Progress In Electromagnetics Research, Vol. 125, 295–309, 2012

LOSS MEASURING OF LARGE APERTURE QUASI-OPTICS FOR W-BAND IMAGING RADIOMETER SYSTEM

W.-G. Kim[1], N.-W. Moon[1], J.-M. Kang[2], and Y.-H. Kim[1,*]

[1]Microwave Sensor System Lab., School of Information and Mechatronics, Gwangju Institute of Science and Technology, #123 Cheomdangawiro, Buk-Gu, Gwangju 500-712, Republic of Korea

[2]Korea Astronomy and Space Science Institute, 776 Daedeokdae-ro, Yuseong-gu, Daejeon 305-348, Republic of Korea

Abstract—A loss of large aperture quasi-optics which consist of a lens and a feed antenna is firstly measured using a radiometer receiver via the modified reference control method for a W-band imaging radiometer system. The quasi-optical loss is mainly decided by the dielectric loss of the lens with good quasi-optical transformation efficiency between the lens and the feed antenna. The quasi-optics composed of an aspheric lens and a dielectric rod antenna are designed for high resolution, low aberration, and compact size. The fabricated quasi-optics with the aperture diameter of 500 mm have the quasi-optical transformation efficiency of more than 95%. The radiometer receiver is designed applying a total power type and a direct conversion topology for simplicity, compact size and low temperature sensitivity. The manufactured receiver has the temperature sensitivity less than 1 K for both a hot source and a cold source. The calculated and measured results of the quasi-optics are very well matched by approximately 1.6 dB. The expected measurement errors by the reference control method are also analyzed as the functions of the characteristic parameters of the radiometer receiver.

Received 5 January 2012, Accepted 24 February 2012, Scheduled 1 March 2012
* Corresponding author: Yong-Hoon Kim (yhkim@gist.ac.kr).

1. INTRODUCTION

Analysis of large aperture quasi-optics/antennas has recently been given more attention due to increasing interest in the development of high resolution and low noise radar and radiometer systems for many applications such as remote sensing, medical, security, defense and surveillance [1–4, 20]. At frequencies above microwave, a lens antenna is useful as quasi-optics for an imaging radiometer system due to size, price, weight and beam efficiency at the expense of a dielectric loss against a reflector antenna [5–8, 20]. A loss of quasi-optics is simply summed by a dielectric loss of a lens, a reflection loss on the air-lens interface and a transformation loss from a lens to a feed antenna. If the quasi-optics have good transformation efficiency, the quasi-optical loss is mainly dominated by the dielectric loss of the lens. In an imaging radiometer system, the loss of the quasi-optics as a system front-end should be considered because it is a critical factor to reduce noise performance of a radiometer receiver which deals with a radiated weak signal close to a noise signal. It leads to necessity to measure the quasi-optical loss for estimating the total noise temperature of the imaging radiometer system. However, the loss measurement of the large aperture quasi-optics is difficult because of measurement complex and spatial constraints to cover the required large test space. There are several methods to measure a loss or a noise temperature of RF passive and active components and receivers. As a general method, Y-factor method measures two output ratios with two sources of the different temperatures or a matched noise source at on- and off-state. This method is used to measure a noise temperature of electric components, such as amplifier [9, 10], mixer [11, 12] and receiver/radiometer [13–15]. Another reference control method is introduced by Machin in 1952 and it is used for balancing between an antenna temperature and a reference temperature of a Dicke radiometer by controlling an attenuator in a feedback loop [16]. Sometimes a radiometer receiver needs an off-set voltage in low frequency (LF) part to amplify a low level DC output signal of a detector for proper signal processing. In this case, the reference control method is better than the Y-factor method to measure a loss of quasi-optics using a radiometer receiver due to simpler equation and test set-up.

This paper shows the design and measurement results of the quasi-optics and the radiometer receiver for a W-band large aperture imaging radiometer system in Sections 2 and 3, respectively The measured dielectric constant and loss tangent of PE and the theoretical loss of the quasi-optics are described in Section 4. In Section 5, we present the experimental loss of the quasi-optics and the error analysis. Conclusion follows in Section 6.

2. LARGE APERTURE QUASI-OPTICS DESIGN AND MEASUREMENT

Large aperture quasi-optics configuration, shown in Figure 1, consists of a lens and a feed antenna. The W-band aspheric thick lens is designed by CODE V optical design simulator focusing on high resolution, low aberration and compact size. The fabricated components of the quasi-optics are shown in Figure 2. The lens has the aperture diameter (D) of 500 mm, the center thickness of 145 mm and the edge thickness of 20 mm. The dielectric rod antenna (DRA) as a feed antenna is designed by CST Studio simulator considering high gain and low return loss. The feeder is composed of a tapered dielectric rod and a WR-10 waveguide with 33.18 mm length. The dielectric lens and dielectric rod of the feed antenna are fabricated with polyethylene (PE) which is the characteristics of relatively low dielectric constant, low density and high strength.

The dielectric rod antenna has the measured return loss of −15 dB within full W-band as shown in Figure 3. The measured radiation beam pattern on H-plane, shown in Figure 4, has gain of 15.3 dB, side lobe level of below −15 dB and 10 dB beam-width of 48.6 at 94 GHz. The results of DRA show that the simulated and measured data are almost the same patterns.

For obtaining the effective focal length (F) of the quasi-optics, the relative received power at the feed antenna is measured via the image distance (S_i) from the lens to the feeder on the image plane as shown in Figure 5 when the object distance (S_o) between the lens and

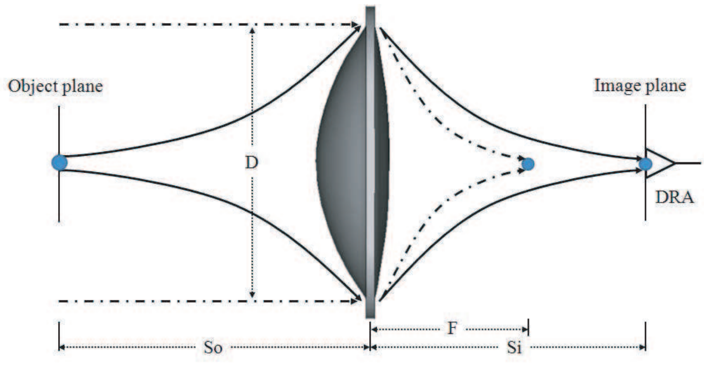


Figure 1. Large aperture quasi-optics configuration.

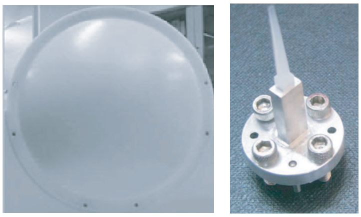
the transmitter on the object plane is fixed by 2380 mm. The actual effective focal length of 42.7 cm or F-number of 0.85 is calculated with the measurement results of $S_i = 520$ mm and $S_o = 2380$ mm using Gaussian thin lens equation as follows.

$$\frac{1}{F} = \frac{1}{S_i} + \frac{1}{S_o} \tag{1}$$

The measurement of the focused H-plane beam pattern of the quasi-optics on the image plane is performed at three different frequencies of 90, 94 and 98 GHz when the feed antenna is placed on the focal point of 520 mm. As shown in Figure 6, the focused H-plane beam patterns are very similar at all frequencies and have about 3 dB beam width of about 6 mm. The details of the quasi-optics have been described in Reference [20].

3. W-BAND RADIOMETER RECEIVER DESIGN AND MEASUREMENT

W-band radiometer receive block diagram in RF part is shown in Figure 7. We designed the receiver based on a total power radiometer type and a direct conversion topology due to simple architecture and low temperature sensitivity. It consists of a dielectric rod antenna, a waveguide to GCPW (Grounded Coplanar Waveguide) transition, MMIC based LNAs and a square law detector. The T-shaped radiometer receiver shown in Figure 8 is fabricated including RF part, LF part and DC to DC part. To verify the radiometer receiver, the measurement of its output voltage is performed via the two-port calibration method. Figure 9 shows the measured output voltages of the hot and cold sources of an absorber in the room temperature (290 K) and an absorber in liquid nitrogen (77 K) during 60 seconds. The measured temperature sensitivity as indicated in Table 1 is less than 1 K for both hot and cold sources.



(a) (b)

Figure 2. Photos of designed (a) lens and (b) DRA. (Courtesy by millisys Inc.).

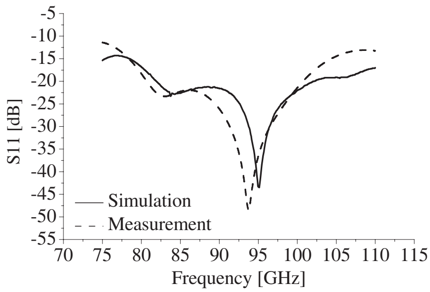


Figure 3. Return loss of DRA in W-band.

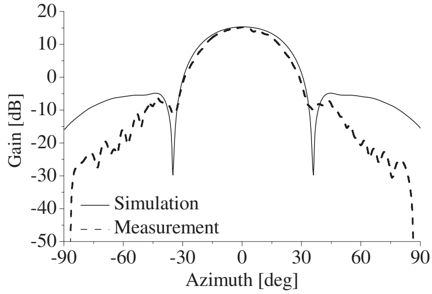


Figure 4. Radiation beam pattern on H-plane of DRA at 94 GHz.

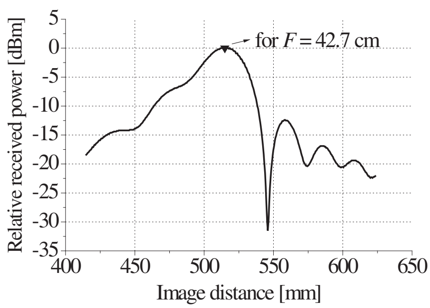


Figure 5. Relative received power at various image distances (S_i) when the object distance (S_o) is fixed by 2380 mm.

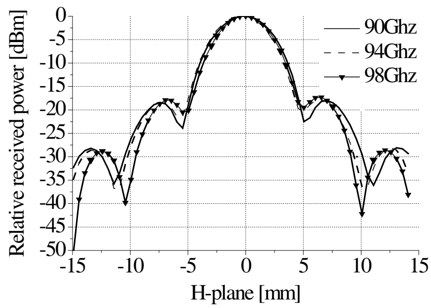


Figure 6. Focused beam pattern on H-plane of the quasi-optics at focal point of 520 mm.

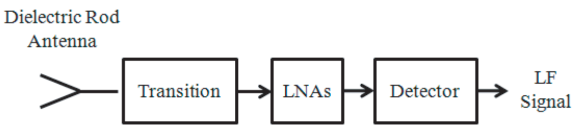


Figure 7. W-band radiometer receiver block diagram in RF part.

4. THEORETICAL LOSS OF QUASI-OPTICS

The radiometer imaging system generally consists of quasi-optics and a radiometer receiver as shown in Figure 10. The field map of focused beams through the quasi-optics on the image plane is shown in Figure 11. Each beam size is different depending on the feed antenna position on the image plane because the quasi-optical transformation

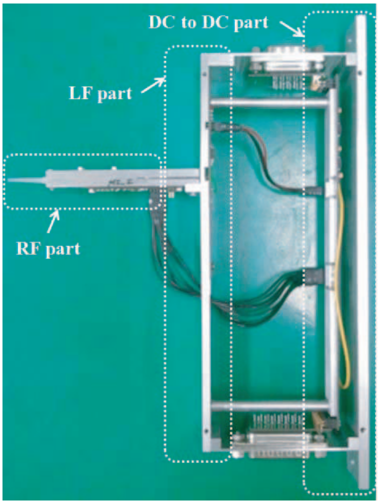


Figure 8. Fabricated W-band radiometer receiver (Curtesy by millisys Inc.).

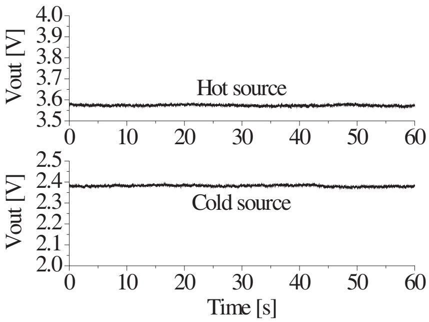


Figure 9. Measured output voltage of radiometer receiver for each hot and cold source.

Table 1. Measured temperature sensitivity of radiometer receiver.

	Cold Source (77 K)	Hot Source (290 K)
Temperature Sensitivity	0.7 K	1.0 K

efficiency is unequal at the different place. It means that there are differences of the quasi-optical loss on the image plane following the trend of the quasi-optical transformation efficiency. In generally, the quasi-optical loss becomes lower toward edge of the image plane.

The loss of the quasi-optics is an important factor to estimate total system noise figure (NF_{Total}) which is summed by its quasi-optics noise figure (NF_Q) and radiometer receiver noise figure (NF_{Rx}). It means that the quasi-optical loss directly affects total noise temperature (T_{Total}) and temperature sensitivity (dT_{Total}) of the radiometer imaging system. The relationship equations between the quasi-optical loss and the system parameters are as follows,

$$NF_Q = L_Q \,[\text{dB}] \tag{2}$$

$$NF_{\text{Total}} = NF_Q + NF_{Rx} \,[\text{dB}] \tag{3}$$

$$T_{\text{Total}} = 290 \cdot \{10 \wedge (NF_{\text{Total}}/10) - 1)\} \,[\text{K}] \tag{4}$$

$$dT_{\text{Total}} = \frac{T_A + T_{Total}}{\sqrt{B \cdot \tau}} \,[\text{K}] \tag{5}$$

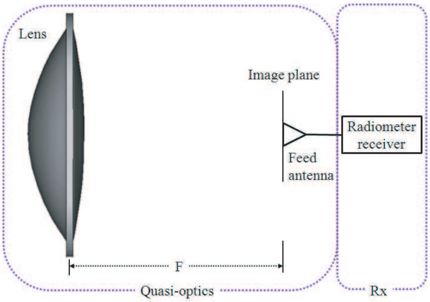


Figure 10. Radiometer imaging system configuration.

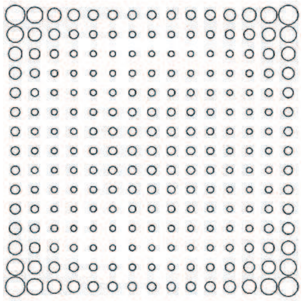


Figure 11. Field map of focused beams on image plane.

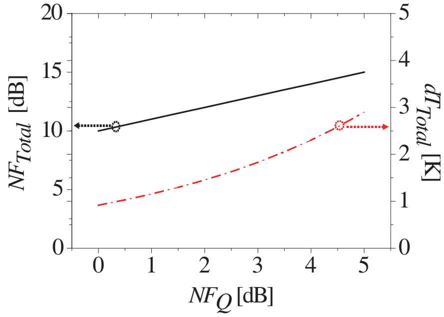


Figure 12. Total system noise figure and temperature sensitivity via quasi-optical noise figure.

where L_Q is the quasi-optical loss and equal to NF_Q because the quasi-optics is the front-end in the imaging system. T_A is an input temperature of the feed antenna. B and τ are RF bandwidth and integration time of the radiometer receiver. The effects of the quasi-optical noise figure on the total system noise figure and the total temperature sensitivity of the radiometer imaging system are shown in Figure 12 using the above equations. If the quasi-optical loss is 1 dB, NF_{Total} of 11 dB and dT_{Total} of 1.15 K when $NF_{Rx} = 10$ dB, $B = 1$ GHz, $\tau = 10$ ms and $T_A = 290$ K. In other words, 1% increase of NF_{Total} by the quasi-optics finally leads to 26% degradation of dT_{Total}. The degradation degreed of the total system temperature follows the tendency of the quasi-optical loss on the image plane.

A loss of quasi-optics is simply summed by a dielectric loss of a lens, a reflection loss on the air-lens interface and a transformation loss from a lens to a feed antenna. If quasi-optics have good transformation

Table 2. Theoretical dielectric loss of polyethylene at 94 GHz.

	[18]	[19]	This work
ε_r	2.306	2.3065	2.279
$\tan\delta$	0.00053	0.0004	0.00046
Lens loss [dB]	1.92	1.45	1.69

efficiency, a loss of quasi-optics is mainly dominated by a dielectric loss of a lens. The designed quasi-optics have high transformation efficiency of more than 0.95 when the 10 dB edge taper angle (ψ_w) of the feed antenna is 20 to 80 degrees [15]. To calculate the loss of the quasi-optics, the dielectric loss of the quasi-optics is only taken into account. As mentioned in Section 2, the lens is manufactured by polyethylene (PE) with the center thickness of 145 mm corresponding 45.3λ at 94 GHz. The theoretical loss of the quasi-optics can be obtained using the dielectric loss equation as follows [17],

$$L_{\varepsilon_r} = 27.3 \cdot \tan\delta \cdot \frac{n}{n-1}\ [\mathrm{dB}/\lambda] \tag{6}$$

where ε_r, $\tan\delta$ and n are a dielectric constant, a loss tangent and a refractive index of the used dielectric material, respectively. As shown in Equation (6), the correct dielectric constant and loss tangent are necessary to compute the accurate dielectric loss of the quasi-optics. Gerhard et al. reported both values of several polymers, such as polypropylene, polyethylene, teflon, rexolite, plexiglas, PVC and nylon, at 76.5, 85 and 94 GHz using a broad-band free-space measurement system [18, 19]. We also measured the dielectric parameters of polyethylene using the transmission line method within 92 to 96 GHz as shown in Figures 13 and 14. The measurement results of the dielectric constant and loss tangent of PE are 2.279 and 0.00045 at 94 GHz, respectively. The dielectric constant and loss tangent of polyethylene of the reference and our measurement data are summarized in Table 2. There are a little difference between the references and the measurement results because of the actual different test sample material and the different test method. At the high frequency, it is also difficulty to measure the accurate dielectric characteristics of PE due to the physical size and state of the fabricated test sample and its mounting state on the test jig.

5. EXPERIMENTAL LOSS OF QUASI-OPTICS

The designed radiometer receiver needs the off-set voltage which is inserted to the video amplifier in LF part to increase the weak output

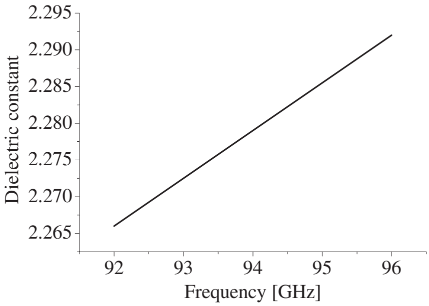


Figure 13. Measured dielectric constant of PE.

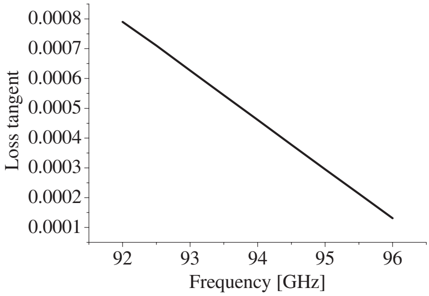


Figure 14. Measured loss tangent of PE.

signal of the square law detector up to enough high voltage level for signal processing. The offset term makes the test procedure and the necessary equation for the general method, such as Y-factor and Z-factor method, complex to measure the loss of the quasi-optics using the radiometer receiver. To measure the quasi-optical loss, the reference control method is used because it doesn't take account for the off-set term. Figures 15 and 16 show the experimental set-up to measure the quasi-optical loss via the modified and optimized the reference control method using the fabricated W-band radiometer. Two different sources of an absorber in the air (290 K) and an absorber in the liquid nitrogen (77 K) are used as the hot and cold sources for the reference control method.

To measure the loss of the quasi-optics, the first step is to get the linear characteristic of the radiometer receiver without the lens by calibrating the receiver on each hot and cold source as shown in Figure 15. The measured characteristic of the receiver is plotted by a solid line and is derived by the output voltage (V_{OUT}) of the receiver as the function of the input brightness temperature (T_B) in Figure 17. As second step, the output voltage of the radiometer receiver with the lens positioning on the effective focal point of the lens is measured for the cold source as shown in Figure 16. The measured value is pointed by a circle (o) in Figure 17. The quasi-optical loss can be calculated with the measurement results using the equations based on the modified reference control method as follows,

$$A = \frac{V_H - V_C}{T_H - T_C} \tag{7}$$

$$B = V_H - A \cdot T_H \tag{8}$$

$$T_{C+\mathrm{LENS}} = \frac{(V_{C+\mathrm{LENS}} - B)}{A} \tag{9}$$

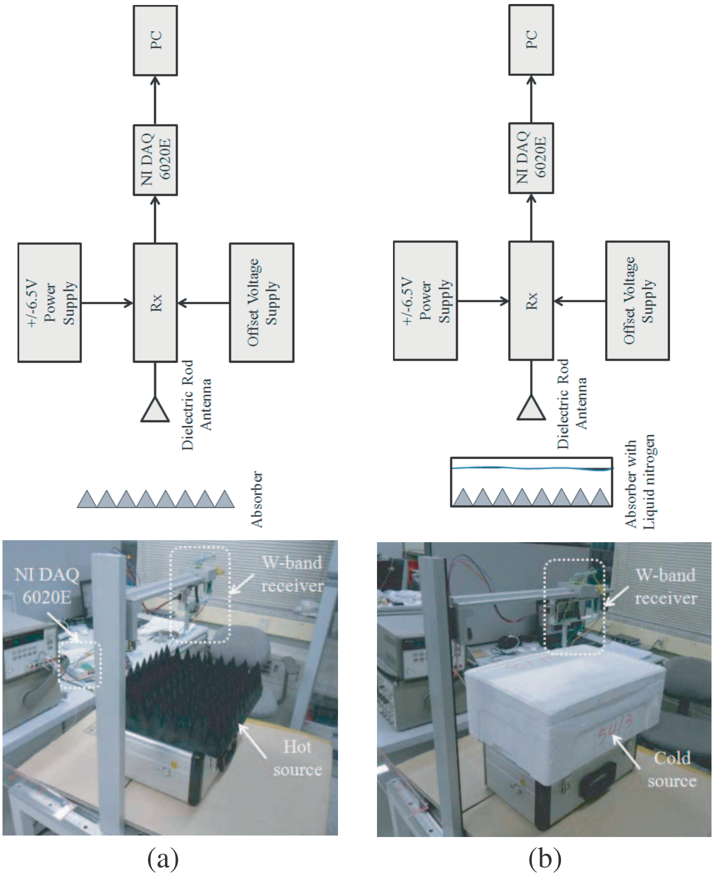


Figure 15. Experimental set-up of radiometer receiver without lens for (a) hot and (b) cold source measurement.

$$L_{\text{LENS}} = \frac{T_C - T_H}{T_{C+\text{LENS}} - T_H} \tag{10}$$

where T_C of 77 K and T_H of 290 K are the temperature of the hot and cold sources. V_H and V_C are the output voltages of the radiometer receiver for each hot and cold source. In Figure 17, the parameters, such as 'A' of the slope and 'B' of the y-intercept value, present the linear characteristics of the radiometer receiver. The output voltage ($V_{C+\text{LENS}}$) reflects the total brightness temperature which is the summation of the cold temperature and the noise temperature caused by the loss of the quasi-optics. The measured loss of the quasi-optics is 1.6 dB and the measured parameters relating to the

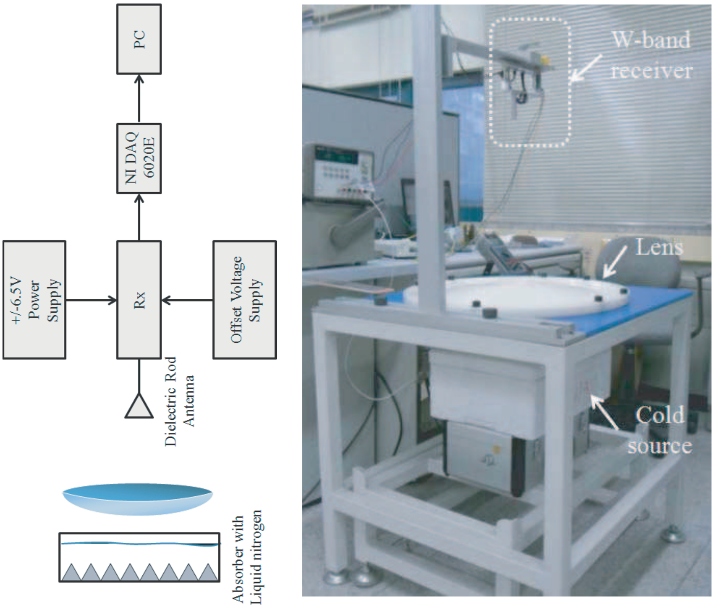


Figure 16. Experimental set-up of radiometer receiver with lens for only cold source measurement. (Courtesy by millisys Inc.).

Table 3. Measured results of quasi-optics based on the reference control method.

Parameter	Value
A	0.005596
B	1.950719
$V_{C+\text{LENS}}$ [V]	2.75
$T_{C+\text{LENS}}$ [K]	142.68
L_{LENS} [dB]	1.6

Equations (7) to (10) are depicted in Table 3. There is a little difference between the theoretical loss and the experimental loss of the quasi-optics. It can be caused by the non-correct dielectric constant and loss tangent of PE at W-band, the misalignment on testing the quasi-optics, the stability of the two sources and the gain variation of the radiometer receiver during the experiment.

The Figure 18 shows the expected loss error of the quasi-optics by each 'A' and 'B' variation depending on the receiver stability. Based on the reference control method using the radiometer receiver, it gives the

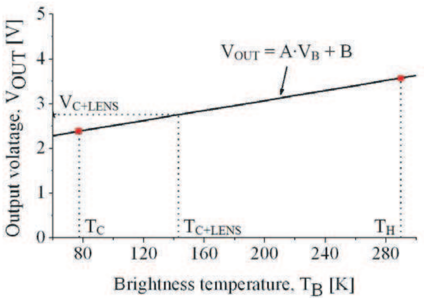


Figure 17. Measurement results of radiometer receiver with lens and without lens.

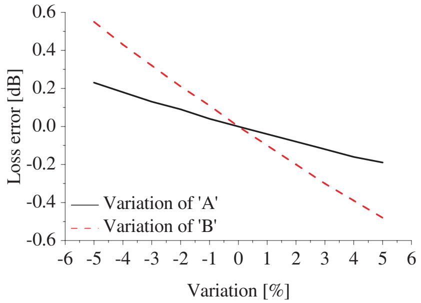


Figure 18. Loss error via each variation of 'A' and 'B'.

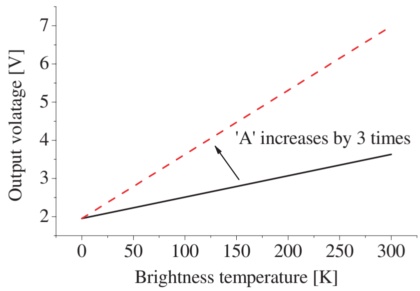


Figure 19. Linear characteristic curve of radiometer receiver through 'A' value.

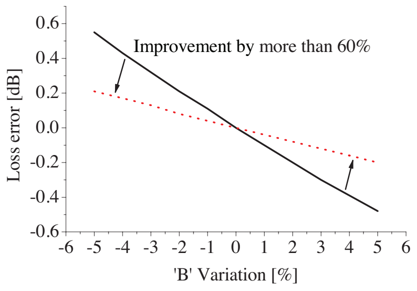


Figure 20. Loss error reduction by 'A' improve-ment via 'B' value.

error of less 2.5% within 1% variation of 'A'. It means if the numerator, $(V_H - V_C)$, of 'A' in Equation (7) varies by about 12 mV, the loss error of 0.04 dB happens. The error of less 6.3% (= 0.1 dB) occurs within 1% variation of 'B' that is affected by the values of 'A' and V_H. As shown in Figures 19 and 20, if the value of 'A' is increased by 3 times of the original, the error reduction can be achieved by more than 60%. At that time, the acceptable variation range of $(V_H - V_C)$ can be extended by 36 mV with the same error by 'A'. In the condition of the fixed temperature sensitivity of the radiometer receiver, the enhancement of 'A' is achieved by the improvement of the receiver responsiveness which is decided by the performance of the detector and the voltage magnification of the video amplifier. However, it is limited by the dynamic range and the output range of the radiometer receiver.

6. CONCLUSION

The modified reference control method is proposed to measure a loss of large aperture quasi-optics using a radiometer receiver in an imaging radiometer system. The measurement of the quasi-optical loss is important to know the total system noise figure and temperature sensitivity of the radiometer system because the quasi-optics directly affect the system parameters as the front-end. The radiometer receiver and the quasi-optics are designed and fabricated in W-band. The total power radiometer receiver has the temperature sensitivity of less than 1 K. The analytical and experimental results of the quasi-optics with the aperture size of 500 mm show that the quasi-optical loss is about 1.6 dB. It is also confirmed that the measurement error by the modified reference control method can be reduced through enhancing the radiometer responsiveness.

ACKNOWLEDGMENT

The work was supported by the basic research program from the Agency for Defense Development (ADD) and by the BK21 program at Gwangju Institute of Science and Technology in Republic of Korea. All radiometer hardwares were manufactured and supported by millisys Inc. through DUTC (Dual Use Technology Center) project. We would like to thank Ph.D. Hyuk Park for the guidelines of the introduction to the conclusion in this work.

REFERENCES

1. Ye, D., S. Xi, H. Chen, J. Huangfu, and L.-X. Ran, "Achieving large effective aperture antenna with small volume based on coordinate transformation," *Progress In Electromagnetics Research*, Vol. 111, 407–418, 2011.
2. Zhang, Y. W., C. H. Yang, S. M. Wu, A. van Roij, W. J. van der Zande, D. H. Parker, and X. M. Yang, "A large aperture magnification lens for velocity map imaging," *Review of Scientific Instruments*, Vol. 82, Jan. 2011.
3. Hsu, H.-T., F.-Y. Kuo, and H.-T. Chou, "Convergence study of current sampling profiles for antenna design in the presence of electrically large and complex platforms using fit-UTD hybridization approach," *Progress In Electromagnetics Research*, Vol. 99, 195–209, 2009.
4. Hu, B., X.-W. Xu, M. He, and Y. Zheng, "More accurate hybrid PO-MoM analysis for an electrically large antenna-radome

structure," *Progress In Electromagnetics Research*, Vol. 92, 255–265, 2009.

5. Qi, F., V. Tavakol, D. Schreurs, and B. K. J. C. Nauwelaers, "Limitations of approximations towards fourier optics for indoor active millimeter wave imaging systems," *Progress In Electromagnetics Research*, Vol. 109, 245–262, 2010.
6. Dou, W.-B., H. F. Meng, B. Ni, Z.-X. Wang, and F. Yang, "Scanning antenna at THz band based on quasi-optical techniques," *Progress In Electromagnetics Research*, Vol. 108, 343–359, 2010.
7. Andres-Garcia, B., L. E. Garcia-Munoz, V. Gonzalez-Posadas, F. J. Herraiz-Martinez, and D. Segovia-Vargas, "Filtering lens structure based on srrs in the low THz band," *Progress In Electromagnetics Research*, Vol. 93, 71–90, 2009.
8. Rehan Ashraf, M., A. Ghafar, and Q. A. Naqvi, "Fields in the focal space of symmetrical hyperbolic focusing lens using Maslov's method," *Journal of Electromagnetic Waves and Applications*, Vol. 22, Nos. 5–6, 815–828, 2008.
9. Engen, G. F., "A new method of characterizing amplifier noise performance," *IEEE Transactions on Instrumentation and Measurement*, Vol. 19, Nov. 1970.
10. Williams, G. L., "Measuring amplifier noise on a noise source calibration radiometer," *IEEE Transactions on Instrumentation and Measurement*, Vol. 44, Apr. 1995.
11. Lobanov, Y. V., C. Y. E. Tong, A. S. Hedden, R. Blundell, B. M. Voronov, and G. N. Gol'tsman, "Direct measurement of the gain and noise bandwidths of HEB mixers," *IEEE Transactions on Applied Superconductivity*, Vol. 21, 645–648, Jun. 2011.
12. Jiang, L., W. Zhang, Q. J. Yao, Z. H. Lin, S. C. Shi, S. I. Svechnikov, Y. B. Vachtomin, S. V. Antipov, B. M. Voronov, N. S. Kaurova, and G. N. Gol'tsman, "Characterization of a quasi-optical NbN superconducting hot-electron bolometer mixer," *PIERS Proceedings*, Vol. 1, No. 5, Hangzhou, China, Aug. 22–26, 2005.
13. De Wachter, E., A. Haefele, N. Kampfer, S. Ka, J. E. Lee, and J. J. Oh, "The seoul water vapor radiometer for the middle atmosphere: Calibration, retrieval, and validation," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 49, 1052–1062, Mar. 2011.
14. Li, L. C., J. Y. Yang, J. T. Xiong, J. J. Wu, Z. M. Jiang, and X. Zheng, "W band Dicke-radiometer for imaging," *International Journal of Infrared and Millimeter Waves*, Vol. 29, 879–888,

Sep. 2008.

15. Deuber, B., N. Kampfer, and D. G. Feist, "A new 22-GHz radiometer for middle atmospheric water vapor profile measurements," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 42, 974–984, May 2004.
16. Ulaby, F. T., *Microwave Remote Sensing — Active and Passive*, Vol. 1, 1981.
17. Volakis, J. L., *Antenna Engineering Handbook*, 4th edition, 2007.
18. Friedsam, G. L. and E. M. Biebl, "Precision free-space measurements of complex permittivity of polymers in the W-Band," *IEEE MTT-S International Microwave Symposium Digest*, 1997.
19. Goldsmith, P. F., *Quasioptical Systems — Gaussian Beam Quasioptical Propagation and Applications*, 4th edition, 1998.
20. Thakur, J. P., W.-G. Kim, and Y.-H. Kim, "Large aperture low aberration aspheric dielectric lens antenna for W-band quasi-optics," *Progress In Electromagnetics Research*, Vol. 103, 57–65, 2010.