NMC-NMIJ Bilateral Comparison of Millimeter-Wave Attenuation in WR-15 Waveguide Band at 50 GHz and 54 GHz

H. Iida[a,*] , T.Y. Wu[b]

[a] National Institute of Advanced Industrial Science and Technology, National metrology Institute of Japan, Central 3, 1-1-1 Umezono, Tsukuba, Ibaraki, 305-8563, Japan
[b] National Metrology Centre, Agency for Science, Technology and Research, 1 Science Park Drive, Singapore 118221, Singapore

* Corresponding author: E-mail: h-iida@aist.go.jp

Abstract. This paper reports on a bilateral comparison of millimeter-wave attenuation in WR-15 waveguide band between the National Metrology Institute of Japan (NMIJ) and the National Metrology Centre, A*STAR (NMC). Different types of attenuation measurement systems were independently developed at both laboratories. The systems are based on a stabilized single-channel intermediate frequency (IF) substitution method at NMIJ, and a dual-channel audio frequency substitution method at NMC. A comparison was carried out at 50 GHz and 54 GHz using a programmable step attenuator fitted with precision coaxial to waveguide adaptors as a travelling standard. Good agreement of the measurement results between both laboratories was verified in the attenuation range up to 60 dB.

Keywords:
Bilateral comparison
Millimater-wave attenuation
Attenuation standard
Uncertainty estimation
Degree of equivalence

1. Introduction

The demand for radio frequency (RF) attenuation standards in broadband frequency ranges has been increasing recently. Each national metrology institute (NMI) widely provides attenuation calibration services of which international equivalence is guaranteed [1]. For international comparisons of RF attenuation, the key comparison CCEM.RF-K19.CL has been carried out at 60 MHz and 5 GHz and completed in 2009 [2]. Moreover, the new key comparison CCEM.RF-K26 was started in the frequency range up to 40 GHz in 2014 [3]. To meet the industry's demand, some NMIs have established the attenuation standard in the millimeter-wave range [1], however, to the authors' best knowledge, there has been no comparison of the attenuation measurements over 50 GHz among the NMIs.

NMIJ and NMC have independently developed the attenuation standards including WR-15 waveguide band (50-75 GHz) to date [4]. To verify the validity of the attenuation measurement system in NMIJ and NMC, a bilateral comparison of attenuation in WR-15 waveguide band was conducted from December 2013 to March 2014. A programmable step attenuator fitted with precision waveguide to coaxial adaptors was used as a travelling standard (TS), and the attenuation was measured at 50 GHz and 54 GHz. NMC had served as the pilot laboratory, provided the TS and performed the first measurement of the TS. In this paper, we describe the measurement system used in each NMI and report on the results of this bilateral comparison.

2. Travelling standard and measurement protocol

To carry out a reliable comparison, it is important to select an appropriate attenuator as the TS. A rotary-vane attenuator (RVA) is commonly used in the waveguide band. The RVA has an advantage covering a full waveguide band frequency range, however, it requires particular attention as follows [6]:

(1) The RVA requires especial care in shipping because it is very sensitive to mechanical stress.

(2) Repeatability gets worse (due to its setting resolution) when it is used in higher attenuation range.

On the other hand, a programmable coaxial step attenuator has been adopted for the key comparisons [2, 3]. Moreover, it is easy to integrate into the measurement systems of both laboratories. Therefore, we have attentively selected the programmable step attenuator. A coaxial step attenuator (Agilent Technologies 84905M, Serial No. MY46150166) fitted with precision waveguide to coaxial adaptors was selected as the TS, as shown in Fig. 1. The step attenuator can set the attenuation from 0 to 60 dB in 10 dB steps. According to the manufacturer's specifications, the upper operating frequency of the attenuator is 50 GHz since it has used 2.4 mm connectors for its input and output ports. However, since the theoretical upper limit of the cutoff frequency of the 2.4 mm connector was 56.5 GHz [7], the performance of the attenuator was carefully checked at 50 GHz and 54 GHz prior to the start of the comparison. Consequently, good port impedance matching, stability and repeatability were confirmed at both frequencies. Therefore the comparison was carried out at these two frequencies. To convert the coaxial ports of the attenuator to waveguide flanges UG385/U for WR-15, precision adaptors (Flann Microwave, 25095-VM70) are attached to the coaxial ports. The adaptors should remain connected to the attenuator to ensure good repeatability throughout this comparison. The TS is driven by a control unit Agilent 11713A/B/C (option 24 V) which provides both manual and remote control (via computer).

The incremental attenuation in dB of the TS from the datum position (0 dB) to the setting value is the primary measurand. Each laboratory should provide the following measurements at 50 GHz and 54 GHz: Nominal attenuation steps 10 dB, 20 dB, 30 dB, 40 dB, 50 dB and 60 dB. The switch setting of the control unit required to set the attenuation values is shown in table 1.

Fig. 1. Travelling standard for attenuation in WR-15 waveguide band.

Table 1. Attenuator switches setting for this comparison.

Attenuation (dB)	Activated Switch		
	1	2	3
0			
10	X		
20		X	
30	X	X	
40	X		X
50		X	X
60	X	X	X

3. Measurement techniques

3.1. NMIJ's method

NMIJ has developed an attenuation measurement system based on a single-channel intermediate frequency (IF) substitution method using an inductive voltage divider (IVD) as a reference standard [8]. The system achieves highly stable measurement by using a phase-locked loop (PLL) technique. Fig. 2 shows simplified diagram of the attenuation measurement system in WR-15 waveguide band (Details of the measurement principle are described in [4]). The system uses double conversion technique to obtain the IF signal of 10 kHz which is stabilized by the PLL circuit after the second conversion. At the insertion point of the device under test (DUT), each test port has tuners with isolators for minimizing the mismatch uncertainty. Even if a reflection coefficient of the DUT is comparatively large, the mismatch uncertainty can be reduced because this system can adjust the reflection coefficient of the test port to a minimum value by the tuners.

The RF attenuation of the DUT is directly calibrated with the IVD by the null detection up to 80 dB. The null is achieved by adjusting the IVD according to the DUT settings. The attenuation is determined from the ratio of the IVD values. The value of the IVD to maintain null balancing state at a detector is D_i when the DUT is set to 0 dB. In the same manner, the IVD is adjusted to D_f when the DUT is set to a particular attenuation. Then the attenuation is determined as

$$A = 20\log_{10}\frac{D_f}{D_i} \text{ (dB).} \qquad (1)$$

The system achieves a wide dynamic range by a direct measurement, whereas the NMC's measurement system uses a gauge block attenuator for the attenuation range over 30 dB. Therefore, the contribution of linearity should be carefully considered. The linearity was evaluated by measuring a particular attenuator at different signal levels [4]. Then the uncertainty due to the linearity was estimated from the difference of the attenuation measured at each signal level. The IVD is traceable to the Japan national standard of AC voltage ratio at 10 kHz. All measurements were carried out at the room temperature of (23 ± 1) °C and the relative humidity of (50 ± 20) %.

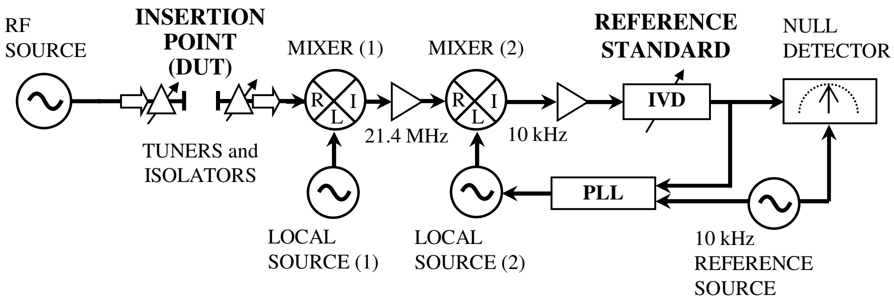

Fig. 2. Block diagram of the attenuation measurement system in WR-15 waveguide band at NMIJ.

3.2. NMC's method

NMC has developed an attenuation measurement system using a dual-channel audio frequency (AF) substitution method. Fig. 3 shows the diagram of the attenuation measurement system in WR-15 waveguide band. The measurement principle is similar to another WR-10 band attenuation measurement system of NMC which had been described in [5]. The mm-wave signals are down-converted to main-path and reference-path AF signals at 5.02 kHz. The reference AF signal provides a frequency reference to a lock-in amplifier (LIA) to ensure accurate measurement of the main AF signal. An IVD is used as a traceable voltage ratio reference standard with an accuracy of a few parts in 10^6. The DUT's millimeter-wave attenuation can be derived from the IVD voltage ratio at 5.02 kHz. All measurements were carried out at the room temperature of (23 ± 2) °C and the relative humidity of (55 ± 10) %.

When a DUT is set to its datum position (0 dB), the IVD ratio is set to D_1 and the LIA detects a signal with magnitude of V_1. After the DUT is set to a particular attenuation range, the IVD ratio is adjusted to a ratio of D_2 so that the LIA detects a signal with magnitude of $V_2 = V_1$. The incremental attenuation of the DUT can be derived from

$$A = 20\log_{10}\frac{D_2}{D_1}\ \text{(dB)}. \qquad (2)$$

A waveguide level-set attenuator (LSA) is used to control the signal level at the receiver input and avoid compression error in the main subharmonic mixer and the RF mixer. The isolators in the source side and receiver side are used to reduce the reflection from the multiplier and the main subharmonic mixer, respectively. Two matching pads (waveguide attenuators) are used to reduce the mismatch error in the attenuation measurement. For a DUT with attenuation ranging from 30 to 50 dB, the LSA's attenuation is set to 0 dB and an indirect measurement method is used to measure the attenuation difference (A_d) of the DUT with reference to its attenuation setting of 30 dB. The DUT with its attenuation set to 30 dB is also referred to as gauge block attenuator (GBA), with its attenuation value (A_{GBA}) calibrated by the measurement system. The attenuation of the DUT is obtained by

$$A_{dut} = A_{GBA} + A_d \qquad (3)$$

For a DUT with attenuation ranging from 50 to 60 dB, an indirect measurement method is used to measure the attenuation difference (A'_d) of the DUT with reference to its attenuation setting of 50 dB, where the 50 dB GBA's attenuation has been calibrated as A'_{GBA} . The attenuation of the DUT is obtained by

$$A_{dut} = A'_{GBA} + A'_d \qquad (4)$$

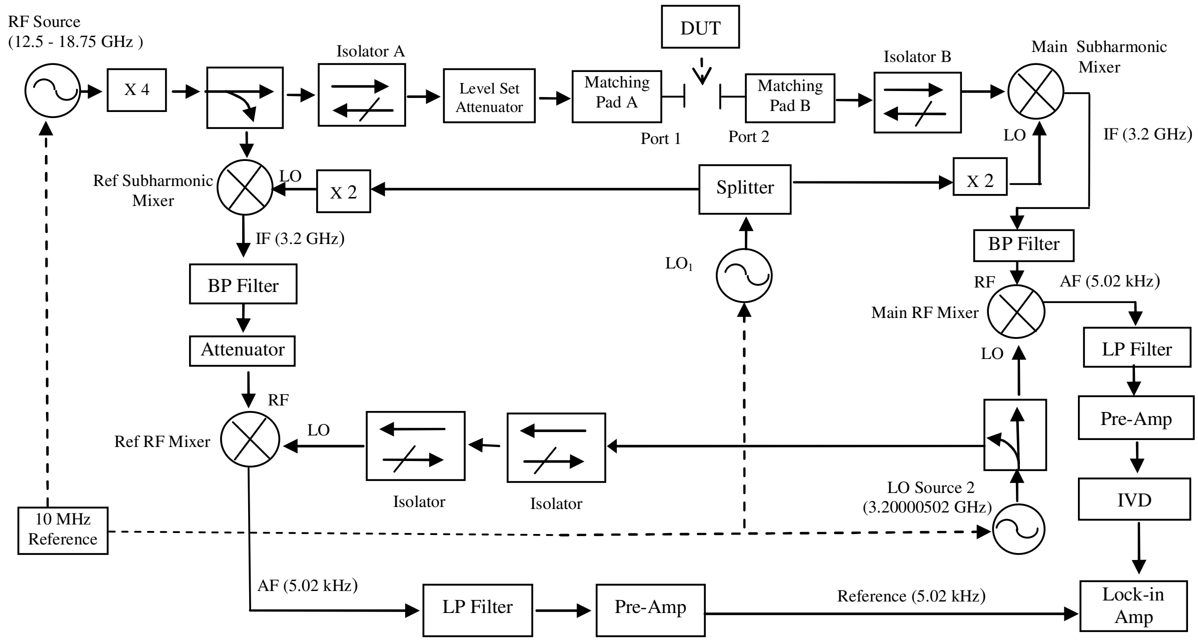

Fig. 3. Block diagram of the attenuation measurement system in WR-15 waveguide band at NMC

4. Comparison results and analysis

The measured results, combined standard uncertainties and degree of equivalence are summarized in tables 2 and 3 for 50 GHz and 54 GHz, respectively. The degree of equivalence, DoE, of the measurements between both laboratories and its expanded uncertainty (k=2), U_{DoE}, were calculated as follows [9]:

$$\mathrm{DoE} = \left|A_{NMC} - A_{NMIJ}\right| \qquad (5)$$

$$U_{DoE} = 2\sqrt{u_{NMC}^2 + u_{NMIJ}^2} \qquad (6)$$

where A_{NMC} and A_{NMIJ} are the measured attenuation of the TS at each laboratory, u_{NMC} and u_{NMIJ} are the corresponding standard uncertainties, respectively. Graphical illustrations of the results with their expanded uncertainty (k=2) for each attenuation step of the TS are shown in Fig. 3 (a)-(f) and Fig. 4 (a)-(f) for 50 GHz and 54 GHz, respectively. From analysis by the degree of equivalence and their expanded uncertainties, the results show good agreement between NMIJ and NMC. The measurement uncertainty of each laboratory was evaluated following *the ISO Guide to the Expression of Uncertainty in Measurement* (GUM) [10].

Table 2. Summary of reported measurements, standard uncertainty and degree of equivalence at 50 GHz.

Nominal attenuation (dB)	NMIJ		NMC		DoE	U_{DoE}
	A_{NMIJ} (dB)	u_{NMIJ} (dB)	A_{NMC} (dB)	u_{NMC} (dB)		
10	9.997	0.011	10.027	0.028	0.030	0.060
20	19.867	0.010	19.835	0.028	0.032	0.059
30	29.805	0.012	29.822	0.028	0.017	0.061
40	40.002	0.012	40.021	0.041	0.019	0.085
50	49.871	0.016	49.843	0.041	0.028	0.088
60	59.767	0.015	59.832	0.062	0.065	0.13

Table 3. Summary of reported measurements, standard uncertainty and degree of equivalence at 54 GHz.

Nominal attenuation (dB)	NMIJ		NMC		DoE	U_{DoE}
	A_{NMIJ} (dB)	u_{NMIJ} (dB)	A_{NMC} (dB)	u_{NMC} (dB)		
10	9.812	0.008	9.826	0.018	0.014	0.039
20	19.594	0.008	19.581	0.018	0.013	0.039
30	29.350	0.007	29.371	0.018	0.021	0.039
40	39.279	0.008	39.292	0.025	0.013	0.052
50	49.049	0.014	49.068	0.025	0.019	0.057
60	58.859	0.010	58.904	0.037	0.045	0.077

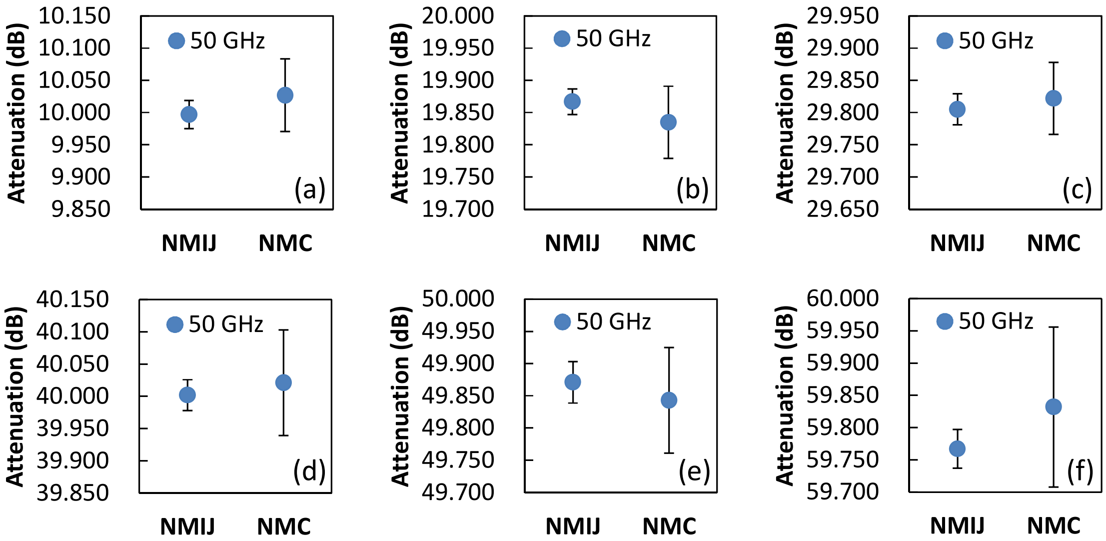

Fig. 3. Results of attenuation measurements with the expanded uncertainty (*k*=2) at NMIJ and NMC at 50 GHz: (*a*) 10 dB, (*b*) 20 dB, (*c*) 30 dB, (*d*) 40 dB, (*e*) 50 dB and (*f*) 60 dB.

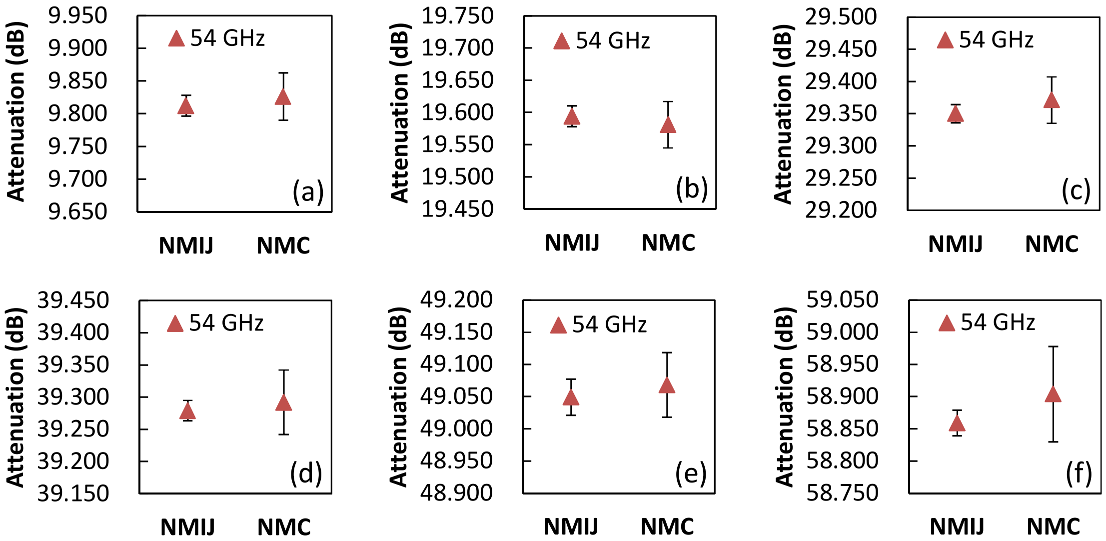

Fig. 4. Results of attenuation measurements with the expanded uncertainty (*k*=2) at NMIJ and NMC at 54 GHz: (*a*) 10 dB, (*b*) 20 dB, (*c*) 30 dB, (*d*) 40 dB, (*e*) 50 dB and (*f*) 60 dB.

4.1. Uncertainty evaluation at NMIJ

The uncertainty budgets of NMIJ measurements are shown in tables 4 and 5 for 50 GHz and 54 GHz, respectively. Details of individual uncertainties estimation has been given in [4]. Because the TS has relatively large reflection coefficient due to the coaxial-to-waveguide adaptors, the mismatch effect is a dominant source of uncertainty in this measurement. However, the effect is minimized by adjusting the reflection coefficient of the test ports with the tuners. The mismatch uncertainties were evaluated by Eq. (29) in [11]. Reflection coefficients of the TS and the test ports were measured by a vector network analyzer (VNA). In this report, the reflection coefficient of the test ports was estimated to be less than 0.015 including its measurement uncertainty.

Table 4. NMIJ's uncertainty budget of the measurement at 50 GHz.

Source of uncertainty		Type	Probability distribution	Attenuation					
				10 dB	20 dB	30 dB	40 dB	50 dB	60 dB
				u_i (dB)	u_i (dB)	u_i (dB)	u_i (dB)	u_i (dB)	u_i (dB)
u_1	Random	A	Normal	0.0006	0.0010	0.0010	0.0011	0.0021	0.0017
u_2	IVD (reference standard)	B	Rectangular	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002
u_3	residual voltage of IVD	B	Rectangular	0.0000	0.0000	0.0001	0.0001	0.0010	0.0010
u_4	loading effect of IVD	B	Rectangular	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005
u_5	gain change of IF amplifier	B	Rectangular	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
u_6	linearity	B	Rectangular	0.0007	0.0007	0.0007	0.0007	0.0044	0.0044
u_7	stability	B	Rectangular	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012
u_8	RF leakage	B	Rectangular	0.0000	0.0000	0.0002	0.0002	0.0013	0.0013
u_9	IF leakage	B	Rectangular	0.0000	0.0000	0.0002	0.0002	0.0020	0.0020
u_{10}	detector noise	B	Rectangular	0.0013	0.0013	0.0022	0.0022	0.0061	0.0061
u_{11}	mismatch	B	U shape	0.0106	0.0092	0.0116	0.0117	0.0126	0.0116
Combined standard uncertainty				0.011	0.010	0.012	0.012	0.016	0.015
Expanded uncertainty (k=2)				0.022	0.020	0.024	0.024	0.032	0.030

Table 5. NMIJ's uncertainty budget of the measurement at 54 GHz.

Source of uncertainty		Type	Probability distribution	Attenuation					
				10 dB	20 dB	30 dB	40 dB	50 dB	60 dB
				u_i (dB)	u_i (dB)	u_i (dB)	u_i (dB)	u_i (dB)	u_i (dB)
u_1	Random	A	Normal	0.0010	0.0008	0.0011	0.0021	0.0014	0.0021
u_2	IVD (reference standard)	B	Rectangular	0.0001	0.0001	0.0002	0.0002	0.0002	0.0002
u_3	residual voltage of IVD	B	Rectangular	0.0000	0.0000	0.0001	0.0001	0.0010	0.0010
u_4	loading effect of IVD	B	Rectangular	0.0004	0.0004	0.0004	0.0004	0.0005	0.0005
u_5	gain change of IF amplifier	B	Rectangular	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
u_6	linearity	B	Rectangular	0.0007	0.0007	0.0007	0.0007	0.0044	0.0044
u_7	stability	B	Rectangular	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012
u_8	RF leakage	B	Rectangular	0.0000	0.0000	0.0002	0.0002	0.0013	0.0013
u_9	IF leakage	B	Rectangular	0.0000	0.0000	0.0002	0.0002	0.0020	0.0020
u_{10}	detector noise	B	Rectangular	0.0013	0.0013	0.0022	0.0022	0.0061	0.0061
u_{11}	mismatch	B	U shape	0.0075	0.0069	0.0056	0.0071	0.0110	0.0054
Combined standard uncertainty				0.008	0.008	0.007	0.008	0.014	0.010
Expanded uncertainty (k=2)				0.016	0.016	0.014	0.016	0.028	0.020

4.2. Uncertainty evaluation at NMC

The uncertainty budgets of NMC measurements are shown in tables 6 and 7 for 50 GHz and 54 GHz, respectively. The measurement uncertainty analysis at 50 GHz and 54 GHz is similar to those given in [5]. The measurement repeatability is from 0.0008 to 0.0031 dB. A 10 dB matching pad is used at port 1 and port 2 respectively for measuring DUT attenuation below 50 dB. The matching pad at port 2 was reduced to 5 dB for measuring DUT attenuation of 60 dB. The estimated mismatch uncertainty is quite high at 50 GHz due to higher reflection coefficient of the TS and the test ports (measured by a VNA). The standard uncertainty due to receiver nonlinearity is estimated to be 0.0012 and 0.0021 dB at 50 GHz and 54 GHz, respectively. The nonlinearity has been estimated by measuring a 0-10 dB variable attenuator at decreasing signal levels at port 1 [5]. The gauge block attenuator's calibration uncertainty has been included as one component in the uncertainty budget for measurement of attenuation from 40 to 60 dB.

Table 6. NMC's uncertainty budget of the measurement at 50 GHz.

Uncertainty Components	**Type**	**Probability distribution**	**Nominal Attenuation (dB)**			
			0 - 30	**40**	**50**	**60**
IVD error	B	Rectangular	0.0004	0.0004	0.0004	0.0004
Nonlinearity	B	Rectangular	0.0012	0.0012	0.0012	0.0012
Mismatch	B	U shape	0.028	0.030	0.030	0.046
Receiver noise	B	Rectangular	0.0014	0.0027	0.0041	0.0054
Gauge block attenuator calibration uncertainty	B	Normal	0.000	0.028	0.028	0.041
Meaurement repeatability	A	Normal	0.0016	0.0008	0.0010	0.0013
Combined Standard Uncertainty			0.028	0.041	0.041	0.062
Expanded Uncertainty (*k* =2)			0.056	0.082	0.083	0.12

Table 7. NMC's uncertainty budget of the measurement at 54 GHz.

Uncertainty Components	**Type**	**Probability distribution**	**Nominal Attenuation (dB)**			
			0 - 30	**40**	**50**	**60**
IVD error	B	Rectangular	0.0004	0.0004	0.0004	0.0004
Nonlinearity	B	Rectangular	0.0021	0.0021	0.0021	0.0021
Mismatch	B	U shape	0.0175	0.0170	0.0170	0.0263
Receiver noise	B	Rectangular	0.0016	0.0031	0.0031	0.0047
Gauge block attenuator calibration uncertainty	B	Normal	0.0000	0.0178	0.0178	0.0251
Meaurement repeatability	A	Normal	0.0017	0.0010	0.0031	0.0008
Combined Standard Uncertainty			0.018	0.025	0.025	0.037
Expanded Uncertainty (*k* =2)			0.036	0.050	0.050	0.073

5. Conclusion

The results of the bilateral comparison of millimeter-wave attenuation in WR-15 waveguide band at 50 GHz and 54 GHz between NMIJ and NMC are reported. A programmable step attenuator fitted with precision waveguide to coaxial adaptors was used as a travelling standard. The measurement uncertainty budget of both NMIs have also been presented. The degree of equivalence for all the attenuation measurements were analyzed, and good agreement between NMIJ and NMC was verified within their expanded uncertainties.

References

[1] BIPM website http://kcdb.bipm.org/AppendixC/ (accessed 2015-04-02)

[2] C. Eiø and J. Howes, Final report on CCEM key comparison CCEM.RF-K19.CL (GT-RF/00-2): Attenuation at 60 MHz and 5 GHz using a Type N step attenuator, Metrologia 46 (2009) 01006.

[3] BIPM website http://kcdb.bipm.org/appendixB/KCDB_ApB_info.asp?cmp_idy=1432&cmp_cod=CCEM.RF-K26&prov=exalead (accessed 2015-04-02)

[4] H. Iida, A. Widarta, T. Kawakami, K. Komiyama, Attenuation standard in the frequency range of 50-75 GHz, IEEE Trans. Instrum. Meas. 59 (2010) 2921-2929.

[5] T.Y. Wu, Accurate measurement of millimetre-wave attenuation from 75 GHz to 110 GHz using a dual-channel heterodyne receiver, Measurement 45 (2012) 1105-1110.

[6] F.L. Warner, Microwave Attenuation Measurement, Peter Peregrinus Ltd., London, UK, 1977.

[7] IEEE Instrumentation and Measurement Society, IEEE Standard for Precision Coaxial Connectors (DC to 110 GHz), IEEE Std 287-2007.

[8] H. Iida, A. Widarta, T. Kawakami, K. Komiyama, An accurate microwave attenuation measurement system using an inductive voltage divider based on a single-channel IF substitution method, Meas. Sci. Tech. 17 (2006) 1947-1949.

[9] M.G. Cox, The evaluation of key comparison data, Metrologia 39 (2002) 589-595.

[10] JCGM 100:2008, Evaluation of Measurement Data-Guide to the Expression of Uncertainty in Measurement, Joint Committees for Guides in Metrology, 2008.

[11] I.A. Harris, F.L. Warner, Re-examination of mismatch uncertainty when measuring microwave power and attenuation, IEE Proc.-H 128 (1981) 35-41