# Realization and Performance Comparison of Untethered and Minimally Tethered Helmet Mounted Broadband fNIR

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***Abstract* —Broadband (30-1000MHz) frequency modulated spectroscopic measurements of brain tissue using near infra red wavelengths is used to get an accurate extraction of absorption and scattering coefficients of various regions of brain. The design and realization challenges of developing this system are discussed in this paper. The challenges lie in developing small size, low power consuming, efficient custom designed modules on a helmet for broadband NIR spectroscopy and high speed wireless or minimally wired communications to a remote processing unit. The design requirements and expected performance of the custom designed modules is conducted using IBM 90nm CMOS technology. Finally, a comparison between the system level performance of untethered and a minimally tethered systems is shown in terms power consumption and implementation.**

***Index Terms* — Near IR Imaging, Brain Tissue Parameters, Optical Transmitters and Receivers, Wireless Communication design, CMOS technology.**

## I. Introduction

Diffused photon near near-infrared (DPNIR) is a non-invasive optical spectroscopy technique that employs NIR light to quantify the level of oxygenated and de-oxygenated hemoglobin using optical properties of tissues (i.e., absorption and scattering). Quantitative DPNIR methods employing time or frequency domain photon migration have recently been applied for breast tumor detection, functional brain monitoring, wound healing prognosis, and pain assessment [1]. A broadband frequency domain DPNIR method monitors level of oxygenated and deoxygenated blood in the brain with high accuracy and spatial resolution, which could lead to understanding the functionality of different parts of brain as functional NIR (fNIR). Spectroscopic studies at 680nm, 780nm, 830nm, and 980nm reveals level of oxygenated/de-oxygenated hemoglobin, blood and water flow in tissue. Therefore, any disorder in brain functionality could then be registered [2] as excess changes in the absorption of oxygenated and de-oxygenated hemoglobin. Commercial fiber based fNIR systems [3] are significantly tethered and are not field deployable. Moreover, these systems are designed based on unmodulated or narrow band frequency domain operation and higher extraction accuracy and spatial resolution is reported in broadband than narrow band frequency modulated systems [4].

The system block diagram is shown in Fig. 1. It consists of 18 optical transmitters and 22 optical receivers along with wireless transceiver chip placed on a helmet structure. The design challenges for free-space optical transmitter and receiver are addressed earlier[5-6], while this paper addresses custom hardware realization of a broadband fNIR system on chip (SOC) using 90nm CMOS technology from IBM for low power design constraints .

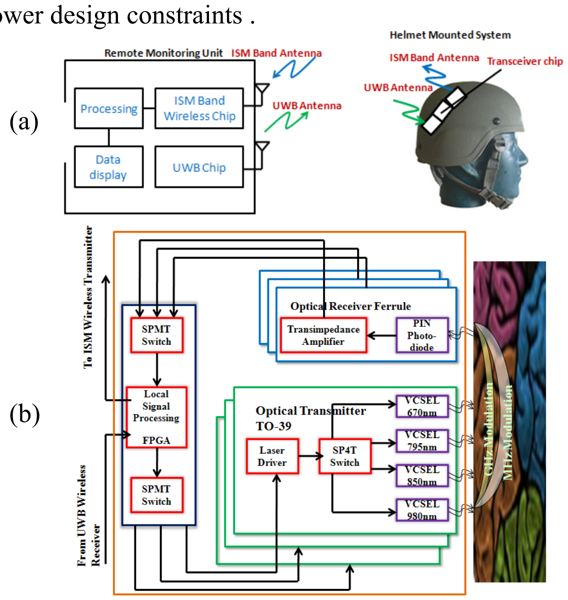


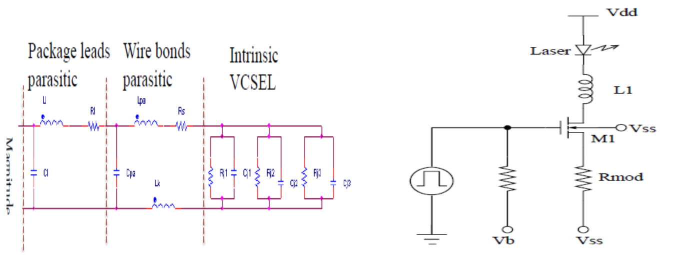

Fig. 1. a) Block diagram of untethered free-space fNIR brain imaging system in wireless communication with remote monitoring; b) Block diagram of fNIR brain imaging system using custom designed optical transmitters in low profile TO-49 cans and the optical receiver ferrules.

The Ultra Wide Band (UWB) protocol at 5GHz is employed for communication between remote monitoring unit and helmet mounted fNIR, while medium rate wireless transmission protocols are used for communication between the on helmet local signal processor and the remote monitoring unit as shown in Fig. 1a. Broadband data (30-1000MHz) is then passed to one of 18 optical transmitters using a 1:32 switch and one of 4 VCSEL laser diodes is to be alternatively excited using 1:4 SP4T switch, as shown in Fig. 1b. Amplitude and phase of the modulated NIR is impacted by passing through the brain (diffused medium) and is then collected by optical receivers at any of 22 possible locations using SPMT. The information from these receivers is then averaged over 50MHz of frequency bandwidth using an FPGA and then provided to the remoting unit at a medium data rate [7].

## II. Custom Optical System Design And Modeling

The helmet mounted fNIR system is envisioned to have 18 optical transmitters and 22 optical receivers mounted in strategic locations on a helmet, which is in physical contact with head. Each optical transmitter module consists of four wavelengths VCSEL, along with a SP4T switch, and laser driver to provide RF modulation to a corresponding NIR VCSEL. A SP32T switch using a corporate feed network of SPDT switches is designed to provide isolation between various optical transmitters. These switches are in interface with the custom designed UWB receiver. The SP32T switch for separating the input RF signal to the individual optical transmitters unit is designed for Insertion Loss of 4.9 dB and isolation of 61dB at the operating frequency of 1GHz. The power consumption for this switch is set to 64mW.

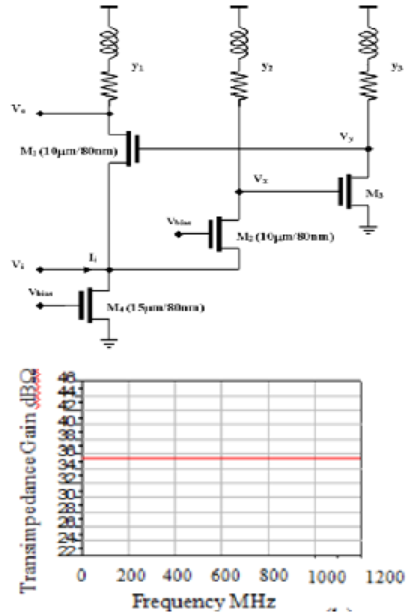
A laser driver IC is also designed to provide 11mA DC bias current and 3mA RF modulating current to each individual VCSEL mounted in a TO-39 can. Schematic of the laser diode extracted from best fitting of the measured and simulated reflection coefficient of VCSEL is depicted in Fig. 2a. The schematic of the optimum laser driver is shown in Fig 2b using the IBM 90nm NMOS. The SP4T switch with IL of 3.7 dB and isolation of 45 dB at 1GHz is designed for integration with the laser driver IC in the TO can. The power consumption all the device is 30mW.




(a) (b)

Fig. 2. a) Equivalent circuit model of VCSEL. b) Circuit schematic of laser driver for 11mA DC and 3mA RF currents.

The optical receiver consists of a GRIN lens integrated to a TO-39 can along with a PIN photodiode integrated with a transimpedance amplifier (TIA) to provide the required gain to compensate for optical loss through skull, CSF, and cortex of about 50dB for source-detector separation distance of about 2cm. Transimpedance amplifier has been implemented in a single ended configuration using 90nm CMOS. In conventional regulated cascade (RGC) [12-13] topology the headroom of two gate–source voltages and one gate–source plus one drain–source saturation voltage at the circuit node are required. Two gate–source voltages exceed the voltage supply limit of 1 V, if the transistors are biased at least at half the supply limit. The biasing of the transistors could be decreased to fit into the 1-V supply limit. The drawbacks of regulated cascade can be overcome by using a common gate feed forward [14] TIA topology shown in Fig 3. It is a simple modification of RGC, where a transistor M2 has been inserted, which acts as a pass transistor and shifts the gate voltage of M3 to a higher level. This circumvents the problem of conventional RGC, which requires two transistor gate–source voltages at the node. By introducing M2, all amplifying transistors can be biased at a gate–source and a drain– source voltage equal to or higher than 0.5 V. The implemented TIA is a common gate topology with a gain-enhancing feed forward path and an input-impedance reducing feedback. The predicted TIA gain of 35dBΩ is depicted as a function for frequency in Fig. 3b.




(a)

(b)

Fig. 3. Feed Forward transimpedance amplifier. a) Circuit schematic, b) frequency response for 35dBΩ gain.

Signal to noise ratio (SNR) of free-space optical link through brain is predicted using optical insertion loss and phase calculated from Diffusion equation [8]. The absorption and scattering parameters in skull, CSF, and cortex [9] for different wavelengths are employed. Comparison of expected SNR performance of PIN-TIA and the commonly used APD based optical receivers are compared for an identical optical receiver overall gain. The results are compared in Fig. 4, as the overall direct modulation link performance is product of optical transmitter & receiver gains and the square of the link current transfer function [10]. SNR for the optical receivers using PIN with TIA is similar to APD with TIA thus avoiding high voltage of APD. The overall electrical noise floor of the optical receiver is -70 dBm.

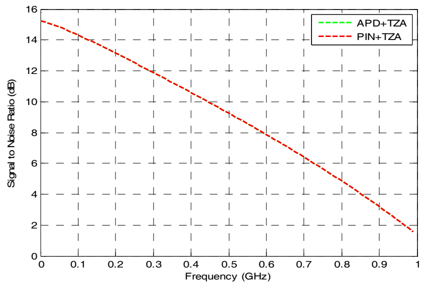



Fig. 4. SNR of the optical link for two different receiver topologies and 2cm separation of optical Tx and Rx.

## III. Wireless System Design And Modeling

A completely mobile and untethered system requires a broadband low power wireless communications system for high speed data transfer. Since the RF input is swept from 30-1000MHz, the bandwidth for communication between monitor and sensor would be around 1000MHz. The optimum system architecture, as depicted in block diagram in Fig. 5, is to locally process the received signals of over 30-1000MHz from the optical receivers by performing averaging in time and in frequency every 50MHz as each amplitude and phase data. Therefore, the transmission rate reduces to 50Mbps. A commercially available wireless communication chip (e.g., Wisair WSR601) is to be employed for wireless communication between the helmet and the remote monitoring. This chip could be operated between 3.1 and 4.8GHz band with a max data throughput of up to 480Mbps. A custom designed ultra wide band communication system with 1GHz bandwidth operating at a center frequency of 5GHz is also designed for communication from the remote unit and the helmet. The system design requirements are based on indoor communications with a path loss exponent of 2.2 and with the anticipated path loss of 50dB over distance of 3m [11]; the wireless system has to be designed for overcoming this wireless path loss. The key components of this wireless data link are based on low noise amplifier, Gilbert cell mixer (GCM) as down-convertor, driver amplifier before passing through the SPMT switch of 1:32.

The low noise amplifier (LNA) is used for amplification of received signal and boosting the signal power level without increasing the noise level significantly at the receiver. It is the first stage of a wireless receiver. Our custom design LNA has a simulated gain of 20dB centered at 5GHz and a noise figure of 1.5dB. The total power consumption of this device is around 100mW.

A Voltage Controlled Oscillator (VCO) is used for providing the fixed LO signal for the Gilbert Cell Mixer. The VCO is designed for an operating frequency of 4501MHz with the output power level of 5dBm. The VCO has a carrier to phase noise level of -52dBc/Hz at an offset frequency of 10 kHz using on-chip passive components for the parallel LC circuit and Q of 5.

The overall system on chip receiver is composed of LNA, VCO, and Gilbert Cell Mixer (GCM). The schematic of GCM [15] is depicted in Fig. 5, where both LO and RF signals are inter mixed to generate base band signal of 30-1000MHz. Optimum mixer design performance goals of 10dB conversion gain and low DSB noise figure of under 2dB and high input IP3 level of at least -10dBm. The achieved performance of the CMOS GCM is a gain of 6dB as compared to a loss of 4dB reported for an HBT based GCM design [16]. The expected performance are for RF frequency of 5 GHz and LO frequency of 4.5 GHz resulting in IF frequency of 500 MHz bandwidth. The single side band noise figure for this GCM design is to be 4dB (1dB of DSB noise figure). The input IP3 value for the mixer was evaluated to be -10dBm with the input 1-dB compression point to be -20dBm. Since the input RF power into the mixer will be around -40 dBm, the effects of gain compression and inter modulation distortion will be about 60dB below fundamental. The power consumption of the mixer is around 20mW.

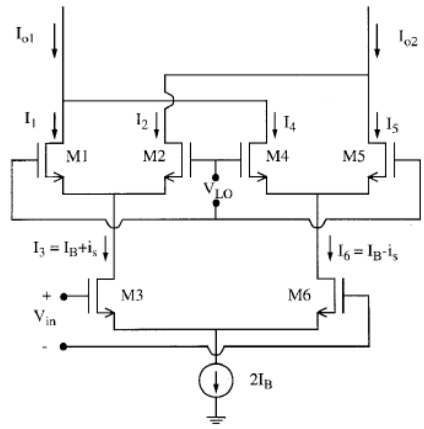



Fig. 5. Schematic of UWB differential GCM.

To achieve optimum □s for the GCM to ensure low noise performance, an inductor of 4nH is used for better admittance matching between GCM and LNA. Since the entire circuit is to be fabricated on a chip, active inductors as shown in [17] are considered for this purpose. The combined GCM-LNA performance shows a gain of 24dB and a combined noise figure of 4dB with the LO input power of 0dBm. The gain variation is 3dB and NF variation is 1dB between the operating frequencies of 4531MHz and 5501MHz RF input frequencies.

The efficiency of the system can be improved using frequency averaging. Thus data over 50MHz of bandwidth can be averaged into a single value of amplitude and phase and then transferred over the wireless system. A Virtex 6 FPGA is considered for this purpose, where a power consumption of 65mW and max operating rate of 5Gbps, are expected. AD9266 ADC from Analog Devices can be used for analog to digital conversion. This 16-bit ADC has 80MSPS with a power dissipation of 66mW.

## IV. Comparison To Minimally Tethered Device

An alternative approach to the wireless communications is a minimally tethered using ultra high-speed interconnection from the remote unit to the helmet. A USB cable connection could provide connections in place of the UWB wireless link and another one for the interface from the local signal processor to the remote unit. The option of storing in a local flash memory and then transferring information to the monitor device using USB interface is also explored to reduce the data rate. The expected throughput for the FPGA is 50Mbps and the total operating time for our device is around one hour. Thus a 32GB flash drive supported by USB 2.0 interface can be used for data storage and then transferring directly to the monitoring device, which is an approach similar to the reported custom designed serial to USB data interface [18]. The total power consumption of the USB device and flash memory is around 50mW. Even though the mobility is to be minimally restricted, but it will reduce the power consumption challenge of wireless communication system.

## V. Conclusion

A high speed wireless system and minimally tethered systems are considered as complement to a free space optical system as a helmet mounted field deployable fNIR brain imaging system. Challenges of the custom designed low power consuming SOC for wireless receiver combined with four optical VCSEL driver and transimpedance amplifier using 90nm CMOS technology from IBM are presented in addition to the comparison of hybrid local signal processor and wireless transmitter or flash memory/USB interface circuits.

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## References

[1] A. C. Merzagora, R. Polikar, M. T. Schulthesis, B. Onaral, "Combined fNIRS and EEG for the assessment of cognitive impairments following traumatic brain injury", *Society of Applied Neuroscience Intl. Conf.* 2008.

[2] F. Irani, S. M. Platek, S. Bunce, A. C. Ruocco, D. Chute, "Functional Near Infra Red Spectroscopy (fNIRS): An Emerging Neuroimaging Technology with Important Applications for the Study of Brain Disorders", *The Clinical Neuropsychologist 21*:9-37,2007.

[3] A. Villringer, U. Dirnagl, "Coupling of brain activity and cerebral blood flow: basis of functional neuroimaging", *Cerebrovasc Brain Metab,* Rev. 1995 fall: 7(3_:240-76.

[4] http://www/hondanews.com/categories/1097/releases/4975.

[5] K. Manseta, E. Sultan, A. M. Khwaja, K. Pourrezaei, A. Joshi, A. Gandgbakhche, A. Daryoush, "Development Challenges of Brain Functional Monitoring using Untethered Broadband Frequency Modulated fNIR System," IEEE *Microwave Photonics Proc.*, Montreal, Canada, Oct. 2010.

[6] K. Manseta, A. M. Khwaja, E. Sultan, K. Pourrezaei, L. Najafizadeh, A. Gandgbakhche, A. Daryoush, "Untethered Helmet Mounted fNIR?" *International Microwave Symposium 2011*, Baltimore June 2011.

[7] A. M. Khwaja, P. Daruwalla, K. Manseta, A. M. Khwaja, K. Pourrezaei, L. Najafizadeh, A. Gandgbakhche, A. Daryoush, "UWB Wireless Link Design and Implementation Challenges in Broadband Frequency Modulated fNIR Biomedical Imaging" *IEEE Radio and Wireless Symposium 2011*, Phoenix AZ, Jan 2011.

[8] Afshin S Daryoush, "*RF and Microwave Photonics in Biomedical Applications*," Microwave Photonics, Stavros Iezekiel, Ed, Chapter 13, Wiley & Sons, UK, 2009.

[9] F. Bevilacqua, D. Piguet, P. Marquet, J. D. Gross, B. J. Tromberg, C. Depeursinge, "In vivo Local Determination of Tissue Optical Properties: Applications to Human Brain", *Appl. Opt.* 38 (22), pp 4939-4950 (1999).

[10] A. Daryoush, E. Ackerman, N. Samant, S. Wanuga and D. Kasamset, "Interfaces for high-speed Fiber-optic Links: Analysis and Experiments," *IEEE Transactions on Microwave Theory and Techniques*, vol. 39, no. 12, December 1991.

[11] J. Proakis, "*Digital Communications*", 4th Edition, McGraw Hill Publications.

[12] S. M. Park and C. Tournazou, "Low Noise current-mode Transimpedance Amplifier for giga-bit optical communication," *Proc IEEE Int. Symp. Circuits and Systems (ISCAS)*, vol. 1, June 1998, pp. 293-296.

[13] J. Lee, S-J Song, S. M. Park, C-M Nam, Y-S Kwon and H-J Yoo, "A multichip on oxide 1 Gbps 80 dB fully differential CMOS trans impedance amplifier for optical interconnect applications," *IEEE Int. Solid-State Circuits Conf. (ISSCC) Dig. Tech. Papers*, Feb 2002, pp. 80-81.

[14] C. Kromer, G. Sialm, T. Morf, M. L. Schmatz, F. Ellinger, D. Erni, H. Jackel, "A low-power 20GHz 52-dB Transimpedance Amplifier in 80-nm CMOS," *IEEE Journal of Solid-State Circuits*, Vol. 39, No. 6, June 2004 885.

[15] M. Terrovitis and R. Meyer, "Noise in Current-Commutating CMOS Mixers," *IEEE Journal of Solid State Circuits*, Vol. 34, No. 6, June 1999.

[16] A. M. Khwaja, P. Miranda, C. Hinton, V. Mistry, S. Garg, A. Sharma and A. S. Daryoush, "Ultra Wide Band System Realization for 4x4 MIMO Test Bed," *IEEE Radio and Wireless Symposium 2010*, New Orleans, Jan 2010 Pp 508-511.

[17] U. Rohde and A. Poddar, "Active Inductor Oscillators and Noise Dynamics", *IEEE International Microwave Symposium 2011*, Baltimore June 2011.

[18] F. A. Jolfaei, N. Mohammedizadeh, M. Sadri and F. FaniSani, "High Speed USB 2.0 Interface for FPGA Based Embedded Systems," *Int. Conf on Embedded and Multimedia Computing*, South Korea 2009.