Small Loop Antenna Simulations

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***Abstract*— A discussion on the results of Momentum simulations on small loop antennas.**

I. INTRODUCTION

A previous technical note [1] discussed closed form calculation of small loop antennas. In this technical note we detail the characteristics of these loops when studies in Agilent's Momentum 2.5D EM simulator (contained in the ADS package).

II. LOOP IN FREE SPACE

A. Port Characteristics

First, a 6-mm loop antenna in free space was simulated in Momentum. As with the structure studied in [1] a square 6-mm (on a side) single winding loop with a trace width of 400 μm a thickness of 3 μm and a gap of 300 μm was simulated. An illustration of the physical and electrical characteristics of the antenna under study is given in Fig. 1.

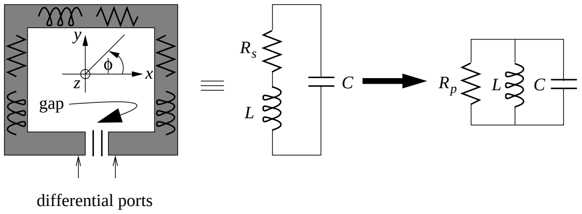

Fig. 1. Physical and electrical characteristics of the loop antenna under study.

An S-parameter simulation in Momentum using differential ports calculates the S_{11}. This measure can be used to find the effective impedance of the antenna via

$$Z_{in} = \frac{1}{Y_{in}} = Z_0 \frac{1+S_{11}}{1-S_{11}} \tag{1}$$

where Z_0 is the impedance of the ports driving the loop (out of deference to tradition we usually choose $Z_0 = 50\ \Omega$, but the actual choice does not matter as long as it is properly accounted for in the extraction equations like the above).

The parallel equivalent resistance is obtained with

$$R_p = \frac{1}{\text{Re}\{Y_{in}\}}. \tag{2}$$

And the inductance and capacitance are found through

$$L = \frac{\omega}{\text{Im}\{Y_{in}\}} \left(\frac{1}{\omega_0^2} - \frac{1}{\omega^2} \right) \tag{3}$$

and

$$C = \frac{\text{Im}\{Y_{in}\}\omega}{\omega^2 - \omega_0^2} \tag{4}$$

where ω_0 is (angular) resonant frequency, and is obtained from simulation, by noting the frequency at which a resonant peak occurs (for $|Z_{in}|$) around the frequencies of interest (only frequencies from 2.5 GHz to 10 GHz were swept). For a loop antenna in free-space, the resonant frequency, f_0, occurs at 7.25 GHz (again from simulation).

The series resistance, R_s, which is the sum of the radiation resistance, R_r, and the loss resistance R_l is obtained from

$$R_s = \frac{R_p}{Q^2+1} \tag{5}$$

where the quality factor is calculated with

$$Q = \frac{R_p}{\omega L}. \tag{6}$$

A summary comparison of the calculated and simulated results is given in Table I. A fair agreement is present except for the factor-of-two disparity between the L values (and hence the derived Q results). It is likely, that there is a flaw in the L calculation rather than the value extracted from simulation. Also, the resistance simulated for the free-space loop at 10 GHz is twice as high as the calculation. No reasonable explanation for this is available at the moment.

TABLE I

CIRCUIT CHARACTERISTICS OF 6-mm COPPER LOOP ANTENNA ($w = 400\ \mu m$, $t = 3\ \mu m$) IN FREE SPACE

	f_0 [GHz]	$R_r + R_l$ [Ω]	Q	L [nH]	C [fF]
Calculation (Free Space)	2.50 5.50 10.0	1.05 5.60 46.4	326 135 29.5	21.8 21.8 21.8	- - -
Simulation (Free Space)	2.50 5.50 10.0	1.04 5.18 91.5	211 88.0 6.91	14.0 13.2 10.3	34.5 36.5 46.9

B. Radiation

Before jumping into a discussion of the radiation parameter results, it should be noted that radiation simulations become grossly inaccurate (e.g. predicting $\eta = 100\%$ at 5.5 GHz) when the ports are directly applied to the structure as shown in Fig. 1. The ADS Momentum manual warns the user of potential problems when feeding into discontinuities of the type present in Fig. 1 (i.e. transmission lines immediately perpendicular to the feeding ports).

For such simple structures, the remedy is straightforward: feed the antenna with a sufficiently long transmission line such that the simulator can more easily account for the oddity at the feeding point. In this case, rather then being abutted directly at the input (again, as in Fig. 1) the probes were applied to the structure through two 3-cm long (quarter wavelength for a

Many thanks to the friends of FishLab.

TABLE II
RADIATION CHARACTERISTICS OF 6-mm COPPER LOOP ANTENNA
($w = 400\ \mu m, t = 3\ \mu m$) IN FREE SPACE

	f_0 [GHz]	η [%]	G [dB]	θ [deg]	ϕ [deg]
Calculation (Free Space)	2.50 5.50 10.0	18.4 78.9 96.6	-5.60 +0.70 +1.50	- - -	- - -
Simulation (Free Space)	2.50 5.50 10.0	19.6 80.2 99.6	-10.9 3.39 4.72	-90 -90 -166	90 90 90

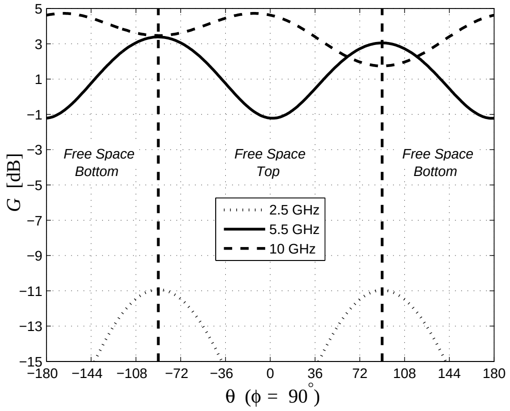

Fig. 2. The gain of the 6-mm loop entirely in free-space.

2.5-GHz signal in free space) microstrip lines (with the same width, thickness, and resistivity as the antenna proper). When calculating the results eventually recorded in Tables I and II the effects of these feeding microstrip line were calibrated out (automatically and painlessly within Momentum).

Now, returning to our simulation results, Table II the pertinent behaviors. The azimuth angle, ϕ is as indicated in Fig. 1, the elevation angle is θ and starts at the x-axis (increasing on its way down to the cut-plane defined by ϕ). A plot of the gain versus θ (for $\phi = 90°$) is shown in Fig. 2.

The simulation results do not differ markedly from the calculations aside from the gain which is more optimistic in simulation by over 3 dB (not, however, at 2.5 GHz). It is possible that the (maximum) gain calculations were made for the wrong direction. Also interesting is the simulated direction of maximum gain (perhaps pointing to the core of the problem in the calculations).

For 2.5-GHz and 5.5-GHz oscillations the maximum gain is in the plane of the antenna ($\theta = -90°$ defines the direction “below” the antenna, that is into the page with reference to Fig. 1). This is clear from Fig. 2 where, at 5.5 GHz, a 4-dB drop in gain in available power is experienced for signals perpendicular to the coil plane (relative to signals parallel to the coil plane).

At 10 GHz, the situation is changed somewhat. From Table II we see that maximum gain is achieved at $-166°$. Also, a nearly identical gain is available at $\theta \approx -10°$. Overall, the loop at 10 GHz is closer to an isotropic radiator than at the two lower frequencies considered.

TABLE III
CIRCUIT CHARACTERISTICS OF 6-mm COPPER LOOP ANTENNA
($w = 400\ \mu m, t = 3\ \mu m$) ON GLASS

	f_0 [GHz]	$R_r + R_l$ [Ω]	Q	L [nH]	C [fF]
Calculation (Free Space)	2.50 5.50 10.0	1.05 5.60 46.4	326 135 29.5	21.8 21.8 21.8	- - -
Simulation (No Loss Glass)	2.50 5.50 10.0	1.00 10.8 211	216 35.7 0.67	13.7 11.2 7.27	65.7 80.7 124

III. LOOP ON LOSSLESS GLASS

We now move towards a more realistic consideration of the antenna, one resting on a lossless glass substrate with relative permittivity $\epsilon_r = 4$, zero loss tangent, and a thickness of 700-μm.

A. Port Characteristics

The port characteristics of the 6-mm loop resting on the glass substrate (compared to free space calculations) are given in Table III. The resonant frequency of the antenna occurs at 5.3 GHz.

A striking result from the simulations is the substantial series-equivalent resistance ($R_r + R_l$) increase at 5.5 and 10 GHz. At 10-GHz especially, the antenna has quite a high resistance (as impedances in the RF-world go). For these frequencies, we apparently have some leeway to reduce size. Also, as frequencies go up and antenna size is kept constant it may be wise to check for resonance harmonics.

B. Radiation

The radiation characteristics of the loop antenna sitting on glass are summarized in Table IV and Fig. 3. All gain values plummet at the boundary of the free-space and glass regions, a relic of the Momentum simulation which assumes that the glass substrate extends to infinity in all directions. Clearly, for a finite substrate the gain will not be negligible in the plane of the loop, however exactly what it will be is not possible from this simulation.

Perhaps the most significant difference between the free-space and glass antenna simulations is the overall degradation of the efficiency in the latter. Although comparable at 2.5 GHz, the on-glass antenna seems to saturate at about a 64% efficiency by 5.5 GHz, far short of the 99.6% efficiency simulated for the 10-GHz loop surrounded by free-space.

At 2.5 GHz there is little difference between the (simulated) loop antenna in free space and the one implemented on glass other than the fact that the maximum gain of the on-glass loop exceeds the free-space loop by 2-dB.

Also, the gain performance of the antenna at 10 GHz on glass is similar to its behavior in free-space albeit with a lower gain (on glass). As was the case for the free-space antenna the maximum gain occurs perpendicular to the loop at 10 GHz.

As is apparent from Fig. 3, the on-glass loop at 5.5 GHz is rather close to an isotropic radiator with only about a 1-dB variation in gain (ignoring the glass/space boundary region).

TABLE IV

Radiation Characteristics of 6-mm Copper Loop Antenna

($w = 400\ \mu m, t = 3\ \mu m$) on Glass

	f_0 [GHz]	η [%]	G [dB]	θ [deg]	ϕ [deg]
Calculation (Free Space)	2.50	18.4	-5.60	-	-
	5.50	78.9	+0.70	-	-
	10.0	96.6	+1.50	-	-
Simulation (No Loss Glass)	2.50	18.2	-9.00	106	90
	5.50	64.3	0.66	-127	90
	10.0	64.4	3.02	-175	90

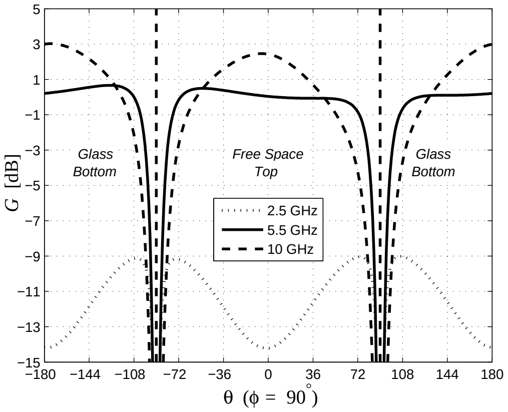

Fig. 3. The gain of the 6-mm loop on glass.

References

[1] S. Magierowski, “Small loop antenna calculations,” Tech. Rep., June 6 2007.

[2] S. Magierowski, “Basics of antenna power transfer,” Tech. Rep., June 2 2007.