Can an Antenna Be Cut Into Pieces (Without Affecting Its Radiation)?

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1 Introduction

When the conductors of an antenna have length greater than $\lambda/4$, where λ is the broadcast wavelength, the current distribution may have nodes where the current vanishes. If so, it would seem that the conductors could be cut at these nodes, creating small gaps, without any effect on the radiation of the antenna.

The possibility of nodes in the current distribution of an antenna is suggested by the familiar approximation of Pocklington [1] that the current distribution in a thin, perfectly conducting wire of an antenna is sinusoidal in space and time.[1] A typical example of this prescription is that the current distribution along a center-fed antenna of length L has the form

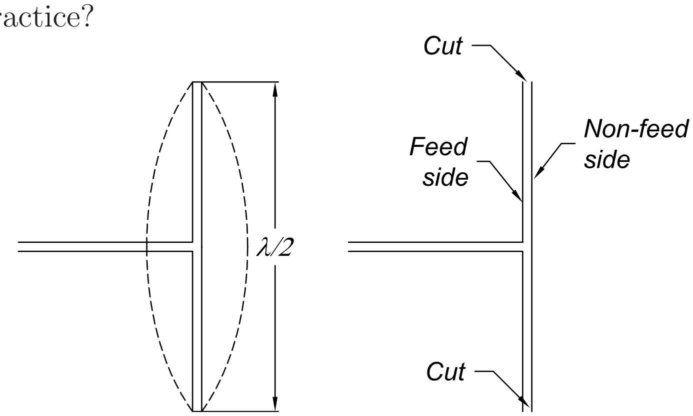
$$I(s,t) = I_0 \sin[k(L/2 - |s|)] \cos \omega t, \tag{1}$$

where $k = \omega/c = 2\pi/\lambda$ is the wave number, and c is the speed of light. The distribution (1) has nodes at distances

$$|s| = \frac{L - n\lambda}{2}, \tag{2}$$

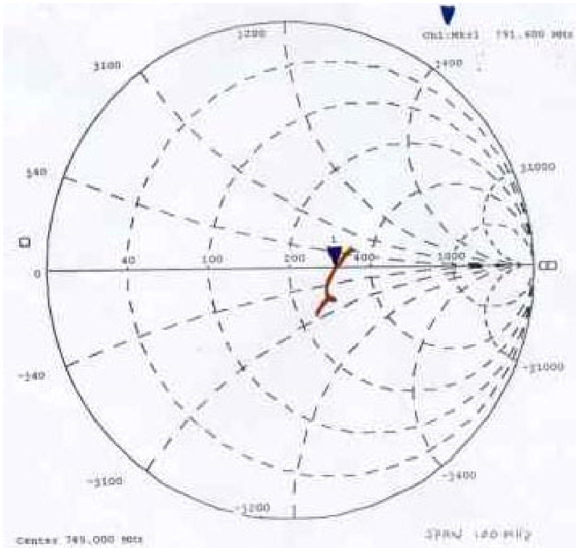
for integer n.

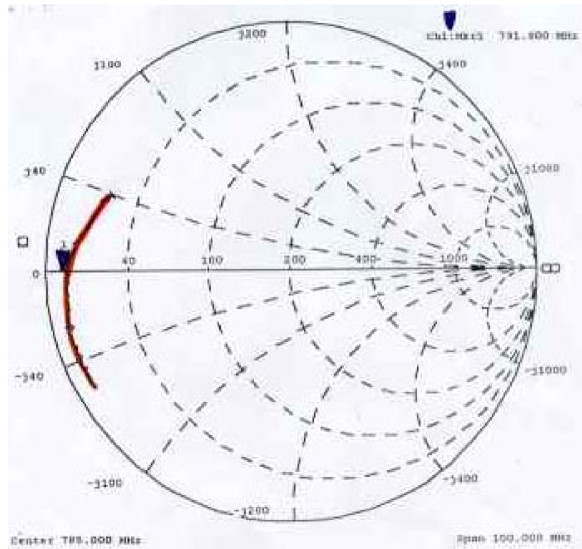
Is this true in practice?



One of us (DJJ) has performed an experiment with a half-wave[2] folded dipole antenna [3], which has current nodes at the ends of the antenna according to eq. (2), as shown in the left of the figure above. However, the radiated power from the cut antenna (above right) was much less than that of the uncut antenna, as shown in the Smith charts [4] below.

[1] A review of Pocklington's argument is given in sec. 2.1 of [2].
[2] The total length of conductor is $L = \lambda$, so the physical height of the antenna is $\lambda/2$.



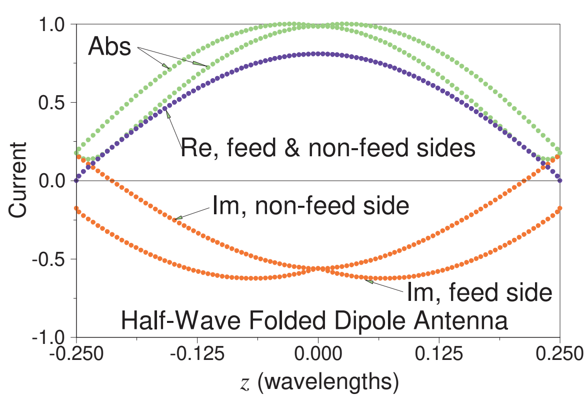


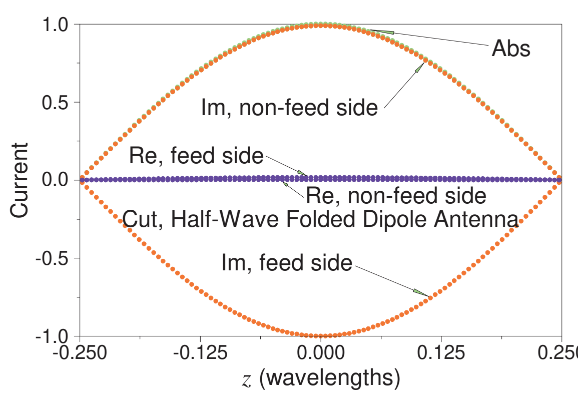
The radiation resistance of the whole antenna was about 300 Ω, as determined by an HP8714C network analyzer, while that of the cut antenna was only a few ohms. The resonant frequency of both the uncut and cut antennas was 790 MHz, the total length of the antenna conductor (feed side + non-feed side) was 32 cm, and the frequency scan was from 735 to 835 MHz.

To obtain greater understanding of the possibility of cutting antennas, we have made several models with the NEC4 [5] simulation program. NEC4 uses the method of moments [6] to deduce the current distributions on the surface of perfectly conducting antennas, given a sinusoidal excitation voltage at an appropriate feedpoint. The near and far field patterns are then calculated from the current distributions.

2 Half-Wave Folded Dipole Antenna

The current distributions as calculated by the NEC4 program for a half-wave folded dipole antenna (for which the total length of conductor is λ) are shown on the left of the figure below, while the current distributions after the antenna has been cut at its ends are shown on the right of the figure below.



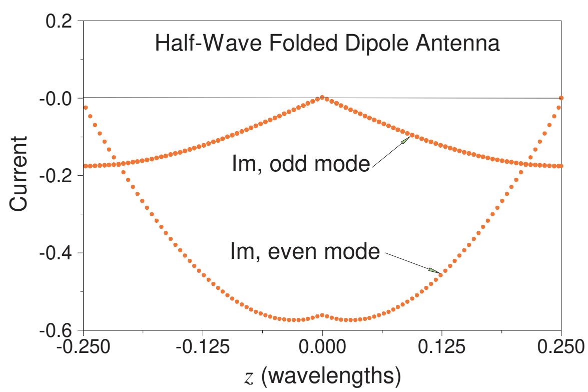


We find that the calculation of the imaginary part of the current distribution is the most sensitive to details of the input geometry. Good numerical stability is only achieved when the segment diameter is less than about 0.01 of the segment length, which insures that we are working in the thin-wire approximation.[3] The model includes a single segment at each end of the antenna that joins the two "vertical" lengths of the antenna. The length of these segments must be at least the same as the length of the segments of the "vertical" portions of the antenna for numerical stability of the fields very close to the antenna.

The real part of the current (*i.e.*, the part that is in phase with the instantaneous drive voltage) is seen to follow eq. (2) quite closely, and vanishes at the ends of the antenna. The real parts of the current on the feed and non-feed sides of the antenna have the same sign, which means that they flow in the same direction in space. Thus, the real part of the current in an "even" mode, meaning that currents on the feed and non-feed sides are the same.

In contrast, the imaginary part of the current (which is a "real" physical current that is 90° out of phase with drive voltage) does not vanish at the ends of the uncut antenna. The nonzero current at the end of the feed side of the antenna flows over to the non-feed side and reverses direction. Hence, the sign of the imaginary part of the current at the ends of the non-feed side is opposite to that at the ends of the feed side. The figure below shows the decomposition of the imaginary part of the current into "even" and "odd" modes according to

$$I_{Im,\mathrm{even}} = \frac{I_{Im,\mathrm{feed}} + I_{Im,\mathrm{non-feed}}}{2}\,, \qquad I_{Im,\mathrm{odd}} = \frac{I_{Im,\mathrm{feed}} - I_{Im,\mathrm{non-feed}}}{2}\,. \tag{3}$$



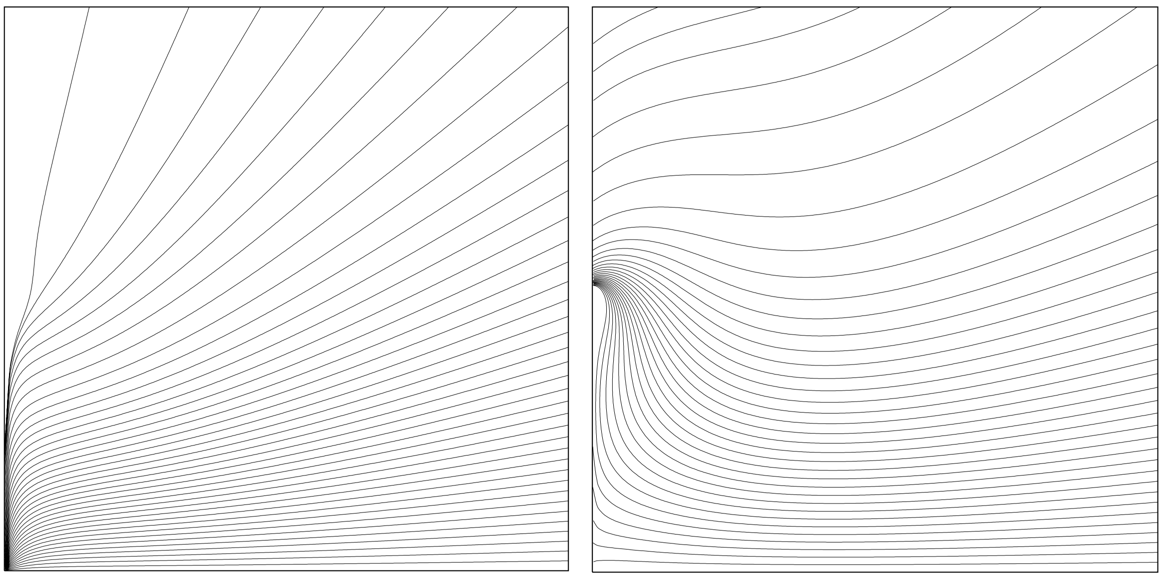
We see from the righthand figure on the bottom of p. 2 that cutting the antenna at its ends results in a substantial perturbation to the current, whereby the imaginary part of the current becomes much larger than the real part, and we cannot expect the radiation of the cut antenna to be the same as that of the uncut case. The imaginary part of the current is now almost entirely in the "odd" mode, while the tiny real part of the current is a mixture of "even" and "odd" modes.

We infer that the desired "even" mode of the real part of the current can exist only in the presence of some "odd" mode in the imaginary part of the current for which the current is nonzero at the ends of the folded dipole. Cutting the antenna at its ends eliminates the "odd" mode with nonzero current there, which in turn suppresses the "even" mode of the real part of the current. As a further consequence, the radiated power is greatly reduced in the cut antennna.

[3]NEC4 can make accurate simulations of thick wires, but our pedagogic interest is in the thin-wire limit where eq. (1) might be expected to hold.

The calculated impedance of the folded half-wave dipole antenna is $325 + 225i\ \Omega$, while that of the antenna after is has been cut at its ends is $0.06 + 3.7i\ \Omega$, in good agreement with the measurements reported on p. 2.[4] That is, cutting the folded dipole antenna at its ends reduces the output power by a factor of 2000.

We also show below plots of lines of the time-average Poynting vector in the near field of the uncut (left) and cut (right) half-wave folded dipole. The plots cover the first quadrant of the y-z plane. The feedpoint of the antenna is in the lower left corner. The antennas run along the lower half of left vertical edge (z axis) of the plots.[5]



Since the antenna is assumed to be made of perfect conductors, there can be no tangential electric field at the surface of the antenna, and consequently no lines of the Poynting vector, $\mathbf{S} = \mathbf{E} \times \mathbf{H}$, can emanate from the antenna conductors. Rather, the lines of the Poynting vector all emanate from the feedpoint of the uncut antenna (above left), and the conductors of the antenna serve to guide those lines through the near zone into the far zone.

It is noteworthy that the lines of Poynting vector emerge from the cut ends of the cut, folded dipole antenna (right figure on p. 3), rather than from the feedpoint. Recalling the geometry of the cut antenna, shown in the righthand figure on p. 1, we see that the cut antenna is in effect a pair of transmission lines that tee off from the feedpoint. The currents in the feed and non-feed sides of the cut antenna are equal and oppositely directed in space, as inferred from the righthand figure on p. 2, and hence are indeed in the (odd) transmission-line mode. The power from the feedpoint is guided down these transmission lines and emerges from their opens ends. However, an open-ended transmission line is a poor antenna, so very little power is radiated by the cut, folded dipole antenna.

We can also use to NEC4 program to produce plots of lines of the electric and magnetic

[4]The NEC4 calculations were performed for a folded dipole of total length (feed plus non-feed side) exactly equal to λ, in which case the antenna is not quite at resonance; hence, the large imaginary part to its impedance.

[5]Because the power feed connects to only one of the two vertical arms of the folded dipole antennas, their near-zone radiation patterns are not symmetric about the x-z plane (left edge of plots), but they are symmteric about the y axis (bottom of plots).

fields in the near zone of an antenna. For example, NEC4 calculates the amplitude E_0 and phase ϕ of the Fourier component of the electric field at a specified spatial point $\mathbf{r}$,

$$\mathbf{E}(\mathbf{r}, t) = E_0(\mathbf{r}) e^{i\phi(\mathbf{r})} e^{-i\omega t}. \tag{4}$$

Of course, only the real part of eq.(4) has physical significance, so we wish to plot

$$\begin{aligned} \mathbf{E}(\mathbf{r}, t) &= Re[E_0(\mathbf{r}) e^{i\phi(\mathbf{r})} e^{-i\omega t}] = E_0(\mathbf{r}) \cos[\phi(\mathbf{r}) - \omega t] = E_0 \cos[\phi(\mathbf{r})] \cos \omega t] + E_0 \sin[\phi(\mathbf{r})] \sin \omega t] \\ &= Re[E_0(\mathbf{r}) e^{i\phi(\mathbf{r})}] \cos \omega t + Im[E_0(\mathbf{r}) e^{i\phi(\mathbf{r})}] \sin \omega t \end{aligned} \tag{5}$$

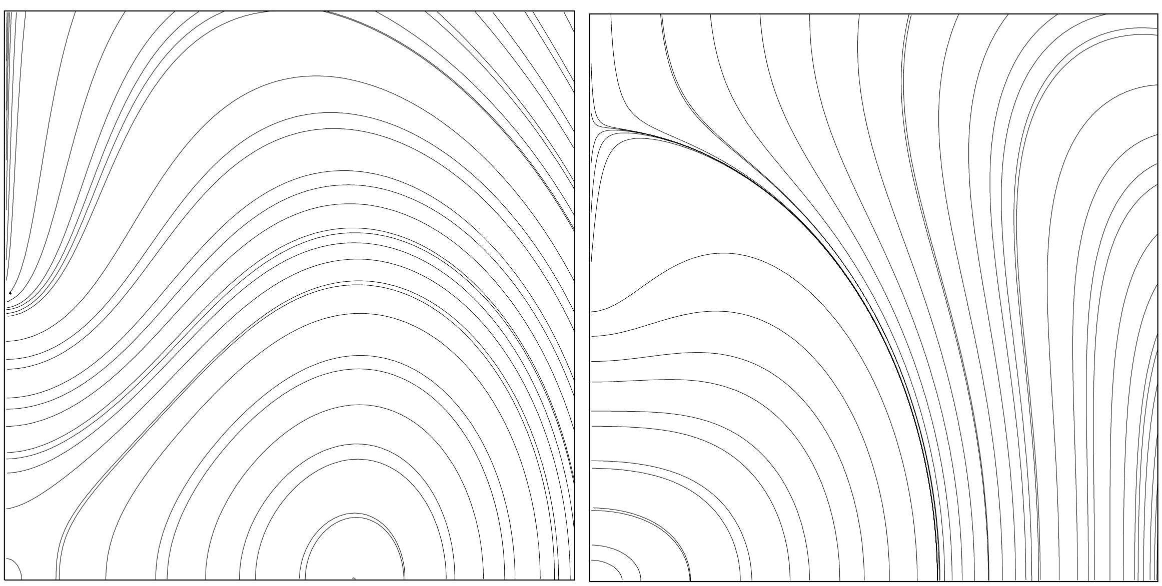
Thus, for example, the electric field at time $t = 0$ is given by

$$\mathbf{E}(\mathbf{r}, 0) = Re[E_0(\mathbf{r}) e^{i\phi(\mathbf{r})}] = E_0(\mathbf{r}) \cos[\phi(\mathbf{r})], \tag{6}$$

and the electric field 1/4 of a cycle later is given by

$$\mathbf{E}(\mathbf{r}, t = \pi/2\omega) = Im[E_0(\mathbf{r}) e^{i\phi(\mathbf{r})}] = E_0(\mathbf{r}) \sin[\phi(\mathbf{r})]. \tag{7}$$

The plots below show lines of the electric field at time $t = 0$ (left) and $t = \pi/2\omega$ (right) for the uncut, folded half-wave dipole antenna.

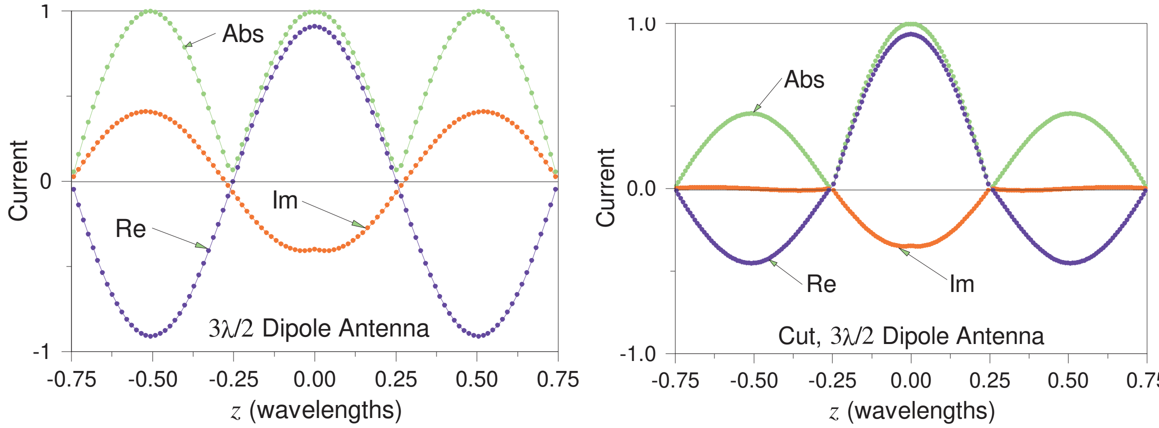


Note that the lines of $\mathbf{E}$ emerge from the antenna (which lies along the lower half of the left edge of the plots above) at right angles to the surface of the conductor, as required for good/perfect conductors.

3 $3\lambda/2$ Center-Fed Linear Antenna

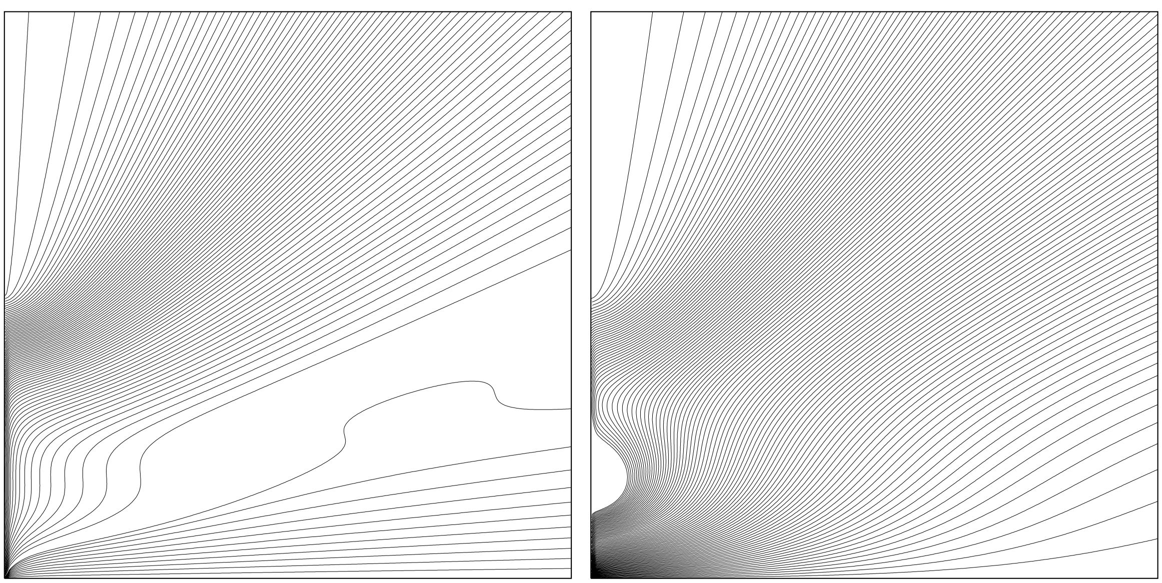
Shown on the next page are the current distributions in uncut (left) and cut (right) $3\lambda/2$ dipole antennas, as calculated with the NEC4 program. Both the real and imaginary parts of the current vanish at the ends of the antenna, as they must. The real part of the current distribution in the uncut antenna has nodes at $|z| = \lambda/4$, as predicted by eq. (2), but the nodes of the imaginary part of the current distribution are at $|z| \approx 0.27\lambda$. Hence, cutting the antenna at $|z| = \lambda/4$ will cause a change in the current distribution, as seen in the righthand plot.

The calculated impedance of the uncut $3\lambda/2$ dipole antenna is $110 + 49i\ \Omega$, while that of the antenna after is has been cut at $\pm\lambda/4$ is $60 + 23i\ \Omega$.



Shown below are plots of lines of the Poynting vector in the first quadrant of the y-z plane for uncut and cut $3\lambda/2$ dipole antennas. The feedpoint is again in the lower left corner, and the antenna runs along the left edge of the plot for about 40% of its length. The leftmost line of the Poynting vector emerges from the feedpoint and runs parallel to the surface of the antenna up to its tip, where it bends by a few degrees before heading into the far zone.[6]

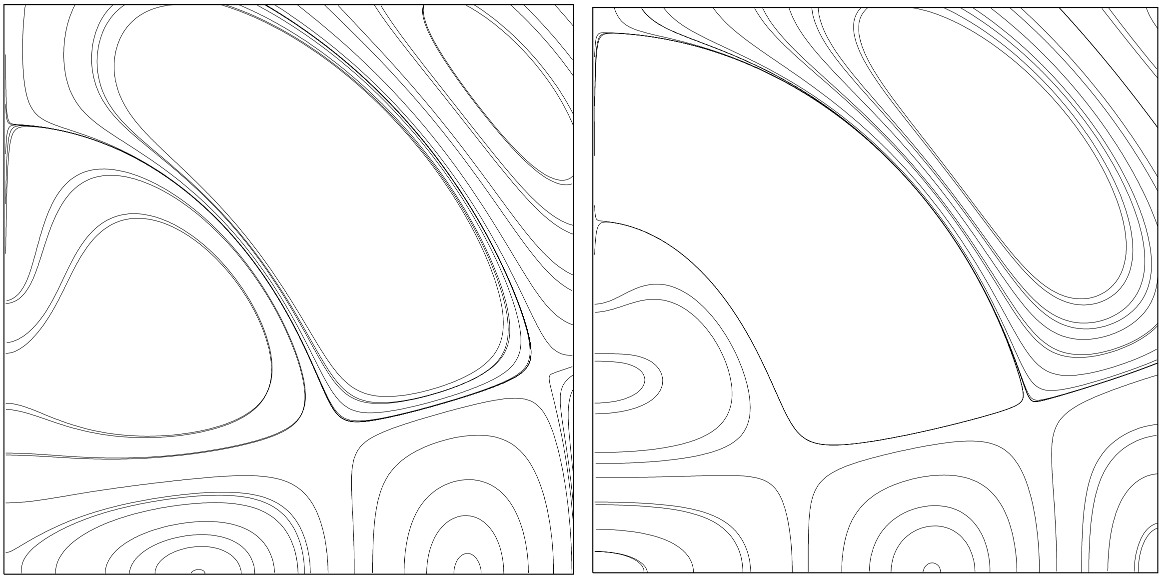
On the righthand plot (of the cut antenna) the lines of Poynting flux are observed to make a detour around the location of the cut.



The plots on the next page show lines of the electric field at time $t = 0$ (left) and $t = \pi/2\omega$ (right) for the uncut, $3\lambda/2$ dipole antenna.[7]

[6]The radiation patterns of the center-fed linear dipole antennas are symmetric about both the left and bottom eges of the plots.

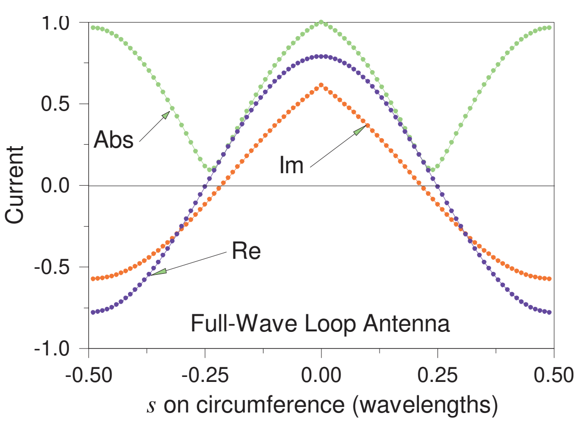
[7]A 10-frame animation of the time evolution of the near electric field of the $3\lambda/2$ dipole antenna can be

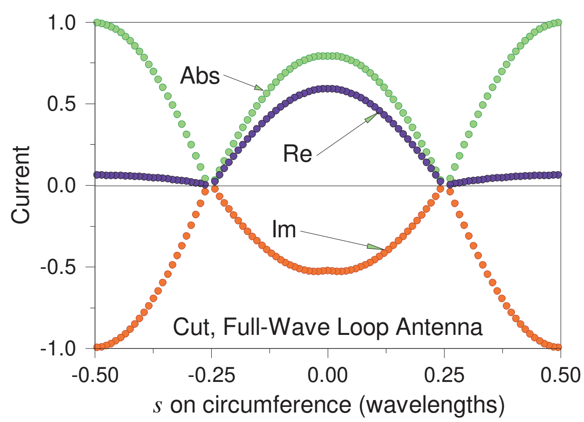


4 Full-Wave Loop Antenna

The current distributions in uncut and cut full-wave loop antennas, as calculated with the NEC4 program, are shown below.[8] The currents are, of course, continuous at the "ends" of the loop ($|s| = 0.5\lambda$), since the conductor forms a continuous loop. Hence the currents need not vanish at $|s| = 0.5\lambda$, and indeed do not.

The real part of the current distribution in the uncut (left) antenna has nodes at $|s| = \lambda/4$, as predicted by eq. (2), but the nodes of the imaginary part of the current distribution are at slightly different positions. The nodes in the real and imaginary parts of the current cannot be made to coincide by tuning the drive frequency (as we verified with several runs of the NEC4 program). Hence, cutting the antenna at $|s| = \lambda/4$ (righthand figure) again shows a significant change in the current distribution.





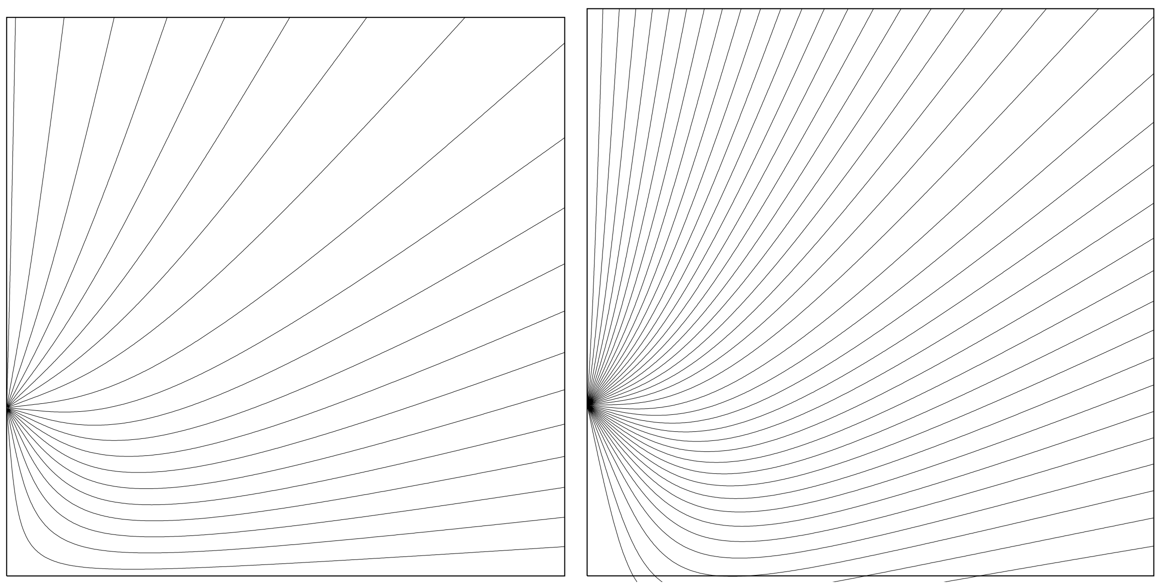
The calculated impedance of the uncut full-wave loop antenna is $122 - 95i\ \Omega$, while that of the antenna after is has been cut at $\pm 90°$ from its feedpoint is $103+91i\ \Omega$. In this example,

viewed at http://physics.princeton.edu/~mcdonald/examples/dip3_anim2.gif

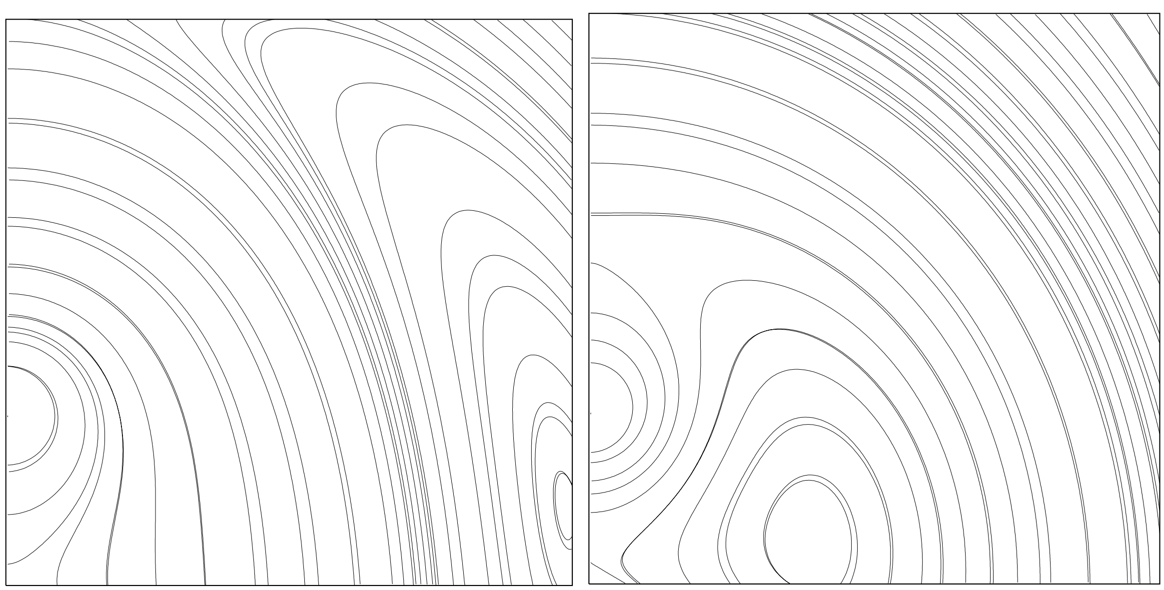
[8]In the models of the loop antenna, the wire radius is 0.1 times the segment length.

unlike the previous two cases, the cut antenna actually performs somewhat better than the uncut antenna.[9]

Also shown below are lines of the Poynting vector in the first quadrant of the y-z plane. The loop lies in the x-z plane (perpendicular to the page) with its center at the lower left corner of the plot. The feedpoint is on the z axis at the "top" of the loop, from which the lines of Poynting vector are seen to emerge.[10]



The plots below show lines of the magnetic field at time $t = 0$ (left) and $t = \pi/2\omega$ (right) for the uncut, full-wave loop antenna.



[9]However, for full-wave loop antennas made from very fine wire the radiation resistance of the cut version is smaller than that of the uncut antenna.

[10]Because there is only a single feed for a loop antenna, the near-zone radiation pattern is not symmetric about the y axis (bottom edge of plots), although it is symmetric about the x-z plane (left edge of plots).

5 Summary

Although the oft-used approximation for current distributions in antennas built with wires suggests that the radiation would be unaffected by cutting the wires at the locations of current nodes, a more detailed (numerical) calculation of the current distributions in three simple antennas shows that there are no current nodes. Hence, these antennas cannot be cut into pieces without affecting their radiation.

6 Acknowledgement

The authors wish to thank Alan Boswell for stimulating conversations about antennas in general and the topic of this note in particular, as well as for the use of his code to produce the plots of Poynting flux from NEC4 output. KTM also thanks Jerry Burke for discussions on the use of the NEC4 code.

References

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