Homebrew quagi antenna for the PMR band (446 MHz)

Antenna from a few bucks

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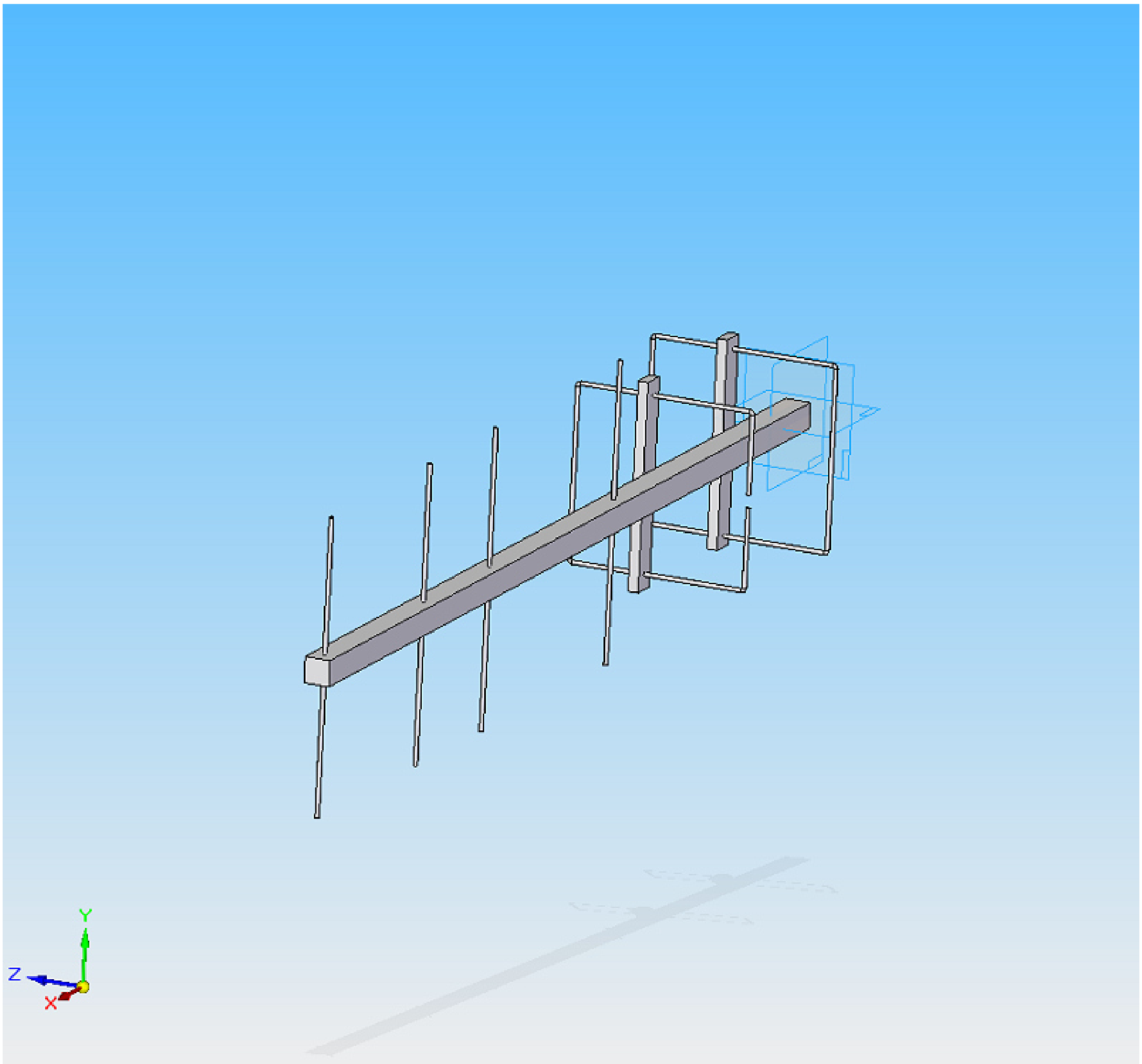


Written by Andor Rábay („andorpapa”)

e-mail: mecsekpmr@freemail.hu

Why should we build our own antenna?

There are very few antennas on the market in Hungary, which are portable and cover the PMR446 band. The cheapest one is the polish made Dipol ATK-5 which has 7.5 dBi gain at 446 MHz. The ATK-5 is a good „backpacker" antenna: its length is only half meter (1 ½ ft), its weight is 0.5 kg (1.1 pounds) and the price is only 1800 Ft + shipping (about 11 EUR). An other manufacturer, Carant has 7 element yagis for this band, they have gain between 9 and 10.5 dBi, their length is 70 cm (27 ½ inches) and weight is between 0.5 and 1.5 kg (1.1-3.3 pounds). But these are more expensive models.

The DIY antenna manufacturing has two advantages: you can build a cheap antenna, exactly with the parameters you need. If you want to build an atenna for backpacker DX purposes than you can construct it with few elements and lightweight materials, or if you're planning a stable one up to the roof than you can build 2-3 meter (6-9 feet) long antennas, focusing on the weatherproof design.

The quagi

My plan was to create an antenna what is easy to build, cheaper than the ATK-5, but has at least the same gain as the yagi. Hence I choose the quagi. The quagi was developed in the early '70s by two radio amateurs. Imagine a standard yagi with ordinary boom and directors. Now replace the dipole and the reflector with quad elements, and you've got a quagi! The quad radiator is a square shaped element usually made from wire or thin rod, each side has the length of $\lambda/4$. The reflector has the same shape but it has a little bit longer sides. The directors are the same what we know from yagis. The boom made from a non-conductive material, wood or fiberglass.

What are the benefits of the quagi?

- cheap materials
- easy to build, doesn't need advanced tools
- 50 Ω feedpoint impedance, so doesn't need impedance transformer
- easy to tune
- has the same gain as the yagis

Well, the quagi has disadvantages too, for example a yagi equipped with a folded dipole has much wider bandwidth and there are some pitfalls through the construction, but I will explain them later. Let's start with the required materials!

- wooden slat/rod/chairleg etc (105-110 cm which is around 3 ½ ft) with arbitrary cross-section (mine is 25x25 mm which is 6 1/3 inches)
- 3 mm (1/8 inch) brass rod (3 meter, nearly 10 ft)
- 22-23 cm (9 inches) long wooden stick (2 pieces)
- screws

That's all! Most of these stuffs are already available at home, except the brass rod, which costs 290 Ft (1 EUR) per meter, so the material's price could be kept under 1000 Ft (around 3 EUR). An additional cost reducing method is to replace the brass directors with cheaper metals. An antenna mounting part (shackle) is required too, it's about 300 Ft (1 EUR).

Dimensions

The developers of the quagi specified the dimensions for 446 MHz, so this is a good origin, but don't forget that the thickness and optional insulation of the elements has strong influence of dimensions. The original description mentions directors with 3 mm (1/8 inch) diameter from any metal (copper, brass, aluminium). For the quad elements it suggests the #12 TW house wire which is an insulated copper wire with 2.8 mm diameter. Since I used 3 mm thick non-insulated rods for the quads, I had to increase the length of the elements. The new dimensions can be found in this list (on the internet most of the dimension tables are containing the original dimensions based on the 2.8 mm thick insulated wire):

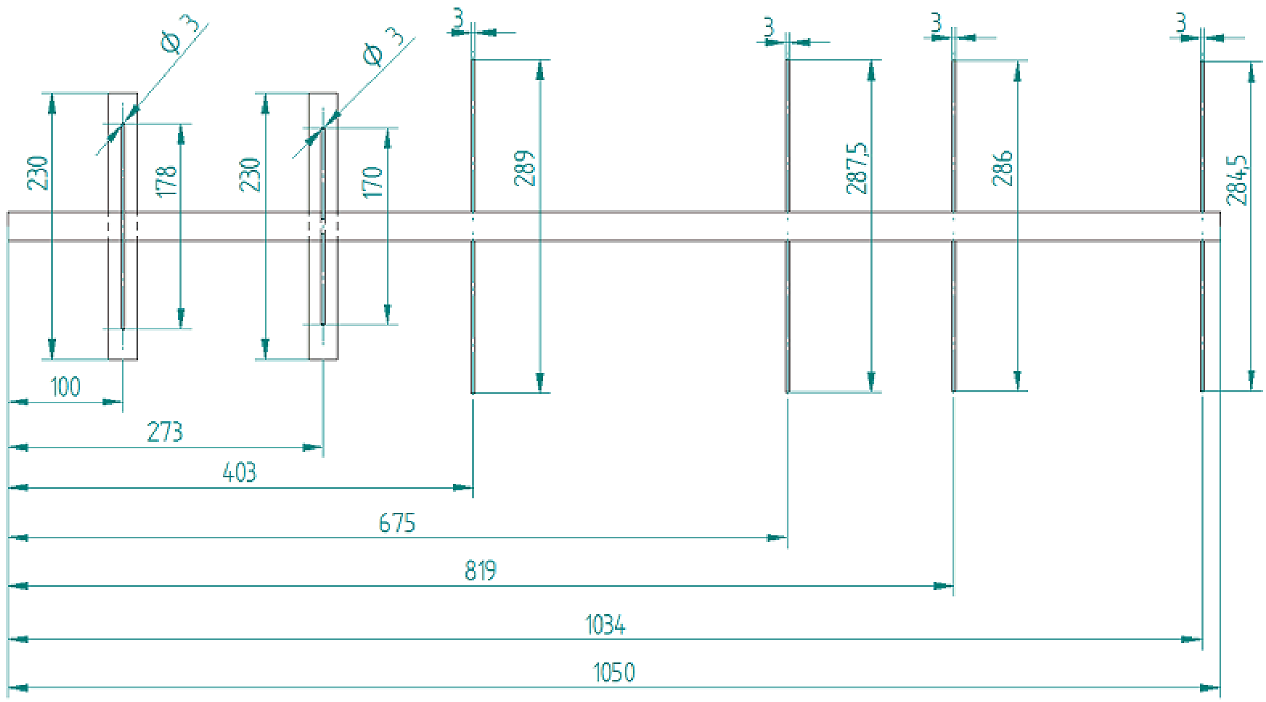
R	712 mm
DE	680 mm
D1	289 mm
D2	287.5 mm
D3	286 mm
D4	284.5 mm

R is the length of the reflector, DE is the driven element and D1-D4 are the directors.

The distances between the elements:

R-DE	173 mm
DE-D1	130 mm
D1-D2	272 mm
D2-D3	144 mm
D3-D4	215 mm

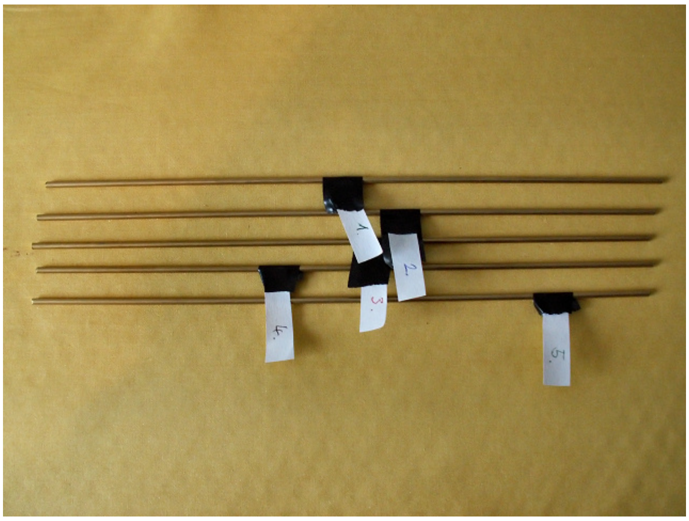
So the overall length of the boom is 934 mm (36 1/3 inches) but it is recommended to leave some space for the mounting section. I left 10 cm (nearly 4 inches) at the end of the boom for these purposes. But you can mount the quagi not only at its end, but between D1 and D2. In this case try to avoid metal support, use wooden or fiberglass supporting methods.



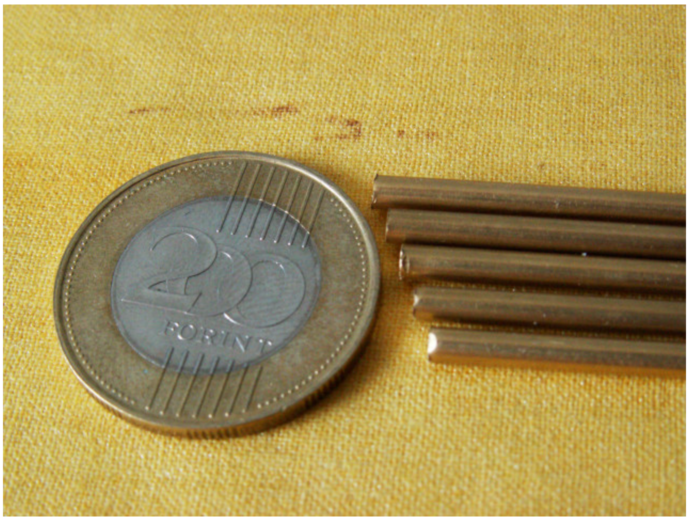
Construction

I recommend to start with the brass rods. You can cut them with saw, wire cutter, tooth, nails or anything. At the first round cut a little bit longer pieces because it's allways easier to cut more later than extend a too short rod. Every director is shorter 1.5 mm (1/16 inch) than the previous one so precise, accurate work needed. But don't be afraid, it doesn't require special tools. I cutted 3-4 mm longer pieces compared to the proper length, than I refined it with a minor angle grinder. Remember: don't cut with the angle grinder but refine! Believe it or not with a small angle grinder you can set the elements length with 0.3 mm accuracy. Finally use a file or rasp to achieve the perfect length. Do the same with quad elements.

Practical tip: put stickers on the directors with their number after you've cut them because they've got almost the same length and it's easier to identify them if they are labeled (you can see this on the following pictures).



1. picture – The labeled directors



2. picture – The difference between the directors' length

Let's prepare the boom! I used 25x25mm (1x1 inch) wooden slat because I found it in the backyard and seemed to be good for this project. You can use slats with different cross-section too. After cutting the proper length of wood, mark the place for the elements. If you want to mount the antenna at its end, don't forget to leave enough space for the mounting hardware! The original description talks about directors going through the boom which is an easy way to mount the elements – if you can drill straight hole into the wood. I can't, because handiness is not my strength. So I chose another way: terminal block. I fastened the brass rod into a piece of terminal block and screwed it to the boom. If you want to mount the elements through the boom, drill holes with the diameter of the directors. Push the rods through the boom and fix them with a drop of glue.

The quad element will be a harder job. You have to not only bend them but to construct support wooden support for them. The quagi's driven element has its feedpoint at the middle of one side, so you have to bend symmetrical the brass rod. The polarization depends on whether the directors and the fed side of the quad driven element stays horizontal or vertical. On the PMR band we need vertical polarization, so we use directors staying vertical and feed one of the perpendicular side of the quad element.

Bending the brass maybe the most difficult part of the quagi construction. Because you have to consider that the folded part necessarily has a bending radius and during the bending procedure the brass lengthen a little bit which results longer quad elements overall. You can bend the quads with everything you have: chuck, edge of the table etc, but try to keep the bending radius minimized. Remember: after bending the rod to U shaped, the whole element must be planar.

3. picture – The folded brass rod

After bending the brass rod to U shape, let's create the quad support wooden element. Drill two holes on the wooden stick and push through the legs of the U shaped brass on the holes. The last step is to „close” the quad, so you have to bend the U shaped legs to form a square. Yes, a square with equal side lengths, not a rectangle. You can solder the 2 open ends together for the reflector element, or you can use terminal block to clamp them. This method has an advantage: with the terminal block you have an about 1 cm (2/5 inch) long tuning section for the reflector.

The driven element's open ends are the feedpoints. Solder the coax cable's inner lead to one end, the outer lead to the other. Use a small amount of glue to fix the brass rod to the support wood. You can connect the quad elements through their support stick to the boom with the same method as the directors. You can screw or glue them. Don't forget the proper distances between the elements!

4. picture – The reflector element (beta version, a little bit asymmetric)

Let's solder the cable! The brass with diameter of 3 mm is easily solderable. First I was a little bit afraid because I've got only a trashy soldering iron with 30W power output, but it was more than enough for this job. I suggest to use heat shrink tube after soldering. It's not just for the better look but it's providing more resistance against mechanical damages of the soldered connection cause the movement of the coax cable. You can find on the internet other feeding methods too: many quagi builders solder BNC or N connector to the 2 open ends. That's fine too.

Most of the sources mentioned that tha cable should run away from the feedpoint, perpendicularly from the elements to avoid interactions.

Tuning the quagi

The quagi's most important advantage is that the feedpoint impedance is exactly 50 Ω in case of proper sizing, so no need of impedance transformer, like gamma matching or 1/2 λ phasing section (also known as 4:1 balun), so you can feed the quagi directly with coaxial cable. But the quagi is a symmetric antenna and the coax is an asymmetric feedline, so the cable act as a radiator and causes some loss. The „quagists" reported that using various symmetry transformers causes bigger losses than feeding directly with coax, so most of the builders uses only a simple choke balun, which is not a real balun but it do what it have to do: it keeps the feedline from radiating.

The choke balun around 400 MHz is created from 3-4 loops of the coax with relatively small diameter (4-5 cm / 1 ½-2 inches) as close to the feedpoint as possible. Bind the turns with 2-3 tie wraps, and that' it, you've got a choke balun. The diameter of the loop depends on the coax cable you use. For example: an RG-58 is more flexible than a H-155 or H-500, so be careful with the balun: too small diameter causes damage in the cable, so always choose the proper radius for the type of your cable.

Tuning the quagi is not a complicated procedure, but you must have an SWR meter, without it there is no use building the antenna (I forgot to tell it in the introduction, sorry). The first step of the tuning is the SWR measurement at the operating frequency, which is now 446 MHz. If the antenna's dimensions are OK than you can achieve az SWR around 1:1. So if you measure value higher than 1.2 than you can still tune the quagi. As I observed it is very easy to find the frequency where the SWR is minimal (the SWR curve isn't flat), so if you're perfectionist, you can tune the resonance frequency exactly to 446 MHz.

So we have to find the frequency where the SWR is minimal. If this frequency is lower than 446 MHz, then you have to shorten the reflector and the driven element, and if it's higher, then you need longer quad elements, which is an annoying situation. But you don't have to affraid about it, since we cut longer rods than what we really need, so the initial resonance frequency must be under 446 MHz. Now we have to desolder the coax from the driven element and shorten the quads with angle grinder, file or rasp. What are the required new dimensions? The formula below helps to calculate the proper lengths:

$L_{new} = L_{old} * f(SWR_{min})/f(446\ MHz)$

L is overall length of the driven element and $f(SWR_{min})$ is the frequency where you measured the minimal SWR (in MHz). The reflector's new length based on the new length of the driven element:

$Lref_{new} = Lref_{old} * L_{new}/L_{old}$

Lref is the legth of the reflector and L is the legth of the driven element. I will explain some experiences about the dimensions soon.

It is recommended to keep the SWR as low as possible but don't forget that the shape of the driven element and the reflector can't neglible too, so the modification of the mounted elements' lengths can distort the square shape which is also important because of the radiation pattern. At the SWR value of 1.3 only 1.7% of the output power will be lost, at 1.5 only 3% is the loss.

Hidden traps, my own experiences

I've claimed in the introduction that it's easy to build a quagi but this statement isn't exactly true. Cutting the elements is not a big trick, but the bending procedure is more complicated because the 3 mm thick brass is rigid enough, so after bending it's hard to restore to its previous shape. So you have to work precisely because you can't modify too much the completed driven element and reflector. I have to admit that I made some quad elements to experiment the proper lengths for the PMR466 band. During these works I observed that changing the length about 2-3 mm (3/4” - 1 1/6”) also changes the resonance frequency about 1 MHz. 1 cm means 4 MHz! So if you want to use metal rod with other diameter or with insulation, you have to experiment the proper lengths as I've done.

I observed that the precise scaling of the driven element is critical. While changing the length of the reflector changes the SWR value within 0.2 range, every millimeters of the driven element matter. But don't forget: the reflector's size is very important, it has significant influence over the radiation pattern. So size does matter, and that's why I can't promise that you can build a perfect quagi with the dimensions I've published. As I mentioned, the brass rod lengthen with millimeters during the bending procedure, so bending the 4 corner can detune the quagi with some MHz. The soldering also effects the SWR, but this is not astonishing since it can mean millimeters.

But don't be afraid, building a quagi doesn't require professional tools or skill, just precise construction.

The completed quagi

- Number of elements: **6**
- Length of the boom: **105 cm** (41 1/3 inches)
- Weight (without coax cable): **430 g** (0.95 pound)

It is also possible to reduce the weight: you can cut in half the thickness of the boom. A quagi based on a 12x25 mm (1/2 x 1 inch) slat would be rigid enough while the weight decreases under 300 gramms (2/3 pound). An other way to reduce the weight is to choose light materials, like fiberglass.

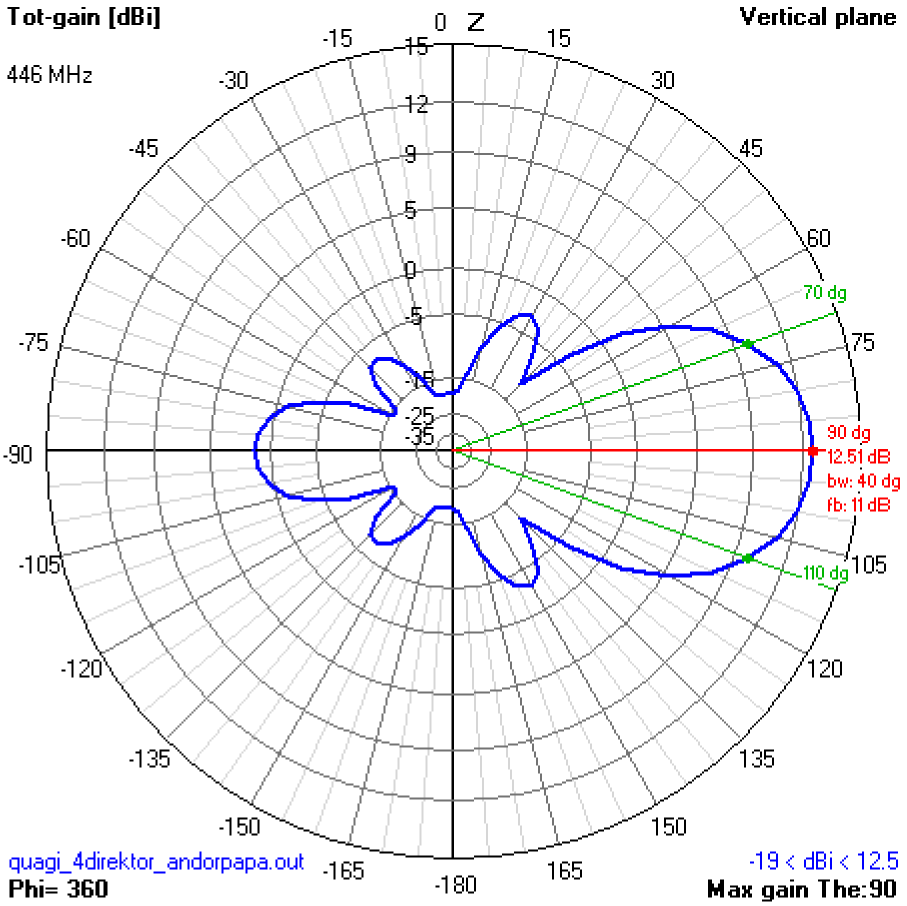
5. picture – The completed quagi, ready for the tuning procedure

Theoretical results

I made the radiation pattern with computer. With the dimensions described above the antenna simulation software gave the following results (it is a free space simulation, so it doesn't calculate with the effect of the ground):

- Antenna gain: **12.5 dBi**
- F/B ratio: **11 dB**
- Vertical beamwidth: **40°**
- Horizontal beamwidth**: 50°**

Since these aren't measured values, it is recommended to handle them as the values given by the antenna manufacturers: they're just guides, the real performance can deflect. From these numbers you can find out one of the drawbacks of this quagi: the low F/B ratio. I found a website where true measurements confirm this disadvantage. The antenna simulation software promises development opportunity about the F/B ratio, but this would be an other project.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446 MHz
Z
70 dg
90 dg
12.51 dB
bw: 40 dg
fb: 11 dB
110 dg
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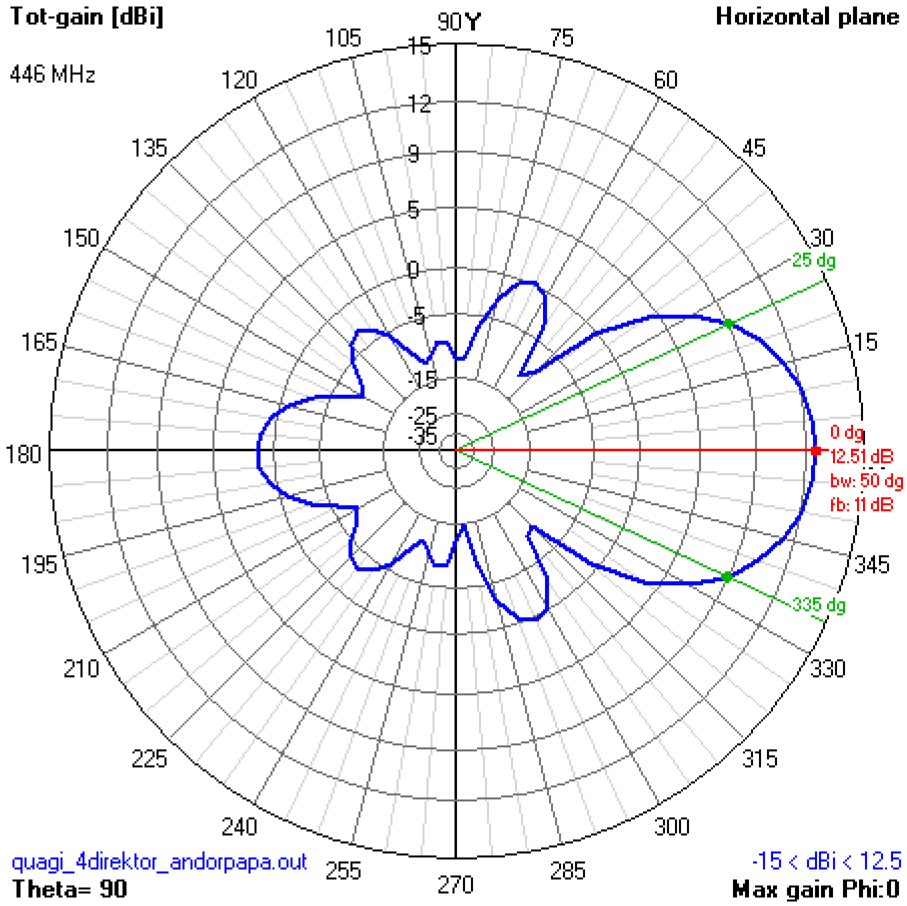
Phi= 360
-19 < dBi < 12.5
Max gain The:90


Tot-gain [dBi]
Horizontal plane
446 MHz
Y
25 dg
0 dg
12.51 dB
bw: 50 dg
fb: 11 dB
335 dg
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Theta= 90
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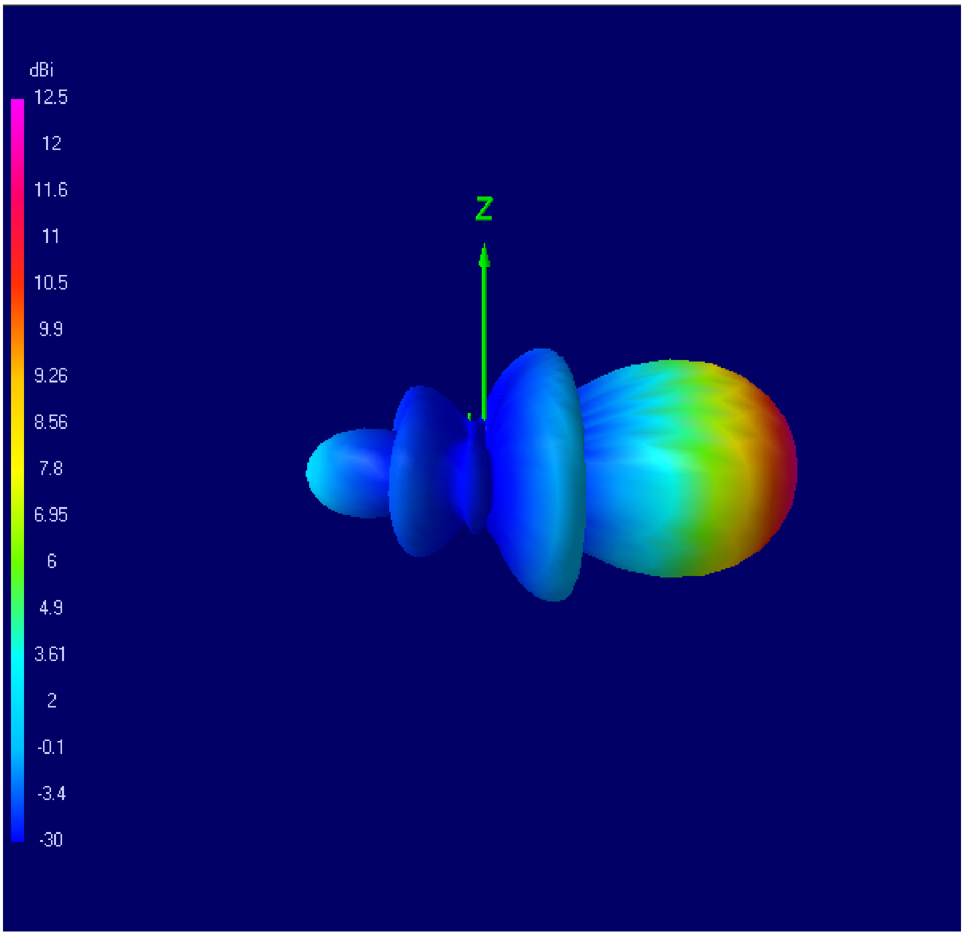
Max gain Phi:0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12
11.6
11
10.5
9.9
9.26
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6
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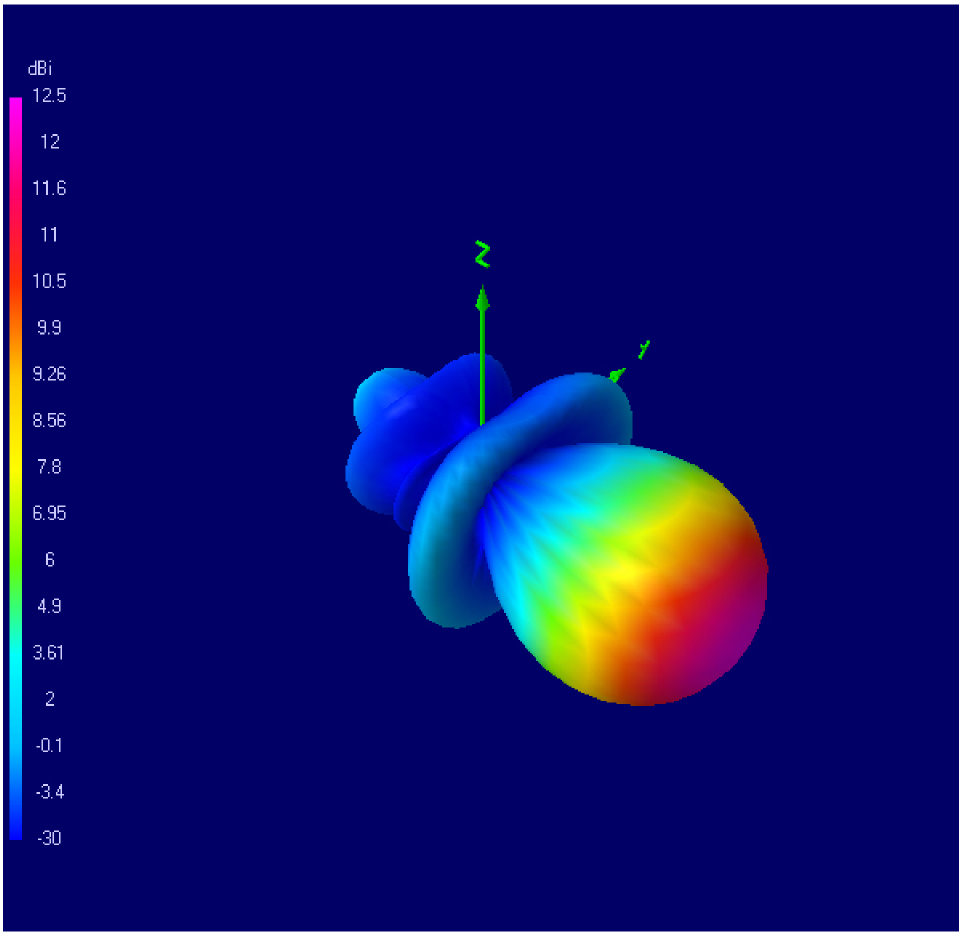
-3.4
-30
Z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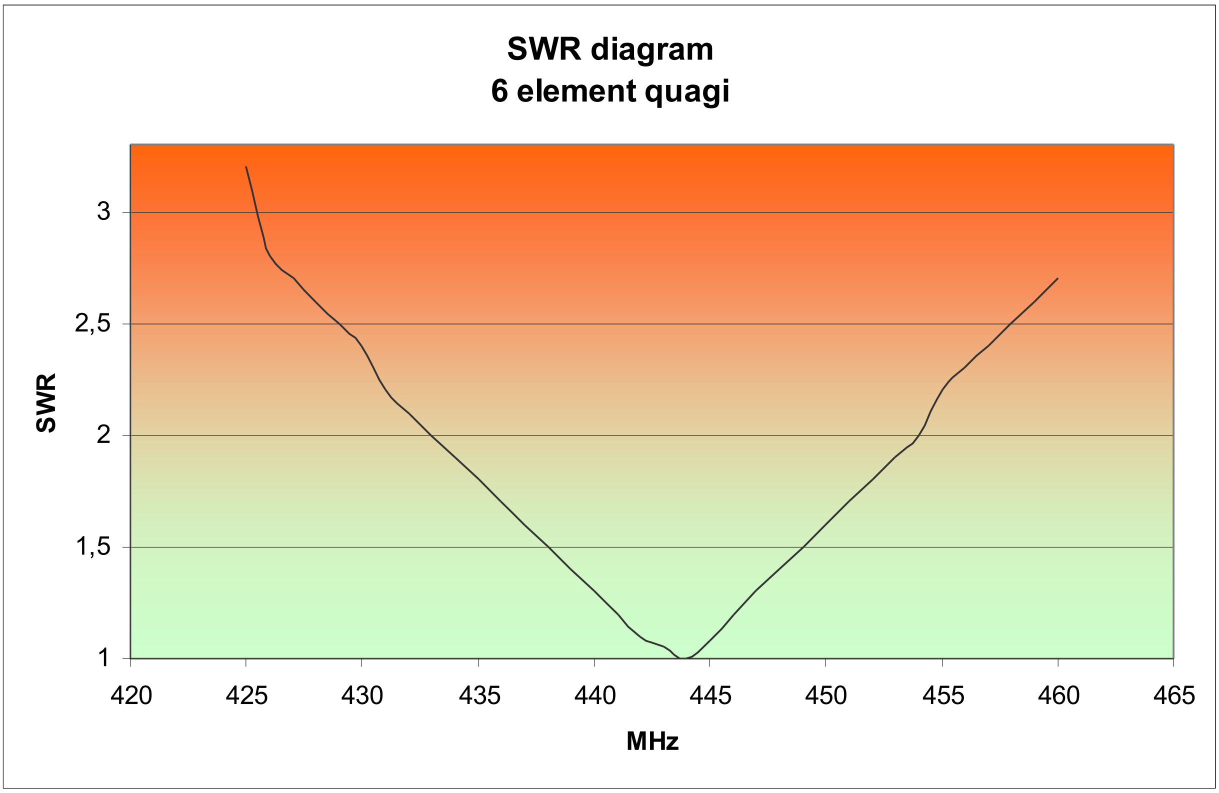
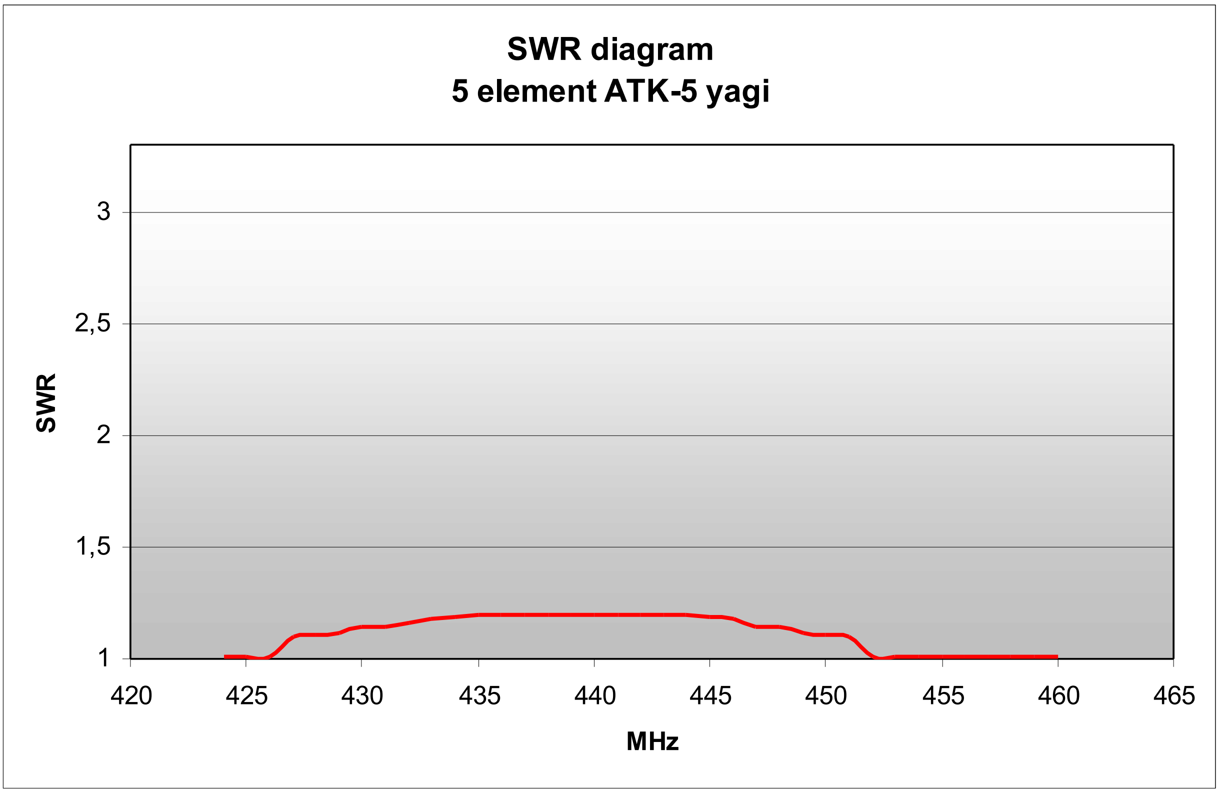
y

SWR measurements

There is an important parameter of the antenna what we have to know: the SWR bandwith. Thus I measured the SWR within a 20 MHz range around the target frequency. I made the same measurement with the folded dipole based ATK-5 yagi I mentioned in the introduction.





The SWR measurement shows clear that quagi has a well defined resonance frequency. If the SWR curve is flat than the distance between the elements or the ratio between the driven element's and the reflector's lengths isn't correct. You can simply recognize that my work wasn't absolutely precise because the SWR minimum is at 444 MHz instead of 446 MHz. But I achieved an SWR of 1.2 at the PMR band, so I didn't find necessary to rasp millimeters from the driven element. Don't forget: after a lot of soldering the insulation between the coaxial cable's two lead can melt, and of course it happened to me while I was experimenting the proper length of the driven element. But the dimensions you can find in this document are corrected for 446 MHz operation. Due to the SWR diagram we can define the SWR bandwith for the 6 element quagi:

- Bandwidth (SWR < 1.5): **10 MHz**
- Bandwidth (SWR < 2.0): **20 MHz**

Compared to the folded dipole based ATK-5 yagi we can observe that the quagi has much smaller bandwidth. The average yagis with folded dipole have 50-100 MHz bandwith (where SWR under 1.5). But this is not a tragedy because we want to use our quagi only on the PMR band, and if it's necessary, we can also use it on the 70 cm HAM band, as the SWR value is around 2 there.

Don't forget (and this would be a good advice for other antenna projects too): always measure the antenna's SWR at it's final place of application! There is no fixed position for a portable antenna, but try to measure in a similar environment. I measured the SWR two times. First in a window upstairs (about 7 meters / 23 ft above the ground), second time mounted to a steel barrier 2 meters (6 ½ ft) above the ground. The SWR diagram shows the result of the first measurement. In the second case I recognized that the resonance frequency increased from 444 MHz to 445 MHz and the SWR of the PMR band decreased from 1.2 to 1.07, none the less I made no modifications over the quagi. The distance above the ground and the metallic objects near the atenna have influence over the SWR. So if you want to use the antenna on the roof, don't take measurements in the garage!

Quagi's real life performance

The low SWR is a good thing but it only talks about the impedance match. Without the proper tools I wasn't able to do correct measurements, so I can't tell you values about the real gain, F/B ratio or beamwidth but I can talk about the performance I experienced since I've built it. I will mention some situations when I was able to compare the quagi to my other antennas:

- I was scanning the local traffic when I heard an older man from the distance of 30 km (nearly 19 miles). The quagi produced stronger signal compared to the ATK-5, since I was nearly unable to hear anything with the yagi but I could receive continuously with lower noise thanks to the quagi..
- I tried the quagi and the ATK-5 from the top of the mountain called Mecsek. I asked a report from the city of Balatonalmádi which is 105 km (65.6 miles) away. The ATK-5 and the quagi produced the same value on the S meter, and when the S value was fluctuated between S3 and S4, the quagi reached the higher value. After this measurement we tried to compare the quagi and tha yagi with the following method: we connected the yagi to a radio which has a power output of 0.8 W and the quagi to a radio which produces only 0.5 W. We achieved the same S value for the the two setup. After the test I recognized that the reflector's open ends slipped out from the terminal block so it didn't form a perfect quad element.

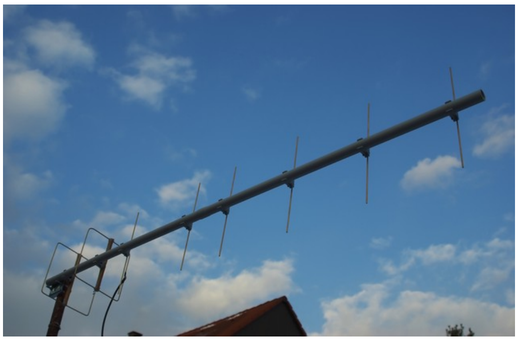
- So I cured the reflector and tried it again on an other weekend. I asked a report from Polgárdi which is 106 km (66 ¼ miles) away. The 6 element quagi easily outperformed the ATK-5 with one S value. The difference was noticeable: the connection was more stable with less noise.
- I was able to compare the quagi with the ATK-5 yagi and the Hy-Gain V-4R collinear (which has 5.2 dBi gain) at the same time. I observed that that the yagi and the collinear produced noisy reception, the quagi gave more clearer, noiseless connection.
- There were many situations when I wasn't able to receive a transmission with the Hy-Gain collinear because the weak signal didn't open the squelch, but the quagi was a good solution for this problem.

I don't want to guess about the gain based on these experiences. An antenna is good if it's possible to talk far with it. With the quagi I was able to do it, and I can confirm without any precise measurement that my 6 element quagi simply outperforms the 5 element ATK-5 yagi and the High-Gain V-4R collinear antenna.

Summary

I managed to build an antenna which costs less then the cheapest commercial yagi on the market, but has higher gain. This is not a fair comparison due to the different lengths, element numbers and materials but if only price matters, the homebrew solution is unbeatable.

I demonstrated how to build the conventional quagi, but there are many ways to improve this design: with a little imagination you can create quagis with less weight, detachable elements, more directors, plastic boom etc. This was my first quagi project. Since there I extended it to 10 element and built an 8 element lightweight quagi based on PVC boom, with detachable elements for backpacker DX purposes (take a look at the pictures below). So the quagi is very versatile antenna.



Many websites claim that the quagi compared to a yagi with the same element number always has higher gain. It was maybe true when the quagi had been developed, but computer simulations proved that this advantage is only theoretical today since there were many improved yagi designs developed by the amateurs in the last 20 years. But quagi is still a good choice if you want to build antenna with high gain and cheap materials without difficult construction steps and impedance transformer.

I hope that the practical and theoretical principles I've described will help you to build your own antenna – from a few bucks, as I promised. 73 DX