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Optical Transcutaneous Link for Low Power, High Data Rate Telemetry

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***Abstract*— A low power and high data rate wireless optical link for implantable data transmission is presented in this paper. In some neural prosthetic applications particularly in regard to neural recording system, there is a demand for high speed communication between an implanted device and an external device. An optical transcutaneous link is a promising implantable telemetry solution, since it shows lower power requirements than RF telemetry. In this paper, this advantage is further enhanced by using a modified on-off keying and a simple custom designed low power VCSEL driver. This transmitter achieves an optical transcutaneous link capable of transmitting data at 50 Mbps through the 4 mm tissue, with a tolerance of 2 mm misalignment and a BER of less than 10^{-5}, while the power consumption is only 4.1 mW or less.**

I. INTRODUCTION

In the past few decades, there has been great progress in implantable medical devices. A lot of diseases and disabilities can be treated by implanting an electronic chip inside the human body. These implanted devices, such as cardiac pacemakers, defibrillators as well as cochlear prosthesis, greatly improve the standard of living of patients. In some applications, for the purpose of improving devices' future performance, simple information at low data rate should be collected from implantable device. In other applications, particularly in regard to neural recording system [1] shown in Fig. 1, there is a demand for high speed communication between an implanted device and an external device and the data rate of wireless communication should be from Mbps range to tens of Mbps. This high data rate demand brings a great challenge when realized with low power requirements.

Transcutaneous communication can be accomplished by various methods, such as percutaneous wires, RF, ultrasound, UWB or infrared optical light, each of which have cons and pros. Compared with other methods, percutaneous wires have a larger bandwidth and lower power consumption, but it physically traverses human skin, which increases the possibility of infection. RF is a mature technology which is currently used in most implantable systems. Recently, a high speed RF has been reported capable of transmitting data at 24 Mbps, [3]. However, the power consumption is still large (30 mW). Another obstacle of RF is interference from other sources. RF is regulated by FCC (Federal communication commission), and the only frequencies dedicated for implantable system are from 402 to 405 MHz, which is well known as MICS (medical implants communication service) band. As an alternative, UWB data transmission has been employed [4]. The main drawback of UWB is high

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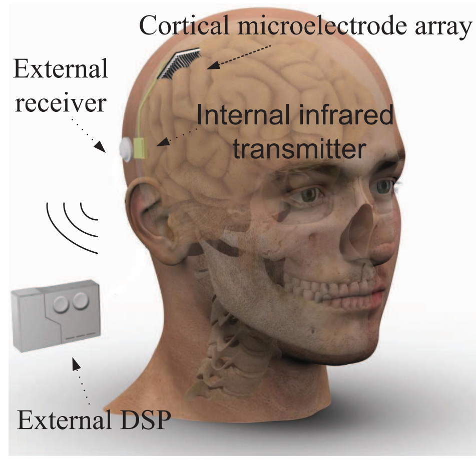

Fig. 1. Optical transcutaneous link with neural recording system [2]

absorption ratio at high frequencies. Ultrasonic transmission requires high voltages to operate and are limited in speed

Due to the large bandwidths available, the partial transparency of skin at infrared wavelengths and lack of telecommunication interference, an optical transcutaneous link is an excellent choice for very high data rate transcutaneous information transfer. The main source of interference is ambient light which can be easily HP-filtered electronically, since it has merely low frequency changes when compared to the data signal. Originally, the optical transcutaneous link which included an LED (light emitting diode) and a photodiode was intended to be used in low speed communication applications, supporting data rate of 9600 bps [5]. In 2005 [6], a VCSEL (vertical cavity surface emitting laser) was first used in place of an LED, which enabled a data rate up to 80 Mbps, meeting the demand of high speed transcutaneous communication. A remaining challenge for the optical transcutaneous link is power consumption. The transmitter employed in [6] consumed an unacceptable 90 mW, even when one should assume that the optical approach is much more power efficient.

To understand optical data transmission to and from implanted devices, it is necessary to discuss the property of the transmission medium–Human skin, which is partially transparent to light at wavelengths ranging from 600 to 1,300 nm [7]. Scattering and absorption coefficients are the two important optical properties of skin. Due to these two reasons, only 10% to 30% of incident optical power can be transmitted through skin of typical thickness (2 to 6 mm) [8]. In this work, a VCSEL with 850 nm wavelength was chosen, because this wavelength is within the optimal range.

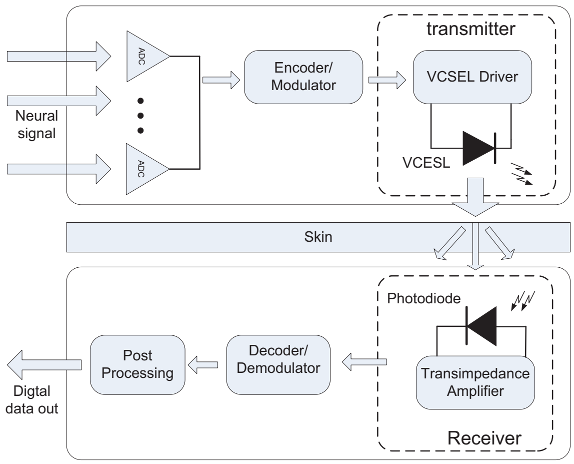

Fig. 2. Block diagram of transcutaneous optical link

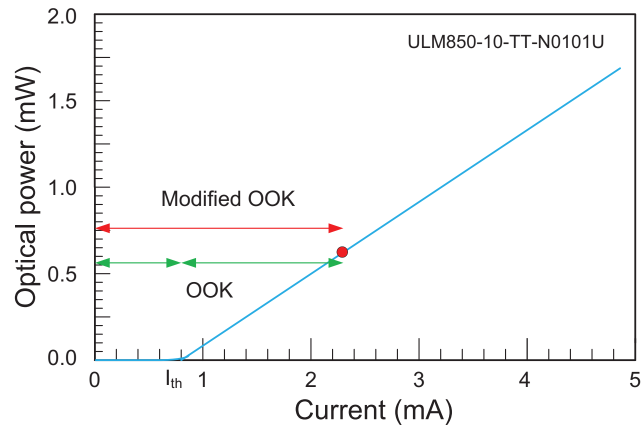

Fig. 3. Comparison between the VCSEL works with OOK and modified OOK, for optical transcutaneous link through 2mm skin, data rate at 50Mbps, 2mm misalignment, BER below 10^{-5}

II. Proposed System Architecture

A. Modified on-off keying

The block diagram of transcutaneous optical link is sketched in Fig. 2. The proposed system architecture is in the dotted boxes. The VCSEL driver receives the digital data from the ADC while it also changes the signal from voltage domain to current domain to feed the VCSEL. The VCSEL transmits the modulated optical signal through the skin. On the other side of the skin, the photodiode receives the optical signal and works with a transimpedance amplifier for data recovery.

The VCSEL drive current can be divided into two parts: the biasing current and the modulation current. The biasing current biases the VCSEL to operate over the laser threshold region, which minimizes the turn-on time, and thus makes the VCSEL have a faster response. The modulation current is responsible for modulating the data onto the VCSEL's optical output, and thereby to OOK the optical output.(The extinction ratio which is the ratio of a logic-one power level relative to logic-zero power level is infinite.) Nowadays, VCSELs can work in the tens of GHz range. However, in neural recording applications, the VCSEL only needs to work approximately three orders of magnitude slower. Thus, for the purpose of reducing the power consumption, a modified on-off keying is used in the optical transcutaneous link. The biasing current is removed and only the modulation current is given to solely turn the VCSEL on-off. The penalty associated with this modified on-off keying is that the response time of the VCSEL will increase. Therefore the speed of the VCSEL will decrease. However, experimental results show it is still easily capable of transmitting data above 50 Mbps.

To illustrate the benefit of the modified on-off keying, the electro-optical characteristic of the VCSEL used in this paper is shown in Fig. 3. We assume 2mm misalignment for the optical link and put a 2-mm skin between the transmitter and receiver. Measurement results show, in order to achieve a BER below 10^{-5}, it needs approximately 2.26 mA forward current which corresponds to 0.7 mW optical output power. In the upper case, the optical transmitter needs 0.8 mA all the time in order to drive the VCSEL into lasing mode, and 1.46 mA with 50% duty cycle as additional signal current. This makes $0.8 + 50\% \times 1.68 = 1.64mA$ in average. In the lower case (modified OOK), it still need 2.26 mA for the transmission of the data, but the whole 2.26 mA is 50% duty cycle. Thus it reduces the average current by 26%.

B. Implantable VCSEL driver and VCSEL

Fig. 4 shows the schematic of the prototyped VCSEL driver which consists only of a simple current mirror. The circuit was realized in 180nm high voltage X-FAB technology together with a neural recorder prototype. According to the data sheet, the used VCSEL needs 2.15 V when the operation current is 8 mA, and at least another 150 mV is required for M5 to keep it in the saturation. Thus, 2.3 V is the lowest voltage that can make the VCSEL generate 2.7 mW optical power. Transistor M1 combined with the external variable resistor sets the modulation current. M2 and M4 mirror the current to the VCSEL branch. M3 works simply in the linear range as a switch. The die photograph of the VCSEL driver combined with a glued on and bonded VCSEL is shown in Fig 5. The VCSEL used in this work is ULM850-10-TT-N0101U, chosen because of its low threshold current (0.8

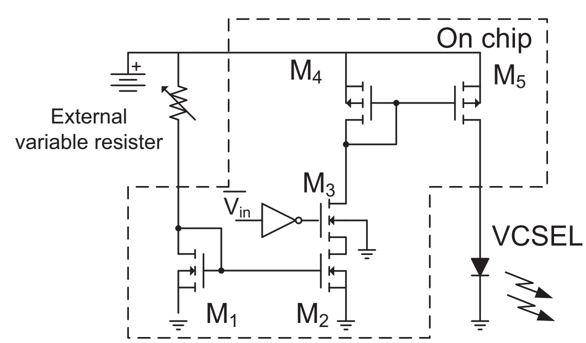

Fig. 4. Schematic of a current mirror based low power VCSEL driver

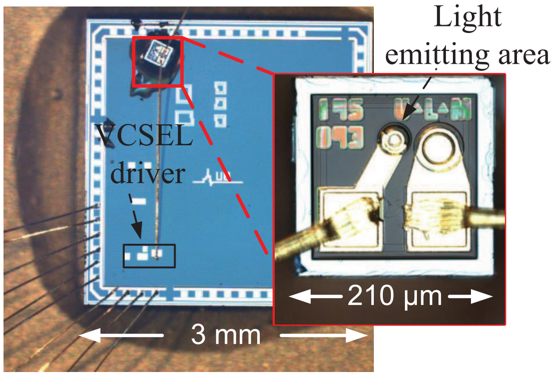

Fig. 5. Die photograph of the VCSEL driver fabricated in 180nm high voltage X-FAB technology and the VCSEL chip

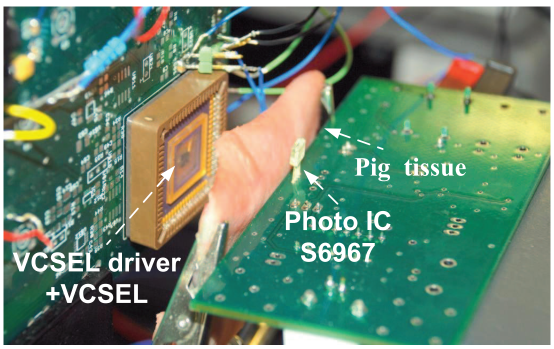

Fig. 6. Photograph of experimental setup

mA). It should be noted here, that the power reported in the following only includes the VCSEL branch. The biasing branch is only a small additional fraction of the VCSEL branch current due to the current mirror gain, which can be chosen large, just allowing to drive the mirror branch in sufficient speed. In the case of this design, rise and fall times in the order of several ns are sufficient.

C. External Receiver

The detector used in this work is a high-speed photodiode IC (Hamamatsu Photonics S8046) which has the photodiode combined with the transimpedance amplifier, chosen because of its small package, high bandwidth as well as its monolithic structure immune from external noise. The output of the photodiode is driven by 50 Ohm line driver (74LS140) to match impedance of the BER tester.

D. Tissue Samples

Due to the optical properties resemblance between human and pork skin [10], pieces of pork tissue were used as samples. For all samples, each consists of 2 mm skin (epidermal and dermal layers) plus adipose layer which was chosen as 0, 2 or 4 mm. Therefore the thickness of tissue is 2, 4, or 6 mm.

E. Link performance

BER was measured with the pattern generator and the error analyzer. The testing data was a pseudo-random binary

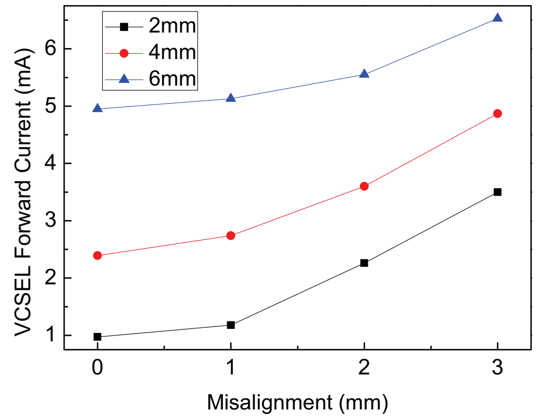

Fig. 7. The required VCSEL forward current relative to misalignment for different tissue thicknesses, with all BER below 10^{-5}

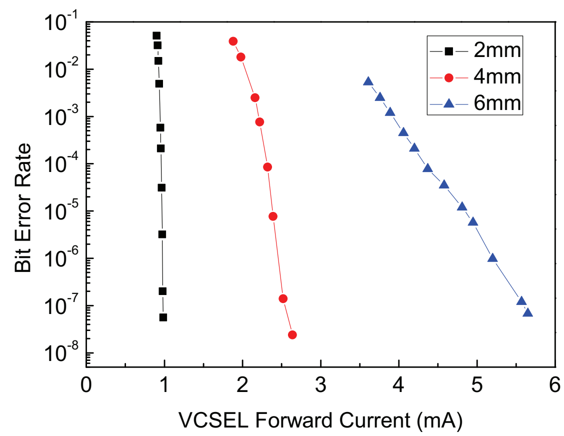

Fig. 8. The required VCSEL forward current relative to the BER through different thickness of skin tissue, no misalignment

sequence (PRBS 10^7-1) at 50 Mbps, that is because neural signals are typically sampled at 25 Kbps [8], assuming the ADC has a resolution of 10-bit and Manchester code has been used for encoding, and a total of 100 channels is recorded simultaneously.

[8] showed that once the BER is below 10^{-5}, the probability of false spike detection is negligible. Therefore, a BER of 10^{-5} has been chosen in this research as the criterion to determine the power requirement.

F. Experimental setup

Fig. 6 shows the photograph of the measurement setup. The transmitter board which contains the VCSEL driver and the VCSEL was fixed with a bracket. The receiver board which contains the photo IC and the 50 Ohm line driver was fixed in the platform. The platform can be moved vertically to adjust the misalignment between the VCSEL and the photodiode. The tissue displayed in this figure does contact with transmitter or receiver. But in real experiments, the inner (adipose) and skin (epidermal) side are in contacted with the VCSEL and photodiode respectively without compression.

TABLE I

COMPARISON OF THE TRANSCUTANEOUS OPTICAL LINK FEATURES

Author (Year)	Link Speed	Transmitter Power	Emitter Power	Skin Thickness (all porcine)	Misalignment	BER
K. S. Guillory(04) [6]	80 Mbps	90 mW	-	3 mm	2 mm	$< 10^{-14}$
J. L. Abita(04) [10]	115.2 Kbps	-	-	6.9 mm	-	-
E. Okamoto(05) [11]	9600 bps	162 mW 122 mW	-	45 mm 20 mm	20 mm 15 mm	-
D. M. Ackermann (07) [8]	40 Mbps	-	4.3 mW	3 mm	2 mm	$< 10^{-5}$
S.Parmentier(07) [9]	16 Mbps	16 mW	-	4 mm	2 mm	$< 10^{-9}$
This work (12)	50 Mbps	2.6 mW 4.1 mW 6.4 mW	2 mW 3.3 mW 5.5mW	2 mm 4 mm 6 mm	all 2 mm	$< 10^{-5}$

III. RESULTS AND DISCUSSION

Fig. 7 illustrates the required VCSEL forward current relative to misalignment for 3 different tissue thicknesses, with all BER below 10^{-5}. With increasing thickness, the curve becomes more flat. This result is consistent with previous research [9]: an optical transcutaneous link with thicker tissue is more tolerant against misalignment than thinner tissue due to beam spreading and scattering. Fig. 8 demonstrates the performance of the optical link transmitting data through 2, 4 and 6 mm skin, displaying the BER over increasing forward current of the VCSEL.

Table 2 summarizes the performance compared to some optical transcutaneous telemetry system since 2004. The emitter power in the fourth column refers to the electro-optical devices such as LED or VCSEL. Compared with previous the state of the art [8], this optical link needs even less power while transmitting through a thicker tissue. The transmitter power in the third column refers to the power consumption of the driver and the electro-optical devices. As mentioned before, the power reported here only includes the VCSEL branch since the mirror branch adds only a fraction depending on the mirror gain. Compared with [9], the transmitter power has also been decreased a lot. Though a recently reported RF link [3] can transmit larger distance at 1 m, it only achieves a data rate at 24 Mbps and consumes 30 mW power. This proposed optical transcutaneous link can work faster and needs less power. Thus, the main task of traversing the skin barrier wirelessly is obviously achieved better with the optical approach.

IV. CONCLUSION

This paper presents a low power optical transcutaneous link. By choosing a low threshold VCSEL, a modified OOK and an easy mirror based driver, the power of the optical transmitter can be decreased substantially. The proposed optical transcutaneous link is capable of transmitting data at 50 Mbps through a sufficiently thick tissue with also sufficient tolerance against misalignment. It can sustain a transcutaneous communication with a BER below 10^{-5}, while the total power consumption can be as low as 1.1 mW to 6.4 mW depending on misalignment and thickness.

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