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# Ultra-Wideband Transceivers for Cochlear Implants

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Ultra-wideband (UWB) radio offers low power consumption, low power spectral density, high immunity against interference, and other benefits, not only for consumer electronics, but also for medical devices. A cochlear implant (CI) is an electronic hearing apparatus, requiring a wireless link through human tissue. In this paper we propose an UWB link for a data rate of 1.2 Mbps and a propagation distance up to 500 mm. Transmitters with step recovery diode and transistor pulse generators are proposed. Two types of antennas and their filter characteristics in the UWB spectrum will be discussed. An ultra-low-power back tunnel diode receiver prototype is described and compared with conventional detector receivers.

**Keywords and phrases:** broadband antenna, cochlear implant, detector receiver, step recovery diode, back tunnel diode, ultra-wideband.

## 1. INTRODUCTION

A cochlear implant is an electronic hearing device intended to help severely 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. Sounds are picked up by a microphone which feeds the speech processor that converts the sound into electrical signals. The transmission system transmits the electrical signals, transcutaneous or percutaneous, to the implanted electrodes. The electrode or an electrode array, inserted into the cochlea by a surgeon, stimulates the auditory nerves. The majority of the CI manufacturers (Nucleus, Clarion, Med-El) use a transcutaneous link with an external and an implanted coil for the radio frequency link.

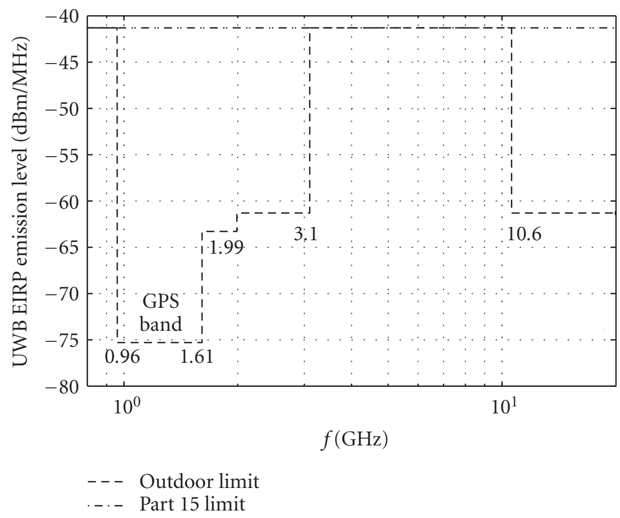


Figure 1: FCC ultra-wideband outdoor emission limits, bandwidth: 3.1 GHz–10.6 GHz, −41.25 dBm/MHz EIRP (equivalent isotropic radiated power).

The drawbacks of the presently used coil, for inductive transmitting to the receiver (stimulator), are the high power consumption, the size, and optical reasons. On the other side the RF link is also used for power supply and no implanted battery is necessary. The big challenge is to substitute the inductive communication system with an alternative system like an infrared or a microwave link. A wireless ultra-wideband (UWB) system is a new low power technology for reusing previously allocated RF bands without any licenses and by hiding the signals below the noise floor [2].

UWB signals are signals where the fractional bandwidth $\eta$ is greater than 0.2 or the signal occupies 0.5 GHz or more of the spectrum [3]. The fractional bandwidth is defined as

$$\eta = 2\frac{f_H - f_L}{f_H + f_L}, \tag{1}$$

where $f_H$ and $f_L$ are the frequencies measured at the −10 dB emissions points. Operating over a large bandwidth, UWB or impulse radio can be classified as a spread spectrum technique for transmitting information. For high data rate applications (up to 500 Mbps) a DS-CDMA (direct-sequence code-division multiple access) and a multiband OFDM (orthogonal frequency-division multiplexing) system have been proposed to the IEEE 802.15.3a group for standardization [4]. On the other hand there is impulse radio (IR) which is carrierless and relies on a specific unchanging pulse-type waveforms to be transmitted in time with pulse-position modulation or on-off keying (OOK). IR transmitters and receivers are very elementary and of low power compared to DS-CDMA and OFDM. These single-period monopulses are very short in time duration and have a very low power spectral density across an ultrabroad frequency spectrum. The UWB transmitter and its antenna can be included into the speech processors case, the receiver and its antenna are beneath the skin and connected to the implant. The drawback using an UWB link, the lifetime of the implant's battery, is of capital importance, because for every changing, a surgery is necessary. The optimization of the implants power consumption demands highest priority.

## 2. SPECIFICATIONS

Nearly all parts of the transmitter and the receiver have to be implemented in a submicron CMOS process to minimize power and size. The power consumption for the receiver should be below 100 $\mu$W as a mean value over time. The spectrum of the UWB signal has to fulfill the FCC requirements, shown in Figure 1, in order to allow coexistence with other systems [3, 5]. The required transmission distances are 5 to 50 mm transcutaneous and 500 mm via air.

There should be a transcutaneous wireless connection between speech processor and implant and on the other hand optional features, like connections to a digital music player, a mobile phone, or another electronic audio device. It can also be envisaged to make stereo hearing possible by connecting the ipsilateral and the contralateral implants via the speech processor by an UWB wireless link, through or around the head. The antennas should be as small as possible and the radiated pulse should be able to penetrate human tissue with low attenuation. The safety issues for the patient concerning electromagnetic fields (EMF) are far below the restrictions compared with the EMF restrictions of the WHO (World Health Organization). In the United States for time-varying electric and magnetic fields from 0.3 to 6 GHz, a whole-body average specific absorption rate (SAR) of 0.08 W/kg and a spatial peak SAR in the head of 1.6 W/kg is permitted. If all the maximum output of an UWB device of 0.56 mW is absorbed by 1 kg of human tissue around the ear, it is still 2800 times below the critical spatial peak value. If we consider the free space loss of the link, then the absorbed power is again reduced by more than two decades. The input signal of our transmitter prototype is ΣΔ-modulated with 1.2 Mbps, as it is also used by some CI manufacturers.

## 3. TRANSMITTER

The 1.2 Mbps ΣΔ-modulated signal perfectly fits to on-off keying (OOK) modulation. OOK uses monophase modulation, where a pulse $w(t)$ transmits a "1" and no pulse transmits a "0" as shown in Figure 2 [6]. The transmitted signal can be defined as in (2). The symbol time $T_S$ is divided by the number of frames $N_S$ (number of pulses per symbol), whereas each frame lasts $T_f = T_S/N_S$ seconds. The discrete amplitude $a_k$ is "1" for a high bit $k$ and "0" for a low bit $k$.

For the system analysis it is convenient to consider a normalized energy for the pulse. Thus we will assume that the waveform used to transmit a bit has an energy $E_b$. This implies that the energy of a monocycle is $1/N_S$:

$$s(t) = 2\sqrt{E_b}\sum_k a_k \sum_{n=0}^{N_s-1} w(t - nT_f - kT_s). \tag{2}$$

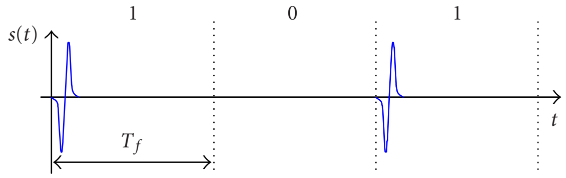


Figure 2: On-off keying principle.

One major problem in an UWB transmitter is the pulse generation with a pulse spectrum containing relevant power only 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 are required for fast pulse generation. Gerrits [7], Kim [8], and Azakkour [9] presented fundamentals to generate different pulse shapes on integrated circuits. However, CMOS is still too slow for 250 ps pulses with an amplitude of 0.5 $V_{pp}$, but this goal will be reachable soon, due to rapid advances in semiconductor technology making an ultra-low-power UWB transmitter feasible. For our prototype we used an ACT-TTL logic and a step recovery diode (SRD) pulse sharpener circuit. In Figure 3 the transmitter principle is shown [10]. The 50 MHz pulse repetition frequency (PRF) is ∼ 42 times the symbol rate of 1.2 Mbps. This allows to transmit several pulses per bit which guarantees a higher interference resistance and a lower power spectral density. The transmitter output signal is shown in Figure 4. The problem with this prototype (see Figure 5) is the high bias current of the SRD; hence for a low power application a transmitter in CMOS technology is obligatory. By using fast SiGe bipolar transistors (BFP 640F, etc.) instead of the SRD, the average transmitter power can be dropped below 1 mW and the pulses become two times faster than with a SRD pulser. Further research work is planned in this field.

## 4. ANTENNA

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 tenth of a dB counts in an UWB system [11]. For our prototype we used very simple monopole antennas and planar dipole antennas shown in Figure 6 and described in [6].

The antenna, a $\lambda/2$ monopole or Marconi antenna, was designed for a center frequency of 5 GHz. The ground plane is the outer conductor of the SMA connector. The *VSWR* (voltage standing wave ratio) of the manually enfolded monopole antenna 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 to fulfill the FCC requirements is needed. The planar dipole antenna has a much better filter performance at an attenuation difference of 20 dB between 2 and 4 GHz as shown in Figure 7a. For our prototype the monopole antenna was used, because the output pulses of the transmitter are not short enough to send the whole power above 3 GHz. The spectrum of the transmitted signal produced by the transistor pulser and shaped by the dipole antenna is shown in Figure 7b. Presently the spectrum of the transmitted signal is not FCC compliant. A better fit into the FCC spectrum will be reached by using a bipolar transistor pulse generator. This future pulse signal will result in a higher attenuation through the human tissue, but a FDTD (finite difference time domain) antenna simulation can improve the matching, the gain, and the filter characteristics and will compensate this problem.

## 5. RECEIVER

An asynchronous or noncoherent receiver is sufficient for a communication link from the speech processor to the implant. The first proposed receiver prototype [6] consisted of a low noise amplifier (LNA), a detector diode, or a detector IC, which rectifies the signal and a lowpass filter for recovering the envelope and an operational amplifier which amplifies the signal back to a TTL level [12]. This type of receiver is not applicable for implantation into the head, because of its high power consumption in the 10–100 mW range. For less power consumption tunnel diodes or back tunnel diodes can be used. In the tunnel diode, the semiconductor materials used for forming a junction are doped to the extent of one thousand impurity atoms per ten million semiconductor atoms. This heavy doping produces an extremely narrow depletion zone similar to that in a 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 of a tunnel diode is illustrated in Figure 8. The three most important aspects of this characteristic are the forward current increases to a peak ($I_P$) with a small applied forward bias, the decreasing forward current with an increasing forward bias to a minimum valley current ($I_V$), and the increasing forward current with a further increase 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 (BTD) are tunnel diodes with a maximum forward voltage of ∼100 mV and a minimum reverse voltage of ∼400 mV. These diodes operate in reverse mode as a very sensitive pulse detector (∼1000 mV/mW). 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.

The backward diode is connected in reverse direction and rectifies very small signals down to −15 dBm without any biasing as a real passive part. The prototyped receiver only consists of a BTD and a resistor connected to a 2 MHz lowpass filter. The rectified output signal of the receiver is plotted in Figure 9a. The envelope of this signal recovers the 1.2 Mhz input signal as shown in Figure 9b.

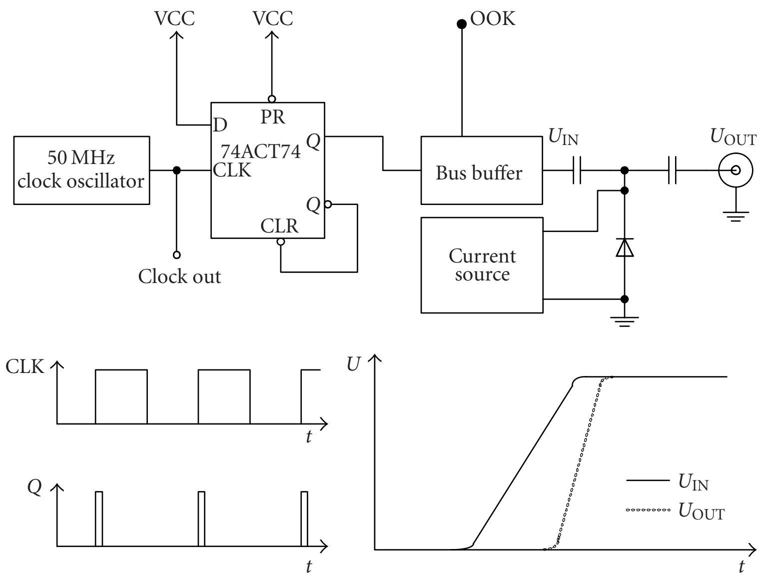


FIGURE 3: UWB transmitter with OOK and SRD pulse sharpener.

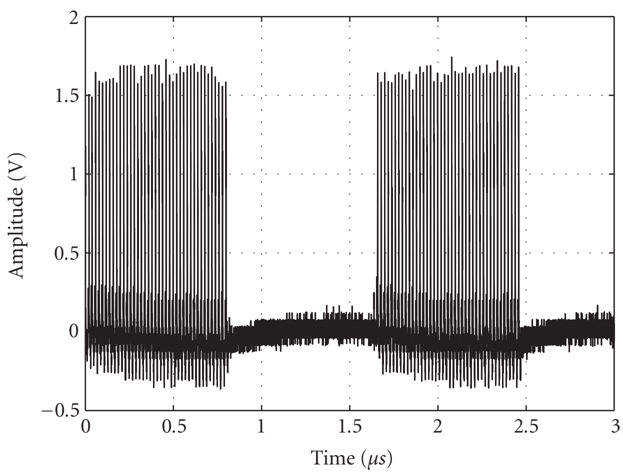


FIGURE 4: OOK transmitter output, PRF = 50 MHz, symbol rate is 1.2 Mbps.

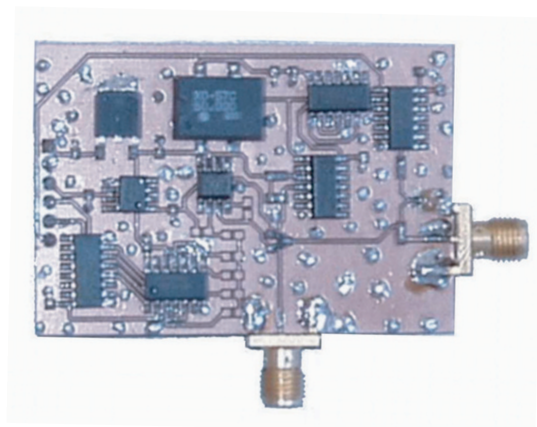

FIGURE 5: UWB transmitter prototype.

## 6. RESULTS

The SRD transmitter shown in Figure 5 and three different detector receivers with an LTC5508 (7 GHz RF power detector from Linear Technologies), a tunnel diode receiver, and a back tunnel diode receiver have been used for prototype UWB systems. If a hand encloses each antenna, as shown in Figure 10, the signal is still received perfectly. In Table 1 the three different receiver prototypes are compared in relation to input power range, sensitivity, and power consumption.

The best results in terms of power consumption are obtained with a back tunnel diode. The power consumption of the receiver can be minimized to zero, because it is a passive detector, but there is the drawback of a shorter propagation distance by the minimum input power of −15 dBm. The only power needed is for an active lowpass filter after the receiver, which can be easily implemented with less than 100 $\mu$W consumption. The output of the lowpass filter is fed to the stimulator. If a person has two CIs, with a transceiver in each ear, it should be possible to connect the two CIs over

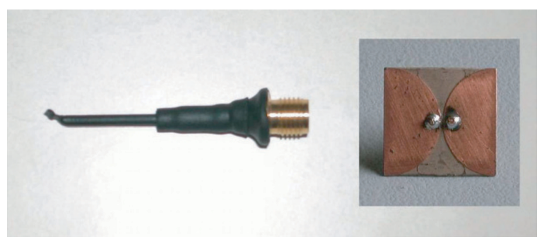

FIGURE 6: 30 mm monopole antenna (left) and a 20×20 mm$^2$ planar dipole antenna (right).

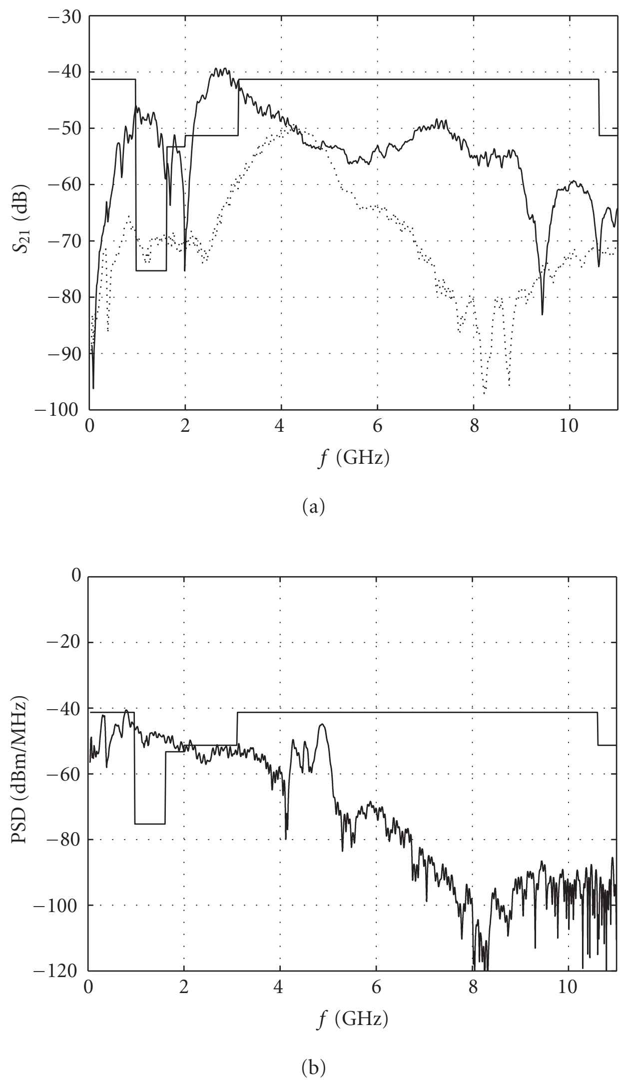


Figure 7: (a) $S_{21}$ of a planar dipole antenna pair (dotted line) and a monopole antenna pair (solid) over 50 mm line of sight distance together with the FCC spectrum mask. (b) Transmitted signal and FCC indoor spectrum mask.

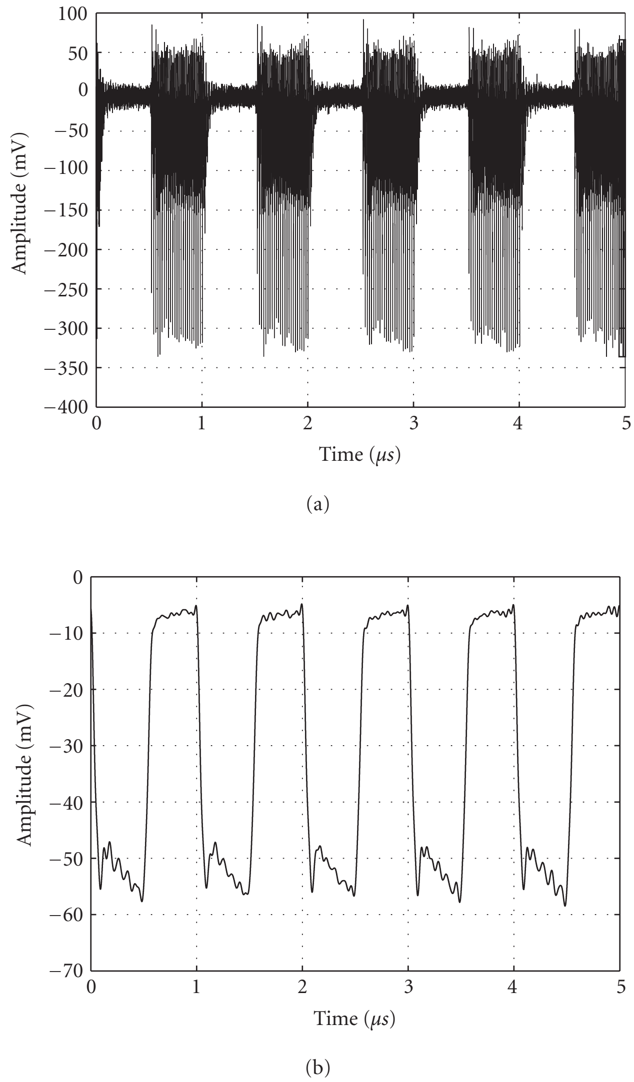


Figure 9: (a) Output of the BTD receiver and (b) output of the 2 MHz lowpass filter.

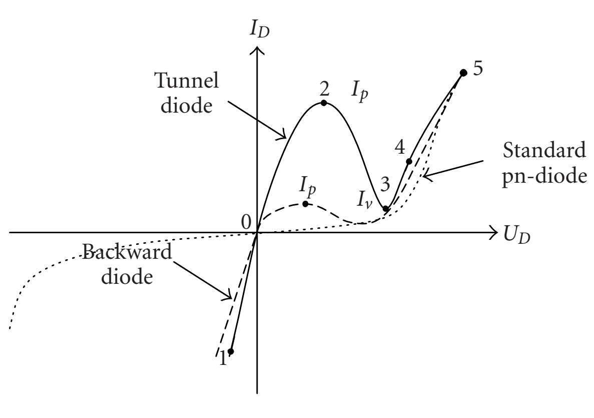


Figure 8: Characteristic diagram of a tunnel diode.

a wireless UWB link with the speech processor. This offers new solutions in stereo hearing for deaf persons and generates a big challenge for the implementation of the required digital signal processing. Interference between the transmitters can be eliminated with a transmit protocol controlled by the speech processor. A back-telemetry link with a low power transistor pulser in the implant is of high importance for the transmit protocol. If it is at a very low rate the battery lifetime in the implant will not be stressed too hard. The quality of the communication link is dependent on the distance. The LTC 5508 receiver had a good transmission quality for distances up to 500 mm, with the back tunnel diode the quality gets week at distances longer than 80 mm, in transcutaneous (through two hands) propagation channels.

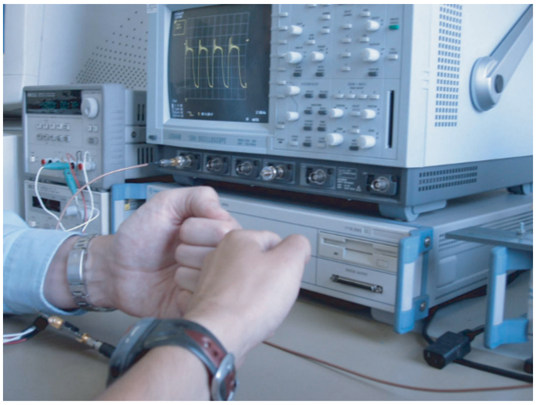

Figure 10: Transmitting through human tissue.

Table 1: Comparison of different detector receivers.

| Type of detector receiver | Input power range (sensitivity) | Power consumption |
|---|---|---|
| Receiver with LTC5508 + LNA | −30 dBm–12 dBm | 50 mW |
| Tunnel diode receiver | −38 dBm–5 dBm (600 mV/mW) | 2–10 mW, biasing necessary |
| Back tunnel diode receiver | −15 dBm–5 dBm (800 mV/mW) | 0, no biasing |

## 7. CONCLUSION

An electronic hearing apparatus, like the cochlear implant with its low power consumption requirements, is an ideal application for an UWB communication link. A prototype system for this application has been 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 and the planar dipole antenna have a good performance in radiating through human tissue. Three different detector receivers with a ready detector IC, tunnel diodes, and backward diodes have been compared in relation to power consumption and sensitivity. The use of UWB communication systems for cochlear implants will become soon realistic if all the components can be integrated in a fast CMOS process and the pulse detection in the receiver can be performed by a passive element like the back tunnel diode, to reach a long battery lifetime of the implant. Because of the low detection sensitivity of back tunnel diodes the propagation distance can only be increased by a higher antenna gain, which is generally dependent on the directivity and the size. Improvement reserves for the proposed prototypes are the use of faster and more broadband pulses, antennas with a better performance, and more sensible detector receivers.

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