Microstrip Patch Antenna Simulation, Analysis, and Optimization for 28 GHz Operation

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Date: 12/01/2024

Introduction

High-frequency antennas, particularly microstrip patch designs, are widely used in modern wireless communication systems due to their low profile, ease of fabrication, and compatibility with integrated circuits. The challenge lies in accurately matching the antenna to the desired operating frequency to minimize reflection (power loss) and maximize radiation efficiency.

This report details the simulation of a microstrip patch antenna with a target frequency of 28 GHz. The antenna design was modeled in Ansys HFSS, focusing on substrate and air box dimensions derived from established design principles and ensuring an adequate radiation boundary. After simulating the initial configuration, we observed that the antenna did not achieve its best match at 28 GHz. Instead, it displayed a local minimum in power loss (S11) at around 25 GHz and a global minimum at approximately 36.3 GHz. This document outlines the design parameters, the observed discrepancies, and recommendations to shift the antenna's resonance closer to the desired 28 GHz.

Antenna Design Parameters

1. **Substrate Dimensions:**
- Size: 10 mm (X) × 12 mm (Y) × 1.6 mm (Z)
The chosen substrate thickness and dielectric properties, Choose a dielectric substrate material (e.g., FR4 with ϵr=4.4\epsilon_r = 4.4ϵr=4.4), significantly influence the antenna's resonant frequency. Typically, thinner substrates or higher permittivity materials tend to lower the resonant frequency, while changes in substrate dimensions can help fine-tune the frequency response.

2. **Ground Plane Dimensions**:
-Size: 10.5 mm × 12.5 mm
The ground plane extends slightly beyond the substrate footprint. This margin can help ensure a uniform ground reference but may need adjustment if the antenna's resonant frequency deviates significantly from the target.

3. **Air Box Dimensions**:
- Size: 15.5 mm (X) × 17.7 mm (Y) × 7 mm (Z)

The air box size was chosen based on the guidelines that the radiation boundary should be at least a quarter-wavelength away from the antenna. At 28 GHz, the wavelength is approximately 10.7 mm, making a quarter-wavelength about 2.7 mm. By placing the radiation boundary (air box) several millimeters away, reflections from the boundary are minimized. In this experiment, a box of 15.5 mm × 17.7 mm × 7 mm ensured sufficient spacing on all sides and above, mitigating undesired boundary reflections and allowing a more accurate representation of free-space conditions.

Observations and Results

The primary goal was to minimize power loss and achieve a well-matched condition near 28 GHz. An ideally matched antenna would show a reflection coefficient (S11) well below -10 dB at the target frequency, indicating that most of the input power is transferred into the antenna rather than being reflected back.

Key Findings:

- Local Minimum at 25 GHz: A dip in the S11 curve was observed around 25 GHz, suggesting partial resonance. Although this frequency is close to the desired 28 GHz, it remains lower than intended. This indicates that the antenna's effective electrical length or substrate properties are currently tuned for a slightly lower frequency.

- Global Minimum at ~36.3 GHz:A more pronounced minimum in S11 was noted at approximately 36.3 GHz, far above the target frequency. This suggests a higher-order mode or a different resonance arising from the patch and feed configuration. The presence of a global minimum well above 28 GHz may result from the patch dimensions or feed line placement relative to the substrate's effective permittivity and thickness.

Discussion

The discrepancy between the target frequency (28 GHz) and the observed resonant frequencies (25 GHz and ~36.3 GHz) suggests that the current geometry—particularly the patch dimensions and possibly the feed location—is not optimal. Antennas at millimeter-wave frequencies are highly sensitive to small dimensional changes. Even a fraction of a millimeter in patch length or width can shift the resonant frequency by a few gigahertz.

Factors Influencing Resonance:

1. Patch Dimensions (Length and Width):
The resonant frequency of a patch antenna is primarily determined by its length. For a rectangular patch, the fundamental mode typically resonates when the patch length corresponds to approximately half a guided wavelength. If the observed resonance is too low (25 GHz), slightly reducing the patch length could shift the resonance upward toward 28 GHz. Conversely, if higher-order modes (like the 36.3 GHz resonance) are strong, altering the aspect ratio (width to length ratio) might help suppress or shift them.

2. Feed Position:
The feed line's location along the patch edge influences the input impedance. Moving the feed point closer or farther from the patch centerline can affect the matching at the desired frequency. A small adjustment in feed position can improve S11 at 28 GHz without drastically changing the patch size.

3. Substrate Properties:
Although not changed in this specific scenario, the dielectric constant and thickness of the substrate influence the antenna's effective dielectric environment. A substrate thickness of 1.6 mm might be fine-tuned (if permissible) to better align the resonant frequency with 28 GHz.

Recommendations for Optimization

To achieve a well-matched resonance at 28 GHz, consider the following adjustments:

1. Slightly Reduce Patch Length:
If the patch is currently too long, it resonates at a lower frequency. By reducing the patch length by a small percentage (e.g., 2–5%), you can shift the fundamental mode upward from 25 GHz closer to 28 GHz.

2. Adjust Patch Width for Impedance Matching:
Changing the width can help in fine-tuning the bandwidth and coupling characteristics, potentially reducing the prominence of the 36.3 GHz mode. This may require iterative simulation: shorten the patch to raise the fundamental resonance and then adjust the width or feed position to tame the higher-frequency mode.

3. Refine the Feed Position:
Move the feed point along the patch edge to achieve better impedance matching at 28 GHz. Even a 0.1–0.2 mm shift in feed location can improve the return loss significantly at the desired frequency.

4. Parametric Sweep in HFSS:

Conduct a parametric study, systematically varying patch length and feed position. For example, start with the current dimensions and reduce the patch length in 0.1 mm increments. After each change, re-run the simulation and observe how the resonance and S11 response shift. This will help pinpoint the optimal geometry.

Conclusion

The initial antenna configuration yielded resonances at approximately 25 GHz and 36.3 GHz, rather than the desired 28 GHz. To bring the resonance closer to 28 GHz, careful dimension adjustments are needed. Reducing the patch length slightly can shift the lower-frequency resonance upward, while fine-tuning the feed position and width can help improve matching at the intended operating frequency and mitigate unwanted higher-frequency resonances.

Through iterative simulations and minor geometric tweaks, the antenna can be brought into resonance at 28 GHz, achieving a lower reflection coefficient and minimizing power loss, thereby meeting the design objectives more closely.