Low-profile helic Simulation and

INTRODUCTION

The theory and practice of helical antennas have been developed largely by J D Kraus and his associates at Ohio State University [1].

For circular polarisation applications, the axial-mode helix antenna is an interesting candidate, because its good polarisation performance is an inherent attribute of the antenna shape without the need for a special feeding arrangement. Polarisation properties of the helix have been the subject of several publications since the early work of Kraus [2, 3].

A typical helical antenna operating in the axial mode has a circumference $C = \pi D$ of approximately one wavelength and a pitch spacing, S, of approximately one quarter-wavelength.

Traditionally the pitch angle, an important parameter of the helix, may range from about 12 to 16°; approximately 12° (pitch = 30mm) is typical in most 2.4GHz satellite receiving helices.

The pitch, α, is the angle that a line tangent to the helix wire makes with the plane perpendicular to the axis of the helix, and it can be found from the relation $\tan(\alpha) = S / \pi D$, where S is pitch spacing and D = diameter of helix.

This paper refers to the simulation and measurements of some forward-fire-mode helices with very low-profiles. In the past, low-pitch helices have been recognised as ineffective radiating elements for a circularly-polarised wave. Field measurements and numerical results using *NEC-Win Pro* and *NEC-Win Synth* [4] however, lead to some low-pitch helices with gains comparable to that of a conventionally long helix.

> ## NEC-WIN SYNTH
>
> *NEC-Win Synth* is designed to allow users to build complex antenna structures quickly. The structures can be created in several ways; the 47 predefined models, together with the ability to import NEC, ASCII, and DXF files, allow for very creative ways to generate 3D structures. Geometric data are displayed in a spreadsheet with access to 134 predefined functions and constants and 52 user-defined variables. Dialogue boxes linked to the spreadsheet make it easy to rotate, move or scale individual wires or complete models. As you build and modify your model, the structure is displayed and dynamically updated as edits are made. We used *NEC-Win Synth* to build the circular reflector for the helix.

WAVE POLARISATION

A circularly-polarised wave radiates energy in both the horizontal and vertical planes as well as in every plane in between. The difference, if any, between the maximum and the minimum signal peaks as the antenna rotates through all angles, is called the axial ratio, or ellipticity, and is usually specified in decibels (dB). Normally, if the axial ratio is less than 2dB, the antenna is said to be circularly-polarised. If the axial ratio is greater than 2dB, the polarisation is referred to as elliptical.

The polarisation, orientation, and sense of each antenna in a system should be identical in order to optimise the signal strength between stations. For example, linearly-polarised antennas that are identically-orientated (eg vertical or horizontal) work best together as do circularly-polarised antennas that are using the same sense (RHC, LHC). Even so, circularly-polarised antennas are compatible with linearly-polarised antennas, and *vice versa*, because a linearly-polarised antenna can receive components of the circularly-polarised signals in its linear plane.

When linearly-polarised antennas are misaligned by 45°, the signal strength will degrade by 3dB, resulting in up to 50% signal loss. When misaligned by 90°, the signal strength degrades 20dB or more. Likewise, in a circularly-polarised system, both antennas must have the same sense, or a loss of 20dB or more will be incurred. Combining a linearly-polarised transmitting antenna with circularly-polarised receiving antenna, will incur a loss of 3dB in signal strength between the two formats.

STANDARD HELICES

The famous work of J D Kraus on helices started in 1946, but only in the 90s was the simulation study carried out by D T Emerson [5], a very important starting point for those interested in the simulation and manufacture of axial helical antennas. Before starting the simulation phase, using *Nec-Win Pro* and *NEC-Win Synth*, we tried to define the main parameters and the general performances of our antennas (power gain, radiation angle, input SWR and axial ratio).

The power gain of the helices can be easily estimated using the graph of **Fig 1** where the performances, at 2.4GHz, of different lengths of antenna are compared. The range from 2λ to 6.5λ is covered, corresponding to 8.3 to 27 turns. The constant parameter of the helices is the pitch between two

Fig 1

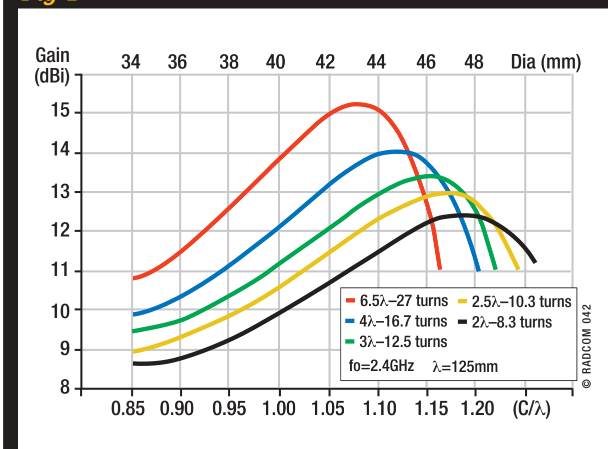

Fig 2

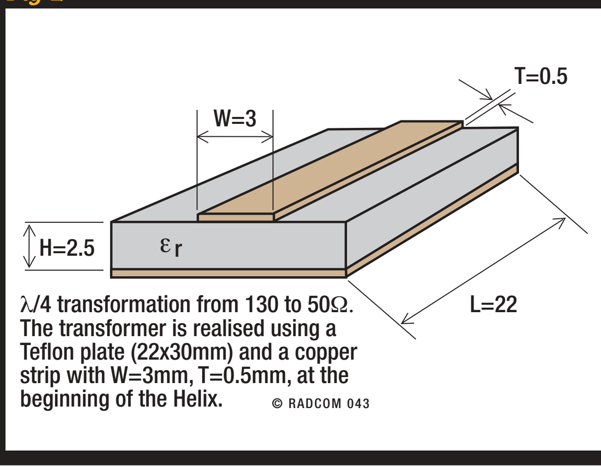

***Fig 1:** NEC-2 simulated gain versus helix diameter and C/λ at 2.4GHz.*

***Fig 2:** Layout of the λ/4 Teflon transformer calculated using HP-AppCad.*

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es for 2.4GHz: measurement

contiguous turns that is S = 0.24λ (or α = ~12°, corresponding to 30mm @ 2.4GHz). In this graph, the power gain is plotted versus C/λ. This means that for each antenna length there is an optimum turn diameter that maximises the gain.

The beamwidth (radiation angle) and the power gain (in dB) are closely connected to each other by the following relationship:

$$G = 10\log_{10}\left(\frac{360^2\eta}{\pi\theta^2}\right) \cong 10\log_{10}\left(\frac{41253\eta}{\theta^2}\right),$$

where θ = half power beam width in degrees and η = efficiency (<1).

If we do not consider the efficiency, the equation represents the antenna directivity, which is easier to measure than the power gain at 2.4GHz because it can be calculated through the simple measure of an angle.

The power gain and the directivity are also affected by the size and shape of the ground plane; this can be square or circular, but it needs a side or a diameter equal to λ (125mm @ 2.4GHz) to obtain good performance.

With a smaller dimension screen we take the risk of the inversion between the main lobe and the back one of the antenna!

The SWR is guaranteed by the matching between the typical 120-130Ω input impedance of the helix and the 50Ω impedance of the feeding coaxial cable. This is obtained using a λ/4 transformer made using an industrial Teflon support with h = 2.5mm and line width W = 3mm, (Z approximately 81Ω). The transformer layout is shown in **Fig 2** and was designed using the Agilent software *AppCAD* [12]. The axial ratio values are included within 1 - ∞ and are defined by:

$$AR = \frac{|E_\phi|}{|E_\theta|},$$

Where E_ϕ and E_θ are the electric fields in time-phase quadrature, perpendicular to the axial direction of the helix.

The polarisation is as much circular as the AR ratio is near unity (0dB). The matching of this requirement can be confirmed by analysing the radiation patterns generated by the *NEC-Win Pro* simulation program.

The following criteria are suggested for the design.

- Use a copper wire, gold or silver plated, having a suitable diameter: 0.024λ (3mm @ 2.4GHz).
- W ind the helix in a cylindrical shape.
- Divide each turn in 10 segments in order to satisfy the Nec-Win-Pro rule that fix the minimum ratio between the length of the segment and the wire radius for better simulation accuracy. The use of 20 segments per wavelength is suggested only for critical regions (complex shapes).
- Use a 6mm stub between the ground plane and the helix, during the simulation phase, to minimise the current induced in the screen by the proximity of the first turn of the helix winding.

Using the above criteria, we simulated and built two different antennas (see the photograph), one to receive the AO-40 satellite [6] having 16.7 turns (simulation results: power gain 14.5dB, radiation angle 26°) and another with 5 turns (power gain 12dB, radiation angle 45°) to be used both as a reference antenna and as transmitting antenna for the directivity measurements described later. The simulation files are available to experimenters on request.

LOW-PROFILE HELICES

The behaviour of the current versus length of a typical helix shows three different regions.

- Near the feed point where the current decay is exponential.
- Near the open end with a visible standing wave.
- Between the two helix ends where there is a relatively uniform current and small SWR (transmission line).

There are two ways to obtain a good circular polarisation helix: firstly, tapering the helical turns near the open end, to reduce the reflected current from the arm end; secondly, using only the first helical turns where the decaying current travels from the feedpoint to the first minimum point (see **Fig 3** for a 5-turn helix).

Starting from these considerations, our final low-profile helix uses a pitch S = 0.16λ (20mm @ 2.4GHz) and is both conically wound with a cone of 62/41mm diameter and very short

Fig 3: Helix current distribution at a frequency near the centre of the axial-mode region.

Fig 4: NEC-Win Pro simulated radiation diagram of the 1.7-turn conical 2.4GHz helix. (Pitch = 20mm, Cone dia = 62/41mm).

Fig 3

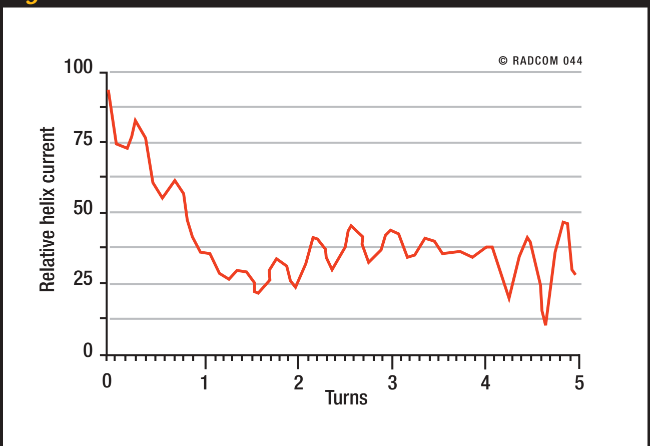
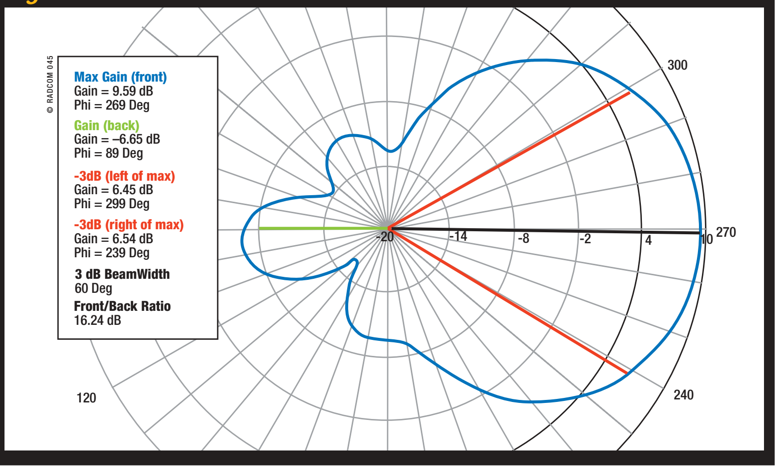
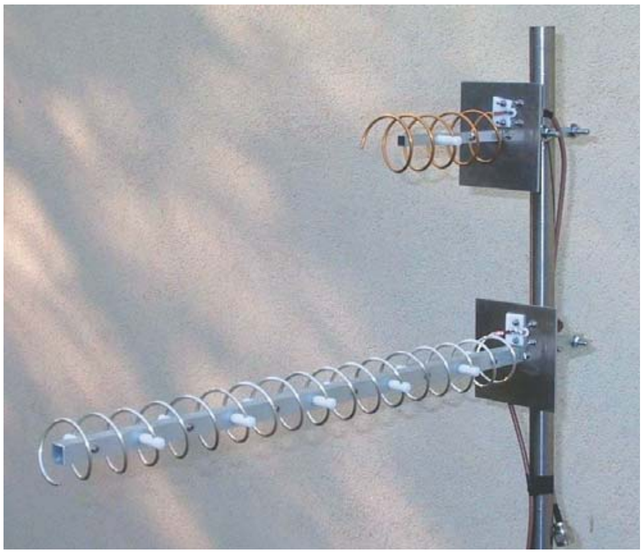


Fig 4





Above left: Low-profile helix with 1.7 conical turns.

Above right: Field test: 5-turn and 16.7-turn helices.

(only 1.7 turns – see the photograph).

The simulated and measured results are very interesting and the directivity is not significantly different from that of a conventional multi-turn helix. See **Table 1** for comparison between low-profile and standard helices.

The equivalent directivity obtained from radiation angle measurements is about 10dB for the low-profile helix (only 40mm thick) and 11dB for the 150mm-long 5-turn helix. The measured radiation angles (-3 dB) are respectively 58° and 45°. Thanks to the very small mechanical dimensions, this antenna is particularly useful also for Wi-Fi (wireless LAN) applications.

The results obtained with *NEC-Win Pro* are very interesting. The radiation diagram and the input impedance (Smith chart) of the low-profile 2.4GHz helix are shown in **Fig 4** and **Fig 5.**

Table 1: Comparison between measurements and simulation for standard and low-profile helices.

Table 1

Type	Measured radiation angle (°)	Equivalent directivity (dB)	Simulated radiation (°)	Simulated directivity (dB)	Notes
16.7 turns	28	13.5	26	14.5	AO-40 type
5.0 turns	45	11.0	42	12.0	Reference
1.7 turns	58	10.0	60	9.6	Low-profile

Table 2: Simulation of gain, radiation angle and front-to-back ratios for different 1.7-turn helices.

Table 2

	Helix type	Frequency (GHz) 2.0	2.2	2.4	2.6	Reflector
		Gain (dB)				
A	Dia 67/45mm conic	9.17	9.49	9.64	8.80	125 x 125mm
B	Dia 62/41mm conic	8.93	9.35	9.73	9.84	125 x 125mm
C	Dia 62/41mm conic	8.84	9.31	9.59	9.44	**Dia = 124mm**
D	Dia = 56mm **linear**	9.03	9.38	9.68	8.52	125 x 125mm
		Radiation angle (°)				
A	Dia 67/45mm conic	63	59	58	56	125 x 125mm
B	Dia 62/41mm conic	64	61	57	57	125 x 125mm
C	Dia 62/41mm conic	67	63	60	58	**Dia = 124mm**
D	Dia = 56mm **linear**	62	58	56	65	125 x 125mm
		Front-to-back (dB)				
A	Dia 67/45mm conic	18.0	18.0	20.0	17.0	125 x 125mm
B	Dia 62/41mm conic	17.3	17.6	18.0	19.0	125 x 125mm
C	Dia 62/41mm conic	14.0	15.0	16.0	18.0	**Dia = 124mm**
D	Dia = 56mm **linear**	17.0	17.0	17.0	24.0	125 x 125mm

From the response plots of **Fig 6** we can also see the improved bandwidth resulting from conical helices. Also shown in **Table 2** is a comparison of the simulated values of gain, radiation angle and front-to-back ratio of four different 1.7-turn helices (conical, linear, different diameter, square or circular reflector).

MEASUREMENT ERRORS

It's not very difficult to design and make helices for different working frequencies and gains. More difficult, for the serious experimenter, is making precise measurements.

The first critical point is the low-SWR measurement, because extremely high-quality cables and adapters are needed. The time and money spent on high-quality cables can be wasted if there are large impedance mismatches within the connectors, at the connector-cable interface and with the adapters (only N or SMA for the 2.4GHz tests). David Slack of Times Microwave Systems [7] writes: "…a microwave cable assembly is not 'just a wire'. It is a passive, TEM-mode, microwave component and an integral part of a system…"

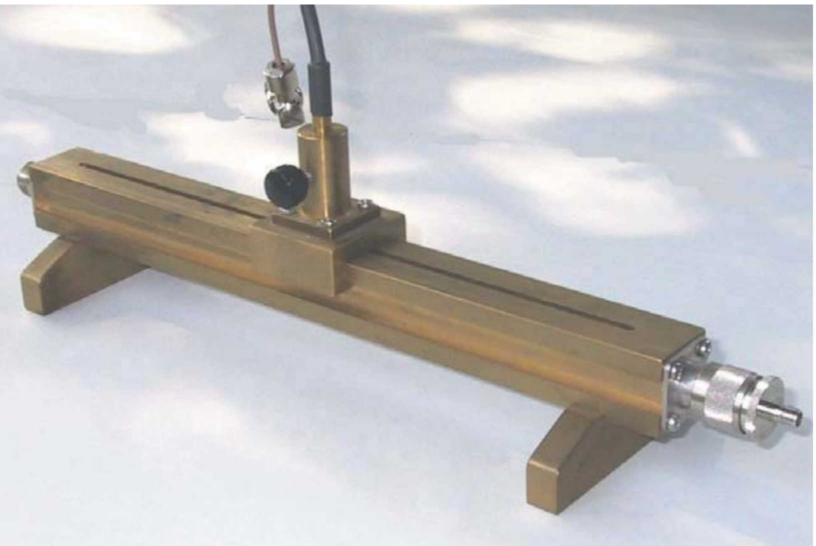
Assuming a high-quality cable is used, the predominant contributor to the SWR of a cable assembly (on a 10-50cm short assembly) is the connector. Improperly-compensated geometry changes in the connector interface will exhibit very poor SWR characteristics.

Previously, trial and error was a key part of high-performance design, but today the computer simulation of discontinuities in connectors is an art and the practical results are visible when the SWR performance of a very good cable assembly is analysed. Another cause that can affect the characteristic impedance is the SWR induced by the incorrect characteristic impedance of parts of the line [8, 9], in particular, the transition between the inner conductor and the N-type panel connector lead may have different dimensions.

The use of a slotted line is becoming a lost art, but learning it is not too difficult. The first suggested measurement with a slotted line is the SWR of a system with a very good commercial termination. Our first results with an old HP termination model 909A (N-male connector) are not the best. Better results are obtained using the Minicircuits termination type Anne-50 with an SMA-male connector (SWR = 1.03 @ 3GHz) and a good Amphenol adapter N-male/SMA-female. The measured values on our self-made slotted line (shown in the photograph) are shown in **Fig 7**. For almost all the tests we used a generator (2.2 to 2.7GHz) composed of a VCO type JTOS-3000 followed by the 3x3mm wide-band amplifier type MNA-6 (complete package).

RF signal levels during the measurements.

The output level from the oscillator is very high (+10 dBm), but some attenuation was included for stability (the wide-band amplifiers will oscillate with loads of not exactly 50Ω). Using



the Boonton RF Millivoltmeter (model 92B) as a detector, there is a sensitivity loss of about 10dB @ 2.4GHz (referred to the maximum suggested operating frequency of about 1.2GHz) and, consequently, the level sampled by the probe of the slotted line is very low (typically 0.3 to 3mV).

In future measurements we will use a 2.2 to 2.6GHz heterodyne system composed of a harmonic mixer and a 1.0GHz fixed-frequency local oscillator. The IF will be in the range 100-500MHz, limited by a 550MHz low-pass filter. This solution is free from oscillation risks and the gain is obtained with a simple wide-band 100-500MHz amplifier followed by the RF millivoltmeter. In effect it's very important to minimise the coupling between the probe and the line to obtain reliable results.

The RF power supplied to the 5-turn transmitting helix is also about 10mW (+10dBm) followed by a 6dB N-attenuator.

To reduce the measurement errors, the distance between the transmitting and receiving antennas has to be considered. To determine this distance, you need to be able to measure the signal level with a filtered RF voltmeter having a 20 - 30dB dynamic range. Also, the wave reaching the receiving antenna should be as planar as possible.

The first condition can be easy established starting with the received power and calculating the attenuation experienced by the wave in free space:

$$A = 32.4 + 20\log(f) + 20\log(d) - Gt - Gr .$$

Here, A is the attenuation in decibels, *f* is the frequency in megahertz , *d* is the distance in kilometres, Gt is the gain of the transmitting antenna in dBi, and Gr is the gain of receiving antenna, also in dBi, obtained by simulation.

There is also a simple, easy-to-remember method of calculating the free-space attenuation by considering the distance between the two antennas in terms of wavelengths. When $d = \lambda$, A is always 22dB between isotropic antennas.

This equates to 12.5cm at 2400MHz. The attenuation increases by 6dB for each doubling of the path distance. This means that the free space attenuation is 22dB at 0.125m, 28dB at 0.25m, 34dB at 0.5m, etc. To make the wave reaching the receiving antenna as planar as possible, the capture area in square metres of the receiving antenna is:

$$Ac = Gr.\lambda^2 / 4\pi .$$

This expression is valid for an antenna with no thermal losses and was certainly useful for our experiments. With a circular capture area, the minimum distance in metres between the antennas is:

$$d > n.Gr.\lambda / \pi^2$$

A maximum acceptable phase error will also be considered.

For a phase error of 22.5°, which is usually enough, n = 2. If a phase error of only 5° is required, n = 9. In the case where one dimension prevails, the maximum length, instead of the capture diameter, is used. In this case, the minimum distance in metres becomes [10, 11]:

$$d > n.L / \pi^2 ,$$

where L is the maximum length in metres (50cm for the 16.7-turn helix).

A site in the garden was found to be particularly useful for all our helix measurements (d = 4m = 32λ at 2400MHz). ◆

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Fig 5

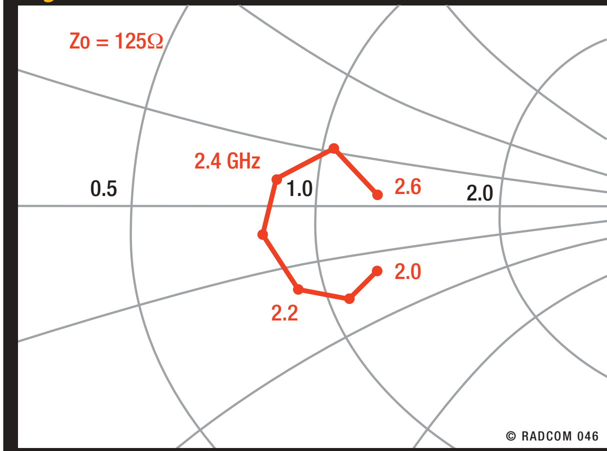

Fig 6

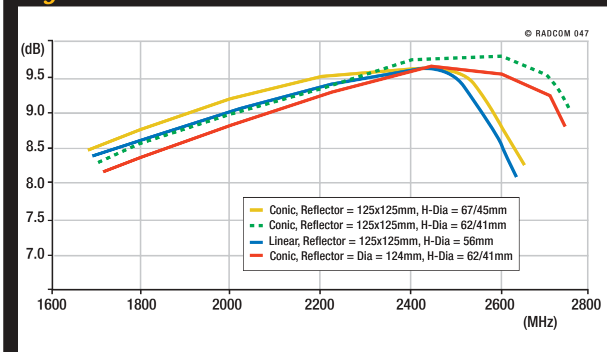

Fig 7

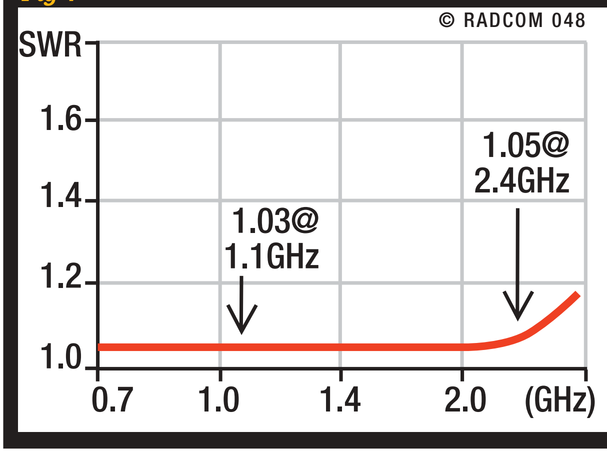

Fig 5: Input impedance simulation (Smith chart) of the low-profile helix.

Fig 6: Frequency responses of four different 1.7-turn helices (pitch= 20 mm).

Fig 7: Slotted line measured values of SWR up to 2800MHz.

Top left: A complete 1-3GHz home-made slotted line.