Small Gap-Resonated HF Loop Antennas

Improved formulas for the loop current lead to an accurate determination of close-near fields, far-field null depths, and antenna efficiency.

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The small gap-resonated, high-frequency circular loop antenna has received much attention in Amateur Radio since John H. Dunlavy, Jr., patented[1] his efficient small loop that can be tuned over wide bandwidths. The now-expired patent spawned a multitude of homebrew loops and several commercial products aimed at hams. Loop studies and analyses date back more than a century to the earliest days of radio. The July/August 2018 loop antenna themed issue of *QEX*[2] features articles from several authors who investigate the patterns, efficiency, matching, coupling to ground, and other aspects of small HF gap-resonated loops.

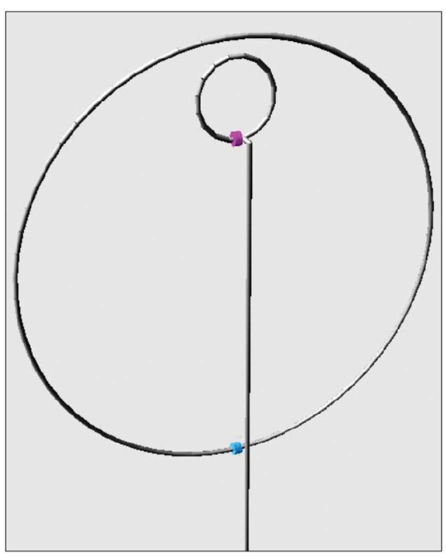

Figure 1 — The electrically small HF loop includes a main loop and a secondary feeding loop, both in the same zx-plane, and a coaxial cable feed line also in the zx-plane, but slightly displaced in the y-axis, so that the cable does not touch the bottom of the main loop. A resonating capacitor connects across a gap at the bottom of the main loop.

Here, we show the effects of loop current variation along the loop circumference, the loop impedance, and the effects of the secondary feeding loop in general terms. We provide details about the loop near fields and far-field null filling that are a direct result of considering a non-uniform loop current. We also find the effect of loop currents coupling to a coaxial feedline shield and loop coupling to the ground, as well as determine the loop efficiency.

Small Loop Currents and Fields

Figure 1 shows the circular loop rendered in *4nec2* software. The primary loop radius is $b = 0.4534$ meter, the loop wire radius is $a = 0.00406$ meter, and the angular extent along the loop circumferences is ϕ, with the loop gap at $\phi = 0°$. The resonating capacitor, with a $Q_c = 2{,}400$ in our model, connects across the gap at the bottom of the primary loop. The secondary feeding loop radius is $b_2 = 0.077$ meter and the conductor radius is $a_2 = 0.002$ meter. A coaxial cable feed connects across a gap at the bottom of the smaller secondary loop. The loop centers are displaced by 0.343 meter. Our loop dimensions closely match those of the AlexLoop[3] antenna by Alex Grimberg, PY1AHD.

The Dunlavy Loop Patent

John Dunlavy discovered that a one-turn primary (main) loop antenna having a circumference of less than ⅜ of a wavelength and interrupted along its length by a gap, with a tuning capacitor connected across the gap, can be tuned over a wide tuning range. A single-turn secondary (feeding) loop, much smaller than the primary loop, is inductively coupled to the primary loop. Both loops are in the same plane. The secondary loop diameter is selected to bear an optimum relationship to the diameter of the primary loop so that variation in feed impedance is minimized over the band of operation. A low impedance transmission line (50 Ω) connects to the terminals of the secondary loop.

Here, we sparingly included only the critical formulas. The full set of equations and details are available in *QEX*,[4] and at **www.arrl.org/qst-in-depth**.

Loop Current

The loop current, which is usually assumed constant, is actually a Fourier series in cos($n\phi$) terms along the loop circumference angle ϕ. We retained just the first two terms — a constant and the cos(ϕ) term. The critical result here is that the current around the circumference of the loop is not the constant (I_0) assumed in previous articles, but varies along the circumference with angle ϕ,

$$I(\phi) = I_0\left\{1 - 2C_\lambda^{\,2}\cos(\phi)\right\} \qquad \text{[Eq. 1]}$$

where C_λ is the loop circumference in wavelengths. This instantly reveals that the current amplitude variation term depends solely on the loop circumference in wavelengths. Figure 2 shows the current along the circumference of our loop at 7, 14, and 30 MHz. The loop current [Eq. 1] is valid for $C_\lambda < 0.3$, and is used to solve for the loop fields in classical fashion.

Loop Fields

Any good electromagnetics text[5] describes how the electric and magnetic fields can be found everywhere in space once you know the currents on the loop. We solved for the fields in *Mathcad* software, and validated those analytical results with completely independent simulations in an NEC model using *4nec2* software[6] (see the **www.arrl.org/qst-in-depth** web page).

> *"In practice, the best match is accomplished by adjusting the main loop resonating capacitor."*

Small Loop Impedance

The main loop impedance with just radiation loss is:

$$Z_{loop} = [\text{Radiation Resistance}] + j[\text{Loop Reactance}] \qquad \text{[Eq. 2]}$$

and the [Loop Reactance] is tuned by the capacitor across the loop gap. The loaded radiation Q_{rad} of the antenna is:

$$Q_{rad} = \frac{1}{2}\frac{\text{Loop Reactance}}{\text{Radiation Resistance}} \qquad \text{[Eq. 3]}$$

The primary loop loss resistance R_{loss} includes the main loop conductor losses. The capacitor Q_c contributes to losses in the form of parallel resistance across the capacitor. The net loaded Q_L of the antenna is:

$$Q_L = \frac{0.5}{\dfrac{1}{Q_C} + \dfrac{[\text{Radiation Resistance}] + R_{loss}}{[\text{Loop Reactance}]}} \qquad \text{[Eq. 4]}$$

from which we can find the loop radiation efficiency *eff* as:

$$eff = \frac{Q_L}{Q_{rad}} = \frac{[\text{Radiation Resistance}]}{R_{total}} \qquad \text{[Eq. 5]}$$

The value of Q_L can be obtained from [Eq. 4] or from direct measurements. For convenience, we represent the total series-equivalent loss resistance, including the capacitor loss and radiation resistance, by R_{total}.

The Secondary Feeding Loop

The main and feeding loops are coupled by mutual inductance M_{12}, which is 57.3 nH for our loop, obtained using the Jordan and Balmain[7] high-frequency extension to the Neumann formula (see the **www.arrl.org/qst-in-depth** web page).

The main loop impedance, including the tuning capacitor, is transformed to the feed-point impedance at frequency f by

$$Z_{feed} = \frac{(2\pi f M_{12})^2}{R_{total} + j\Delta} + j2\pi f L_{feed} \qquad \text{[Eq. 6]}$$

based on the circuit model[8] of Milton Cram, W8NUE. Cram points out that the feed-point reactance is not zero when the main loop is resonant because of the feed-loop inductance L_{feed} term, which equals 0.361 µH for our antenna. To compensate for this inductance, we simulated tuning of the main loop by choosing a Δ at each frequency for a best match to 50 Ω. In practice, the best match is accomplished by adjusting the main loop resonating capacitor.

Figure 3 illustrates that the load resistance presented to the coax feed line

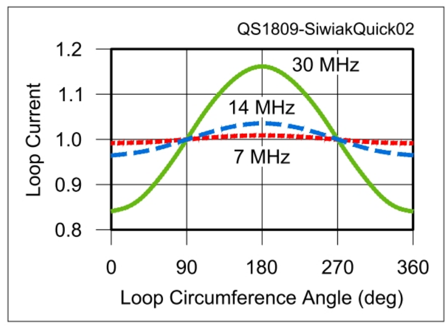

Figure 2 — Loop currents at 7, 14, and 30 MHz along the loop circumference vary in amplitude due to the inclusion of a Fourier series expansion term.

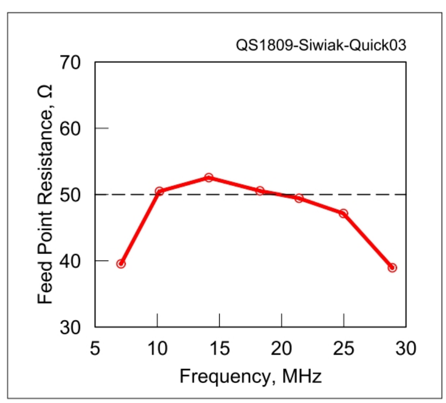

Figure 3 — The resistance presented to the coax feed line is not much different from 50 Ω across the entire tuning and operating range of this loop.

> "The secondary loop diameter and location bear an optimum relationship to the diameter of the primary loop so that variation in feed impedance is minimized over the band of operation."

stays close to 50 Ω across the full operating range of this loop, and illustrates a key characteristic taught by the Dunlavy patent. The feed-loop diameter and location bear an optimum relationship to the diameter of the main loop so that variation in feed impedance is minimized over the band of operation.

Loop Center, and the Far-Field Null

Because our loop current term *varies* with ϕ, we find a non-zero electric field E_{center} and the magnetic field H_{center} at the loop center — see the **www.arrl.org/qst-in-depth** web page, and a *QST* article[9] from the July 2015 issue. The wave impedance Z_W at the loop center is a measure of how well the loop discriminates between the electric and magnetic fields and is:

$$Z_W = \frac{E_{center}}{H_{center}} = -j\eta_0 C_\lambda \qquad \text{[Eq. 7]}$$

where η_0 =376.7 Ω. [Eq. 7] clearly reveals the dependence of Z_W on the loop circumference. Had we omitted the current variation, both E_{center} and Z_W would be erroneously reported as zero!

We introduce a simple formula for the far-field peak-to-null ratio, which depends on the current variation term in a simple way for $C_\lambda < 0.3$:

$$N_{dB} = -20\log(2C_\lambda) \qquad \text{[Eq. 8]}$$

Figure 4 shows the null depth across 7 to 30 MHz using the [Eq. 8] formula, a detailed loop near-field analysis in *Mathcad*, and the null simulated by the NEC model. The formula and analysis use the two-term [Eq. 1] current formula, and show signs of losing accuracy around 30 MHz, which indicates that additional Fourier terms are needed above 30 MHz.

The null becomes shallower as the frequency increases for a fixed-size loop. At $C_\lambda = 1$, we have the familiar full-wavelength loop with its peak broadside directional gain of about +4 dBi.

Common-Mode Coupling to the Coax Feed Line

An unbalanced coaxial cable feeds the smaller secondary loop directly, so there is opportunity to generate common-mode currents (CMC) on the coax feed line. We varied the length of the coax in our NEC model, and searched for the maximum current on the coax cable shield, just like on a previous study involving CMC on the feed line to a dipole.[10] We found that the maximum CMC occurs for a coaxial feed-line length of 0.45 λ. We therefore recommend that common-mode chokes (clamp-on ferrites) should be installed on the feed line at least a loop diameter away from the loop, and then at intervals of less than about 0.3 wavelength (at the highest operating frequency) thereafter.

Vertical Loop Coupling to the Ground

We estimated the loop coupling to the ground by finding the mutual inductance *M* between the main loop and its image in the ground, normalized to the loop self inductance L_1. This coupling affects the impedance of the loop antenna system, which is quite distinct from the ground reflections that affect the antenna elevation patterns. We calculated the coupling for a perfect electric conductor (PEC) ground, and then estimated the effects over "average" and "poor"

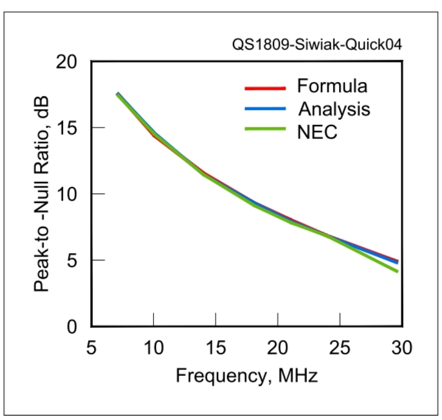

Figure 4 — The null depth steadily decreases across the 7 to 30 MHz operating band. Omitting the current variation term would result in an erroneous infinite null depth.

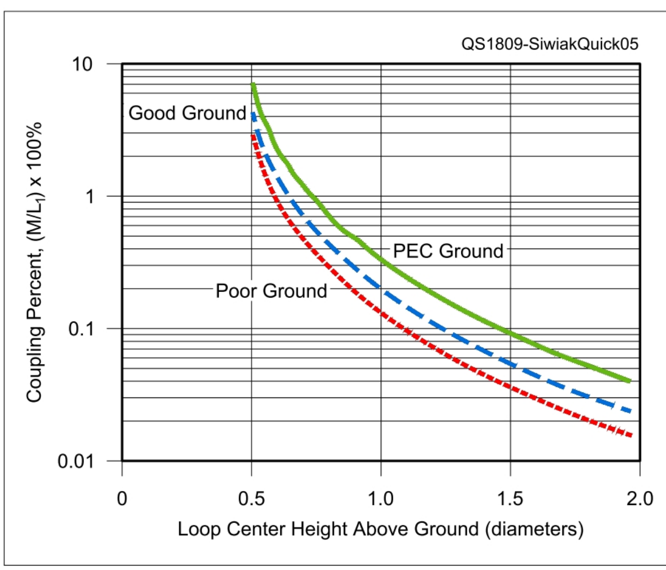

Figure 5 — The percent coupling to ground for this small HF loop is very small when the loop center is at least one loop diameter above the ground. Coupling is strongest for a PEC ground, and decreases significantly for realistic grounds.

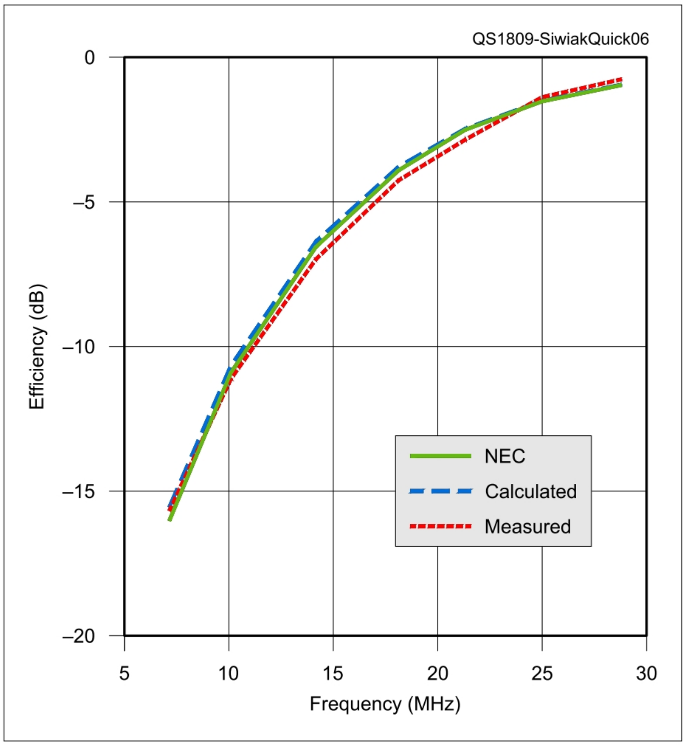

Figure 6 — Small loop efficiency simulated in NEC (solid), calculated from loop equations (long dashes), and measured using the Q method (short dashes). The close agreement among three methods validates the analysis, the Q measurements, and the completely independent NEC model.

grounds by reducing the PEC ground coupling by the magnitude of the refection coefficient for normal incidence on the ground. The reflection coefficient magnitude is 1.0 for the PEC, 0.6 for the "average" ground, and 0.4 for "poor" ground at 14.1 MHz (see Figure 5). Even for a worst-case PEC ground, the coupling is less than 0.4% for a loop, with its center more than one loop diameter above ground.

Efficiency of the Small Loop

We compared three methods to estimate the radiation efficiency of the small loop. In one calculated method, we determined the total Q_L using [Eq. 4] and compared that to the Q_{rad} from [Eq. 3], and then applied [Eq. 5] for the efficiency.

In a second method, we measured Q_L using a matched transmitter, and the classic bandwidth formula:

$$Q_L = \frac{\sqrt{F_H F_L}}{F_H - F_L} = \frac{\text{Frequency}}{\text{Bandwidth}} \qquad \text{[Eq. 9]}$$

where F_H and F_L correspond to the 2.62:1 SWR points on each side of the center frequency.

Finally, we used the completely independent NEC model to simulate efficiency. Figure 6 shows that all three methods of determining efficiency are within 0.5 dB of each other across 7 to 29.7 MHz, inspiring confidence in all three methods.

Conclusions

Our improved formulas for the small HF loop current and loop impedance are needed to adequately describe loops up to at least 0.3 wavelength in circumference. The improvements result in simple and accurate expressions for fields at the center of the loop, for the far-field null depth, and for loop antenna efficiency.

Notes

[1]J. H. Dunlavy, Jr., "Wide Range Tunable Transmitting Loop Antenna," *US Patent 3,588,905*, issued June 28, 1971.
[2]Loop Antenna Issue, *QEX*, July/Aug. 2018.
[3]P. Salas, AD5X, "Short Takes: The AlexLoop Walkham Portable Antenna," *QST*, Nov. 2013, p. 67.
[4]K. Siwiak, KE4PT, and R. Quick, W4RQ, "Small Gap-resonated HF Loop Antenna Fed by a Secondary Loop," *QEX*, July/Aug. 2018, pp. 12 – 17.
[5]E. C. Jordan and K. G. Balmain, Chapter 10, *Electromagnetic Waves and Radiating Systems*, Second Edition, 1968, Prentice–Hall, Inc., Englewood Cliffs, NJ.
[6]The *4nec2* NEC-based antenna modeler and optimizer, by Arie Voors, **www.qsl.net/4nec2**.
[7]E. C. Jordan and K. G. Balmain, Section 14.16, p. 598, op. cit.
[8]M. E. Cram, W8NUE, "Small Transmitting Loop Antennas: a Different Perspective on Determining Q and Efficiency," *QEX*, July/Aug., 2018, pp. 3 – 8.
[9]K. Siwiak, KE4PT, "Near Fields of an Electrically Small Loop Can Affect Direction Finding" (Technical Correspondence), *QST*, July 2015, pp. 63 – 64.
[10]R. Quick, W4RQ, and K. Siwiak, KE4PT, "Does Your Antenna Need a Choke or a Balun?," *QST*, Mar. 2017, pp. 30 – 33.

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Richard Quick, W4RQ, is a retired Electronics and Metrology Engineering Technician. He was first licensed in 1977, and now holds an Amateur Extra-class license. Richard is a member of ARRL. He has built and tested several small-loop transmitting antennas, studying the effects of using various materials and components, and has modeled them using Numerical Electromagnetic Code. Richard has co-authored the *QST* articles "Does Your Antenna Need a Choke or Balun?" (March 2017) and "Live Trees Affect Antenna Performance" (February 2018). Richard enjoys operating at low power levels and from portable locations. He is an avid CW operator. You can reach Rich at **w4rq@arrl.net**.

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