60 GHz antenna measurement setup using a VNA without external frequency conversion

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Abstract—The typical antenna measurement system setup working above 20 GHz makes use of frequency multipliers and harmonic mixers, usually working in standard waveguide bands, and thus several parts need to be procured and interchanged to cover several frequency bands. In this paper, we investigate an alternative solution which makes use of an external frequency conversion units. The operational capability of the Planar Near-Field (PNF) Antenna Measurement Facility at the Technical University of Denmark was recently extended to 60 GHz employing an Agilent E8361A VNA (up to 67 GHz). The upgrade involved procurement of very few additional components: two cables operational up to 65 GHz and an open-ended waveguide probe for tests in U-band (40-60 GHz). The first tests have shown good performance of the PNF setup: 50-60 dB dynamic range and small thermal drift in magnitude and phase, 0.06 dB and 6 degrees peak-to-peak deviations over 4 hours. A PNF measurement of a 25 dBi Standard Gain Horn (SGH) was carried out and the results were compared to those from the DTU-ESA Spherical Near-Field Facility with a good agreement in the validity region. Uncertainty investigations regarding cable flexing effects at 60 GHz have shown that these introduce an uncertainty of about 0.02 dB (1 sigma) around the main beam region indicating a very good performance of the PNF setup.

I. INTRODUCTION

The interest in the millimeter wave spectrum (30-300 GHz) has increased lately due to a number of benefits which it brings in wireless communications systems: operation in an unlicensed band, wide available bandwidth and large transmission capacity of information, secure communication and frequency reuse due to special propagation characteristics of mm waves (oxygen and water absorption), miniaturization and ease of integration of the Agilent E8361A VNA, procurement of two cables operational up to 65 GHz and an open-ended waveguide probe for tests in U-band. The probe is based on a WR-19 waveguide Orthomode Transducer (OMT) from Millitech [10] and manufacturing of an open-ended circular waveguide probe for U-band. The latest upgrade carried out in the spring of 2014 included integration of the Agilent E8361A VNA, procurement of two cables with 1.85 mm connectors operational to 65 GHz (from Pasternack [10]) and manufacturing of an open-ended circular waveguide probe for U-band. The probe is based on a WR-19 waveguide Orthomode Transducer (OMT) from Millitech [12], but is currently used only in one polarization; the connection of the available waveguide switch is planned for the near future. The side view of the DTU PNF Facility is shown in Fig. 1.

In order to reduce the loss in the cables, the length of these was chosen to be as small as possible. The cable connecting...
the VNA to the moving probe has the length of 120 cm, while the cable connecting the VNA to the AUT has the length of 150 cm, see Fig. 1. The maximum scan area for the probe used at 60 GHz is currently limited to some 200 x 220 mm². Thus the shape of the moving cable varies rather smoothly ensuring minimum changes in its electrical characteristics.

The return loss of the cables show values larger than 20 dB in the 40-60 GHz band and transmission loss is around 7 dB and 10 dB at 60 GHz for the short and long cables, respectively. The measured return loss of the probe is above 15 dB in the whole 40-60 GHz band.

**III. FIRST TESTS IN THE 40-60 GHz BAND**

A series of simple tests were carried out to choose optimum parameters of the VNA and analyze the performance of the PNF measurement setup at 60 GHz.

**A. System dynamic range**

It is desired to have as large dynamic range as possible and thus the VNA measurement settings were optimized to reduce the noise, while keeping the measurement time small. The IF bandwidth was set to 1 kHz and the signal source power level was set to 2 dBm (maximum level around 60 GHz). For the setup consisting of the two cables and the probe described above, and a SGH with 25 dBi gain, the received power level was measured to be around -30 dBm, while the noise floor measured by disconnecting the AUT cable, was measured to be around -90 dBm. Therefore the system dynamic range of about 60 dB was obtained through the whole 40-60 GHz frequency range. With these VNA settings for 11 frequency points, a single line scan with 3 mm steps over the 200 mm range takes about 3.5 min. Depending on the gain of the measured antenna and number of the frequency points, the VNA settings can be changed either to improve the dynamic range or to reduce measurement time.

**B. Drift**

Thermal drift is one of the error sources in antenna measurements, and it is especially important for near-field measurements, which may take several hours depending on the electrical size of the measured antenna. A magnitude and phase drift test over 4 hours was performed measuring the signal level every minute; the results are shown in Fig. 2 and Fig. 3.

![Fig. 2. Magnitude drift at 60 GHz over 4 hours](image1)

From Fig. 2 it is seen that excluding the initial 30 minutes of cable settling and warming up, the magnitude variation resembles noise with the peak to peak variation of about ±0.03 dB. This peak to peak difference, however, corresponds to a noise floor at about -50 dB, thus the drift gives an additional contribution equivalent to decreasing the dynamic range by 10 dB. The phase drift, as seen from Fig. 3, has monotonic behavior changing with the rate of about 1.5° per
hour. For 60 GHz, this 1.5° phase change corresponds to a length change of merely 21 µm which is likely to have occurred due to temperature change during measurement (for a typical metal of 1 m length this corresponds to 1°-2° of temperature change). For a long data acquisition it is necessary to keep the temperature very stable; in addition, reference point measurements and corresponding phase correction may be applied to reduce the phase drift.

C. Cable flexing

Since a major concern for the setup is the cable flexing effect on the measured results a series of tests were carried out in order to quantify magnitude and phase variations due to cable flexing. The transmission loss $S_{21}$ between the probe and the SGH was measured by performing several identical horizontal line scans, each taking 3.5 minutes and the Equivalent Error Signal (EES) was calculated using (1) Section V; the results are shown in Fig. 4.

The EES curve indicates a level around -49 dB which causes a peak to peak deviation of 0.01 dB (1 sigma). The results show small magnitude variations between repeated line tests, slightly exceeding the noise floor level of -50 dB.

To further analyze the magnitude and phase variations due to flexing cable, measurements of the reflection coefficient $S_{22}$ were carried out with the cable connected to the moving OMT which was short circuited in the aperture. The measured magnitude and phase variations from 5 consecutive horizontal and vertical line scans each taking 3.5 minutes, are shown in Fig. 5 to Fig. 8.

It can be seen from Fig. 5 and Fig. 6 that the magnitude and phase from five sequential measurements along the horizontal scan axis are not identical. The first scan, and to some extent the second scan, obviously reflects a start-up problem and it can be disregarded. Hence the following analysis is based on the last 3 scans.

The magnitude and phase absolute difference between the last three scans is less than 0.05 dB and around 1°. Within one horizontal line scan the peak to peak magnitude and phase variations show values around 0.07 dB and 1.7°.

Vertical line scans (Fig. 7 and Fig. 8) show maximum magnitude and phase variations of approximately the same order as for the horizontal scans. Also here the first scan is noticeably different from the remaining ones. The maximum deviations occur at the beginning and the end of the vertical line scan (Fig. 7, Fig. 8) with a good repeatability in the middle of the range with deviations of the order of hundredths of dB and tenths of degrees. Since the data show relatively small magnitude and phase variations and the results indicate rather a random behavior, no correction is applied to compensate for the cable flexing. Also, taking into account that the results shown are for the reflection coefficient, (not
transmission coefficient) it can be assumed that the magnitude and phase deviations are only half of observed values for the transmission case. Therefore, it can be considered that the cable flexing effect on magnitude and phase stability is rather minor. In order to clarify how the observed magnitude and phase differences would affect the far field data, uncertainty investigations were performed as documented in Section V.

IV. SGH Measurement

A. PNF measurement of the SGH

Finally, a full-scan PNF measurement of a SGH with 25 dBi gain was carried out. The scan plane size was 220 x 200 mm$^2$ with the step size of 2.5 mm both along x- and along y-axes. The distance between the SGH aperture and the probe aperture was 30 mm, and with the SGH aperture dimensions of 30 x 40 mm$^2$, the angular validity region for the SGH far-field pattern was calculated to be ±72° in the E-plane and ±69° in the H-plane. The full-scan measurements were done first for the horizontal and then for the vertical probe polarizations with manual rotation of the probe. For 80x88 scan points, the duration of a full scan measurement for one polarization was around 8 hours. Probe correction was applied on the measured data.

B. Comparison with the reference results

Reference results for the radiation pattern of this SGH were obtained from measurements at the DTU-ESA Spherical Near-Field (SNF) Facility. A comparison of the co-polar and cross-polar patterns at 60 GHz in the E-plane ($\phi = 0°$) and in the H-plane ($\phi = 90°$) from the PNF Facility and from the SNF Facility are shown in Fig. 9.
of reflections in the PNF setup. The agreement in the cross-
polar pattern is also rather good, even though the shape 
is quite different. It is noted that the cross-polar pattern is 
clearly asymmetric, which may also be explained by the room 
reflections in the PNF setup. The absorber treatment of the 
PNF setup is very limited, as can be seen from Fig. 1; it is 
planned in the near future to cover the scanner frame, the floor 
and ceiling with additional absorbers.

The other reasons for the asymmetry of the PNF pattern 
and difference between the PNF and SNF results can be the 
other sources of uncertainty, e.g. planarity of the PNF scan 
plane, effects of the drift and the flexing cable, scan plane 
truncation, and also incomplete probe correction. However 
despite of the long measurement time of a full scan, the 
comparison of the SNF and PNF shows a good agreement 
indicating rather a minor effect of the thermal drift on the PNF 
measured data. Concerning probe correction, the full-sphere 
probe pattern was accurately measured in the SNF Facility, but 
the channel balance for the probe orientations was assumed to 
be 1; the magnitude and phase difference due to bent cable 
may contribute to the SGH pattern uncertainty.

C. Back projection

In order to further verify the quality of the PNF mea-
urement results the commercial software DIATOOL from 
TICRA was used to perform back projection of the radiated 
far field obtained from the PNF setup. The antenna aperture 
field was reconstructed on 10x10 cm surface. (Fig. 10). The 
amplitude of the tangential x and y components of the E-
field at 60 GHz for the SGH are shown in Fig. 10 and 
the SGH aperture is represented by the black rectangle. The 
x-component shows the expected aperture field distribution 
typical for a SGH, while the y-component has the expected 
low level with some asymmetry; as explained above, this 
asymmetry is most probably caused by the room reflections 
of the PNF setup.

V. FLEXING CABLE UNCERTAINTY INVESTIGATION

Since the major concern for the mm wave PNF measurement 
system are the cable signal magnitude and phase variations a 
detailed investigation on this uncertainty term is performed.
To verify the cable flexing impact on the far field pattern, the 
raw near-field data was modified with values taken from the 
measured variations of the magnitude and phase of the reflec-
tion coefficient from the short-circuited OMT. The modified 
data was then processed to obtain the far field. As noted in 
Section IV, it can be assumed that the differences in magnitude 
and phase obtained from the measurements of the reflection 
coefficient are twice larger than those for the transmission 
coefficient. To investigate the cable magnitude and phase vari-
ations effect, the corresponding maximum difference between 
the measurements of the reflection coefficient was divided by 
2, then added or subtracted to the magnitude and phase of the 
near field data and the obtained modified near-field data was 
transformed to the far field. Since for the vertical scans (y-axis) 
the variations of the cable in phase and magnitude are quite 
small in the center of the scan area region, the compensation 
was done only for the x-axis variations. For completeness, the 
near-field data modified with the full difference (not half) in 
magnitude and phase was analyzed as well.

For the obtained far-field pattern with modification and 
without modification (as measured), the EES was then cal-
culated. The EES was obtained by subtracting the modified 
far-field pattern from the non-modified far-field pattern at 60 
GHz in linear scale and by converting the result back to dB 
using the following formula:

\[
EES = 20 \log_{10} \left| \log_{10}^{-1} \left( S_{dB}/20 \right) - \log_{10}^{-1} \left( (S_{dB} + \delta_{dB})/20 \right) \right| 
\]

Here, \((S_{dB} + \delta_{dB})\) indicates the modified far-field pattern 
and \(S_{dB}\) indicates the non-modified far-field pattern. The 
normalized patterns and the EES are shown in Fig. 11.

It can be seen from Fig 11 that the EES curve in the E-
plane \(\phi = 0^\circ\) for the data modified with half value of the 
cable variations has a peak value around -48 dB and for the 
data modified with the full difference in magnitude and phase, 
a peak value around -42 dB. For the H-plane, \(\phi = 90^\circ\), the EES
values are below -70 dB since for this plane no modification of the magnitude or phase was performed.

The pattern standard uncertainty in dB due to the flexing cable is calculated by considering that the standard deviation is 1/3 of the corresponding peak to peak variation calculated with (1):

$$\Delta_{dB} = 20 \log_{10} \left( \max \left( \log_{10} \left( \frac{EES}{20} \right) \right) \right) + \frac{1}{3} + 1 \quad (2)$$

In the E-plane ($\phi = 0^\circ$), the EES level of -42 dB causes the standard deviation of $\Delta_{dB} = 0.02$ dB around the main beam peak, while the EES level of -48 dB causes the standard deviation of $\Delta_{dB} = 0.01$ dB. The above calculations show, that the effects of the magnitude and phase variations due to the flexing cable are rather small.

VI. CONCLUSIONS

The PNF Antenna Measurement Facility at DTU was recently upgraded to 60 GHz without external frequency conversion devices. An Agilent E8361A VNA and few additional hardware components, two cables operational up to 65 GHz and U-band (40-60 GHz) open-ended waveguide probe, were employed. The series of tests has shown high performance of the upgraded measurement setup: 50-60 dB dynamic range, small magnitude and phase drift, and relatively small flexing cable effects. A comparison of the results from the full scan PNF measurement of a 25 dBi SGH with the reference results from the DTU-ESA Spherical Near-Field Facility has shown very good agreement in the co-polar pattern and reasonable agreement in the cross-polar pattern. A detailed investigation of the flexing cable effect on the obtained far-field pattern of the SGH has shown standard uncertainty between 0.01 - 0.02 dB. The overall results indicate that in the upgraded PNF setup the magnitude and phase variations due to flexing cable have a minor effect on the obtained far-field patterns.

It is planned to continue development of the PNF Facility by performing investigations on the scan plane planarity, applying appropriate absorbers around the scanner, improving the alignment capabilities of the antenna support and by employing a dual polarized probe in order to reduce the measurement time.

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