Richard A. Formato, Ph.D., WW1RF

Improving VHF Antenna System Performance with High Impedance Yagis

1.
INTRODUCTION

One of the reasons that building good antennas is a challenge is that key parameters are often incompatible. This note considers the incompatibility between very efficient transmission lines, which have a high characteristic impedance, and typical Yagis, which have low input impedance. Antenna optimisation often ignores the transmission line. It is selected only after the Yagi design is complete, and it is almost always coax. The antenna/transmission line system is then made to work by adding a matching network. This approach is not necessarily the best. Designing the antenna and transmission line together may provide better overall performance, a point which is illustrated by the 12 element Yagi example discussed below.

2.
FEED SYSTEM LOSS AT VHF

The problem at VHF is that coaxial cable loss increases dramatically with frequency, often robbing the antenna *system* of its full potential. On 2 meters, for example, the matched-line attenuation for widely used RG-8 foam dielectric coax is about 2.1dB/100 feet (1), which is quite substantial. This is the lowest possible value, because the attenuation increases as SWR goes up (which also reduces system bandwidth). Another source of attenuation is the required matching network and balun. Even the simplest network introduces losses in its electronic components and coax connectors, and these losses are usually much higher at VHF than at lower frequencies.

	Zo (Ω)			
AWG	300	350	400	450
10	0.622	0.945	1.434	2.176

Table 1: Conductor Spacing (Inches) for Various Wires Size and Characteristic Impedance

At VHF, where fractions of a dB can make a difference, using a transmission line with the lowest possible loss is obviously very important. The best transmission line is air-insulated open wire (not window line).

An open wire line made with #12 AWG conductors has an attenuation of only 0.25dB/100 feet on 2 meters (1). For comparison, 200 feet of open wire line delivers 89% of the input power to the antenna, while the same length of RG-8 delivers only 38%.

But there are problems with open wire line. Practical conductor spacings result in high characteristic impedance, which is difficult to match to a low impedance Yagi. Table 1 shows the centre-to-centre conductor spacing to achieve different line impedance with common wire sizes. The impedance is

computed from the formula Zo=276 log(2S/d), where S is the centre-to-centre spacing and d is the conductor diameter, both in the same units (2).

3.

HIGH IMPEDANCE YAGIS

The easiest way to take advantage of the extremely low attenuation of open wire is to design a good Yagi with a *high* input impedance.

One approach is to use a half-wave folded dipole as the driven element(3). Another is to increase the input impedance of the usual centre-fed linear dipole driven element (DE) by proper placement of the arrays parasitic elements.

The feasibility of this design approach will be demonstrated by a 12-element Yagi that provides a nearly perfect match to 300-ohm open wire line and excellent overall performance. An added advantage of this design is that the balanced antenna is fed by a balanced line.

The balun required to match the unbalanced transmitter output to the line can therefore be placed at the transmitter output terminal instead of the antenna input.

4.
YGO2

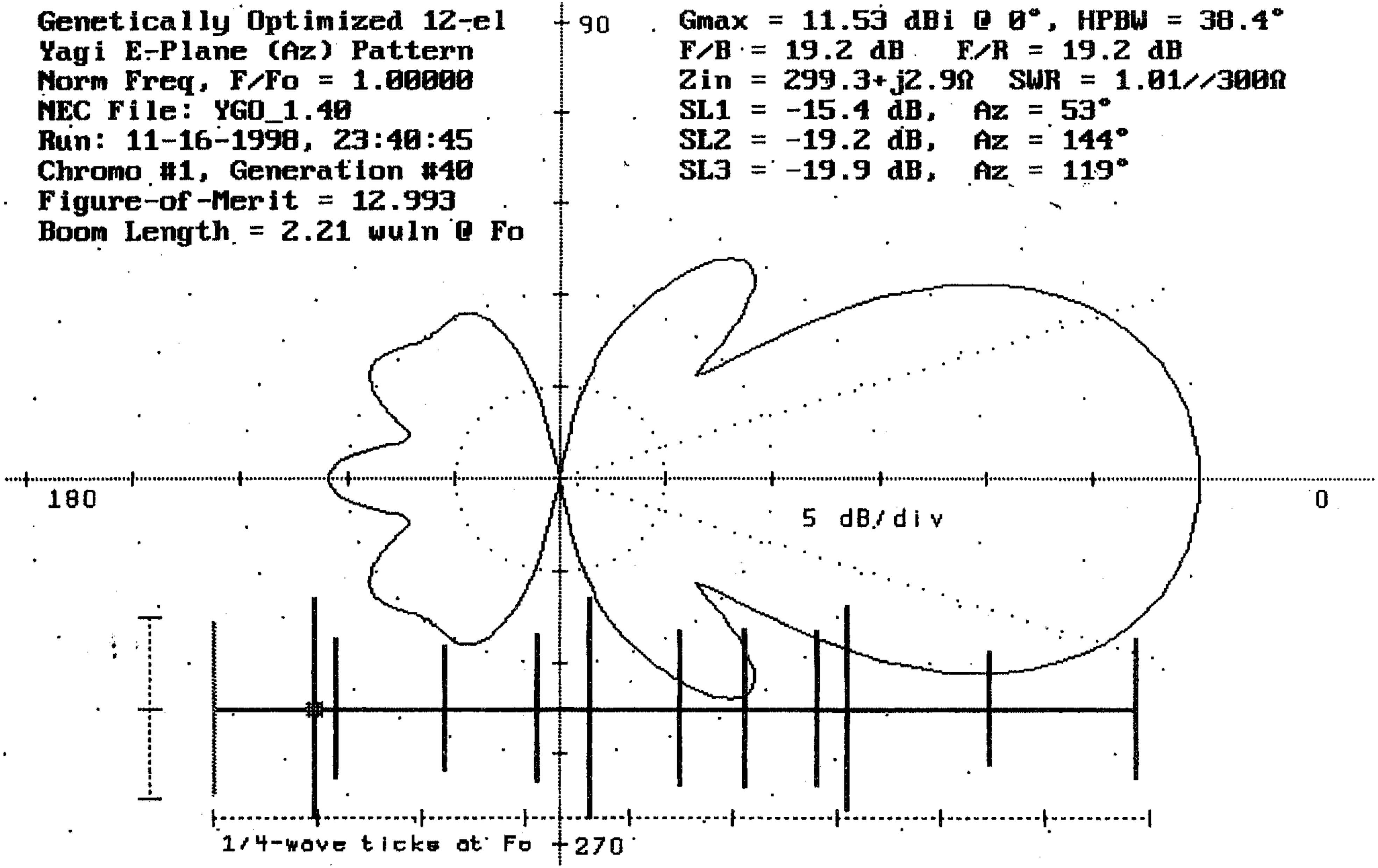
The array was designed using the Yagi Genetic Optimiser version 2, which is a freeware program available on the web (4). YGO2 models Yagis using NEC-2D (Numerical Electromagnetics Code, Ver. 2, Double Precision), which is also on the web (4) or directly from ACES(5). Essential data from the YGO2 configuration file, and the NEC-2D input file for the final optimised array, appear in the Appendix.

The optimisation was done iteratively. The initial runs optimised only the input impedance by setting the coefficients d, e and f to zero, and by assigning a low value to coefficient a (see Appendix and YGO2 literature). Once a geometry was evolved that would provide a good match to 300Ω, the corresponding chromosome was used to seed subsequent optimisation runs in which the coefficients a, d, and e were gradually increased (f was always zero). This process was repeated until the desired balance between Zin, gain, FB and FR was achieved. All runs were at one frequency (146 MHz). The element diameter of 0.0122 waves is equal to 1 inch divided by the wavelength at 144 MHz (299.8/frequency in MHz). Somewhat fat elements were chosen to broaden the Yagis response. Smaller diameter elements (but not too small) should provide more gain at the expense of bandwidth, but this was not investigated in detail.

5.
12 ELEMENT, 300Ω YAGI

The Yagis geometry appears in Table 2. All dimensions are in wavelengths at the design frequency Fo. *Length* is the end-to-end element length. *Spacing* is the separation along the boom from the previous element. *Position* is the distance along the boom from element #1 (the reflector). Element #2 is driven at its centre (centre-fed linear dipole). All elements have the same diameter (0.0122 wave at Fo).

Fig.1 shows the YGO2 output screen, which plots the E-plane (azimuthal) radiation pattern and provides a scale representation of the array. The display is annotated with key performance data. The pattern is very clean, and its structure is typical of well-designed Yagis. One interesting aspect of this Yagi is its unusual geometry. Unlike standard designs (progressively shorter directors with increasing spacing away from the DE), the element lengths show no particular pattern, and some of them are quite out of the ordinary. The DE, for example, is the second longest



```
Genetically Optimized 12-el
Yagi E-Plane (Az) Pattern
Norm Freq, F/Fo = 1.00000
NEC File: YGO_1.40
Run: 11-16-1998, 23:40:45
Chromo #1, Generation #40
Figure-of-Merit = 12.993
Boom Length = 2.21 wuln @ Fo
```

```
Gmax = 11.53 dBi @ 0°, HPBW = 38.4°
F/B = 19.2 dB   F/R = 19.2 dB
Zin = 299.3+j2.9Ω  SWR = 1.01//300Ω
SL1 = -15.4 dB,  Az = 53°
SL2 = -19.2 dB,  Az = 144°
SL3 = -19.9 dB,  Az = 119°
```

Fig.1: YGO2 Output Screen

El #	Length	Spacing	Position
1	0.4839	0.0000	0.0000
2(DE)	0.5992	0.2397	0.2397
3	0.3865	0.0500	0.2897
4	0.3453	0.2635	0.5532
5	0.4094	0.2229	0.7761
6	0.6000	0.1224	0.8985
7	0.4306	0.2212	1.1197
8	0.4412	0.1559	1.2756
9	0.4271	0.1700	1.4456
10	0.5647	0.0729	1.5185
11	0.3141	0.3482	1.8667
12	0.3824	0.3447	2.2114

Table 2: Yagi Geometry (dimensions in wavelengths at Fo)
(note - all elements are 0.0122 wave diameter)

element (0.5992 wave), the reflector is much shorter (0.4839 wave), and the longest element is director #6 (0.6 wave). Usually, the reflector is the longest element, the DE is close to half-wave, and the directors become progressively shorter.

Another quite unusual feature is the position of director #1 (D1), which is very close to DE (only 0.05 wave separation). D1 appears primarily to function as an impedance matching parasitic, rather than as a true director. Even though it contains 12 elements, this Yagi seems to act more like an 11 element array.

The similarity to an 11 element array is even more apparent when the 12 element Yagi is compared to the 144 MHz family in ***The ARRL Antenna Book***(6). Its 11-element array has a boom length of 2.2 waves, a gain of 14.15dBi (12 dBd), a front-to-back ratio (FB) of 19dB, and an input resistance of 38Ω (reactance not specified). The 12-element Yagi in Fig.1 has the same boom length (2.21 waves), a gain of 11.53dBi, FB and front-to-rear (FR) ratios of 19.2dB, and it provides a nearly perfect SWR of 1.01 on 300Ω open wire line.

The 12 element Yagi thus provides nearly the same performance as the ARRL 11-element array, with two notable differences. First, it seems clear that the extra element increases the input impedance while contributing little to the gain. In fact, taken together, DE and D1 look much like a folded dipole. It is interesting that YGO2s solution places D1 as close as possible to DE (0.05 waves). Had the minimum spacing in YGO2.CFG (see Appendix) been lower, say 0.025 wave, YGO2 might have placed

D1 even closer, which would make DE/D1 look even more like a folded dipole.

The second (and more important) difference is that the 12-element Yagis gain is lower than the 11-elements by 2.62dB. But, while this gain reduction is significant, it is not realised in practice. If the two antenna *systems* are properly compared by taking into account transmission line loss, then the 12-element Yagi may well be better. It provides more overall gain than the 11 element array for any transmission line longer than 142 feet (assuming #12 AWG open wire and foam dielectric RG-8). And this result excludes matching network and connector losses. These are likely to be quite a bit higher for the coax than for the open wire line, which again gives an edge to the 12 element array.

Open-wire line is easily fed with a simple, very low loss air-core inductive circuit that impedance matches the unbalanced transmitter output to the balanced line(7). This circuit can be located at the transmitter, which is not possible with coax because the balun must then be at the antenna input. Placing the network in the shack reduces the weather-related losses and maintenance that are inevitable with outdoor networks. Another consideration favouring open wire line is the lines effect on signal-to-noise ratio. In a receiver noise limited system, SNR is reduced by the amount of transmission line attenuation. At VHF, extremely low loss open wire line is therefore advantageous both for receiving and transmitting. It can provide better SNR than coax, and it delivers more power to the antenna.

6.

Input Impedance & SWR

Figs. 2-7 provide more detailed performance data for 12-element, 300Ω Yagi. On each plot the abscissa is the normalised frequency, F/Fo, where Fo is the design frequency at which the array dimensions are computed. For convenience, the ratio F/Fo will be denoted by a lower case, italic f. Each parameter is plotted over a 10% bandwidth, 0.95 f 1.05.

Fig.2 shows the input resistance. The design value of 300Ω is achieved at 3 frequencies, f = 0.97, 1.00, and 1.006. Maximum resistance is 350Ω at f = 0.957, with a secondary peak of about 330Ω at f = 1.003. The resistance is between 200 and 350Ω for frequencies from 0.95 to just below 1.01. Input reactance is plotted in Fig.3. Four resonances (Xin = 0) occur at f = 0.968, 0.992 ,1.00, and 1.044. The maximum reactance of about +140Ω (inductive) occurs at f =

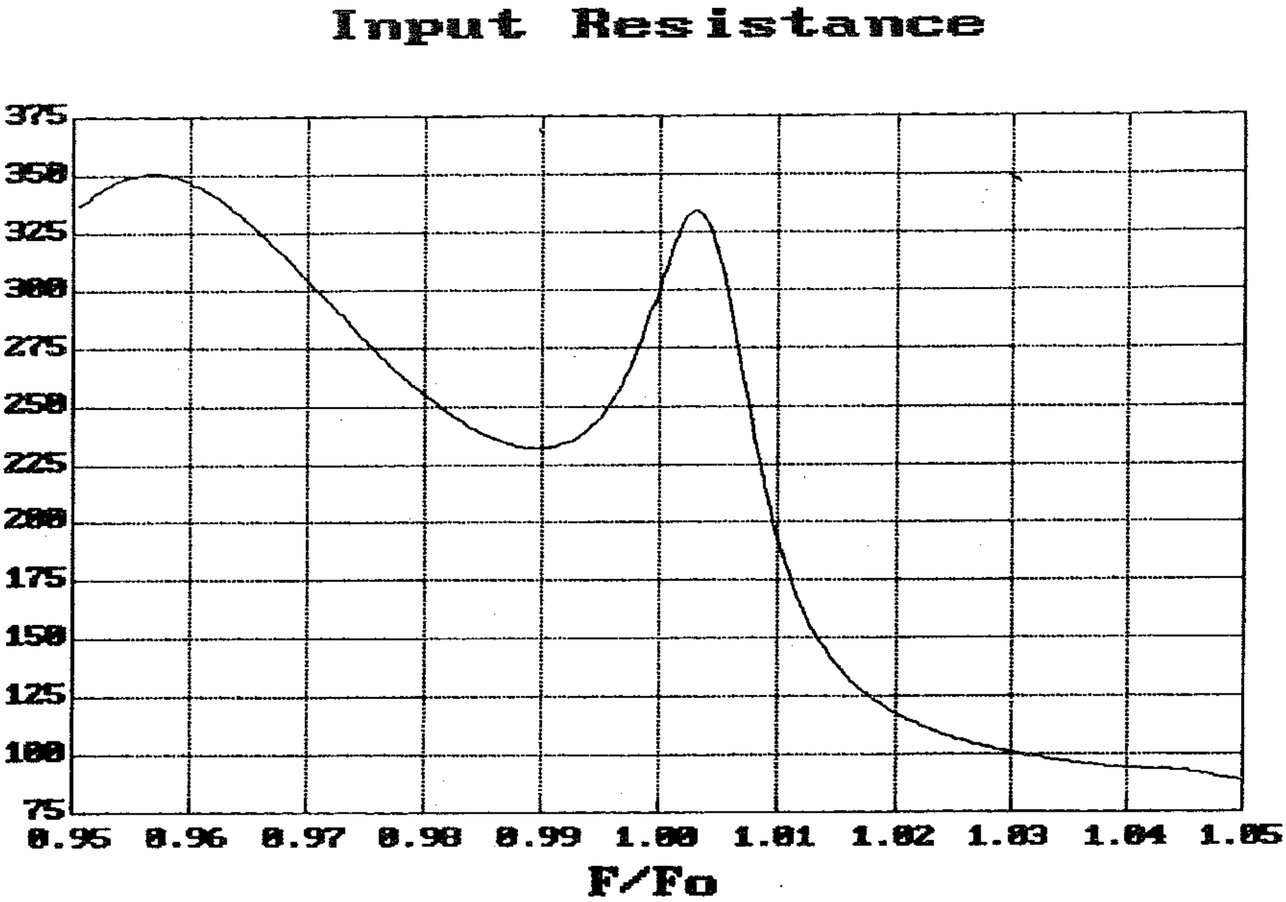

Input Resistance
375
350
325
300
275
250
225
200
175
150
125
100
75
0.95
0.96
0.97
0.98
0.99
1.00
1.01
1.02
1.03
1.04
1.05
F/Fo

Fig.2

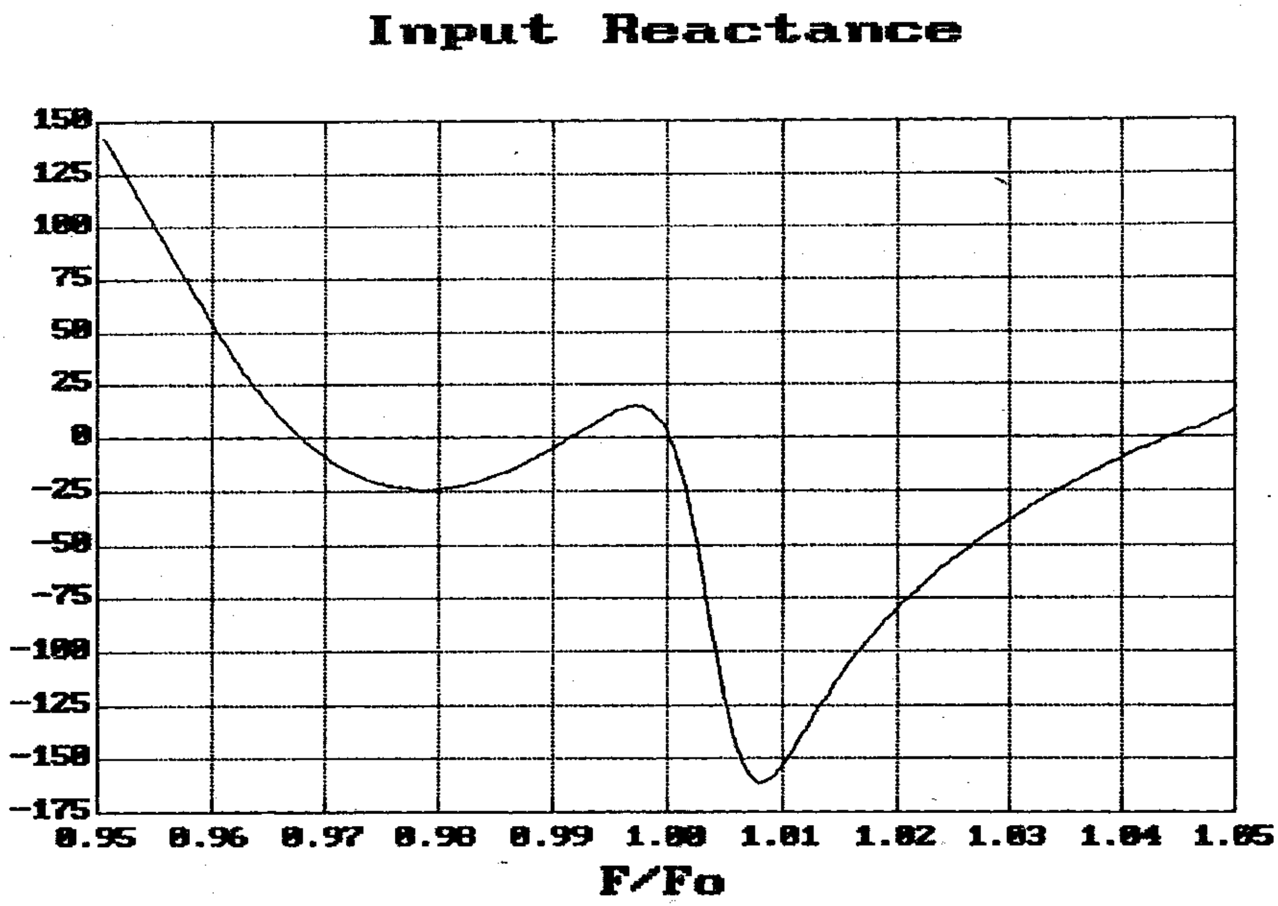

Input Reactance
150
125
100
75
50
25
0
-25
-50
-75
-100
-125
-150
-175
0.95
0.96
0.97
0.98
0.99
1.00
1.01
1.02
1.03
1.04
1.05
F/Fo

Fig.3

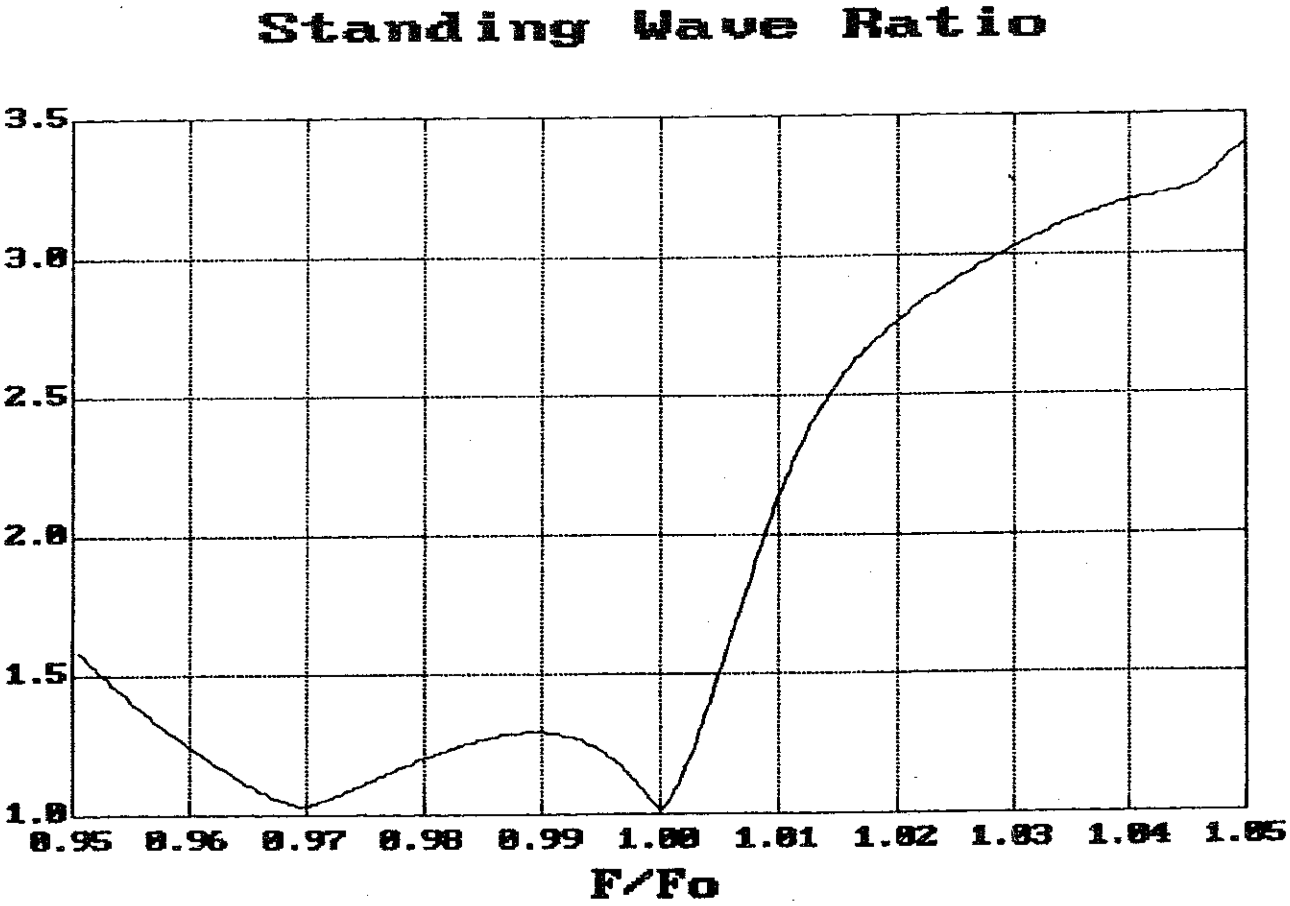

Standing Wave Ratio
3.5
3.0
2.5
2.0
1.5
1.0
0.95
0.96
0.97
0.98
0.99
1.00
1.01
1.02
1.03
1.04
1.05
F/Fo

Fig.4

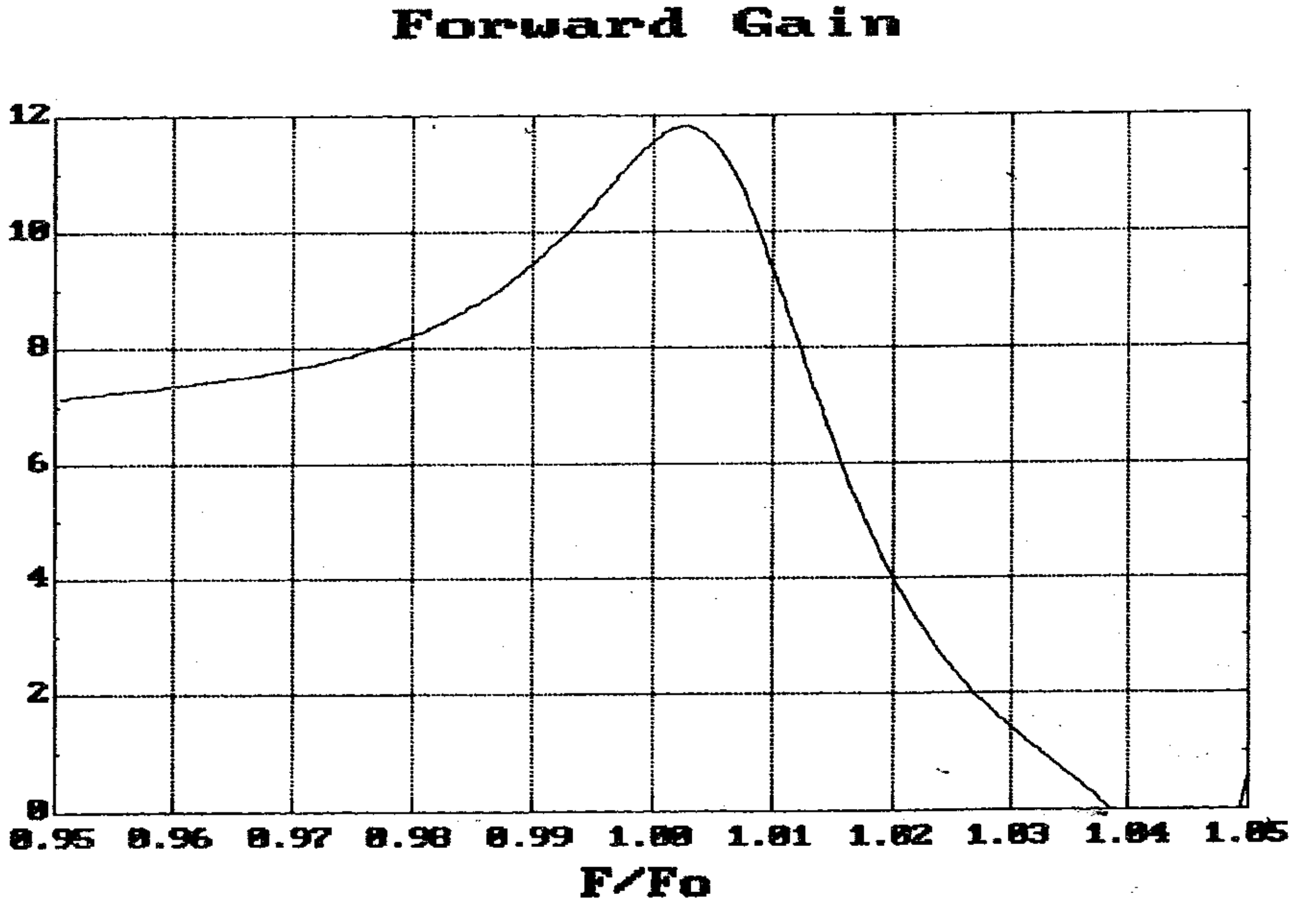

Forward Gain
12
10
8
6
4
2
0
0.95
0.96
0.97
0.98
0.99
1.00
1.01
1.02
1.03
1.04
1.05
F/Fo

Fig.5

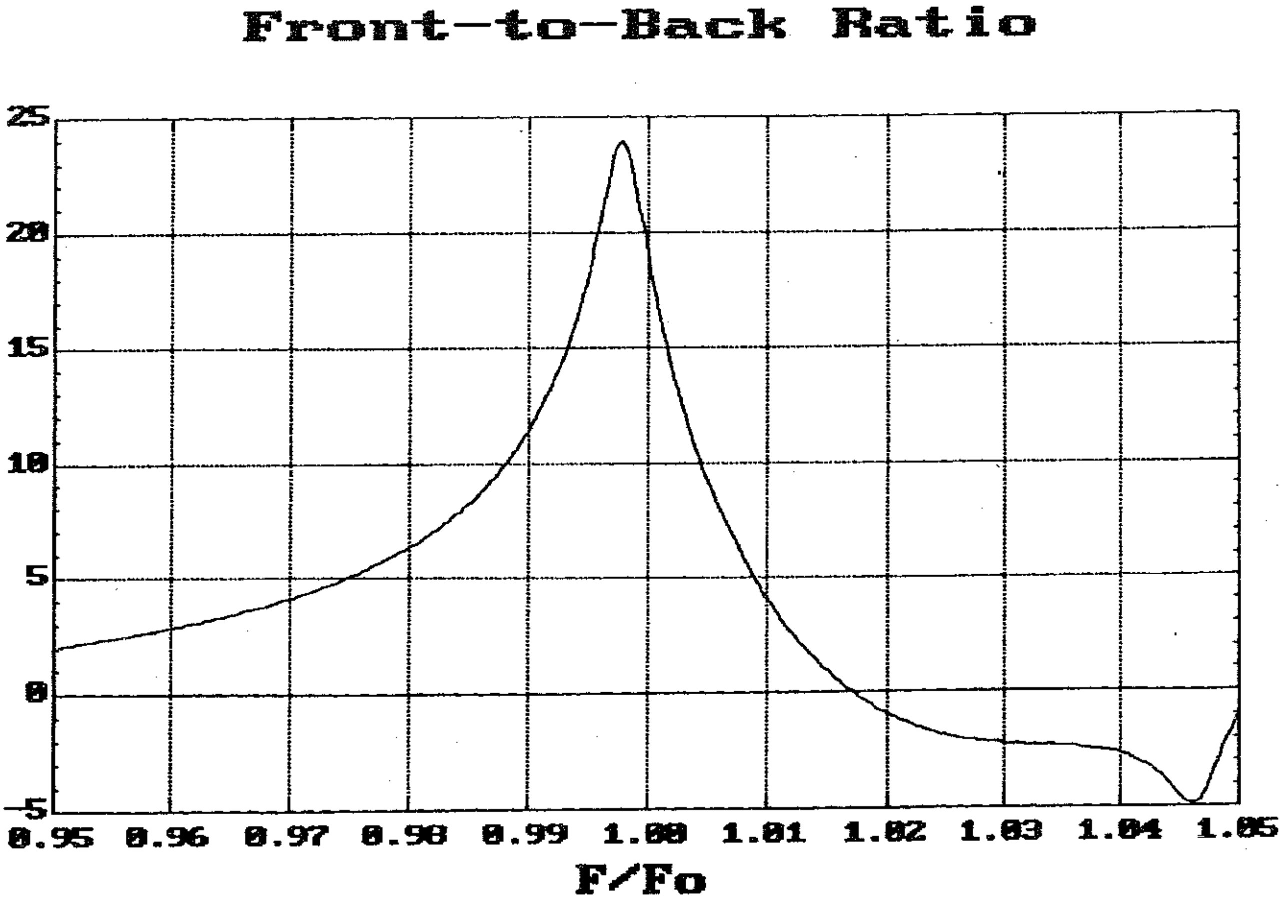

Front-to-Back Ratio
25
20
15
10
5
0
-5
0.95
0.96
0.97
0.98
0.99
1.00
1.01
1.02
1.03
1.04
1.05
F/Fo

Fig.6

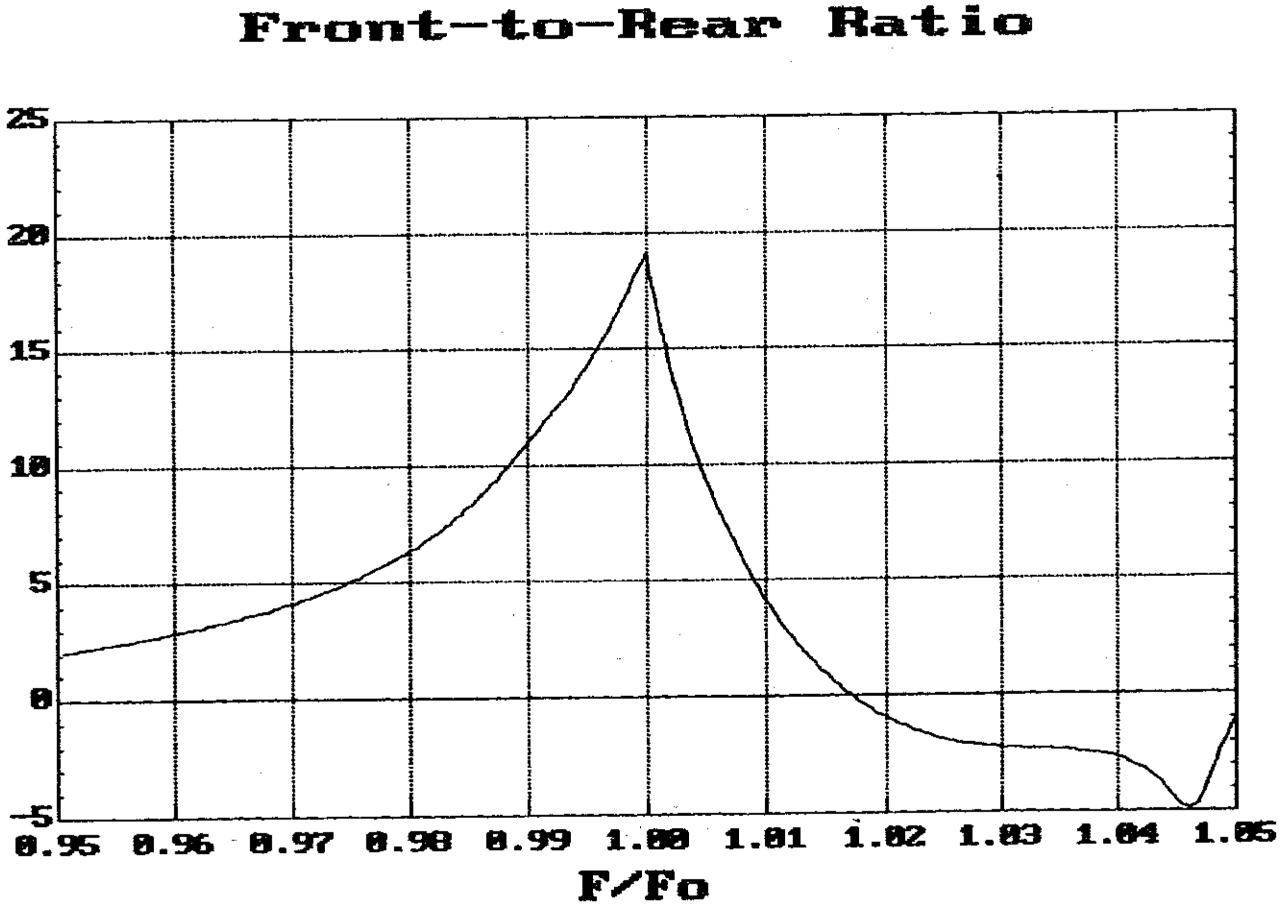

Front-to-Rear Ratio
25
20
15
10
5
0
-5
0.95
0.96
0.97
0.98
0.99
1.00
1.01
1.02
1.03
1.04
1.05
F/Fo

Fig.7

0.95, while the minimum of -161 Ω (capacitive) is at *f* = 1.008. The reactance is less than 10% of the desired 300Ω input resistance from *f* = 0.963 to 1.002 (3.9%). For practical purposes, the Yagi is resonant over this entire range of frequencies. Of course, the most important antenna impedance parameter is SWR, which is plotted in Fig.4. At the lower band edge, the SWR is just over 1.5. It is below 1.5 from *f* = 0.953 to 1.005, yielding a 1.5:1 SWR bandwidth of 5.2%. The 2:1 SWR bandwidth is more than 5.9%, which is quite good.

7.

Gain & FB/FR Ratios

Forward gain in dBi (dB relative to an isotropic radiator) appears in Fig.5. Maximum gain is 11.8dBi at *f* = 1.003. The gain is above 10dBi from *f* = 0.993 to 1.009, a 10dBi gain bandwidth of 1.6%. The half-power (-3 dB) frequencies are 0.986 and 1.011, yielding a -3dB bandwidth of 2.5%.

The FB ratio (Fig.6) peaks at 23.9dB at *f* = 0.998. FB is above 20 dB from *f* = 0.996 to 1.00 (0.4%), above 15dB from 0.993 to 1.002 (0.9%), and greater than 10 dB from 0.988 to 1.004 (1.6%). FR (Fig.7) shows similar behaviour, but its peak value is lower. Maximum FR is 19.2dB at *f* = 1.00. It is above 15dB from *f* = 0.996 to 1.002 (0.6%), and greater than 10dB from 0.988 to 1.004 (1.6%).

8.

Conclusion

The 12 element 300Ω Yagi is indeed a very good antenna. It directly matches extremely low loss, balanced 300Ω open wire line. As a system, the 12 element Yagi with open wire line outperforms an optimised 11 element array of the same boom length fed by RG-8 coax, as long as the transmission line is longer than 142 feet (ignoring matching network and balun losses). The 12 element system provides more overall gain and better SNR. To the extent that the coax matching network/balun has higher losses than the open-wire network, which is very likely, the 12 element Yagi will provide better performance even for lines shorter than 142 feet.

There is a substantial potential advantage in designing high input impedance Yagis that operate directly with high impedance open wire lines. The design example discussed here shows that this objective can be achieved with very robust antenna system performance.

9. Literature

1. The ARRL Antenna Book, 17th ed., R. Dean Straw, editor, American Radio Relay League, Inc., Newington, CT 06111, USA, 1994, Fig.22, p. 24-16.
2. *ibid.*, Eq. (20), p. 24-14.
3. Antennas, 2nd ed., John D. Kraus, McGraw-Hill Inc., New York, 1988, p. 483.
4. Ray Anderson, WB6TPUs, NEC Archive web site, URL: http://www.qsl.net/wb6tpu
5. Applied Computational Electromagnetics Society (ACES) Attn: Dr. Richard W. Adler, ACES Executive Officer, ECE Dept., Code ECAB, Naval Postgraduate School, 833 Dyer Road, Room 437, Monterey, CA 93943-5121 USA.
6. The ARRL Antenna Book, 17th ed., R. Dean Straw, editor, American Radio Relay League, Inc., Newington, CT 06111, USA, 1994, Table 11, p. 18-25.
7. *ibid.*, Figs. 2(A), 2(C), p. 25-3.

10. Appendix - Yagi Modelling Data

Essential Data from File YGO2.CFG

Name of NEC Executable File - NEC2D100.EXE

NEC Input Files/Gen in Output - 5

starting with generation number - 20

Number of Elements in Array - 12

Number of Segments per Element - 7

Feed System Zo - 300 ohms resistive

Assume Feed Reactance Tuned Out? NO

```
------------------------------------------------------------

Population Size  - 10 (# chromosomes)

Max # Generations - 1

Save Percentage - 2.0 (% best chromos/gen saved)

Crossover Probability - 0.8000

Mutation Probability - 0.0200

Max Mutation Rate - 2 bits/chromosome

------------------------------------------------------------

Selection Method # - 1

(1-Binary Tournament, 2-Proportionate)

Minimum Fitness [0-1] - 0.5 (proportionate only)

------------------------------------------------------------

FoM Terminology

-----------------------

Gfwd - Forward Gain (dBi)

FB - Front-to-Back Ratio (dB)

FR - Front-to-Rear Ratio (dB)

Rin - Feed Point Input Resistance, ohms

Xin - Feed Point Input Reactance, ohms

MaxSLL- Maximum Sidelobe Level (dB//Gfwd)

^ - Exponentiation

* - Multiplication

/ - Division

ABS - Absolute Value

------------------------------------------------------------

Figure-of-Merit (averaged over all frequencies):

FoM = {a*Gfwd-b*ABS(Zo-Rin)-c*ABS(Xin)+d*FB+e*FR-f*MaxSLL}/(a+b+c+d+e+f)
```

FREQUENCY TABLE

 # FREQUENCIES USED - 1

Freq #	Freq(MHz)	DE	a	b	c	d	e	f
1	146.00	2	260.0	4.0	6.0	1.0	85.0	0.0
2	144.20	2	40.0	2.0	3.0	0.0	0.0	0.0
3	144.30	2	40.0	2.0	3.0	0.0	0.0	0.0
4	144.40	2	40.0	2.0	3.0	0.0	0.0	0.0
5	144.50	2	40.0	2.0	3.0	0.0	0.0	0.0
6	144.60	2	40.0	2.0	3.0	0.0	0.0	0.0
7	144.70	2	40.0	2.0	3.0	0.0	0.0	0.0
8	144.80	2	40.0	2.0	3.0	0.0	0.0	0.0
9	144.90	2	40.0	2.0	3.0	0.0	0.0	0.0
10	145.00	2	40.0	2.0	3.0	0.0	0.0	0.0
11	145.10	2	40.0	2.0	3.0	0.0	0.0	0.0
12	145.20	2	40.0	2.0	3.0	0.0	0.0	0.0
13	145.30	2	40.0	2.0	3.0	0.0	0.0	0.0
14	145.40	2	40.0	2.0	3.0	0.0	0.0	0.0
15	145.50	2	40.0	2.0	3.0	0.0	0.0	0.0

Target FoM - 9999 (not normalised)

Crossover allowed only at gene boundary? YES

Print Percent - 20 (% chromos/gen printed in output file)

Use Seed Chromosome? YES

Seed Chromo:

```
0110000100000000000000000010110110000000000000000111111100000000000000
0000100000100000000000000010011011110100000000010001101111111100000000
1001010011110110000000000100000110000011111000000000111100001101100000
0000001000101000001110000000001011000000011000000000001001010101100010
00000000011100101
```

Print Chromo Sequences in YGO.DAT? NO

GENE TABLE

```
                                 Length          Min            Max
Gene #      Name                 (bits)          (wvln)         (wvln)

  1,     "Refl_Length ",           8,           0.3000,        0.6500
  2,     "Refl_Radius ",           8,           0.00610,       0.00610
  3,     "Refl_Spacing ",          8,           0.0000,        0.0000
  4,     "DE_Length ",             8,           0.3000,        0.6500
  5,     "DE_Radius ",             8,           0.00610,       0.00610
  6,     "DE_Spacing ",            8,           0.0500,        0.428
  7,     "D1_Length ",             8,           0.3000,        0.6500
  8,     "D1_Radius ",             8,           0.00610,       0.00610
  9,     "D1_Spacing ",            8,           0.0500,        0.428
 10,     "D2_Length ",             8,           0.3000,        0.6500
 11,     "D2_Radius ",             8,           0.00610,       0.00610
 12,     "D2_Spacing ",            8,           0.0500,        0.428
 13,     "D3_Length ",             8,           0.3000,        0.6000
 14,     "D3_Radius ",             8,           0.00610,       0.00610
 15,     "D3_Spacing ",            8,           0.0500,        0.500
 16,     "D4_Length ",             8,           0.3000,        0.6000
 17,     "D4_Radius ",             8,           0.00610,       0.00610
 18,     "D4_Spacing ",            8,           0.0500,        0.500
 19,     "D5_Length ",             8,           0.3000,        0.6000
 20,     "D5_Radius ",             8,           0.00610,       0.00610
 21,     "D5_Spacing ",            8,           0.0500,        0.500
 22,     "D6_Length ",             8,           0.3000,        0.6000
 23,     "D6_Radius ",             8,           0.00610,       0.00610
 24,     "D6_Spacing ",            8,           0.0500,        0.500
 25,     "D7_Length ",             8,           0.3000,        0.6000
 26,     "D7_Radius ",             8,           0.00610,       0.00610
 27,     "D7_Spacing ",            8,           0.0500,        0.500
 28,     "D8_Length ",             8,           0.3000,        0.6000
 29,     "D8_Radius ",             8,           0.00610,       0.00610
 30,     "D8_Spacing ",            8,           0.0500,        0.500
 31,     "D9_Length ",             8,           0.3000,        0.6000
 32,     "D9_Radius ",             8,           0.00610,       0.00610
 33,     "D9_Spacing ",            8,           0.0500,        0.500
 34,     "D10_Length ",            8,           0.3000,        0.6000
 35,     "D10_Radius ",            8,           0.00610,       0.00610
 36,     "D10_Spacing",            8,           0.0500,        0.500

              ------------- End of Gene Table --------------

    ************** End of File YGO2.CFG *************
```

NEC-2D Input File for YGO2-Optimized Array

```
CM NEC File: YGO_1.40 (Run ID: 11-16-1998, 23:40:45)
CM Chromosome #1, Generation #40
CM Figure-of-Merit = 12.993
CM Feed System Zo = 300 ohms resistive
CE
GW 1,7,0.,.241961,0.,0.,-.241961,0.,.0061
GW 2,7,.239741,.299608,0.,.239741,-.299608,0.,.0061
GW 3,7,.289741,.1932355,0.,.289741,-.1932355,0.,.0061
GW 4,7,.5532,.172647,0.,.5532,-.172647,0.,.0061
GW 5,7,.776141,.204706,0.,.776141,-.204706,0.,.0061
GW 6,7,.898494,.3,0.,.898494,-.3,0.,.0061
GW 7,7,1.11967,.215294,0.,1.11967,-.215294,0.,.0061
GW 8,7,1.275552,.220588,0.,1.275552,-.220588,0.,.0061
GW 9,7,1.445552,.2135295,0.,1.445552,-.2135295,0.,.0061
GW 10,7,1.518493,.282353,0.,1.518493,-.282353,0.,.0061
GW 11,7,1.866728,.157059,0.,1.866728,-.157059,0.,.0061
GW 12,7,2.211434,.1911765,0.,2.211434,-.1911765,0.,.0061
GE
GN-1
FR 0,1,0,0,299.8,0.
EX 0,2,4,0,1.,0.
RP 0,1,181,1001,90.,0.,0.,1.,10000.
XQ
EN
```