Test Report on a Printed Implementation of the YU1AW Inverted Amos Serially Fed 2.45 GHz 7-Element Dipole Array 15 dBi Sector Antenna

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***Abstract*—This report discusses a 2.45 GHz Inverted Amos sector antenna under test (AUT) machined out of standard FR4 circuit board material and the electric and electromagnetic properties of this implementation. All results are presented in comparison with the extensive simulations done by the inventor of the Amos antenna design Dragoslav Dobričić, YU1AW, which were published by himself in 2007 [1] and in 2008 [2]. The experimental results presented here are in very good agreement with the simulations, which were conducted by YU1AW without a radome. All key characteristics of the antenna, like the input impedance and the radiation pattern calculated by YU1AW, could be confirmed by the measurements conducted.**

I. Introduction

Many radio frequency engineers agree in that the contribution of the antenna characteristics to the overall wireless link quality is commonly underestimated. Often it is assumed among application engineers that sufficient link quality can still be achieved by increasing the transmission power to compensate for low quality antennas. However, using the right antenna has many benefits and avoids the disadvantages of the increased power approach which usually remain unmentioned. Instead, it can and should be considered an indication of link quality when a wireless link needs less power to be established at constant signal to noise ratio. In fact, many wireless links could be operated with significantly less power (and, hence, also less waste of it) if the antennas involved would be operated in their resonance point, for example. Such an antenna demands a good design and sufficient reproducability of it during manufacturing, or at least a means of tuning and optimising the characteristics after manufacturing and before its deployment. The post-production adjustment approach is often very limited in effect and requires sophisticated equipment, whereas the proper design approach requires more time for design validation by tests before start of production, controlled manufacturing conditions and material quality during the production phase. Both methods are often not feasible when building devices for license-free wireless link applications due to high competitional cost-restrictions during production and lack of equipment on the customer and user side during deployment. On the other hand, it is common for commercial mobile communications providers to use well designed and professionally produced antennas and to do on-site spectral and network analysis at their base stations.

Adequate quality of the antennas used within a wireless link optimises other, secondary effects at the same time, such as the noise level seen by other wireless links using the same spectrum and it helps avoiding interferences with other equipment. The minimisation of transmit power while maintaining link quaility by using antennas which optimally fit their purpose has many benefits and probably even provides the most economic overall solution. It even provides the best argument in the ongoing debate on biological effects of electromagnetic fields, because it seems an acceptable common denominator even within this debate, that the smaller the field strength is, the smaller are its effects.

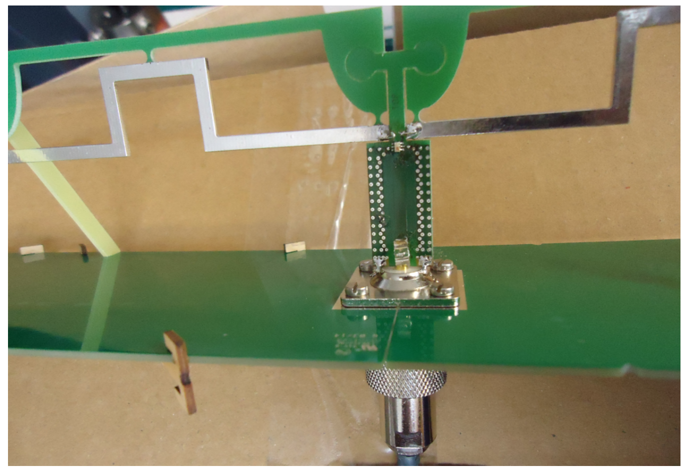

Fig. 1. AUT feeding board connecting the N flange and the AUT radiating elements.

II. Discussion of the Original YU1AW Design

The original Amos design can be described as a symmetric serial array of dipoles, which are all end-fed (apart from the central dipole, which is center-fed) and interconnected by phased lines. Like all phased array antennas this design also provides increased antenna gain by narrowing the angle of the radiated energy, i.e. narrowing the vertical angle in this design. Vertical here is defined as the axis of the serial alignment of the dipoles. The other main influence on the radiating characteristics of the Amos design is the use of a reflector, which renders the radiation pattern in the horizontal plane non-uniformly and is the principal cause for the sectoral radiation pattern in the horizontal plane. Due to the serial arrangement of the dipoles, only one feeding point is necessary. Other designs of phased arrays often use power splitting and individual feeding of the single radiating elements. The advantage of the

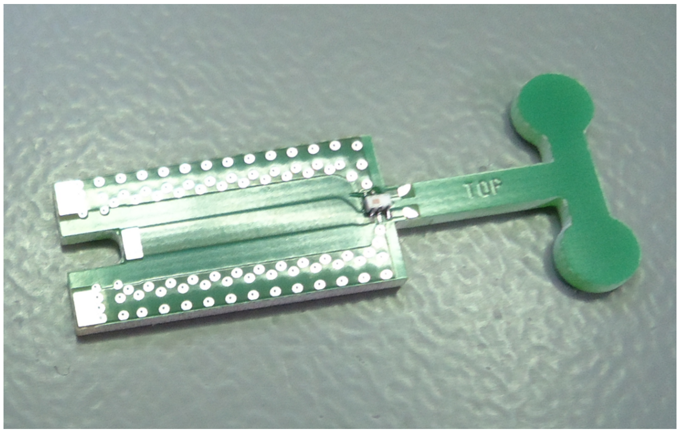

Fig. 2. AUT feeding board with microstrip and LTCC balun component.

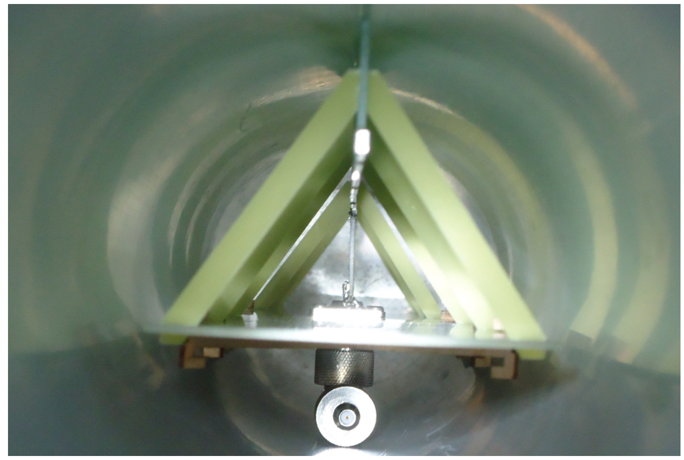

Fig. 3. AUT inside the radome.

power splitting approach is that all elements ideally receive the same power in case of a transmission. Its disadvantage is, however, that it requires power splitters, which need to have minimal attenuation at the working frequency and which may involve manual tuning during or after production. Another disadvantage is that exactly cut feeding lines are needed to provide correct phase alignment among the radiating elements. These disadvantages of the power splitting method increase overall complexity and affect the costs of such an antenna. With the Amos design, the radiated power is distributed non-uniformly over the interconnected dipoles, because the central element radiates the most power whereas the outer elements radiate with decreased power, i.e. decreased by the amount of already radiated power of the elements located further to the center of the array. Hence, increasing the number of dipoles in a linear Amos design becomes less and less effective with respect to increasing the antenna gain [2]. Due to the rule of antenna reciprocity the same reasons apply to the receiving case, respectively.

Another characteristic of the Amos design is its generic two-plane design. This means there is the reflector in a first plane and the radiator which is fold up in the second plane. The two planes are exactly perpendicular to another. This simple mechanical structure can be considered an advantage with respect to manufacturing the antenna out of planar elements.

III. Printed Antenna Construction

Implementing the Amos design for a printed circuit board (PCB) manufacturing process significantly reduces the dimensional variations involved in, for example, modeling the radiating elements out of a long piece of wire. The mentioned manufacturing process commonly provides dimensional manufacturing tolerances of approximately 200 μm. Due to the high dielectric losses of standard FR4 at 2.45 GHz the printed Amos tested here provides two design measures that minimise these losses constructively. Firstly, all spaces of high field strength are kept void of FR4 material, i.e. especially the space around the radiating dipoles, between the reflector and the dipole array and also the area framed by the phased lines in between the dipoles. Secondly, the radiating element has metal-coated edges which completely enclose the carrying FR4 substrate with a conductor. Because the field does not penetrate the FR4 underneath the coating due to the skin-effect, dielectric losses are avoided physically by this construction.

The Amos design has a characteristic input impedance of 200 Ω and requires a balanced feed. Given that the most common and economic way to carry a 2.45 GHz signal is an unbalanced coaxial line with an impedance of 50 Ω, a 1:4 input to output impedance transformation and a balun are necessary. The original YU1AW design implements a coaxial $\lambda/2$ balun 1:4 transformer. This type of transformer needs to be made with high precision taking into account the electrical characteristics of the actually used coaxial feedline at 2.45 GHz. Connecting the transformer to the central dipole in a reproducible way as to provide predictable antenna characteristics was found to be practically very difficult. Hence, in the implementation presented in this report the coaxial balun was replaced by a low-temperature co-fired ceramic (LTCC) balun transformer, which is fed by a microstrip line connected to an N flange jack. The latter also mechanically and electrically connects the two halves of the reflector. The balun is specified for 3 W of RF power, which also enables licensed applications. The known variations of FR4 permittivity, which mainly determine the impedance of the microstrip line, are considered less critical than the possible variations in impedance using a coaxial line balun due to the high degrees of freedom involved when connecting the coaxial balun to the central Amos dipole. This is especially true when no means of post-assembly or end of line tests of the antenna are available.

A practical application of the inverted Amos requires some sort of mechanical protection of the delicate arrangement. Although this may be debatable for indoors applications, it is essential for applications of the antenna outdoors. Hence, the tests of this report were conducted with the AUT placed inside a plastic pipe of 100 mm inner diameter, 2 mm wall thickness and 1 m of length. The effect of this simple radome was a slight increase of the resonance frequency (see Fig. 4).

The printed implementation of the original Inverted Amos 7 design significantly reduces the degrees of freedom during the assembly of the antenna and very economically provides highly predictable and reproducible microwave characteristics and will be discussed next.

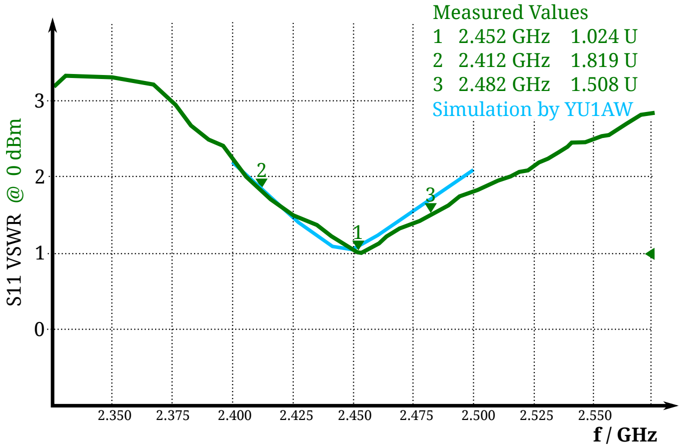

Fig. 4. S11 VSWR.

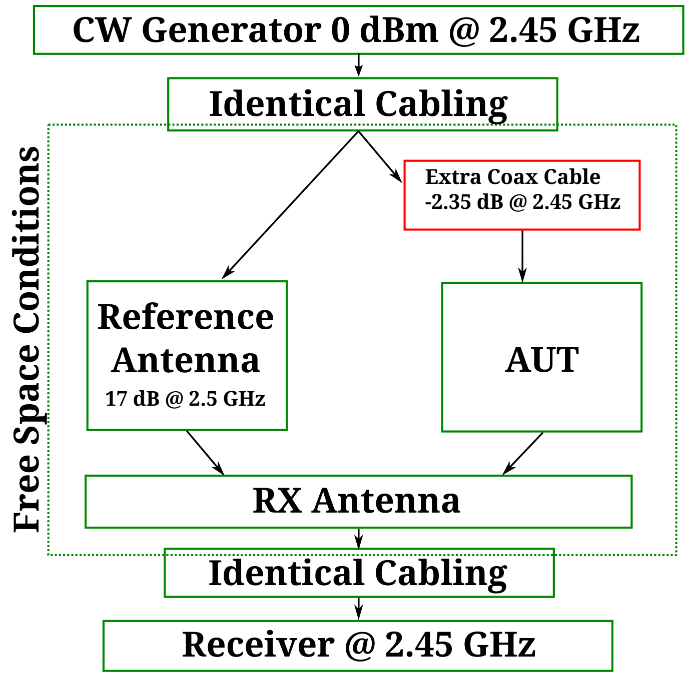

Fig. 5. Block diagram for the gain measurements.

IV. Antenna Input Impedance and Gain

A. Input Impedance Matching

The input impedance of the AUT shows fairly good matching at 2.452 GHz, the center frequency of channel 9 (for 802.11b/g) with a VSWR of 1.024. Channel 2 at 2.412 GHz has a VSWR of 1.819 and channel 14 a VSWR of 1.508. In between the three mentioned points, the VSWR changes almost linearly which allows for good estimation of the VSWR for all other channels even without the VSWR plot in Fig. 4. The input impedance is in very good agreement with the calculations conducted by YU1AW and the shift of the resonance frequency can be explained by the influence of the plastic radome, which was not part of the simulations.

The impedance measurements revealed that the feeding cable should not be run close to either of the narrow ends of the reflector, because it was observed that the tip of the outer dipoles are likely to couple onto the cable and the impedance matching is thereby reduced.

B. Antenna Gain

The antenna gain of the AUT was determined by comparing it to an antenna with a known gain. The underlying assumption here is that a constant transmission signal causes a reception signal that is proportional to the gain of the antenna. When leaving the setup identical, except for swapping the reference antenna with its known gain with the AUT, the unknown gain can be determined by simply comparing the strength of the two received signals. The comparison is carried out in a setup, which is only altered by the change of antennas, i.e. the reference antenna is replaced by the AUT. In this practical case an additional feeding cable had to be introduced to the setup during the AUT measurements, because the AUT is smaller than the reference antenna, but it had to be positioned at the same point where the reference antenna was positioned to allow for comparable results (see Fig. 5). The attenuation of the additional cable was determined to be 2.35 dB at 2.45 GHz by network analysis and will be considered in the following calculations. The third antenna involved in the setup is a receiving antenna, which is connected to a receiver, which in turn measures the received voltage at 2.45 GHz. The signal used for the measurement is a continuous wave with a frequency of 2.45 GHz and a power of 0 dBm or 1 mW. The reference antenna has a gain of 17 dBi at 2.45 GHz and there is only one measurement of the reference antenna necessary to determine the strength of the received signal for the known gain, if linear and time-invariant conditions can be assumed, as it is done here. The measured voltages at the receiver are given in Tab. 1 depending on the position of the AUT.

Tab. 1. Receiver voltages during the gain measurements.)* It could be reconstructed that during the measurements the H-plane tilt of the AUT did not occur mechanically independent of a V-plane tilt which introduced a decrease in the V-plane angle (not planned) during the increase in the H-plane angle (planned). As it is obvious from Fig. 6, a decrease of the V-plane angle results in a decrease of the gain, which is what is observed here as superimposed on the effect of the dominant sidewards H-plane tilt. Geometrically interpreted, the measured values are points on a locus starting from the front tip of the main lobe and continuing on the upper left side of the main lobe to which Fig. 7 represents a top view and Fig. 6 represents a side view. Please refer to [2, Fig. 6] for a three dimensional representation of the radiation pattern mentioned here.

∠V plane	∠H plane	U_{ref}	U_{AUT}
90°	90°	49 dBμV	45 dBμV
84°	90°		40 dBμV
90°*	112.5°		43 dBμV*
90°*	135°		38 dBμV*
90°*	157.5°		32 dBμV*

C. Calculation of the Gain

Eq. 2 shows the relation between the gain of the antenna under test G_{AUT}, and the voltage at the receiver U_{AUT}, in dependence on the received voltage U_{ref}, of the reference antenna in the position of its known gain G_{ref}, and the attenuation introduced by the extra cable A_{AUT}.

$$(G_{AUT,v,h} - G_{ref,90°,90°}) = (U_{AUT,v,h} - U_{ref,90°,90°}) + A_{AUT} \quad (1)$$

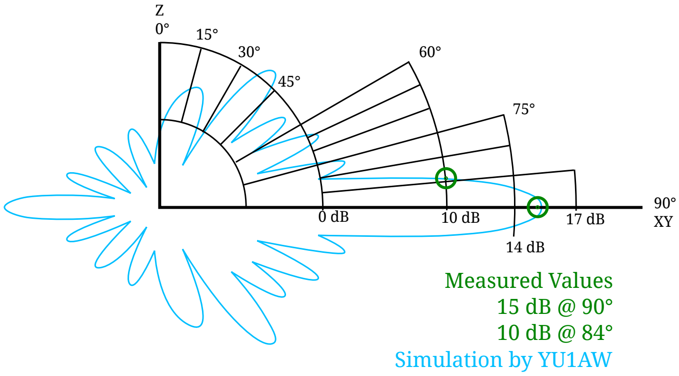

Fig. 6. AUT directional diagram in the V plane.

Because the extra cable is attenuating the 0 dBm signal fed into the antenna it must be added to the voltage value at the receiver to be comparable with the reference antenna.

Tab. 1 shows that $U_{AUT,90°,90°}$ was 45 dBμV, whereas the voltage of the reference antenna was 49 dBμV. The difference of these voltages plus the gain of the reference antenna of 17 dB at 2.45 GHz plus the attenuation of the extra AUT cable at 2.45 GHz (for sake of simplicity a value of 2 dB was used in the calculations here for the cable attenuation although the exact value was determined to be 2.35 dB by network analysis) results in a gain of the AUT of 15 dB (see Eq. 2), which is very close to the value YU1AW calculated (see [2] for details on the simulations).

$$G_{AUT,90°,90°} = (45\ \text{dB}\mu\text{V} - 49\ \text{dB}\mu\text{V}) + 17\ \text{dB} + 2\ \text{dB} = 15\ \text{dB} \quad (2)$$

When the antenna is tilted downwards by 6°, a gain of 10 dB results from the measurements, which again is in agreement with the calculations done by YU1AW (see Fig. 6).

Similarly, the original simulations could be confirmed for the horizontal antenna pattern in Fig. 7, although after the measurements it was found that turning the AUT sidewards also introduced a proportional change in vertical tilt. Please refer to the caption above Tab. 1 for details on the effects of my inexperience.

V. Not-exclusively Technical Summary

The benefits of open-source technology are obvious. When it comes to communications technology the values of independence and stability are to be considered and it may make sense to establish basic building blocks with a confirmed level of quality and, preferably, even a high level of quality. This gives access to the full potential of a given technology, i.e. wireless links can be designed with higher range and, hence, network coverage of a given area can be achieved quicker, by less effort and cost or simply more reliably.

This report qualifies a printed implementation of the YU1AW open-source antenna design from a microwave engineering point of view. It is fit for community organised manufacturing and deployment, preferably for wireless user access points used at the periphery of a wireless mesh network. Mesh networks have prooven economic and reliable, for example, in the form of ad-hoc emergency installations in the case of a natural disaster or as a permanent or auxiliary infrastructure in economically low developed or otherwise challenged regions.

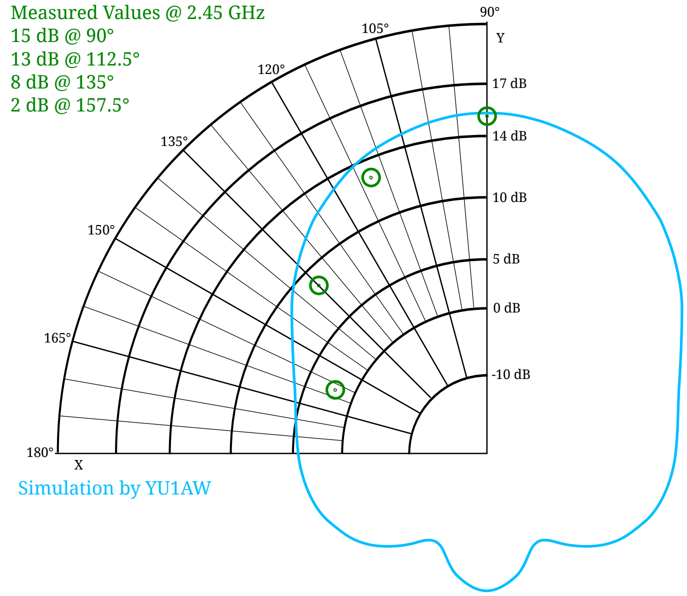

Fig. 7. AUT directional diagram in the H plane. For details, please see Tab. 1

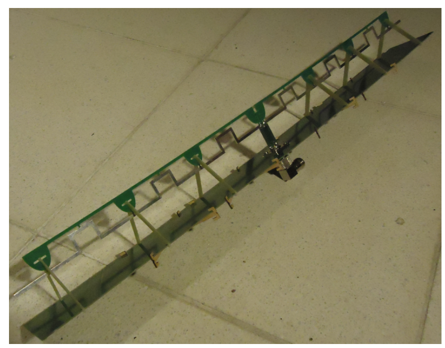

Fig. 8. Printed inverted amos 7 AUT (without the radome).

Tab. 2. Bill of materials for the AUT

2x	Radiating Element (2 layer FR4 w/ metal-plated edges)
2x	Reflector Element (1 layer FR4)
6x	Support Element (bare FR4)
1x	Balun PCB (2 layer FR4 with solder stop)
1x	LTCC 1:4 Balun 0805
1x	N Flange Jack
4x	M3 x 6 Screw
4x	M3 Washer
4x	M3 Nut
1x	Plastic Pipe Radome, L = 1 m, 100 mm inner Ø
2x	Plastic Pipe End Cover

References

[1] Dragoslav Dobričić, YU1AW, *AMOS - Antenna with Semicircular Radiation Diagram for 2.4 GHz*, *antenneX* Issue No. 127, November 2007.

[2] Dragoslav Dobričić, YU1AW, *Inverted Amos Sector Antenna for 2.4 GHz WiFi*, *antenneX* Issue No. 130, February 2008.