An Ultra Low Power Transcutaneous Impulse Radio Link for Cochlea Implants

THOMAS BUCHEGGER, GERALD OSSBERGER
Linz Center of Mechatronics GmbH, Altenbergerstraße 69, 4040 Linz, Austria
E-mail: thomas.buchegger@lcm.at, gerald.ossberger@lcm.at

ERWIN HOCHMAIR
Leopold Franzens University of Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria
E-mail: erwin.hochmair@uibk.ac.at

ULLA FOLGER
Cantonal Hospital of St.Gallen, 9007 St. Gallen, Switzerland
E-mail: ulla.folger@kssg.ch

ALEXANDER REISENZAHN, ANDREAS SPRINGER
Johannes Kepler University of Linz, Altenbergerstraße 69, 4040 Linz, Austria
E-mail: a.reisenzahn@icie.jku.at, a.springer@icie.jku.at

Abstract— The big potential of ultra wideband radio, in particular low power consumption, low power spectral density, high immunity against interference, affords many benefits, not only for consumer electronics, but also for medical devices. A cochlea implant is an electronic hearing apparatus, where a wireless link through human tissue is required. In this paper we propose a UWB link for a data rate of 1.2 Mbps and a propagation distance up to 500 mm. Transmitter, antennas and receivers are described and proposals for semiconductor integration are made.

Key words— **broadband antenna, cochlea implant, detector receiver, step recovery diode, tunnel diode, ultra wideband.**

I. INTRODUCTION

A cochlea implant is an electronic device intended to help severely to profoundly deaf individuals who gain little or no benefit from hearing aids [1]. It consists of two main parts: an internal implanted part and an external part known as the speech processor. The speech processor can be worn discreetly behind the ear as shown in Fig. 1. Sounds are picked up by a microphone (1) and turned into an electrical signal, which goes to the speech processor (2) where it is coded into a special pattern of electrical pulses ($\Sigma\Delta$-modulation). These pulses are sent to the coil (3) and are then transmitted across the intact skin (inductive) to the implant (4). The implant sends a pattern of electrical pulses to the electrodes in the cochlea. The auditory nerve (5) picks up these electrical pulses and sends them to the brain. The brain (6) recognizes these signals as sound.

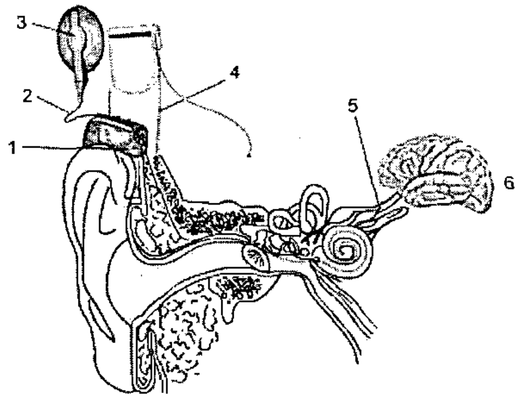

Fig. 1: How a cochlea implant works.

The drawbacks of the presently used coil (3), for inductive transmitting to the receiver (stimulator), are the high power consumption, the size and optical reasons. The big challenge now is, if it is possible, to substitute the inductive communication system with an UWB system and fulfill all the claimed requirements. The transmitter and its antenna will be included into the speech processor's case, the receiver and its antenna are beneath the skin and connected to the implant. The lifetime of the implant's battery is of capital importance, because for every changing, a surgery is necessary,

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which is high in costs and nasty for the patient. Another reason than low power consumption for UWB is the low spectral density which should be more healthful for brain and body than a constant magnetic field.

II. Specifications

First of all the FCC requirements [2] should be fulfilled (bandwidth: 3.1 GHz – 10.6 GHz). Nearly all parts have to be implemented in a CMOS (0.18 μm) process to save power and space. The power consumption for the receiver should be below 100 μW as a mean value over the time. The distances should be 5 to 50 mm transcutanous and 500 mm in the air. There should be a transcutanous wireless connection between speech processor and implant and on the other hand between an MP3 player, a mobile phone or another electronic audio device and the speech processor. It is also intended to make stereo hearing possible by connecting each ear's speech processor by a UWB wireless connection, through or around the head. The antennas should be as small as possible and its radiated pulse should be able to penetrate human tissue. The input signal of the transmitter is ΣΔ - modulated with 1.2 Mbps.

III. Transmitter

This 1.2 Mbps ΣΔ - modulated signal is perfect for an on-off keying (OOK) modulation. OOK uses mono phase modulation, where a pulse transmits a "1" and no pulse transmits a "0" as shown in Fig. 2. The transmitted signal can be defined as in Eqn. 1. The symbol time T_S is divided by the number of frames N_S (number of pulses per symbol), whereas each frame lasts $T_f = T_S/N_S$. Variable a_k, which is „1" for a high bit and „0" for a low bit. E_s accords to the energy of one symbol.

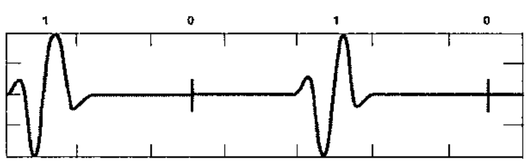

Fig. 2: OOK principle.

$$s(t) = \sqrt{E_s}\sum_k a_k \sum_{n=0}^{N_s-1} w(t - nT_f - kT_s) \qquad (1)$$

The major problem in a UWB transmitter is the pulse generation with a pulse spectrum above 3.1 GHz. The pulse duration for Gaussian monocycle pulses has to be below 300 ps for the spectral requirements, therefore CMOS or SiGe BiCMOS processes would be desirable for fast pulse generation. Gerrits [3], Kim [4] and Azakkour [5] presented fundamentals to generate different pulse shapes on integrated circuits. Anyway CMOS is still to slow for 250 ps pulses with an amplitude of 0.5 V_{pp}, but this goal is very soon reachable and an ultra low power UWB transmitter can be manufactured. For our prototype we use an ACT - TTL logic and an SRD pulse sharpener circuit. In Fig. 3 the transmitter principle is shown.

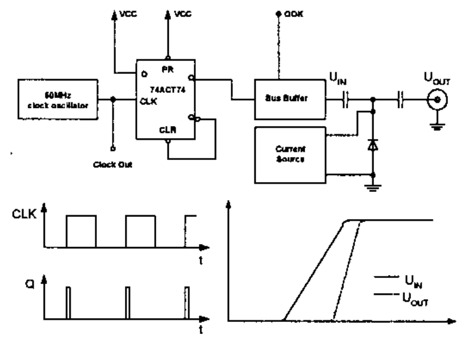

Fig. 3: UWB transmitter with OOK and SRD pulse sharpener.

A 50 MHz crystal clock oscillator generates a TTL output, which triggers a D-flip flop and resets itself immediately. The short output pulse of the D-flip flop has a duration of about 2.5 ns, which is to long for a UWB pulse. With a SRD pulse sharpener the rise time of this pulse can be fastened up to 70 ps for 3.5 V of amplitude [6]. The 50 MHz pulse repetition frequency (PRF) is ~ 40 times the symbol rate of 1.2 Mbps. The transmitter output signal is shown in Fig. 4. The problem with this prototype of Fig. 5 is the high bias current of the SRD, hence for a low power application a transmitter in CMOS technology is obligatory.

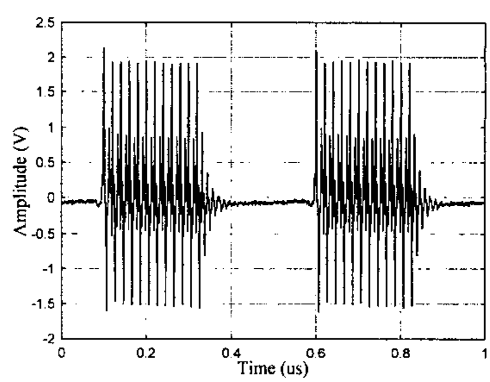

Fig. 4: OOK transmitter output, PRF = 50 MHz, symbol rate = 1.2 Mbps.

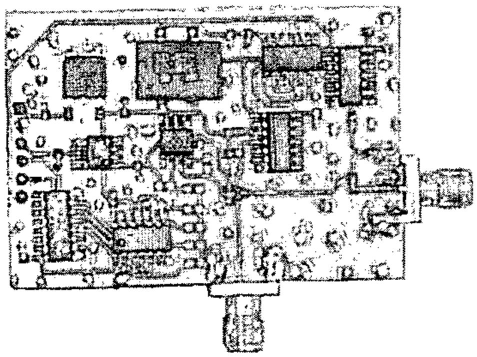

Fig. 5: UWB transmitter prototype.

IV. ANTENNAS

Ultra Wideband antennas are nowadays of huge interest based on the enormous demand in broadband wireless systems. Because of the small power levels authorized by the FCC, every dB counts in a UWB system [7]. Antennas can be categorized into magnetic and electric antennas. Magnetic Antennas are loops or slots and generate a high magnetic field close to the Antenna which have excellent propagation characteristics in human tissue in contrast to the nearly non invasive electric antennas (dipoles, horns, etc.), having an intense electric field around. The bandwidth of an antenna describes the nearly constant characteristics in a frequency interval. Important values are the input impedance, the radiation pattern and the polarization. If the VSWR (voltage standing wave ratio), defined in Eqn. 2 fulfills Eqn. 3, the antenna is called broadband antenna.

$$VSWR = \left|\frac{\underline{U}_h + \underline{U}_r}{\underline{U}_h - \underline{U}_r}\right| = \frac{1+|S_{11}|}{1-|S_{11}|} = \frac{1+|r|}{1-|r|} = s \qquad (2)$$

$$VSWR \leq 2{,}0 \text{ in the range of } \frac{f_o}{f_u} \geq 2{,}0 \qquad (3)$$

For our prototype we used very simple monopole antennas shown in Fig. 6.

Fig. 6: 30 mm monopole antenna.

A 1.5 mm thick copper wire, soldered with an SMA connector and packaged in a shrinkable tubing, was used. This is no special broadband antenna, but it is very small in size and it is possible to penetrate human tissue with UWB pulses. The antenna a λ/2 monopole or Marconi antenna was developed for a center frequency of 5 GHz. The ground plane is the outer conductor of the SMA connector. In Fig. 7 the VSWR of the manually enfolded monopole antenna is plotted and exhibits in the range of 1.8 GHZ to 3.7 GHz a wanted poor matching, which results in nearly no radiation below 3.7 GHz, therefore no filter for the FCC requirements is needed.

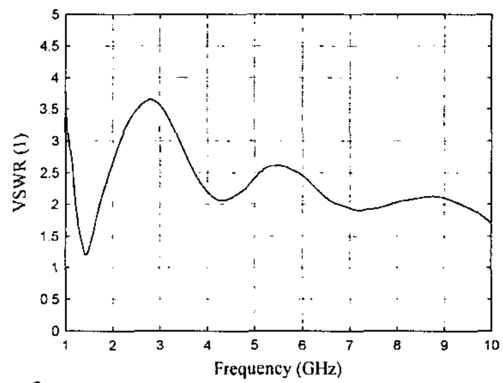

Fig. 7: VSWR of the manually enfolded monopole.

V. RECEIVER

An asynchronous or non coherent receiver is sufficient for a communication link from the ear to the implant. The first receiver prototype in Fig. 8 consists of an LNA, a detector diode, which rectifies the signal of Fig. 9, a low pass filter for getting the envelope and an operational amplifier which amplifies the signal back to a TTL level. Instead of the detector diode a ready chip from Linear Technology can be used (LTC 5508), which results in a signal like in Fig. 10 [8]. The printed circuit board of this prototype is shown in Fig. 11.

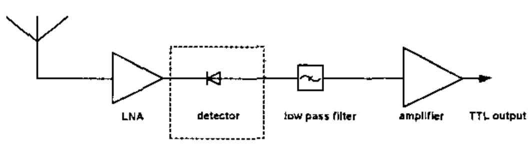

Fig. 8: Non coherent UWB Receiver.

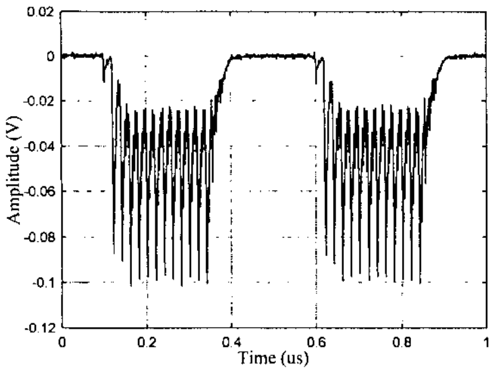

Fig. 9: Detector diode output, rectified signal.

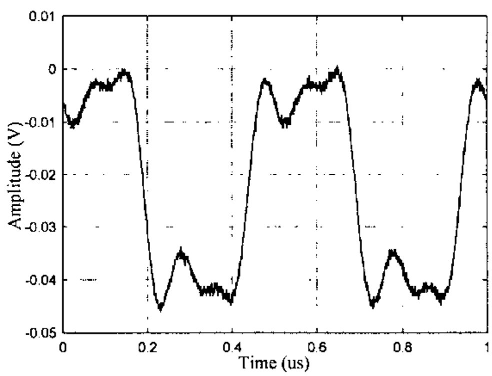

Fig. 10: Output of the LTC 5508 detector chip.

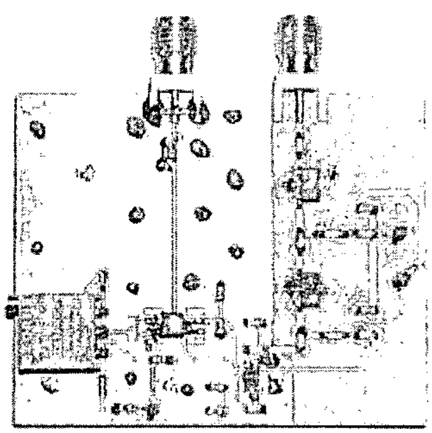

Fig. 11: Receiver prototype.

For less power consumption tunnel diodes or back tunnel Diodes can be used. In the tunnel diode, the semiconductor materials used in forming a junction are doped to the extent of one-thousand impurity atoms for ten-million semiconductor atoms. This heavy doping produces an extremely narrow depletion zone similar to that in the Zener diode. Also because of the heavy doping, a tunnel diode exhibits an unusual current-voltage characteristic curve as compared with that of an ordinary junction diode. The characteristic curve for a tunnel diode is illustrated in Fig. 12. The three most important aspects of this characteristic curve are (1) the forward current increases to a peak (I_P) with a small applied forward bias, (2) the decreasing forward current with an increasing forward bias to a minimum valley current (I_V), and (3) the normal increasing forward current with further increases in the bias voltage. The part of the characteristic curve between I_P and I_V is the region of negative resistance. Backward diodes or back tunnel diodes are tunnel diodes with a maximum forward voltage of ~ 100 mV and a minimum reverse voltage of ~ 500 mV. These diodes operate in reverse mode as a very sensitive pulse detector. Because of the high sensitivity no more LNA is needed. The drawbacks of diode biasing and LNA power consumption disappear when using this diode. By using back tunnel diodes it should be possible to fulfill the $< 100\,\mu$W power consumption requirement for the receiver.

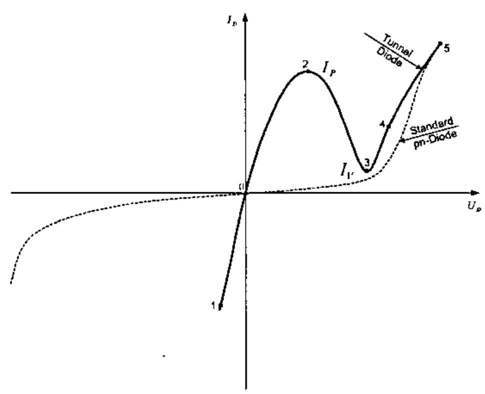

Fig. 12: Characteristic diagram of a tunnel diode.

VI. Results

Two different prototypes for an ultra short distance UWB communication link below 500 mm were developed. On the photo of Fig. 13 the SRD transmitter on the left side and the detector receiver with an LTC5508 is pictured. If a hand encloses each antenna, as shown Fig. 14 the signal is still received perfectly as shown on the scope screen behind. Better results are reached with a tunnel diode detector or receiver. The power consumption of the receiver can be minimized to 1.5 mW. This 1.5 mW consist of the tunnel diode bias current and the active low pass filter. By using the back tunnel diode a degradation of the power consumption of a decade should be possible.

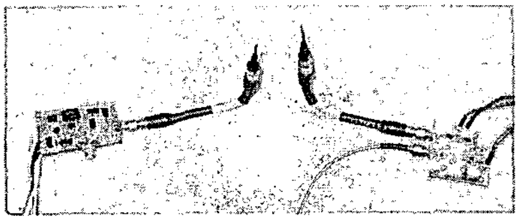

Fig. 13: A UWB communication link prototype, left: transmitter, 2 monopole antennas, right: non coherent receiver.

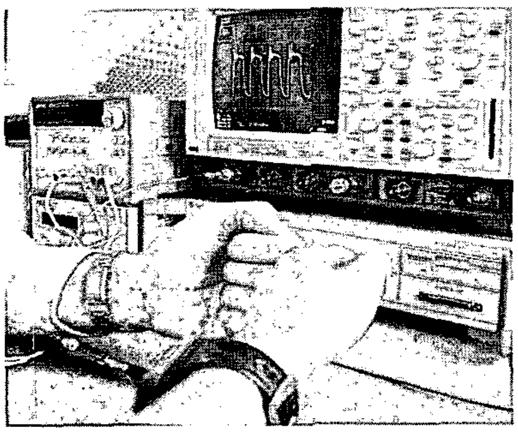

Fig. 14: Transmitting through human tissue.

VII. CONCLUSION

An electronic hearing apparatus, like the cochlea implant with its low power consumption requirements, is an ideal application for a UWB communication link. A complete prototype system for this application is proposed. The OOK transmitter with a data rate of 1.2 Mbps has a pulse repetition frequency of 50 MHz and is based on pulse generation with step recovery diodes. The monopole antenna only transmits in the FCC spectrum and has excellent propagation characteristics through human tissue. Three different detector receivers with a ready detector IC, tunnel diodes and backward diodes are compared in relation to power consumption and sensitivity. The use of UWB communication systems for cochlea implants becomes soon realistic if all the components are integrated in a fast CMOS process as described and the pulse detection in the receiver can be done by a passive element like the back tunnel diode, to reach a long battery lifetime in the implant.

VIII. ACKNOWLEDGMENT

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