Antenna Options: A Yagi Case Study Part 2—Element Material Options

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In the first episode of this *Tale of Three Yagis*, we explored the design options for a 3-element 2-meter Yagi with intended field use and restricted to a 30-inch or smaller boom. Our options included high-gain, high-front-back, and wide-band versions of the antenna. For each option we provided design dimensions for round-tubing elements ranging from 0.125 inch up to 0.5 inch in diameter. In this episode, we shall examine some of the element materials other than round tubing that we may use and how we may go about the process of correlating these materials to the dimensions in the first part of this exercise on antenna options.

However, let's make no mistake—the design options presented do not represent a comprehensive view of all of the Yagi design variations that we might bring to the planning table. There are designs with wider bandwidths and designs with higher gain—all generally within the initial guidelines for the exercise.

For example, we may develop a very wide-band Yagi by slaving a second driver to the original driver. Technically, this becomes a 4-element Yagi if we view the driver as a parasitic element, but it is not a true director except at the very low end of the operating passband. Table 1 shows the dimensions for such a very-wide-band Yagi using 0.125-inch diameter elements. The performance figures appear in Table 2 and in Fig 1 and Fig 2. As the table shows, the antenna is capable of very acceptable performance for at least the 140 to 150-MHz range, with lesser performance beyond. The first graph—taken from an *EZNEC* frequency sweep and displayed on AC6LA's *EZPlot*—shows the relatively even gain, which varies by only 0.4 dB across the passband. The line marked "front/sidelobe ratio" actually provides the worst-case front-to-back value, in contrast to the 180° front-to-back ratio that shows higher values across part of the operating passband. The second graph records the modeled feed-point resistance, reactance and 50-Ω SWR values from 140 to 150 MHz. Note that the SWR does not rise to 1.3:1 within the passband. The performance overall is comparable to the wide-band design in Part 1, but with a much wider passband. However, in exchange for the

Table 1—4-Element Very-Wide-Band Yagi Dimensions for 0.125" Round Elements

Dimensions: L = Element half-length—double the L-value to obtain the full element length. Dimensions in inches—multiply by 25.4 to obtain dimensions in millimeters.

Ref L	*Dri L*	*Dir 1 L*	*Dir 2 L*	*R-Dr Sp*	*R-Dir 1 Sp*	*R-Dir 2 Sp*
21.01	21.20	18.69	17.76	7.41	8.89	21.16

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extended passband, the design requires an extra element and exceptionally careful construction and field adjustment to achieve the performance promised by the model. In the rigors of field operation, the chances of maladjustment due to bumps and other accidental deformations are too great for inclusion in the design pool.

There are ways to achieve higher gain from the same boom length as our three original designs. One technique is to use a pair of phased elements as a driver, as exemplified by the design in Table 3. The antenna is essentially a *phagi*, that is, a phased horizontal array with one or more parasitic elements. We may also call this a log-cell Yagi, although the phased driver set is not large enough to constitute a true LPDA on its own. The dimensions specify 0.1875-inch diameter elements for 2 meters. The phase line between the two rear elements consists of a 50-Ω line with a reversal between elements. The electrical length is 20.26 inch, allowing lines with a 0.66 velocity factor to meet the need. The native feed-point impedance at the 146-MHz design frequency is about 15 + *j*23 Ω. Since the impedance is inductive reactance, we may apply beta-match techniques to raise the impedance to 50-Ω resistive—or close to that value. A shunt capacitor with about - *j*35.5 Ω reactance across the feed-point gap will do the job. At 146 MHz, this amounts to about 30.7 pF, the equivalent of a 12.27-inch electrical length of 50-Ω transmission line used as an open stub.

Table 4 tabulates the performance between 145 and 147 MHz, while Figures 3 and 4 provide a graphical view of the same data. The design provides almost an extra dB of forward gain relative to the high-gain design in Part 1, while preserving a high front-to-back ratio within the listed passband. Typical of most Yagi designs—the worst-case front-to-back ratio is relatively even across the passband, while the 180° value tends to peak at a high value. As with many higher gain Yagi designs, the SWR and impedance curves suggest that the antenna may be useful below the lower limit of the passband, but the performance graphs suggest that the use is limited by decreasing gain and front-to-back ratios.

I have not included this design in our general pool because it involves phasing techniques. To construct the phagi would require extensive measurement and adjustment, for example, to determine the precise velocity factor of the line used for phasing the rear-ward elements. Listed velocity factor values are simply not accurate enough from one batch of line to the next to ensure proper line length to achieve the modeled performance. The phase line becomes an extra element to carry into the field, not to mention the need for connectors at each end as part of the antenna structure.

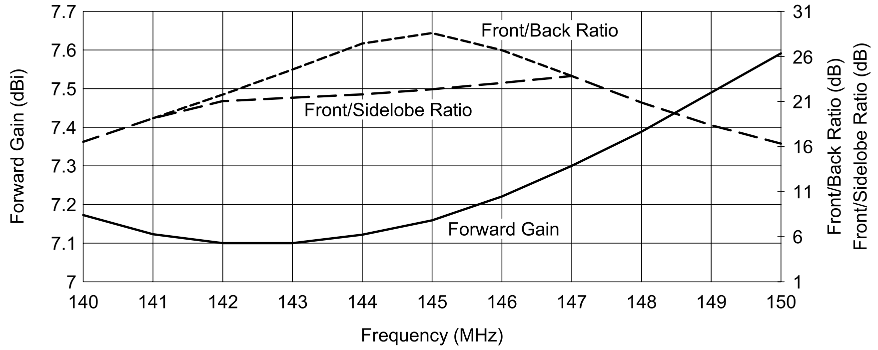

Fig. 1—Very-wide-band 4-element Yagi gain and 180° worst-case FB ratios.

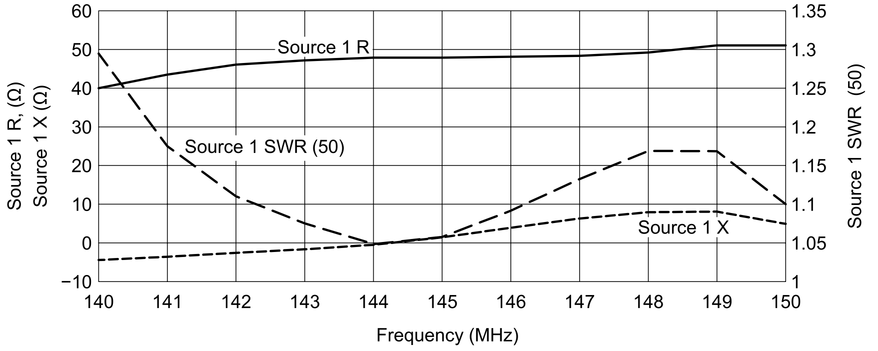

Fig. 2—Very-wide-band 4-element Yagi feed-point resistance and reactance; 50-Ω SWR.

Table 2. 4-Element Very-Wide-Band Yagi Modeled Performance Across 2 Meters

0.125" Diameter Elements

Freq. MHz	*Free-Space Gain dBi*	*Front-to-Back Ratio dB*	*Feedpoint Z R +/- jX Ω*	*50-Ω SWR*
140	7.17	16.51	39.5 - *j*4.7	1.294
142	7.10	21.78	45.9 - *j*3.0	1.110
144	7.12	24.61	47.7 - *j*0.6	1.050
146	7.22	26.80	48.0 + *j*3.6	1.089
148	7.39	20.92	49.5 + *j*7.7	1.167
150	7.59	16.33	51.1 + *j*4.7	1.100

Table 3—3-Element Phagi Dimensions for 0.1875 inch Round Elements

Dimensions: L = Element half-length—double the L-value to obtain the full element length. Dimensions in inches—multiply by 25.4 to obtain dimensions in millimeters. The elements marked "Ref" and "Dri" actually form a phased pair of driven elements.

Ref L	*Dri L*	*Dir L*	*R-Dr Sp*	*R-Dir Sp*
19.80	19.45	17.63	10.25	28.70

Nevertheless, these two brief examples of alternative designs are reminders that we do not exhaust the full set of design options in the ones that we included in Part 1. Rather, these options only scratch the surface of a wide variety of Yagi and related designs. We chose them only because they form a relevant collection of straightforward designs that promise relative ease of replication in most home shop settings. As a final design reminder, all of the designs in both this part and the first episode involve elements that are insulated and isolated from a metallic boom and indeed prefer a non-metallic boom. However, to say more about boom materials would leap into the last part of this series and skip our trips to the home improvement center and our survey of element materials.

Part 2—Element Materials for the Three Yagi Designs

It would seem on the surface that the range of rod and tubing sizes reported in the dimension tables of Part 1 would cover the territory indicated by the Part 2 subtitle. We have already noted that one may use aluminum, brass, or copper tubing or rods for the elements with no significant change in performance. Once an element reaches a certain diameter for a given frequency, the differential in material losses for common conductive materials no longer makes a difference to performance. At 2 meters, that semi-critical element size is about 1/8 inch.

I have not included common metric sizes of tubing and rod material. For example, the common 4-mm material used in Europe for VHF arrays is about 0.1575 inch in diameter, half way between 1/8 inch and 3/16 inch US sizes. I have also omitted AWG wires sizes, although AWG #8 (0.1285 inch) would make a usable substitute for 1/8-inch elements with no design modification. Elements smaller than 1/8 inch tend to be flimsy, while those larger than 1/2 inch tend to be physically impractical. As a result, the range of sizes that we have provided in the dimension tables covers most of the reasonable materials for 2-meter Yagi construction.

Some might assume that builders want to use elements having a circular cross section. I have learned over the years that we should never make this assumption. Antenna builders will latch onto almost any material at hand, including dime-store collapsible whips, flat stock, L-stock, and even channel and square stock. For special purposes, some antenna builders will use the metal tape that comes in

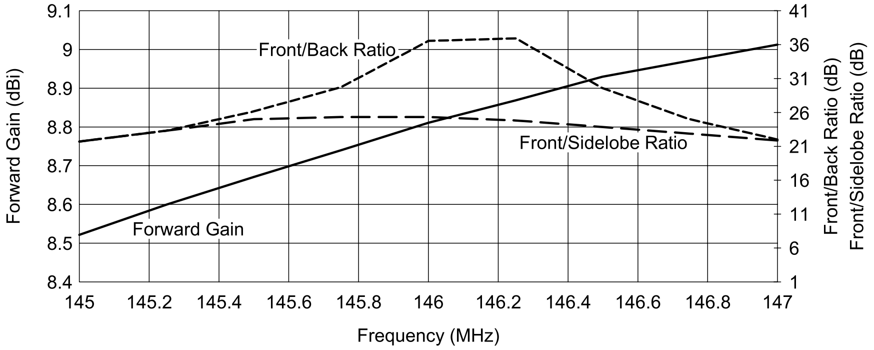

Fig. 3—Gain and 180° worst-case FB ratios for 3-element phagi.

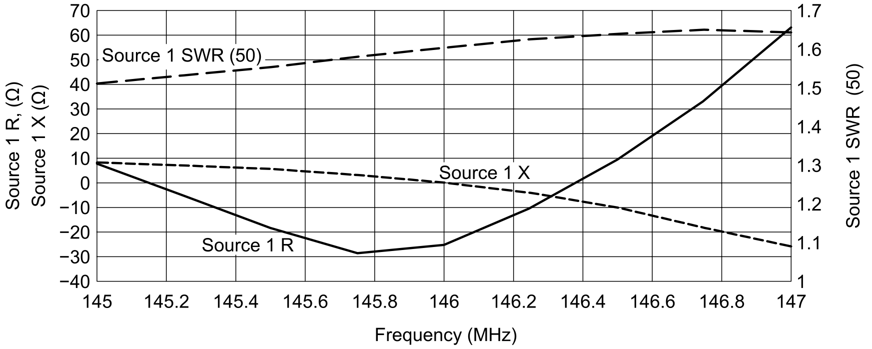

Fig. 4—Feed-point resistance and reactance; 50- Ω SWR for 3-element phagi.

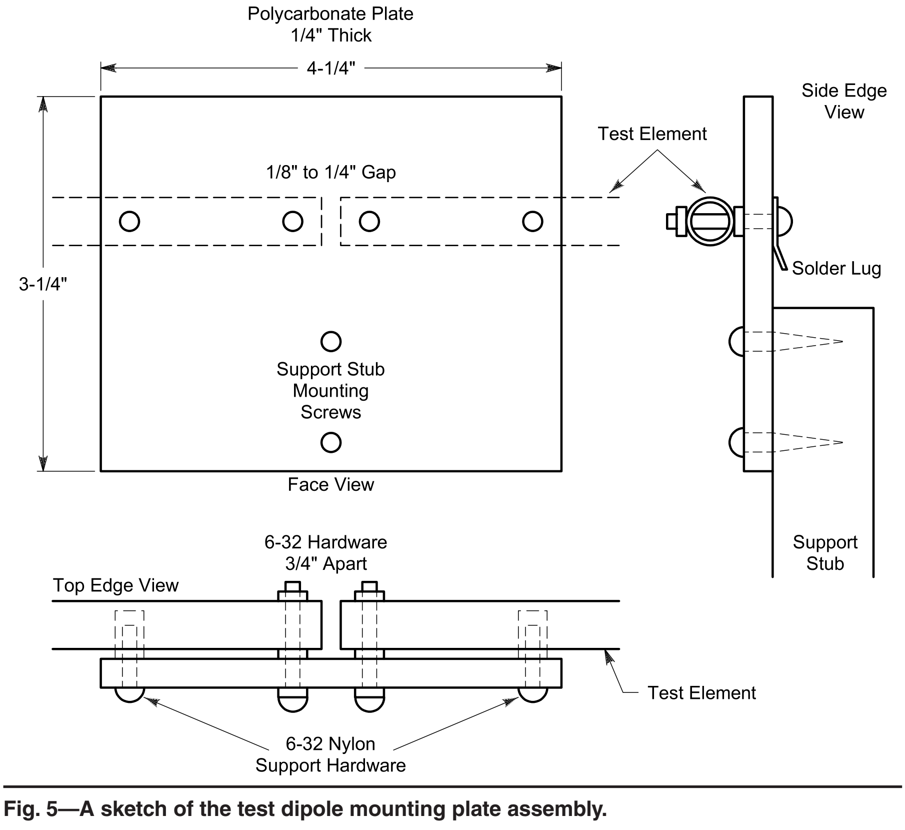

Fig. 5—A sketch of the test dipole mounting plate assembly.

spring-loaded tape measures.

Proposals to use these materials come with one question—with what round element size does the size of each variant material equate? The notes in this section will present a few of my findings for some of the materials at 146 MHz. More important than the results is the procedure that I used to determine them. I shall outline a very practical procedure for use on 2 meters that will allow anyone to replicate my experiments and to find the best approximation of a round conductor that matches a novel material proposal. All that we require is a reasonably accurate antenna analyzer, a standardized center hub for a dipole, and a mast-stand fixture on which to perform the experiments.

The method that I used to compare a variety of materials was to create dipoles resonant at 146 MHz. Using an MFJ-259B analyzer, first calibrated to my station receiver, I made and pruned dipoles for each round conductor listed in the dimension tables of Part 1 and then made and pruned dipoles for each variant material that I could think of and easily obtain. I added a round 0.75 inch diameter dipole to the group, because many substitute materials are close in performance to this size round element. The key feature of the procedure is not absolute agreement with modeled predictions for the round conductors, but instead a method that would ensure consistency from one dipole to the next.

The dipole hub assembly that I used is designed to provide a consistent dipole-center environment from one test to the next. Fig 5 shows the general outline of the plate, which I made from a scrap of 1/4-inch thick polycarbonate. Hence, there is no magic, but only convenience, in the plate length and width. Each dipole candidate mounts both physically and electrically by way of the two #6-32 nuts and bolts at the upper plate center. For each dipole, I used a bolt length to have the least excess threaded length beyond the limits of the dipole material. The two outer holes in the plate use nylon screws into threaded plastic tubes that sit within holes in the dipole for support of the element. I removed the support tubes for the tape elements, since they are too thin to support drilling 1/4-inch holes. For the rod elements, I used

Table 4—3-Element Phagi Modeled Performance from 145 to 147 MHz.

0.1875" Diameter Elements

Freq. MHz	*Free-Space Gain dBi*	*Front-to-Back Ratio dB*	*Feedpoint Z R +/- jX Ω*	*50-Ω SWR*
145	8.52	21.57	40.8 + *j*7.8	1.305
145.5	8.67	26.82	47.2 + *j*5.6	1.137
146	8.81	36.48	54.7 + *j*0.0	1.093
146.5	8.93	29.55	60.9 - *j*10.5	1.315
147	9.01	21.89	61.2 - *j*25.7	1.652

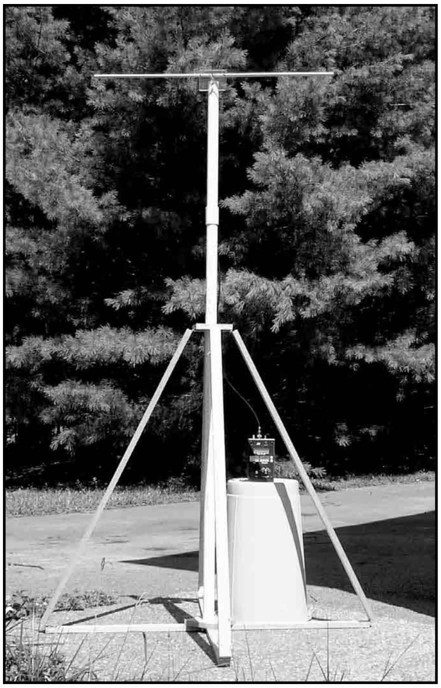

Photo A—The complete test assembly with a tubular dipole attached and the antenna analyzer stationed closer to the ground.

Photo B—A close-up of the center plate with a thin rod element clamped in place and supported by the outer posts.

Photo C—The same assembly as in Photo B, but with an L-stock element—the outer support posts pass though holes in the element.

square washers at the inner screws to electrically clamp the inner rod ends, while the rod itself rested on top of the outer tubes.

The plate mounts to a section of PVC with a pair of sheet-metal screws. Because the assembly is only temporary, you can use any clean hardware. The area above the support stub and behind the dipole center is clear so that I could mount a length of coax with solder lugs, avoiding the use of a connector at this point. The coax length is 1/2 λ, allowing for the velocity factor of the RG-8X that I used. (Note that RG-8X has different velocity factors from different makers. However, do not rely on manufacturer's specifications for velocity factor. Measure the line for an electrical 1/2 λ. My line had a listed velocity factor above 0.8, but measured about 0.735. The distant line end should replicate the feed-point impedance at the dipole terminals, while minimizing body effects during measurements.)

I have a wood test stand that I use for various purposes. It appears in the photos. It holds a 5-foot section of 1 1/4 inch Schedule 40 PVC for this test. The upper section of the mast, using a coupling (not cemented), is a 2-foot section of the same material, and that is the support stub to which I attached the dipole plate. For pruning, I simply lifted the upper section off, carried it into the shop, and sawed, clipped, or sanded the element ends, according to which material was under test.

The 7 foot total height of the assembly placed the antenna about 1 λ above ground, a sufficient height to minimize ground effects on the dipole's resonant frequency. For each test, I placed the test stand in the same position with the dipoles oriented the same way. The goal was not laboratory precision, but usable consistency from one test to the next.

Photo A shows the complete assembly with a tubular dipole attached and the antenna analyzer stationed closer to the ground. Photo B is a close-up of the center plate with a thin rod element clamped in place and supported by the outer posts. The last picture in this series, Photo C, shows the same assembly with an L-stock element—the outer support posts pass though holes in the element.

You may replicate this type of system—adding your own improvements—to test any number of materials for comparison with the round elements presumed by antenna modeling software. In the interim, the following notes record the results that I obtained.

Round Conductors

Table 5 shows the results of tests with round conductors that form the reference values for all of the subsequent tests. Also included in the table are the *NEC-4* modeled values for the lengths of each size of tubing.

Round conductors offer the best combination of strength vs weight and ability to slip the wind to minimize loading from that source. As well, they tend to resist ice build-up better than most flat or L-stock elements. Hence, for a long-term station installation, I would recommend them. For most purposes 6061-T6 and 6063-T832 aluminum stock, available by mail order if not in stock locally, are the best antenna element materials. Nevertheless, there are reasons and occasions for using other materials.

Interestingly, the round elements all measure well within 0.5% of the *NEC-4* modeled lengths, except for the 3/4-inch tubing, which comes in with under 1.0% variance relative to the modeled value.

Table 6 provides the measured data on all of the tested alternatives to round conductors. The table lists not only the length of the dipole that turned out to be resonant on 146 MHz, but as well the size of the most nearly equivalent measured round conductor. This value permits the builder to refer to the dimensions in Part 1 that most closely approximate the dimension needed for the alternative material.

Table 5—Modeled and tested resonant lengths of round-element 146 MHz dipoles.

El. Diameter (inches)	*Modeled Length (inches)*	*Tested Length (inches)*
0.125	38.42	38.31
0.1875	38.28	38.25
0.25	38.10	38.06
0.375	37.80	37.81
0.5	37.60	37.44
0.75	37.30	36.94

Table 6—Tested 146-MHz resonant lengths of alternative element materials.

Material	*Tested Length (inches)*	*Nearest Round Element*
Aluminum Flat Stock (size in inches)		
1/2 by 1/16	37.31	0.5
1/2 by 1/8	37.19	0.5
3/4 by 1/16	37.06	0.75
Aluminum L-Stock (size in inches)		
1/2 by 1/2 by 1/16	37.44	0.5
3/4 by 3/4 by 1/16	37.00	0.75
Collapsible Whips (size in inches)		
1. 5-section TV "rabbit ear," maximum extension 48.5 inches with "button" tip. Approximate diameters: 0.25, 0.219, 0.1875, 0.125, 0.0625		
a. With largest sections fully extended		
	37.88	0.375
b. With smallest section fully extended		
	40.00	<0.125
2. Radio Shack 5-section cordless telephone replacement (#270-1405A); maximum extension 23 inches with button tip. Approximate diameters: 5 mm, 4.125 mm, 3.25 mm, 2.375 mm, 1.5 mm		
Roughly equal section extension		
	38.88	*<0.125*
Metal Measuring Tapes (size in inches)		
1 (15/16 with curve)	37.38	0.5
3/4 (11/16 with curve)	37.63	0.375 to 0.5
5/8 (9/16 with curve)	37.88	0.375
1/2 (15/32 with curve)	38.25	0.1875

Flat Stock

Flat stock holds two advantages for home construction. First, it is readily available at home centers. Second, it is flat. Hence, we can drill it easily on any equally flat surface and avoid the difficulty of drilling a round surface. The disadvantage of this stock is that the 1/16 inch thick type is very flimsy and bends all too easily. The 1/8 inch thick type is sufficiently sturdy for a permanent installation, but may be needlessly heavy for field use.

The flat stock plays very close to its measured round counterparts. Some modelers advocate using round wires having the same surface area as the flat stock. The closest round wire to 1/2 inch by 1/16 inch flat stock is 0.375 inch tubing. However, the measured lengths for both the 1/16 inch and 1/8 inch flat stock is 0.5 inch tubing, which has about 1.4 times the surface area per unit length. As well, the 3/4-inch by 1/16-inch flat stock measures closest to the 0.75 inch round tube.

L-Stock

L-stock that is 1/16-inch thick combines the benefits of offering flat surfaces to drill with excellent rigidity and easy availability at home centers. In addition to Yagi service, builders have used the stock for both the horizontal element-portions of quads and for Moxon rectangles. It is half the weight of square stock with equal outer dimensions. The down side of L-stock is that it offers considerably more wind resistance than a round conductor. It also is prone to snagging in field exercises, such a fox hunts in wooded areas.

As with flat stock, L-stock appears to approximate its round counterpart element material in both the measured half-inch wire and the modeled 3/4-inch wire. Within the limits of my measurements (1/16 inch), there is no significant difference between the flat stock and the L-stock.

Collapsible Whips

For field antennas, collapsible whips offer a certain convenience, since we can shorten the elements to the whip's minimum length for transport. In addition, most whips adapted from TV and cell-phone replacement service have a plug in the lower end. The plug has a mounting hole, which permits the builder to swivel the elements in line with the boom for an even more compact assembly during transport to and from the working site.

For this test, I salvaged whips from very old TV rabbit ears as a test of larger diameter versions. Since the whips extended to about 48 inches, I performed two tests—one with the larger section dominating the element length at 146 MHz, the other with the thinnest sections fully extended. I also obtained two Radio Shack cell-phone whips that extend only to 28 inches per unit. These whips give an indication of equivalent lengths for the thin-whip style. In both cases, I used the square washer clamp method of fastening that I used with aluminum rods in the initial tests.

With the large whips using their fattest sections, the dipole length is closest to 3/8 inch round wire. The same whip using its inner largest-diameter section (about 0.25 inch) and its smallest section (about 1/16 inch) requires a length of 40.0 inches, which is longer than needed for 0.125-inch uniform-diameter material. The small whip required a dipole length of 38.88 inches, also longer then needed by the smallest round element tested.

The excess length required by collapsible whips, even with fat button ends, owes to the stepped-diameter structure on each side of the dipole centerline. The first test used the fattest large-whip sections, resulting in the smallest step, and the result is the shortest of the required whip lengths. The second large-whip test had the greatest step in diameter, and yields the longest resonant overall length. The cell-phone replacement begins with a smaller diameter, from which we might expect a longer overall length. However, the steps in diameter are small and regular so that its length is shorter than required for the second large-whip test. All of these results coincide with fundamental theory regarding elements that taper from the center to their tip.

Measuring Tapes

The final group of tests involves a material used almost exclusively by foxhunters—cannibalized measuring tape. Although the tape is steel, it is satisfactory for field antennas. By judiciously buying a few bargain tapes and replacing some very worn tape measures in the shop, I managed to find four tape widths. Measuring tape is very thin, but the exact thickness may vary with brand and age. Hence, the values shown in the table are indicative, but not absolute, for each width.

The advantage of a tape-measure element is its ability to bend at a field snag and to bounce back to position with no damage (at least, no damage in the short run). Because a 3-element, 2-meter Yagi, perhaps of the maximum front-to-back design, requires about 10 feet of tape for its elements, a single long tape measure provides material for many replacement elements or for several individual Yagis. Replacement tapes without the cases and mechanisms are difficult to find locally these days, so expect to destroy a complete tape-measure unit if you opt for this element material. However, bargain tape measures abound.

The measured resonant lengths for tape-measure material all indicate an equivalence to round conductors about half as much in diameter as the tapes were wide. Unlike the flat stock, which had a significant thickness, the tapes are very thin. Hence, their wide surfaces alone did not suffice to bring them close to the resonant lengths of round conductors with the same cross dimension.

Summary of Findings

The measured values for the alternative materials held a few surprises. Perhaps the performance of flat stock was the most dramatic. Nevertheless, I would not claim that the near-equivalencies at 2-meters would hold up at HF, where one might trade the greater difficulty of constructing the requisite number of long dipoles for finer gradations of measurement.

The survey of alternative element materials is not by any means complete or ultra-precise. However, the technique used to find their nearest equivalent round conductor has proven quite reliable in adapting designs. Reliability here means that the results are usable for the adaptation of round wire designs to alternative stock used in the home-construction of antennas. Neither my tape measure nor my antenna analyzer meets anything like laboratory standards, and the testing circumstances are not of calibrated range or chamber quality.

One final caution is in order. With non-round conductors, the inter-element coupling between adjacent elements may not be identical to the coupling from round elements. Hence, some final field adjustment of element lengths may be necessary, even for materials listed as equivalent to a round conductor. This caution is especially true of the driver-director relationship, where small director length adjustments tend to yield considerable changes in the Yagi performance curves at 2 meters.

Field adjustment, of course, presumes that we have already built our Yagi design of choice. Even within the constraints of this exercise, we have options. Some of those options will be the subject of "Part 3—Building 3-Element Yagis for Different Uses." □□