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Patterns and Polarizations of Modestly-Sized Loop Antennas

Patterns and polarizations of square loops up to about 0.4 wavelengths in perimeter are examined.

In "Small Gap-resonated HF Loop Antenna Fed by a Secondary Loop[1]", K. Siwiak, KE4PT, and R. Quick, W4RQ, provide improved formulas for loop current and impedance, leading to an accurate determination of far-fields and null depths for loops up to 0.3 λ (wavelengths) in circumference. See also, KE4PT and W4RQ, "Small Gap-Resonated HF Loop Antennas[2]". In "Effect of Small HF Loop Near Fields on Direction Finding[3]", KE4PT shows how the near-field response of a small loop can provide polarization at right angles to the normal far field polarization, with the normally expected null in the response being filled in by the near-field response. The combined response can skew the expected loop pattern while direction finding or searching for RFI.

This note investigates some features of the patterns and polarizations in the far field of modestly sized square loops, up to about 0.1 λ on a side.

The expected radiation in the horizontal plane from a very small circular or square vertical loop, as illustrated in many text books, is shown in Figure 1. Figure 1A shows the physical orientation of the vertical loop, and how the horizontal radiation pattern relates to the loop orientation. In the analysis here the square loop is fed in the center of the bottom straight section, and is resonated by a capacitor (not shown) in the center of the top section. Figure 1B shows the far field radiation pattern in the horizontal plane. The pattern was calculated for a very small loop, less than 0.01 λ in size, in free space. In this article any effects of ground are not included. The calculations were performed using *EZNEC Pro*/4[4], which is based on *NEC4*. Details of the feed arrangement are not shown, and any distortions produced by a feeder cable are not included. The radiation peak occurs in the plane of the loop, and is vertically polarized. As expected, there is no significant horizontally polarized radiation, and there is a deep null in the vertically polarized radiation

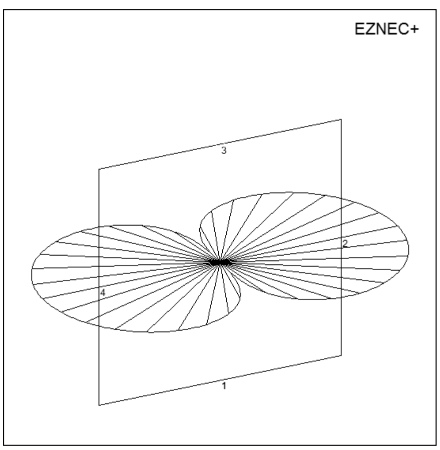

Figure 1A — Orientation of the very small vertical square loop. The loop is fed at the center of the lowest horizontal section (marked "1") with a resonating capacitor at the center of the top horizontal section "3". Radiation pattern is vertically polarized, and with nulls in the broadside directions.

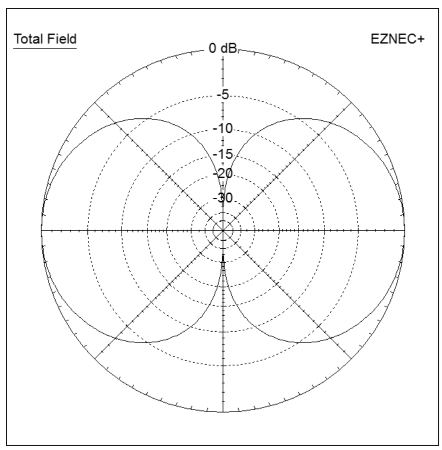

Figure 1B — The far-field radiation pattern of a very small vertical loop, in the horizontal plane. The loop is vertical, in free space, with the plane of the loop running left-to-right. The radiation is vertically polarized, and peaks in the plane of the loop. There is a deep null in the broadside directions.

broadside to the loop.

Figure 2A shows the far-field radiation pattern of a small loop, but where the sides of the loop are now are increased to 0.05 λ, giving a total perimeter of 0.2 λ. This still qualifies as a "small loop", but is beginning to show some of the characteristics of a larger loop. The vertically polarized radiation is shown in the dashed line of Figure 2B, and as expected peaks in the plane of the loop, with a deep vertically polarized null broadside to the loop. There is now some horizontally polarized radiation broadside to the loop, only about 7 dB weaker than the vertically polarized radiation in the plane of the loop. This is shown by the dotted line. The total radiation, a combination of vertical and horizontal polarization, is shown by the solid line at the periphery of the polar diagram. The sharp and deep nulls of the total radiation from the smaller loop, which had been apparent in Figure 1A, are now significantly broadened and relatively shallow.

If used to hunt for RFI, this small loop can give very confusing results. If the source of RFI, even in the far field of the loop, is vertically polarized then only the dashed line in Figure 2B is the relevant polar diagram to use. Using the relatively sharp null in this pattern to identify the RFI, the source of RFI would appear broadside-on to the loop. This is what is normally expected for a small loop. However, if the RFI, still in the far field, happens to be horizontally polarized then the relatively sharp null in the relevant antenna pattern (dotted line) would be found in the plane of the loop, 90° away from the normally expected direction of a null**.** Further, radiation received via the ionosphere has, in general, a continuously changing polarization. For such radiation, no well-defined and stable null in the loop pattern might be discerned at all. This is not a good loop for direction finding.

As the size of a small loop is gradually increased, the relative amplitude of the broadside radiation increases. For a somewhat larger size of 0.1 λ on a side, the resulting far-field radiation pattern is shown in Figures 3A and 3B. A loop of this size barely qualifies as a "small" loop, although still "modest", but the loop now has some very interesting properties.

The vertically polarized radiation is shown by the dashed line in Figure 3B, while the horizontal polarization is shown by the dotted line. The total radiation, a combination of vertical and horizontal polarization, is shown by the solid line. The total power radiation pattern is now nearly omnidirectional in the horizontal plane — within ±0.08 dB in this particular example. With this size of loop the amplitude of horizontally polarized radiation, that peaks broadside to the loop, is almost equal to the vertically polarized radiation in the plane of the loop.

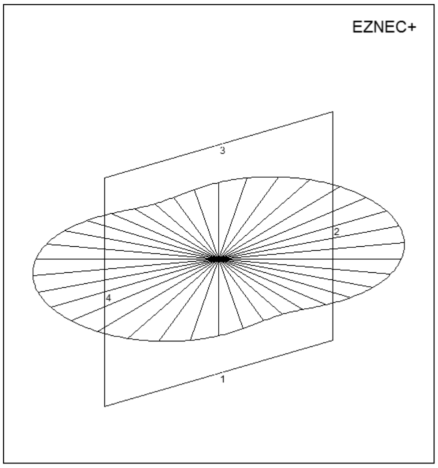

Figure 2A — Far field patterns of a square loop with 0.05 wavelengths sides. The loop is vertical and in free space, fed in the middle of the lower horizontal segment with a resonating capacitor in the middle of the top section.

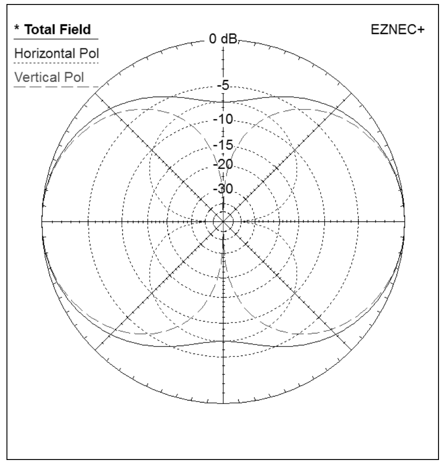

Figure 2B — The horizontally polarized radiation (dotted) broadside to the loop and the vertically polarized radiation (dashed) in the plane of the loop. The nulls in the total field (solid line) are broadside to the loop, now only about 7 dB down on the peak.

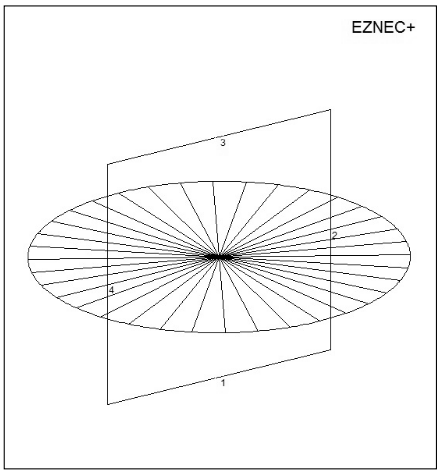

Figure 3A — As in Figure 2, but with the sides of the loop now increased to 0.1 wavelengths. The loop is vertical and fed in the lower, horizontal section, with a resonating capacitor in the center of the top horizontal section. The pattern is shown for the horizontal plane.

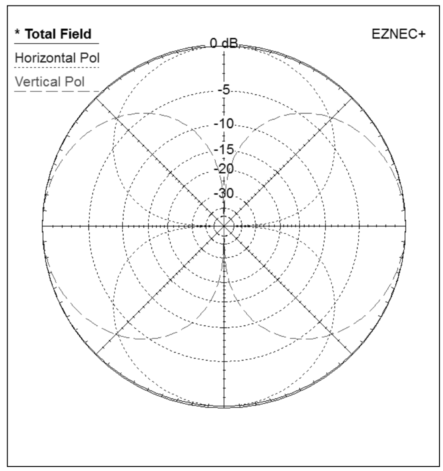

Figure 3B — The horizontally polarized radiation (dotted) broadside to the loop is now very nearly equal to the vertically polarized radiation (dashed) in the plane of the loop. The total radiation (solid) in the horizontal plain is nearly perfectly omni-directional.

Ratio of Horizontal to Vertical Polarization for Small Loops

From Eqn (1) of [*op. cit.*[2]], for a given loop current, the difference between loop current at the top of the loop and current at the bottom of the loop (at the feed point) is proportional to the square of the loop circumference; that is, proportional to the square of the loop diameter. The far field is proportional to this difference in currents, times the effective length of the segments radiating, which is also proportional to the loop diameter. Therefore, for horizontal polarization for a given feed current one would expect the far field to be approximately proportional to the cube of loop diameter. Although that equation applied to a circular loop, one might reasonably expect a comparable expression for a square loop.

For vertical polarization, for small loops the far field is proportional to the length of segment radiating, multiplied by the sine of the phase difference from one side of the loop to the other; the phase difference results from the propagation delay from one side of the loop to the other. For small loops, this sine is

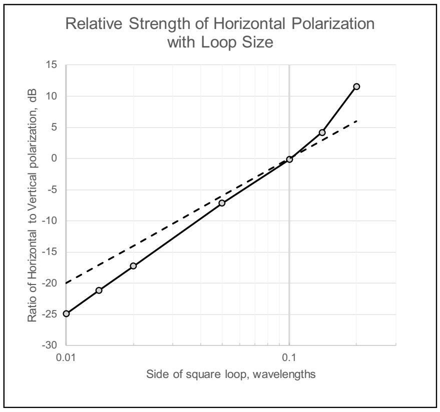

Figure 4 — The ratio of horizontal polarization broadside to the loop compared with vertical polarization in the plane of the loop expected from a small to modest-sized loop. (Note the logarithmic scale used in the horizontal axis for the loop size.) The slope of the dashed line illustrates the expected difference, in dB, based on the very simple discussion in the text. The solid line illustrates the ratio calculated using *EZNEC*, which is not too different from the simple derivation.

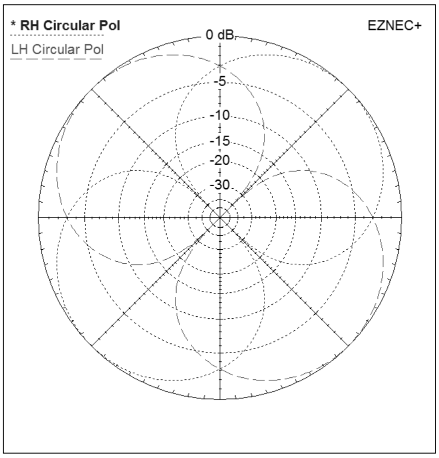

Figure 5 — Far field pattern of the antenna shown in Figure 3, here for circular polarization. The circular polarization can be quite pure. For example, in the top-right quadrant at 45° from the broadside direction the *RH* circular peaks, and the *LH* circular radiation is more than 30 dB down.

approximately proportional to the size of the loop. Therefore for a given loop current one would expect the vertically polarized far field to increase approximately as the square of the loop size. Then for small loops the ratio of horizontally polarized to vertically polarized far field should be approximately proportional to (size cubed)/(size squared), or the ratio of fields should then simply be proportional to the size of the loop. The ratio of radiated powers would be proportional to the square of loop size.

Figure 4 shows the relative strength of broadside horizontal and end-on vertical polarization, calculated using *EZNEC* for square loops of side 0.01 λ up to 0.2 λ. The dashed line illustrates the expected slope of line of the relative ratio if it were indeed just proportional to size of loop, as derived above. The *EZNEC* simulations (solid line with circles) give a slightly stronger dependency on loop size, but given the many approximations inherent in the above simplified discussion, the agreement with the *EZNEC* calculation is fairly good, at least up to loop sides of about 0.1 λ.

Circular Polarization

At an angle 45º away from the plane of the loop, the resultant radiation is a combination of both nearly-equal linear polarizations. Figure 5 shows the same loop as Figure 3, but now the radiation pattern is plotted for left- and right- circular polarization.

At 45º to the plane of the loop, in the upper right quadrant of Figure 5, the *RH* circular radiation (dotted line) peaks. At the same time, the amplitude of the *LH* circular term (dashed line), is more than 30 dB down. At this angle, the circular polarization is very pure. The amplitude at the peak of the *RH* circular varies approximately as cos(θ), where θ is the angle offset from the peak. The amplitude of the *LH* circular term at this point varies approximately as sin(θ). So the ratio of the power in the *LH* circular term compared to that of the *RH* circular term varies as,

$$\frac{LHC}{RHC} = \left[\frac{\sin(\theta)}{\cos(\theta)}\right]^2 .$$

From this equation, the cross-polarized *LHC* term becomes 10 dB below the *RHC* at an angle offset of ±17.5º from the peak *RHC*, for a total effective *CP* beam width of 35º. This is exactly the same result that can be obtained by just comparing the *RHC* and *LHC* powers plotted in Figure 5.

This can be a convenient form of antenna for producing circularly polarized radiation. Apart from the potential use for receiving circularly polarized satellites, this can be a useful HF receive antenna. The received radiation from the ionosphere is often circularly polarized. If both the ordinary and the extraordinary circularly polarized ionospheric rays are being received, then the combination is in general an elliptically polarized wave whose major axis rotates according to the relative phase of the ordinary and extraordinary wave. This rotation (Faraday Rotation) is one of the main causes of fading on HF links. By orientating this loop antenna at 45º to the incoming wave, only one sense of circular polarization can be received, with high rejection of the opposite sense of polarization. This should significantly reduce the fading on the signal. Of course, ground reflections will modify the precise sensitivity to different polarizations.

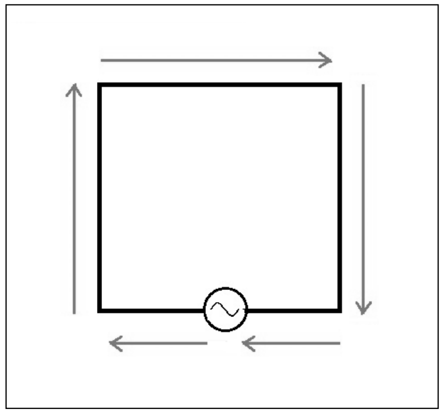

Figure 6 — Square loop fed at the center of the lowest wire, with a tuning capacitor (not shown) at the center of the top wire. The instantaneous phase of current around the loop, as seen broadside on, is very nearly constant. The magnitude of the currents in the left and right vertical sections are equal, although the currents in the two horizontal sections are not. The arrows illustrate the instantaneous direction of current flow.

For circular polarization to be generated, there must be a 90º phase difference between the vertical and horizontal components of the radiation. How is that 90º produced in this loop antenna? In a square loop such as this, the current flowing in the two vertical segments of the antenna are equal in magnitude but opposite in direction; see Figure 6. This cancels the vertically polarized radiation broadside to the antenna, but in the plane of the loop, the propagation delay from the left side of the antenna to the right side introduces a phase difference. The fields from the vertical currents, as seen from a far-field distance in the plane of the loop, no longer cancel. So, vertical radiation in the plane of the loop takes place.

Consider the horizontal segments at the top and the bottom of the loop. Because the wires are end-on in the horizontal direction in the plane of the loop there is no radiation from these wires in that direction. The phases of the current in the top and bottom horizontal segments are very nearly equal — the *EZNEC* simulations for the antenna of Figure 3A showed the phases of the currents to be the same within 0.1º. However, Siwiak and Quick [*op. cit.*[1, 2]] showed that the *amplitude* of the currents on the opposite sides of a small circular loop can be significantly different. The *EZNEC* simulation of this antenna showed the current in the top section, opposite the feed point, to be less than half of the current in the bottom section. So, the horizontally polarized radiation from the top and bottom sections of the loop no longer cancel, because

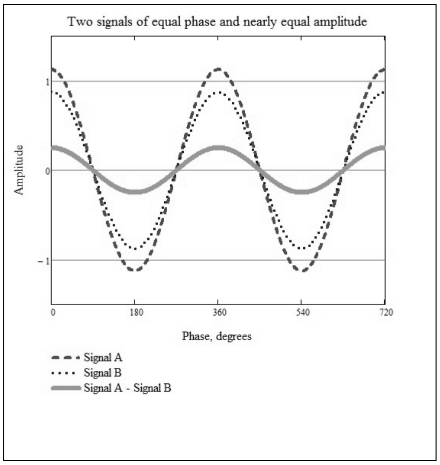

Figure 7A — Signals *A* and *B* represent two cosine waves of equal phase, but slightly different amplitudes. After subtracting the signals, the resultant phase is the same as the phase of the original signals.

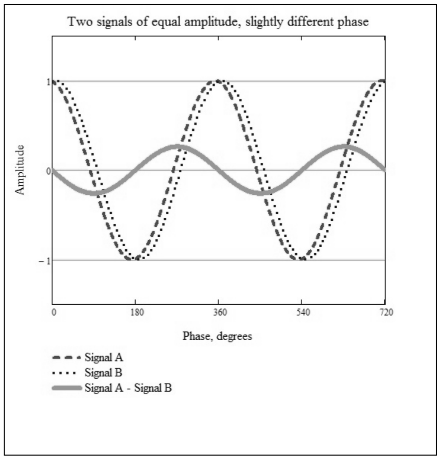

Figure 7B — Signals *A* and *B* represent two cosine waves of equal amplitude, but slightly different phase. After subtracting the signals, the resultant phase is 90° different from the average phase of the original signals.

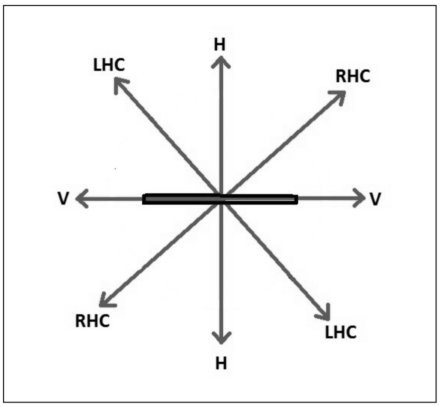

Figure 8 — This loop is sensitive to linear vertical (*V*) or horizontal (*H*) polarization in the plane of the loop or broadside to the loop, or right hand circular (*RHC*) or left hand circular (*LHC*) in the ±45° directions.

of the unequal currents.

For complete cancellation of radiation, the magnitude of the currents in two equal segments must be the same, and their phases must differ by 180º. If there is incomplete cancellation because of unequal magnitude, such as between the top and bottom horizontal sections of the loop, then the phase of the resultant radiation is the same as that of the stronger current. However, if there is incomplete cancellation because of the phases of the current not being 180º different, even though the magnitudes are equal, then the resultant radiation is in quadrature to the mean phase of the original currents. This can be shown easily from the well-known trigonometric relationship for the difference of two cosines. Figure 7B shows graphically how the 90º phase shift appears. For a square loop of side d, at a wavelength λ the propagation delay in the plane of the loop causes a phase change of $\pm(d\pi/\lambda)$ radians relative to the mid-point of the loop.

The phase difference between radiation of vertical and horizontal polarization is exactly what is required for the production of elliptically polarized radiation. If the magnitudes of the vertical and horizontal components are equal in a given direction, then the radiation will be 100% circularly polarized. For a square loop of side 0.1 λ, very pure circularly polarized radiation occurs at ±45º to the plane of the loop.

Conclusions

A small loop antenna with its plane vertical is sensitive in the horizontal direction primarily to vertically polarized signals coming from the end-on directions, in the plane of the loop. However, as the loop size in wavelengths increases, there is increasing sensitivity to horizontal polarization from the direction broadside to the loop. For a loop 0.05 λ on a side, or a perimeter of 0.2 λ, this cross-polarized far-field sensitivity is only about 7 dB below the main vertical polarization. In the near field, the situation is more complex. If the loop is used as a directional antenna to search for RFI, depending on the polarization of the transmitted RFI, the measured direction can be as much as 90º in error.

If the loop size is increased to about 0.1 λ on a side, with a perimeter of 0.4 λ, then the sensitivity to horizontal polarization broadside to the loop approximately equals that of vertical polarization end-on to the loop. For reception of signals of arbitrary polarization, the antenna is effectively omnidirectional. At directions ±45° away from the broadside direction, the radiation from the loop becomes circularly polarized, with opposite sense of circular polarization 90º away. Figure 8 illustrates how the loop is sensitive to vertical polarization (*V*) in the plane of the loop, horizontal polarization (*H*) broadside to the loop, or right hand circular (*RHC*) and left hand circular (*LHC*) at the intermediate ±45º directions. Ground reflections still must be considered, but this can prove to be a convenient design of antenna if circular polarization is required, or as a tool to investigate polarization of incoming waves.

Acknowledgement

I wish to thank Jan Hofman, PD2PCH, for many fruitful discussions and experiments with small and moderately sized HF loop antennas.

Darrel Emerson, AA7FV, was first licensed in 1964 as G3SYS, and still holds that call. He obtained a BA in physics from the University of Oxford, and in 1973 a PhD in radio astronomy from the University of Cambridge. His thesis was the first aperture synthesis study of the 21 cm hydrogen emission in the Andromeda galaxy M31. After working for several years at radio astronomy observatories in Germany (becoming DJØOE) and in France (as F6HYR), he came to the USA in 1986 to work for the National Radio Astronomy Observatory as Director of the millimeter-wave observatory at Kitt Peak, AZ. Darrel was part of the design team for the international ALMA radio observatory now in operation in the Atacama Desert in northern Chile, and helped with antenna testing and adjustment during the construction phase. ALMA consists of an interferometric array of 66 precision antennas, observing from 35 to 950 GHz. Darrel retired from NRAO in 2012, and is now a consultant for CORF, a committee which helps to safeguard the frequency spectrum allocated for passive scientific use. He regularly travels to Geneva as a delegate to the ITU. Darrel was very active operating through amateur satellites. He now concentrates on the HF bands using CW and WSPR. Darrel has two sons, Christopher, N7PTE, and Nicholas, KB7OBA. His wife Pam holds the call sign N7UGL.

Notes

[1]K. Siwiak, KE4PT, and R. Quick, W4RQ, "Small Gap-resonated HF Loop Antenna Fed by a Secondary Loop". *QEX* Jul./Aug. 2018, pp.12-17.

[2]K. Siwiak, KE4PT, and R. Quick, W4RQ, "Small Gap-Resonated HF Loop Antennas, *QST* Sep., 2018, pp. 30-33.

[3]K. Siwiak, KE4PT, "Effect of Small HF Loop Near Fields on Direction Finding, Technical Correspondence", *QST* Jul. 2015, pp. 63-64.

[4]Patterns were calculated and plotted in *EZNEC Pro/4* Version 5. Several versions of *EZNEC* antenna modeling software are available from developer Roy Lewallen, W7EL, at **www.eznec.com**.