

## Application Example

# Design and Matching of a 60-GHz Printed Antenna

Using NI AWR Software and AWR Connected for Optenni

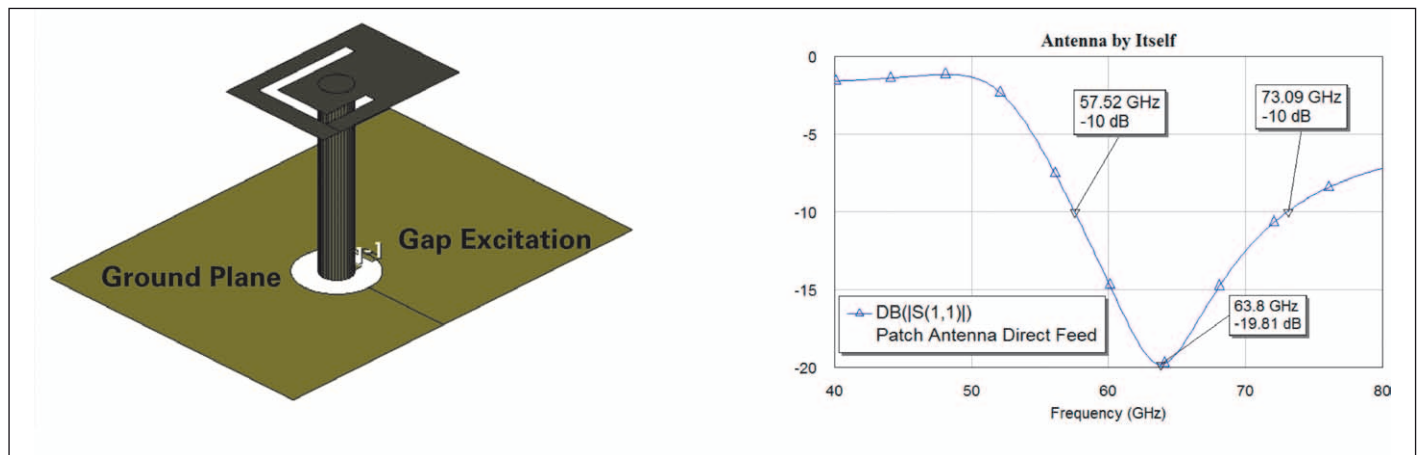


Figure 1: Patch antenna performance.

**Impedance matching of high-frequency components is a key part of antenna design to ensure maximum transfer of power between the antenna and the transmitter/receiver circuitry. Antennas can be tuned to resonate at the desired frequencies much more quickly and efficiently by first designing a matching circuit rather than by making modifications to the antenna's physical dimensions.**

This application example describes the design and matching of a 60-GHz printed antenna using a unique design flow that combines NI AWR Design Environment, specifically Microwave Office for RF/microwave circuit simulation and AXIEM for planar EM analysis, with Optenni Lab matching circuit software. Together, these tools offer an integrated workflow that accelerates antenna design and integration with other front-end components.

A step-by-step description follows for designing the entire antenna model, including the matching circuit, the antenna, and any other considerations that influence the antenna performance, as well as the analysis of radiation efficiency, gain, polarization, and radiation pattern.

## Step 1: Feeding Considerations

The first step for this design was taken from a public domain antenna structure. It is essentially a patch antenna with carefully designed slots that create successive resonances over a wide frequency band (Figure 1).

The reference antenna was designed to cover a very wide frequency range centered at approximately 60 GHz. It was decided to target the band of operation for this antenna around the unlicensed band between 57 and 64 GHz. The original reference

design was carried out on a very thick substrate ( $H = 1.575$  mm), but for the new design a thinner substrate ( $H = 0.127$  mm) was chosen. The reference frequency is 63.8 GHz. The bandwidth (using -10 dB as the reference point) is 15.57 GHz.

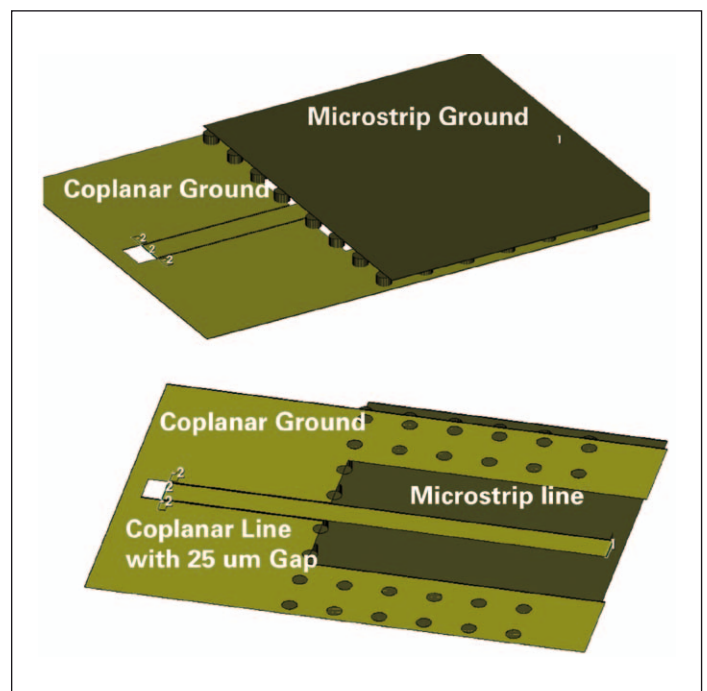


Figure 2: Top and bottom views of the antenna feed.

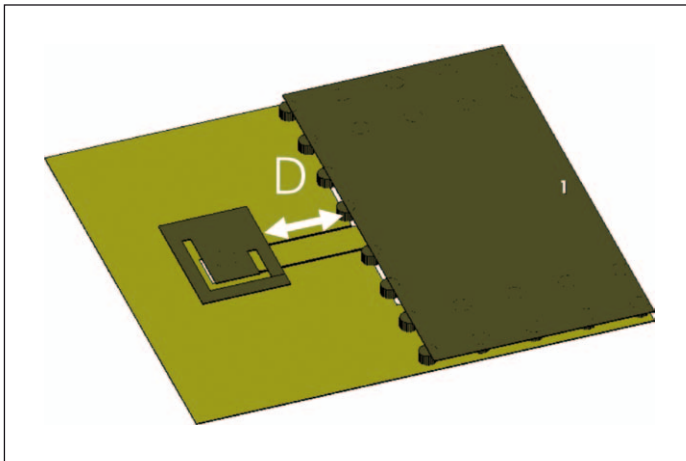


Figure 3: The layout of the antenna on the board.

These results do not include any feed network, which is discussed next.

The original design used a coaxial feed coming up from below the ground plane and attaching to the pin feeding the antenna. The antenna in the new design needed to be integrated onto the same printed circuit board (PCB) as the rest of circuitry, therefore the feed geometry needed to be altered. The pin was fed by a coplanar feed, the side grounds of the coplanar line forming the ground plane of the antenna. The coplanar line then transitioned to a microstrip line so that the various tuning circuitry could be added (Figure 2).

On the bottom side (shown in Figure 3), the microstrip lines transition to the coplanar line.

The coplanar line's impedance was 50 Ohms, to match the 50 Ohm microstrip line. The width of the coplanar line was the same as the microstrip. This determines the gap width to the side grounds. For this design, it is 25  $\mu\text{m}$ .

### Step 2: Pre-Tuning the Antenna Geometry

Figure 3 shows the initial geometry of the design. Parameter  $D$  characterizes the distance of the antenna from the microstrip ground plane. The problem was easily parameterized in AXIEM using the software's edge length and spacing modifiers and enabled the designers to study several different parameter values for  $D$ . Note that the

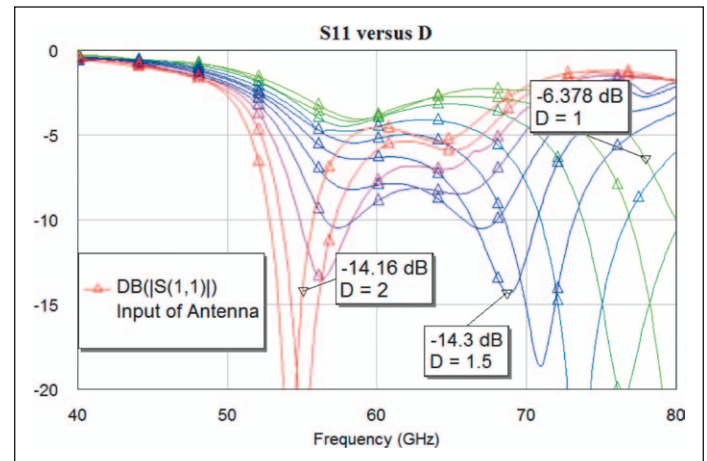


Figure 4: S11 as a function of the parameter  $D$ .

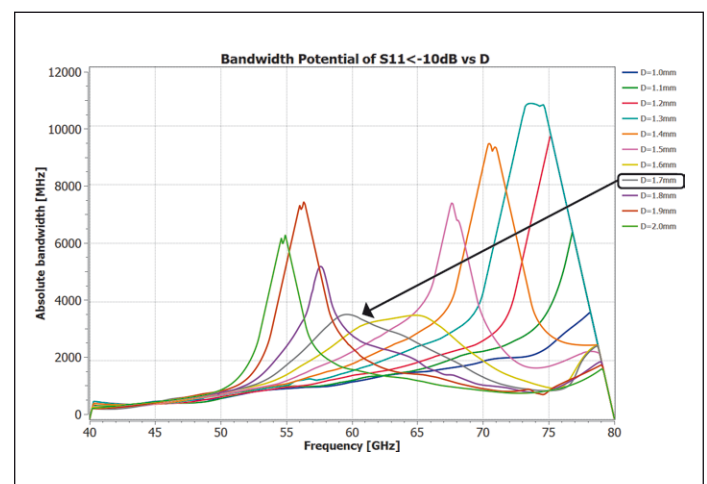


Figure 5: Optenni Lab bandwidth potential analysis.

coplanar waveguide dimensions were chosen to provide very low junction discontinuity from the microstrip.

Figure 4 shows the result of S11 versus Parameter  $D$ . The design is quite sensitive to the distance between the antenna and the

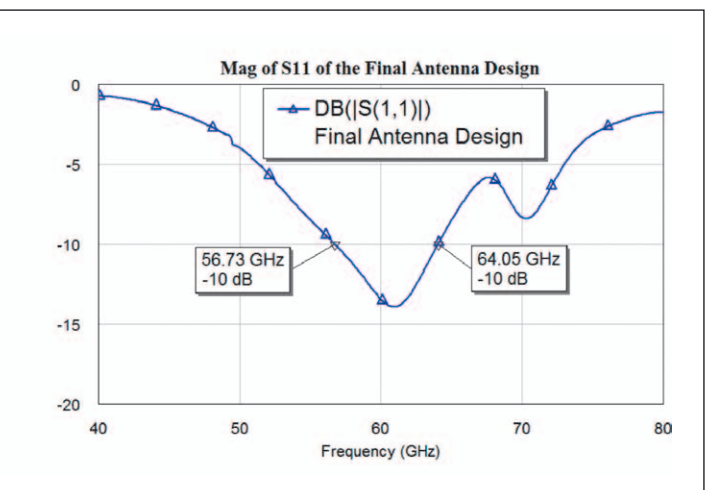
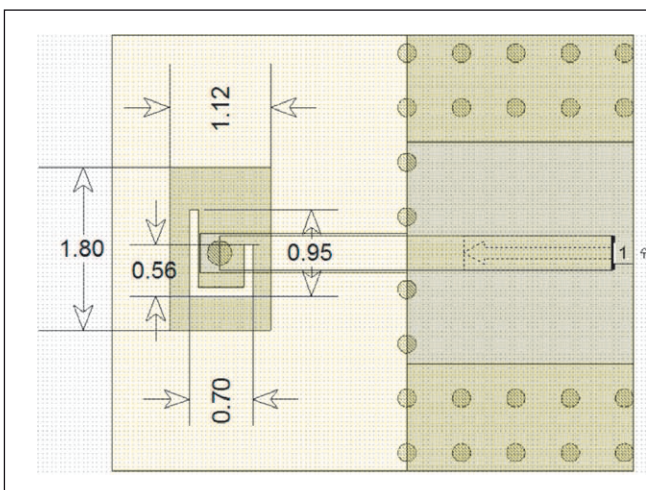
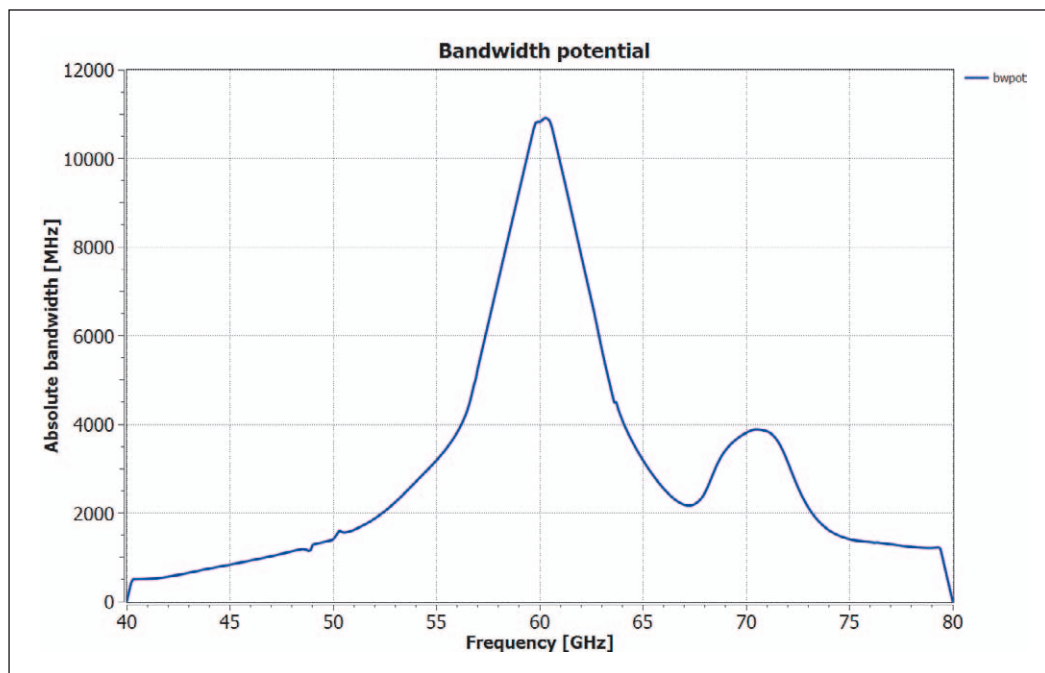


Figure 6: The final patch (slot dimensions) were determined by running several cases in AXIEM (left). The right picture shows S11, with  $>10$  dB return loss for the target bandwidth of 57...64 GHz shown on right.



**Figure 7: Bandwidth potential analysis for the final antenna design.**

microstrip ground plane. It was therefore critical to pick the distance correctly.

However, the S11 curves do not reveal a great deal of information about how much bandwidth is achievable by applying a simple matching network. Optenni Lab offers a bandwidth potential analysis tool that optimizes the symmetric bandwidth for every frequency point using two ideal matching components. Bandwidth potential provides pre-matching analysis that reveals where the antenna is best matched and if there is enough

bandwidth available. With this information, a design team will know before committing valuable resources that the matching network for the entire band can be realized.

In the bandwidth potential calculation, the Optenni software constructs a two-component matching circuit and calculates the obtained maximal impedance bandwidth for each frequency. It repeats the analysis for all frequencies and gives a curve that shows what bandwidth can be obtained when considering

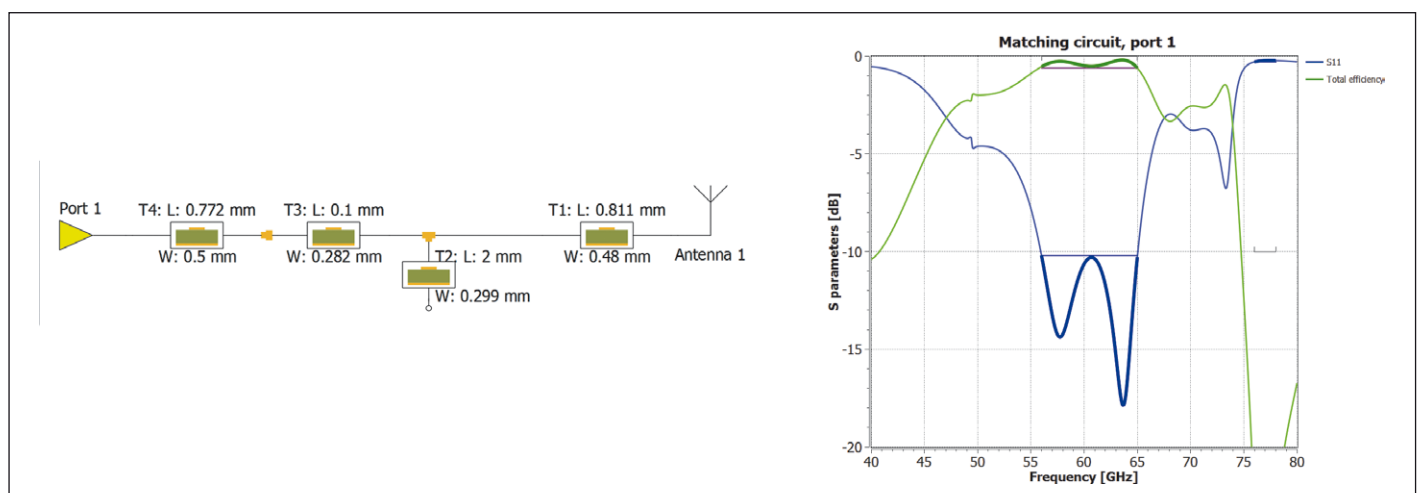
each frequency as the center frequency point.

With the bandwidth potential calculation, designers can compare different antenna candidates to show which one offers the best obtainable bandwidth, verify if the bandwidth is large enough for the desired application even if the antenna was not originally resonant, and provide information for which frequencies the maximal antenna bandwidth is obtained. The bandwidth potential calculation speeds up the antenna design process by allowing designers to quickly

estimate the obtainable antenna bandwidth from a measured or simulated prototype without explicitly tuning the antenna to the desired frequency range. If the bandwidth is not sufficient, designers can focus on the antenna design and re-calculate the bandwidth potential until the specifications have been met. Then the antenna can be tuned to resonance by generating a matching circuit with Optenni Lab.

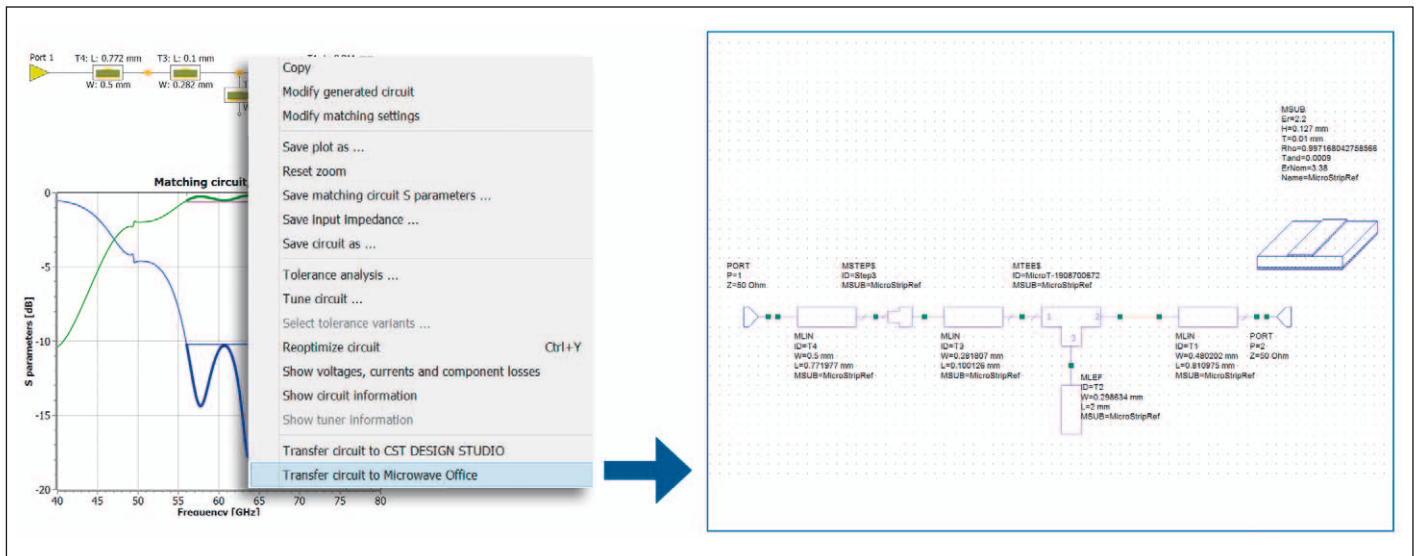
Figure 5 shows the results of Optenni Lab bandwidth calculation for the various values of D. A value for D of about 1.7 mm seemed to provide the widest bandwidth at  $f_c = 60$  GHz. The target was 7 GHz bandwidth, and unfortunately the available bandwidth for D = 1.7 mm was only about 3.5 GHz. Based on these results, it was determined that a redesign would be required to enhance the available bandwidth without having to struggle with an explicit matching circuit design that was doomed to fail.

For redesign, the designers parameterized the antenna structure and key dimensions such as the patch width and length, as well as dimensions of the slot width (Figure 6) in order to modify the geometry, thereby tuning the electrical response. In short order, a design was derived that provided >10 dB return loss for the target bandwidth of 57...64 GHz (Figure 6). The designers brought the S-parameter



**Figure 8: Most promising topologies were synthesized and optimized.**





**Figure 9: Synthesized matching circuits were transferred to Microwave Office with a single click. The synthesized circuit in Optenni a) was brought into Microwave Office b) and the resulting schematic layout c) was extracted to AXIEM.**

data of the project redesigned in Microwave Office back into Optenni Lab for another bandwidth potential analysis, which indicated a “sweet spot” at 60.5 GHz, with an available bandwidth of over 10 GHz as shown in Figure 7.

### Step 3: Matching Circuit Synthesis

The next step was to synthesize the physical design using a multi-section microstrip matching circuit to provide 1 GHz additional bandwidth on each edge of the band (56...65 GHz) and a stop band at 76...78 GHz. Multiple microstrip topologies were synthesized and optimized. The circuit with four matching sections shown in Figure 8 appeared promising.

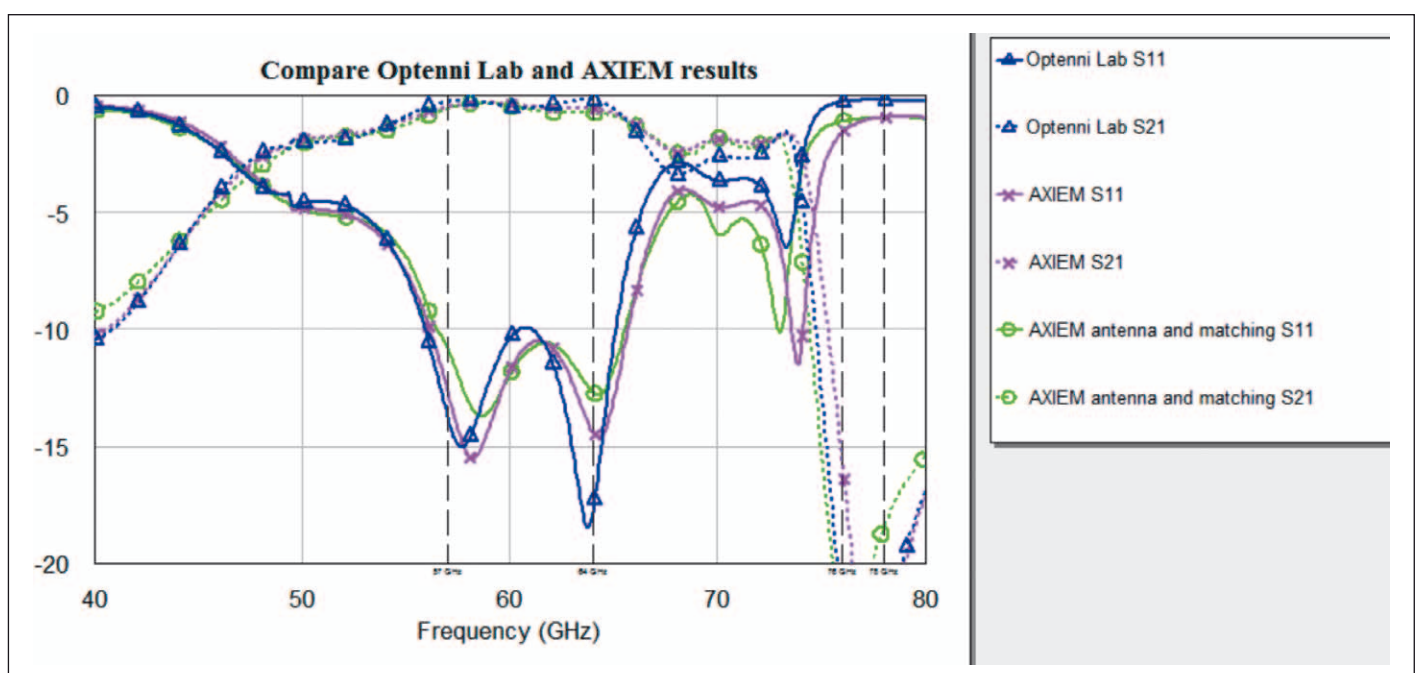
The matching provided a minimum of 10 dB return loss across the band of interest and a very good attenuation at the stop band. The synthesized

matching circuit was exported from Optenni Lab (Figure 9a) to Microwave Office using a single-click design transfer (Figure 9b). The resulting layout (Figure 9c) was then extracted to AXIEM and simulated.

The circuit in Figure 10 compares the results of the matching circuit as designed in Optenni using models, the AXIEM simulation of the layout of the matching circuit, and the AXIEM simulation of the mat-

ching circuit with the antenna attached.

The measurements named Optenni Lab S11 and S21 are imported directly from Optenni. They are based on standard microstrip models. The measurements AXIEM S11 and S21 are from AXIEM simulations of the matching section as shown in Figure 9c. The measurements AXIEM antenna and matching S11 and S21 are from the AXIEM simulation of the matching struc-



**Figure 10: S-parameters for the matching section.**

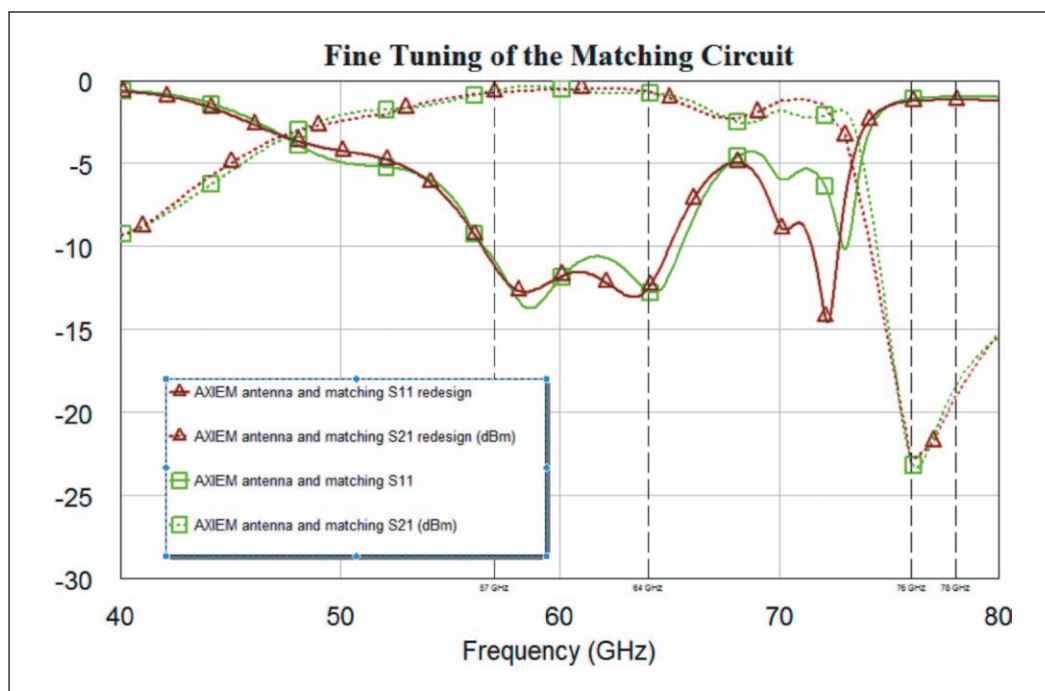


Figure 11: S-parameters for the AXIEM simulations of matching circuitry and antenna.

ture placed in the final layout with antenna and coplanar feed structure. To measure the S21 of the matching section with the antenna attached, the feed line to the antenna was cut and a series port added. The power could then be measured going through the port, thereby giving the S21.

## Step 4: Optimization and EM Verification

The good agreement between the AXIEM models (matching circuit on ideal ground and antenna separately versus matching circuit on antenna on the same EM document with non-ideal ground) shows that the

antenna does not directly couple very much to the matching circuit. From a design perspective, the main concern was that the AXIEM simulation with the antenna exhibits a 0.5 GHz frequency shift up at the pass band, compared to the Optenni Lab result. This was fixed by re-optimizing the pass band down

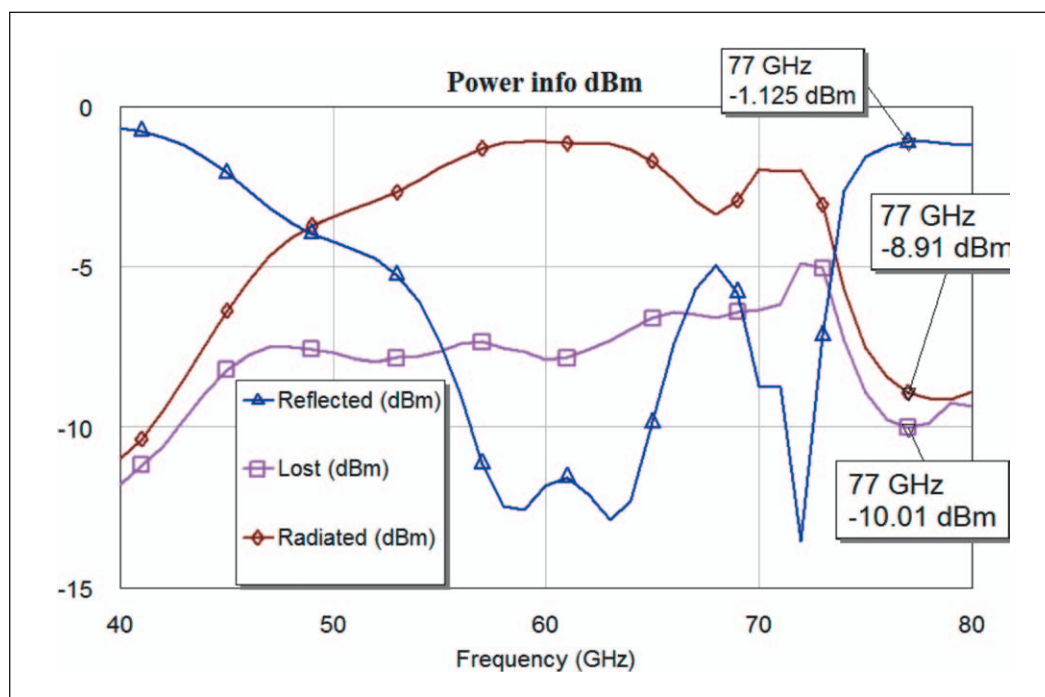


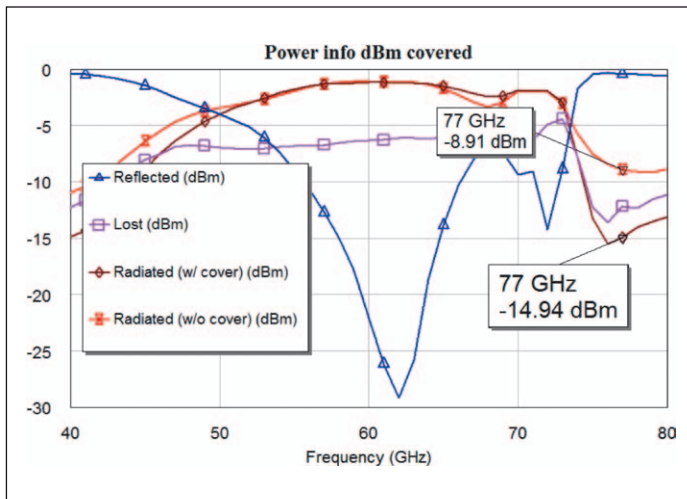
Figure 12: The reflected, lost through heating, and radiated power calculated using AXIEM.

0.5 GHz in Optenni Lab. Figure 11 shows the results before and after fine tuning the dimensions of the matching circuitry. The result (brown line) has improved pass band performance, albeit the lower edge of the pass band did not shift as hoped for. Designers felt there should be enough margin in the bandwidth of the antenna for the design to work.

## Step 5: Results Radiated Power

The next step was to evaluate the radiation efficiency of the matched antenna using the Microwave Office Power Info measurement tool. This measurement is able to calculate what happens to the power going to the antenna, in other words, how much of it is reflected, radiated, and dissipated through dielectric and conductor loss. AXIEM calculates the radiated power by integrating the far field energy from the known currents on the antenna. Because AXIEM assumes an infinite substrate, part of the power is potentially lost in surface waves propagating down the substrate. This will not occur with a finite sized substrate, which can lead to AXIEM giving a conservative number for the radiated power. If necessary, a more accurate analysis of the radiation efficiency for a finite dielectric can be achieved by using a 3D arbitrary EM solver based on finite element methods such as Analyst EM finite element method (FEM) simulator in Microwave Office.

The power being radiated, reflected, and absorbed in heating the dielectric and conductors, is shown in Figure 12. The incident power going into the antenna and matching circuit is 0 dBm. The radiated power is about -8.9 dBm in the upper stop band of the antenna, or about 77 GHz. This was a problem. In Figure 10, the curve AXIEM antenna and matching S21 (dB) shows a value of -21.8 dB at 77 GHz. Remember that a series port (Port 2) was added to the layout after the matching



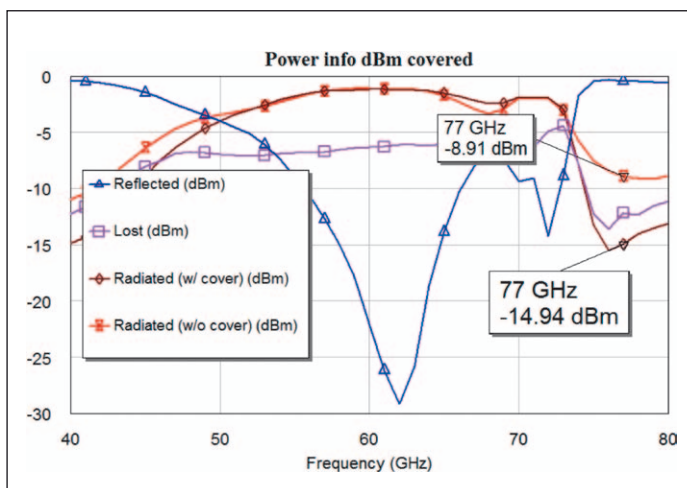
**Figure 13: The cover reduced the radiation from the matching section by 6 dB.**

section and before the antenna. Therefore, the S21 shows the amount of power that goes into the antenna, which is much lower than the overall radiated power from the entire antenna and matching structure. The conclusion was that the matching circuit itself radiating. A quick trial showed that placing a shield 0.5 mm below the matching circuit and extending it 1 mm beyond the microstrip coplanar waveguide solved this problem without significantly affecting the antenna's performance.

With the shielded matching circuit, the radiation was reduced about 6 dB to nearly -15 dBm, or about 0.03 mW, or 3 percent of the 1-mW input power (0 dBm).

Figure 13 shows that the return loss was better than -12.7 dB over the band of interest. The final step for the shielded design was to analyze the radiation efficiency, defined as the ratio of power radiated from the antenna to the power delivered to the antenna. The power info measurement in Microwave Office was used to calculate that the radiation efficiency was 75...78 percent over the band of interest (Figure 14).

Part of the power was lost in the surface waves in the model, making this figure pessimistic, but, on the other hand, metal surface roughness increased the losses, making this figure optimistic. Analyzing these loss



**Figure 14: The radiation efficiency is 75...78 percent from 57...64 GHz.**

factors more carefully showed that a surface roughness of a little less than 1  $\mu\text{m}$  was equivalent to the power lost in surface waves. Such a roughness is probably quite close to what can be expected for 10  $\mu\text{m}$  line thickness on a millimeter wave board, so the expected realistic radiation efficiency was thus about 75 percent.

### Gain, Polarization and Radiation Pattern

The 3D radiation pattern at 60 GHz is shown in Figure 15. The antenna directivity varied between 5.7 dB and 6.3 dB over the band. Assuming radiation efficiency of 75 percent, the antenna gain varied between 4.5-5.1 dB. The 3D radiation pattern shows three main lobes:

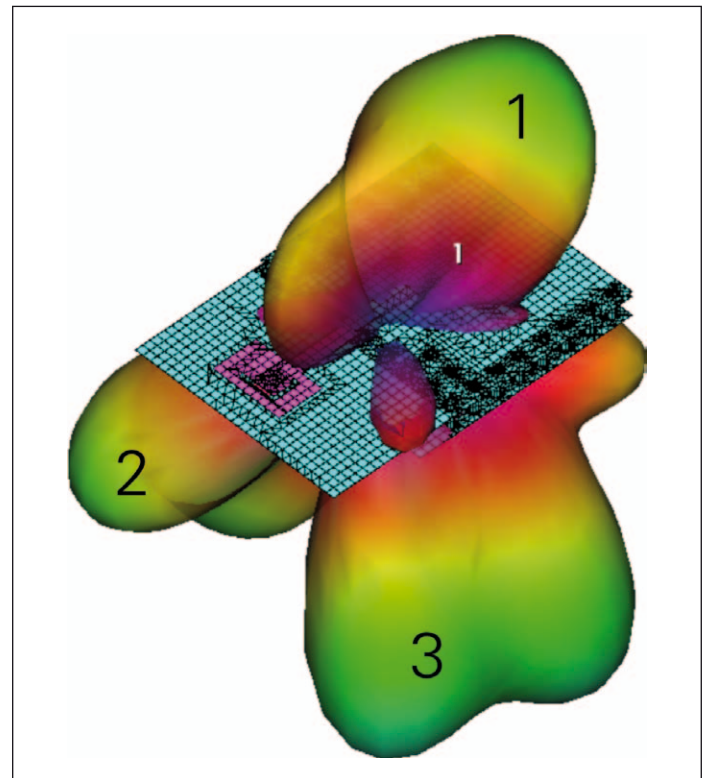
- Lobe 1: 0°/35° horizontal polarization, 1 dB beamwidth = 30°
- Lobe 2: 135°/135° left hand circular polarization, 1 dB beamwidth = 38°
- Lobe 3: 225°/120° right hand circular polarization, 1 dB beamwidth = 27°

By proper weighting in an array, the desired polarization could be generated.

### Conclusion

This application example highlights a unique, step-by-step mmWave antenna design and analysis flow that combines NI AWR Design Environment and AWR Connected for Optenni. Bandwidth potential was used to rank design candidates and Optenni Lab synthesized the microstrip matching circuits for simultaneous optimization of pass-band and stop-band behavior. A synthesized model was exported into Microwave Office, where it was extracted for AXIEM EM simulation. This flow provides an excellent starting point for building composite models that include the antenna and matching circuitry together.

Special thanks to Jaakko Juntunen of Optenni Lab for his contributions to this application example. ◀



**Figure 15: The radiation pattern shows three main lobes. The frequency shown is 60 GHz.**