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First-Time-Right Antennas for Wireless Product Teams

How laminate, thickness and feed placement decide whether a 5.8 GHz patch antenna covers its band on every board, not just the first prototype.

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Method
Cavity and transmission-line patch models with Monte Carlo tolerance analysis

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Abstract

Printed patch antennas are narrowband, and their resonance depends on laminate permittivity, thickness and etched length. We model probe-fed rectangular patches for the 5.725 to 5.850 GHz band with the cavity and transmission-line models, including slot self and mutual conductance, conductor, dielectric and radiation quality factors and probe reactance, and estimate production yield by Monte Carlo sampling of material and etch tolerances. The model reproduces a textbook design example to three significant figures and an independent closed-form radiation Q within 2 %.

On 0.813 mm RO4003C the −10 dB bandwidth is 94 MHz, too narrow for the band. At 1.524 mm it is 150 MHz with 93 % efficiency; FR-4 at 1.6 mm reaches 198 MHz but only 65 % efficiency. A 0.1 change in permittivity shifts resonance by about 77 MHz, so tolerances dominate: with the feed tuned to spread the match across the band, coverage rises from about a third (33 %) to 66 % of boards on 1.524 mm RO4003C and to 100 % at 2.0 mm, against 37 % for 1.524 mm FR-4.

Keywords: microstrip patch antenna, 5.8 GHz, cavity model, quality factor, manufacturing tolerance, yield

1. Introduction

The rectangular microstrip patch is the default antenna for 5.8 GHz video links, telemetry and fixed wireless because it is flat, cheap and printed with the rest of the board [1]. It is also narrowband. A patch on thin laminate covers only a few percent of its center frequency, and its resonance depends directly on the laminate's permittivity, thickness and the etched patch length. Antennas that work on the first prototype can drift off band in production when laminate lots and etching vary.

This paper asks how laminate choice and thickness decide whether a probe-fed patch covers the 5.725 to 5.850 GHz band [7] with margin, and what fraction of boards still cover it once material and etch tolerances are included.

2. Model and Method

The patch (Figure 1) is analyzed with the transmission-line and cavity models [1], [2]. Width follows the standard design rule $W = c/(2f)\sqrt{2/(\varepsilon_r+1)}$; effective permittivity and the fringing extension ΔL follow Hammerstad [4], and the resonant frequency is $f_r = c/(2(L+2\Delta L)\sqrt{\varepsilon_{eff}})$. Each radiating edge is a slot of conductance G_1, coupled to the other through mutual conductance G_{12}; both are evaluated by numerical integration of the slot radiation integrals [1]. The edge resistance is $R_0 = 1/(2(G_1+G_{12}))$, and a probe inset y_0 from the edge lowers it as $R_0\cos^2(\pi y_0/L)$.

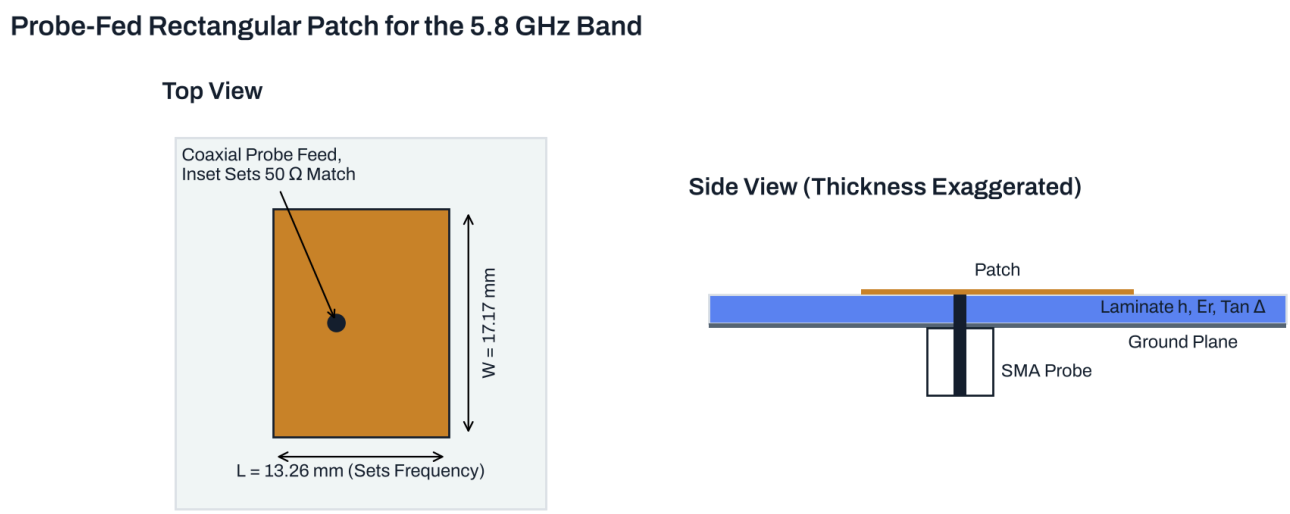


Figure 1. Probe-fed rectangular patch. Patch length L sets the resonant frequency; the probe position along L sets the input resistance. Dimensions shown are for the 1.524 mm RO4003C design.

Near resonance the patch is a parallel RLC circuit in series with the probe reactance X_p [5]:

$$Z_{in}(f) = R \,/\, [1 + jQ_t(f/f_r - f_r/f)] + jX_p, \quad 1/Q_t = 1/Q_{rad} + 1/Q_c + 1/Q_d \tag{1}$$

The radiation quality factor is the ratio of stored cavity energy to slot-radiated power, $Q_{rad} = \omega\varepsilon_0\varepsilon_r WL/(4h(G_1+G_{12}))$; conductor and dielectric terms are $Q_c = h\sqrt{\pi f\mu_0\sigma}$ and $Q_d = 1/\tan\delta$ [1]. Radiation efficiency is Q_t/Q_{rad}. The probe is an SMA pin of 0.635 mm radius. Directivity comes from numerical integration of the two-slot far-field pattern over the upper hemisphere (infinite ground plane).

Each design is sized so that its best match falls at 5.7875 GHz, the band center. Three laminates are compared: RO4003C (design ε_r 3.55, $\tan\delta$ 0.0027 [6]) at 0.813 and 1.524 mm, and a representative FR-4 (ε_r 4.4, $\tan\delta$ 0.02) at 1.6 mm. Production spread is modeled by Monte Carlo sampling (2,000 to 4,000 boards per case) with uniform

tolerances: ε_r ±0.05 for RO4003C [6] and ±0.2 for FR-4, thickness ±0.038 mm for RO4003C and ±10 % for FR-4, and ±25 µm etch on L and W. A board passes if |S11| stays below −10 dB across the whole band.

3. Verification

Check	Reference	Result
Design example: ε_r 2.2, h 1.588 mm, 10 GHz	Worked example in [1]: W 1.186 cm, ε_{eff} 1.972, ΔL 0.081 cm, L 0.906 cm	W 1.185 cm, ε_{eff} 1.972, ΔL 0.081 cm, L 0.905 cm
Slot conductance, narrow slot	Asymptote $W^2/(90\lambda_0^2)$ [1]	0.03 % difference
Radiation Q, 1.524 mm RO4003C	Independent closed form of Jackson and Alexopoulos [3]	24.3 against 24.7
Radiation Q, FR-4 1.6 mm	Same	26.5 against 26.7
Radiated power, two routes	Pattern integral against slot conductance	Agree within 6 % (mutual-coupling and slot-height approximations)

Table 1. Verification of the patch model.

4. Results

4.1 Nominal Bandwidth and Efficiency

Quantity	RO4003C 0.813 mm	RO4003C 1.524 mm	FR-4 1.6 mm
Patch W × L (mm)	17.17 × 13.54	17.17 × 13.26	15.76 × 11.91
Probe inset from edge (mm)	4.92	4.80	4.41
Q_{rad} / Q_t	47 / 40	24 / 23	26 / 17
Radiation efficiency	85 %	93 %	65 %
Directivity / gain (dBi)	6.4 / 5.7	6.5 / 6.1	6.2 / 4.3
−10 dB bandwidth (MHz)	94	150	198
Shift per +0.1 in ε_r (MHz)	-78	-77	-62
Shift per +25 µm in L (MHz)	-10	-10	-10
95 % spread of match frequency (MHz)	83	79	260
Boards covering the band, resonant-inset feed	0 %	33 %	29 %

Table 2. Nominal performance and production spread of three designs centered at 5.7875 GHz.

The 125 MHz band is 2.2 % of its center frequency. On 0.813 mm RO4003C the patch's −10 dB bandwidth is only 94 MHz, so even a perfect board cannot cover the band (Figure 2). Doubling thickness to 1.524 mm halves Q_{rad} and widens the band to 150 MHz with 93 % efficiency. FR-4 at 1.6 mm is wider still, 198 MHz, but mostly because dielectric loss lowers Q: its efficiency is 65 %, 1.8 dB less gain than the RO4003C design.

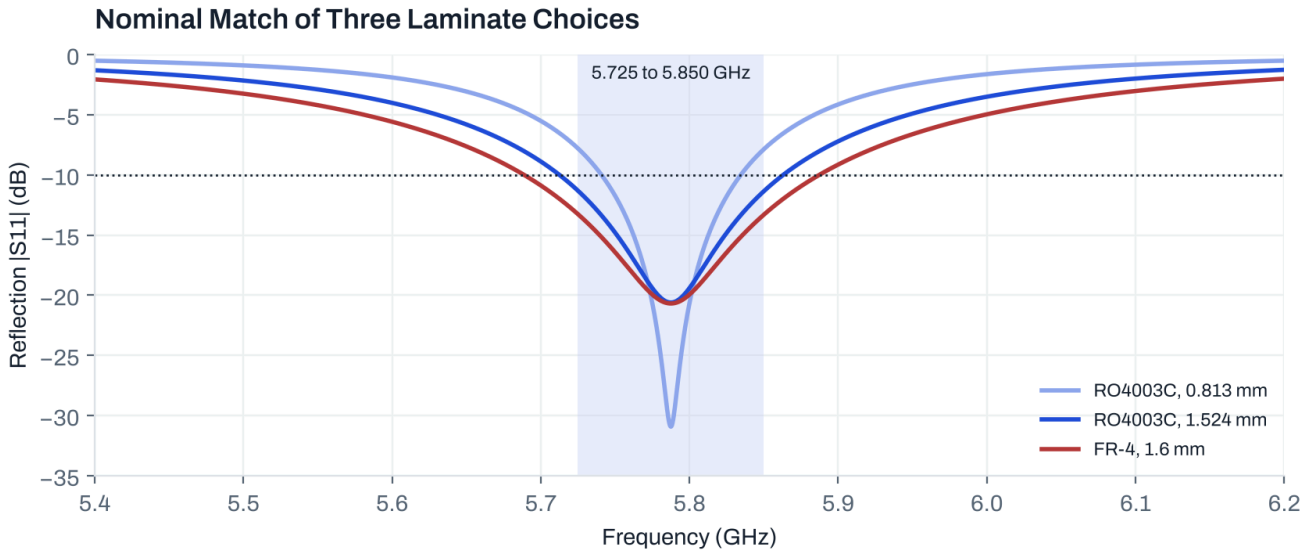


Figure 2. Reflection of the three nominal designs, each centered on the 5.725 to 5.850 GHz band (shaded). A board covers the band when |S11| stays below −10 dB (dotted) across it.

4.2 Production Tolerances and Yield

Tolerances decide the rest. A change of 0.1 in ε_r moves the match by 77 MHz on RO4003C, more than half the band. With RO4003C's ±0.05 the 95 % spread of match frequency is 79 MHz; with the FR-4 ±0.2 assumed here it is 260 MHz. Only 33 % of 1.524 mm RO4003C boards and 29 % of FR-4 boards cover the band with a feed placed for best match at resonance. Moving the probe so the match is spread across the band rather than deepest at center raises the RO4003C figure to 66 % at 1.524 mm and 100 % at 2.0 mm; FR-4 reaches 60 % at 2.0 mm (Figure 3). With 2,000 sampled boards per case these shares carry a binomial standard error of about one percentage point. A 2.0 mm thickness is not a standard single-ply RO4003C product, so in practice it means a bonded two-ply stack or a different low-loss laminate.

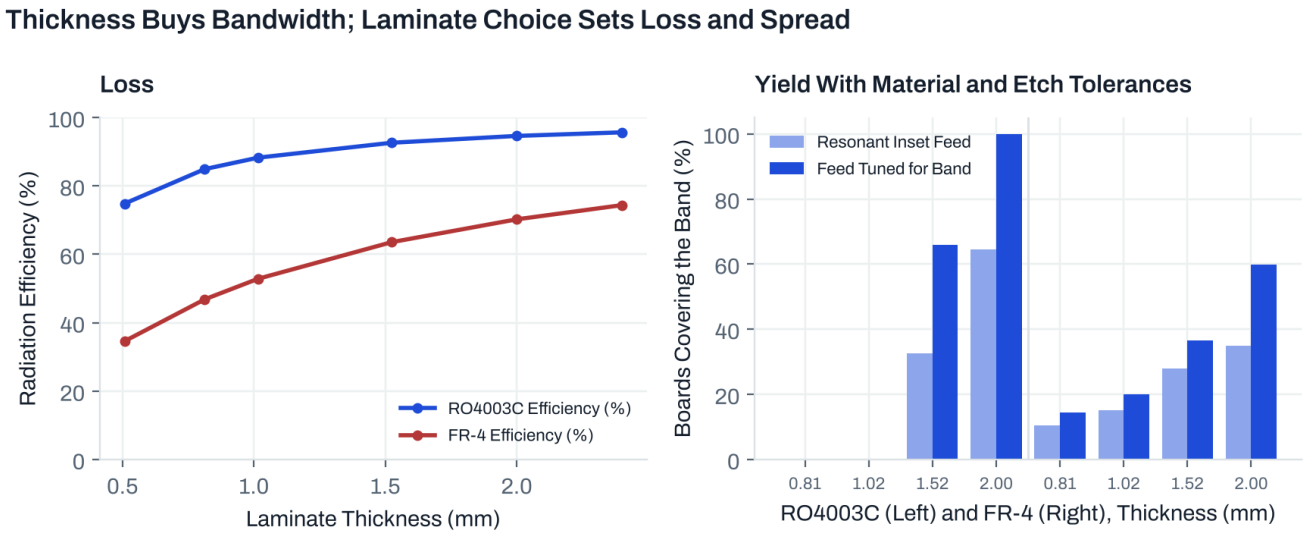


Figure 3. Left: radiation efficiency against laminate thickness. Right: share of simulated boards whose |S11| stays below −10 dB across 5.725 to 5.850 GHz, with ε_r, thickness and etch tolerances, for a feed placed for best match at resonance and for a feed tuned to spread the match across the band.

5. Discussion

For a single-layer probe-fed patch in this band, three design choices matter more than fine geometry. First, thickness: below about 1 mm on low-loss laminate the patch cannot cover 125 MHz at all. Second, laminate: FR-4 looks wider in bandwidth but pays in efficiency, and its permittivity spread moves the resonance by more than the band is wide. Third, the feed point: placing the probe for a moderate match across the band rather than a deep notch at center is free and roughly doubles yield on a low-loss laminate. Teams that need FR-4 for cost should plan for per-lot tuning or a wider-band geometry (stacked or slotted patches) [5].

Limitations. The cavity and transmission-line models neglect surface-wave loss, which grows with thickness, and finite ground plane effects; probe reactance uses a closed-form approximation; copper roughness is ignored; tolerance ranges are uniform and representative rather than taken from a specific vendor's lot data, except the RO4003C permittivity tolerance [6]. Final designs should be confirmed with a full-wave solver and a measured prototype.

6. Conclusions

1. A 5.8 GHz patch on 0.813 mm RO4003C has 94 MHz of −10 dB bandwidth and cannot cover the 125 MHz band; 1.524 mm gives 150 MHz at 93 % efficiency.
2. Permittivity is the dominant tolerance: 0.1 in ε_r moves the resonance about 77 MHz, against about 10 MHz for 25 µm of etch.
3. FR-4 at 1.6 mm loses 1.8 dB of gain to dielectric loss; with ±0.2 permittivity spread, 1.524 mm FR-4 covers the band on about 37 % of boards even with a tuned feed.
4. Thicker low-loss laminate with a band-tuned feed point reaches 100 % coverage at 2.0 mm in this model.

References

1. C. A. Balanis, *Antenna Theory: Analysis and Design*, 4th ed. Hoboken, NJ: Wiley, 2016.
2. Y. T. Lo, D. Solomon and W. F. Richards, "Theory and experiment on microstrip antennas," *IEEE Transactions on Antennas and Propagation*, vol. 27, no. 2, pp. 137–145, 1979.
3. D. R. Jackson and N. G. Alexopoulos, "Simple approximate formulas for input resistance, bandwidth, and efficiency of a resonant rectangular patch," *IEEE Transactions on Antennas and Propagation*, vol. 39, no. 3, pp. 407–410, 1991.
4. E. O. Hammerstad, "Equations for microstrip circuit design," in *Proc. 5th European Microwave Conference*, Hamburg, 1975, pp. 268–272.
5. R. Garg, P. Bhartia, I. Bahl and A. Ittipiboon, *Microstrip Antenna Design Handbook*. Norwood, MA: Artech House, 2001.
6. Rogers Corporation, *RO4000 Series High Frequency Circuit Materials*, data sheet.
7. U.S. Code of Federal Regulations, Title 47, Part 15, Section 15.247, "Operation within the bands 902–928 MHz, 2400–2483.5 MHz, and 5725–5850 MHz."

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