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Microstrip Antenna Efficiency & Metals

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Abstract: The change in square microstrip antenna radiation efficiency using different metals for the patch and groundplane is investigated. The non-radiation losses for a typical microstrip antenna increase as the conductivity decreases. An optimum efficiency radome is introduced, which increases the radiation efficiency with the metals studied. The dielectric loss of the microstrip antennas with a dielectric cover becomes essentially constant with conductivity, suggesting the dielectric losses without a cover may be from a non-radiative surface wave loss.

Contents

1 Introduction 1

2 HFSS Analysis of Square Microstrip Antennas 1

2.1 Efficiency of Microstrip Antenna vs. Various Metals 2

2.1.1 Square Microstrip Antenna 2

2.1.2 Square Microstrip Antenna with Radome 2

3 Conclusion 6

A Appendix: Properties of Metals Studied 8

1 Introduction

This paper presents the constituent losses* of a square patch antenna designed using various metals. The design frequency is 2450 MHz. The constituent losses are radiation efficiency η_r, surface wave efficiency η_{sw}, conductor efficiency, η_c, and dielectric efficiency, η_d. The method used to determine the constituent losses for each metal design uses HFSS computed Q values. The Q of the antenna, the Q of the antenna with the conductors replaced with perfect electrical conductors, and finally the Q with lossless dielectric and restored conductors allow the computation of the constituent losses.[1]

In the case of metals with negligible magnetic permeability ($\mu_r \approx 1$), the computed Q's are well-behaved when conductors are replaced with perfectly electrical conductors (PEC).

Metals with large permeability ($\mu_r \gg 1$), can alter the Q calculated by HFSS with PEC in place of the metal. The PEC substituted for the metal conductor is given the same μ_r as the original metal. The mismatch can be large enough to justify moving the feedpoint, to re-match the antenna, so as to obtain a more accurate Q when PEC has been introduced. The frequency is often shifted somewhat, but rescaling the patch to maintain a constant resonance frequency changes the geometry, and when performed, often produces negative values for Q.

2 HFSS Analysis of Square Microstrip Antennas

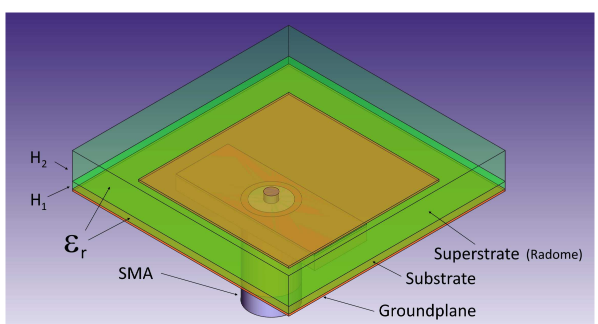

Figure 1: Geometry of Microstrip Antenna with a dielectric cover (radome).

*These will also be called efficiencies, depending on context.

The geometry of a dielectric covered square microstrip antenna is given in Figure 1. The substrate thickness is H_1. The dielectric cover has a thickness of H_2, which is zero when analyzing the antenna without a radome.[†] A standard SMA connector is used to drive the square microstrip antenna.

2.1 Efficiency of Microstrip Antenna vs. Various Metals

2.1.1 Square Microstrip Antenna

Table 1 has the constituent losses of a square microstrip antenna for a number of metal conductors. The antenna is designed to operate at 2450 MHz. The microwave substrate has a relative dielectric permittivity of 2.6, a loss tangent of 0.0025, and a thickness, H_1, of 1575 μm. The relative permeability of the groundplane and patch is approximately one for this table. The materials are either non-magnetic, or very slightly diamagnetic or paramagnetic. The relative dielectric permittivity is ϵ_r, the relative permeability is μ_r, and σ is the conductivity. The conductor thickness, T_c, is 17 μm in all cases.

We see in Table 1, that as the conductivity decreases, so does the antenna efficiency. This is expected. The overall range of radiation efficiencies is from 85.40 % for silver, down to 59.45 % when stainless steel is employed. The loss difference from silver to stainless steel is about -1.6 dB. What is interesting, is that as the conductivity σ, decreases, the surface wave loss, η_{sw}, *increases*, and dominates the loss components until we reach titanium, which has a very poor conductivity. When the conductivity is large, the dielectric losses are the next largest loss component. But as the conductivity decreases, the conductor losses slowly approach, and then surpass the dielectric losses, which remain stable by comparison. Stainless steel has a conductor loss component larger than the surface wave or dielectric component.

Table 2 has three strongly paramagnetic metals: Iron, Nickel, and Cobalt. In this case, the conductor losses, η_c, dominate the loss components. Iron eliminates the surface wave loss component completely. The dielectric losses are miniscule compared with the conductor losses.

2.1.2 Square Microstrip Antenna with Radome

It is known that the introduction of a radome with the same relative dielectric permittivity as the substrate can increase antenna efficiency for low values of

[†]In HFSS the dielectric cover is simply removed from the model.

Microstrip Antenna Efficiency vs Type of Metal
($\mu_r \approx 1$)

Metal	ϵ_r	μ_r	σ	η_r	η_{sw}	η_c	η_d
Silver - Ag	1	0.999 98	61.000 MS/m	85.40 %	6.46 %	2.02 %	6.12 %
Copper - Cu	1	0.999 991	58.000 MS/m	85.32 %	6.45 %	2.11 %	6.12 %
Gold - Au	1	0.999 96	41.000 MS/m	84.67 %	6.87 %	2.46 %	6.01 %
Aluminum - Al	1	1.000 021	38.000 MS/m	84.52 %	6.76 %	2.63 %	6.09 %
Zirconinum - Zr	1	1	24.400 MS/m	83.21 %	7.37 %	3.44 %	5.98 %
Magnesium - Mg	1	1	22.500 MS/m	82.94 %	7.55 %	3.62 %	5.89 %
Rhodium - Rh	1	1	22.200 MS/m	82.85 %	7.65 %	3.62 %	5.89 %
Tungsten - W	1	1	18.200 MS/m	82.01 %	8.10 %	4.12 %	5.77 %
Molybdenium - Mo	1	1	17.600 MS/m	81.87 %	7.99 %	4.30 %	5.85 %
Zinc - Zn	1	1	16.700 MS/m	81.59 %	8.29 %	4.38 %	5.75 %
Brass	1	1	15.000 MS/m	81.04 %	8.47 %	4.80 %	5.69 %
Bronze	1	1	10.000 MS/m	78.58 %	9.80 %	6.27 %	5.34 %
Palladium - Pd	1	1.000 82	9.300 MS/m	78.08 %	9.93 %	6.63 %	5.36 %
Platinum - Pt	1	1	9.300 MS/m	78.07 %	9.93 %	6.63 %	5.36 %
Tin - Sn	1	1	8.670 MS/m	77.58 %	10.13 %	6.95 %	5.34 %
Chromium - Cr	1	1	7.600 MS/m	76.56 %	10.63 %	7.58 %	5.22 %
Indium - In	1	1	6.440 MS/m	75.27 %	11.32 %	8.36 %	5.06 %
Tantalum - Ta	1	1	6.300 MS/m	75.08 %	11.44 %	8.43 %	5.05 %
Lead - Pb	1	0.999 983	5.000 MS/m	73.10 %	12.27 %	9.73 %	4.90 %
Titanium - Ti	1	1.000 18	1.820 MS/m	63.81 %	15.26 %	16.64 %	4.29 %
Stainless Steel	1	1	1.100 MS/m	59.45 %	15.69 %	20.67 %	4.20 %

Table 1: The design frequency is 2450 MHz. Substrate $\epsilon_r = 2.6$ with $H_1 = 1575$ μm and $H_2 = 0$. The metal cladding thickness is 17 μm

Microstrip Antenna Efficiency vs Type of Metal
($\mu_r \gg 1$)

Metal	ϵ_r	μ_r	σ	η_r	η_{sw}	η_c	η_d
Cobalt - Co	1	250	10.000 MS/m	36.97 %	3.57 %	56.91 %	2.55 %
Nickel - Ni	1	600	14.500 MS/m	31.92 %	4.38 %	61.50 %	2.20 %
Iron - Fe	1	4000	10.300 MS/m	14.80 %	0.00 %	84.08 %	1.13 %

Table 2: The design frequency is 2450 MHz. Substrate $\epsilon_r = 2.6$ with $H_1 = 1575$ μm and $H_2 = 0$. The metal cladding thickness is 17 μm

dielectric permittivity.[2] Whatever lossy mode exists which produces a non-radiative surface wave loss, also appears to contribute to extra conductor and dielectric losses. In this section, we add a radome of optimum electrical thickness, $0.32\lambda_{\epsilon_r}$, to optimize efficiency.

Table 3 presents the same designs as presented in Table 1, but with the addition of a dielectric cover with the same relative dielectric permittivity, ϵ_r, as the substrate. We note that the overall radiation efficiency is higher for all the radomed antennas when compared with the non-radome covered patches of Table 1. Using each uncovered antenna as a reference, we see that the radiation efficiency gained by the introduction of an efficiency optimized dielectric cover increases steadily, but for all cases is less than 1.2 dB. For the case of the three strongly paramagnetic materials used, a radome can increase the power radiated by over 3 dB.

When the dielectric cover is not present, the dielectric loss decreases with decreasing conductivity. When the optimum efficiency cover is added, the dielectric loss becomes essentially stable for all conductivities. This suggests that whatever bound-wave might exist in the uncovered case, the optimal radome thickness has removed that component of loss almost entirely, with only the intrinsic dielectric loss remaining.

The loss attributed to the conductivity of the antenna and groundplane, is higher for each type of metal antenna without a radome, than for those with an optimum radome present. The conductor loss component increases monotonically with decreasing conductivity. Again, it appears that whatever the bound wave is that produced the larger dielectric and conductor losses in the uncovered case, has decreased, or been removed.

The component which has been traditionally attributed to surface wave

Microstrip Antenna Efficiency vs Type of Metal
($\mu_r \approx 1$)
0.32 λ_{ϵ_r} Dielectric Cover

Metal	ϵ_r	μ_r	σ	η_r	η_{sw}	η_c	η_d
Silver - Ag	1	0.999 98	61.000 MS/m	92.69 %	4.03 %	0.88 %	2.40 %
Copper - Cu	1	0.999 991	58.000 MS/m	92.64 %	4.04 %	0.92 %	2.40 %
Gold - Au	1	0.999 96	41.000 MS/m	92.34 %	4.23 %	1.07 %	2.36 %
Aluminum - Al	1	1.000 021	38.000 MS/m	92.26 %	4.20 %	1.14 %	2.40 %
Zirconinum - Zr	1	1	24.400 MS/m	91.66 %	4.47 %	1.48 %	2.39 %
Magnesium - Mg	1	1	22.500 MS/m	91.53 %	4.57 %	1.56 %	2.34 %
Rhodium - Rh	1	1	22.200 MS/m	91.50 %	4.64 %	1.56 %	2.31 %
Tungsten - W	1	1	18.200 MS/m	91.11 %	3.68 %	2.91 %	2.30 %
Molybdenium - Mo	1	1	17.600 MS/m	91.02 %	4.86 %	1.82 %	2.30 %
Zinc - Zn	1	1	16.700 MS/m	90.89 %	4.88 %	1.93 %	2.30 %
Brass	1	1	15.000 MS/m	90.64 %	4.98 %	2.08 %	2.30 %
Bronze	1	1	10.000 MS/m	89.42 %	5.44 %	2.82 %	2.32 %
Palladium - Pd	1	1.000 82	9.300 MS/m	89.16 %	5.50 %	2.96 %	2.28 %
Platinum - Pt	1	1	9.300 MS/m	89.16 %	5.60 %	2.96 %	2.28 %
Tin - Sn	1	1	8.670 MS/m	88.92 %	5.75 %	3.07 %	2.27 %
Chromium - Cr	1	1	7.600 MS/m	88.45 %	5.96 %	3.36 %	2.23 %
Indium - In	1	1	6.440 MS/m	87.70 %	6.13 %	3.86 %	2.31 %
Tantalum - Ta	1	1	6.300 MS/m	87.61 %	6.23 %	3.89 %	2.27 %
Lead - Pb	1	0.999 983	5.000 MS/m	86.54 %	6.43 %	4.70 %	2.33 %
Titanium - Ti	1	1.000 18	1.820 MS/m	81.13 %	8.56 %	8.14 %	2.18 %
Stainless Steel	1	1	1.100 MS/m	78.37 %	9.72 %	9.82 %	2.09 %

Table 3: The design frequency is 2450 MHz. Substrate $\epsilon_r = 2.6$ with $H_1 = 1575\ \mu m$. The metal cladding thickness is 17 μm

losses, is also decreased with the introduction of a dielectric cover. This loss also increases with decreasing conductivity. Whatever the origin of this component of loss is, it is either the residual of bound-wave loss, or is attributable to a lossy surface wave that is independent of the attenuated loss.

Microstrip Antenna Efficiency vs Type of Metal
($\mu_r \gg 1$)
0.32 λ_{ϵ_r} Dielectric Cover

Metal	ϵ_r	μ_r	σ	η_r	η_{sw}	η_c	η_d
Cobalt - Co	1	250	10.000 MS/m	59.89 %	4.75 %	33.68 %	1.68 %
Nickel - Ni	1	600	14.500 MS/m	54.48 %	4.46 %	39.49 %	1.57 %
Iron - Fe	1	4000	10.300 MS/m	30.57 %	0.27 %	67.94 %	1.21 %

Table 4: The design frequency is 2450 MHz. Substrate $\epsilon_r = 2.6$ with $H_1 = 1575$ μm. The metal cladding thickness is 17 μm

Table 4 has strongly paramagnetic materials with an optimum thickness radome. Again the conductor losses with a radome are lower than those without. Table 5 summarizes the efficiency increase, in dB, obtained for the designs with, (η_{radome}), and without, (η_r), a radome. For the slightly magnetic materials studied, the losses increase in proportion to decreasing conductivity. For the strongly paramagnetic materials, $\mu_r \gg 1$, the increase in efficiency is proportional to the increase in permeability. The increase is significant, but is with respect to a much worse initial efficiency when compared with essentially non-magnetic materials.

3 Conclusion

This paper has examined the electrical performance and feasibility of using non-traditional metals to fabricate microstrip antennas. For a square microstrip antenna without a dielectric cover, using essentially non-magnetic metals, the radiation efficiency decreases with decreasing material conductivity. The non-radiative surface wave loss component is larger than the conductor and dielectric loss components with the exception of stainless steel. The surface wave losses increase with decreasing conductivity as do the conductor and dielectric loss components. When strongly paramagnetic metals

Microstrip Antenna Efficiency vs Type of Metal

Non-Magnetic Diamagnetic & Paramagnetic

Metal	η_r	η_{radome}	Increase (dB)
Silver - Ag	85.40 %	92.69 %	0.36 dB
Copper - Cu	85.32 %	92.64 %	0.36 dB
Gold - Au	84.67 %	92.34 %	0.38 dB
Aluminum - Al	84.52 %	92.26 %	0.38 dB
Zirconinum - Zr	83.21 %	91.66 %	0.42 dB
Magnesium - Mg	82.94 %	91.53 %	0.43 dB
Rhodium - Rh	82.85 %	91.50 %	0.43 dB
Tungsten - W	82.01 %	91.11 %	0.46 dB
Molybdenium - Mo	81.87 %	91.02 %	0.46 dB
Zinc - Zn	81.59 %	90.89 %	0.47 dB
Brass	81.04 %	90.64 %	0.49 dB
Nickel	31.92 %	54.48 %	2.32 dB
Bronze	78.58 %	89.42 %	0.56 dB
Iron	14.80 %	30.57 %	3.15 dB
Cobalt	36.97 %	59.89 %	2.10 dB
Palladium - Pd	78.08 %	89.16 %	0.58 dB
Platinum - Pt	78.07 %	89.16 %	0.58 dB
Tin - Sn	77.58 %	88.92 %	0.59 dB
Chromium - Cr	76.56 %	88.45 %	0.63 dB
Indium - In	75.27 %	87.70 %	0.66 dB
Tantalum - Ta	75.08 %	87.61 %	0.67 dB
Lead - Pb	73.10 %	86.54 %	0.73 dB
Titanium - Ti	63.81 %	81.13 %	1.04 dB
Stainless Steel	59.45 %	78.37 %	1.20 dB

Table 5: The design frequency is 2450 MHz. Substrate $\epsilon_r = 2.6$ with $H_1 = 1575\ \mu m$. The metal cladding thickness is 17 μm

are used, conductor losses dominate the overall non-radiation losses. As the magnetic permeability is increased, so are the conductor losses. The dielectric losses decrease slightly as the permeability is increased. The surface wave losses are low, but vanish when iron ($\mu_r = 4000$) is used for patch and groundplane conductors.

When a dielectric cover (radome) of optimum thickness to maximize microstrip antenna radiation efficiency is introduced, the efficiency is enhanced for all cases; but over the conductivity range studied, only increases the efficiency from 0.36 dB to a maximum of 1.20 dB. What is of interest is that the dielectric loss component becomes essentially constant over the conductivity range studied. This suggests that with the surface wave component minimized by the choice of radome, the dielectric loss becomes the intrinsic dielectric loss of the microstrip antenna. The dielectic loss is also constant for two of the three paramagnetic materials analyzed with a radome present. The radiation efficiency increase seen with an optimal radome is substantial for the paramagnetic materials, ranging from 2.10 to 3.15 dB.

A Appendix: Properties of Metals Studied

Table 1 lists the metals studied from highest to lowest electrical conductivity. The first four metals listed, Silver, Copper, Gold, and Aluminum are all commonly used metals. Silver has the highest conductivity of all metals. It is not a very reactive metal, and even when red hot does not react with air. Sulfur, and its compounds, will react with silver in the presence of air and tarnish it.

...

Copper is ubiquitously used in electronics, and for RF/Microwave applications. Copper forms a brown-black oxide, reacting with oxygen in the air. This layer of oxide protects the metal from further oxidation. Recent research indicates this oxide layer might have a significant effect on the Q of resonant cavities.[3]

...

Gold has the desirable properties that it is both electrically and thermally conductive, and also the most corrosion resistant of all metals.

...

Aluminum has the advantage that it is light-weight. Table 6 has a comparison of the densities of silver, copper, gold, and aluminum. It is clear that aluminum is much less dense than the others, and three times less dense than copper.[‡] Aluminum also forms an oxide layer which protects the metal from further corrosion. A drawback of aluminum is that it is not readily solderable.

Metal Density Comparison

Metal	Density
Aluminum	2.80 g/mL
Copper	8.93 g/mL
Silver	10.49 g/mL
Gold	19.30 g/mL

Table 6: Densities of four common metals used in electronics

Zirconium is a metal that in powdered form is quite flammable, when solid, less so. Zirconium is very corrosion resistant, and often used in alloys that are exposed to aggressive environments. Zirconium is frequently used in space vehicles where heat resistance is important.

...

Magnesium is mostly of academic interest, as it is highly flammable. Its conductivity is high enough that only about a 1% extra loss occurs for a patch made with aluminum versus magnesium.

...

Rhodium is hard and durable and does not normally form an oxide. It is also one of the rarest elements. Rhodium's conductivity is high enough that its losses are only about 3% worse than when the square patch antenna uses silver conductors.

...

Tungsten has the highest melting point of all the elements. It is difficult to work unless it is very pure. It has the highest tensile strength of all known metallic elements. Tungsten has the lowest coefficient of expansion of any pure metal. It is also chemically very non-reactive. It has a high density of 19.25 g/mL, which is near that of gold.

...

Molybdenum has a very high melting point. It has little to recommend it for an antenna engineering application, and is comparable to brass, which

[‡] 1 mL of water has a mass of one gram

is a much more available material.

...

Zinc is often used as an anti-corrosion agent to coat iron or steel. It does not find common use in electronics.

...

Brass is an alloy of copper and zinc. It can be soldered with ease, and has a hardness that is higher than copper alone. It is more brittle than copper.

...

Bronze is an alloy of copper and tin. It does not find much use in the electronics world.

...

Palladium finds use in consumer electronics for capacitor electrodes. Its conductivity is comparable to bronze.

...

Platinum's electrical performance is essentially identical to palladium. It is chemically very non-reactive, and has exceptional resistance to corrosion.

...

Tin is a fairly soft metal. It is resistant to corrosion by water. Tin forms a protective oxide layer that prevents further oxidation of the metal below. Tin has ten stable isotopes, the most of any element. Oxides of tin (and indium) are conductive, and also optically transparent.

...

Chromium is an extremely hard metal which resists corrosion by forming a thin protective layer of oxide. It can react with nitrogen in the air and become brittle.

...

Indium is a soft metal that can easily be cut with a knife.

...

Tantalum is a dark blue-grey metal that is very hard, readily fabricated, and a good conductor of both heat and electricity. It is also highly resistant to acids. It is generally used to produce tantalum capacitors for electronics.

...

Lead is also soft, and tarnishes when exposed to air, but is relatively non-reactive. It is also toxic.

...

Titanium has a density between that of aluminum and copper. It has the highest strength to density ratio of any metallic element. It has a 60% greater density than aluminum, but is more than twice as strong. Titanium is also very corrosion resistant. Titanium immediately oxidizes when exposed to air (like aluminum and magnesium) producing titanium dioxide. It immediately forms a 1-2 nm layer of oxide, which increases to about 25 nm in four years. This layer protects titanium like aluminum's passivation layer does.

...

Stainless Steel is a corrosion resistant alloy of iron which typically has a minimum of 11% chrominum. Stainless steel also produces a passive film that protects the alloy below from corrosion. This is due to the added chrominum, which also self-heals when abraded with oxygen present.

References

[1] Bancroft, R. "Microstrip Antenna Efficiency and Surface Wave Loss" *IEEE Transactions on Antennas and Propagation* VOL. 69, NO. 8, August 2021, pp 5032-5035

[2] Bancroft, R. "Dielectric Covered Microstrip Antenna Efficiency and Surface Wave Loss" Offered on Randwulftech.com as an open access paper.

[3] Park, J.H. and Park, J.G. "Uncertainty analysis of Q-factor measurement in cavity resonator method by electromagnetic simulation" *SN Applied Sciences* April 2020