here, equation (5) is modified as follows,

\[
M_l = -8.686 \text{Re} \left\{ S_{11} \Gamma_G + S_{22} \Gamma_L + (S_{21}^2 - 1) \Gamma_G \Gamma_L \right\}
\] ............................... [6]

by assuming the \( |\Gamma_G|, |\Gamma_L|, |S_{11}|, |S_{22}| \) are small (e.g., less than 0.1) and the networks are reciprocal \((S_{21} = S_{12})\). Therefore, the law of error propagation is easily implemented and then \( u(M_l) \) can be certainly derived.

d. **Double Step Measurement Technique.**

Measurement capabilities of the RF/MW Attenuation Calibration System are limited to the dynamic range of the system, i.e., the difference between the compression power level and the noise level of the receiver. To overcome this restriction, a double step measurement technique using a gauge block attenuator (GBA) was developed [11]. The GBA, which is a repeatable step attenuator, is connected in series with the device under test (DUT) and is switched out when the DUT is switched into the circuit during the measurement. This approach keeping the linearity of the receiver remained high, thus providing the ability to accurately measure high attenuation.
4. RESULTS AND DISCUSSION

The measurable attenuation range or dynamic range of the system is mostly determined by the linearity properties of the system, including the frequency mixer and IF receiver.

Figure 3 shows the linearity evaluation results of the system, as for instance, obtained by measuring 10 dB change of a step attenuator at 33 GHz. The measurements were done in different input power levels as shown by the horizontal axis. The results were normalized based on the measurement results at the mixer input level of -30 dBm. The measurement results are indicated with the dots, obtained with the number of repetition was ten. The standard deviations are indicated with the error bars. The limits of non-linearity were obtained as ±0.0007 dB for measurements up to 60 dB (−20 dBm to −80 dBm). For attenuation greater than 60 dB, the use of the ‘Double Step Measurement Technique’ needs to be implemented.

Figure 4 demonstrates the calibration stability of the system. A particular 40-dB step attenuator was simultaneously measured from 1 to 18 GHz in 1-GHz intervals and observed in four years long span started from 2013. The expanded standard uncertainties (k=2) of the results are indicated with the error bars. It is shown that highly stable results were obtained, with the deviations are less than the measurement uncertainties for all frequency observations.

Traceability route of the ‘RF/MW attenuation calibration system’ is ensured by performing periodic calibration to the IF attenuation reference standard assembly using the originally developed ‘Precision IF Attenuation Calibration System’.
Fig. 5. Attenuation stability of 10-dB, 20-dB, 40-dB and 60-dB steps of the IF standard attenuator assembly calibrated using the precision IF attenuation calibration system based on the voltage ratio of IVD.

Figure 5 shows the calibration results of the 10-dB, 20-dB, 40-dB and 60-dB steps of the standard. Two times calibrations i.e., in 2013 and 2016 have been done to observe the stability of this IF standard. The expanded standard uncertainties (k=2) of the results are indicated with the error bars. It is shown that the extremely high stable results were obtained, with the deviation of less than 0.001 dB for all attenuation settings.

Fig. 6. Numerical simulation results of mismatch uncertainty $u(M_I)$ for a 20 dB fixed attenuator measurements.

Figure 6 shows the numerical simulation results of mismatch uncertainty $u(M_I)$ for a 20 dB fixed attenuator measurements. The reflection coefficients of the DUT, $|S_{11}|$, $|S_{22}|$ were varying from 10 mU to 100 mU. $u(M_I)$ changes smoothly, ranges from 0.003 dB to 0.006 dB as for $|\Gamma_G|=|\Gamma_L|=60$ mU (the lower curves in the picture). For comparison, the $u(M_I)$ without correction was also calculated and the results are shown by the upper curves in the picture. It is shown that $u(M_I)$ results by the developed technique are more than 10 times smaller than the one without correction procedure. The procedure outlined above is also simply applied to variable attenuators as DUTs.

Figure 7 shows the improvement effects of the developed double step technique for the measurement of high attenuations (80, 90, 100, 110 dB) of a step attenuator (8496H), comparing with the normal or direct technique without the GBA. The results obtained by the use of the normal technique are indicated by asterisks, and the results obtained by the proposed technique are indicated by filled circles. In the scale of the graph, the results by the proposed technique approximately same to all nominal values. However, the results of the normal technique were different in the higher nominal values for the influence of non-linearity.
5. MEASUREMENT CAPABILITY

a. Uncertainty Budget

Uncertainty evaluation on the developed RF/MW attenuation calibration system has been carried out in detail both theoretically and experimentally to estimate the standard uncertainty budget. Table 1 show the summary of the uncertainty estimation of variable attenuator calibration in the frequency range of 10 MHz to 12 GHz.

b. Calibration and Measurement Capabilities

The calibration and measurement capabilities (CMC) of the system are summarized as follows.

1) Quantity: RF Scalar Attenuation (Attenuation in coaxial line)
2) Artefact: Passive device, variable and fixed attenuators
3) Instrument Type or Method: IF substitution method
4) Measurand Level or Range: 0 dB to 110 dB
5) Frequency Range: 10 MHz to 50 GHz
6) Absolute expanded uncertainty: 0.002 dB to 0.068 dB ($k = 2$, level of confidence 95%)

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Category</th>
<th>Attenuation [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_1$ IF Attenu. Standard</td>
<td>B</td>
<td>$u(Xi)$</td>
</tr>
<tr>
<td>$u_2$ Non-linearity</td>
<td>B</td>
<td>$u(Xi)$</td>
</tr>
<tr>
<td>$u_3$ Leakage</td>
<td>B</td>
<td>$u(Xi)$</td>
</tr>
<tr>
<td>$u_4$ Drift</td>
<td>B</td>
<td>$u(Xi)$</td>
</tr>
<tr>
<td>$u_5$ Digital reading of receiver</td>
<td>B</td>
<td>$u(Xi)$</td>
</tr>
<tr>
<td>$u_6$ Stability</td>
<td>B</td>
<td>$u(Xi)$</td>
</tr>
<tr>
<td>$u_7$ Gauge block</td>
<td>B</td>
<td>$u(Xi)$</td>
</tr>
<tr>
<td>$u_8$ Mismatch</td>
<td>B</td>
<td>$u(Xi)$</td>
</tr>
<tr>
<td>$u_9$ Standard deviation of the mean</td>
<td>B</td>
<td>$u(Xi)$</td>
</tr>
<tr>
<td>($u$) Combine standard uncertainty</td>
<td></td>
<td>0.0010 0.0024 0.0033 0.0038 0.0103 0.0164</td>
</tr>
<tr>
<td>($U$) Expanded uncertainty</td>
<td>$k=2$</td>
<td>0.002 0.005 0.007 0.008 0.021 0.033</td>
</tr>
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</table>
6. CONCLUSION

At NMIJ/AIST, an accurate RF/MW attenuation calibration system has been developed and used as a national standard of attenuation. The system works on principle of IF substitution technique by employing a calibrated resistive step-attenuators assembly as an IF reference standard. The traceability of the system is ensured by calibrating the IF reference standard using the IF attenuation calibration system based on voltage ratio of the IVD. A broadband mismatch correction technique and a double step measurement technique have been developed for minimizing the influence of impedance mismatch and reducing the influence of noise on high attenuation calibrations, respectively. The calibration and measurement capabilities range from 0 dB to 110 dB at the frequency range from 10 MHz to 50 GHz with the expanded uncertainty range from 0.002 dB to 0.068 dB (k=2, level of confidence 95%).

REFERENCES


