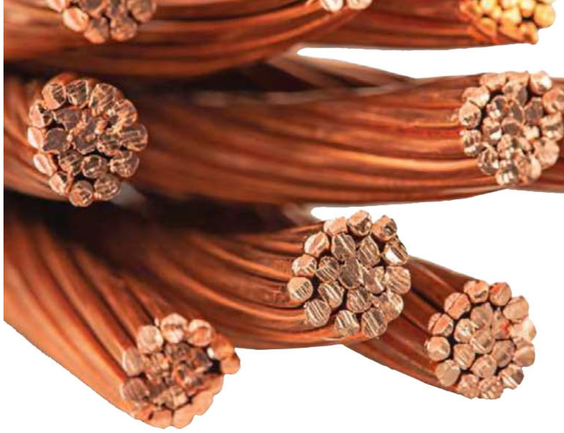

The Best Metal for an Antenna

Revisiting the question of the best metal to use for a wire dipole.

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A series of comments (see "Correspondence" in the September 2022 issue of *QST*) about Pete Varounis', NL7XM, "The Better Antenna: Copper Versus Aluminum" (see the April 2022 issue) caught my attention, though they were in jest. Pete's April Fool article refers to the role of the electrons of copper and aluminum atoms in their electrical properties, as well as their effect on the sag of dipole wires. The title of the article refers to the age-old question: *Is it convenient to replace copper with aluminum in the legs of a dipole?* Copper wires are relatively expensive, heavy, and easily deformed, and they increasingly sag with time and high temperatures. It seems logical to seek aluminum as an alternative due to its electrical properties and low density ($\delta_{Al} = 2.71 g/cm^3$ versus $\delta_{Cu} = 8.94 g/cm^3$). This suggests that lighter wires will be subjected to lower stresses, and they consequently will have less sag and deformation. However, there is concern about reducing the efficiency of the antenna by changing to a metal with a conductivity almost 37% lower ($\sigma_{Al} = 3.8 \times 10^7$ S/m versus $\sigma_{Cu} = 6.0 \times 10^7$ S/m) than copper.

Ohmic Resistance

Consider two half-wave dipoles, each with a total length of l and fed at the center. One dipole is made of copper wire, with a diameter of d_{Cu}, and the other dipole is made of aluminum, with a diameter of d_{Al}. While trying to create antennas with similar efficiencies, the diameters are chosen so the wires have the same electrical resistance. When accounting for skin effect, the resistance of the copper wire is

$$R_{Cu} = \frac{l}{d_{Cu}} \sqrt{\frac{f \mu_0}{\pi \sigma_{Cu}}} ,$$

as detailed in the seventh edition of Matthew Sadiku's *Elements of Electromagnetics*, where μ_0 is the permeability in a vacuum. Because we want the dipole made with aluminum to have the same resistance, the following must be true:

$$d_{Cu} \sqrt{\sigma_{Cu}} = d_{Al} \sqrt{\sigma_{Al}} .$$

So, the diameter of the aluminum wire should be

$$d_{Al} = \sqrt{\frac{\sigma_{Cu}}{\sigma_{Al}}} d_{Cu} = \sqrt{\frac{6}{3.8}} \times d_{Cu} = 1.26 \times d_{Cu} .$$

That is, it must have a diameter 26% larger than that of the copper wire. Thus, if $d_{Cu} = 1.627$ millimeters (#14 AWG), then $d_{Al} = 2.050$ millimeters (slightly smaller than #12 AWG).

It isn't convenient to use metals with lower conductivity, such as steel, because it would require a thick wire. The magnetic permeability of the steel also increases the resistance. However, due to skin

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depth, it is possible to use copper-clad steel (CCS) wires with diameters similar to d_{Cu}.

The most important parameter in antenna performance is efficiency, where the relevant comparison is radiation resistance. This resistance represents the conversion of the electrical power delivered to the antenna into electromagnetic wave radiation, and it is strongly dependent on antenna size. Per Lew McCoy's, W1ICP, *Lew McCoy on Antennas*, for instance, the radio amateur's concern should be with using the maximum possible size rather than with the conductivity of the material. The discussion about the most suitable metal is relevant in relation to the mechanical properties of the dipole's materials.

Wire Weight

Compare the weight of a dipole made with #14 AWG copper wire and another dipole with #12 AWG aluminum wire of equal length (l). The mass is

$$m_{\mathrm{Cu}} = l\frac{\pi}{4}\left(d_{\mathrm{Cu}}\right)^2 \delta_{\mathrm{Cu}} .$$

Because both wires are the same length,

$$\frac{m_{\mathrm{Cu}}}{\left(d_{\mathrm{Cu}}\right)^2 \delta_{\mathrm{Cu}}} = \frac{m_{\mathrm{Al}}}{\left(d_{\mathrm{Al}}\right)^2 \delta_{\mathrm{Al}}} .$$

Therefore,

$$\begin{aligned} m_{\mathrm{Al}} &= \frac{\delta_{\mathrm{Al}}}{\delta_{\mathrm{Cu}}}\left(\frac{d_{\mathrm{Al}}}{d_{\mathrm{Cu}}}\right)^2 m_{\mathrm{Cu}} \\ &= \frac{2.7}{8.94}\left(\frac{2.052}{1.627}\right)^2 m_{\mathrm{Cu}} \\ &= 0.480 \times m_{\mathrm{Cu}} . \end{aligned}$$

An aluminum dipole with the same ohmic resistance would be half the weight of a copper dipole.

If a CCS wire of the same diameter (d_{Cu}) is used, assuming an average density, $\delta_{\mathrm{CCS}} = 8\ \mathrm{g/cm^3}$ as (8/8.94) ~ 0.9, the CCS dipole would weigh only 10% less than the copper dipole. So, the biggest difference between copper and CCS is in the elastic properties. The properties of copper, aluminum, and steel are explored, for instance, in the ninth edition of *Materials Science and Engineering* by William D. Callister, Jr., and David G. Rethwisch.

Wire Sag

Due to mass, a wire dipole suspended from two ends sags in the center, forming a catenary curve that can be approximated by a parabola, as explained in the 24th edition of *The ARRL Antenna Book*. Therefore, the wire sag (h) is related to the magnitude of the wire weight per unit length (w), the total horizontal distance between the two supports of the wire (S), and the magnitude of the tensile stress (T) at each end of the wire according to

$$h = \frac{wS^2}{8T} .$$

Conclusions

The stress must be less than the elastic limit (yield strength) of the material so the wire does not undergo permanent deformation. Therefore, a working criterion is to design with a stress equal to about half the elastic limit. However, because the yield strength of aluminum is practically halved (35 MPa for aluminum and 69 MPa for copper), wire weight and stress are reduced by roughly the same amount, so both dipoles will have similar sag. In addition, if the modulus of elasticity of each material is considered (69 GPa for aluminum and 110 GPa for copper), the mechanical properties of aluminum are again much poorer than those of copper because for the same tension applied, the deformation elongation of the aluminum wire will be 59% longer than for copper. Additionally, if we add to all these considerations that it is easier to obtain copper wire of any type and size, it does not seem convenient to replace it with aluminum.

On the other hand, CCS wire is not quite ductile, as it permanently twists and becomes difficult to work with. However, as it has a much higher yield strength (180 MPa), CCS is the best material to use for the longest wire dipoles. This metal can tolerate higher stresses, which considerably reduces wire sag.

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