Jean-Claude Hénaux

39 Avenue du Général de Gaulle, 17730 Port des Barques, France;
jeanclaude.henaux@free.

Franck Daout

34 Rue Roque de Fillol, 92810 Puteaux, France;
fdaout@parisnanterre.fr

Build Your Own 'Gun' (Disk Yagi) Antenna

This high directivity antenna has moderate bandwidth and is easy to build.

We propose to rediscover and build an antenna that is particularly well suited for use in the 1 to 4 GHz frequency range, see **Figure 1**. The 'Gun' (or Disk Yagi) antenna belongs to the end-fire antenna family. It is easy to build and does not need a balun. For the same directivity, it is less bulky than a horn antenna. The relative bandwidth, *B*, for an SWR of 2 is about 5% to 7%. In the following, we will see how its geometry determines its radiation pattern. The Gun antenna dimensions must be chosen according to the frequency of use and the desired directivity. We provide a computer program to calculate all dimensions of the antenna according to these objectives. Some construction advice is given and a realization is presented.

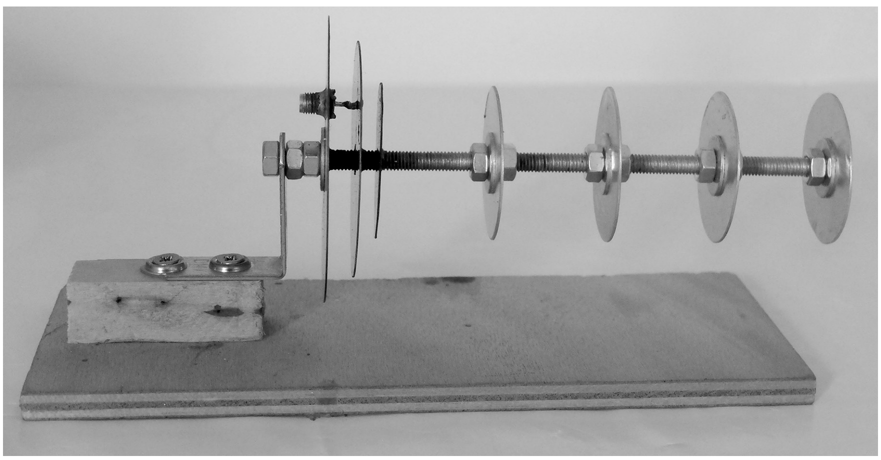


Figure 1 — A Gun (Disc Yagi) antenna for operation at 2,100 MHz.

End-fire antennas use surface waves

These antennas essentially consist of a moderately directional transmitter and a surface waveguide (SWG) that propagates a wave with a speed v_m that is less than the speed of light c. The role of the SWG is to sharpen the radiation pattern.

The complete analytical calculation of an end-fire antenna is not feasible, and a more qualitative and experimental approach was initially required. Since the first papers on the subject were published, powerful tools are now available. On the one hand for synthesis we use numerical simulation (*NEC*, *HFSS*, *CST*, etc.), and on the other hand for measurement we use Vector Network Analyzers. These tools allow us to compare precisely the predictions and the measurements, and bring the realization of the projects.

What is in a Gun antenna?

This antenna resembles a Yagi antenna whose dipoles have been replaced by metal disks. The following work was inspired by the achievements of Alexander Kryukov, alias "Kreosan," see YouTube **[1]**. **Figure 1** shows an end-fire antenna for the reception of 2,100 MHz transmissions. The two disks on the left are the excitation transmitter — a circular patch antenna — and the disks on the right, spaced by 33 mm, are the SWG. The 54 mm disk provides a smooth transition between the patch antenna and the SWG. The electric field is applied between the injection point and the ground. The disks are conveniently connected at their center by a threaded rod and nuts.

The radiation of the antenna is due partly to the direct radiation of the patch, and partly to the radiation shaped by the SWG. The superposition of the two for well-chosen dimensions of the SWG results in far field radiation pattern narrower than that of the patch alone. The patch and the SWG can be modeled independently. However, the coupling between the two elements (the coupling zone) does not lend itself to analytical study, and it is necessary to use numerical modeling to study the influence of the interval (9 mm in **Figure 1**) in which the radiation from the patch is partially transferred to the surface waveguide.

The patch considered alone

This type of antenna is well documented, **[2], [3], [4], [5], [6]**. The patch behaves like a resonator with quality factor Q_r depending mainly on the radiation losses.

The radiation represents the "losses" of this cavity. However, it is the useful result of the transfer of energy from the source to space, and must therefore be maximized. The bandwidth *B* for an SWR < 2 depends on Q_r **[4]**,

$$B = \frac{0.75}{Q_r}.$$

Since the SWG has a wide bandwidth, it is the bandwidth of the patch that limits the bandwidth of the whole antenna. It is necessary to have a significant value of *h*, the dielectric patch height — and therefore a low value of Q_r — for the antenna to have a suitable bandwidth **[7]**.

The resonant frequency of the patch alone

The circular patch may be studied alone to define the convenient diameter for a working frequency **[7]**. In addition to the diameter *r*, its resonant frequency also depends on *h* (11 mm in **Figure 1**). Unfortunately, the theoretical formulas are not suitable for Gun antennas. The analytical calculation of the resonant frequency assumes an infinite reflector plane. If the reflector plane is small, it is not possible to use these relations directly. We note that these formulas deviate from the experimental results for large *h*.

The 'a priori' choices

The adopted value of $h/r = 0.21$ (where $h/\lambda_0 = 0.0574$, and where λ_0 is the wavelength in air), results from a compromise between the bandwidth (large *h*) and the value of the parasitic inductance of the supply probe, which must be as low as possible.

Furthermore, we have observed through simulation that the use of a reflector with a larger diameter than the one chosen in **Figure 1**, (about one wavelength), increases the directivity without increasing the size too much. Thus, we will use the following two assumptions: $h/r = 0.21$, and the reflector diameter (ground plane) is a wavelength.

Position of the signal injection point from the axis for the patch antenna alone

The distance between the axis and the insertion point is *d*. Three *HFSS* simulations were performed for $h/r = 0.21$ at three frequencies 0.8, 2.45, and 4.1 GHz. After optimizing the injection point to obtain a 50 Ω match, we obtain the curve in **Figure 2**.

The position of the injection point (normalized to *r*) depends strongly on *h*/*r*. The radiation resistance at the edge of the disk increases with frequency **[8]**. To maintain a match to the 50 Ω source as the frequency increases, the signal injection point must move closer to the axis. When considering the complete antenna, the load of the SWG decreases the radiation impedance and forces a change in the position of the injection point.

The surface waveguide – three steps

Our goal is to build an antenna with a desired directivity *D* or beamwidth *BW*. The dimensions of the SWG of a Gun antenna are determined in three successive steps.

Step 1: Select the length of the antenna needed to obtain the directivity *D* or beamwidth *BW* at the –3 dB points, assuming in this step that the SWG is correctly realized. The length of the antenna and the SWG is designated by *L*.

Step 2: determine *L*, the SWG will interact with the radiation of the patch. This interaction is optimal for one value of the index *n* of the virtual material.

Step 3: Physically realize the SWG so that the virtual material has the index *n*. For that, it is necessary to choose correctly the diameter 2*a* of the SWG disks and their spacing.

Step 1: Directivity D determines the antenna length L.

D and *BW* are linked **[9]**. For a half power beamwidth we have the simplified relation,

$$D = \frac{16}{BW^2}$$

where *D* is a linear value, and *BW* is in radians. The directivity and thus the beamwidth will determine the length of the SWG. This length *L* is normalized to λ_0 by

$$L_n = \frac{L}{\lambda_0}$$

For this, graphical aids exist **[10], [11]** (**Figure 3**); the relation between L_n and *BW* in radians,

$$BW = \frac{0.96}{\sqrt{L_n}}.$$

Step 2: The length of the SWG defines the propagation index

Provided that the spacing between the disks is not too large (< 0.3 λ_0), the SWG can be considered as a continuous dielectric cylinder of index *n*, capable of supporting a wave and radiating only at the discontinuities — excitation and end face — as would a cylindrical waveguide, and thus it preserves the polarization of the wave present at the excitation **[12]**. In the dielectric guide, the propagation index is defined as in optics,

$$n = \frac{c}{v_m} = \frac{\lambda_0}{\lambda_m}$$

where $n > 1$ and v_m is the velocity of the slowed wave, and λ_m is the wavelength in

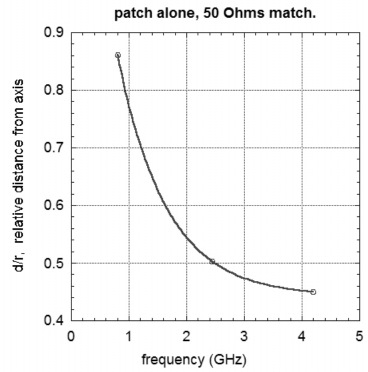


Figure 2 — The optimal position of the signal injection point for the patch antenna alone to be matched to 50 Ω. The height h of the patch normalized to the radius is h/r=0.21.

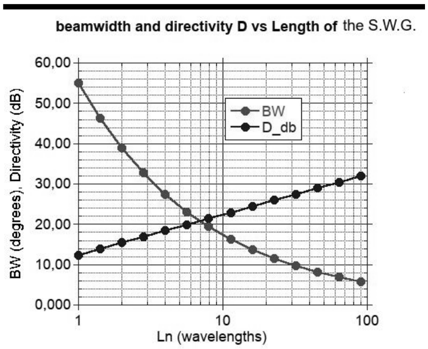


Figure 3 — The descending trace shows the beamwidth, while the ascending trace shows the directivity, as a function of the normalized length of the antenna.

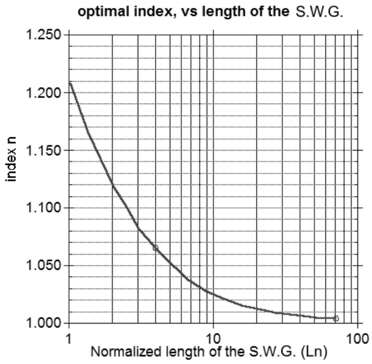


Figure 4 — The index n vs. the normalized length L_n of the SWG.

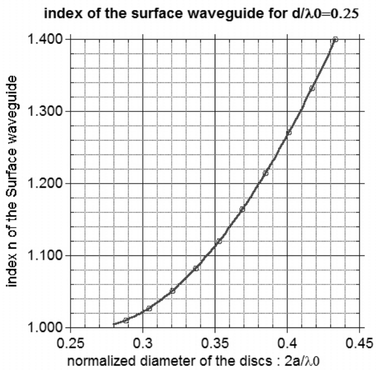


Figure 5 — Index n vs. normalized disc diameter based on Schefer reference data.

the "virtual dielectric cylinder." The optimal directivity couples the length L_n and the index n of the SWG.

We are usually interested in directivity, which we try to maximize. The superposition of the two waves — one emitted by the patch at speed c, and the one guided by the SWG at propagation speed v_m — will produce in the far field a more directive radiation than the one from the patch alone. For this to happen, a phase relation must exist at the end of the SWG between these two waves, thus between v_m and c, and an optimal value of n. Hansen and Woodyard **[13]**, have shown that for an SWG of length large in terms of λ_0, the directivity is maximum when the index value is,

$$n = 1 + \frac{0.465}{L_n} \; .$$

This theoretical value of the index remains the basis of calculations for this type of antenna, but small corrections have been made **[14]**, **[15]**.

The results of later work on these antennas were obtained under quite different calculation and measurement conditions. In **Figure 4**, we plotted the value of the index n versus the normalized length of the SWG from **[10]**. We have used this rule in the following, to get the best directivity for the Gun antennas.

Step 3: Choosing the SWG disk size

The director elements are not considered individually in the SWG, which is globally characterized by its index n. However, as expected, the value of the index n of the dummy material depends on its geometry **[15], [16], [17]**. A theoretical and experimental study was carried out by Schefer **[18]**. To obtain the same index n of the artificial dielectric, it is possible to play on two parameters: the diameter of the disks $2a$, and their spacing d, which define the propagation speed v_m. For convenience, we chose a 0.25 λ_0 spacing and interpolated the plots of Schefer to get the diameter $2a$ of the SWG disks. The result is plotted in **Figure 5**.

Study of a Gun antenna by simulation

In order to communicate in the 2.45 GHz band (λ_0 =122.45 mm), an antenna of this type was previously simulated by the finite element method using *HFSS* software. The starting point for the calculation of the dimensions of the elements is homothetic from **Figure 1** for the frequency 2.45 GHz. However, the relative patch height was taken to be equal to 0.0574 for h/r = 0.21, and the first SWG disk has the same diameter as the other three. **Figure 6** shows all the results obtained. The adopted dimensions are as follows:

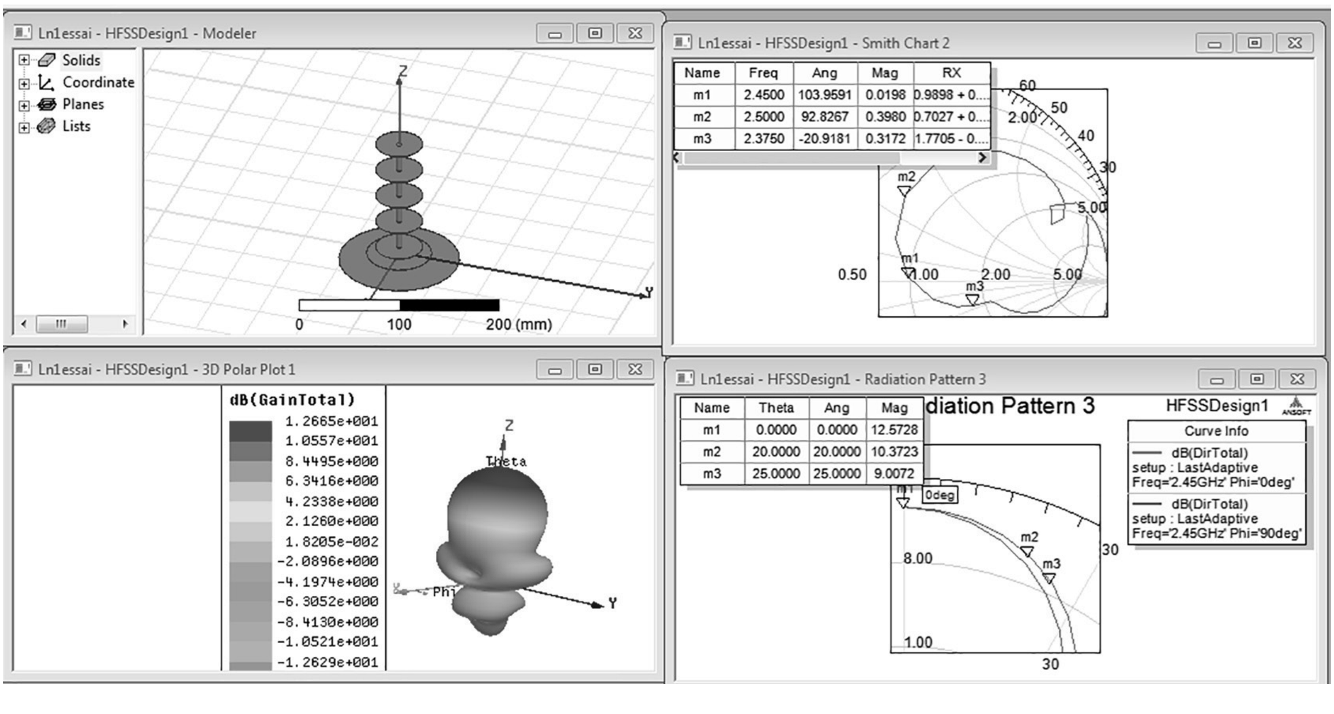


Figure 6 — Results of the simulation for the chosen dimensions. The left-top window shows the antenna with SWG of a wavelength. The right-top window shows the reflection coefficient variation with frequency. The left-bottom shows the radiation pattern in 3D. The window on the right-bottom presents the radiation pattern showing the beamwidth angle in the two planes parallel to the axis.

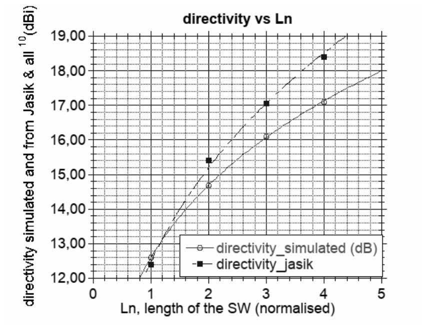
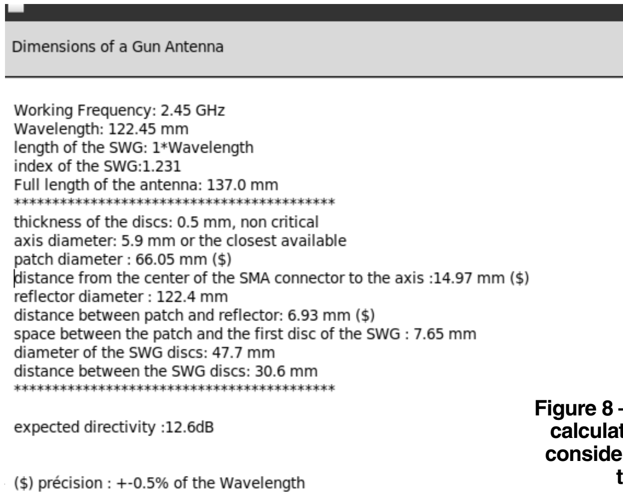


Figure 7 — The increase in directivity (dBi) as a function of antenna length provided by the simulation is not linear. Lengthening the antenna results in more side lobes.



Dimensions of a Gun Antenna

Working Frequency: 2.45 GHz
Wavelength: 122.45 mm
length of the SWG: 1*Wavelength
index of the SWG:1.231
Full length of the antenna: 137.0 mm
****
thickness of the discs: 0.5 mm, non critical
axis diameter: 5.9 mm or the closest available
patch diameter : 66.05 mm ($)
distance from the center of the SMA connector to the axis :14.97 mm ($)
reflector diameter : 122.4 mm
distance between patch and reflector: 6.93 mm ($)
space between the patch and the first disc of the SWG : 7.65 mm
diameter of the SWG discs: 47.7 mm
distance between the SWG discs: 30.6 mm
****

expected directivity :12.6dB

($) précision : +-0.5% of the Wavelength

Figure 8 — An example of using the calculation software for the case considered above: an antenna for the 2.45 GHz band.

- diameter *r* of the patch is 66.05 mm,
- distance *d* from the injection point (center of the connector) to the antenna axis is 14.97 mm,
- index of the virtual dielectric is $n = 1.231$,
- SWG disc diameter is $0.385\lambda_0$ (47.7 mm).

We see that the directivity reaches 12.6 dB, for an aperture at −3 dB *BW* close to 44°. The approximate formula $D = 16/BW^2$ gives 12 dB. The SWR<2 bandwidth is 5%.

Simulation

Thanks to the simulation, the dimensioning of a Gun antenna can be made over a wide frequency band. Subsequently, for different frequencies between 0.8 and 4.2 GHz, and lengths L_n of the SWG ranges from 1 to 4 times the free space wavelength. Analogous simulations using *HFSS* have been performed, to obtain a kind of database. With the objective to match the 50 Ω antenna to the computational frequency, the patch diameter, and the position of the injection point needed in these different cases could be determined. The optimal patch size is not affected by the length of the SWG, which was expected, while the position of the injection point

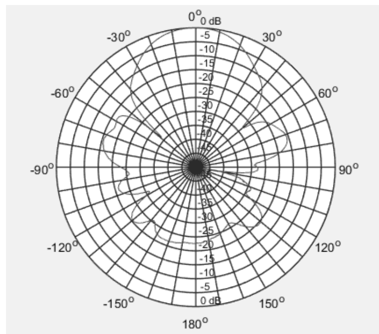


Figure 9 — Measured radiation pattern of the Gun antenna. The maximum gain is 12 dB ±0.5 dB.

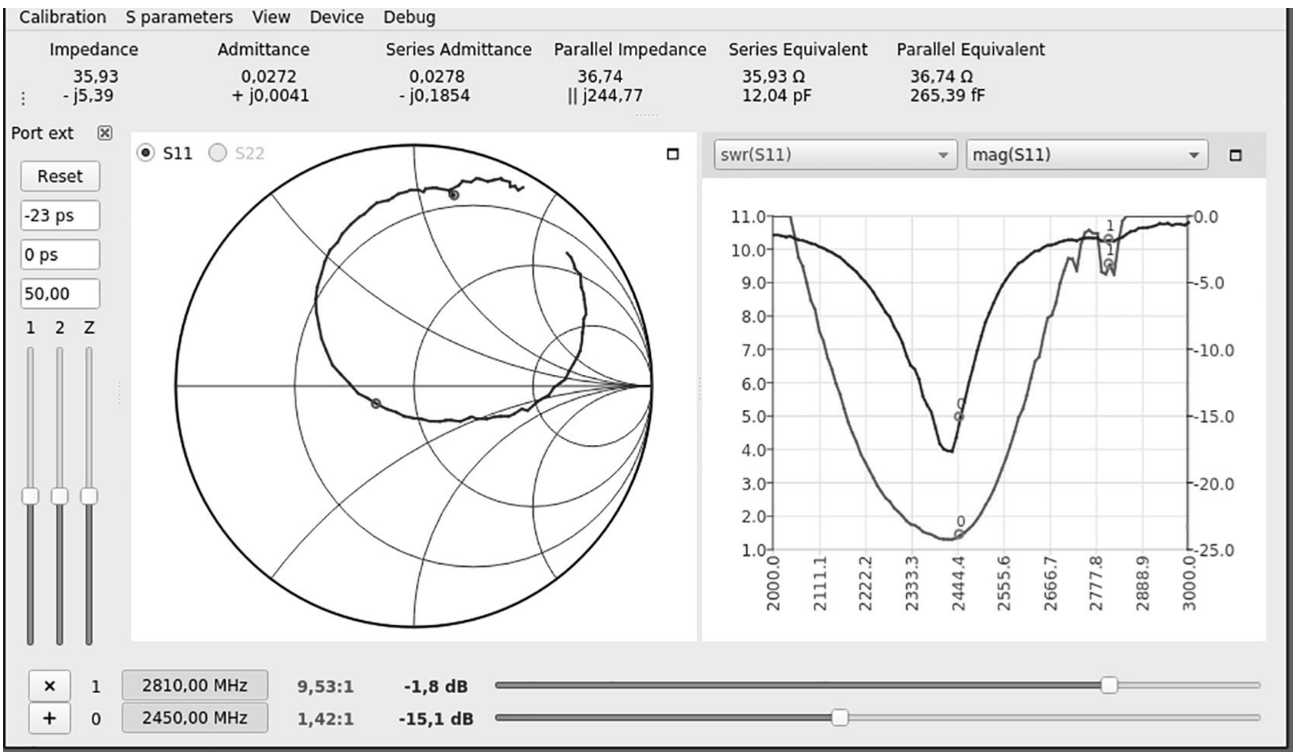


Figure 10 — Measured reflection coefficient vs. frequency at the input of the antenna. In the right panel the inner narrower curve is |S11| in dB (right scale), the outer curve is SWR (left scale).

depends on it, because of the dissipative load that constitutes the SWG.

We were able to obtain by 3D simulation, a mathematical model of these parameters of the patch diameter and position of the injection point, depending on the frequency and the length chosen for the SWG. By also modeling the obtained curves for the SWG index and diameter of the disks (**Figures 4 and 5**), we have what is necessary to establish a software program to calculate all the dimensions of a Gun antenna.

The directivity increases with the length of the antenna. For a length of $4\lambda_0$, a directivity of the order of 17 dB — close to that provided by a pyramidal or conical antenna — can be achieved (**Figure 7**) for a smaller footprint, but with a smaller bandwidth. The growth with length was expected, but it is somewhat lower than predicted by Jasik **[10]**. It does not appear that lengthening beyond $4\lambda_0$ is very beneficial.

A first version of software to calculate all dimensions of a Gun antenna (**Figure 8**) has been written in Python3 language. It is freely available at **arrl.org/QEXfiles** as a complement to this article.

Construction

The construction does not present any particular mechanical difficulty but requires some care, particularly near 4 GHz. For example, at this frequency, an error of 0.5% on the diameter of 40.6 mm (+0.2 mm) increases the modulus of the reflection coefficient from 0.02 to 0.085 (SWR from 1.04 to 1.186).

The losses in the metal remain low and steel can be used. Aluminum is easy to machine but should be avoided for the patch, which requires a soldered connection. Copper is the best electrically but easily deformed for small thicknesses. Brass could be preferred.

To position the input SMA connector, it is convenient to screw the patch disk and its reflector together, then drill a small diameter hole (about 1 mm) in this assembly at the correct distance from the axis, that will be used for the wire connecting to the patch disk. It is best to avoid nuts and washers inside the patch because they degrade the antenna match to the source.

There are videos on the internet that can help **[19]**.

Measurements

Measurement of the radiation pattern: An antenna was built to the exact dimensions of the simulation model. The radiation pattern was measured in an anechoic chamber, see **Figure 9**. The gain (directivity + losses) of 12 dBi was measured in comparison to that of a reference pyramidal horn antenna.

Measurement of the reflection coefficient at the input of the antenna: The measurements show that the antenna is tuned to 2,432 MHz compared go an expected 2,450 MHz. This deviation is currently being analyzed. The SWR is less than 2:1 in a7.7% band, see **Figure 10**.

Conclusions

The Gun or disk Yagi antenna is well suited for applications between 1 and 4 GHz. The lower frequencies are penalized by an excessive size of the reflector, and possibly wind loading. Higher frequencies require high mechanical precision.

Advantages: Antennas are easy and fast to build, no balun is necessary. The construction tolerates small dimensional deviations of the SWG. The gain/dimensions ratio is favorable compared to horns.

Disadvantages: The bandwidth is relatively narrow band because of the excitation by a patch, so the dimensions of the patch must be precise. The diameter of the disk, the position of the injection point, the height *h* of the patch above the reflector disk must be well controlled.

Acknowledgments

This work was carried out thanks to the availability of measurement facilities (anechoic chamber, vector network analyzers) and calculation facilities (3D HFSS simulation) at the Institut Universitaire de Technologie of Ville d'Avray (University of Paris Nanterre).

Jean-Claude Hénaux worked on Josephson effects in superconductive junctions and received his PhD in 1983 from the Paris Sud-Orsay University. As a professor at Paris Sud-Orsay University and Paris Ouest Nanterre, he was involved in the design and measurements on microwave GaAs ICs and taught electronics, and particularly microwave electronics. He is now retired and helps (for pleasure) with student microwave projects at the Ville d'Avray Institute of Technology.

Franck Daout received his MS and PhD degrees in electronics from the University of Nantes (France) in 1996. From 1997 to 1999 he was a Research Engineer at the French Naval Academy, at Brest, France, Groupe de Traitement du Signal in the sonar team. In 1999, he became an assistant professor at the University of Paris-Ouest Nanterre la Defense. His research and teaching courses are in the fields of electromagnetic wave propagation, microwave and signal processing. Currently, he works on radar systems at the Systemes et Applications des Technologies de l'Information et de l'Energie (SATIE) Laboratory, ENS Cachan France.

Notes

[1] **https://www.youtube.com/watch?v=zKcz6rEXamc**.

[2] R. A. Saïnati, *C.A.D. of Microstrip Antennas for Wireless Applications*, Artech House, Chap. 3-10.

[3] J. R. James, P.S. Hall, C. Wood, "Microstrip Antennas, Theory and Design," *IEE Electromagnetic Wave Series 12.*

[4] P.F. Combes, *Micro-Ondes -2*, Dunod. Chap. 15.

[5] R. Garg, P. Barthia, I. Bahl, A. Ittipiboon, *Microstrip Antenna Design Handbook*, Artech House.

[6] J. L. Volakis, T. F. Eibert, *Antenna Engineering Handbook*, McGraw Hill, 2007, Chap. 7.7.

[7] L. C. Shen, S. A. Long, M. Allerding, and M. Walton, "Resonant Frequency of a Circular Disk Printed-Circuit Antenna," *IEEE Trans. Antennas and Propagation*, Vol. 25.

[8] C.A. Balanis, *Antenna Theory, Analysis, and Design*, (4th. Ed) J. Wiley 2016.

[9] S. J. Orfanidis, *Electromagnetic Waves and Antennas*, Rutgers University, Chap. 16-2.

[10] R. C. Johnson, H. Jasik, *Antenna Engineering Handbook*, McGraw.Hill,1993. Chap.12.

[11] T. A. Milligan, *Modern Antenna Design*, J. Wiley & Sons 2005. Chap. 10.

[12] C. H. Chandler, "An Investigation of Dielectric Rod as Waveguide," *J. Appl. Phys.* Vol. 20, Dec. 1949 pp: 118-192.

[13] W. W. Hansen, J. R. Woodyard, "A New Principle in Directional Antenna Design," *Proceedings of the Institute of Radio Engineers*, Vol. 26, No.3, 1938, pp: 333-336.

[14] H. Bach, "Applicability of Hansen-Woodyard Condition," *Proceedings of the IEEE*, Vol. 119, No. 1, Jan. 1972, pp. 38-40.

[15] H. W. Ehrenspeck, H. Poehler, "A New Method for Obtaining Maximum gain from Yagi Antennas," *IRE Transactions on Antennas and Propagation*, (11/1959), pp.379-386.

[16] G. Piefke, "The Transmission Characteristics of a Corrugated Guide," *IRE Transactions on Antennas and Propagation*, Dec. 1959, pp: S183-S190.

[17] A. D. Olver, F. F. Dubrovka, C. G. Parini, "Propagation and Radiation Characteristics of the Disc-on Rod Antenna," *Radio Science*, Vol. 19, No 6, Nov.-Dec. 1984, pp: 1439-1444.

[18] J. Schefer, "Plane Waves on a Periodic Structure of Circular Disks and Their Application to Surface Wave Antennas," *IRE Transactions on Microwave Theory and Techniques*, Nov. 1962, pp: 595-592.

[19] **https://www.youtube.com/watch?v=W5DskYocQRk**.