

Analysis and Design of FSL Antennas

Open Source Hardware Engineering

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A relatively new and popular antenna design uses a large number of ferrite rods arranged as shown in figure 1. These are often called *ferrite sleeve loops* or FSLs for short. A lot of qualitative praise is given to such antenna designs, but there is a dearth of quantitative measurement, or theoretical analysis on the topic. This article endeavors to add some much needed theoretical background to the topic, and methods for predicting the performance of FSL antennas.



Figure 1: A typical FSL antenna

Introduction

A more comprehensive report has been published, containing all of the information in this article, and a lot more about electrically small loop antennas here:

<https://www.osengr.org/Articles/Loop-Antennas.pdf>.

This article contains a small amount of background material to aid in understanding the analysis. Much more detail and background material can be found in the above referenced report.

All of this applies only to electrically small loop antennas. The dimensions of the antenna, and the length of wire used to build the antenna are assumed to be small compared to the wavelength of a radio signal at the frequency of operation.

Effective Height

A key parameter used to characterize antennas is *effective height*, denoted here by the symbol h_e . It quantifies the ability of the antenna to convert a radio signal – electromagnetic wave or EM wave – into a voltage. The open circuit voltage generated by an antenna is simply equal to the effective height (e.g. in meters) multiplied by the electric field strength of the radio signal (e.g. in volts per meter).

$$V_{oc} = h_e E$$

A radio signal with an E-field strength of $100\mu\text{V}/\text{m}$ applied to an antenna with $h_e = 1\text{m}$ will produce an open circuit output voltage of

$$V_{oc} = 1\text{m} \times 100 \mu\text{V}/\text{m} = 100\mu\text{V}$$

For the purposes here, it's not necessary to know the electric field strength of the signal. Knowing that an antenna with twice the effective height produces twice the voltage is the important thing.

Loop antennas actually respond to magnetic, not electric fields. However, it is customary to characterize the performance with respect to the electric field strength. Formulas for effective height include a conversion from electric to magnetic field strengths¹.

When a loop antenna is resonated, the output voltage is increased by the Q of the tuned circuit. Resonant performance is an important but complex subject. While it is touched on in this article, a more complete discussion can be found in the larger report referenced in the introduction.

Ferrite Materials

A second piece of useful background is a rudimentary understanding of how ferrite rods increase the voltage produced by a loop antenna, as a function of their lengths and diameters.

Ferrite materials have an intrinsic permeability, μ_i , which is an indication of how much they can magnify or amplify magnetic fields. This is a frequency dependent property of the ferrite material which is specified by the manufacturer, and does not depend on the shape of a ferrite component. Ferrite materials are available with a wide range of permeability, from 50 or less all the way up to 10,000.

Ferrite has a frequency dependent loss, which is often negligible at low frequencies, and increases with frequency. The frequency above which losses become significant is generally lower with higher values of μ_i .

¹An EM wave propagating in free space (or air) has a fixed ratio between electric and magnetic field strengths, so knowing one allows computation of the other.

Ferrite Rod Antennas

When a ferrite rod is inserted inside a coil, the voltage induced by a radio signal in the coil will increase. The ratio of open circuit voltage with and without the ferrite rod present is an important parameter, called apparent permeability denoted here as μ_{rod} .

The parameter μ_{rod} is a function of the initial permeability of the ferrite material (μ_i), and the ratio of rod length to diameter, aka l/d , aka aspect ratio. It does not depend on the absolute dimensions of the rod. Figure 2 shows the relationship between these parameters. A separate curve is plotted for several values of μ_i between 125 and 10,000.

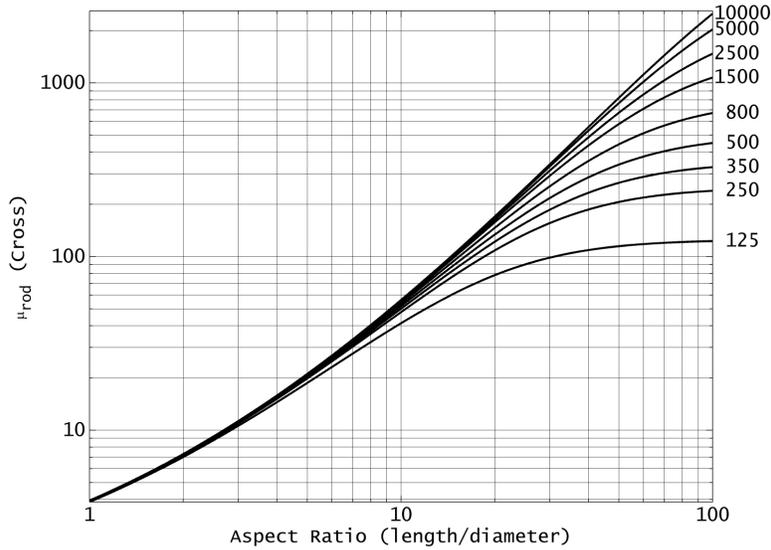


Figure 2: Chart for predicting μ_{rod}

- The chart covers impractical aspect ratios as high as 100:1 only to show the general behavior of the μ_{rod} parameter.
- For large but practical aspect ratios in the range of 10-20 or so, the initial permeability is significant.
- For very small aspect ratios (e.g. less than 5), μ_{rod} is fairly insensitive to μ_i .
- High performance ferrite rod antennas will have μ_{rod} values of 50 to 100 or more.

Calculating h_e

Here is a formula for computing the effective height of a ferrite rod loop antenna:

$$h_e = \beta A n \mu_{rod}$$

- β is the phase constant, equal to the phase shift in the radio signal per unit of distance travelled. That's $2\pi f/c$, where f is the frequency in Hertz, and c is the speed of light

in meters per second. It has units of radians per meter. Because β depends on frequency, take care when comparing effective heights at different frequencies – it’s a bit like comparing apples to oranges.

- A is the cross-sectional area of the ferrite rod ($A = \pi/4 d^2$) with d being the rod diameter. If the antenna is air cored, then d is the inside diameter of the coil.
- n is the number of turns of wire in the coil.
- μ_{rod} is graphed in figure 2 for ferrite rod antennas, and equal to one for air core coils.

There are a lot more details, but this is enough background to proceed with the analysis.

Solid Rods

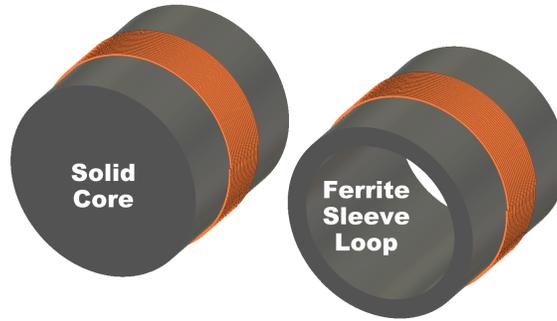


Figure 3: Solid rod versus ferrite sleeve

FSL antennas are mostly air-cored with a relatively thin ferrite sleeve upon which the coil is wound. To make things a bit simpler at first, it’s assumed there are no gaps between individual ferrite rods and that they form a solid sleeve. Replacing the sleeve with a solid rod would be expected to improve antenna performance, and the analysis of antennas built with a solid ferrite rod is straightforward.

The antenna pictured in figure 1 has a sleeve with an outside diameter of 147mm, and is 140mm long. Figure 3 shows the difference between a solid rod and the ferrite sleeve. Computation of effective height and other parameters is easily done in the case of a solid rod.

The example design considered here (figure 1) uses 36 rods, each with a 10x11mm rectangular cross section and 140mm long. The outside diameter of the sleeve is 147mm, and the rods have a specified permeability of $\mu_i = 800$. The sleeve is inserted into a 20-turn coil wound on a 168mm diameter form.

Consider an antenna using a solid ferrite rod with the same outer dimensions as the sleeve – 147mm in diameter and 140mm long. This is a big, fat, stubby rod, and its aspect ratio is tiny, $140/147 \approx 0.95$.

The value of μ_{rod} can be obtained from figure 2, but will be easier using Figure 4, which is another view of figure 2, zoomed in on small aspect ratios².

²These two figures are slightly different; the first one is based on formulas by Ray Cross (see the larger report), while the latter is generated from E-M simulations and may be a bit more accurate.

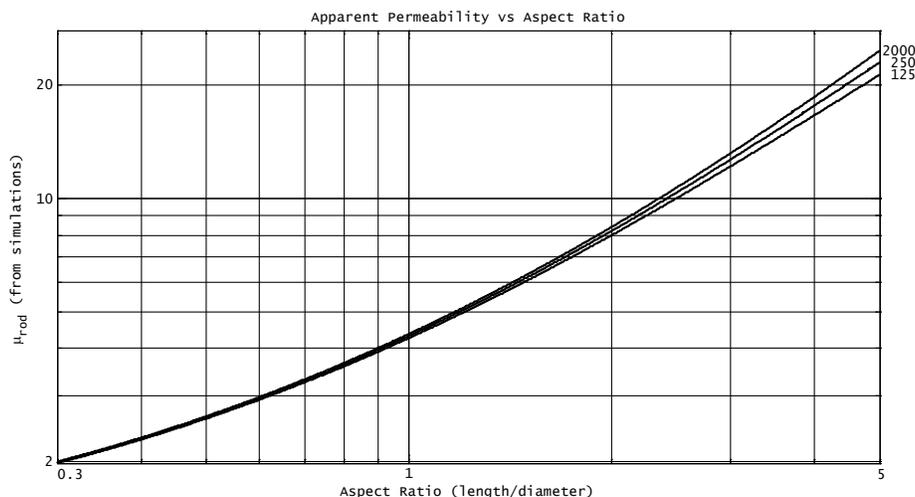


Figure 4: μ_{rod} for small aspect ratios

For the solid rod version of the antenna in figure 1, we've determined that $\mu_{rod} \approx 4.2$, but what exactly does this mean? It's time for a....

Reality Check

Wait. Hold the iPhone. We're talking about μ_{rod} values of a whopping 4.2 here. A high performance single rod design for would have a μ_{rod} value of 50 or more. This bears repeating.

Using a solid 7-inch diameter, 5-1/2 inch long ferrite core to build a loop antenna will only increase the output voltage by a factor of 4.2 (about 12dB), compared to an air core.

And the true benefit isn't even really *that* big. Without the ferrite core it would require more turns in the coil to get the same inductance, and that would reduce the effective benefit. On top of that, the coil is often wound on a form that's significantly larger in diameter than the ferrite sleeve, so the air core version picks up a bit more signal due to the increased diameter as well.

For the antenna pictured in figure 1, it was necessary to increase the turn count 50% to get the same inductance with the sleeve removed, and the coil form is 168mm diameter compared to the sleeve diameter of 147mm. In total, there is a 50% increase in effective height due to added coil turns, plus a 31% gain in area from the increased diameter, $(168/147)^2 \approx 1.31$. This is a total gain of $1.31 \times 1.50 \approx 2.0$ or 6dB, so the net difference between the solid rod and air core antennas is $4.2/2.0$ or about 6.4dB.

The Root Cause

While the ferrite rod does increase effective height, the actual improvement seems small, and you may be wondering why the benefit isn't larger. Well, it's the rod's aspect ratio of 0.95 that kills the apparent permeability (μ_{rod}) – go back and have a look at figure 4.

In a typical, ferrite rod antenna, the aspect ratio is usually at least 8-10 or so, and here it is only 0.95. To increase μ_{rod} from 4.2 up to a more respectable 25, we would need an aspect ratio of about 5:1, and that solid ferrite core would need to be 735mm (29 inches) long.

For the air core version of this antenna with the sleeve removed and a 30-turn coil, the effective height calculation is:

$$h_e = \beta A n \mu_{rod} = \left(\frac{2\pi \times 10^6}{3 \times 10^8} \right) \times \left(\frac{\pi}{4} \times 0.168^2 \right) \times 30 \times 1 \approx 0.014\text{m}$$

With the solid rod and a 20-turn coil, computations for the non-resonant effective height at 1MHz look like this:

$$h_e = \beta A n \mu_{rod} = \left(\frac{2\pi \times 10^6}{3 \times 10^8} \right) \times \left(\frac{\pi}{4} \times 0.147^2 \right) \times 20 \times 4.2 \approx 0.030\text{m}$$

The effective height of 30mm is roughly twice the 14mm height that would result from removing the solid core, and adding 10 more turns to the coil.

From Rod to Sleeve

So in reality it's not quite as bad as all that. Solid 147mm diameter ferrite rods aren't available, and they wouldn't be affordable even if you could find one. Not to mention that it would weigh about 35 pounds. So, let's hollow out the center of the rod, leaving behind only a thin sleeve, This can be approximated by a whole bunch of small rods laid out in a circular pattern, as in figure 1.

Removing material from the center of the solid ferrite core would be expected to reduce μ_{rod} , but the question is: by how much? This was investigated with several electromagnetic (E-M) computer simulations. The reduction in μ_{rod} resulting from removal of some percentage of the ferrite core area depends on both the l/d ratio and the value of μ_{rod} for the solid rod. In general we find that the lower μ_{rod} is with a solid core, the more material can be removed without reducing the permeability too much.

Figure 5 below shows this effect in two different ways. The x-axis on the two graphs is the percentage of original core area remaining in the sleeve for ferrite with $\mu_i=125$. This effect depends on the aspect ratio, so there are separate curves plotted for cores with l/d ratios of 0.8, 1, 2, 4 and 10.

The left side of figure 5, shows the reduction in permeability compared to a completely solid ferrite rod. The smaller the l/d ratio, the less effect there is if some of the core is hollowed out. That suggests small l/d ratios are good.

However, the graph on the right side of figure 5, showing absolute permeability values reveals that small l/d ratios have smaller values of μ_{rod} to begin with. It's not as helpful that you can hollow out the rod without losing much more. You already gave away the farm by choosing a small l/d ratio.

For the example antenna, the percent of remaining core area works out to about 27%,

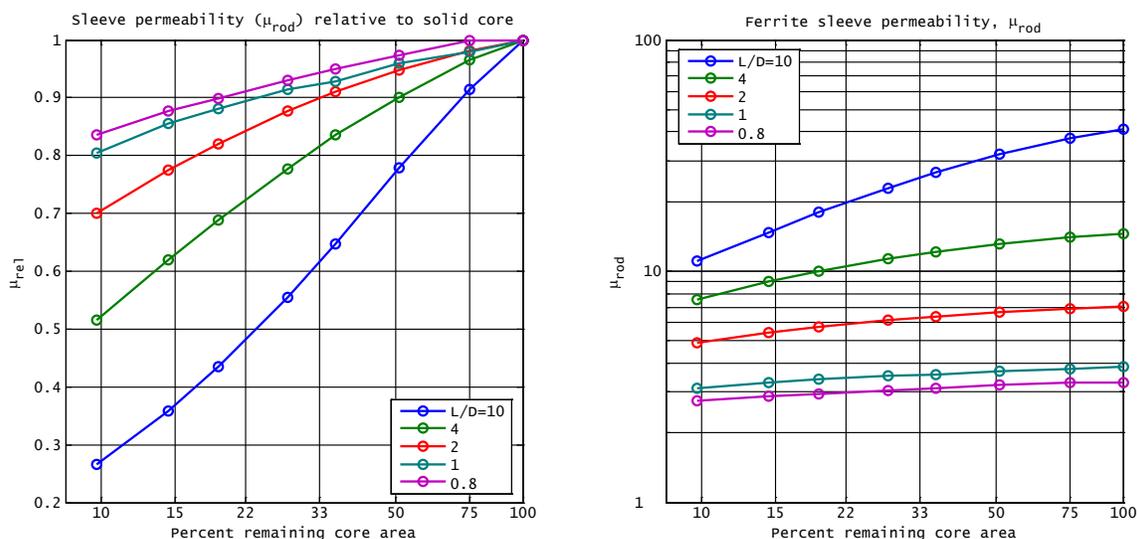


Figure 5: Ferrite sleeve permeability ($\mu_i=125$)

which results in $\mu_{sleeve} \approx 3.9$ for an initial permeability of five hundred³. This reduces the effective height from 30mm (solid rod) to 28mm (ferrite sleeve). Indeed, not much performance has been lost by removing 73% of the ferrite from the core of the solid rod.

Estimating μ_{rod} , aka μ_{sleeve}

The terms μ_{rod} and μ_{sleeve} are used interchangeably in this article, and μ_{sleeve} is sometimes used to make it clear that it refers to a sleeve, not a solid rod. However, μ_{rod} may be used to refer to a sleeve or solid rod depending on the context.

A set of simulation data and interpolation functions are detailed in the larger report mentioned at the beginning of this article. They provide estimates of μ_{sleeve} based on sleeve dimensions, and these tools were used to create the charts and values presented in this article.

An approximate idea of the apparent permeability can also be found by using figures 4 and 5. First, find μ_{rod} for a solid rod with the same outside dimensions as the sleeve, then use chart on the left side of figure 5 to estimate the reduction in μ_{rod} for the sleeve in question. These charts apply for ferrite materials with $\mu_i=125$, but will not be that far off for higher values of μ_i .

Rod and Bar compensation

So far, it's been assumed the ferrite sleeve is solid. Typically, the sleeve is comprised of either small diameter rods, or flat bars arranged on a large diameter circle. Some allowance should be made for the fact that there's less ferrite in this kind of construction than there

³Although the ferrite used had a specified permeability of 800, we suspect it is actually lower due to shock and vibration in shipping, perhaps in the range of 300-500, and that value was used in this calculation.

would be in a solid sleeve. The larger report discusses this compensation in more detail, but for the purposes here, these are minor adjustments.

Additional Factors

The length and position of the coil makes a difference in the overall output voltage. It's important to consider this for normal solid rod designs with typical aspect ratios (e.g. 5:1 or larger). For designs with small aspect ratios, these corrections are probably small and we have not tried to estimate them.

Inductance

We've published a report on estimating the inductance of ferrite rod antennas (with solid rods, not sleeves) here:

<https://www.osengr.org/Articles/Ferrite-Rod-Inductance.pdf>

The formula proposed for estimating inductance therein is a function of the square root of the rod's length-diameter product:

$$L = \mu_o \mu_L \sqrt{ld},$$

where $\mu_o = 4\pi \times 10^{-7}$ H/m, and μ_L depends on both the rod and coil parameters. The article provides data and interpolation functions for the μ_L term. Fully characterizing the μ_L function for ferrite sleeves would have required a huge number of simulations covering a 4-D parameter space, and has not been attempted.

A value of μ_{rod} obtained from figure 4 could be used for μ_L , but it will likely be necessary to build the antenna and measure the inductance, then adjust the turn count as necessary.

In general, μ_L is significantly smaller for full length coils. Actual values of μ_L computed from inductance measurements on two test antennas ($\mu_{sleeve}=3.9$) are $\mu_L=2.3$ for a 110mm long coil, and $\mu_L=4.3$ for a 13mm long coil.

Optimum Coil Length

A few simulation runs show that even for aspect ratios as small as 0.6, μ_L can be half as much for a full length coil compared to a very short one. By that we mean the wire turns are spaced such that the coil occupies the entire length of the ferrite sleeve.

Unlike rods with larger aspect ratios, the amount of signal received does not drop all that much as coil length is increased. This suggests that about 40% more turns of wire could be used if spaced out over the full length of the sleeve, without adding more inductance. Because longer coils don't reduce output very much for small aspect ratios, effective height would be improved by about 40% or 3dB by doing this.

Ferrite Material

In typical ferrite rod designs, materials are used which have low loss at the frequency of operation. For example, 43 material with $\mu_i=800$ has too much loss above 1MHz to be useful in the AM band for a single rod antenna with large aspect ratio. The upper bound on resonant Q due to ferrite losses depends on the ratio μ_i/μ_{rod} . The larger this ratio, the less effect ferrite losses will have on resonant Q.

For a typical single rod design with $\mu_i=125$ and $l/d = 12.5$, this ratio is 10:1. FSL designs have very low values of μ_{rod} (aka μ_{sleeve}), so this ratio is quite large (e.g. $^{800}/_4=200:1$, and higher ferrite losses can be tolerated compared designs with high aspect ratios. For example, 43 material can be used successfully in a ferrite sleeve across the AM band since high losses above 1MHz do not hurt the resonant Q all that much.

Resonant Q

When loops are wound with solid (or stranded) wire, adding a ferrite sleeve may result in a large increase in resonant Q and therefore effective height. This difference seems to be much less or non-existent when loops are wound with Litz wire, and this reduces potential benefits of the FSL version of the antenna. A Litz wire upgrade probably costs less than the ferrite rods, and adds little weight to the design. There's still a gain due to the ferrite sleeve, but as discussed above, this can be offset with more turns on an air-core coil, and/or a somewhat larger diameter.

To determine the net benefit of higher Q, the effect of losses in resonating capacitors, and loading by the receiver must also be accounted for. Depending on these additional losses, the actual net benefit may be close to, or much less than the improvement in unloaded resonant Q.

Designs which use magnetic coupling to the internal ferrite rod antenna of a portable or tabletop MW band receiver will see an improvement equal to the square root of the Q ratio. For example, quadrupling the Q of the tuned loop (keeping all else constant) will increase the signal strength seen by the receiver by a factor of $\sqrt{4} = 2$.

Air Core Equivalents

Based on E-M simulations the FSL design shown at the beginning of this chapter (figure 1) has $h_e=28\text{mm}$ at 1MHz (coil diameter is 168mm). The following air core designs compare favorably in non-resonant effective height (all heights computed at 1MHz).

- A 254mm (10 inch) diameter loop with 29 turns of wire on 2.7mm pitch has $h_e = 31\text{mm}$. Approximate inductance would be $300\mu\text{H}$ and an SRF in the range of 7-8MHz.
- A 220mm (8.7-inch) diameter loop with 38 turns of wire on 3.7mm pitch has $h_e = 30\text{mm}$. It would have an inductance of about $290\mu\text{H}$ and SRF in the range of 3.5-4MHz. With the wide winding pitch, Litz wire might not be required.
- A 185mm (7.3-inch) diameter loop with 43 turns of wire on a 3.3mm pitch would have the same coil length as the original sleeve (140mm) and the same coil diameter.

SRF is again in the 4-5MHz range. The inductance would be about $280\mu\text{H}$ with $h_e = 24.3\text{mm}$, 1.2dB less than the FSL antenna.

This demonstrates that adding ferrite rods to the antenna as a sleeve does improve performance, but the small sleeve aspect ratios typically encountered limit these designs to a modest reduction in size over an equivalent air core coil.

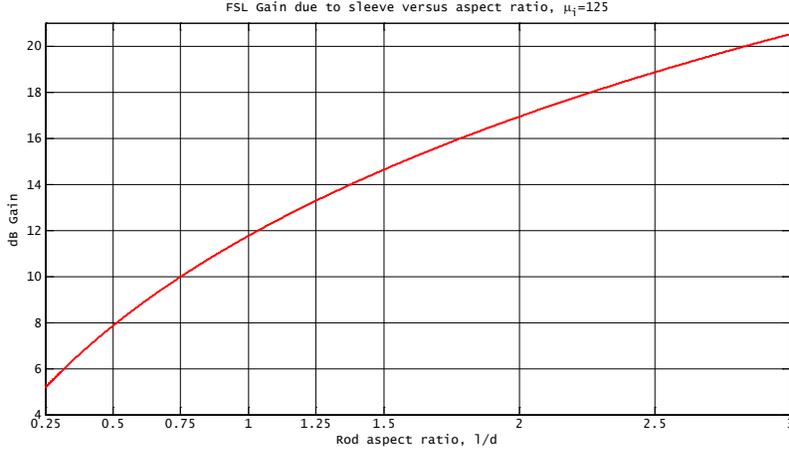


Figure 6: Best possible effective sleeve gain vs aspect ratio

Since μ_{rod} (for a solid rod) can be looked at as a gain term, we can generate a plot of best possible gain due to a ferrite sleeve versus it's aspect ratio, as seen in figure 6. The vertical axis there is $20 \log_{10}(\mu_{rod})$. In published designs, the largest aspect ratio we see is about 2.3, but it's typically much smaller.

This graph is based on a very optimistic scenario, where a solid rod is used instead of a sleeve, the coil diameter is equal to the rod diameter, and no extra turns are added to an air core coil.

Experimental Verification

To test the validity of the above results, signal voltages produced by two FSL test antennas were measured and compared to voltages from several air core loops. Up until recently, the cost of purchasing enough ferrite rods for this purpose was prohibitive. After much searching, an affordable source of ferrite rods was found, which has allowed some experimental verification of predicted effective heights at 60kHz and 560kHz.

Tests performed at 60kHz used a custom receiver with a known input impedance. At 560kHz, antennas were connected directly to the input of the Si473x receiver IC in a Tecsun PL380 portable radio. These tests are less well controlled, since resistive losses at the receiver input are variable (managed by firmware in the radio IC) and unknown⁴. Steps were taken to mitigate this issue as described below.

⁴See the SiLabs Si473x datasheet for details on radio-managed input resistance.

The ferrite sleeve and the three test coils are depicted in figure 7. The two coils on the right side are wound on 6-inch PVC pipe sections in which the ferrite sleeve may be installed, while a third coil (air core only) is wound on a 10-inch (254mm) fiberglass form.



Figure 7: Ferrite sleeve and coils used in testing

The Ferrite Sleeve

A ferrite sleeve was constructed using 36 12x140mm rods. These were affixed on the outside of a glass jar, with a resulting outer diameter (147mm) that fits easily inside the 6-inch PVC pipe sections (152mm inside diameter) used as coil forms. This setup allows the ferrite to be easily inserted and removed during testing.

For computing μ_{sleeve} , the effective mean diameter of the sleeve was set equal to the physical mean diameter. The effective thickness was adjusted to account for the sleeve cross section not being fully filled with ferrite. That yielded an effective OD of 145.7mm and an ID of 126.3mm. Assuming $\mu_i=800$, we computed $\mu_{sleeve}=3.96$, and that was used in computing the effective height of the FSL antenna.

60kHz Tests

These tests used an 83-turn coil close wound on the 6-inch PVC pipe section, with PVC-insulated, stranded 22 AWG wire (lower right coil in figure 7).

The coil was resonated at 60kHz using low-loss polypropylene capacitors. Series resistance was added, lowering the loaded Q to 50; this makes resonance tuning less critical and eliminates differences in Q from the results. As a result, the difference in received signal strength should depend only on the ratio of non-resonant effective heights.

A large 32-inch octagonal loop with a resonant effective height of 4.33m was also compared; this antenna's resonant Q was not lowered 50, as it had been carefully tuned.

The custom receiver adjusts internal gains (AGC) to produce a fixed baseband output voltage, and is therefore an indication of received signal strength. Tests were performed at mid day, when the incoming signal from WWVB is fairly constant, with these results:

Parameter	Air Core	FSL	Large Octagon
Computed h_e	116mm	350mm	4330mm
Rx AGC Gain	40.78dB	31.28dB	10.28dB
FSL vs air core	$\Delta h_e = 9.53\text{dB}$	$\Delta \text{AGC} = 9.50\text{dB}$	
FSL vs octagon	$\Delta h_e = 21.92\text{dB}$	$\Delta \text{AGC} = 21.00\text{dB}$	

The difference between predicted and measured values is only 0.03dB comparing the coil with and w/o the sleeve, and 0.92dB comparing the FSL and large octagon antennas. The variable gain circuitry in the receiver has a typical linearity specification of $\pm 0.5\text{dB}$ ($\pm 2\text{dB}$ maximum). This test provides a reasonable confirmation of the theory presented above.

AM Broadcast Band Tests

Two different air-core antennas were compared to the FSL test antenna at 560kHz. Litz wire containing 47 strands of 40AWG enameled wire was used to wind a 20-turn coil directly adjacent to a 10-turn coil, which could be connected in series to form a 30-turn coil. This coil was wound on a 6-inch PVC pipe section, which allows the ferrite sleeve core to be inserted and removed, without otherwise disturbing the experimental setup. A second air core antenna was wound on a 10-inch form, designed to have the same non-resonant effective height as the FSL antenna. To summarize, these are the three antennas used in the AM broadcast band test:

- 20-turn loop on 168mm PVC form, with ferrite sleeve installed.
- 30-turn loop on 168mm PVC form, w/o sleeve.
- 29-turn loop on 254mm fiberglass form (air core).

Due to the unknown behavior of the receiver input impedance, a strategy likely to remove this uncontrolled parameter was devised. It was reasoned that if each antenna presented the same impedance to the receiver, and very strong signals were avoided, then the receiver would present the same tuned input impedance to each antenna.

Differences in Q were removed from the experiment by adding series resistors to bring all coils down to a Q of 100. The table below shows measured parameters for each of the three antennas, at the test frequency of 560kHz⁵. R_q is the series resistance which reduces the Q at 560kHz to 100. Thick film surface mount resistors (0805) were used.

Core	Coil Dia	Turns	L, μH	Q	R_q, Ω	h_e
Air	168mm	30	297	381	7.9	7.8mm
Ferrite Sleeve	168mm	20	310	468	9.1	15.1mm
Air	254mm	29	300	324	7.5	17.2mm

⁵Measured with LCR meter from 10kHz to 2MHz in 1,2,4,10 sequence. The value at 560kHz is derived from an RLC model fit to the measured data

Test Results

Receiving a local station of moderate strength at 560kHz yielded these results:

Parameter	FSL	6.6-inch air core	10-inch air core
RSSI	61dB	56dB	61 to 62dB
RSSI relative to FSL	0dB	-6dB	+0 to +1dB
h_e relative to FSL	0dB	-5.8dB	+1.1dB

This data agrees with predicted values of non-resonant h_e within $\pm 1\text{dB}$ ⁶. The most convincing comparison is with the 10-inch air core loop. Not only does this antenna present the same impedance to the receiver, but it theoretically also presents the same signal voltage (within 1dB). If the receiver is varying the input losses as a function of signal strength, that should not be a factor in comparing the FSL and 10-inch air core antennas.

Capacitive Noise Pickup

We attempted to ascertain the susceptibility to electrical noise of the FSL antenna and the 10-inch air-core equivalent. Both antennas were operated inside a building where electric noise from 120V wiring is significant. Although in some cases, it seemed like the FSL antenna might be picking up less electric field noise, the results were far from conclusive and repeatable.

When operated outside, at least 30 feet away from electrical noise sources (e.g. buried power lines), there was no perceptible difference in noise levels between the two antennas.

Signal Nulling Capability

Another often discussed performance parameter is the depth of nulls in the antenna pattern. We attempted to compare the FSL and air core antennas in this respect, but were unable to reach a conclusion. The depth of nulls seems quite sensitive to the antenna's immediate surroundings, especially metallic objects. In a range of different situations, we found no consistency in which antenna had deeper nulls. Values ranging from 20-40dB were found with both antennas, as a function of antenna placement, and frequency.

One Alternative to the FSL

Another method that has been used⁷ with multiple ferrite rods to increase loop antenna performance, results in what we refer to as a *fat stack*. Several rods are grouped into a bundle, and several of these bundles are then stacked end-to-end. This results in a larger effective rod diameter, and the end-to-end stacking keeps the aspect ratio from becoming too low.

We took some more of the same ferrite rods used in the example FSL design and made 4-rod bundles with an effective diameter twice that of a single rod. Three of these 4-rod bundles were stacked end-to-end making the total length 420mm, as pictured in figure 8.

⁶SiLabs does not specify the linearity of the Si473x receiver IC's RSSI output.

⁷For example see here: http://sarmiento.eng.br/Loop_Ferrite_Rod_Antenna.htm

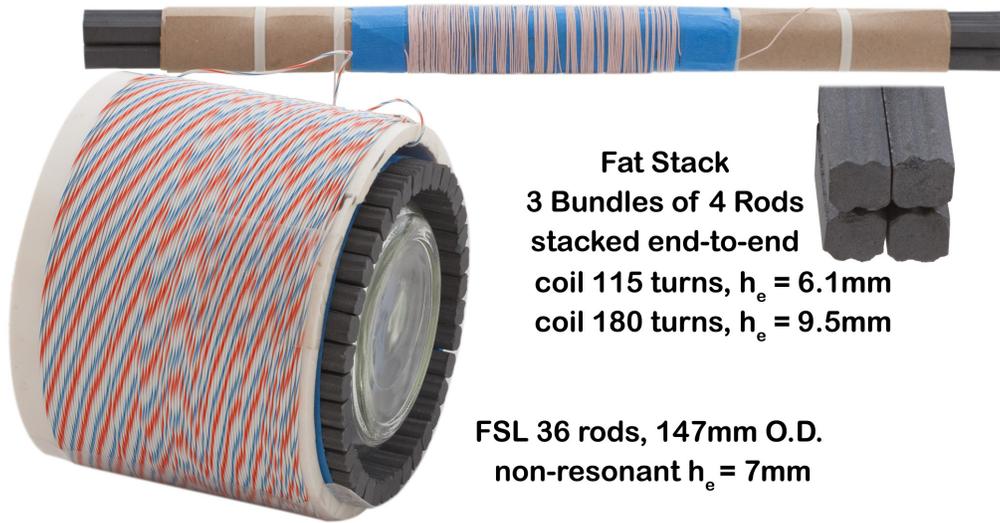


Figure 8: Fat Stack compared to FSL

Compared to a single rod, the aspect ratio was increased from 12:1 to 17.5:1, raising the value of μ_{rod} by about 3.8dB from 64 to 99. Combined with the quadrupling of cross sectional area, an increase in effective height per turn in the coil of 15.8dB is achieved.

For a coil with 115 turns (inductance 2.8mH), the net result was a non-resonant effective height comparable to that of the FSL design example. While this version of the antenna is longer than the FSL, it occupies less volume, requires one third the number of rods (weighing one third as much), and uses much less wire in the coil.

With a 180-turn coil, h_e is raised to more than 9mm and the inductance (6.2mH) is still workable. This coil can easily achieve a Q of 200 for a resonant $h_e=1.9\text{m}$, which is only 7dB less than a large 32-inch octagon design. The actual 180-turn build produced a signal strength 9dB less than the large octagon, and it's suspected the difference is due to air gaps where the bundles butted together.

The next step up could be to put nine rods in each bundle (three times the effective diameter), and stack five bundles end-to-end. It could have a non-resonant height of as much as 17mm, and with a Q of 200 would only be 2dB behind the large octagon. However, it requires 45 ferrite rods and that is getting into big, heavy, expensive monster territory.

The challenge with the fat stack design is keeping the air gaps between rods small enough. It might help to stagger the individual rods so the air gaps don't all occur in the same place, but that wasn't tried here. More detail is available in the larger report.

Summary

In this article, we've attempted to provide some much needed analysis of the workings of FSL antennas. Tests at both 60kHz and at 560kHz showed that measured differences agreed with predicted values within $\pm 1\text{dB}$. This is reasonable evidence to conclude that the analysis presented in this chapter is correct.

In the end, choosing to build an FSL antenna is another engineering trade-off. They can be somewhat smaller than an equivalent air core design, but will be significantly heavier, more costly and more fragile than an equivalent air core antenna. Differences in antenna patterns and susceptibility to electrical noise were not determined in our testing.

We hope others find this information useful for deciding whether to build an FSL antenna, and for designing one of these beasts.

Revision History

Version 2, January 2023

- Minor grammatical changes.
- Added info about 180-turn coil on fat stack example.

