Everything you always wanted to know about UWB radar… : a *practical* introduction to the ultra wideband technology [*]

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Abstract

A practical hands-on description on how to build a prototype of an ultra wideband (UWB) radar is presented. UWB radar, and UWB communication as well, are quite hot topics these days both in the industry and in the academia. Nevertheless many people would like to have working schematics to start prototyping, just to see the "magic" in it. To this end the topic is kept to a very didactic and popular level without boring people, or even frightening, with lots of theory. As a matter of fact, many engineers and scientists already went deep into UWB theory but they were unfortunately unable to start working. Therefore, practicing with UWB is exactly the purpose of this lecture.

Although UWB theory has been described in a series of books [1][2][3][4] published as early as the 80's, the actual electronic circuits presented here are mainly based on what was disclosed in a few US patents [5][6][7][8][9][10], along with direct experience of the author [11][12][13]. The author itself is aware that some patents filed by the US Lawrence Livermore National Laboratory (LLNL) were questioned and reexamined by the United States Patents & Trademarks Office (USPTO) and eventually declared as "anticipated" by other patents filed before by Mr. Larry W. Fullerton and Time Domain Inc.. Apart from any patent litigation, it is the aim of the paper to present a working prototype of a UWB radar from a purely didactic and "amateur" point of view, avoiding infringing any other party rights nor unauthorized disclosing of any other data. Anyway the reader should remember that industrial production and/or sale of the systems presented here might infringe other parties' patent rights. Eventually it is the final responsibility of the reader to use the following information in all but unlawful way.

A UWB radar prototype of the "noise" kind will be detailed with the schematics, a bit of rationale for the various technical solutions adopted, the testing procedures and even how to have fun with it.

1 Introduction

UWB stands for ultra wideband. But the concept of wide spectrum usage, specific to this kind of radio and radar systems, seems not very much friendly yet. A few more basic concepts should be kept in mind when a "conventional" radio or electronics engineer approaches UWB technology.

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The first basic concept is that frequency is meaningless: UWB systems use electromagnetic pulses, just pulses, not short wave-packets. Pulse repetition frequency (PRF) could be declared, but this is not a correct figure of electromagnetic spectrum occupation. PRF is typically in the rang from 1 to 50 MHz. Furthermore the pulse repetition period is often modulated to carry information or coding. A more precise frequency description of UWB emission could be given by the Fourier transform of the pulse. Being the pulse very narrow, in the order of hundreds of picoseconds, frequency spectrum widens up to a few gigahertz often without a clear peak.

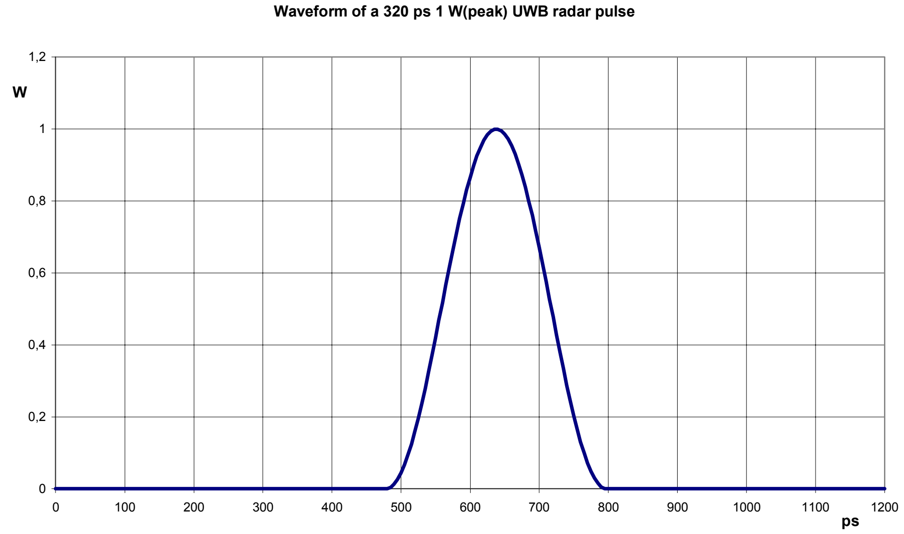

Figure 1. A sinusoidally shaped UWB pulse in the time domain.

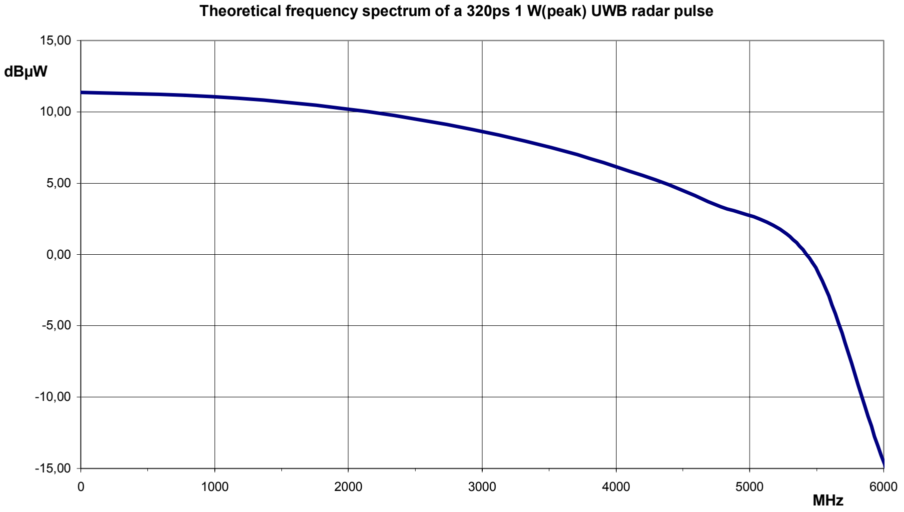

Figure 2. A sinusoidally shaped UWB pulse in the frequency domain (FFT estimate).

As a consequence resonance and UWB-tech are quite opposite concepts. Resonance means narrow band while we go wide, more, we go ultra wide. Unlike conventional radio systems, resonating circuits are not used in UWB radio. Actually they are, or should be, avoided, even if it is not quite easy to do so.

From Figs. 1 and 2 it can be seen that being the pulse extremely concentrated in time, it follows that power is spread in the frequency band. Actual spectrum usage can only be estimated from the FFT of the emitted pulse train or it can be measured with a sensible spectrum analyzer. The frequency tuning concept, quite familiar to radio engineers, is now useless because the time is our "lord". UWB systems are definitely "tuned in time" not in frequency. So high Q-factor components for signals selection in frequency are not needed and precise timing is used instead. To catch the pulses travelling in space you don't need a golden hook, just cast the hook timely. Although timing requirements in a UWB radio are extremely tight, nevertheless UWB technology, using today off the shelf components, is so simple that often resembles a toy, leaving the interested engineer quite skeptical. And, surprisingly, the more skeptical the more he/she digs UWB concepts in deeper detail.

2 Designing an UWB radar

In the following of this lecture we'll remain focused on radar applications. This kind of use of UWB technology being much more easily understandable by the novice. I hope that the interested reader might anyway get enough ideas for UWB "communication" applications. In conventional radar operation (please remember the very simple architecture of the World War II radar systems) there is no presumption on the presence of a target and on the distance of it. By default WWII radar was a scanning radar: as soon as an electromagnetic signal is emitted, the systems starts listening to the echoes and uses timing of echo arrivals to estimate the target range.

In UWB radar operation the distance, or range of the target, is presumed at the beginning of the pulse-echo round trip and the only information out of the system will regard the presence or absence of the target at that, given, range. An UWB radar emits an electromagnetic signal and pause a given time; then a sample of the antenna voltage is taken for the (possible) echo. Let's go to the details of this concept and we will see that this is by no way a limitation of the system.

A simplified UWB radar system emits a pulse, wait for a while and then listens to the echo (if any). As the echo is extremely weak, many samples are averaged to obtain a suitable signal out of the system.

Generally speaking a "noise radar" emits white noise and then cross-correlates the received white noise with the emitted one. We define a white noise as a signal having a flat frequency spectrum. We also know that the spectrum of a very narrow-width pulse has a very large frequency spectrum approaching that of white noise as the pulse becomes narrower and narrower (till reaching the Dirac's delta) as in Fig. 2. As it is actually simpler doing a cross-correlation by averaging synchronously acquired samples, a practical noise radar uses pulses and averages synchronously sampled (delayed) echo signals. For the smart and signal theory interested people, the author would like to recall the old and very much intriguing work of Berndt [14] regarding "one bit" correlation. Therefore it should be suggested to consider an UWB radar or a UWB communication receiver system as a "one-bit" correlator for any practical purposes. So there is nothing really new under the sun.

As depicted in Fig. 3, the pulse coming out of the generator is transmitted and at the same time sent to a delay line. In this way the same pulse is used for controlling the sampling of the received echoes.

Eventually a low pass filter averages the signal with a suitable time constant. Unfortunately a practical UWB radar is not so simple. So let's go examining a few design needs and constraints.

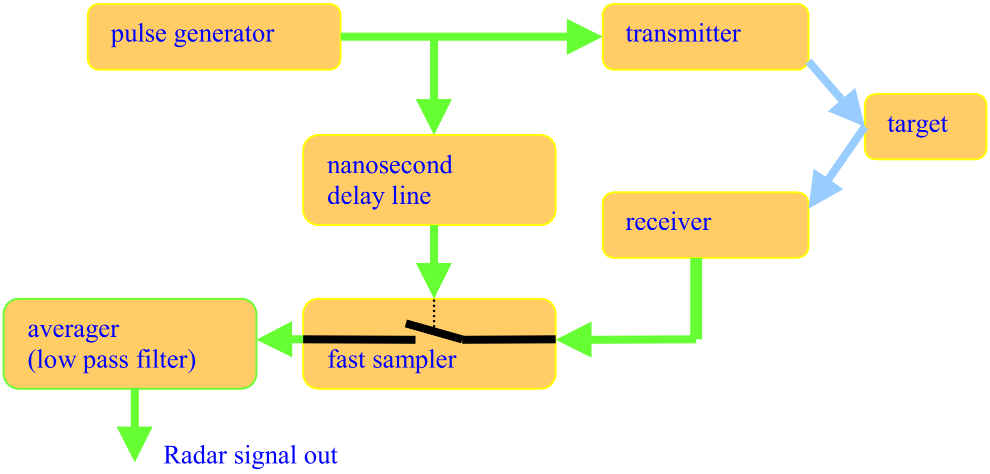

Figure 3.The UWB radar scheme.

An UWB radar cannot operate at a range shorter than one half the "pulse length in space" which is the product of pulse duration by the speed of light in the medium. That is because we need to free the antenna of the emitted pulse before we get ready for receiving any echo.

The "pulse length in space" concept is somewhat the UWB counterpart of the wavelength concept in conventional radio, being the wavelength nothing but the period of the sinusoidal wave multiplied by the speed of light. For the same reason resolution is enhanced by the use of narrower pulses having higher slew rates. Eventually it will follow a wider spreading of the electromagnetic power in the frequency domain so that detectability of this type of radar and interference probability with other services are even more lowered.

It should be remembered that when we sample the "ether" we are not alone! Existing radio services will be sampled too: of course as we are wideband, we cannot use frequency tuning. By introducing a sort of modulation in the pulse repetition period, maintaining synchronous sampling of the echoes, we can overcome beating (i.e. etherodyning) of existing radio services. By the way pulse repetition period modulation is at the base of UWB communication. Many modulation schemes (random, pseudorandom, even chaotic) are now being considered. So we have to add a random modulator in our UWB radar scheme. In so doing we will spread even more the electromagnetic power in the frequency domain and we can also obtain stealth or cover operation by "channelizing" using different pseudorandom sequences of pulses.

3 Is your soldering iron ready?

The very trivial description presented so far should enable the average reader to try assembling a simple UWB radar for didactic purposes: a noise modulated UWB radar.

The circuit depicted in Fig. 4 shows the noise modulated pulse generator used in a patent from LLNL. This architecture appears by no means new. The values of the components were experimentally found by the author and the circuit successfully tested. Whatever transistor type can be used here: the author used unnamed transistors (h_{fe}=50) desoldered from "last century" computer boards. With the values reported a 2MHz mean frequency can be obtained. The curious developer/experimenter do please note the components which can be modified to change the indicated working parameters:

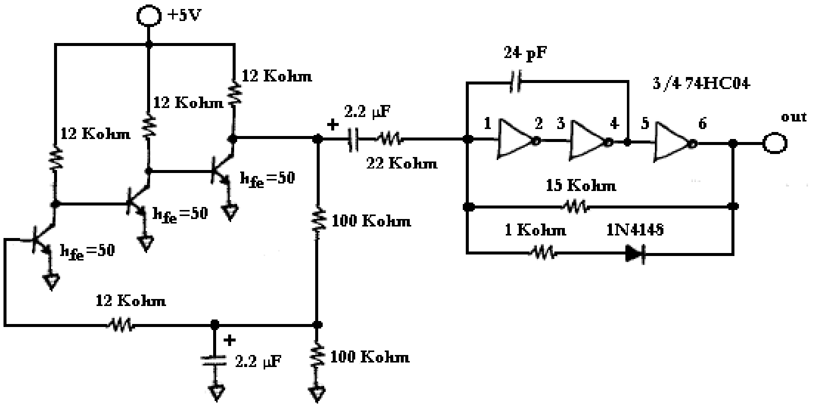

Figure 4. The noise modulated pulse generator.

the 22Kohm resistor at the center of the figure can be changed to vary the modulation depth, that is the random variation of pulse repetition period, while mean pulse repetition frequency can be varied changing the value of the 24 pF capacitor or the 15 Kohm resistor in the oscillator. To test proper functioning of the circuit a 20 MHz oscilloscope would suffice. Triggering the signal in the NORM TRIGGER mode will clearly show just one pulse in the left part of the display. Subsequent pulses will appear flickering in the trace due to the random jitter added by the noise modulation. Use oscilloscope in the NORM TRIGGER mode with a timebase in the order of 0.2 or 0.5 µs/cm. The signal out is at TTL level.

UWB communication (not radar) interested people should apply suitable modulation here (instead of noise). Signal recovery, that is demodulation, is out of the scope of the present lecture as previously said.

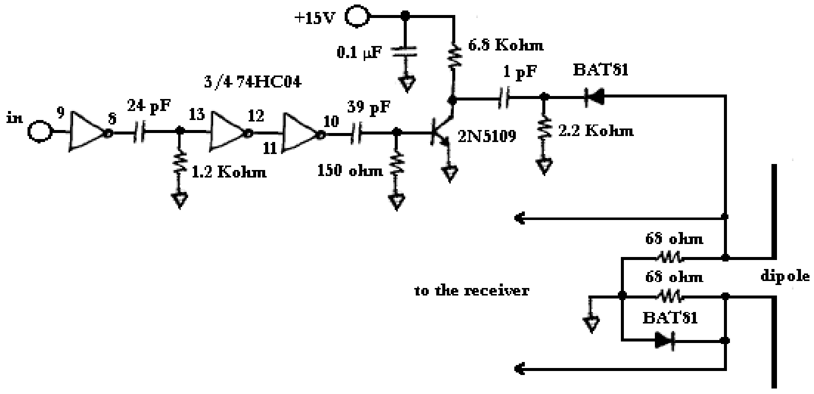

Figure 5. The transmitter.

Input to the pulse shaper and transmitter comes from the pulse generator and it is marked as "in" on the schematic. During prototyping by the author, the schematics and the values of the components have been modified with respect to the original LLNL patent. A very short pulse, with a time duration in the order of 40 ns, is applied to the base of the microwave transistor causing it to rapidly go into the conduction state. The 1 pF capacitor then discharges through the transistor, the schottky diodes and the antenna causing the emission of an electromagnetic pulse. Slew rate on the collector of the transistor is about 1 kV/µs (Fig. 6) and a 2 ns negative going pulse can be measured on the 2.2 Kohm resistor (fig. 7). Shorter duration pulses can be generated using faster diodes and more careful layout. Unfortunately you need at least a 5 Gsamples/sec oscilloscope to obtain the plots in Figs. 6-7.

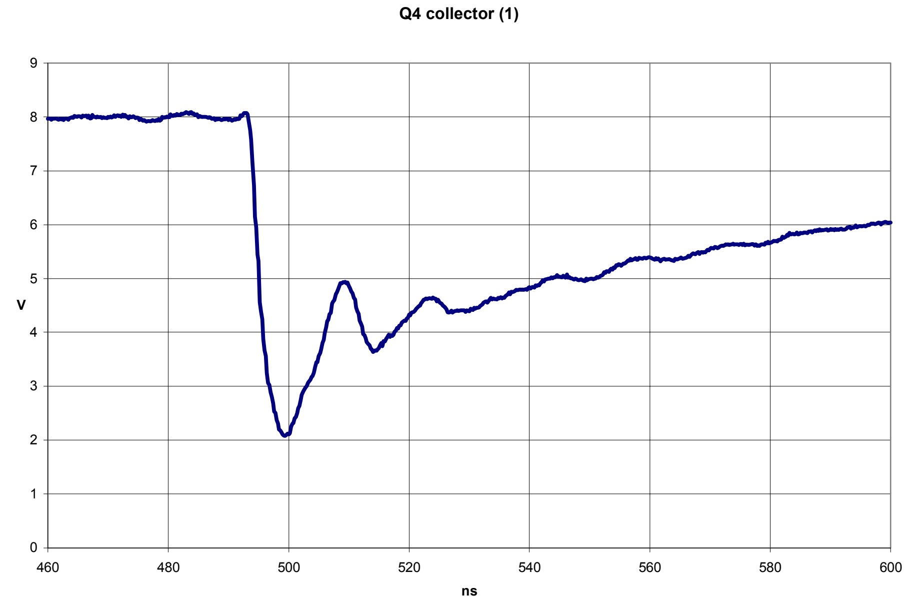

Figure 6. Voltage on the collector of the microwave transistor
(measure obtained with a +8V power supply).

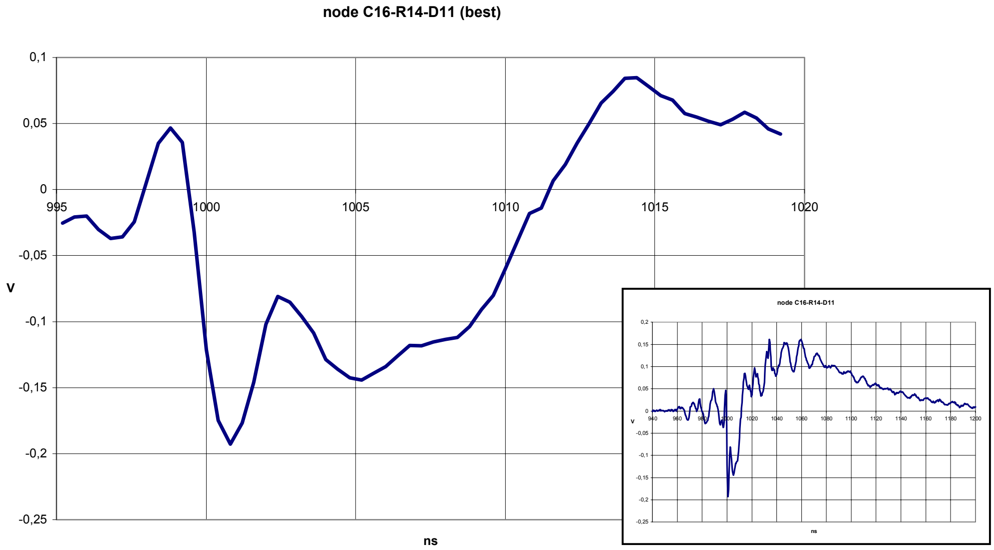

Figure 7. Pulse voltage on the 2.2Kohm resistor after the 1 pF capacitor: a negative going 2 ns pulse is obtained (in the little image the full signal transient is shown, timebase=20 ns/div).

The 1 pF capacitor recharges through the 6.8 Kohm and the 2.2 Kohm resistors which where calculated so to assure complete recharge before the next pulse while minimizing power consumption. The 68 ohm resistors are there to match dipole impedance. The dipole antenna is composed of two brass 2.5 mm diameter wires. Of course it is resonating. Although resonance should be avoided, nevertheless we will use resonance to have a proof of correct system operation.

Any transmitter sends power, not voltage. So let's try some trivial math to have an idea of the power out from this UWB transmitter. The energy stored in the capacitor when this is charged at 15 volt is:

$$E = \frac{1}{2} C V^2 = \frac{1}{2} 10^{-12} 15^2 = 112.5 \cdot 10^{-12} J$$

Supposing this energy being completely delivered in a pulse having a width (Pw) of 2 ns, a 56 mW power pulse results:

$$W = \frac{E}{P_w} = \frac{112.5 \cdot 10^{-12}}{2 \cdot 10^{-9}} = 56 \cdot 10^{-3} W$$

Considering the duty cycle, taking into account mean pulse repetition period (PRF), we obtain a 225 µW mean output power:

$$\overline{W} = \frac{E}{\overline{\overline{PRP}}} = \frac{112.5 \cdot 10^{-12}}{500 \cdot 10^{-9}} = 225 \cdot 10^{-6} W$$

Of course we have supposed that the power delivering fraction to the antenna was 100%. This figure is surely very much optimistic. A 50% or less is a more realistic estimate giving a final, mere, 100 µW mean irradiated power. Furthermore, if we theoretically suppose that this power is spread over a 2000 MHz band we obtain a 50 pW/KHz spectrum usage. UWB "gurus" are grounding on this estimation the request for free and unlicensed UWB operation. It seems unlikely that a so weak power might disturb conventional narrow band radio services even if many UWB systems should be operating at the same time in the same area.

Considering a 30 to 40 dB attenuation in the reflection process from the target, we will have to catch at the receiver a 0.1 µW or less echo power. Although these figures are quite rough estimates, nevertheless they should give the reader the very intense feeling of UWB low power radio communications and radar.

And now let's go to the heart of UWB radio: the UWB receiver.

In Fig. 8 the input to the delay line is the same as for the pulse shaper and transmitter already presented and here it is marked as "in" on the schematics. The same pulse is at the same time irradiated and delayed to be used as control of the sampler in the UWB receiver.

The delay line is extremely trivial, nevertheless it works quite well and it is surely very much suitable for the experimenter's fun. The variable resistor should be changed very carefully to set the range of the radar to an adequate value. Unfortunately this setting is very much critical as a 1 ns more or less makes a lot of difference. Furthermore this delay line architecture is exceptionally temperature sensible and makes the range of the radar a function of the ambient temperature.

Many other less trivial delay line architectures has been developed in the last years, mostly digital and even software programmable using a microprocessor. In this way an automatic target follower should be developed. The 47 pF capacitor in the delay line could be substituted with a varicap diode whose inverse polarizing voltage might be used to change the radar range.

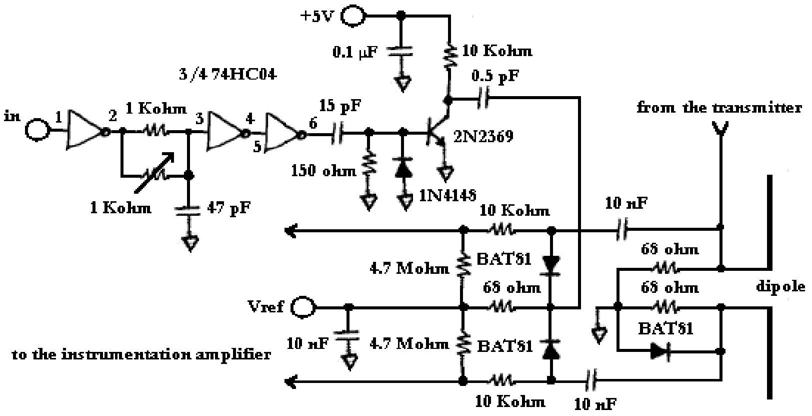

Figure 8. The delay line and the fast sampler-averager.

The fast sampler is operated using two schottky diodes which are placed in the conduction mode by applying a short pulse at the cathodes. In this way the two 10 nF capacitors on the dipole charge with, and integrate, the received echoes. The averaged and very low frequency echo signal is then ready for final amplification.

The concept of process gain is very much linked with UWB receiving technology, unfortunately it is often obscure or described in a very complicated way. So let's follow these trivial calculations. It is known that signal to noise ratio improves with the square root of the number of averaged pulses (assuming a Poisson statistical distribution). By considering the mean number of received echoes during a time epoch equal to the time constant of the low pass filter we get a 30 dB improvement in the signal to noise figure before any active amplification of the signal. The time constant of the averager is:

$$\tau = 2\pi RC = 2 \cdot \pi \cdot 10^{4} \cdot 10^{-8} = 628\,\pi s$$

So the number of received echoes during a time epoch equal to the time constant of the averager is:

$$P_n = \frac{\tau}{PRP} = \frac{628 \cdot 10^{-6}}{500 \cdot 10^{-9}} = 1256$$

It follows an increase of the signal to noise ratio of:

$$S/N = 20\log\left(\sqrt{P_n}\right) = 20\log\left(\sqrt{1256}\right) = +31\,\text{dB}$$

Although this is a rough estimation, nevertheless the concept of process gain in the UWB receiver averaging is clearly shown.

Incidentally a 628 μs time constant in the receiver limits the target detectable moving frequency to about 1200 Hz, that is a maximum target speed is defined above which the UWB radar is no more able to detect it. This is important in those applications in which the target is moving and its position has to be precisely monitored, as in UWB radar non-acoustic echocardiography.

As strange as it may seem, the amplifier section in this UWB radar receiver is composed of a simple instrumentation amplifier working at a very low frequency.

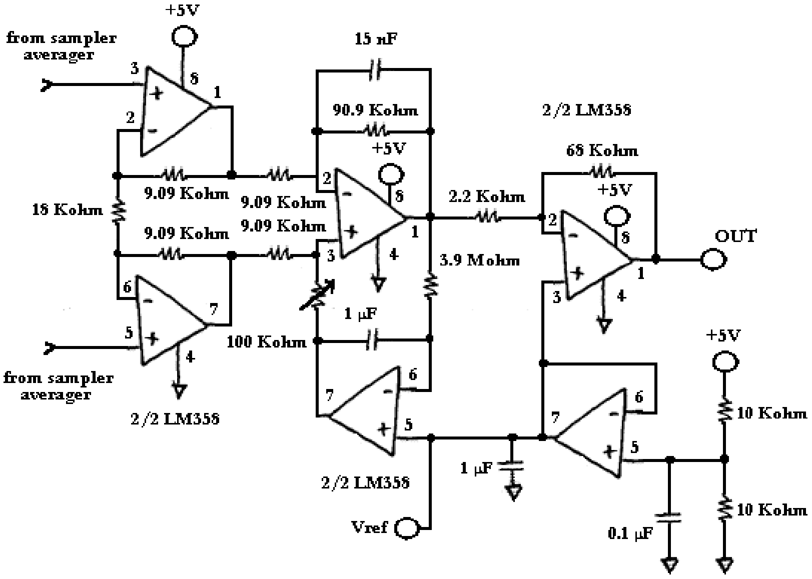

Figure 9. The amplifier.

In the amplifier a high pass filter has been introduced to cancel continuous echo clutter, that is steady echoes coming from all around in the laboratory. This means that anything not moving goes unnoticed by the radar. Please note that the instrumentation amplifier has a unity differential gain: its main purpose is to cancel the 50/60 Hz interference and transform the signal from differential to single-ended. A gain of about 30 is obtained in the last op-amp.

As the whole system is not running from a dual power supply, a reference voltage is generated equal to half the power supply for proper operation of the operational amplifiers which are used. An oscilloscope with timebase in the order of 1 or 2 sec/div and a sensitivity of 50 or 100 mV/div can be connected at the out to monitor the echoes.

4 Antenna, antenna ringing and prototype testing

In this prototype the author suggest the use of a simple dipole because it is a quite efficient antenna and its very easy to build. Unfortunately a dipole is a resonating element. If a dipole is cut at a length of 20 cm as in this prototype, that dipole is expected to resonate in the VHF band or so. Now, what if a pulse is fed to a resonating antenna? A ringing effect will occur. That is the same effect you obtain when hitting a bell with a hammer: although you hit the bell with a sharp stimulus, a sound you can hear with decaying intensity in time.

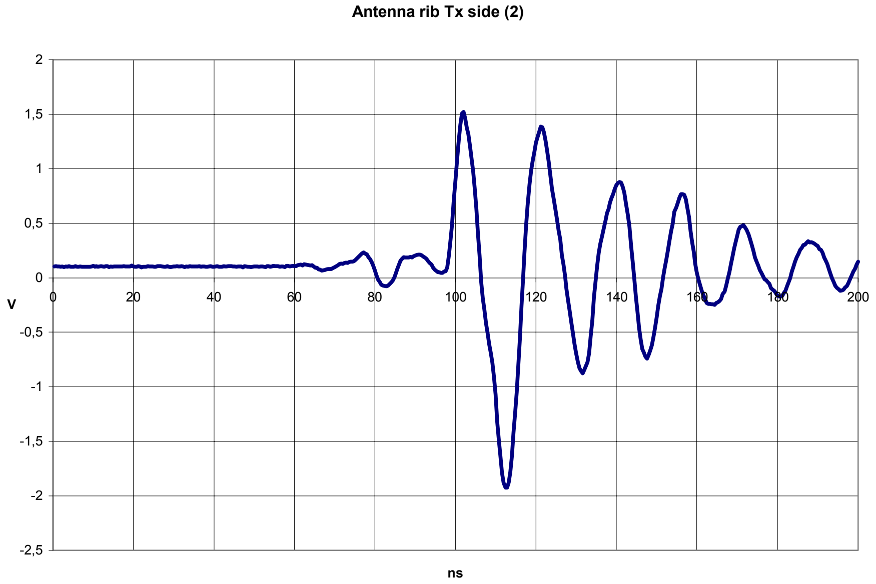

Figure 10. The dipole antenna ringing.

Resonance is not to avoid on the basis that it renders the system narrow band, but because it impedes the emission of a single pulse as you can clearly see in1 Fig. 10. As a matter of fact many pulses will be transmitted in a damping wave fashion and strange target detection (phantoms) will result. Let's study what happens if two pulses in a row are emitted from a UWB radar.

For simplicity sake suppose just a second, unwanted, pulse is emitted unintentionally by the antenna after a certain time delay from the first. It can be seen that a second echo might reach the receiving antenna and interfere with the first one (the main one).

As the second pulse is leaving the antenna after the first one, it might reach back the antenna, at the same time as the first echo, after having been reflected by a nearer target. That is because the second pulse has a shorter time to be back on time at the antenna when the sampling will take place. Of course if there is just one target this effect is of no importance, otherwise more clutter will result. Even with just one target an interesting effect happens: by moving the target toward the antenna, two, three or even four positions of the target will cause the detection by the radar for the *same* time delay. As the antenna has a large lobe the final effect is that of an onion whose invisible layers are present into the air. Each "layer" of the onion is due to a particular pulse.

By measuring spacing of the "onion layers" an estimate of the antenna resonating frequency can be done: the double of this spacing is the wavelength of the antenna at the resonance.

Let's study how we can use this effect for proof of correct working of the UWB radar. The onion effect is by no means disturbing in this UWB radar prototype. Instead it lets us be assured that the system is working: remember, you need an out of this world oscilloscope to directly check the circuit.

First of all you have to prepare an efficient mirror: a frying pan would be fine or a tennis racquet covered with aluminum sheet. Now start looking for the onion sheets into the air at a distance of 50 cm to 250 cm from the antenna on the antenna axis. You may need to carefully and patiently set the range by varying potentiometer of delay line. You must be patient, the system is reliable although critical.

Of course, if you detect onion layers in space you can be assured the system is working as an effective radar and not as an electrometer or a sort of proximity detector. "Onion layers effect" means many pulses are doing the round trip from the antenna to the target and vice versa! After you have been acquainted with the system try using your hand or your body to detect onion layers. You can even put your thorax surface at an onion layer position and do deep breath movements: it should be possible to remotely detect respiration. The power out of this prototype is not adequate to detect any target behind a wall (made of bricks or concrete), but you can try using wooden walls or a pile of books between you and the antenna.

An effective non resonating antenna is hard to design and build. Starting from a common antenna, reaching the "aresonance" could be done in the following steps:

- set the antenna resonating frequency well above the UWB band of interest; the drawback is a loss of efficiency as the physical dimensions of the antenna shrink
- decrease the Q-factor of the antenna to widen the bandwidth; the drawback now is again a loss of efficiency as this is normally done by introducing passive elements in the design of the antenna

Research is in progress for the design of aresonant antennas avoiding reflections inside the antenna structure or by designing-in destructive interference to cancel ringing and, eventually, by using dielectric antennas which appear very much promising.

5 Conclusions

Hope you enjoyed this strange and rare presentation. For those who are novices to the UWB world the references in [15][16] may prove very much useful to start and update.

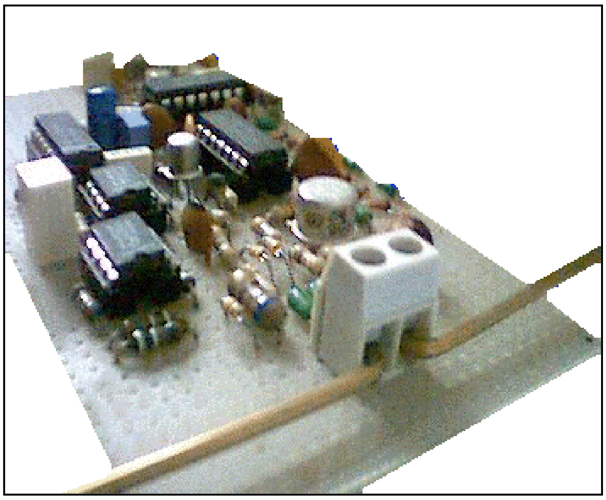

Figure 11. Photo of the prototype.

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