Some Basics of Very-Wide-Band Yagi Design
Part 2: Very-Wide-Band Planar Yagi Performance

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Purpose: In Part 1 of this small study of very-wide-band (VWB) Yagis, we examined an 8-element parasitic array using crossed elements and quadrature feed with potential application to satellite communications in the 250-317-MHz region. In the course of our examination, we encountered some of the principles underlying VWB yagi design. However, those principles in part were compromised by the bandwidth-broadening effect of the quadrature feed system. The Yagi described there, if set out as a planar structure without the crossing elements shows a significant reduction in operating bandwidth.

In this part of our investigation, we shall pose a simple question: can the bandwidth of a planar Yagi be extended to cover the same 67-MHz bandwidth with usable performance? Unlike the crossed-element Yagi, with its implicit satellite communications application, the planar Yagi has no defined application other than those in which we generally use parasitic arrays. Hence, whether a given level of performance attained is indeed usable will remain a user judgment.

In addition to our first question, we shall pose a second question predicated on the very large element diameter (1/2") used in the crossed-element array: can we achieve the desired operating bandwidth with thinner elements, perhaps half the diameter of those in the initial design? We shall be interested not only in the attainment of the desired operating bandwidth in terms of an SWR value, but as well in the consequences for the usual performance criteria of gain and front-to-back ratio.

Background and Principles of VWB Design: The earliest Yagis strove for maximum gain, sacrificing bandwidth to obtain it. The emergence of the DL6WU design principles for VHF and UHF Yagi-Uda arrays ushered in (unnoticed by many) the era of wide-band Yagi performance. DL6WU designs were capable often of covering the entirety of the amateur 420-450-MHz band with under 2:1 SWR (relative to a reference impedance of 50 Ohms). The gain generally peaked high in the operating bandwidth, and the front-to-back ratio described a two-peak curve, with one peak low in the band and another just a bit higher than the gain peak. For a review and appreciation of the DL6WU designs, see "Appreciating DL6WU Wide-Band Long-Boom Yagi Design."

In the 1990s, there emerged from the work of NW3Z and WA4FET a set of HF Yagis using principles that the authors labeled as OWA or optimized wide-band antennas. The OWA Yagi differs in some important respects from the ordinary or DL6WU wide-band Yagi. Both use the reflector-driver-director-1 portion of the array to set the feedpoint impedance. Standard wide-band Yagis tend toward an element spacing in the vicinity of 0.2 wavelength and 0.075 wavelength for the reflector-driver and the driver-director-1 arrangement. The OWA Yagi uses much closer spacing among these elements, so that the first director becomes almost an extra element in some designs. That is to say, the OWA often uses 6 elements on the length of boom where standard design may use 5. In part, the close spacing of the rearmost elements results from the attention paid to the placement of the second and third directors, which often have the same length. The result is a 5-7% operating bandwidth--sufficient for most amateur bands--but far short of the 10% bandwidths attained by DL6WU designs. In return for the more modest bandwidth, the OWA designs are capable of rather tight control of operating parameters, showing only small changes of gain and front-to-back ratio across the passband. As well, one can design OWA Yagis with improved sidelobe suppression and with 50-Ohm SWR values that never rise above 1.25:1. For further information on OWA Yagi design, see "Notes on the OWA Yagi."

Very-wide-band (VWB) design is in effect an extension of DL6WU design, with attention to some special requirements of the VWB situation. The best way to illustrate the principles involved is to try to design VWB Yagis for the same 250-317-MHz band used for the crossed-element Yagi. Initially, we shall use the 1/2" diameter elements of the satellite Yagi in our planar version. However, we shall also explore what happens if we reduce the element diameter to 1/4", or half the initial size.

The Yagis will be designed to obtain a 50-Ohm SWR of under 2:1 across the 23.63% operating bandwidth. As well, the Yagis have as a general goal obtaining as smooth as possible a gain and front-to-back curve set for the band. **Fig. 1** shows the general outlines--to scale--of the arrays that emerged from the initial exercise. Since there is no single final Yagi design when it comes to meeting a set of specifications, these arrays should be considered as typical, but potentially capable of further optimizing.

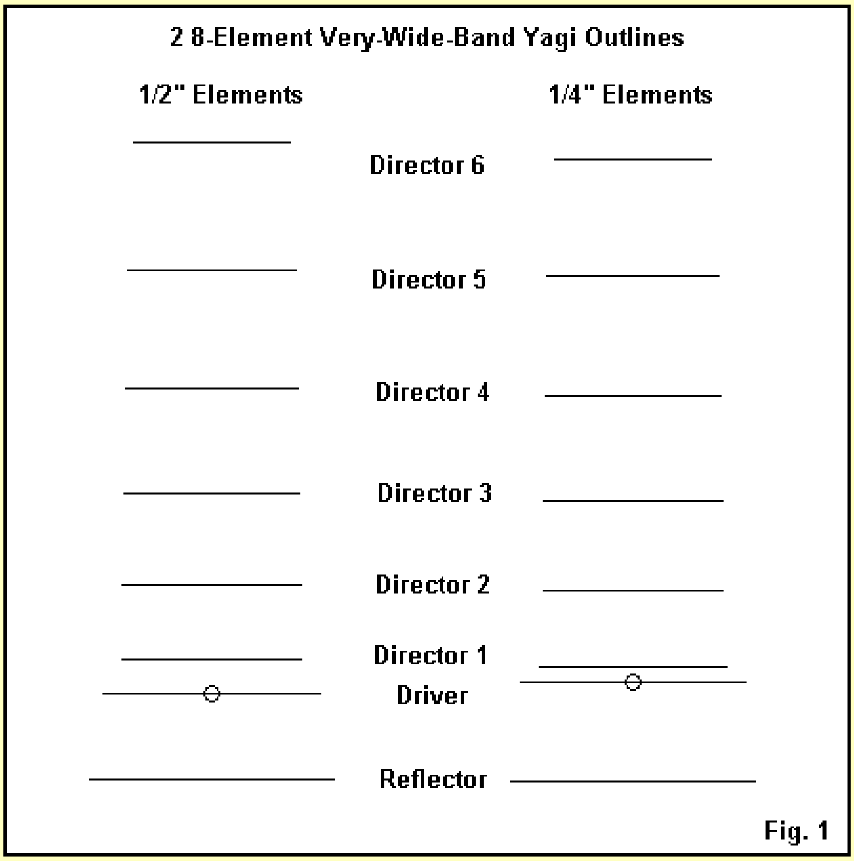


Fig. 1

The Effects of Element Diameter, Length, and Spacing: The following table lists the dimensions for Yagis using both 1/2" and 1/4" diameter elements, with the dimensions of the crossed-element Yagi added for comparison.

1. Dimensions of the 8-Crossed-Element Yagi for 250-317 MHz

All elements: 0.5" diameter 6063-T832 aluminum. Dimensions apply to each linear element in each set of two "wires" making up the crossed element.

Element	**Tip-to-Tip Length (")**	**Distance from Reflector (")**	**Distance from Preceding Element (")**
Reflector	**21.80**	**------**	**------**
Driver	**19.50**	**8.27**	**8.27**
Director 1	**16.82**	**11.10**	**2.83**
Director 2	**16.56**	**18.19**	**7.09**
Director 3	**16.32**	**26.65**	**8.46**
Director 4	**16.09**	**36.48**	**9.83**
Director 5	**15.88**	**47.50**	**11.02**
Director 6	**15.29**	**59.30**	**11.80**

Phase line length: 9.344", 50-Ohm cable, VF=1.0. Match line length: 8.948", 35-Ohm cable, VF=1.0.

2. Dimensions of the 1/2" 8-Element Planar Yagi for 250-317 MHz

All elements: 0.5" diameter 6063-T832 aluminum.

Element	**Tip-to-Tip Length (")**	**Distance from Reflector (")**	**Distance from Preceding Element (")**
Reflector	**22.90**	**------**	**------**

Driver	**20.10**	**7.99**	**7.99**
Director 1	**16.72**	**11.10**	**3.11**
Director 2	**16.58**	**18.19**	**7.09**
Director 3	**16.32**	**26.65**	**8.46**
Director 4	**16.08**	**36.48**	**9.83**
Director 5	**15.70**	**47.50**	**11.02**
Director 6	**14.58**	**59.30**	**11.80**

3. Dimensions of the 1/4" 8-Element Planar Yagi for 250-317 MHz

All elements: 0.25" diameter 6063-T832 aluminum.

Version A

Element	Tip-to-Tip Length (")	Distance from Reflector (")	Distance from Preceding Element (")
Reflector	22.60	------	------
Driver	20.79	9.25	9.25
Director 1	17.32	10.67	1.42
Director 2	16.85	17.72	7.05
Director 3	16.69	26.14	8.42
Director 4	16.22	35.94	9.80
Director 5	15.98	47.05	11.11
Director 6	14.65	57.87	10.82

Version B

Element	Tip-to-Tip Length (")	Distance from Reflector (")	Distance from Preceding Element (")
Reflector	22.60	------	------
Driver	20.79	9.25	9.25
Director 1	17.32	10.67	1.42
Director 2	17.01	17.91	7.24
Director 3	16.77	25.98	8.07
Director 4	16.46	35.43	9.45
Director 5	16.16	47.24	11.81
Director 6	14.02	57.87	10.63

Version C

Element	Tip-to-Tip Length (")	Distance from Reflector (")	Distance from Preceding Element (")
Reflector	22.20	------	------
Driver	20.70	10.60	10.60
Director 1	17.05	12.10	1.50
Director 2	16.93	18.10	6.00
Director 3	16.72	26.80	8.70
Director 4	16.52	36.20	9.40
Director 5	16.20	46.80	10.60
Director 6	15.30	57.40	10.60

Table 1. Dimensions of the 8-element Yagis for 250-317 MHz.

The adjustments made in moving from the crossed Yagi to the planar version--both using 1/2" elements--fall into two groups. First, the first director and the forward 3 directors are shorter in the planar version. These adjustments extend the upper-frequency bandwidth without materially affecting the lower-frequency performance. There is some effect, but it is taken care of when adjusting the reflector and driver, the second group of modifications. The reflector in the planar Yagi is closer to the driver, and both elements are longer than in the crossed-element design. The two sets of adjustments, while not wholly independent of each other, do have minimal impact on each other.

The greatest amount of change occurs when downsizing the elements from 1/2" to 1/4" diameter. Since there is no single set of dimensions that will yield a Yagi with the operating bandwidth specified as the goal, I have developed 3 related designs. Version A had the goal of yielding the smoothest resistance and reactance curves across the 250-317-MHz span. Bunching of the gain peak at the high end of the band led to version B, which attempts to move the gain peak lower in frequency and to increase performance in the lower half of the passband. Version C attempts to compress more systematically the spacing between elements than either of the other versions.

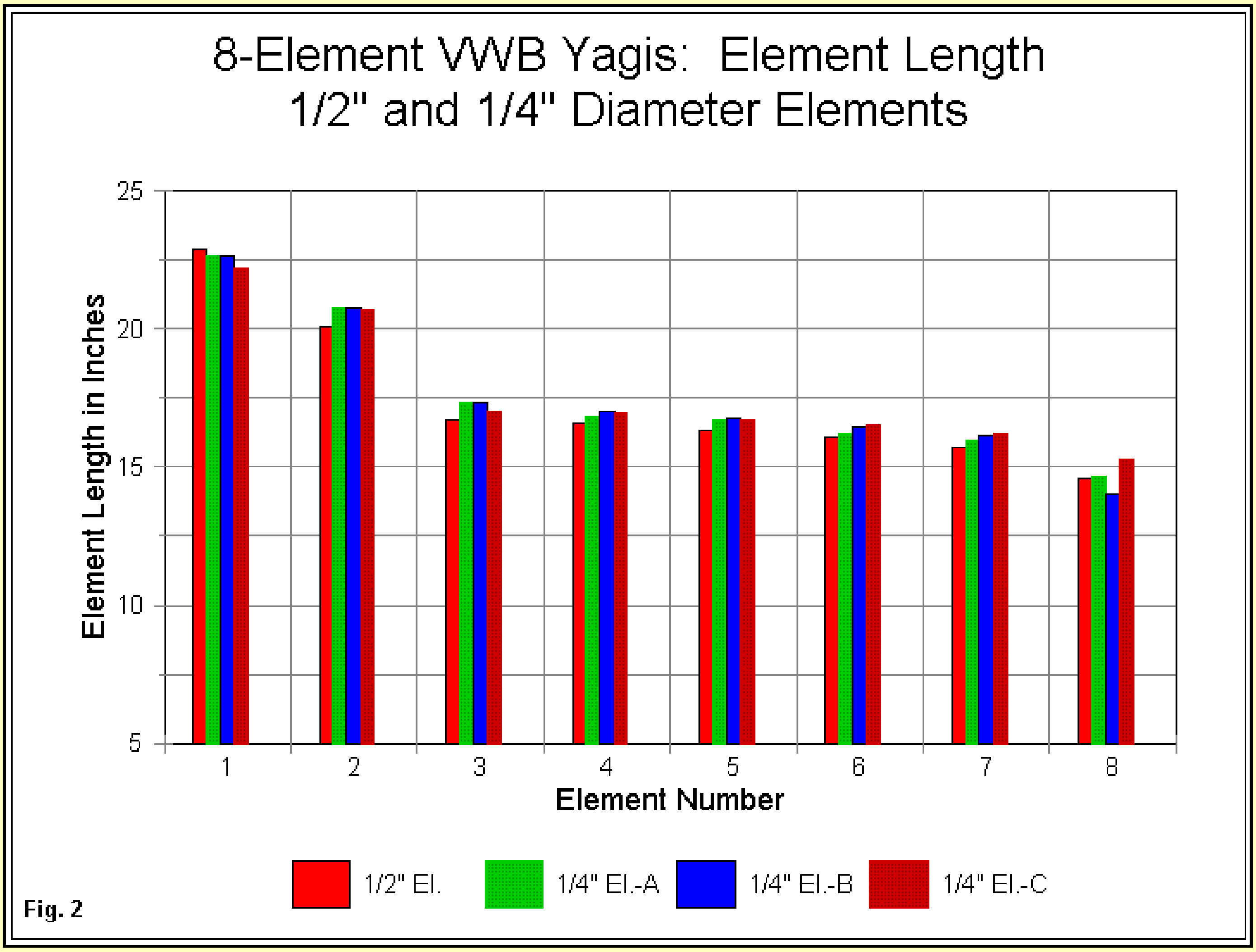


Fig. 2 provides a graphical representation of the element lengths used in the 4 planar designs. As one might expect, the 1/4" elements are all longer than the corresponding 1/2" element, except for the reflector, which is longer than 1/2 wavelength and thus requires greater length in the fatter version.

Among the 1/4" element designs, Version C--with its systematic element spacing--yields the smoothest perimeter curve of element length. Its forward-most director is actually longer than not only the other 1/4" directors, but as well the corresponding 1/2" forward director. In contrast, Versions A and B show considerable variability of element length from one element to the next, with the forward-most director of version B being significantly shorter than any other element in the entire series.

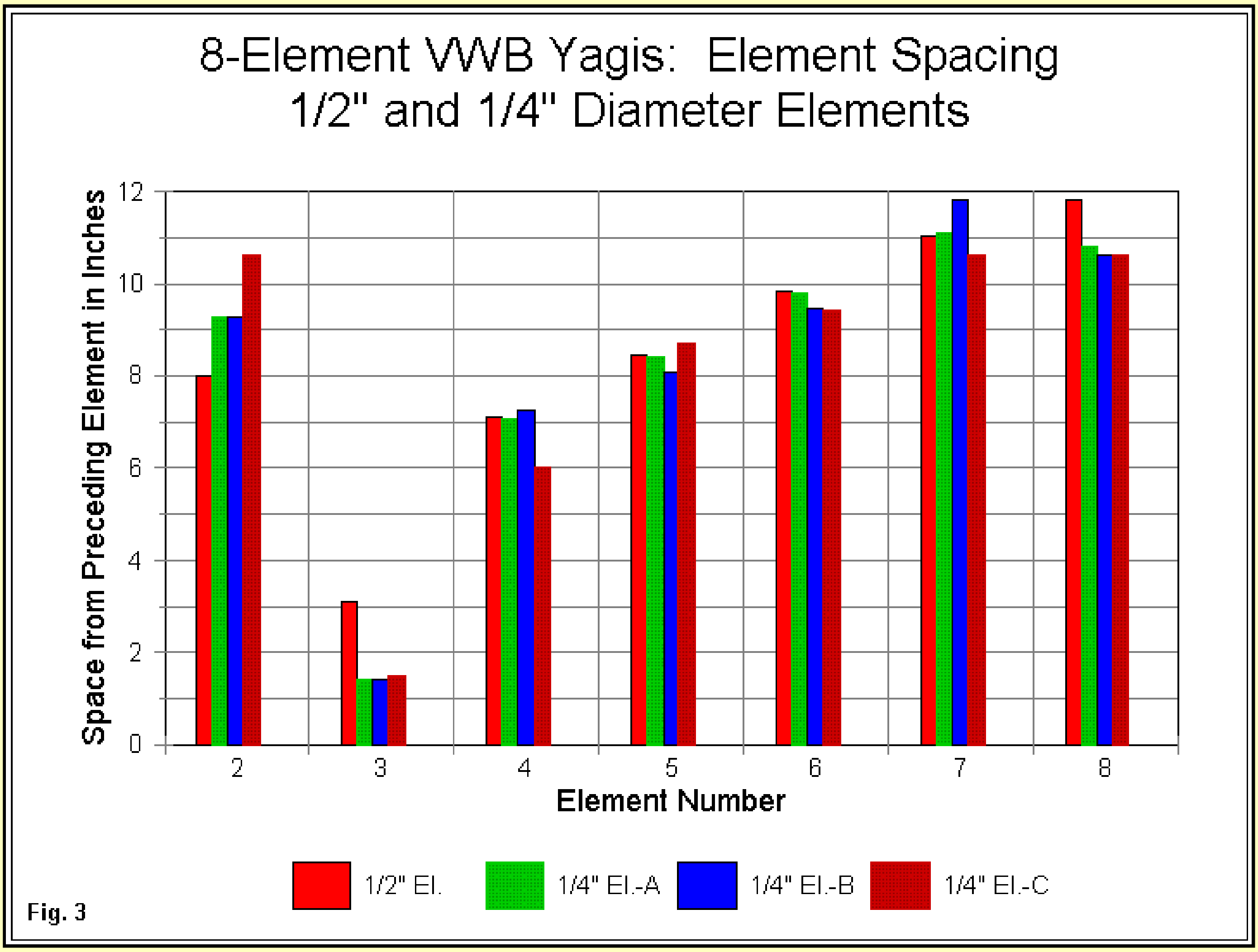


Fig. 3

Fig. 3 provides a similar graph of the spacing between adjacent elements for the designs. Most readily apparent are the changes in the reflector- driver-director-1 spacing. The 1/2" element design employs relatively close spacing of the reflector with wider spacing of the first director, relative to the driver. The 1/4" diameter designs require very close spacing of the driver and first director, with Version C using slightly wider spacing than the other two versions. However, version C also requires the widest spacing to the reflector.

There appears to be a minimum element diameter that will yield a VWB Yagi with up to 25% bandwidth. 1/4" appears to be very close to the limit in the frequency range tested. 1/4" is about 6E-3 wavelength relative to the band-center, 5.3E-3 wavelength at 250 MHz, and 6.7E-3 wavelength at 317 MHz. This diameter is insufficient in any of the three versions tested to yield the level of independence of adjustment at the upper and lower band edges compared to the larger 1/2" element. The 1/2" reflector and driver can be adjusted without significant effect on upper-end performance, and likewise the 1/2" forward-most two directors can be altered to change performance at the upper end of the spectrum with little significant effect on the low end of the band. However, in the 1/4" versions of the array, all adjustments aimed at one end of the band have smaller but significant effects on performance at the other end of the band.

Driver and First Director Current Magnitude: In common with all Yagi wide-band design techniques, the first director becomes the major source of energy for the forward elements at a certain point along the operating passband. In effect, it changes its role from that of the standard parasitic director to that of a secondary or slaved driver. In VWB design, the transition point at which the first director shows a current magnitude that is greater than the current magnitude on the driver occurs about 60% of the way from the lower to the upper end of the passband, with some variability depending upon other elements in the overall design. The curves of first-director current magnitude relative to a standard driver magnitude of 1.0 appear in **Fig. 4**.

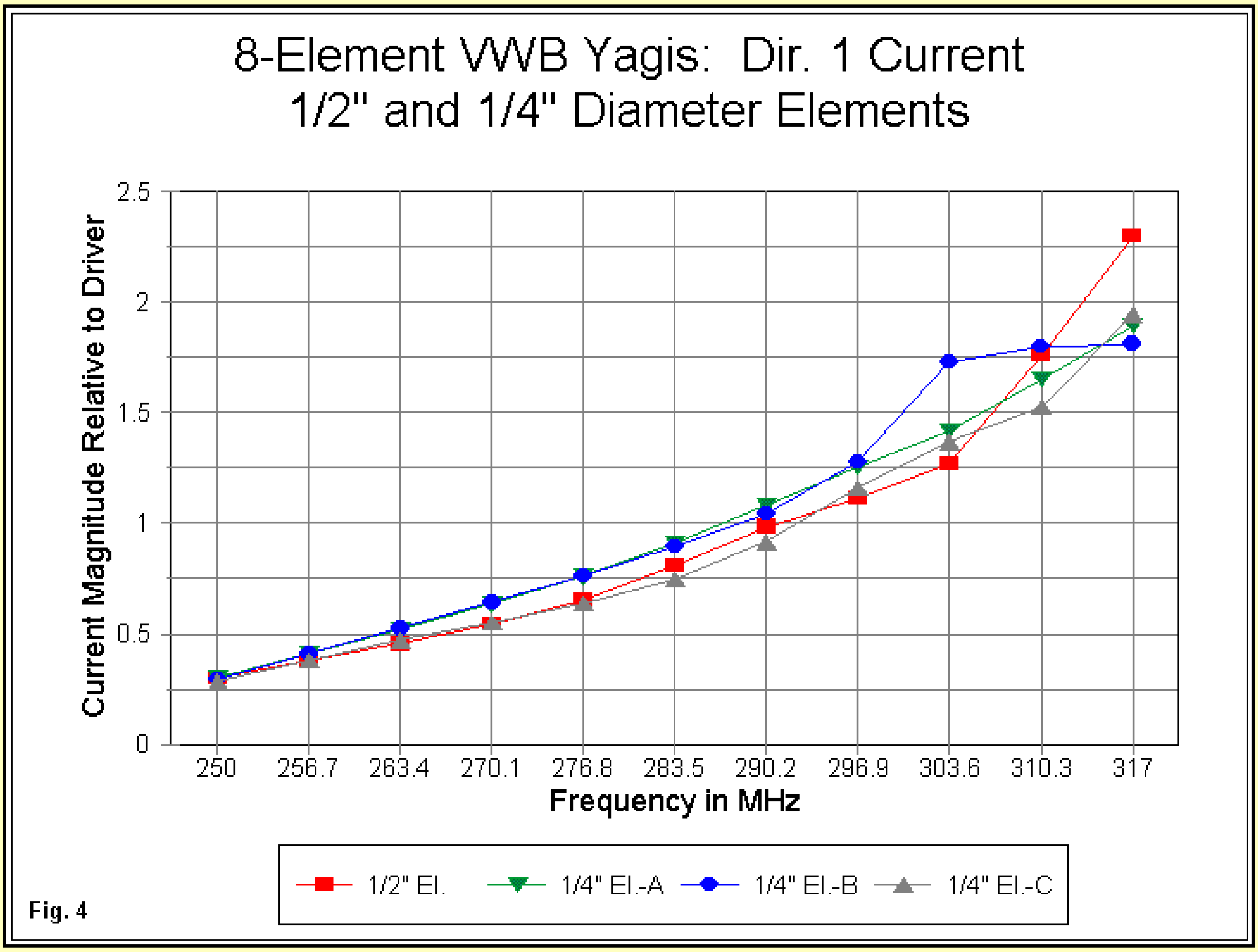


Fig. 4

Below the change-over point, the curves for all four of the planar designs are very similar. However, above the change-over point, the curves show interesting differences. The relative current magnitude for the 1/2" element design shows a steep climb, giving the first director a dominance over high frequency performance that is not shared fully by any of the 1/4" element designs. Version A of the thinner element designs shows the smoothest curve, without any vestige of the sudden rise that marks the fat element curve. The element length and spacing adjustments made to bring the gain peak lower in frequency for version B result in a sudden rise in first-director current magnitude, followed by a leveling off of the value. Version C of the 1/4"-element designs shows the beginnings of steep current magnitude climb only in the upper 10% of the passband.

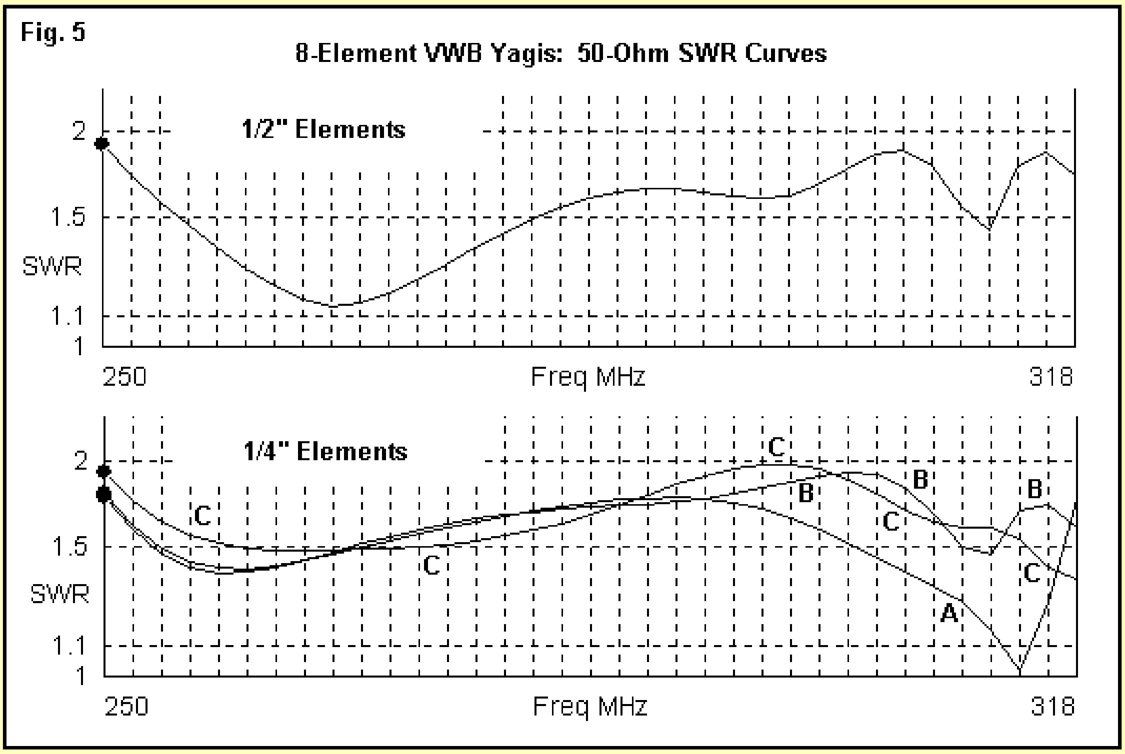


Fig. 5

8-Element VWB Yagis: 50-Ohm SWR Curves

Fig. 5 shows the 50-Ohm SWR curves that result from the various design manipulations. The curve for the 1/2" element design presents 3 SWR minimums across the passband, with the frequency steps between minimums shrinking with increasing frequency. In common with all VWB designs, the SWR minimum off the edge of the graph is followed by a rapid rise in SWR, yielding a sharp upper-end cut-off for the design. The rate of rise at the low end of the passband is always more shallow. Hence, when translating a design from one frequency range to another--especially if relative element diameter changes are involved--the most prudent design procedure is to scale the frequency at or near the upper end of the operating passband and then to make such other adjustments as may be needed to complete the design work for the new passband.

In the lower portion of **Fig. 5**, none of the 1/4" element designs can achieve the low value of SWR attained by the 1/2" design and still arrive at under 2:1 SWR across the entire band. Once more, inter-element coupling forms the basis for this phenomenon. The wide-spacing required by the reflector with thinner elements does not permit the low value of both resistive and reactive components of the feedpoint impedance 25% above the lower end of the band. Indeed, the minimum SWR value for the thinner element designs occurs within 10% to 15% of the low end of the passband.

The smooth impedance curve of version A of the 1/4" element designs results in a swamping of all but one SWR minimum. This minimum corresponds to the unseen minimum for versions B and C that occurs just above the upper chart limit, although the rate of rise in SWR for Version A above 314 MHz is slower than the rise in the other curves in the region of 319-320 MHz. The adjustments made to version B to lower the gain peak frequency result in a curve that is nearly congruent with the curve of the 1/2" element design. The price for congruence, however, is that the SWR values never go as low as those at the upper end of the version A curve. The redesign of the 1/4" element Yagi for version C results in a mixed curve relative to the preceding versions. The multiple dips at the upper end of the spectrum result in a descending SWR value that reaches a minimum near 320 MHz before a very rapid rise out of the range that makes the array usable. However, the minimum SWR in the lower half of the pass band never reaches down to 1.45:1.

Because the inter-element or mutual coupling situation is so different between the 1/2" and 1/4" element versions of the array, the adjustments to the Yagi with thinner elements is much more sensitive to minor variations in element length and spacing. With greater inter-element coupling, the 1/2" element array is far less finicky in the adjustment process.

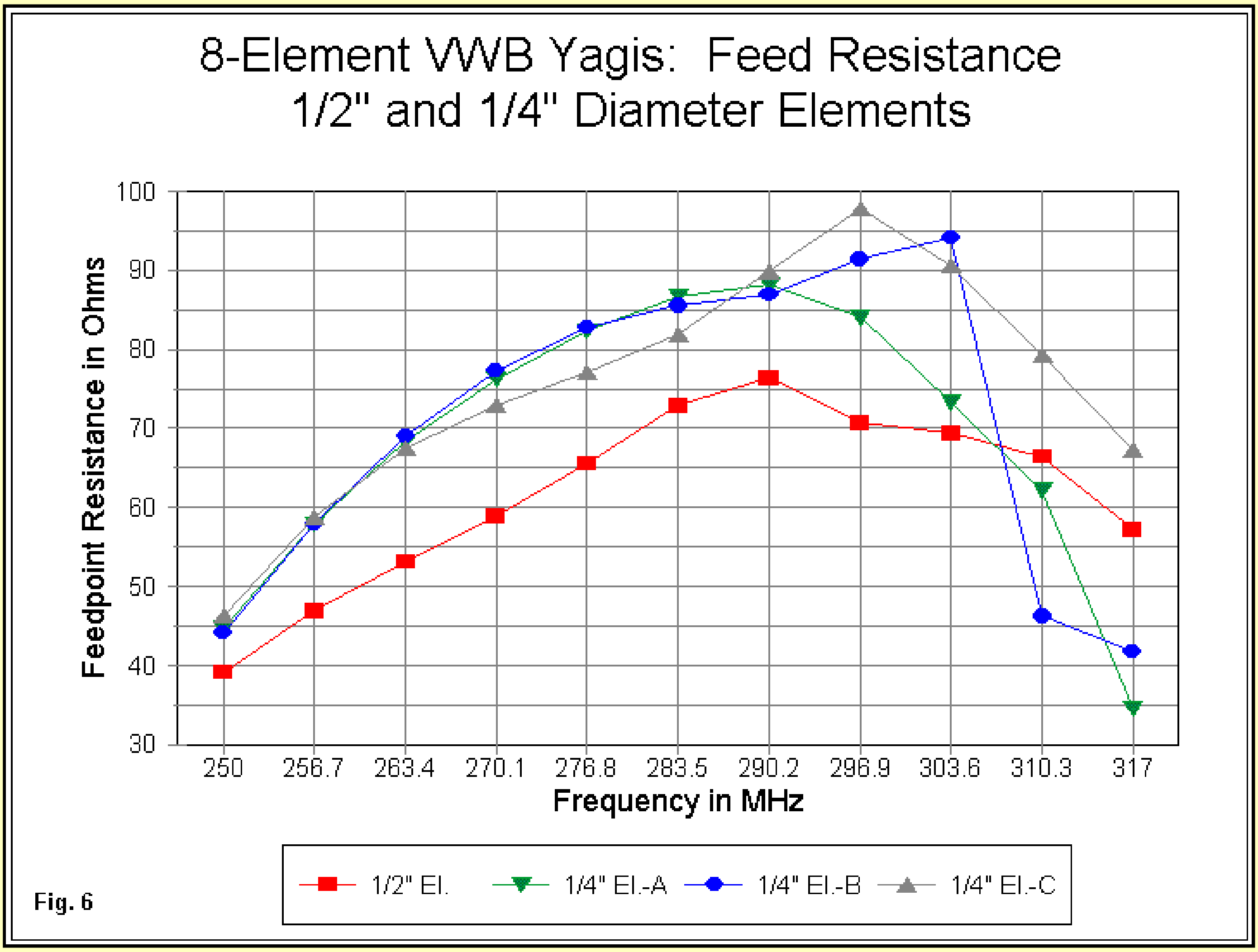


Fig. 6

Fig. 6 tracks the feedpoint resistance for all 4 designs. As expected, the resistive component of the feedpoint impedance for the 1/2" element design traces a tame range of 40 to 77 Ohms across the passband, with a ripple in the curve around the frequency at which the first director becomes the more dominant driving element. Among the 1/4" element designs, version A shows the smoothest resistance curve, with a resistance range of 35 to 88 Ohms. Both of the re-designed 1/4" arrays show much high peaks in resistance--95-98 Ohms--with much greater variability in the progression of values.

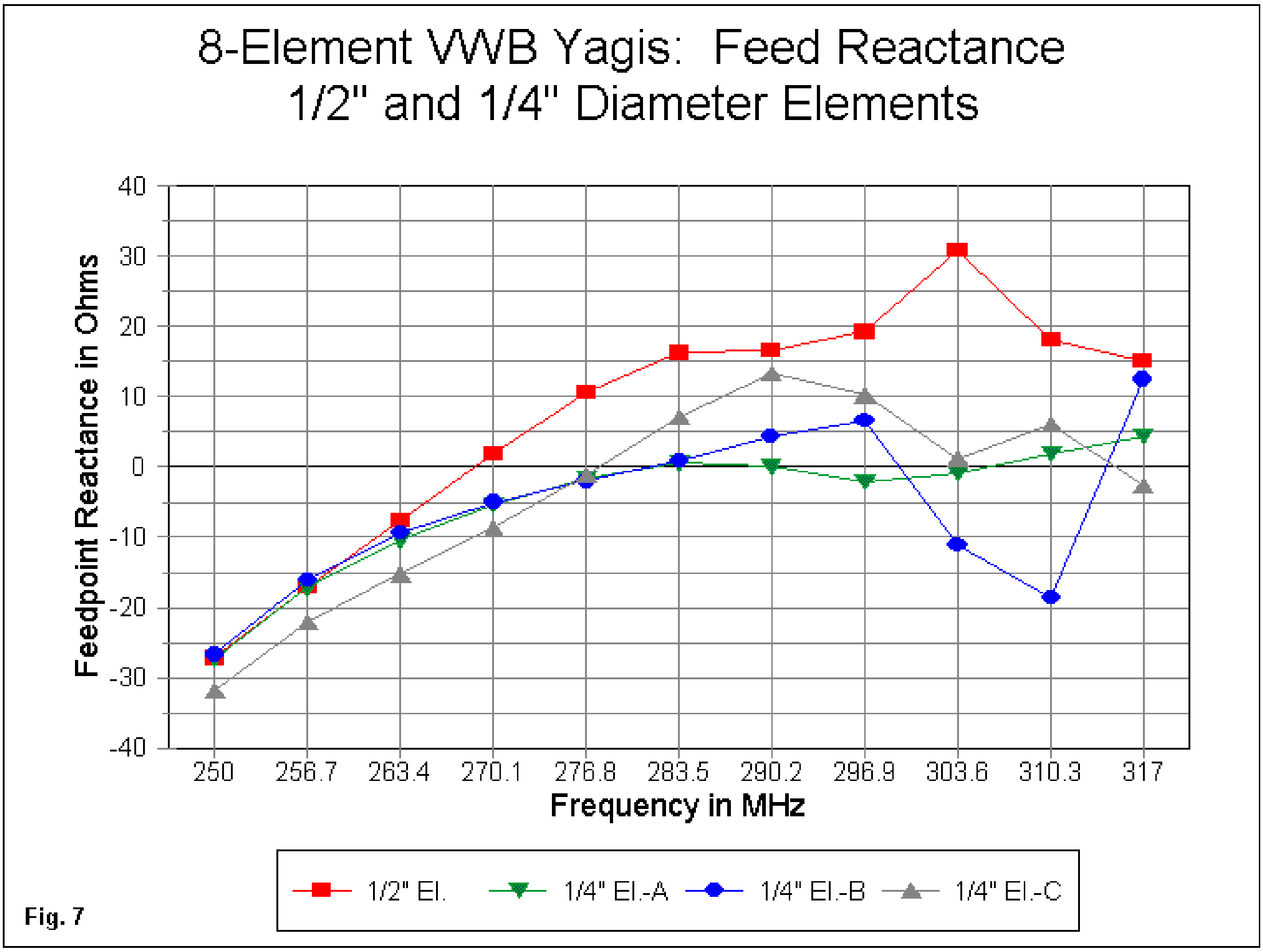


Fig. 7

Corresponding feedpoint reactance curves appear in **Fig. 7**. The 1/2" curve is generally smooth, with a peak in the region of 303 MHz. By way of contrast and by design, the curve for version A of the 1/4" designs shows the least variability of any curve, with the reactance fluctuating between -j5 and +j5 Ohms for the entire upper half of the spectrum. In the same region, the reactance values for version B and C of the 1/4" arrays show considerably greater ranges of variation and more rapid changes in reactance for a given frequency step.

The variations in reactance serve as signals to the designer that one or another limitation on operating bandwidth is approaching. Nevertheless, all three thin-element designs achieve the required operating bandwidth of under 2:1 50-Ohm SWR across the entire region from 250-317 MHz. As previously noted, the reduced mutual coupling among elements for the thinner elements results in a more difficult task of realizing the design physically, relative to the 1/2" design.

Performance: The key performance parameter over and above SWR bandwidth is the level of usable gain for the array across the passband. For the following section, free-space gain will serve as the performance marker. In general and as one might expect, the 1/2" element design is capable of a higher low-end gain and a higher peak gain than any of the thin-element designs. At 250 MHz, the fat-element design achieves about 9.5 dBi gain, with a peak gain approaching 12.3 dBi at 303 MHz. In contrast, the best low-end gain for the 1/4" element designs is 9.0 to 9.1 dBi, with a peak value that ranges from 11.75 to 12.05 dBi. **Fig. 8** shows the gain curves for all 4 designs.

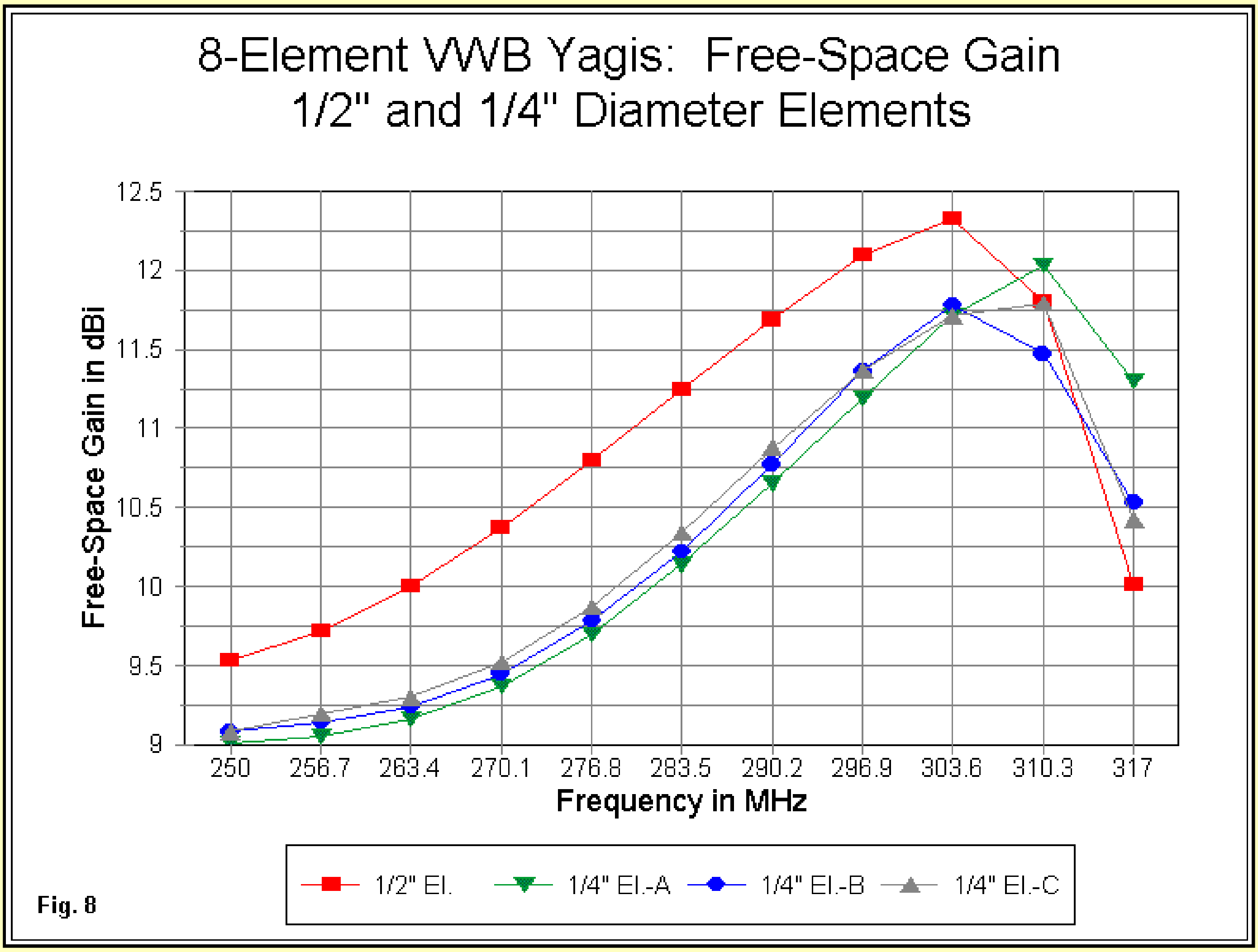


Fig. 8

Among the 1/4" designs, version A best tracks the 1/2" design, with the highest peak gain. However, that peak occurs 10% higher in the band than for the other arrays, the price for the design concentration on smooth resistance and reactance curves. The corrective element length and spacing adjustments made to version B lower the frequency of peak gain to correspond more closely with the 1/2" design. The result is slightly better performance by up to 0.25 dB over the entire lower half of the operating spectrum. The redesign of version C places the peak gain frequency between those of version A and B, with intermediate improvements in gain at the low end of the passband.

Although the curves for all three 1/4" designs show some variability, their inability to achieve the overall gain values of the 1/2" design across the entire spectrum of operation suggests once more a relative deficiency of adequate mutual coupling among elements. Whether that deficiency is sufficient to set the designs below the level of usability depends, of course, on the application specifications brought to the design process.

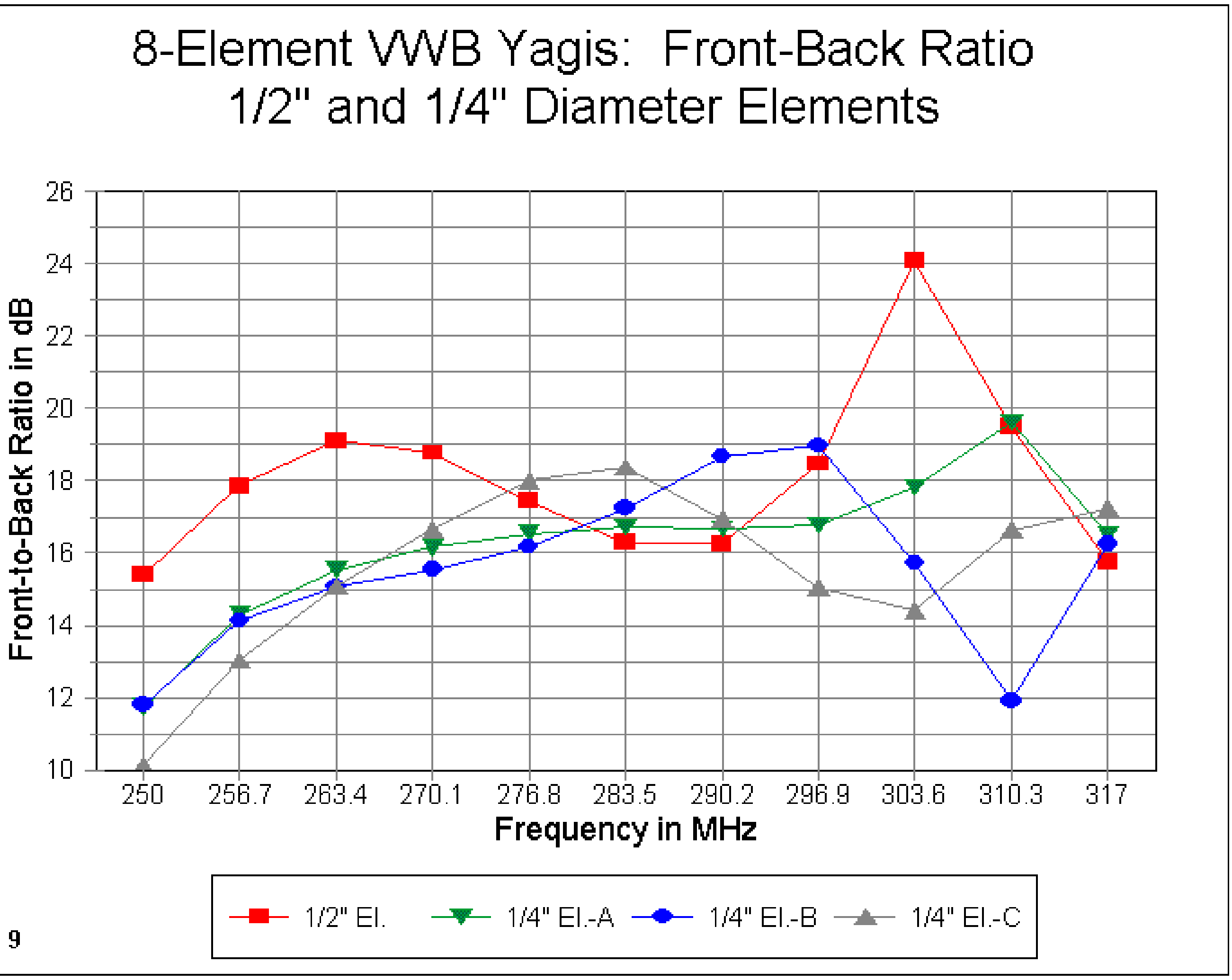
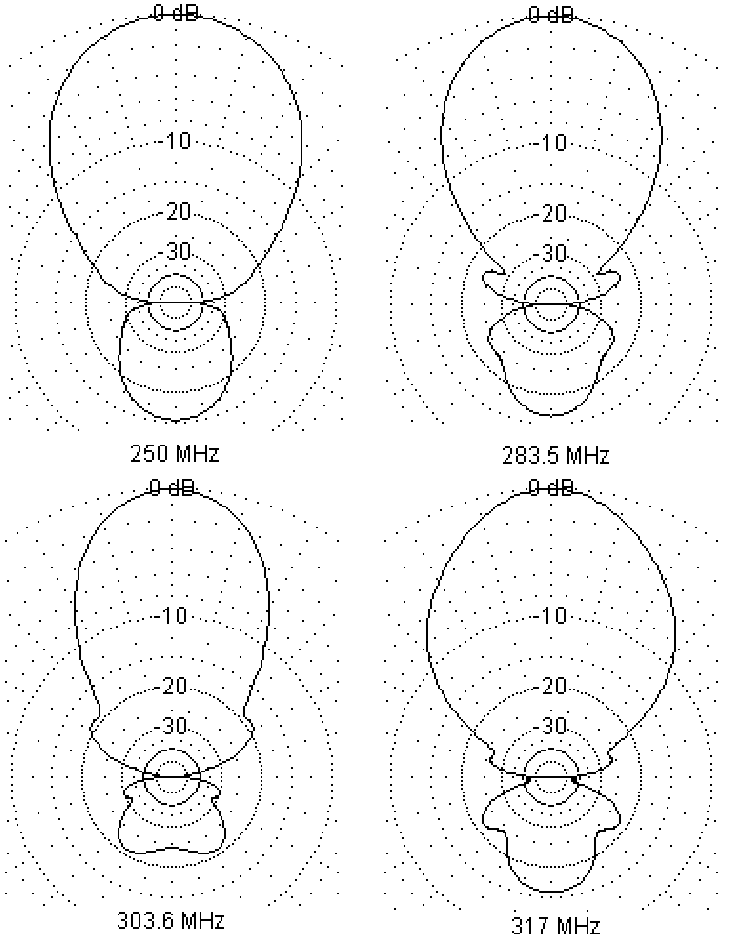


Fig. 9

Fig. 9 provides a glimpse into the more highly variable situation with respect to the array 180-degree front-to-back ratios. All of the curves show at least two front-to-back maximums, although the double dip in the curve for version A of the thin-element designs is not apparent in the 10% frequency steps used in the graph. The 1/2" design attains a minimum front-to-back ratio of better than 15 dB. The peak value is for the 180-degree ratio, and the worst-case front-to-back ratio at 303 MHz is closer to 20-21 dB.

All of the 1/4" designs shows a weaker front-to-back ratio at the low end of the band, with version C barely achieving 10 dB at 250 MHz. Version A best tracks the 1/2" design, with its peak occurring 10% higher in frequency, in concert with its peak gain. The readjustments used to lower the frequency of peak gain in version B result in a dip in front-to-back ratio in the upper 20% of the operating spectrum. How significant the front-to-back ratio is, of course, will vary with the particular application.

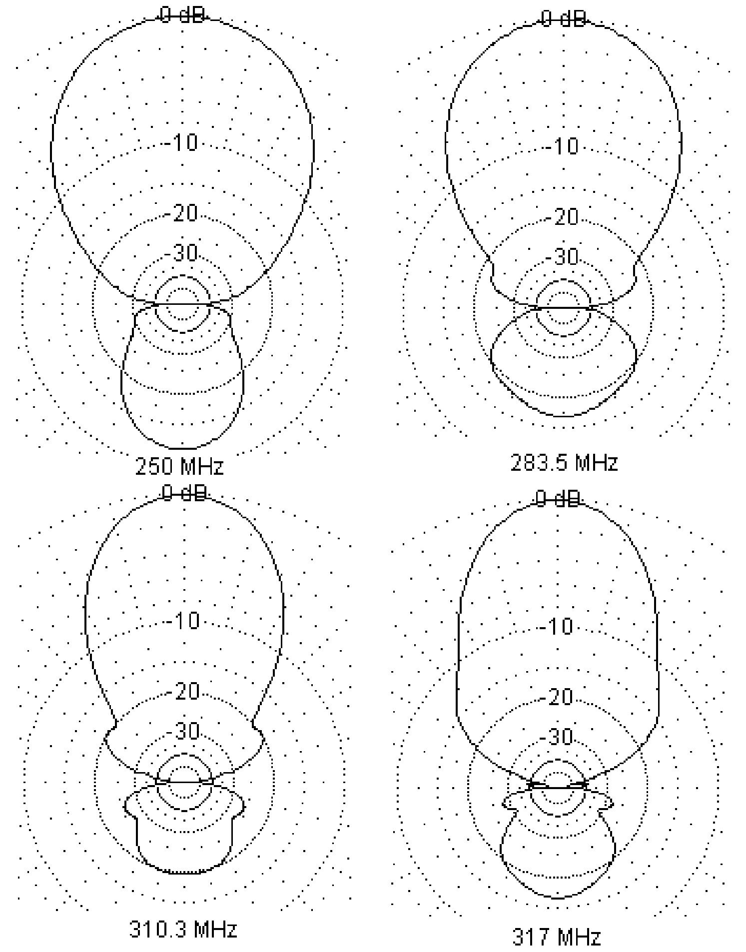
As a secondary gauge on the potential performance of these arrays, we may examine selected free-space E-plane patterns. We shall look at the low end of the band, the mid-point, the frequency of highest gain, and the upper band edge.



8-Element VWB Yagi: 1/2" Elements
Free-Space E-Plane Patterns

Fig. 10

Fig. 10 provides patterns for the 1/2" element design. Operationally, all of the patterns are well-behaved. The forward side lobes of the mid-band pattern grow from -24 dB top -18 dB at the peak-gain frequency. However, they again diminish as the first director dominates array energy supply at the upper end of the band. In contrast, the rearward side lobes enlarge at the upper band limit.



8-Element VWB Yagi: 1/4" Elements
Free-Space E-Plane Patterns

Fig. 11

Because all of the patterns for the 1/4" designs are so similar, the ones presented in **Fig. 11** will suffice as a suitable sample for the thin-element arrays. Most interesting is the fact that they are in every way normal, despite the stretch of the operating bandwidth relative to the element diameter. The side lobes--both forward and rear--do not reach the level of development of those for the 1/2" design. Indeed, side lobe development is in part a function of the degree of excess mutual coupling among elements in an array. At its peak gain frequency, version C shows forward side lobes approaching the -20 dB level, a partial function of the closer spacing between forward parasitic elements.

Conclusion: The design exercise has demonstrated that it is indeed possible to create Yagi arrays with an operating bandwidth of 23.6% or greater, even using elements as thin as 1/4". However, elements as thin as 0.006 wavelength at the design center frequency may approach the limit for such operating bandwidths due to the reduction in sufficient inter- element coupling to sustain operation and due to the reduction in low-end performance that attends reduced element diameters. The 1/2" element design, with an element diameter of about 0.003 wavelength, provides a tamer SWR curve and superior performance curves across the entire span.

The principle design feature of the VWB design is the shift in dominance of the driver and the first director relative to control of the performance characteristics as one moves from the low to the high end of the operating spectrum. The critical spacing and length setting of the reflector, driver, and first director are considerably eased with fatter elements. Indeed, it may be possible to design an array using 1/2" elements for these functions, with thinner elements comprising the remaining directors. However, that task remains to be tested.

Within the limits of the test arrays used for this study, the fatter the elements, the greater the independence between upper and lower frequency adjustments to the array. Thinner elements in the reflector-driver-director-1 section of the array require closer spacing of the driver and first director to achieve sufficient coupling for the desired spectrum coverage, with a consequential need to increase the reflector spacing. Hence, adjustments become more critical, with consequences for the physical implementation of such arrays.

There is no single value of spacing between the driver and first director that will achieve VWB performance. Rather, the spacing is critically dependent upon two interactive variables: the element diameter for a given operating band width and the desired operating bandwidth for a given element diameter. The length and spacing of the remaining directors will then show interactive variables of their own as the designer seeks to achieve a set of particular performance goals within the operating passband.

This study is by no means a final word on VWB design. Instead, it is only an initial exploration into an intriguing venture: to achieve from a parasitic array the widest possible operating bandwidth with usable performance from one end to the other. Much remains to be investigated.

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