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A New Optical UWB Modulation Technique for 250Mbps Wireless Link in Implantable Biotelemetry Systems

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Abstract

We propose an optical UWB modulation based on a new pulsed coding technique for wireless implantable biotelemetry. The solution employs sub-nanosecond laser pulses allowing for both high data rates and reduction of the power consumption compared to the state-of-the-art. Thus, the proposed approach is suitable for upcoming biomedical systems like autonomous implantable neural devices. The developed architecture consists of a transmitter and a receiver employing a pulsed semiconductor laser and a small sensitive area photodiode, respectively, and includes coding and decoding digital systems, biasing and driving analogue circuits for laser pulse generation and photodiode signal conditioning. Experimental findings, obtained by employing discrete components prototype PCBs and FPGA implementations, validate the novel technique showing the capabilities to achieve a BER less than 10^{-9} with data rates up to 250Mbps and an estimated power consumption lower than 5mW. These results enable, for example, the transmission of a 1000-channel neural recording system sampled at 16kHz with 16-bit resolution.

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Keywords: Optical UWB Modulation; Pulsed Coding Technique; Implantable Biotelemetry; High Data Rate Link; Neural Recording System.

1. Introduction

Nowadays, the possibility to directly detect in real-time neuronal signals coming from the brain cortical area allows identifying different neural coding processes. Moreover, improvements in biomedical engineering open the possibility to extract and process information carried out by neural/biological signals and to control external

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electronics life-aid apparatus aimed to recover a satisfactory life quality of patients with neurological diseases. The key issue for achieving real technological progresses in this field is the ability to design innovative integrated electronic microsystems for portable/implantable biomedical devices and clinical applications [1]. To do this, it is necessary to face and overcome new challenges in designing fully implantable devices with reduced size and high efficiency able to provide a large bandwidth bidirectional wireless telemetry link with a high data transfer through the skin and very low Bit Error Rate (BER) for a real-time control of complex prosthetic devices. Additionally, these devices should guarantee low noise electronic circuitries operating at very high frequency, low voltage and reduced power consumption together with high electromagnetic (e.m.) compatibility and signal integrity. In this regard, implantable devices for biotelemetry applications using wireless links, achieving high data rate, low power consumption, small BER, high e.m. compatibility, are preferred respect to percutaneous systems that are uncomfortable and potentially cause of infections and diseases [2]. For these reasons, current carrier-based, narrow-band radio frequency links are the widely used unidirectional communication systems that typically consist of an implantable transmitter and an external receiver. These solutions present high power consumptions at high data rates and operating limitations due to e.m. compatibility constrains [3]. A more specific approach is based on the use of Ultra-WideBand (UWB) architectures whose main drawback is related to the high absorption of e.m. radiation as the carrier frequency increases [4]. On the other hand, optical transcutaneous biotelemetry links could offer new solutions with advantages in terms of reduced device size, high data rate, low BER, low power consumption and high e.m. compatibility [5,6]. Generally, in these systems the transmitting device is a semiconductor laser while the receiving component is a photodiode (PD). In order to improve the optical link performances, the transmitter power is enhanced and/or a PD with large sensitive area is used. Nevertheless, modified On-Off Keying modulations have been also implemented to improve the power efficiency with the increase of the laser response time that limits the maximum achievable data rate. On the contrary, the use of large area PD allows decreasing the transmitted light power at the expense of a significant reduction of the PD bandwidth, the signal-to-noise ratio and the data rate so increasing the BER [7,8].

Aim of this work is to overcome these weaknesses of optical biotelemetry systems by proposing an UWB modulation for wireless optical communications, based on a new coding technique employing sub-nanosecond laser pulses, allowing for a high data rate whilst achieving a significant power reduction compared to the state-of-the-art.

2. The proposed approach: a new modulation technique for bidirectional biotelemetry systems

The architecture reported in Fig.1 shows an example of the implementation of a complete implantable bidirectional optical wireless biotelemetry system. It is composed of an implantable and an external unit each one having two identical sub-systems: the transmitter and the receiver. The transmitter (receiver) of the implantable unit and the receiver (transmitter) of the external unit form the up-link (down-link) module. These two modules could have the same performances and operate simultaneously in a bidirectional mode. More in detail, the transmitter and the receiver handle the main clock and the data stream related to the multichannel conditioning and processing circuitry blocks. The transmitter contains a semiconductor laser and all the analogue and digital electronic circuitry for the laser biasing and driving, the coding system as well as the UWB data processing. The receiver sub-system is composed of a PD detecting the laser pulses together with the related circuitry providing its biasing and signal conditioning, the UWB data processing and the decoding system. In the transmitter, the coding system generates the voltage pulses converted by the laser biasing and driving circuit into current pulses that, in turn, generate the laser pulses. In the receiver, the PD provides photocurrent pulses converted by the PD biasing and conditioning circuitry into voltage pulses processed by the decoding system that recovers the transmitted clock and data stream.

Referring to Fig. 1, the up-link module, highlighted into the dashed box, represents the basic scheme implementing the proposed optical UWB modulation technique that performs the new data coding process using sub-nanosecond laser pulses. The laser is a Vertical Cavity Surface Emitting Laser (VCSEL) able to generate sub-nanosecond pulses while the PD is a Si device with a small active area for fast response times. This approach allows for a high data rate link accomplished with a strong reduction of the power consumption. An example of the timing diagram of the pulsed coding technique performed by the transmitter is shown in Fig. 2. During each bit period, the

VCSEL driving current is maintained at a value I_{min} just above the laser threshold current I_{th} corresponding to the minimum laser power P_{min}. Under these conditions, the VCSEL provides excellent power stability with response times of tens of picoseconds to the variations of the driving current. Therefore, the generated laser pulses have negligible jitter/delay respect to the driving current pulses. In order to transmit both the main clock signal and the data stream, current pulses with the maximum value I_{max} are provided to the VCSEL that generates laser pulses with the maximum optical power P_{max}. On the other hand, at the beginning of each bit period, a laser pulse is always generated independently from the symbol to be transmitted. This allows the transmission of the main clock needed for the synchronisation between the transmitter and the receiver sub-systems. At the half bit period, if the symbol {1} must be transmitted, a second laser pulse is generated, while for the transmission of the symbol {0} the VCSEL driving current is maintained at I_{min} [6].

3. System implementation and experimental results

The up-link module highlighted into the dashed box in Fig. 1 has been implemented through the block scheme reported in Fig. 3, employing as laser a 850nm VCSEL with a 2.2mA threshold current and as PD a high-speed Si-based detector with 47ps response time and 49000μm^2 sensitive area. The VCSEL is controlled by a driving circuit based on current mirrors, while the PD conditioning circuitry is composed by a transimpedance amplifier. All these circuits have been implemented on prototype PCBs designed in AWR Microwave Office with discrete off-the-shelf components operating at 1.8V single supply. In addition, the FPGA board (Xilinx VIRTEX-6 ML605) has been employed for the implementation of data coding and decoding systems for generation/recovery of clock and data stream as well as for the BER evaluation. Several measurements have been conducted with the system operating up to 250Mbps transmitting pseudo-random data streams and evaluating system power consumption and BER.

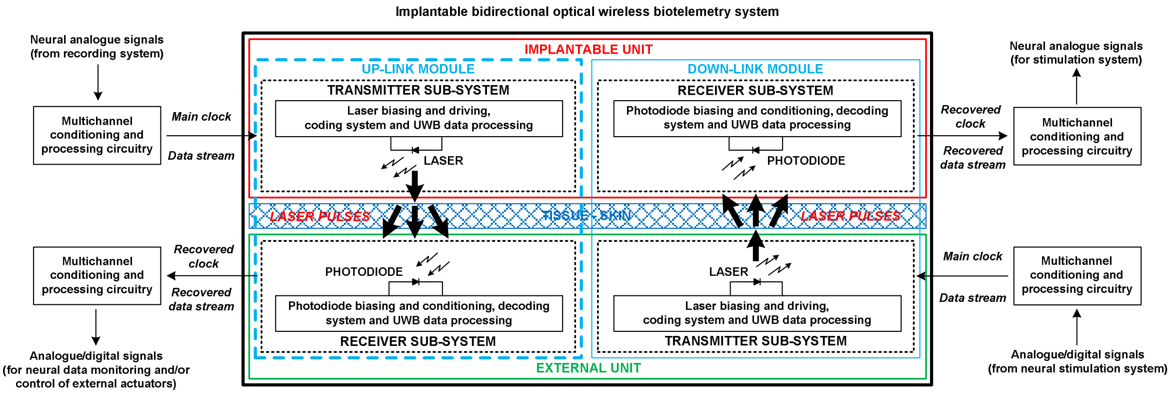

Fig. 1. Example of a complete implantable bidirectional wireless optical biotelemetry system: the proposed developed architecture implements the up-link module highlighted into the dashed box that is identical to the down-link module.

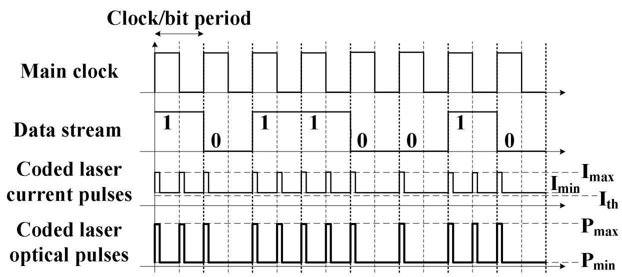

Fig. 2. Optical UWB modulation technique based on the generation of sub-nanosecond laser pulses: example of the timing diagram showing the proposed data coding process performed by the transmitter and the related laser operating conditions.

As reported in Fig. 4, the achieved results demonstrate that the received (i.e., recovered) data stream correctly matches with the transmitted one showing a time delay lower than 20ns due to clock recovery and data decoding processes. The experimental findings validate the new optical UWB modulation technique showing the system capabilities to achieve a BER less than 10^{-9} with data rate up to 250Mbps and estimated total power consumption lower than 5mW. The achieved data rate can allow for the transmission of raw data coming from 1000 intracortical neural recording channels, sampled at 16kHz with 16-bit resolution.

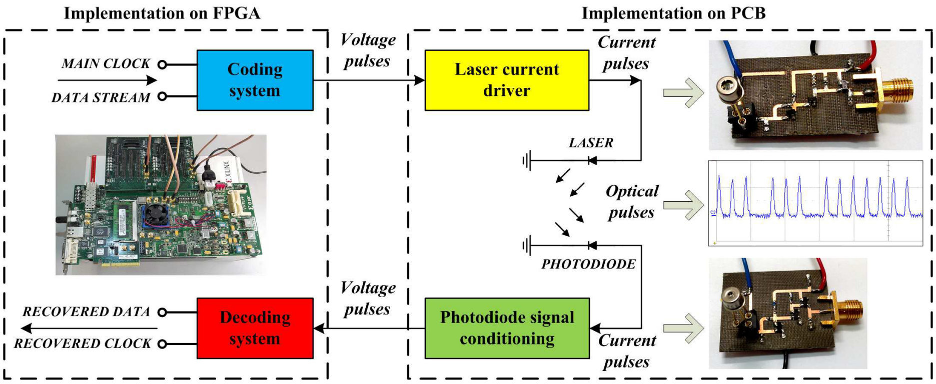

Fig. 3. Block scheme of the implemented optical UWB wireless communication system based on the proposed pulsed coding technique.

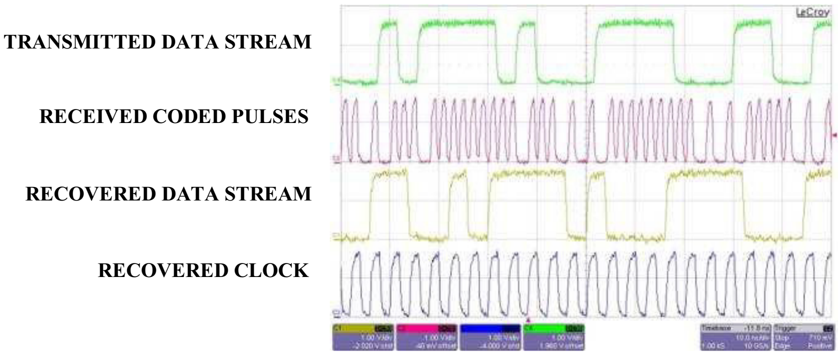

Fig. 4. Experimental main signals of the implemented architecture of Fig. 3 operating at 250Mbps, transmitting a pseudo-random data stream.

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