

# Power Density Simulation Report

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Google LLC

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# 1. Numerical modeling for Power Density (PD) calculations

## 1.1 Full-wave numerical computation tool

To calculate the Power Density (PD) of the phone at FR2 frequencies, a commercial software called HFSS, which is a part of ANSYS Electronics Desktop 2019 R3.7 package, has been used. This software is a 3D full-wave electromagnetic (EM) computational solver based on Finite Element Method (FEM).

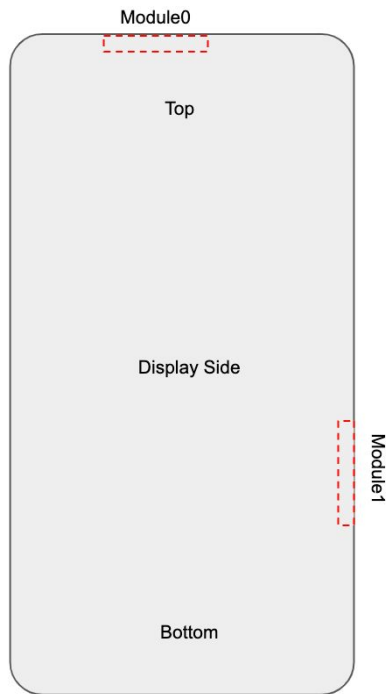
## 1.2 Full-wave simulation setup

### 1.2.1 Simulation model

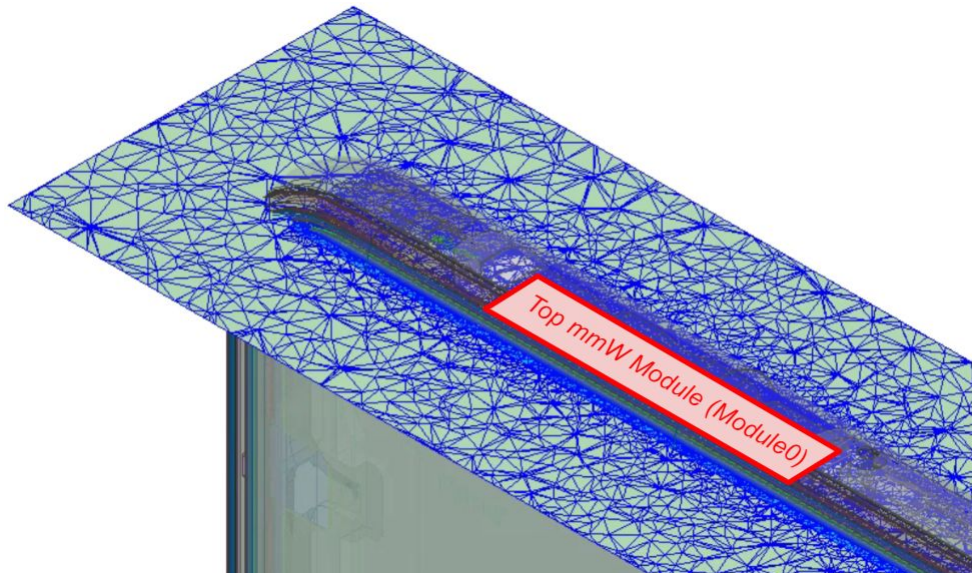
The device includes two mmWave modules, referred to as Module0 and Module1, located at the top and the right side of the device, respectively, as shown in Figure 1-1. In order to obtain accurate PD calculations, it is necessary to have accurate modeling of the mmWave antennas as well as all other components of the device in close proximity to the mmWave antennas. The simulation model therefore must include all components of the device located within a distance of at least one wavelength from the mmWave modules. A list of the components included in the simulation model includes housing, mmWave antenna modules, sub6 antennas, PCB, shield cans, Flexible Printed Circuits (FPCs), battery, etc.

### 1.2.2 Mesh settings and solution setup

ANSYS HFSS features an automatic adaptive mesh refinement algorithm that refines the computational mesh iteratively in regions with strong EM fields and thereby generates very accurate high-frequency simulation results. The steps of adaptive mesh refinement algorithm execution are as follows. First, an initial computational mesh is created, based on the solution setup parameters entered by the user, and is then used to obtain the initial solution for the EM fields of the simulation model. The algorithm then adaptively refines the mesh in each subsequent iteration until a desired solution accuracy, specified by the user, is achieved. The solution accuracy is commonly defined by a convergence parameter called  $\Delta S$ , which is a variation in the magnitude of all S-parameters between the consecutive iterations of the algorithm. The  $\Delta S$  parameter specified for all PD simulations presented in this report is 0.02. Figure 1-1 shows an example cut surface in the model showing a tetrahedral computational mesh created by the adaptive mesh refinement algorithm in one of the HFSS simulation models. A radiation boundary with Absorbing Boundary Condition (ABC) is assigned to the outer surface of an air-box surrounding the simulation model, which allows the EM waves to propagate outward from the boundary of the domain without generating any reflected EM waves.



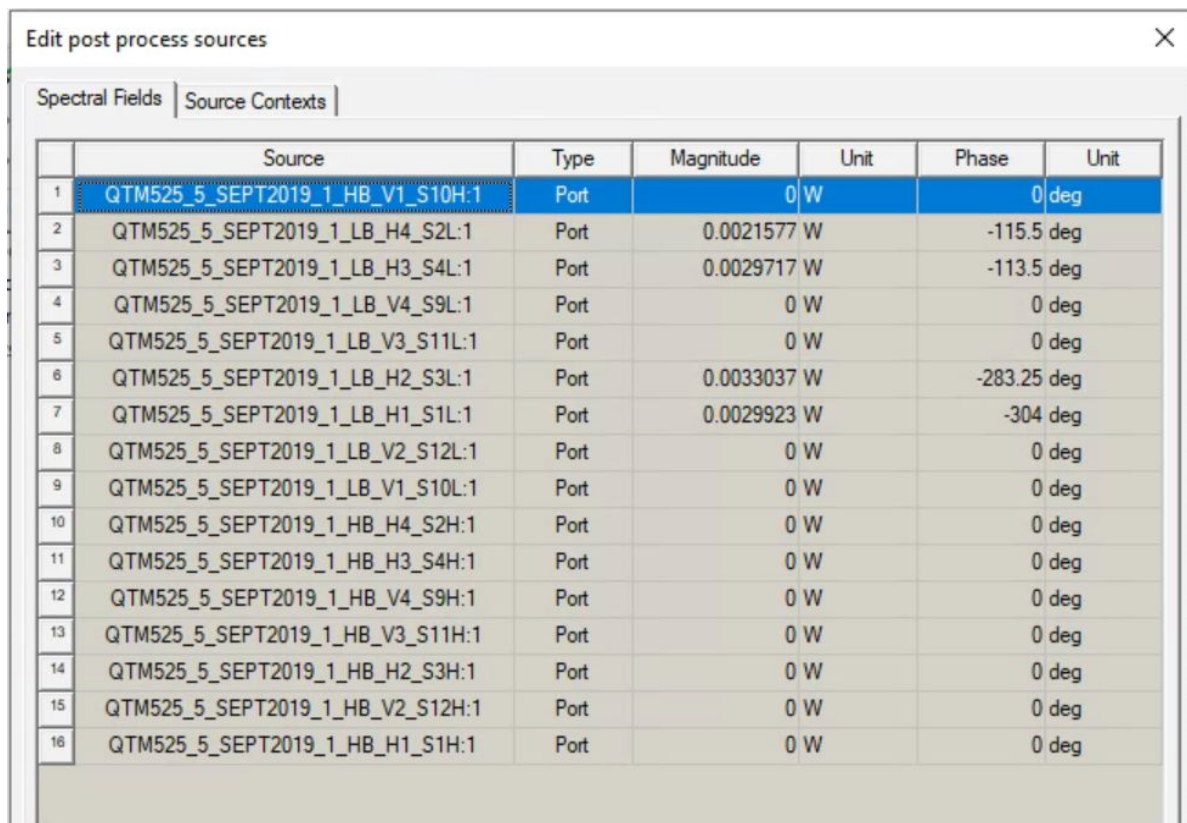
**Figure 1-1** Placement of the two mmWave modules, called Module0 and Module1, at the top and the right side of the device, respectively.



**Figure 1-2** An example cut surface in an HFSS simulation model showing the tetrahedral mesh created by the adaptive mesh refinement algorithm.

The FEM simulations are performed separately for the two mmWave modules. In both of these

two simulations, 16 wave-ports are assigned to the 16 feed points of the mmWave antenna array. Specifically, eight of these 16 wave-ports are located at the eight vertical polarization feed points of the mmWave antenna array, called Antenna Group 0 (AG0), and the remaining eight wave-ports are located at the eight horizontal polarization feed points of the mmWave antenna array, called Antenna Group 1 (AG1). After the FEM simulations are completed and full-wave EM solutions are obtained, the magnitude and phase values of the 16 wave-ports excitation signals are sequentially assigned for each of the beams in the codebook. This is accomplished as a post-processing step by using the “Edit post process sources” tab in the HFSS environment, as shown in Figure 1-3 for one of the beams from the codebook.



	Source	Type	Magnitude	Unit	Phase	Unit
1	QTM525_5_SEPT2019_1_HB_V1_S10H:1	Port	0	W	0	deg
2	QTM525_5_SEPT2019_1_LB_H4_S2L:1	Port	0.0021577	W	-115.5	deg
3	QTM525_5_SEPT2019_1_LB_H3_S4L:1	Port	0.0029717	W	-113.5	deg
4	QTM525_5_SEPT2019_1_LB_V4_S9L:1	Port	0	W	0	deg
5	QTM525_5_SEPT2019_1_LB_V3_S11L:1	Port	0	W	0	deg
6	QTM525_5_SEPT2019_1_LB_H2_S3L:1	Port	0.0033037	W	-283.25	deg
7	QTM525_5_SEPT2019_1_LB_H1_S1L:1	Port	0.0029923	W	-304	deg
8	QTM525_5_SEPT2019_1_LB_V2_S12L:1	Port	0	W	0	deg
9	QTM525_5_SEPT2019_1_LB_V1_S10L:1	Port	0	W	0	deg
10	QTM525_5_SEPT2019_1_HB_H4_S2H:1	Port	0	W	0	deg
11	QTM525_5_SEPT2019_1_HB_H3_S4H:1	Port	0	W	0	deg
12	QTM525_5_SEPT2019_1_HB_V4_S9H:1	Port	0	W	0	deg
13	QTM525_5_SEPT2019_1_HB_V3_S11H:1	Port	0	W	0	deg
14	QTM525_5_SEPT2019_1_HB_H2_S3H:1	Port	0	W	0	deg
15	QTM525_5_SEPT2019_1_HB_V2_S12H:1	Port	0	W	0	deg
16	QTM525_5_SEPT2019_1_HB_H1_S1H:1	Port	0	W	0	deg

**Figure 1-3** An example of magnitude and phase assignment to the wave-ports in the “Edit post process sources” tab in the HFSS environment.

### 1.2.3 Time-average PD calculation

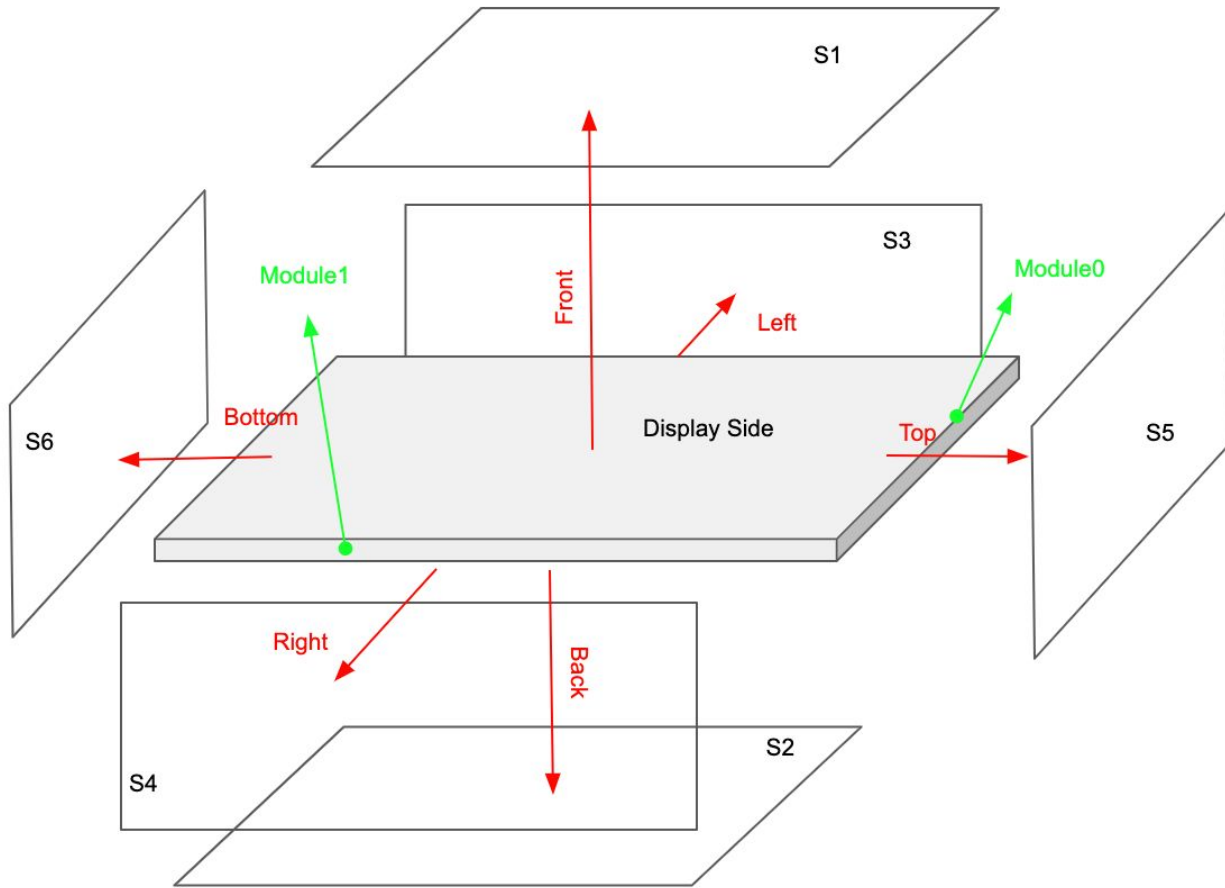
After the convergence criterion is achieved in the last iterative pass, that is  $\text{Max}\{|\Delta S|\}$  is smaller than the specified value of the convergence parameter  $\Delta S$  (that being 0.02 in this report, as mentioned above), the values of the electric and magnetic field vectors respectively are calculated, and then used to calculate the PD by the following formula:

$$PD = \frac{1}{2} \left| \text{Re} \left\{ \vec{E} \times \vec{H}^* \right\} \right|$$

Based on the calculated PD, the time-averaged PD ( $PD_{ave}$ ) over a surface A can be obtained as:

$$PD_{ave} = \frac{1}{2A} \int_A \left| \text{Re} \left\{ \vec{E} \times \vec{H}^* \right\} \right| \cdot dS$$

In order to determine the RF exposure from the mmW antennas in the device, the values of the electric and magnetic field vectors at the six surfaces S1, S2, S3, S4, S5, and S6 shown in Figure 1-4 are needed. Depending on the simulation or measurement setting, the distance from these six surfaces to the device is set to be either 2 or 10 mm. For specific positions and orientations of the mmWave antennas in the device, the surface integration terms in the above formula for the  $PD_{ave}$  corresponding to some of these six surfaces are negligible, and thus can be excluded from the  $PD_{ave}$  calculation. Table 1-1 specifies, via green square markings, which of these six surfaces need to be used in the above formula for the  $PD_{ave}$  for the two mmWave modules in the device. As seen, the surfaces S1, S2, S3, and S5 need to be used in the  $PD_{ave}$  calculations for the Module0, and surfaces S1, S2, and S4 for the Module1  $PD_{ave}$  calculations. In the spatially averaged power density calculations, the surface A is a circle in the evaluation plane with an area of 4 [cm<sup>2</sup>]. Furthermore,  $PD_{ave}$  is calculated at the points of a grid with 0.5 mm step size defined in each evaluation plane.



**Figure 1-4** PD evaluation surfaces: Averaged power densities are calculated and measured on the specified Surfaces (S1, S2, S3, S4, and S5) surrounding the phone.

**Table 1-1** PD evaluation planes considered for each mmWave module on the device.

	S1 (front)	S2 (back)	S3 (left)	S4 (right)	S5 (top)	S6 (bottom)
Module0	□	□	□	×	□	×
Module1	□	□	×	□	×	×

## 2. Simulation and modeling validation

### 2.1 Comparison between simulation and measurement

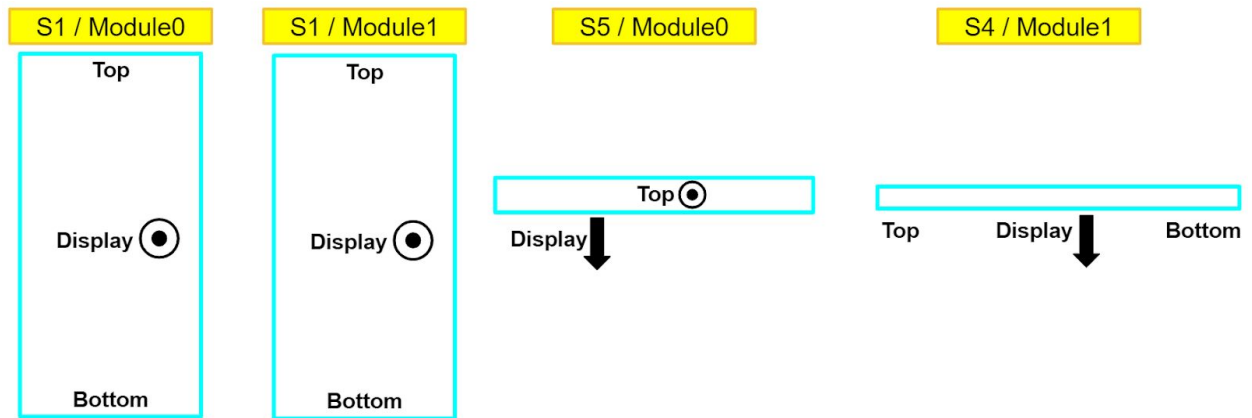
Following the time-average  $PD$  calculation procedure described in section 1.2.3, the distributions of  $PD$  and  $PD_{ave}$  are calculated in the evaluation planes and are compared with the measurements for a selected number of beams from the codebook, whose IDs are listed in

Table 2-1. Also shown in this table are simulated and measured results for the  $PD_{ave}$  for both n260 and n261 frequency bands, as well as both vertical and horizontal polarizations, denoted as AG0 and AG1, respectively.

Figure 2-1 shows orientation of the device for the  $PD$  and  $PD_{ave}$  distribution plots presented in Figures 2-2 to 2-33. The presented plots demonstrate a good agreement between simulated and measured results for both  $PD$  and  $PD_{ave}$ .

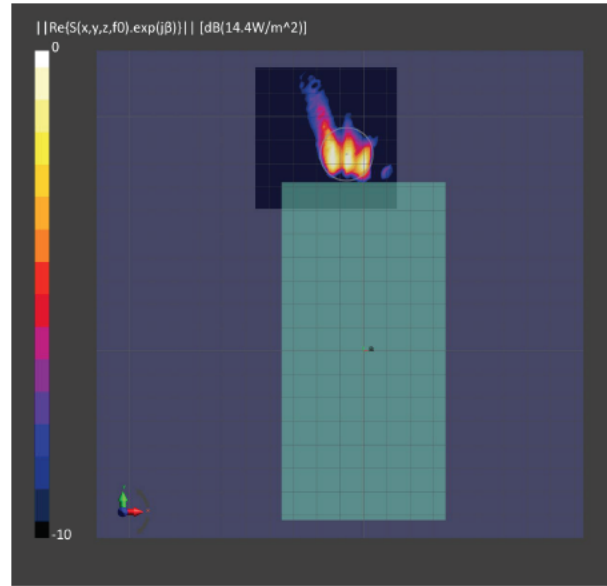
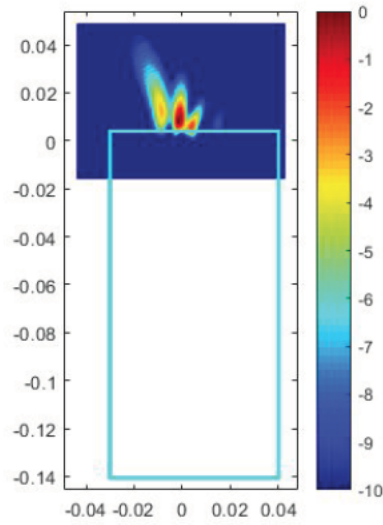
**Table 2-1** Simulated and measured  $PD_{ave}$  for selected beams with 6 [dBm] input power.

Test No.	Mod.	Beam ID	Band	Freq. [GHz]	Pol.	Exp. Surface	Test Separation	Averaged PD [W/m2]		Delta=Sim-Meas	Delta
								Sim.	Meas.		
1	0	20	n260	38.5	AG0	S1 (Front)	2mm	11.66	6.15	2.78	1.38
2	0	156	n260	38.5	AG1	S1 (Front)	2mm	8.52	6.81	0.97	0.96
3	0	28	n260	38.5	AG0	S5 (Top)	10mm	11.21	8.15	1.38	1.38
4	0	154	n260	38.5	AG1	S5 (Top)	10mm	10.58	8.48	0.96	0.96
5	1	13	n260	38.5	AG0	S1 (Front)	2mm	8.73	3.42	4.07	1.96
6	1	152	n260	38.5	AG1	S1 (Front)	2mm	9.88	5.97	2.19	1.02
7	1	13	n260	38.5	AG0	S4 (Right)	10mm	11.59	7.38	1.96	1.96
8	1	152	n260	38.5	AG1	S4 (Right)	10mm	10.44	8.25	1.02	1.02
9	0	19	n261	27.925	AG0	S1 (Front)	2mm	9.79	3.7	4.23	-0.34
10	0	146	n261	27.925	AG1	S1 (Front)	2mm	7.95	4	2.98	0.52
11	0	19	n261	27.925	AG0	S5 (Top)	10mm	9.61	10.4	-0.34	-0.34
12	0	156	n261	27.925	AG1	S5 (Top)	10mm	8.99	7.97	0.52	0.52
13	1	13	n261	27.925	AG0	S1 (Front)	2mm	9.03	4.05	3.48	1.90
14	1	141	n261	27.925	AG1	S1 (Front)	2mm	8.82	4.92	2.54	1.82
15	1	14	n261	27.925	AG0	S4 (Right)	10mm	10.09	6.52	1.90	1.90
16	1	141	n261	27.925	AG1	S4 (Right)	10mm	9.42	6.2	1.82	1.82

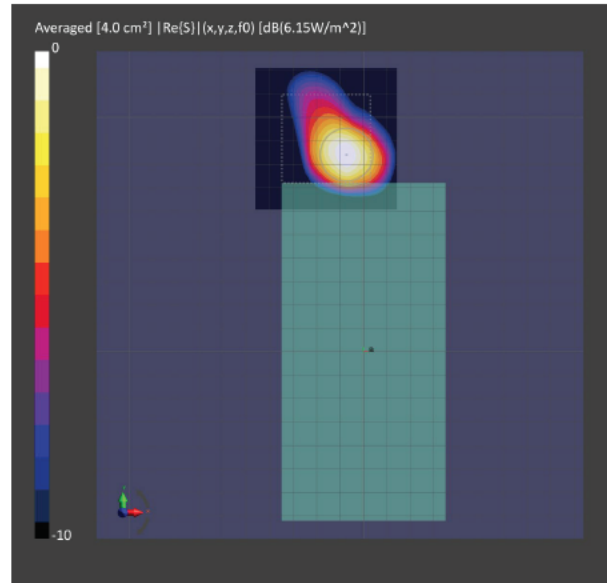
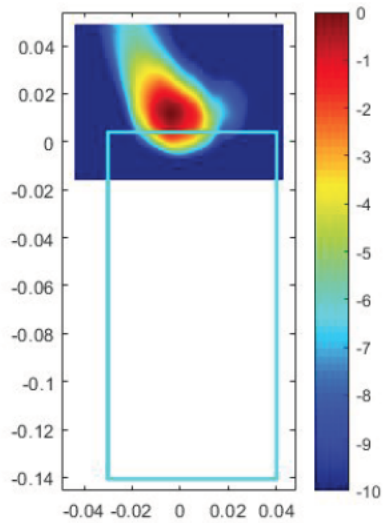


**Figure 2-1** Orientation of the device in the  $PD$  distribution plots.

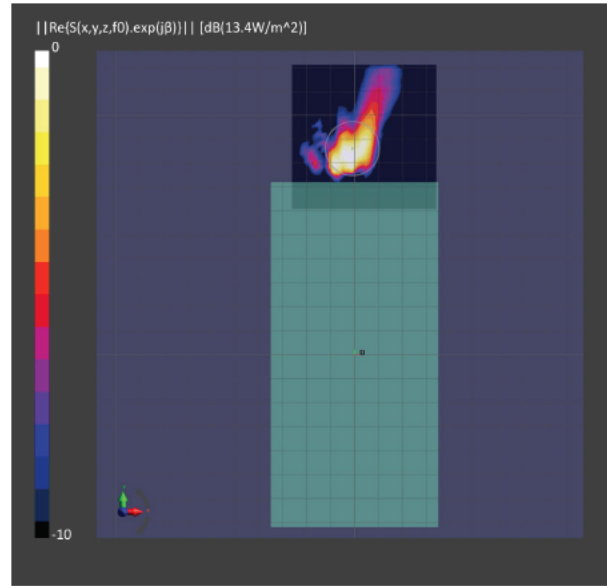
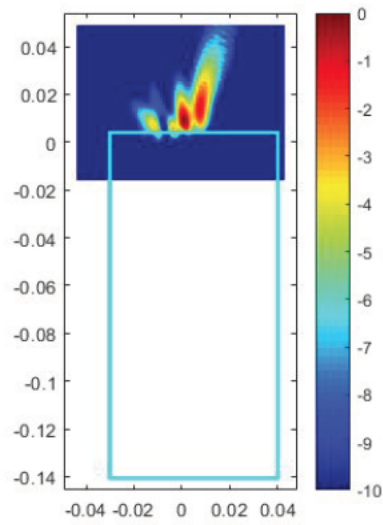




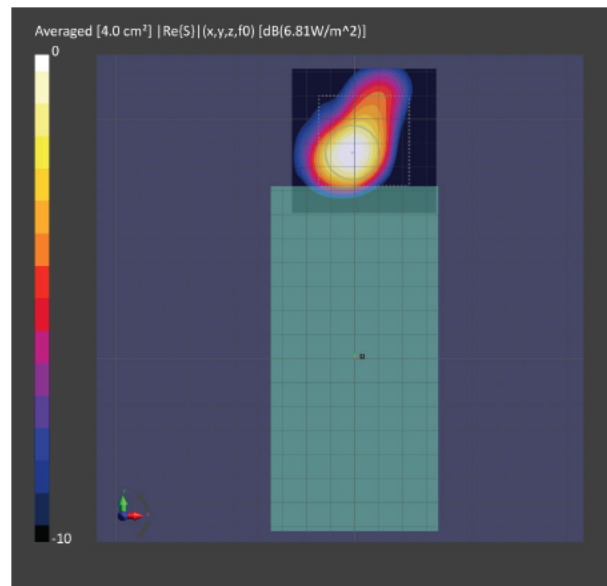
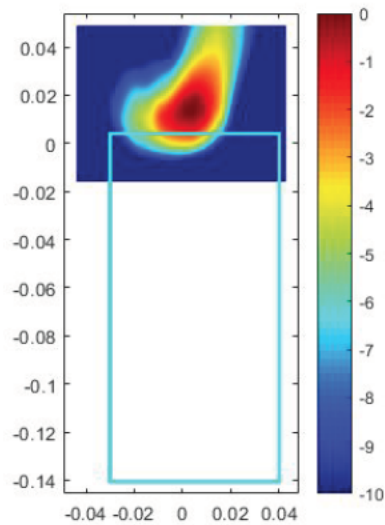
**Figure 2-2** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n260, MID Channel, Beam ID 20, AG0 polarization, Module0, plotted on surface S1 (front) with 2mm separation distance to the DUT.



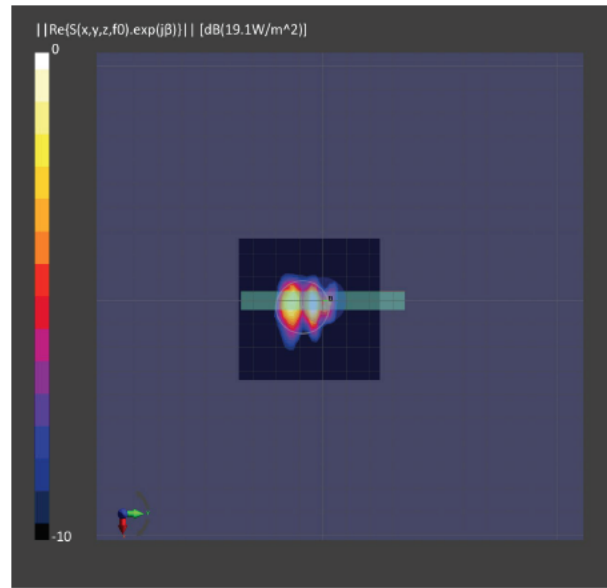
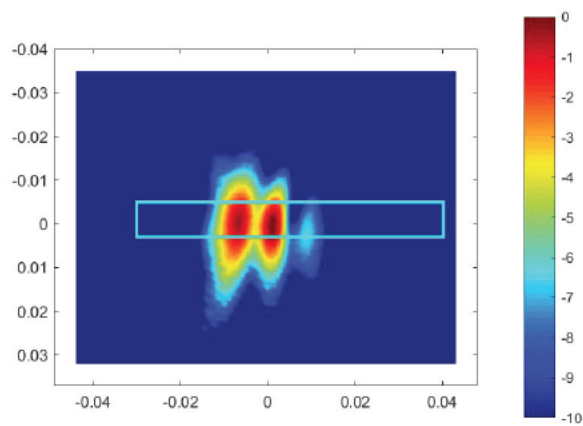
**Figure 2-3** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n260, MID Channel, Beam ID 20, AG0 polarization, Module0, plotted on surface S1 (front) with 2mm separation distance to the DUT.



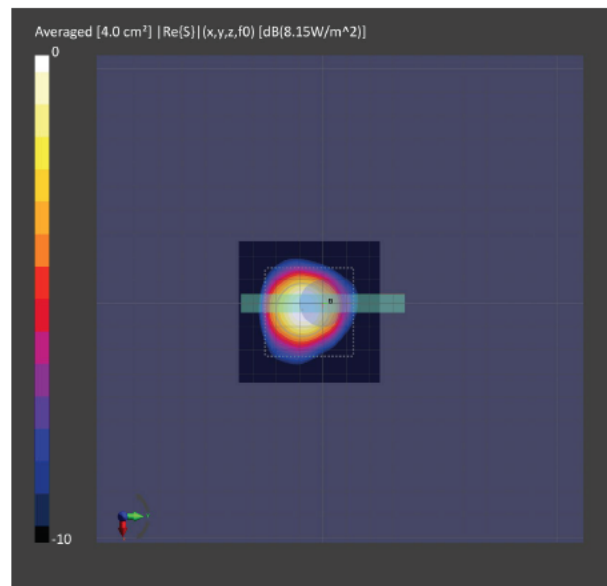
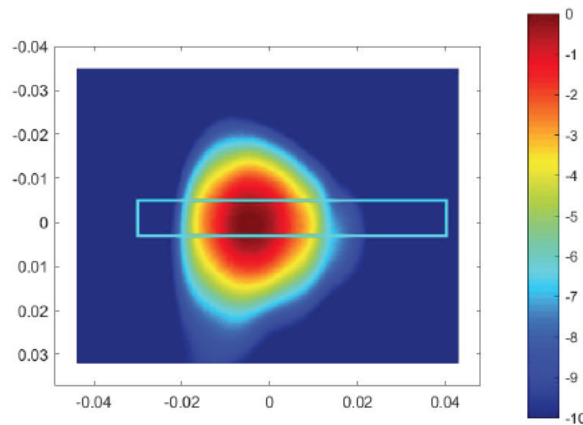
**Figure 2-4** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n260, MID Channel, Beam ID 156, AG1 polarization, Module0, plotted on surface S1 (front) with 2mm separation distance to the DUT.



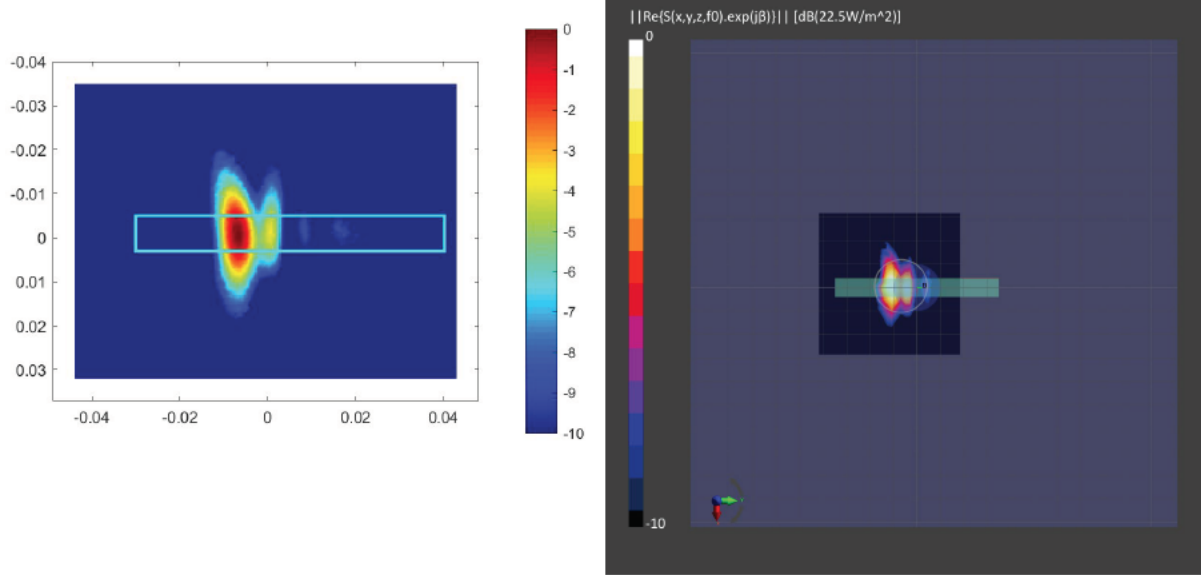
**Figure 2-5** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n260, MID Channel, Beam ID 156, AG1 polarization, Module0, plotted on surface S1 (front) with 2mm separation distance to the DUT.



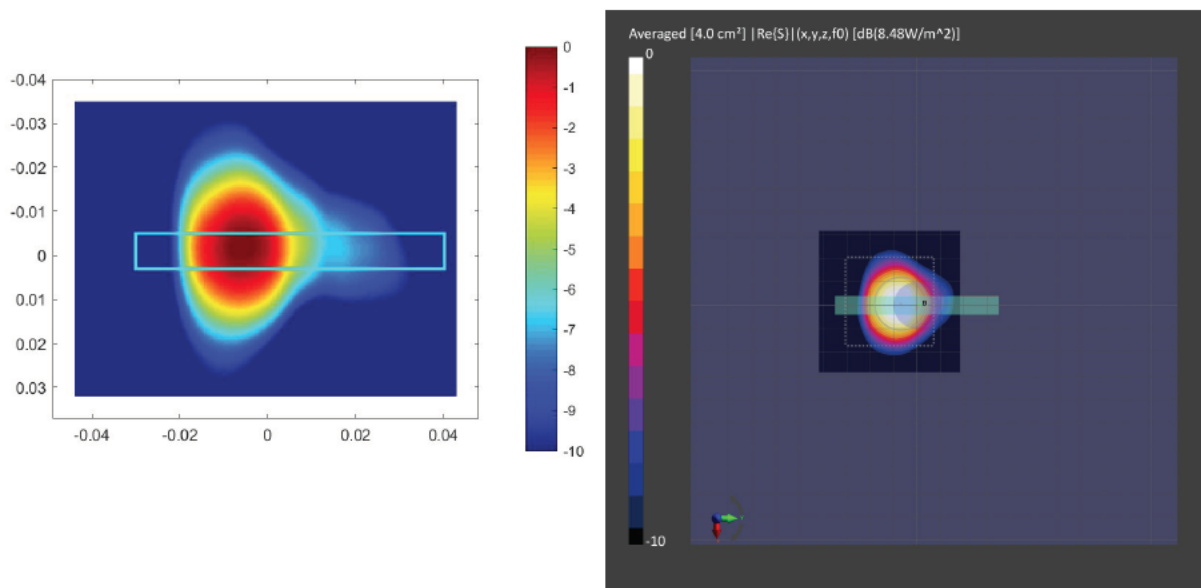
**Figure 2-6** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n260, MID Channel, Beam ID 28, AG0 polarization, Module0, plotted on surface S5 (top) with 10mm separation distance to the DUT.



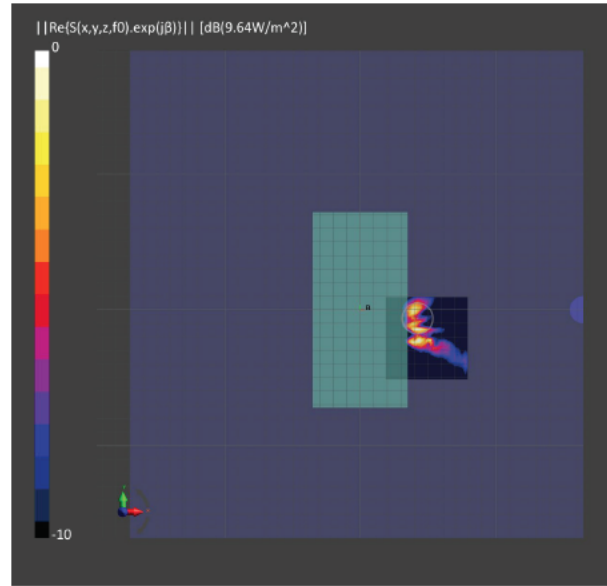
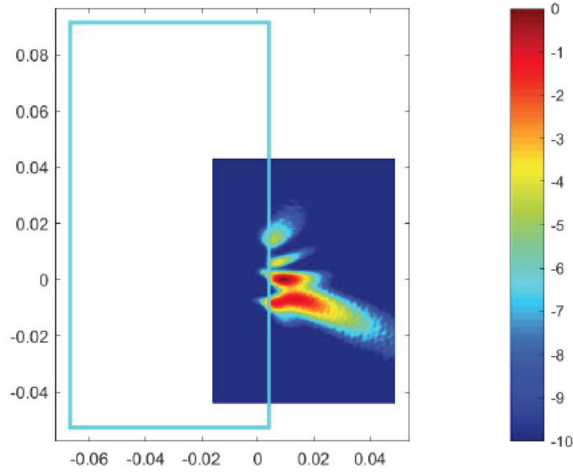
**Figure 2-7** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n260, MID Channel, Beam ID 28, AG0 polarization, Module0, plotted on surface S5 (top) with 10mm separation distance to the DUT.



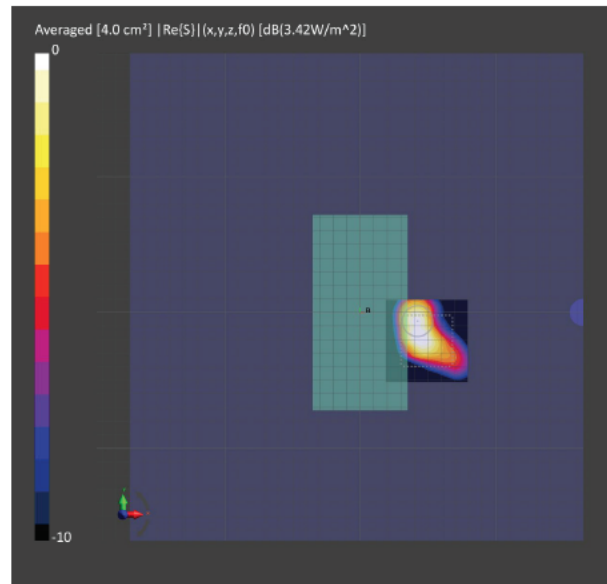
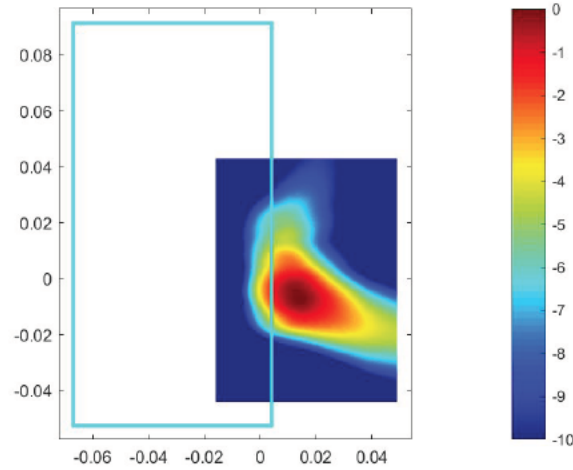
**Figure 2-8** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n260, MID Channel, Beam ID 154, AG1 polarization, Module0, plotted on surface S5 (top) with 10mm separation distance to the DUT.



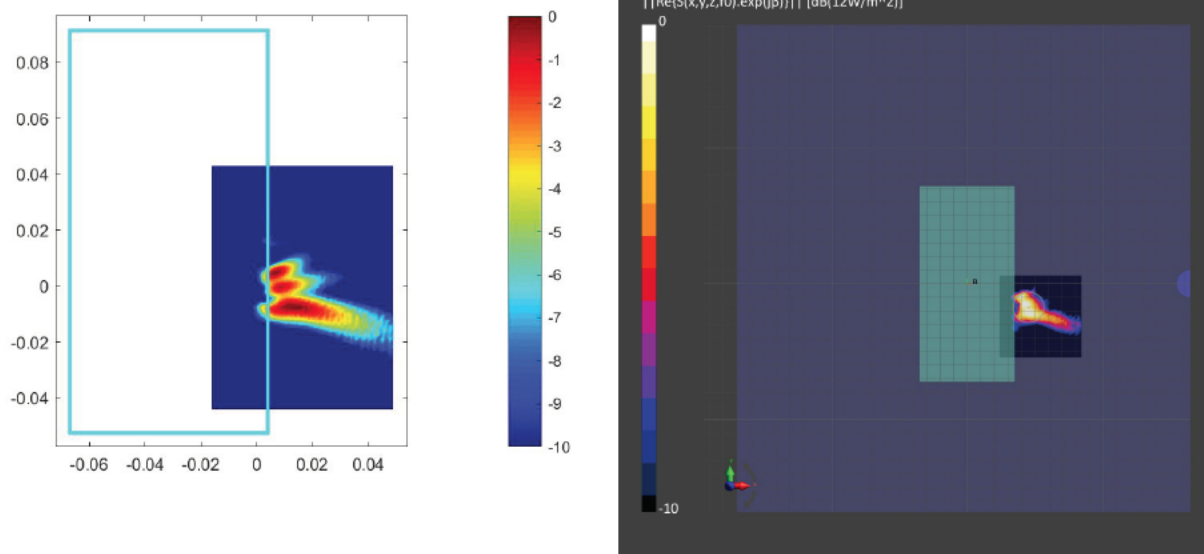
**Figure 2-9** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n260, MID Channel, Beam ID 154, AG1 polarization, Module0, plotted on surface S5 (top) with 10mm separation distance to the DUT.



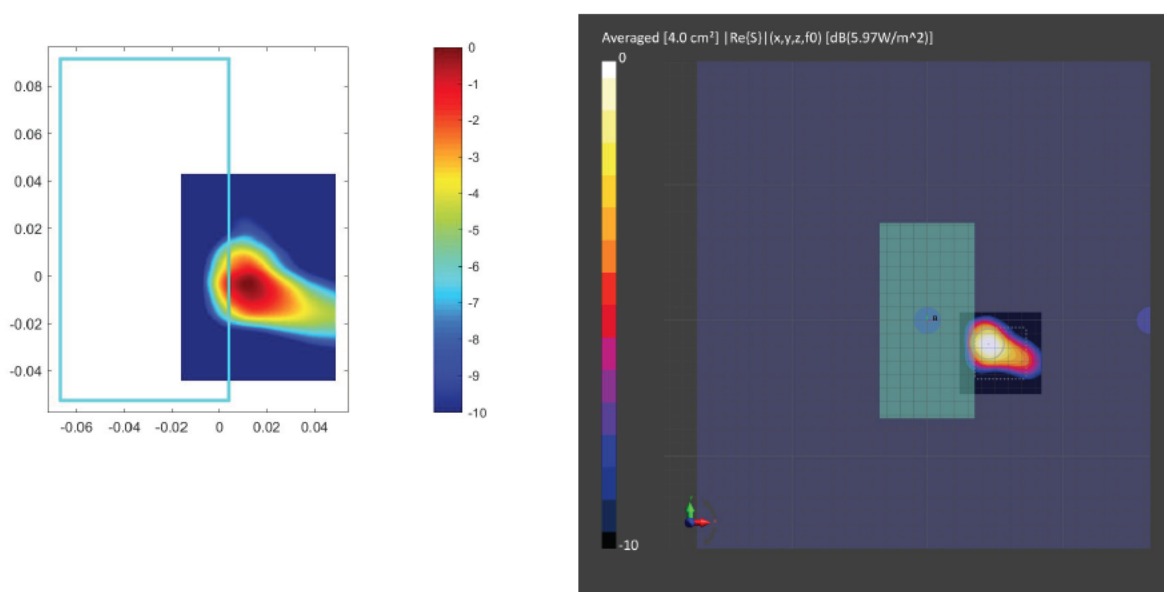
**Figure 2-10** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n260, MID Channel, Beam ID 13, AG0 polarization, Module1, plotted on surface S1 (front) with 2mm separation distance to the DUT.



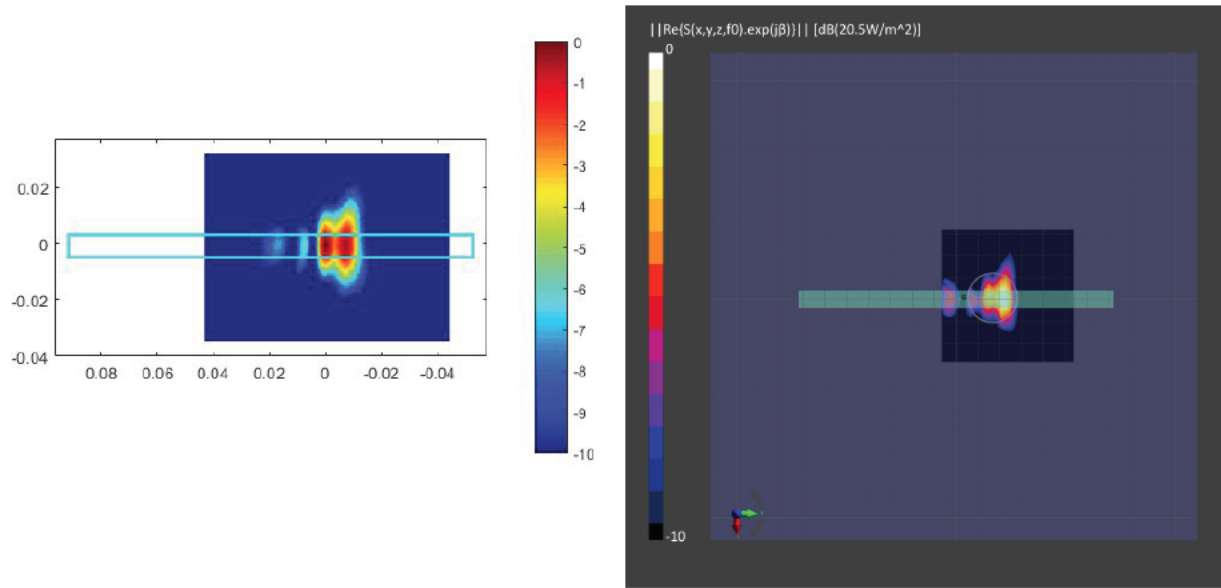
**Figure 2-11** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n260, MID Channel, Beam ID 13, AG0 polarization, Module1, plotted on surface S1 (front) with 2mm separation distance to the DUT.



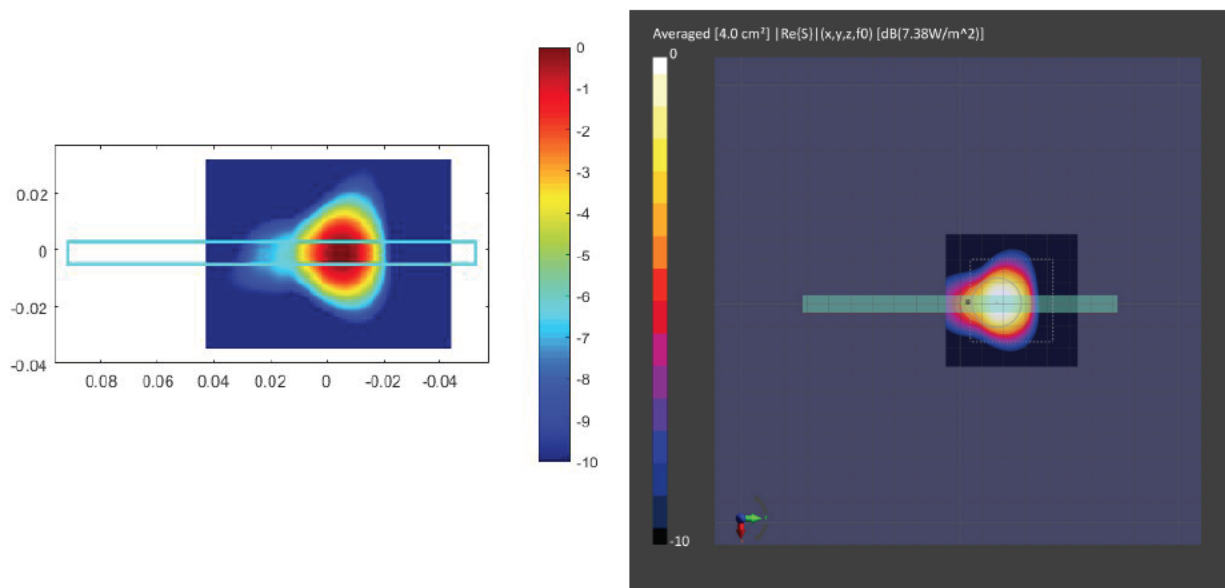
**Figure 2-12** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n260, MID Channel, Beam ID 152, AG1 polarization, Module1, plotted on surface S1 (front) with 2mm separation distance to the DUT.



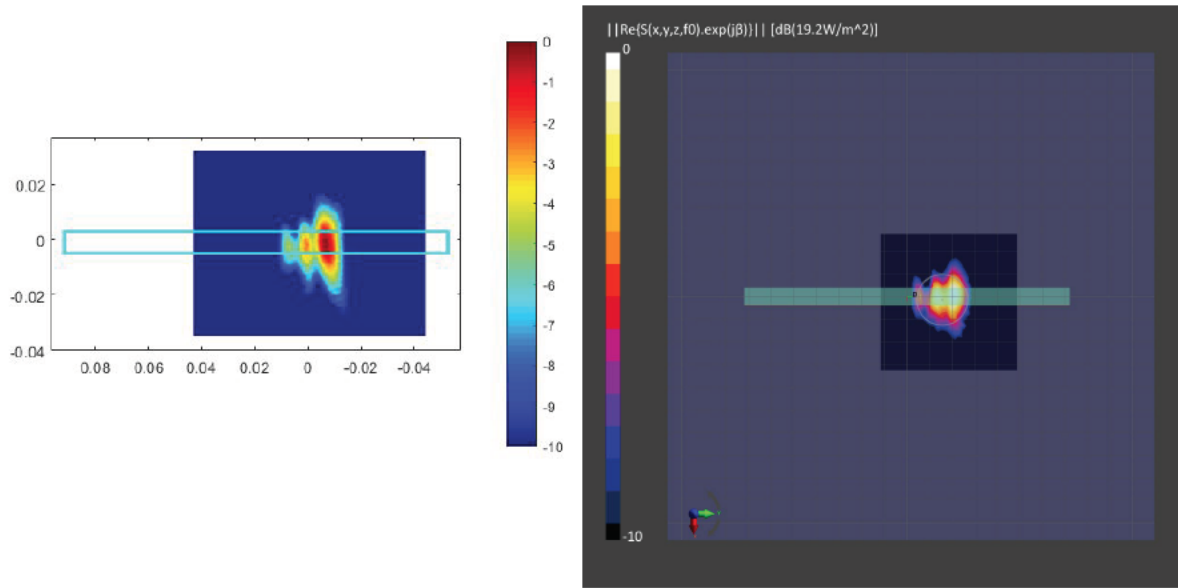
**Figure 2-13** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n260, MID Channel, Beam ID 152, AG1 polarization, Module1, plotted on surface S1 (front) with 2mm separation distance to the DUT.



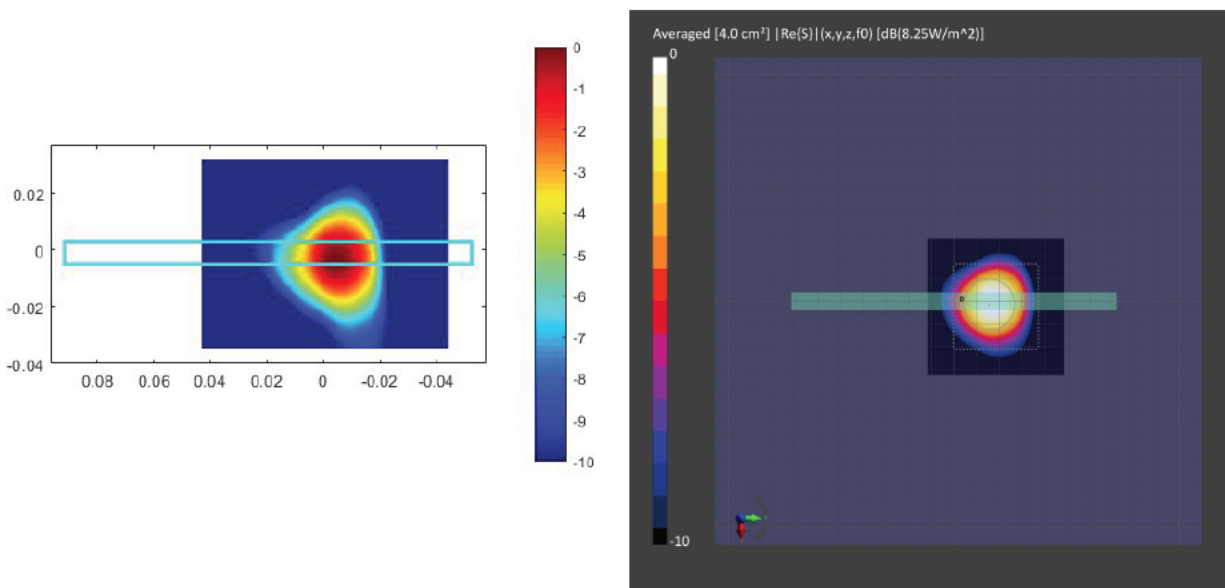
**Figure 2-14** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n260, MID Channel, Beam ID 13, AG0 polarization, Module1, plotted on surface S4 (right) with 10mm separation distance to the DUT.



**Figure 2-15** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n260, MID Channel, Beam ID 13, AG0 polarization, Module1, plotted on surface S4 (right) with 10mm separation distance to the DUT.

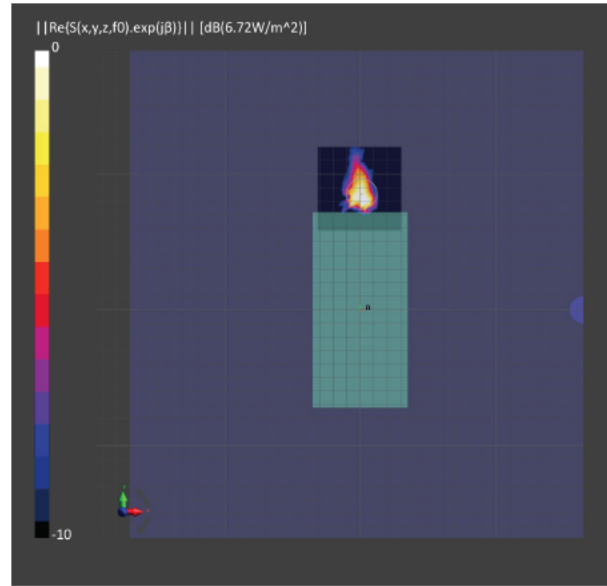
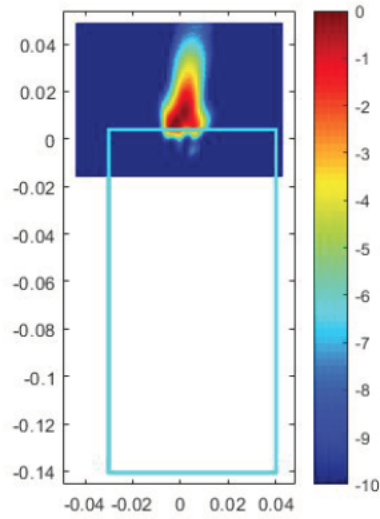


**Figure 2-16** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n260, MID Channel, Beam ID 152, AG1 polarization, Module1, plotted on surface S4 (right) with 10mm separation distance to the DUT.

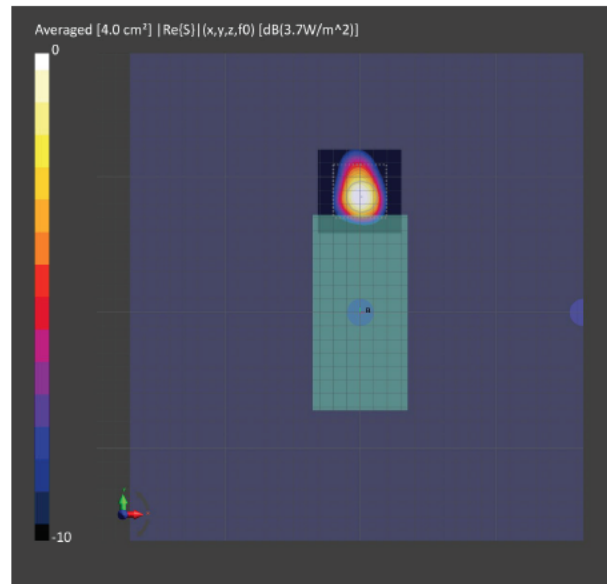
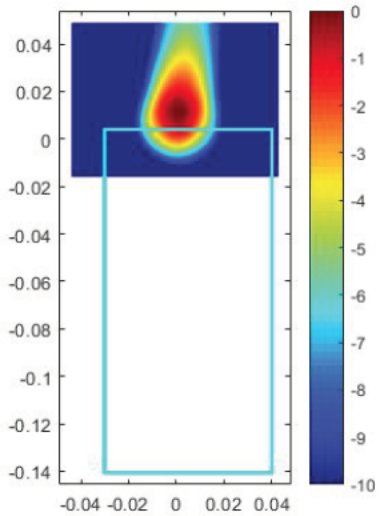


**Figure 2-17** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n260, MID Channel, Beam ID 152, AG1 polarization, Module1, plotted on surface S4 (right) with 10mm separation distance to the DUT.

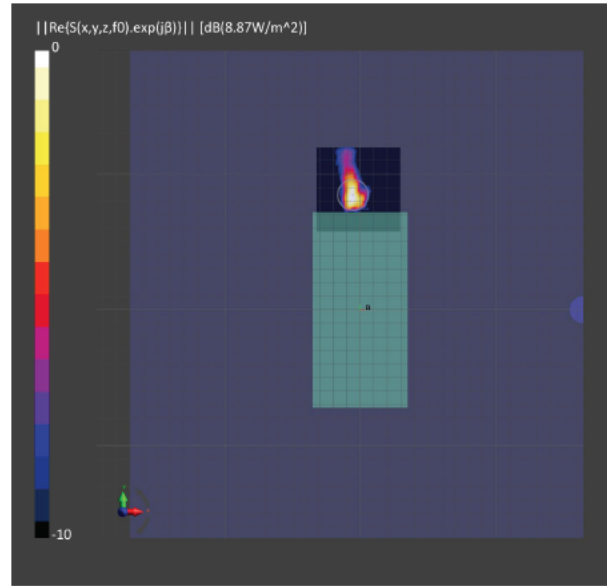
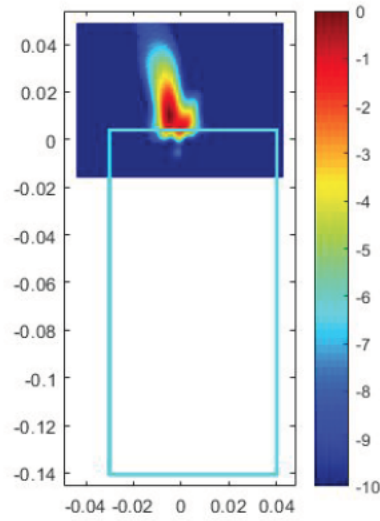




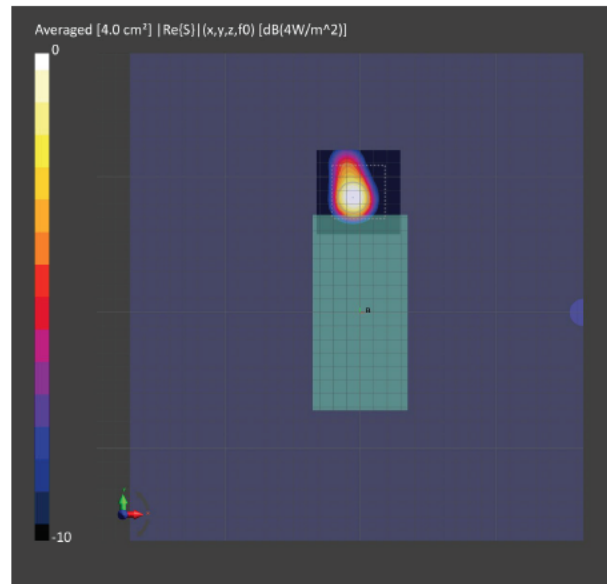
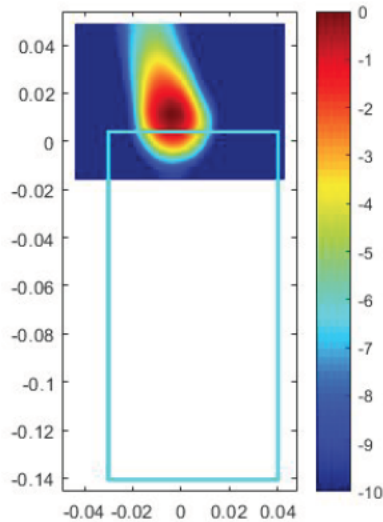
**Figure 2-18** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n261, MID Channel, Beam ID 19, AG0 polarization, Module0, plotted on surface S1 (front) with 2mm separation distance to the DUT.



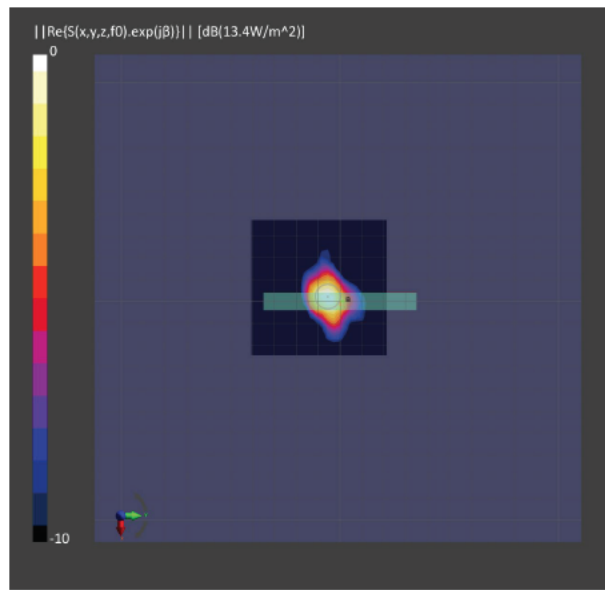
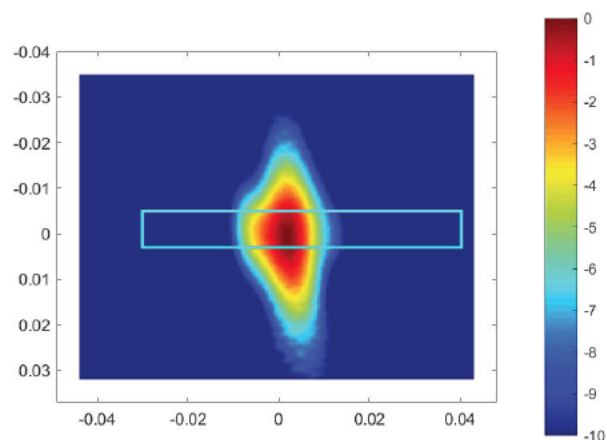
**Figure 2-19** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n261, MID Channel, Beam ID 19, AG0 polarization, Module0, plotted on surface S1 (front) with 2mm separation distance to the DUT.



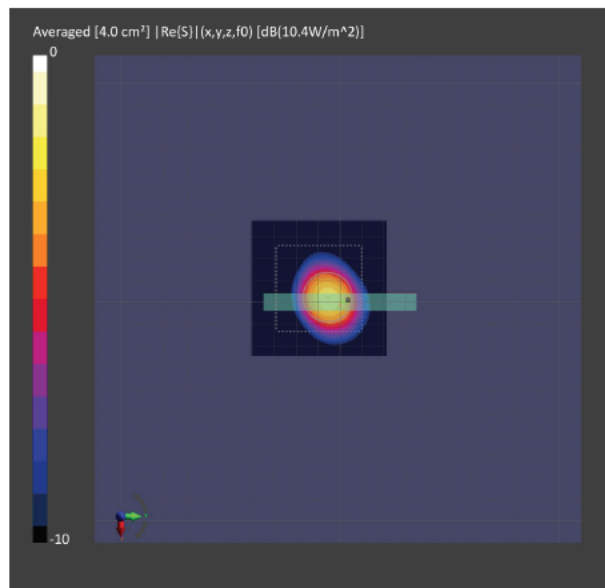
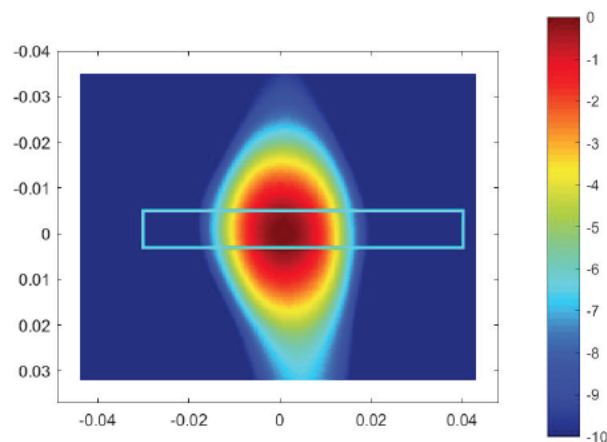
**Figure 2-20** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n261, MID Channel, Beam ID 146, AG1 polarization, Module0, plotted on surface S1 (front) with 2mm separation distance to the DUT.



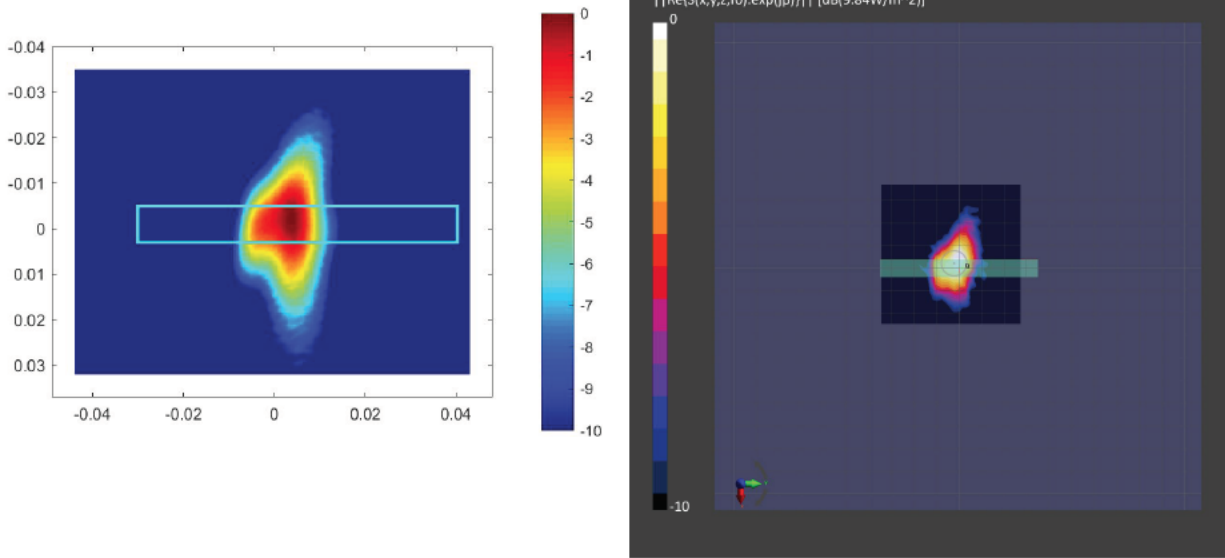
**Figure 2-21** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n261, MID Channel, Beam ID 146, AG1 polarization, Module0, plotted on surface S1 (front) with 2mm separation distance to the DUT.



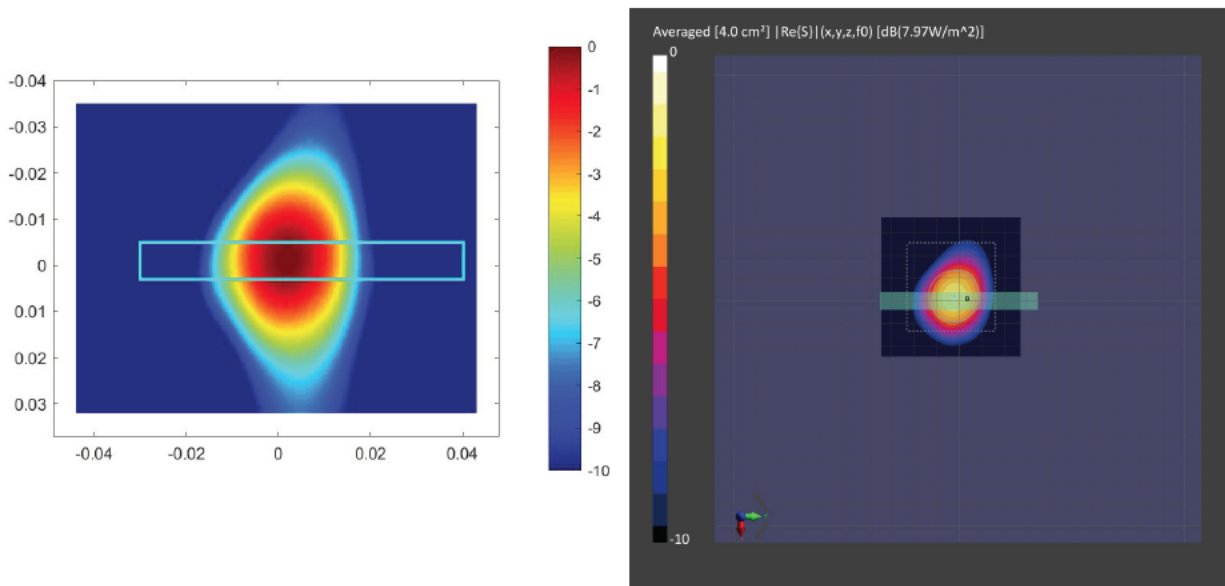
**Figure 2-22** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n261, MID Channel, Beam ID 19, AG0 polarization, Module0, plotted on surface S5 (top) with 10mm separation distance to the DUT.



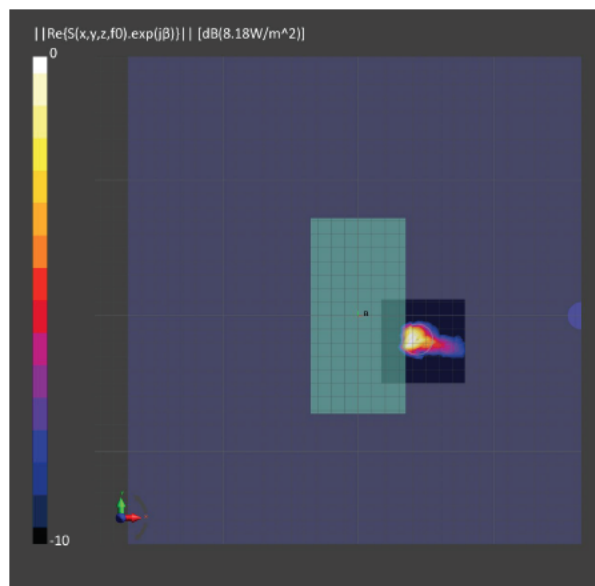
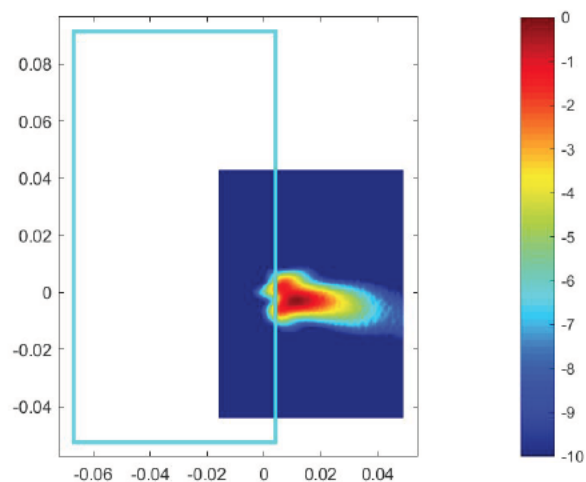
**Figure 2-23** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n261, MID Channel, Beam ID 19, AG0 polarization, Module0, plotted on surface S5 (top) with 10mm separation distance to the DUT.



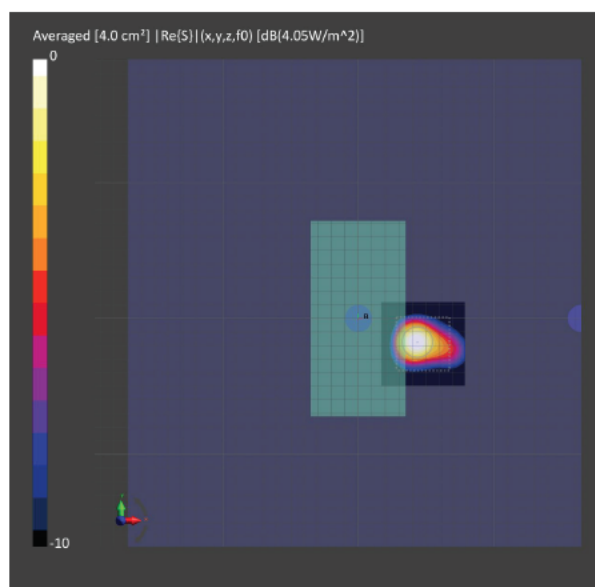
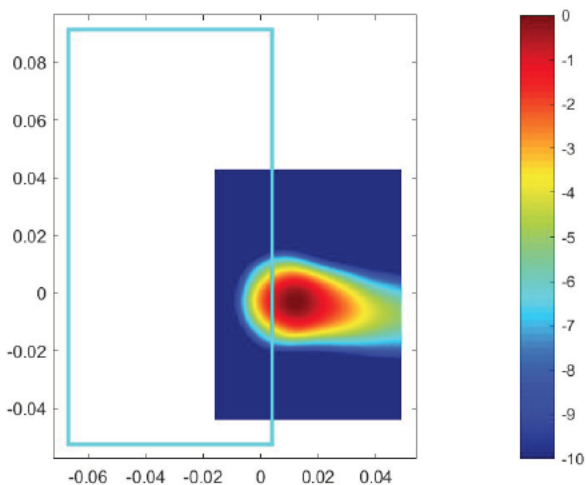
**Figure 2-24** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n261, MID Channel, Beam ID 156, AG1 polarization, Module0, plotted on surface S5 (top) with 10mm separation distance to the DUT.



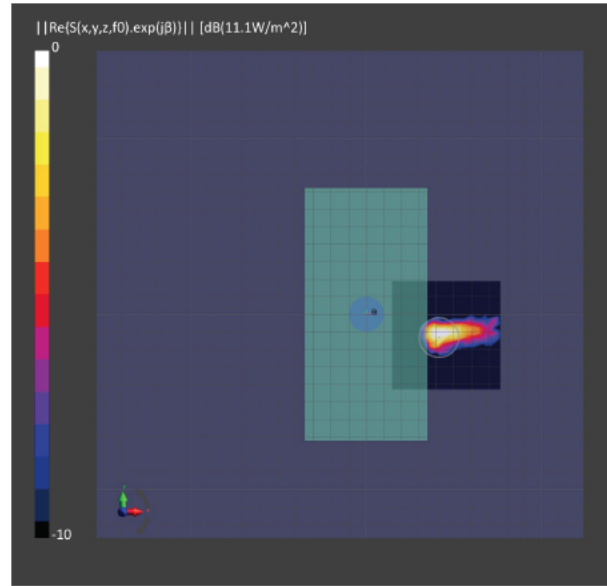
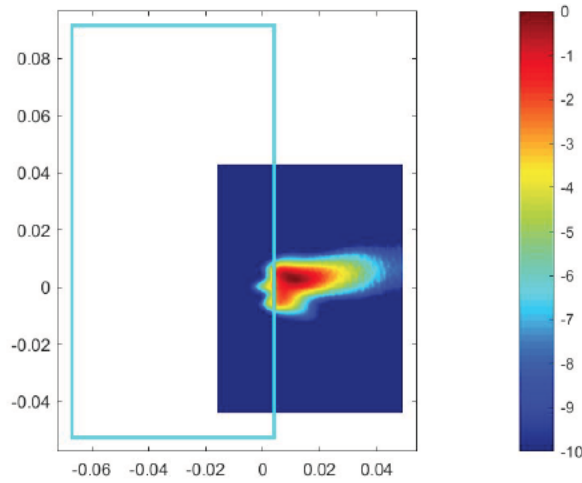
**Figure 2-25** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n261, MID Channel, Beam ID 156, AG1 polarization, Module0, plotted on surface S5 (top) with 10mm separation distance to the DUT.



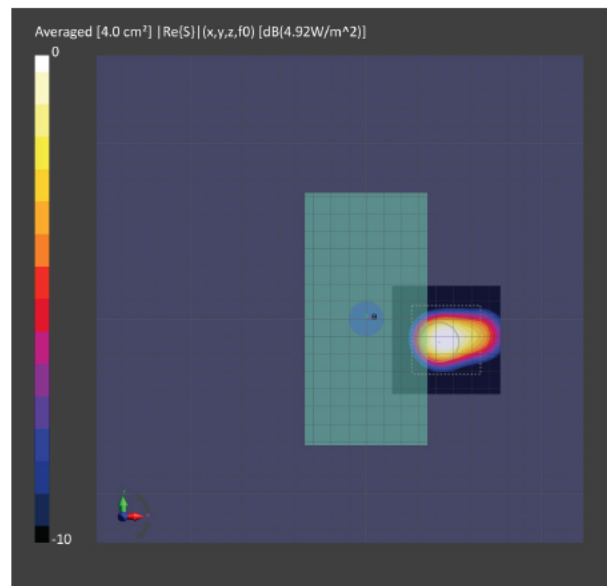
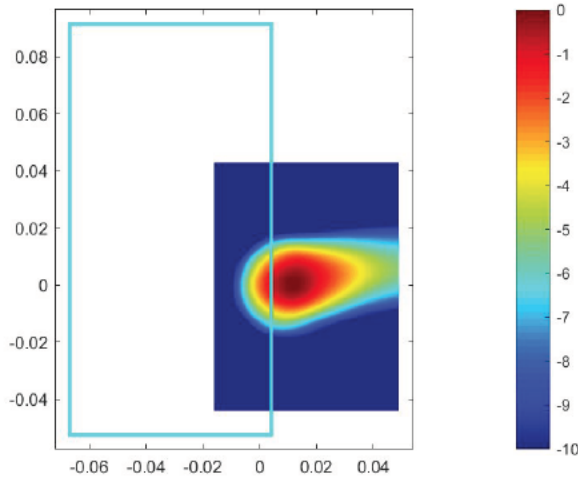
**Figure 2-26** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n261, MID Channel, Beam ID 13, AG0 polarization, Module1, plotted on surface S1 (front) with 2mm separation distance to the DUT.



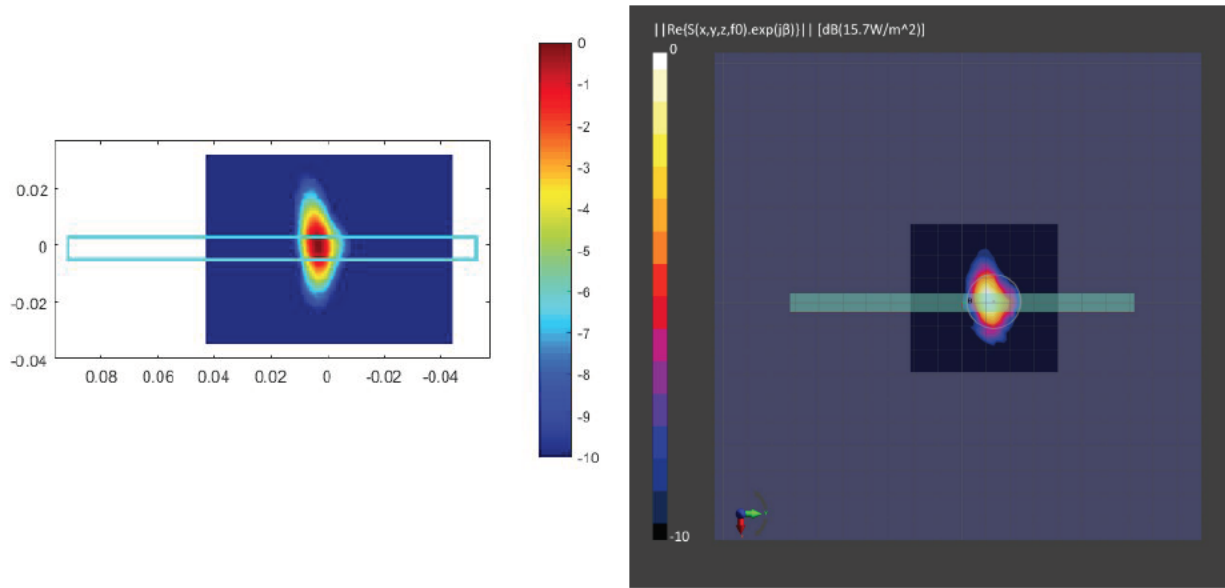
**Figure 2-27** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n261, MID Channel, Beam ID 13, AG0 polarization, Module1, plotted on surface S1 (front) with 2mm separation distance to the DUT.



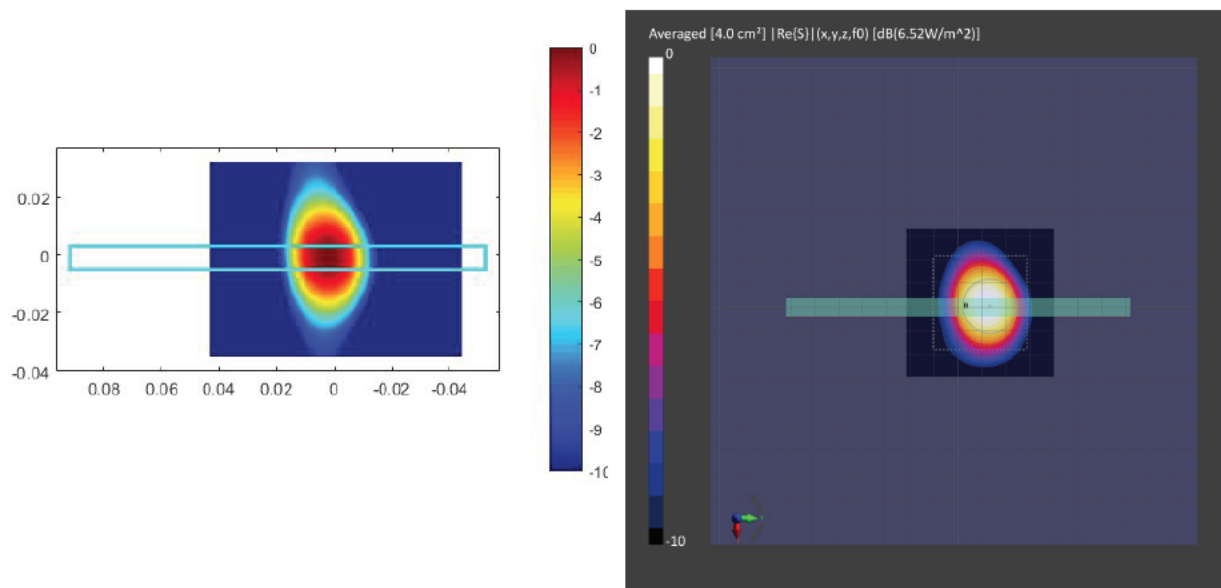
**Figure 2-28** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n261, MID Channel, Beam ID 141, AG1 polarization, Module1, plotted on surface S1 (front) with 2mm separation distance to the DUT.



**Figure 2-29** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n261, MID Channel, Beam ID 141, AG1 polarization, Module1, plotted on surface S1 (front) with 2mm separation distance to the DUT.



**Figure 2-30** Simulated (Left) and measured (Right) PD distribution for the following configuration: Band n261, MID Channel, Beam ID 14, AG0 polarization, Module1, plotted on surface S4 (right) with 10mm separation distance to the DUT.



**Figure 2-31** Simulated (Left) and measured (Right) averaged PD distribution for the following configuration: Band n261, MID Channel, Beam ID 14, AG0 polarization, Module1, plotted on surface S4 (right) with 10mm separation distance to the DUT.