FINAL PROGRESS REPORT
ON

Wireless Optical Fiber Sensor Network (WOFSNet) for Methane

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Technical Monitor:
Dr. Viji Potula
vpotula@cdc.gov

Submitted by

WADDAN SYSTEMS
8801 Encino Avenue
Northridge, CA 91325

Dr. Shelly John Mechery
Principal Investigator
sjmechery@waddansystems.com
Phone No. (661)-257-5741

Dr. Mahendra Singh
President, Waddan Systems
Co-investigator
mahendra@waddansystems.com
Phone No. (661)-257-4172

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ABBREVIATIONS AND ACRONYMS

AC	Alternating Current
WOFSNet	Wireless Optical Fiber Sensor Network
AtoD	Analog to Digital
BDM	Background Debug Mode
BOE	Buffered Oxide Etch
CAD	Computer Aided Design
CCD	Charge Couple Device
CD	Compact Disk
CGI	Combustible Gas Indicator
CPU	Central Processing Unit
DC	Direct Current
DMA	Direct Memory Access
DVI	Digital Video Interface
FFT	Fast Fourier Transform
GSB	Gas Sensing Box
GUI	Graphics User Interface
IC	Integrated Circuit
ICP	In-Circuit Programming
IF	Intermediate Frequency
IOC	Integrated Optics Chip
ISM	Industrial Scientific Medical
KOH	Potassium Hydroxide
LD	Laser Diode
LDAR	Leak Detection and Repair
LNG	Liquefied Natural Gas
MCU	Micro Controller Unit
MD	Monitoring Diode
MSP	Methane Sensor Pack

OS	Operating System
PC	Personal Computer
PCB	Printed Circuit Board
PCI	Peripheral Component Interconnect
PR	Photo-resist
QCL	Quantum Cascade Laser
RAM	Random Access Memory
RMLD	Remote Methane Leak Detector
SBIR	Small Business Innovation Research Program
SLR	Single Lens Reflex
SMD	Surface Mount Device
SPI	Serial Peripheral Interface
TDLAS	Tunable Diode Laser Absorption Spectroscopy
TEC	Thermo-Electric-Cooler
TEOS	Tetra Ethyl Ortho Silicate
USB	Universal Serial Bus
WOFSNet	Wireless Optical Fiber Sensor Network

ABSTRACT PAGE

Title: Wireless Optical Fiber Sensor Network (WOFSNet) for Methane
Investigator: Shelly John Mechery, Waddan Systems, 8801 Encino Avenue, Northridge, CA 91325 (Email: sjmechery@waddansystems.com)
Affiliation: Waddan Systems, Micro-Optics Sensors
State: CA
Telephone: (661) 257-5741
Award Number: 1R43OH010010-01
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Final Report Abstract:

In recent years, accidental explosions in coal mines have become a major cause of fatality among coal mine workers worldwide. Explosions in underground mines and at the surface processing facilities are mainly caused by accumulations of flammable gases such as methane (CH_4) and/or combustible dust in the presence of an ignition source. In United States, the number of fatal occupational injuries are highest in mining industry compared to agriculture and construction jobs (eg. 23.5 per 100,000 workers). Apart from coal mines, methane gas is one of the main constituents of natural gas so its detection is a subject of major importance. Energy consumption is another major source of methane emission. Worldwide, energy consumption is projected to rise 60% over the next 20 years, and use of oil is projected to increase by approximately 40%. Studies have shown that the combustion of coal, oil, and natural gas has increased carbon emissions globally from 1.6 billion tons in 1950 to 6.3 billion tons in 2000. Accurate sensing of CH_4 at trace levels promises potential benefits to many fronts and various safety monitoring applications. The Phase I project goal has been to develop a wireless sensor for the trace detection of methane gas using Waddan Systems' nanoporous active medium technology. In this project, Waddan Systems' approach for developing a nanoporous active medium gas absorption cell enables enhanced sensitivity, employs larger surface area of the sensing medium and direct absorption of light confined through the porous glass medium. Waddan Systems' unique signal processing approach not only eliminates the noise elements from the sensor, but also enhances the signal detection levels.

In Phase I, a wavelength modulated sensor using a Laser Diode emitting at 1650 nm was assembled. The modulated light was introduced into a specially designed active fiber form directly via a lens. The motivation for this project is to develop a low-cost, wireless, highly miniaturized methane sensor pack (MSP) utilizing Waddan Systems' expertise in integrated optic chip (IOC) and micromolding technologies. The ultimate goal is to develop miniature sensors that can be distributed throughout mine at strategic locations including Miner's clothes, helmet, and operating mining machines. In addition to receiving the methane level information locally, a miner can also receive a video mapping of methane distribution throughout the mine. The MSP devices can be remotely programmed for reconfiguration of the network, e.g. making some of them behave as relay node. The MSP is being designed with a goal to operate maintenance free for several years; and will have the capability for the long-term measurement of methane (CH_4) gas at sub parts-per-million (ppm) levels.

SECTION 1 (Final Report)

Grant Number: 1R43OH010010-01

Project Title: Wireless Optical Fiber Sensor Network (WOFSNet) for Methane

Firm: WADDAN SYSTEMS

This is the final report of the research and developmental activities performed by Waddan Systems from September 01, 2011 to February 29, 2012 for the Centers for Disease Control and Prevention for an award of a Phase I Grant No. 1R43OH010010-01**,** under the Small Business Innovation Research Program (SBIR). The main objectives of Waddan Systems' Phase I research work were to develop technology for a wireless opto-sensor network for the trace detection of methane gas in coal mines and other hazardous industrial sites.

Significant (Key) Findings:

During Phase I, Waddan Systems investigated and developed a micromachined based optical sensing technology for trace detection of methane gas. The work proved the feasibility of a small methane sensing package (MSP) and a wireless sensing network that can be safely employed in a coal mine to monitor the pockets of methane gas. The key findings of this initial works are as follows:

a) The sol-gel based micromolding process can form optical sensing structures practically of any desired shape. It is limited only by the mold shape one can make for filling the sol-gel. In Phase I, sensing mediums like round optical fibers and rectangular wave guides in micromachined chips were successfully built.
b) Experimentally determined that light in a porous medium can be absorbed by diffusing methane gas, and the measure of optical attenuation provides the level of methane present. The simple test set-up showed the feasibility of the sensing concept.
c) The sensor sensitivity can be greatly enhanced by increasing the gas interacting structural volume. For fibers it can be done simply by bundling longer lengths in loops. In micromachined structures, this can be achieved by enlarging the gas interactive surfaces, as was done in a test chip.
d) Actual electronic assembly packaging, with modern small scale assembly techniques such as those used for cell phones, an MSP with a very small foot print can be built.
e) The existing ZibBee sensor network protocol provides the best networking option for the WOFSNet. A battery operated MSP can sleep for a long time with trickle power consumption, and wakeup at designated intervals to measure, relay or transmit data to host device.
f) Power management schemes can significantly extend the battery life as even during the active mode, the MSP stays awake only for 2 to 3% of the time during each measurement cycle.
g) It is feasible to manufacture a low cost WOFSNet using commercially available electronics ICs used for many different applications along with the sensors described in item # a) above.
h) The highly integrated ICs—one sensor support IC, one microcontroller, one regulator, one transceiver— will yield a compact device with very small foot print 30 mmX30 mm (1.2 in.X1.2 in).
i) The estimated low price of the MSP at $75 per unit will open the door for many other gas sensing applications.
j) The system can be adapted without any mod for many commercial test applications.

By identifying unsafe locations in a mine through video mapping displays, the network will create a safer working environment, and reduce fatal trappings and accidents.

Translation of Findings:

In recent years, accidental explosions in coal mines have become a major cause of fatality among coal mine workers worldwide. Explosions in underground mines and at the surface processing facilities are mainly caused by accumulations of flammable gases such as methane and/or combustible dust in the presence of an ignition source. In United States, the number of fatal occupational injuries are the highest in mining industry compared to agriculture and construction jobs. Methane is also one of the main constituents of natural gas, which is increasingly being used in the U.S. for power generation. Thus, a method of its detection and distribution at a work site is a matter of major importance. The WOFSNet being developed by Waddan Systems will provide a safe and reliable method of detecting methane and other combustible gases in coal mines and power plants. The timely detection and subsequent safety measures taken by miners themselves and the safety staff can avoid many disasters.

Moreover, the technology being developed under this program is not limited to detecting methane alone. Using different optical wave lengths, detection of other gases like hydrogen, carbon dioxide, ammonia, chlorine etc can be included in future in the same small sensing package, thus, making WOFSNet a multi-gas sensing network—in other words a general gas monitoring network. With mass production and cost reduction such a network eventually an replace the common household smoke detector or carbon mono-oxide detector.

Outcomes/Imapct:

The sensors in WOFSNet will be able to measure methane gas at trace levels, and immediately warn (audibly and/or visibly) miners about dangerous conditions within or prior to entering potentially hazardous areas. The network will be essentially a monitoring network, continuously preparing a mapping of the methane (other gases to be included in future) distribution throughout the mine. It would display a real-time distribution of methane at a Safety Control Room. Whenever the levels are higher than the safe limits in a zone, the lead miner or supervisor would be warned on his hand held communication device. This system when implemented in mines and power plants will keep workers out of the potentially hazardous zones, prevent fires and save lives, thus, aiding in occupational safety and health of the miners and fire-fighting crews.

Its deployment in mines will also be attractive to mine operators. Its lower cost and low maintenance will be a great incentive to the mining companies to install it, as it will save them insurance costs, litigation costs, operational shut downs, mine damage etc in the long run.

The new sensor and assembly technologies will help the U.S. economy by generating high paying jobs.

SECTION 2 (Final Report)

PROJECT SUMMARY

Firm: Waddan Systems

Grant Number: 1R43OH010010-01

Project Title: Wireless Optical Fiber Sensor Network (WOFSNet) for Methane

Abstract:

This is the final report of the research and developmental activities performed by Waddan Systems for the Centers for Disease Control and Prevention for an award of a Phase I Grant No. 1R43OH010010-01**,** under the Small Business Innovation Research Program (SBIR). The main objectives of Waddan Systems' Phase I research work were to develop technology for a wireless optical fiber sensor network (WOFSNet) for the trace detection of methane gas. The underlying principle of WOFSNet gas sensor system is based on optical attenuation of second overtone line of methane gas in a nanoporous active medium as sensor element utilizing wavelength modulation spectroscopy. The final report covers a detailed description of the design and fabrication work performed during the Phase I award period from September 01, 2011 to February 29, 2012.

Identification and Significance of Innovation:

In recent years, accidental explosions in coal mines have become a major cause of fatality among coal mine workers worldwide. Explosions in underground mines and at the surface processing facilities are mainly caused by accumulations of flammable gases such as methane (CH_4) and/or combustible dust in the presence of an ignition source. In United States, the number of fatal occupational injuries are highest in mining industry compared to agriculture and construction jobs (eg. 23.5 per 100,000 workers). Apart from coal mines, methane gas is one of the main constituents of natural gas so its detection is a subject of major importance. Energy consumption is another major source of methane emission. Worldwide, energy consumption is projected to rise 60% over the next 20 years, and use of oil is projected to increase by approximately 40%. Studies have shown that the combustion of coal, oil, and natural gas has increased carbon emissions globally from 1.6 billion tons in 1950 to 6.3 billion tons in 2000. Accurate sensing of CH_4 at trace levels promises potential benefits to many fronts and various safety monitoring applications. The Phase I project goal has been to develop a wireless sensor for the trace detection of methane gas using Waddan Systems' nanoporous active medium technology. In this project, Waddan Systems' approach for developing a nanoporous active medium gas absorption cell enables enhanced sensitivity, emulating the long optical path of multipass gas cell designs such as White cells or Herriot cells. The larger surface area of the sensing medium and direct absorption of light confined through the porous glass medium increases the detection sensitivity. The direct interaction between the light and gas in the active medium with the wavelength modulation sensing mechanism increases the sensitivity of the sensor device. Waddan Systems' unique signal processing approach not only eliminates the noise elements from the sensor, but also enhances the signal detection levels. We have designed a unique electronic demodulation circuit to extract the first and second harmonic modulated signal with high accuracy.

In Phase I project period, a wavelength modulated sensor using a Laser Diode emitting at 1650 nm was assembled. The modulated light was introduced into a specially designed active fiber form directly via a lens. Application of nanoporous materials enables permeation of methane into the optical structure, thus providing a much higher interaction of the guided light with the gas being sensed. This final report details the Phase I work completed by Waddan Systems. The motivation for this project is to develop a low-cost, wireless, highly miniaturized methane sensor pack (MSP) utilizing Waddan Systems' expertise in integrated optic chip (IOC) and micromolding technologies. The ultimate goal is to develop miniature sensors that can be distributed throughout mine at strategic locations as well as integrated in Miner's clothes, or mounted onto a helmet, or on operating mining machines. In addition to receiving the methane level information locally, a miner can also receive a video mapping of methane distribution throughout the mine. The MSP devices can be remotely programmed for reconfiguration of the network, e.g. making some of them behave as relay node. The MSP is being designed with a goal to operate maintenance free for several years (3 to 5 yrs); and will have the capability for the long-term measurement of methane (CH_4) gas at sub parts-per-million (ppm) levels.

Technical Objectives and Work Plan:

The objectives of the project are to establish the feasibility of developing a wire-less, highly miniaturized methane sensor pack (MSP) utilizing Waddan Systems' expertise in integrated optical chip (IOC). Demonstrate ability of accurate and sensitive detection of methane gas in air utilizing wavelength modulation spectroscopy with our WOFSNet design. Demonstrate the proof-of-principle, the optical attenuation of second overtone line of methane gas in a nanoporous active fiber core sensor element utilizing wavelength modulation spectroscopy.

The major tasks performed include:

1. Construction of sensor chip –
   - (i) Development of the nanoporous active fiber waveguide
   - (ii) Development of silicon waveguides integrated with nanoporous rectangular active wave channel
   - (iii) Packaging of these structures in a miniature MSP board design
2. Development of the working model for feasibility study
   - (i) Development of the wavelength modulation of Laser Diode emitting at 1650 nm – design the circuit
   - (ii) Development of demodulation circuit and design electronic circuits to extract the first and second harmonic modulated signal with high accuracy
   - (iii) Performed experiments with nanoporous active fiber core and silicon chip
3. Evaluation of the sensor performance.

Technical Accomplishments:

During Phase I, Waddan Systems has accomplished the following:

1. Constructed a Wavelength Modulated Fiber Optic Sensor System.
2. Developed a procedure to micromold nanoporous active media using the sol-gel approach.
3. Evaluated the Performance of the WOFSNet: Evaluated the sensors for absorption response on exposing 5% methane mixed in nitrogen.

1.0 INTRODUCTION

This document is the Final Research Report of the NIH/CDC SBIR Phase I Grant No. 1R43OH010010. It deals with the development of a Wireless Optical Fiber Sensor Network (WOFSNet). It was sponsored by the Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. It summarizes the work done by Waddan Systems under the grant. The main objective of Waddan Systems' Phase I research were to demonstrate the feasibility of *a low cost and low power wireless optical fiber sensor network* (WOFSNet) for the trace detection and mapping of methane gas.

1.1 Hazard Gas Sensing Problem

Historically, coal mining has been a very dangerous activity. Major mining hazards include suffocation, gas poisoning, roof collapse and gas explosions. Explosions and the resulting fires often kill or trap workers and threaten workers underground. One of the greatest hazards faced by coal miners is the ignition of methane (CH_4) gas. So it is extremely important to detect the build-ups of this hazardous gas. There is a great demand for a technology that will be able to measure methane gas as well as immediately warn (audibly and/or visibly) miners about dangerous conditions within or prior to entering potentially hazardous areas. There are some sensors availabe in the market for methane sensing. Many of these commercially available sensors are nonselective, which means they are often sensitive to most flammable gases and vapors. Combustible gas indicators (CGI) such as Pellistor sensor systems have been the most widely used devices for detecting methane in offshore oil and gas installations. In addition to being costly, these devices are susceptibility to surface poisoning by compounds containing halogens, sulfur, chlorine, and also by materials containing lead and silicon. Metal oxide semiconductor-based gas sensors are another choice for methane detection. Their low sensitivity at temperatures below 350-400^{0}C is a major drawback because CH_4 is thermodynamically more stable than most other reducing gases. Metal oxide sensors also lack stability and selectivity. Infrared Absorption Spectroscopy is another technique for offline detection of molecular species in a gas phase at high resolution. Infrared source based open-path analyzers do not operate well when the windows are wet or icy. Systems such as Picarro's ESP-1000 (utilizing cavity ring down spectroscopy) are very expensive ($45,000) for widespread use. One can also find substantial amount of work to develop gas sensors that utilize nanotubes. Another example for such effort is on tunable diode laser absorption spectroscopy (TDLAS), which is a well established technique for the remote detection of methane gas leaks from pipelines. Optical sensing at the mid-infrared region (2-20 µm), particularly based on Quantum cascade laser (QCL) systems, has been widely reported in literature for methane sensing. Expensive IR transparent fibers are required over traditional long haul optical fibers which are not optically transparent at wavelengths of 2-20 µm. Physical Sciences, Inc. (Andover, MA) has developed an engineering prototype of a handheld sensor. The so-named Remote Methane Leak Detector (RMLD) permits remote detection of methane gas leaks from pipelines using the established optical measurement technology of TDLAS. Smart Leak Detection and Repair system (Smart LDAR) is a modified version of RMLD which enables imaging of leak plumes. However, the major limitation of these mutually related techniques is that the gas plume must be encompassed between the transceiver and topographic scattering surface.

Low maintenance sensors are needed for monitoring multiple locations in a coal mine for a period of several months during mining. Waddan's WOFSNet is being designed to address these concerns. Conceptually shown in Figure 1.1-1, it enables accurate detection and mapping of methane levels wirelessly through out the mine environment. As shown in the figure, a bunch of ultra-miniature methane sensor packs (MSPs) are permanently mounted at key locations (nodes) in the mine. Some MSPs could be embedded in miner's jacket or helmet because these MSPs are expected to weigh less than an ounce. A Host module manages the wireless links to the MSPs. It can actively reconfigure WOFSNet. Some of the MSPs can be commanded to work like relays to transfer data from those having poor RF link to the Host. The Host sends the data received from MSPs to a PC via USB. The PC has the WOFSNet management application running. It addition to providing warning messages, it can also prepare a methane level mapping of the mine and transmit the graphic data to the users. As shown in the figure, the data collection and mapping station can also interface with a central data storage and monitoring facility for several mines.

The MSPs are designed as low cost and low profile devices with unique power management methodology that prolongs their battery life. Most of the time these devices are sleeping; and wakeup only at a designated (programmed) intervals to perform their duty and again go back to sleep. The host module, which is powered by the USB, has full control of the MSPs in the WOFSNet.

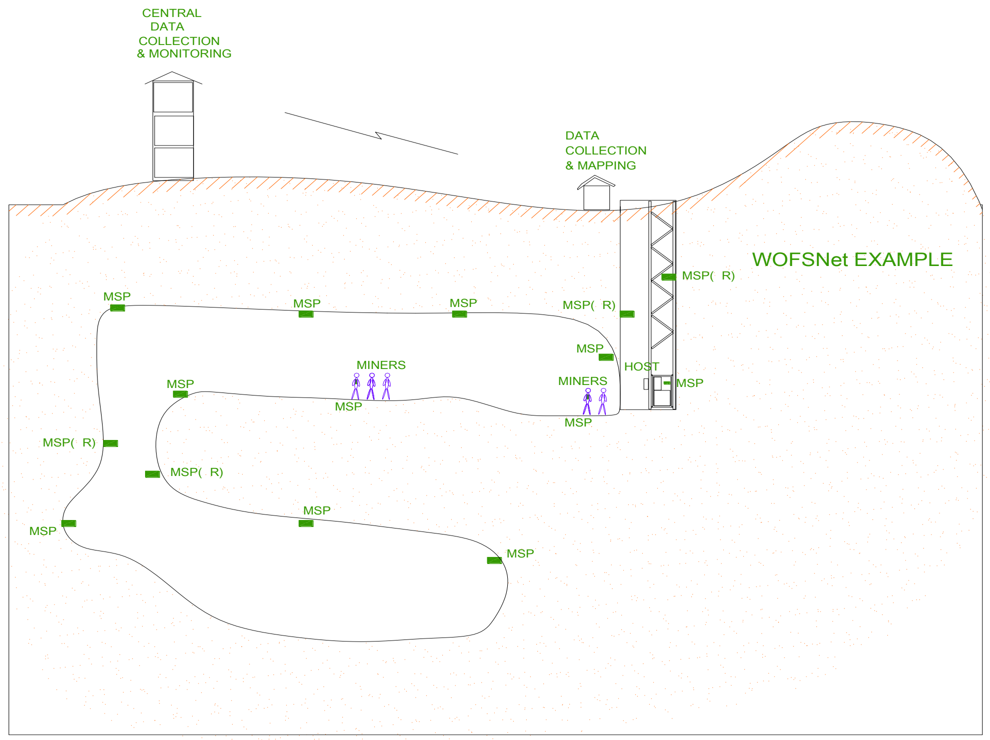


Figure 1.1-1: WOFSNet Concept

There are numerous applications where these MSPs as part of a WOFSNet can be employed. In general, they would be highly suitable for any process control and environmental monitoring applications. In addition to the mines, they can be used in any industrial or medical application where hazardous gasses are involved. Examples include liquefied natural gas (LNG) fired thermal stations, transmission and recovery units of petroleum industries, mines, off-shore drilling platforms, vehicle engines, and in environmental applications such as landfill sites and water treatment plants.

1.2 Methane Sensing Package(MSP)

The feasibility of the multiple aspects the MSP design was evaluated. A process to form the nanoporous optical media in different shapes was developed. This structure is used as a confined region through which the light traverses while interacting with the analyte molecules (CH_4) that diffuse through the nanopores in the medium. Both round and rectangular shaped optical elements were formed to be incorporated in the MSP. An MSP package employing 0603 size surface mount components on a 24mmX48mm fiberglass board was developed. To checkout the assembly process four devices with varied design were assembled by hand soldering under a microscope. To minimize the tedious effort, a computer controlled ramp and soak oven with solder paste dispensed at soldering location can be used for a higher production volumes. Figure 1.2-1 shows one of the four MSP assemblies.

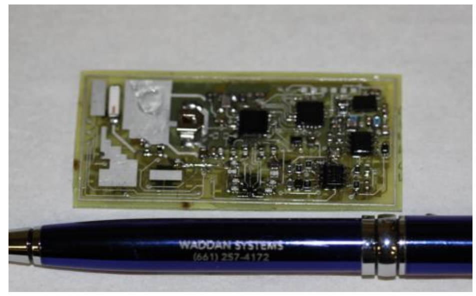


Figure 1.2-1: MSP First Design Iteration Board

The package can be roughly divided into a sensor and an electronic partitions. The sensor partition can be integrally fabricated as a single die using micromachining technology. A trade-off analysis compared three micromachining technologies available at Waddan Systems for forming the sensor structures. The bulk micromachining was found to be the most suitable technology for rugged sensors to be used in a harsh environment. A sensor chip with large surface area to interact with CH_4 was designed. A block diagram of the electronic partition functions necessary for MSP is shown in Figure 1.2-2.

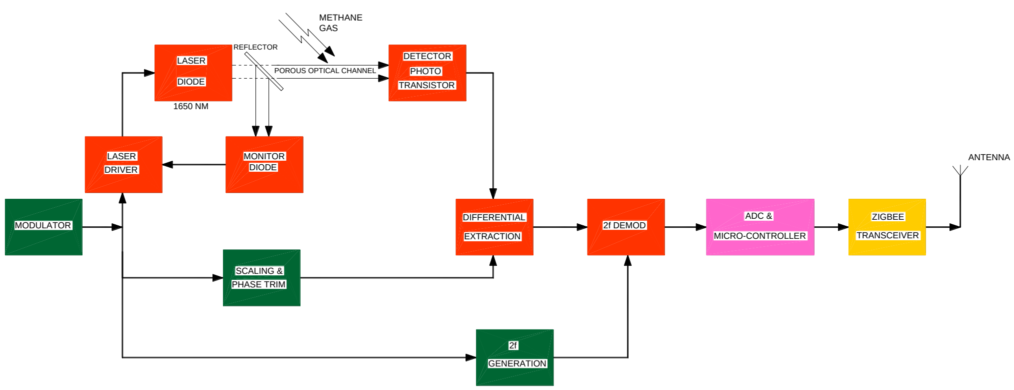


Figure 1.2-2: Block Diagram Of Methane Sensor Pack (MSP)

The analog portion of the circuit implements a modulator, a laser driver, a detector, a differential extractor and a 2*f* demodulator using mostly dual op amps. A microcontroller incorporating 8 channel AtoD converter was selected for handling the sensor data. After comparing short haul networks, ZigBee networking was selected over Bluetooth for wireless transfer of the sensor data form MSP nodes to the Host. The MSP was designed with a background debug mode (BDM) interface for in-circuit-programming (ICP) the microcontroller for its MSP functions.

Although, the current design of the MSP is only for measuring methane levels, the concept and the hardware by no means are limited to measuring only one gas. In future, by integrating sensing structures for other gases, up to seven more gases can be measured without making any changes in the microcontroller or transceiver part of MSP electronics. As WOFSNet evolves, more sensors will be added to the MSP.

1.3 WOFSNet

A comparison of various wireless networks with existing silicon was made. Only ZigBee and Bluetooth are suitable for WOFSNet like applications. Out of these two, ZigBee is a clear winner for WOFSNet because of its features. It is a low power, flexible and longer range alternative. Details of the trade-off analysis are included in Section 4.2.2.

The ZigBee network also allows the capability of active reconfiguration of the network. An example of an active cluster configuration is illustrated in Figure 1.3-1. It could cluster the MSPs in one region of the mine e.g. the bottom cell into a smaller network called Piconet C. The Piconets in turn are interconnected through relay nodes to form a Scatternet encompassing all the MSPs, the relay nodes, and the Host module.

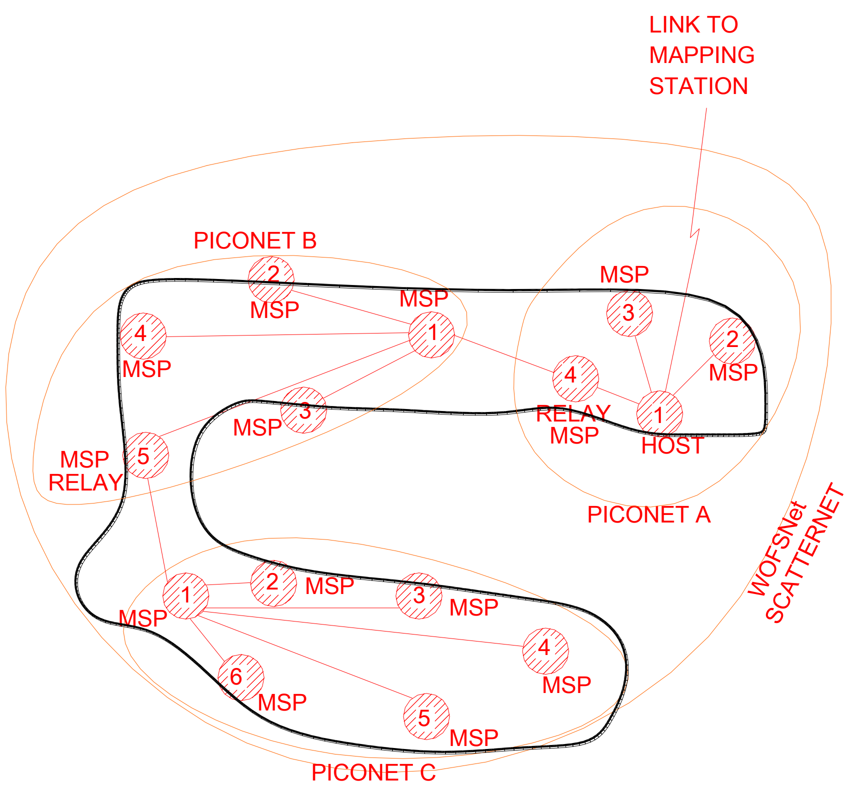
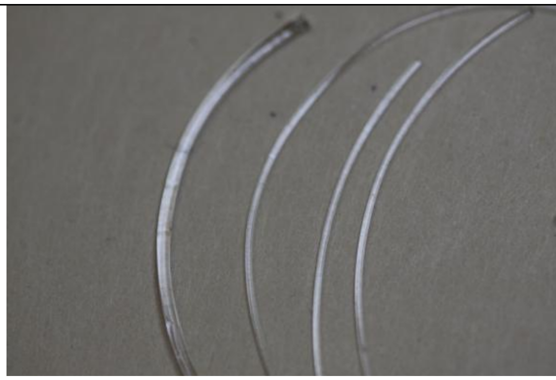


Figure 1.3-1: Active WOFSNet Nodal Networking Scheme

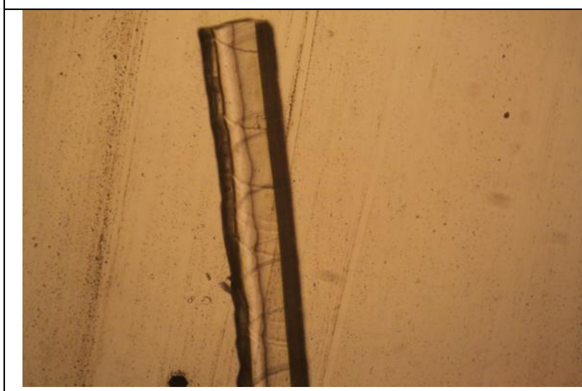
1.4 Initial Characterization of Phase I Structures and Modules

Figure 1.4-1 shows the samples of the structures built using micromolding technology. The round fibers formed by injecting sol-gel in Teflon tubes of different gages are shown in top left photo (a). The integrated optics chip (IOC) form micromachined in <110> silicon with rectangular (30µmX260µm) cross-section is shown in photo (b). The laser output, edge launched into a 100µm channel, is split into nine parallel waveguides, where it interacts with methane gas molecules, and finally recombines into another 100µm channel and exits for detection. The channels aligned along the silicon orientation (111) have the wall surface roughness less than 25 nm (0.025 µm), resulting due to etching along crystal planes. The channel molds are filled with sol-gel.

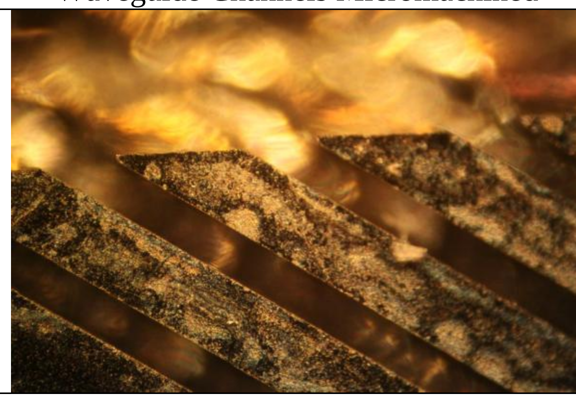


(a) Round Molded Fibers of Different Diameters

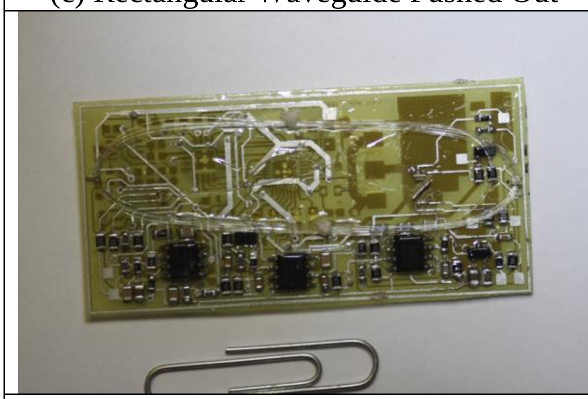
(b) Nine Rectangular (30µmX260µm) Waveguide Channels Micromachined



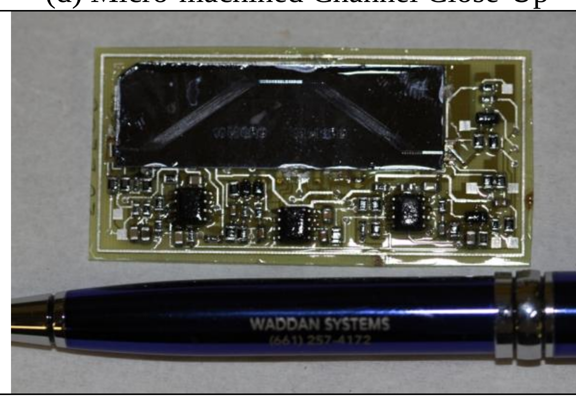
(c) Rectangular Waveguide Pushed Out



(d) Micro-machined Channel Close-Up



(e) MSP Sensor Side with Oval Shape Fiber Bundle Sensor



(f) MSP Sensor Side with Rectangular IOC Sensor

Figure 1.4-1: Photographs of the Processed Structures and Modules

A microscope close-up view of these micromachined channels, where the light splits, is shown in photo (d). The microscope photo (c) shows the structure of a sol-gel made rectangular waveguide, which was pushed out of the channel to photograph. The top side photo of the MSP containing ICs for demod, microcontroller, ZigBee transceiver and the antenna was shown in Figure 1.2-1. The bottom side photo of an MSP with a porous sensing fiber bundle is shown in Figure 1.4-1(e). The bottom side photo of an MSP with a porous rectangular waveguide sensor made in micromachined channels is shown in Figure 1.4-1(f).

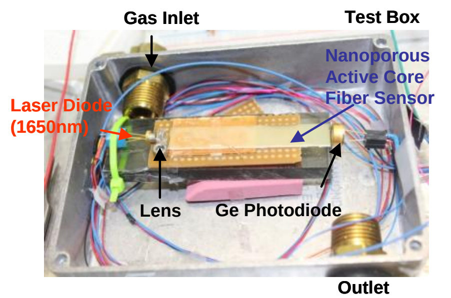


Figure 1.4-2: Methane Sensing Test Box

Using a short length of the fiber shown in Figure 1.4-1(a), Waddan has tested the sensing methodology at very low concentration of methane gas and evaluated the sensor performance. For the Phase I feasibility demonstration, the project team fabricated a test box as shown in Figure 1.4-2. It employs a laser diode (emitting 1650 nm light) running at half power, a short length of the nano-porous active core fiber sensor, and a Ge-photodiode as the detector. Methane mixed with Nitrogen at different concentration comes in through the inlet and exits from the outlet. The box has a sealed gasket cover. All the experimental electronics on breadbord is outside the box. The electrical hookup wires pass through a sealed tap shown on the right wall of the box. The laser diode drive current is modulated at the near infrared region corresponding to the second overtone frequency of methane gas. Circuits were also designed with a unique demodulation approach for extracting the first and second harmonic frequencies. By confining the laser output into a porous waveguide, practically the entire output is utilized in sensing purposes. These innovations allow the MSP (and thereby WOFSNet) to accurately monitor CH_4 even at trace levels. Thus, with low cost and low power, WOFSNet promises significant benefits to various applications of safety monitoring.

2.0 PHASE I TECHNICAL OBJECTIVE

The primary objective of this effort was to develop a WOFSNet employing state-of-the-art technologies to significantly improve the measurement hardware and methodologies currently available for methane gas detection in mines. The specific objective of the Phase I effort was to demonstrate the feasibility of such a system by technical analyses, experimentation and trade-off studies, and to provide a recommended design to build a true scale WOFSNet for evaluation during Phase II.

The first objective of the Phase I effort was to establish by sol-gel experimentation that a nanoporous optical media could be formed that would act as an optical sensor for methane gas. The sensing concept is based on the optical absorption phenomenon of second overtone line of methane gas by utilizing wavelength modulation spectroscopy technique. The ZigBee wireless transceivers from Freescale Semiconductors and Texas Instrument were tested. The results show that it is feasible to build a WOFSNet system using commercially available low power electronics along with a tailor-made nanoporous sensing element. The MSP hardware shown in Figure 1.2-1 reflects that a small and thin device can be built for a methane sensing network in mines. The experimentation also established that the sol-gel can be filled into many different miniature forms or molds, and polymerized as glass forms in those shapes. The resulting forms inherently contain nanopores which would allow gases to permeate through.

The second objective was to demonstrate experimentally that methane levels can be detected using the nanoporous forms. Methane has two absorption bands corresponding to wavelengths 1.33μm and 1.65μm, the latter being more prominent. For the experiment, a test station for safely handling methane gas at low levels was constructed. Analog electronics for modulating a laser emitting at 1.65μm and demodulating the absorption information was developed. The absorption characteristics of the methane gas were observed on a scope, and the delta change of the demodulated signal was measured.

Thus, both the objectives were successfully met during Phase I of the effort, The experimentation also established that very small sensing structures could be formed in micro cavities; and small form factor electronics can be assembled for a low maintenance, low power and low cost WOFSNet.

In Phase II, many other parameters of the sensing structures would be evaluated to optimize the sensor performance. Interfacing effect of the multiple nanoporous media will be investigated. Homogeneity with respect to nanoporous entry points in the sensing material for achieving higher sensitivity will be examined. Last, but not the least, a piezo driven mechanism for dislodging dust from the sensing material will be investigated. This method is already being used for removing dirt from the CCDs in high end SLR cameras.

3.0 PHASE I ACCOMPLISHMENT SUMMARY

The highlights of the Phase I accomplishments are presented here:

a) The sol-gel based micro-molding process of glass structures was established,
b) Micro-molded nanoporous sensing structures as cylindrical and rectangular wave guides were successfully formed. The molding cavities could be either pre-formed (as Teflon tubes) or micromachined cavities for unique structures.
c) A flexible but safe methane gas test station was developed,
d) Sensor test electronics was developed to demonstrate the methane sensing feasibility of the fiber like nanoporous structures. The sensing methodology was successfully demonstrated.
e) For sensor formation trade-off analysis – different micromachining technologies were compared for WOFSNet application. Based upon the analysis, in Phase I bulk micromachining was adapted for WOFSNet apps.
f) For WOFSNet networking, different short haul networking standards were compared and ZigBee was selected as the preferred technology,
g) First design iteration of MSP functional partitions was finalized. A miniature MSP design was developed. An integrated sensor design was adapted for MSP. The electronics for sensing, AtoD conversion, data processing and wireless communication were miniaturized.
h) Host Module functional partitions were finalized for wireless communication, data processing and USB interface control.
i) Four different MSP assembles were made during Phase I. Two and four layer board constructions were compared. Both types of sensing structures—oval fiber bundle and rectangular wave guides—were integrated with MSP boards.
j) Masks for Integrated Optics Sensor Processing were designed and built.
k) ZigBee hardware from Freescale Semiconductors and Texas Instruments were evaluated. Temperature measurements from five nodes were transmitted to the host module connected to a laptop PC displaying the data received.
l) Host management computer designs were analyzed for WOFSNet application,
m) Preliminary design of the Host management GUI for WOFSNet application was completed.
n) Electronics for the Test Station, the MSP and the Host module were designed (See schematics in Appendix B)
o) Two different types of antenna configurations were designed—single chip antenna with a switch for MSP, and a dual printed circuit antenna for the Host.

These accomplishments show that it is feasible to employ ZigBee networking standard along with the nanoporous sensing media technology to yield the proposed WOFSNet.

4.0 WOFSNet Package Development

The trade-off analyses, hardware experimentation and the first design iteration of WOFSNet completed during Phase I are briefly described in the following subsections.

4.1 WOFSNet Description

The WOFSNet consists of three different types of hardware as shown in Figure 4.1-1. A number of MSPs are mounted at key locations on the mine where measurements are to be taken. An MSP senses the measurand (the current design is for methane gas), digitizes the measured value and transmits the converted data to the Host module. The Host module performs multiple tasks. It controls the network, receives data from, and transmits control commands to the MSPs, and communicates with the Host Management Computer over the USB interface. The Host Management Computer is a standard PC running the WOFSNet application for data collection, storage, and reconfiguration of the WOFSNet if necessary. A brief description of these components is provided in the following sub-sections.

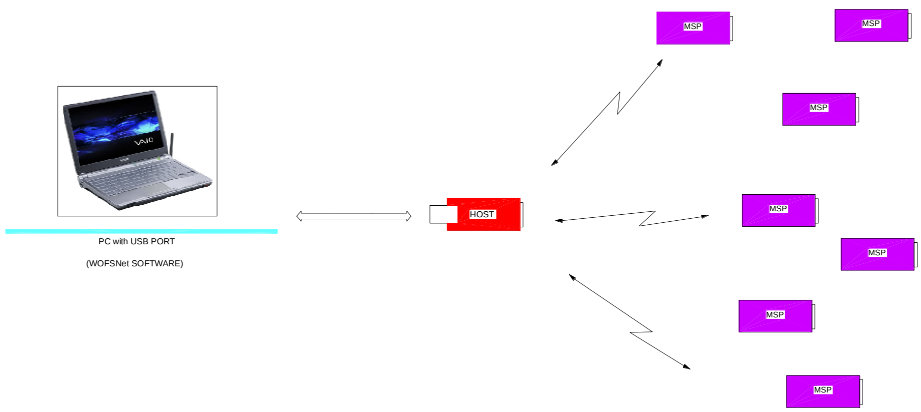


Figure 4.1-1: WOFSNet Hardware Components

4.1.1 MSP Module

A block diagram of the MSP with its main functional elements is shown in Figure 4.1.1-1. It includes a row of sensors providing analog outputs proportional to the trace gases being measured. It also shows the AtoD converters, preferably embedded in the microcontroller, digitizing the sensor outputs. A transceiver chip provides wireless communication support. The microcontroller communicates with transceiver chip via a serial interface. The MSP has to be small, low cost and low power unit so that it can work without maintenance (battery replacement) for 3 to 5 years.

The microcontroller employed during the Phase I design iteration is capable to handle up to 8 AtoD channels as shown in the figure, however, the initial design will be for only one gas (Methane), and thus would require only one AtoD channel. The MSP, as it evolves, can ultimately accommodate up to 8 gases without major design mods.

4.1.2 Host Module

This module links and manages all the radio communication with the MSPs. In theory, it can handle up to 2^{64} MSP nodes. The larger the MSP nodes, the lower is the frequency of data updates. The functional block diagram of the module is shown in

Figure 4.1.2-1. It incorporates a microcontroller and a ZigBee transceiver that could talk to all the MSPs, control their power output, put them in an active or a standby or a doze-off or a relay mode, if necessary, and has a DMA channel to store the collected data in the Host management computer.

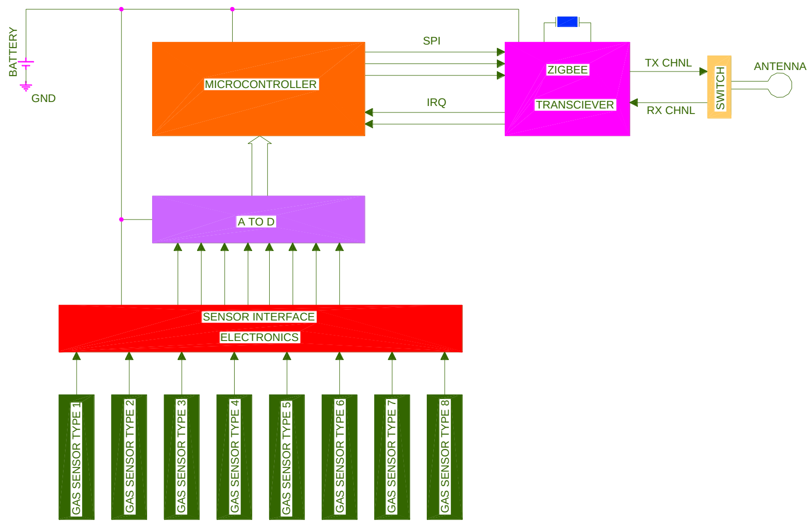


Figure 4.1.1-1: MSP Block Diagram

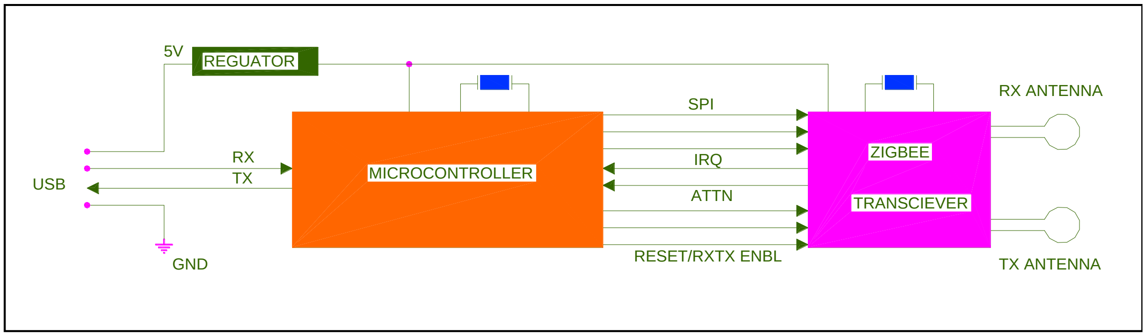


Figure 4.1.2-1: ZigBee Host Module Block Diagram

4.1.3 Host Management Computer

A standard PC with an available USB port can be employed for this function of the WOFSNet. For a field service technician, a small laptop can serve the same function. For configurations where the host needs to be located in tight spaces, a small form factor PC can also be used. Such a small form factor Pico-ITX with a Plugged in Host Module is shown in Figure 4.1.3-1.

4.2 Trade-Off Analyses

Various trade-off analyses were performed to select components for a low cost, extremely low power and feasible WOFSNet design.

Figure 4.1.3-1: Pico-ITX with a Plugged in Host Module

4.2.1 Optical Sensor Design Trade-Off

The underlying principle of the gas sensor involves optical attenuation of the second overtone line due to the gas in a nanoporous active medium. Thus, the sensing mechanism has to have a confined optical path in which the gas molecules can interact with the optical beam. The shape of the sensing medium was obtained by chemical molding technology – an offshoot of Waddan Systems' micromachining technology. Two different forms of optical media were selected for evaluation.

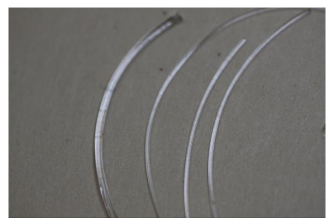


Figure 4.2.1-1: Round Molded Fibers of Different Diameter

In the first case, round fibers were molded by injecting the sol-gel in Teflon tubes used for insulation of hookup wires of different gages. The smallest diameter tube successfully injected for molding the porous fiber during Phase I is of wire gage 30 (255 micron in diameter). Smaller diameter tubes can also be injected by controlling the sol-gel viscosity. The longer lengths of the fiber for higher sensitivity can be obtained by tying the Teflon tube in a form dictated by MSP packaging requirements. Generally larger diameter fibers, although good for optical alignment, were more difficult to handle than the smaller diameter fibers.

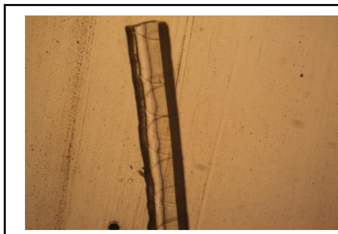


Figure 4.2.1-2: Rectangular Molded Waveguide (X-section 260µmX30µm)

In the second case, porous rectangular wave guides were obtained by filling rectangular channel forms made by micromachining. Since Waddan Systems had three options available for micromachining the rectangular forms, they were compared for making rectangular waveguides. The *bulk micromachining* method employs

Figure 4.2.1-3: Micromachined Rectangular Channels for forming Rectangular Waveguid

the substrate of the wafer as the raw material; and chemical etching, laser trimming and other semiconductor processing methods are used to shape it into a desired form. For smooth wall rectangular grooves, Waddan employs <110> silicon wafers. With properly oriented channel openings, one can obtain smooth high aspect ratio channels. Channels as deep as 300 micros can be routinely obtained by this technology. Deeper dimensions require improved etching methods but are possible to make. By the *surface micromachining* method, the substrate is used merely as a handling device during the processing. The material to form the channels (generally polysilicon) is sputtered or deposited on the substrate in layers along with some sacrificial layers. Since the depth of the channels obtained by this method is limited to about 5 microns, this method is not suitable for building active sensing channels of high aspect ratio. The third method, called *molding* method, also employs a substrate as the handling device during processing. To begin with the substrate is coated with a sacrificial material. A thick photoresist (25 to 50 microns) is used to generate molding cavities using photolithography. Sol-Gel can be filled in the molding channel forms in the photoresist. This method can provide very small sensor channel wave guides, however limited in height to 50 microns. The utility of this method can be further examined later in the development if smaller devices are desired.

Since the MSP has to operate in a harsh environment as an exposed sensor, the bulk micromachining would yield the best structures and features. Rectangular wave guides were built in <110> silicon wafers. In the first iteration (mask design), high aspect ratio channels were obtained by micromachining. The channels dimensions were 10, 20, 30 and 40 microns wide, and 260 microns deep. Thus, the technique resulted in porous waveguides with cross-sections ranging from 10X260 to 40X260 microns.

4.2.2 Bluetooth vs ZigBee

Due to the proliferation of the cellular telephones, there has been a great deal of interest in vendors for designing short haul low power transceivers. The transceiver circuitry has already been reduced to one or two chips which integrate amplifiers, mixers, local oscillator, limiter, IF amplifiers (nearly all the functions between the antenna and baseband, both on receiver as well as transmitter). Different networking standards have also been evolving. A comparison of these approaches is provided in Table 4.2-1.

Table 4.2-1: Comparison of Short Haul Networking Standards

Market Name	**ZigBee**		**Wi-Fi**	**Bluetooth**
stadard	IEEE 802.15.4	GSM/GPRS/CADMA	IEEE 802.11b	IEEE 802.15.1
Application Focus	Monitoring & Control	Wide Area Voice/Data	Web, E-mail, Video	Cable Replacement
System Resources	2KB - 32KB	18MB+	1 MB+	250KB+
Battery Life in Days	100 - 1000+	1 to 7	0.5 to 5	1 to 7
Network Size	2^64(large)	1	32	7
Bandwidth (KB/s)	20 - 250	04 - 128+	11,000+	720
Transmission Range (meters)	1 - 100+	1,000+	1 - 100	1 - 10+
Success Metrics	Reliability, Power, Cost	Reach, Quality	Speed, Flexibility	Cost, Convenience

Source: ZigBee Alliance

From the table it is clear that only Bluetooth and ZigBee networks are suitable for WOFSNet application. Out of these two, ZigBee is a clear winner for WOFSNet because of its features. It is a low power, flexible and longer range alternative. Many different vendors are already providing single chip ZigBee silicon [4-7]. Major vendors such as Texas Instruments [5] (with CC2420 derivatives) and Freescale Semiconductors [4](with MC13191 derivatives) are providing ZigBee evaluation kits, both of which were evaluated. They were comparable, but MC13202 provides more features directly useful to the WOFSNet.

4.2.3 Microcontroller

Low power, high speed, small size, embedded AtoD, ease of interface with wireless networking chip etc are key features necessary in an MSP microcontroller. Again the microcontroller recommended in the Freescale kit was found to be better than the MPC430 utilized by Texas Instrument. So MC9S08QG8 was opted for the MSP. The choice for Host module microcontroller (which receives power via USB from the Host management computer) is not constrained for power or footprint. Any powerful microcontroller with USB and SPI can be used for the Host module.

4.2.4 WOFSNet Management Computer

The choice for the Host management computer is also not very restrictive. Any PC appropriate for mining applications can be used for this purpose.

4.3 MSP Design

The MSP module has to be a light weight, low power and small device, so as not to interfere with the mining operation. Its range has to be as long as possible. Based upon the analyses described in the Section 4.2, a ZigBee based device with nine ICs and a gas sensor is envisioned. A photograph of the two sides of the MSP design developed during Phase I is shown in Figure 4.3-1. The analog portion of the electronics is designed with 5 dual op amps and a single demodulator that provides an analog output proportional to the trace levels of methane gas sensed. The digital portion consists of a microcontroller with built in AtoD converters and a ZigBee transceiver. The current status of the MSP design is described in the following sub-sections.

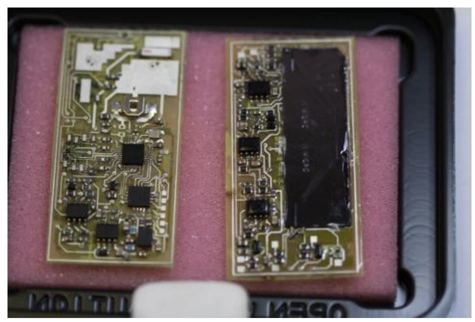


Figure 4.3-1: Two Faces of MSP

4.3.1 Sensor Partitions

A block diagram of the MSP is shown in Figure 4.3.1-1. It can be seen from the diagram that MSP design can be divided into two major partitions – a sensor partition involving optics, and an electronics partition to deal with modulation, data extraction and digitization, and transmission to the host module etc.

The *sensor* partition consists of the following functions:

- Light emitter,
- Nanoporous medium to confine the light in sensitive region
- Detector to measure the light exiting the sensitive region.

The *electronics* partition consists of the following functions:

- Modulator drive for emitter at frequency 1*f*,

- Differential extractor to remove most of the $1f$ information from the detector output,
- $2f$ demodulation of the differentially extracted signal,
- AtoD conversion of the demodulated signal,
- MSP power control,
- Data packet serial transfer to ZigBee transceiver,
- Wireless data interchange with host or another MSP in relay mode.

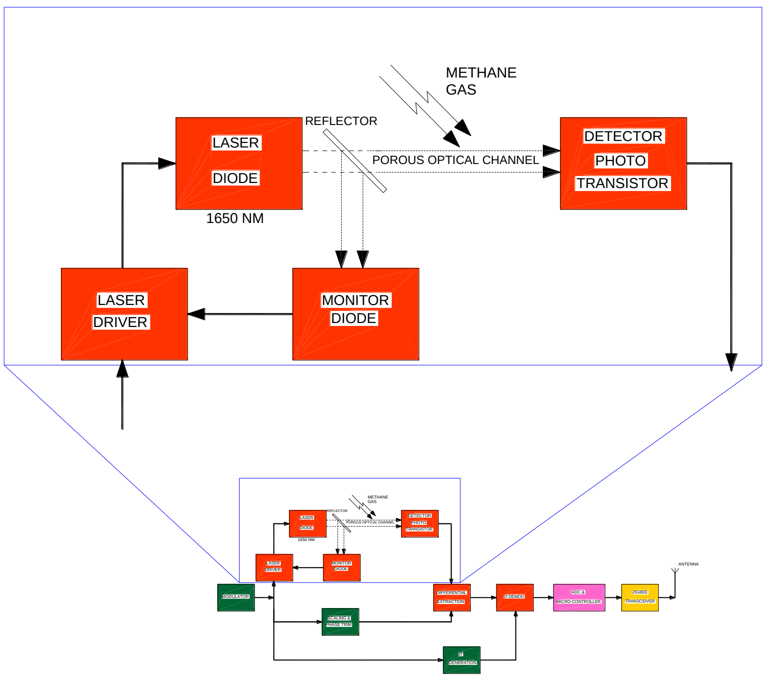


Figure 4.3.1-1: Sensor and Electronics Partitions of MSP

4.3.1.1 Emitter Design

The emitter actually consists of a laser diode (LD) and a monitoring diode (MD). The LD is intentionally *not* run near its full power because that would require the use of a thermo-electric-cooler (TEC). The use of TEC in MSP is undesirable because the MSP has to be a low power device, and TECs are power hungry. To minimize power consumption, the LD is operated at 50% of its maximum output level. The MD collects about 3% of LD output and through feedback maintains the LD output at 50% level.

Figure 4.3.1.1-1 shows the schematic of the LD driver circuit. The first op amp combines the MD feedback and the modulator output, and sends the combined output to the driver op amp, which in turn drives a transistor which provides the drive current to the LD. The circuit is designed to protect the LD from current spikes during turn-on and turn-off sequences. To measure current levels easily during development, a one ohm shunt in series with the current regulating resistor is also provided. The light emitted from the LD is directed into the porous sensing medium. The MSP currently uses a mirrored surface to direct the LD output (approximately 97%) into the sensing fiber bundle or the micro-machined sensing channel waveguide.

Dedicated LD driver ICs are also available. But because of their inflexibility and the non-standard pin out of the LDs on the market, the use of such ICs was discarded.

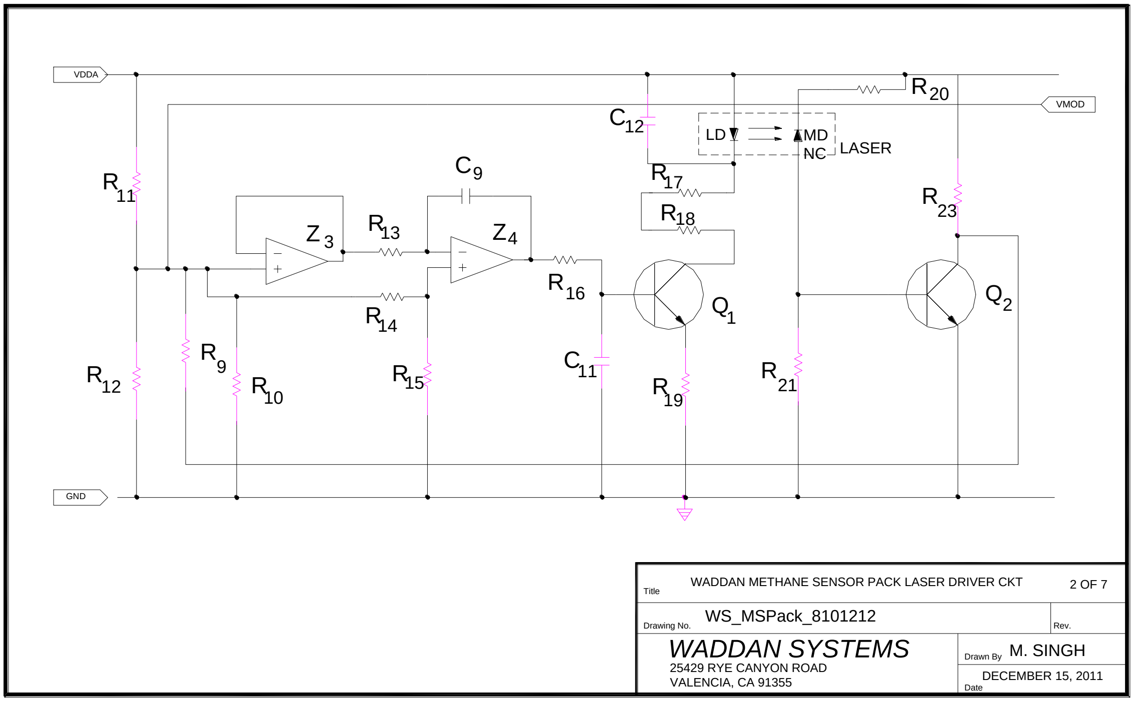


Figure 4.3.1.1-1: LD Drive Circuit Schematics

4.3.1.2 Nano Pore Sensing Medium

For WOFSNet application, where the harsh environment of the mine would be a norm, a rugged sensor design was selected. The gas sensing medium can take many different forms. However, for the first design iteration—a round fiber bundled in an oval shape, and an integrated rectangular waveguide substrate—were incorporated in the design. The methane gas can permeate though the entire length of the bundled fiber. The longer the fiber the higher is the sensitivity. In the micromachined substrate the sensitivity improvement comes by placing multiple parallel optical channels together and doubling of such structures. Basically by increasing the surface area of the optical medium though which gas can permeate through the device, the sensitivity is enhanced. The mask layout for sensing regions is shown in Figure 4.3.1.2-1. A three inch wafer can yield eight 23.3mm X14.9mm devices. By avoiding the middle vertical dicing cut, the same wafer yields four 46.6 mm X14.9mm devices with approximately double the sensitivity.

During the micro-machined channel design phase, a solid model of the MSP chip was created. Some views of the solid model of the chip are shown in Figure 4.3.1.2-2 (a) through (d). The double chip with a Pyrex glass top cover is shown in block (a). Light launching or recovery end is shown in block (b). The optical splitter region is shown in block (c), and a cross-section of the channels is shown in block (d).

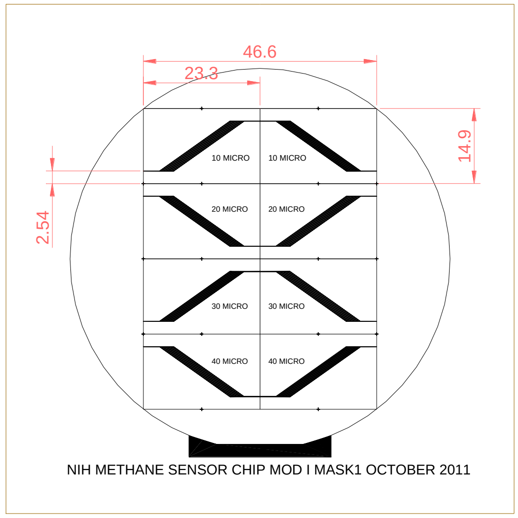


Figure 4.3.1.2-1: Top View of the MSP Sensor Chip Mask

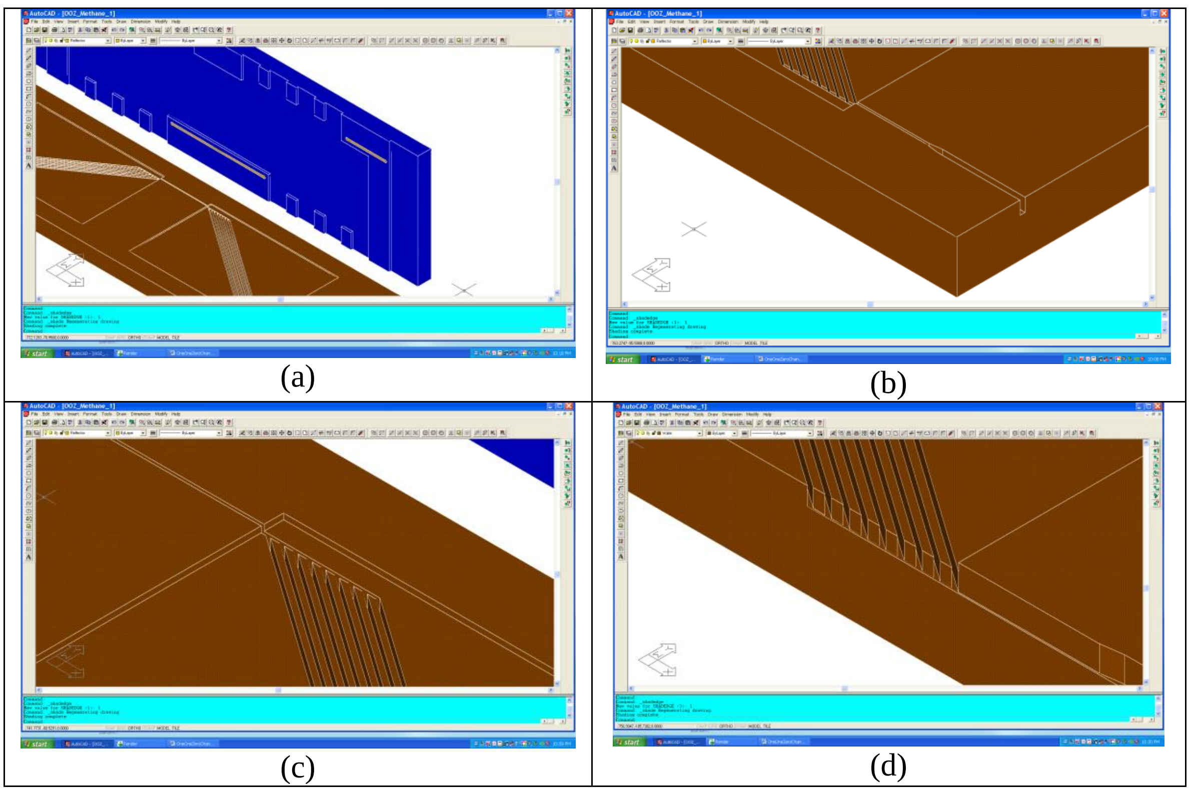


Figure 4.3.1.2-2: MSP Chip with Pyrex Glass Removed

4.3.1.3 Detector Design

Figure 4.3.1.3-1 shows the schematic of the photo detection circuit. The photo detection device is a Ge-photo transistor (or a diode) covering the central wavelength region of 1650nm. An amplifier follows the transistor. To reduce the effects of parasitic inductance noise, the feedback loop resistance of the op amp has been split into two equal parts.

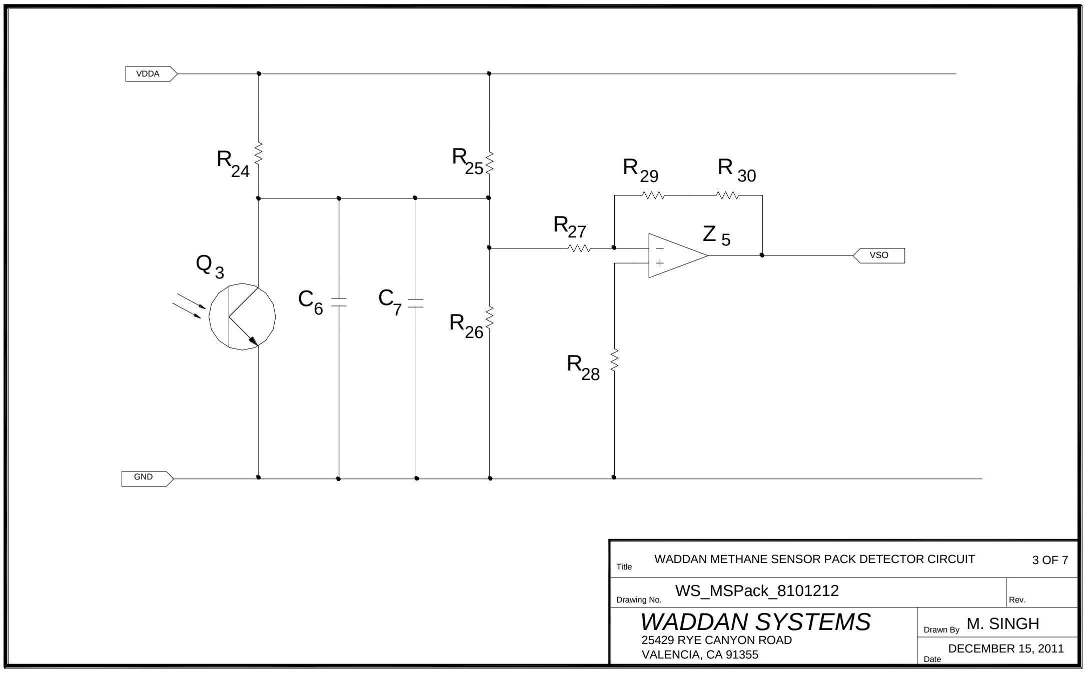


Figure 4.3.1.3-1: Photo Transistor Based Detection Circuit

4.3.2 Sensor Data Extraction Electronics

Generally when light passes through a waveguide, it behaves dominantly as a linear system. In other words if a narrow band of light entering the waveguide is modulated at given frequency then the output is also a signal modulated at that frequency. The output signal is simply scaled depending upon the absorption characteristics of the waveguide. A sinusoidally oscillating input produces a sinusoidally oscillating output at the same frequency. However, if somehow a nonlinearity is imparted to the waveguide the output contains many harmonics of the fundamental modulation frequency tied to the input. When the methane gas enters the nanopores of the waveguide it imparts such a nonlinearity and this effect is proportional to the methane levels present in the nanopores. A significant level of the nonlinearity is expressed by the coefficient of the second harmonic. Intuitively, a measure of the amplitude of the second harmonic can be used as a means for sensor output.

Thus, one approach would be to remove the DC and the first harmonic contents from the detected signal and measure the amplitude of the second harmonic. Another possible method would be to obtain the Fourier Transform of the detector output and isolate the coefficient of the term with second harmonic. If a Fast Fourier Transform (FFT) is to be used, one has to digitize the detector output at sampling rates greater than four times the demodulation frequency. The latter approach would require more powerful microcontroller running at a much higher speed, introduce delays in sensor data conversion and transmission to the Host module. Further evaluation of this approach was deferred for later research. The MSP design currently employs the first simple straight approach. The analog electronics for this extraction is shown in Figures 4.3.2-1 and 4.3.2-2.

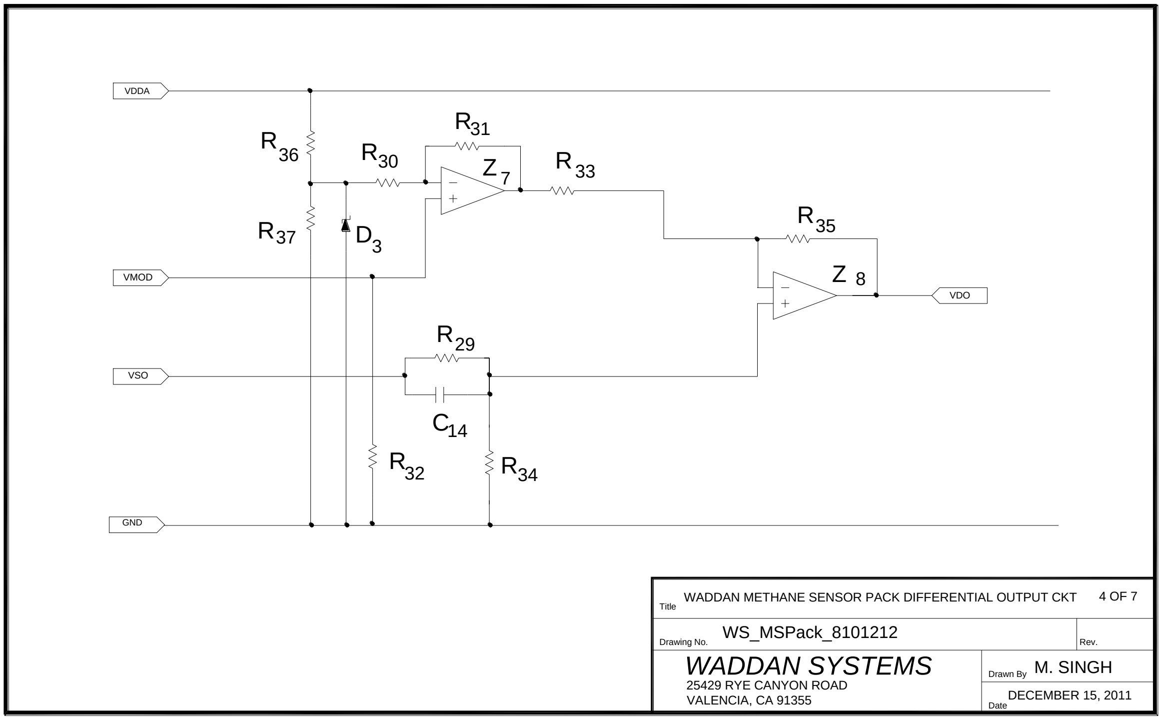


Figure 4.3.2-1: Differential Extraction

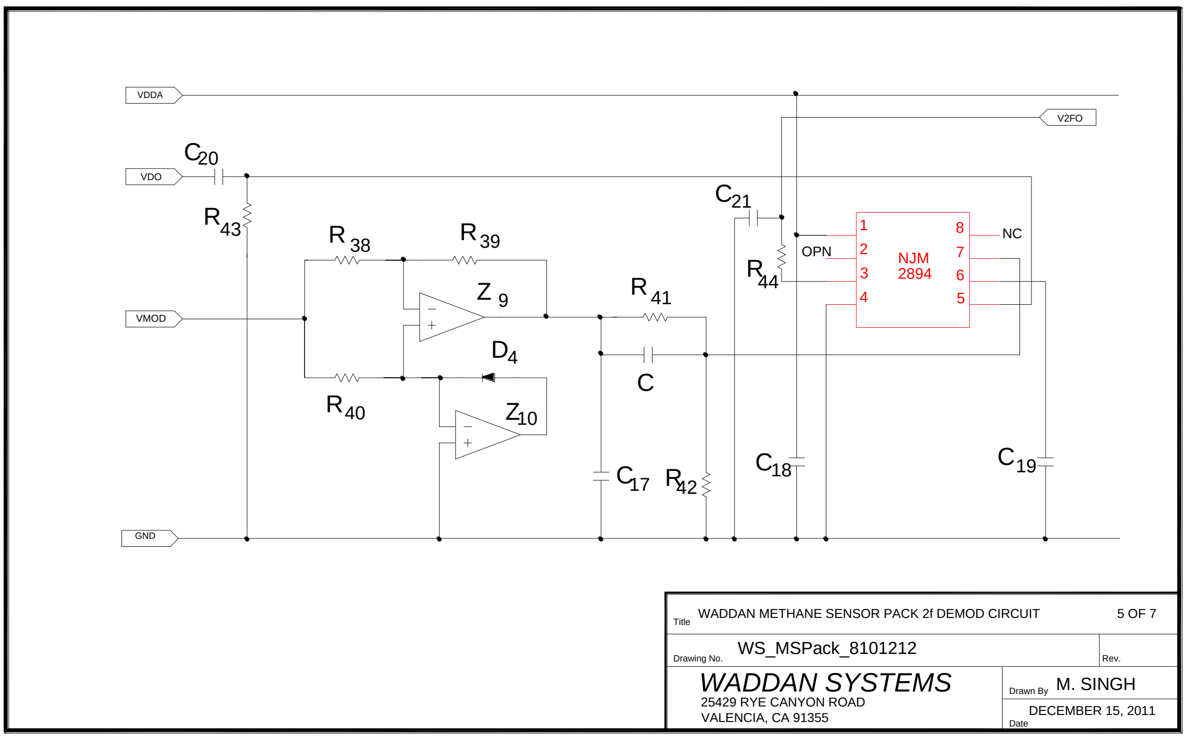


Figure 4.3.2-2: Demodulation at 2*f*

The first stage of extraction, shown in Figure 4.3.2-1, deals with the first harmonic of the sensor output V_{SO}. The phase of V_{SO} is adjusted to approximately match with modulator drive signal V_{MOD}. At the same time the DC offset of V_{MOD} and its AC amplitude is scaled to approximately match that of V_{SO} by Z_7. Then the difference of these signals is extracted by Z_8 as V_{DO}, which mostly contains the 2*f* component of the detector output. The second stage of extraction, shown in Figure 4.3.2-2, deals with 2*f* demodulation of V_{DO} without much distortion. The op amps Z_9 and Z_{10} convert the 1*f* V_{MOD} into a 2*f* reference required by demodulator NJM2894. Thus, the demodulator at pin 3 provides a DC value proportional to the amplitude of the 2*f* component of V_{DO} and some higher frequency noise. A low pass filter removes the higher frequency noise and yields a signal V_{2fO} as a measure of the methane level sensed.

4.3.3 MSP Microcontroller

The MC9S08QG8 is a highly integrated 8-bit microcontroller with low-power consumption. It is a compact, tightly integrated MCU having extended battery life with a maximum performance down to 1.8V. It is recommended for power and size-sensitive applications. Its key features include:

– Up to 20MHz operating frequencies
– 8 K Flash and 512 bytes RAM
– Support for up to 32 interrupt/reset sources
– Enhanced 8-channel, 10-bit embedded AtoD converter
– Three communication interfaces: SCI, SPI and IIC

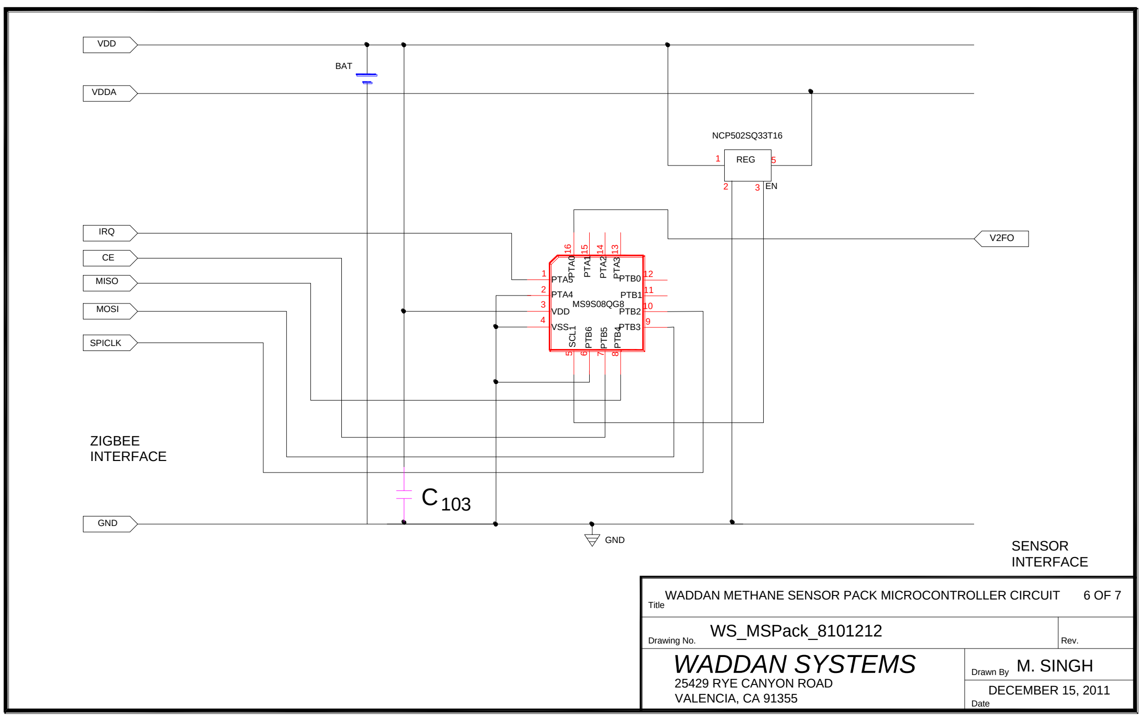


Figure 4.3.3-1: MSP Microcontroller

The schematic of its use in MSP is shown in Figure 4.3.3-1. One channel (pin 16) of the AtoD is connected directly to the gas sensor output V_{2fO}. The power to the sensor electronics (i.e. all analog components) is controlled via a regulator that can be enabled or disabled by the microcontroller. To communicate with the MC13202 (ZigBee transceiver), the SPI is used as shown in the figure.

4.3.4 MSP ZigBee

The networking is implemented with MC13202, which is a short haul, low power, 2.4 GHz Industrial, Scientific, and Medical (ISM) band transceiver. The MC13202 contains a complete packet data modem which is compliant with the IEEE® 802.15.4. The device is recommended for cost-effective solution for short-haul networks. It includes a four wire serial peripheral interface (SPI) for connection with a microcontroller. Figure 4.3.4-1 shows a schematic for interfacing with the microcontroller described in the previous section.

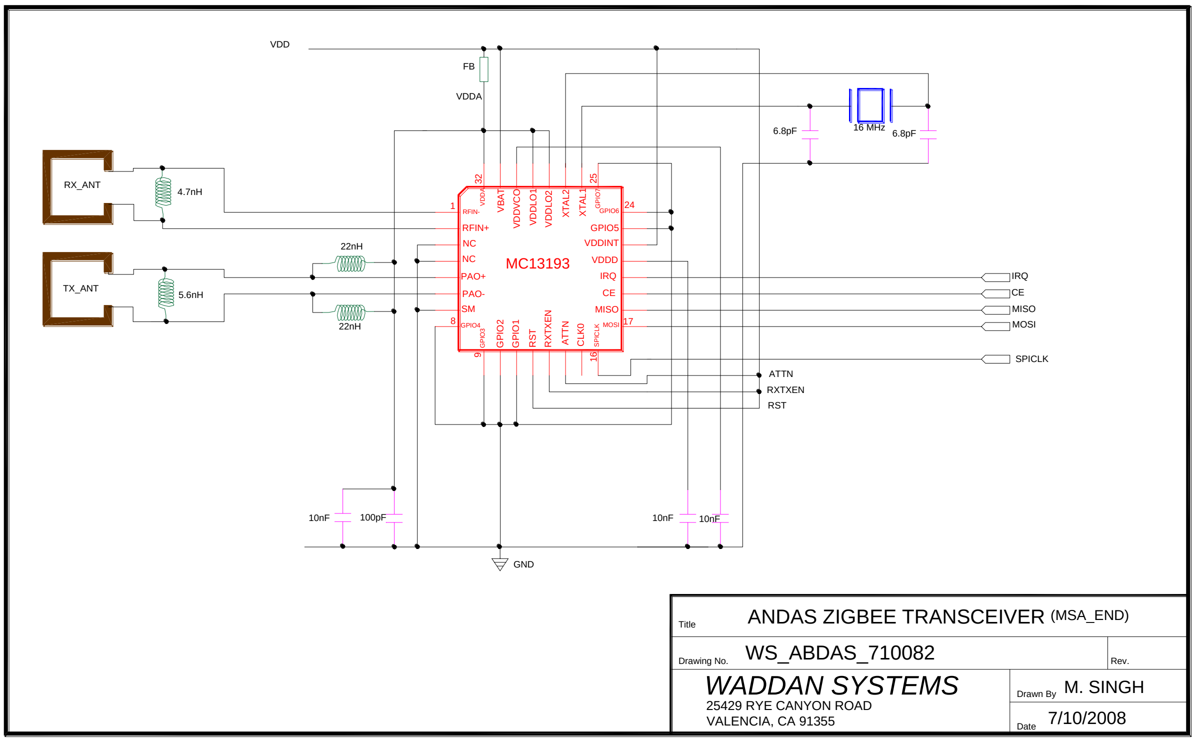


Figure 4.3.4-1: MSP ZigBee

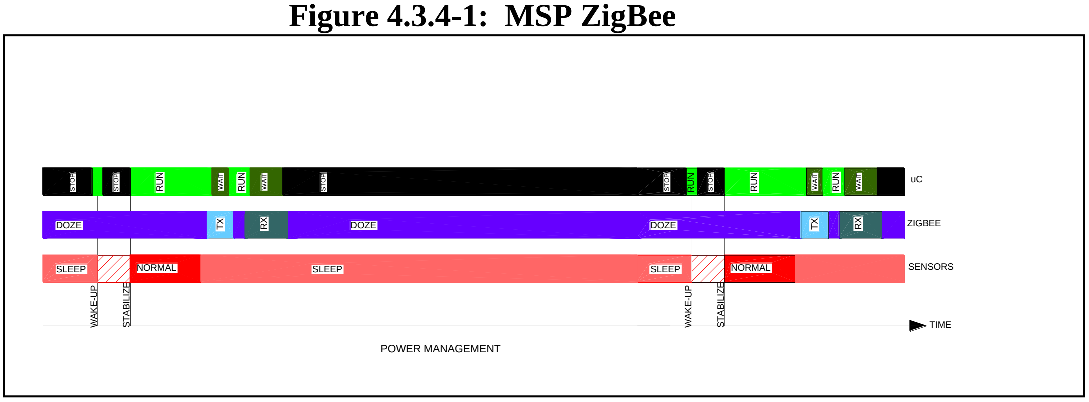


Figure 4.3.5-1: MSP Power Management Strategy

4.3.5 Power Management

As replacement of batteries, in the MSPs mounted at different locations, needs to be avoided, one of the key goals of the MSP design is to extend the battery life as much as possible. In addition to employing components that are designed for extended battery life, an innovative power management strategy is implemented via software as shown in Figure 4.3.5-1. The main events controlled by the microcontroller begin with periodically (at a pre-programmed frequency) waking itself up from a power saving mode, turn on the power to the sensors by enabling the sensor power regulator, sleep while the sensor outputs are getting stabilized. Then it wakes up, reads the sensor outputs and does the AtoD conversion, and puts the sensors back to sleep. It wakes up the ZigBee from its Doze mode and commands it to transmit the sensor data. While the ZigBee is transmitting, the microcontroller goes into a Wait mode. Then it commands the ZigBee for receiving any data and start waiting. The receiving operation can be performed at a much lower frequency. Once the receiving is activated, it could stay on in every cycle until all reception is completed. After completing this, the ZigBee is put to a Doze mode and the microcontroller goes to sleep for a prescribed period. All these functions can be completed fast enough that the MSP can have a data update rate of 50 to 100 Hz (which is not necessay for Methane alone, but will be useful when MSP becomes multi-gas det).

4.3.6 MSP Component Layout

Based upon the designs presented in the previous sections, the complete board level layout of the MSP was created. Two different versions for copper boards were made. They are essentially the same except for the number layers. The one shown in Figures 4.3.6-1 and 4.3.6-2 is a two layer version of the MSP.

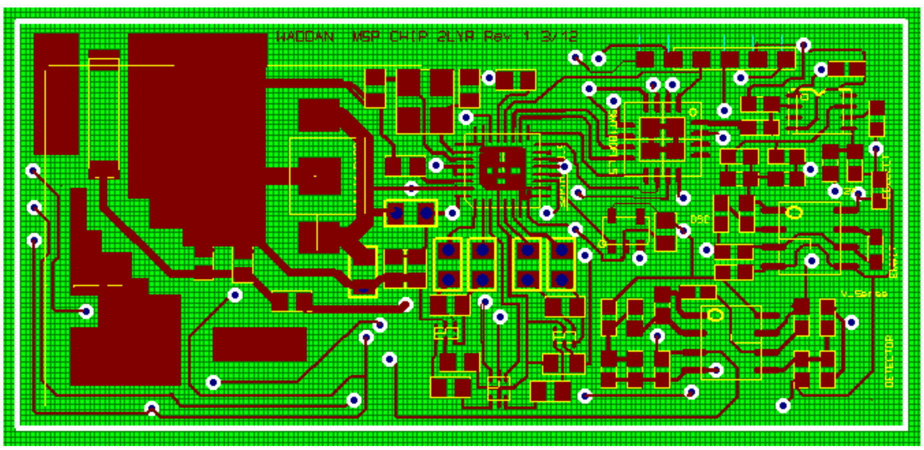


Figure 4.3.6-1:Top Side Of The MSP Board (ZigBee Tx/Rx Side)

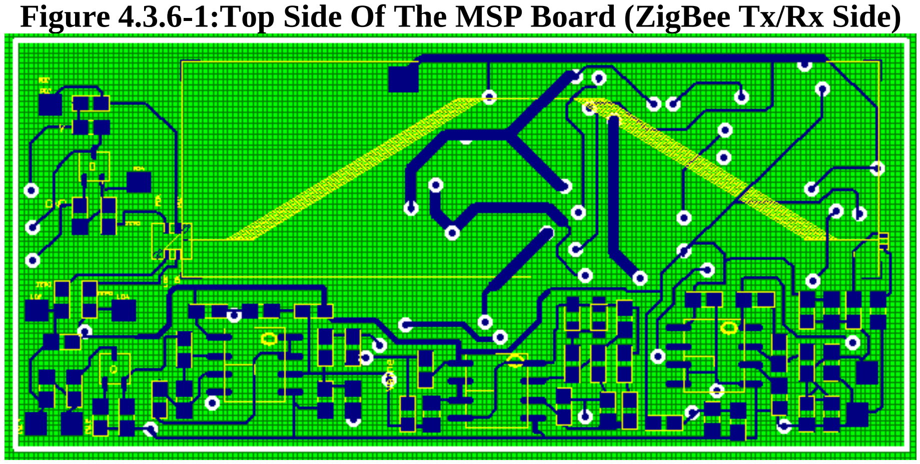


Figure 4.3.6-2: Bottom Side of MSP for Integration with Silicon Chip

4.4 Host Module Design

The Host module design uses the same small footprint considerations used in the MSP design. It also employs the same ZigBee chip, but the microcontroller chosen is little more powerful. It includes a USB interface and has larger flash. The key features of the design are presented in the following sub-sections.

4.4.1 Host Microcontroller

The MCHC908JW32/64 is a low-cost high-performance microcontroller. It can be easily substituted with other members in its family having different functions and memory sizes but the same footprint. Its key features include:

- Maximum frequency: 8MHz
- Oscillators:
  - 4MHz crystal oscillator clock input with 32MHz internal phase-lock loop
  - Internal 88kHz RC oscillator for timebase wakeup
- 32k bytes user program FLASH memory with security feature
- 1k bytes of on-chip RAM
- 29 general-purpose input/output (I/O) ports:
- Serial Peripheral Interface Module (SPI)
- Universal Serial Bus (USB) 2.0 Full Speed functions

A schematic of the chip with USB interface and SPI connections to the ZigBee chip is shown in Figure 4.4.1-1.

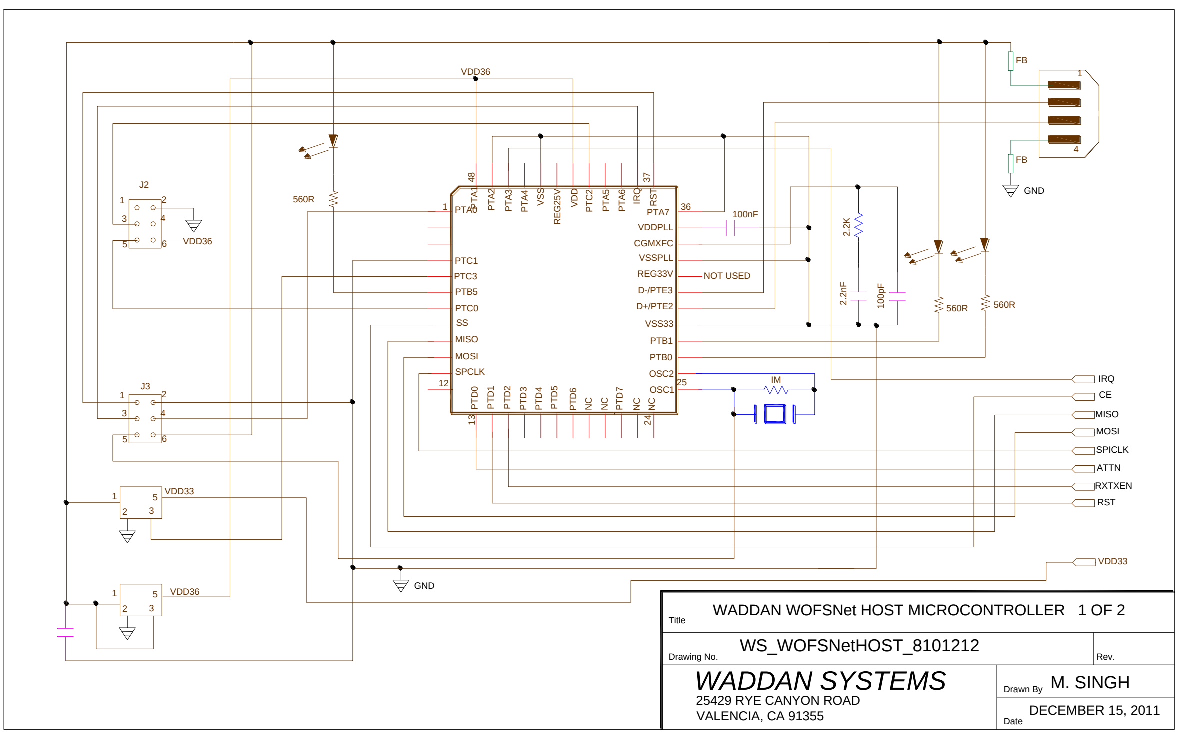


Figure 4.4.1-1: Host Microcontroller

4.4.2 Host ZigBee

This is employed in the same way as in the MSP application. The schematic of its interface with the above microcontroller is shown in Figure 4.4.2-1.

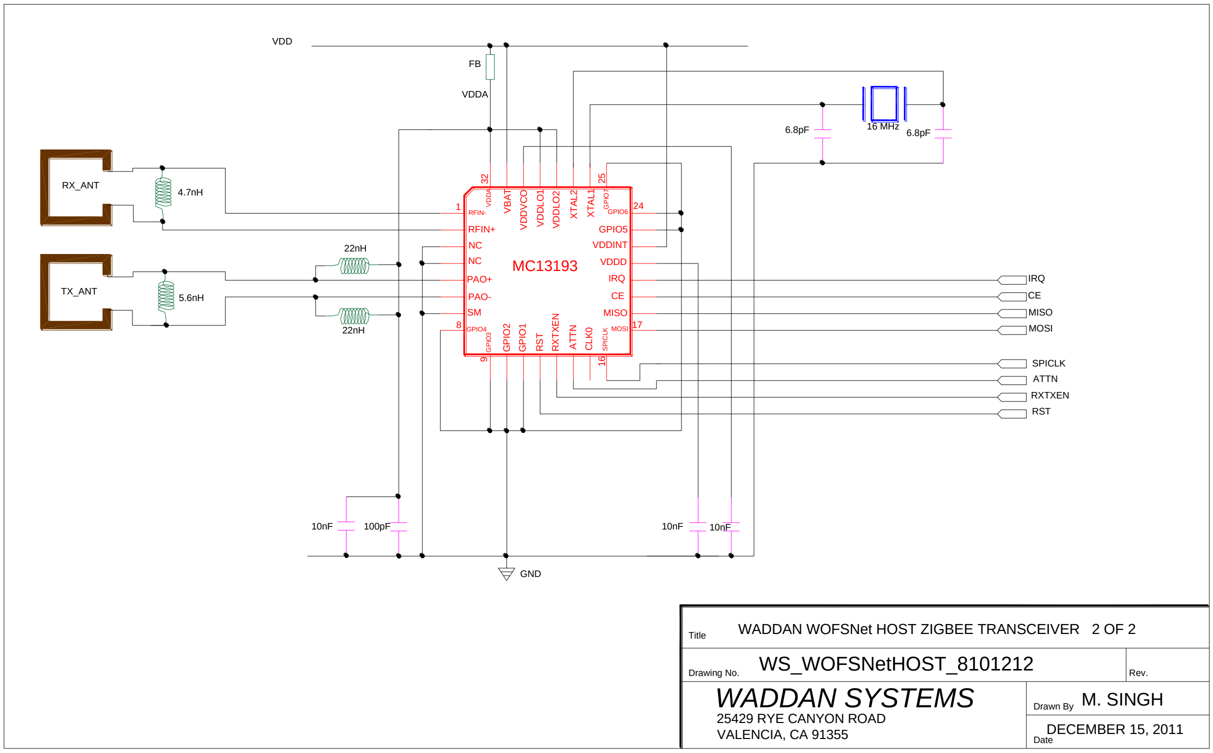


Figure 4.4.2-1: Host ZigBee

4.4.3 Host Module Layout

Based upon the designs presented in the previous sections, the complete board level layout of the Host module was created for a double sided copper board implementation with printed circuit antennae. It is shown in Figure 4.4.3-1.

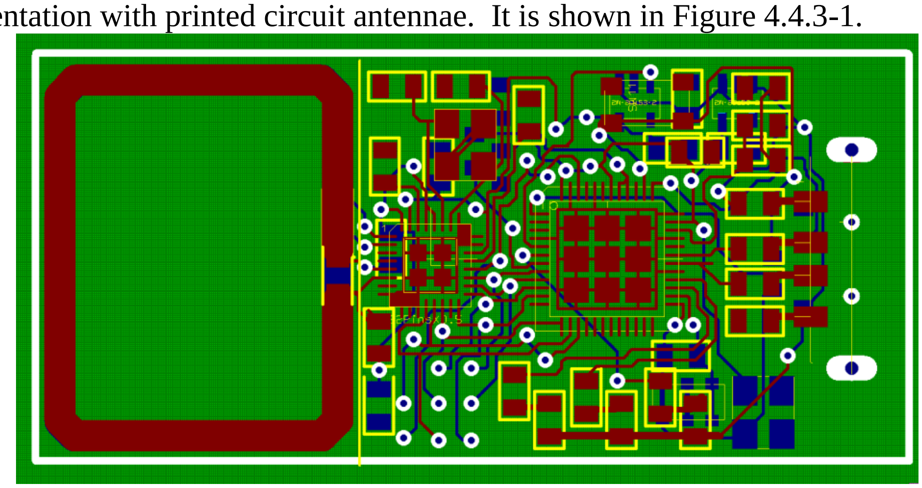


Figure 4.4.3-1: Host Module Component Layout

4.5 Host Management Computer

Any PC with an available USB port can be used for WOFSNet management application. For the harsh environment inside the mine, a rugged industrial computer can be employed. For tight spaces, ultra compact system measuring 145mmX105mmX38mm (6"X4"X1.5") can be used. An example of the compact unit is shown in Figure 4.5-1. The Pico ARTiGO is a full feature ultraminiature computer. It has four built-in USB ports, a fast Ethernet interface, VGA and DVI outputs, a COM port (RS232), PS2 (Kb and Mouse), HD Audio, interfaces for PATA and SATA 2.5" hard drives and RAM support up to 2GB. At present only a limited number of processors are available in this form factor, and it is not as well established as other PC systems.

Figure 4.5-1: Pico-ITX with a Plugged in Host Module

4.6 WOFSNet Software Design

The software requirements for the Host management computer are as follows:

4.6.1 MSP and Host Operating System

Any robust operating system that could be used on the PCI based commercial computers can be utilized for this purpose. The Linux Fedora is the preferred OS as it can work on any computer using a Live CD configuration having no need to load the OS on the computer's hard drive. Thus, any of the software developed in this program will have no royalty strings attached, and can be run on any PC.

4.6.2 ZigBee Network Management Application

This software application manages all the tasks of communication between the Host module and the MSPs. It will be designed in modular form including driver modules for the following functions:

- Sending and receiving of data
- Identifying various MSPs Link address inquiries
- Connection set up
- Authentication
- Diagnostic
- MSP discovery and wakeup etc.

4.6.3 MSP and Host Module Drivers

This software is provided to let the Host management computer talk to the Host Module, whenever it is plugged into its USB port. This includes a GUI to monitor the entire WOFSNet so that the real-time output of each MSP node is displayed on the Host computer screen.

4.6.4 Methane Distribution Map

It is an extension of the GUI mentioned in the last section. However, in this case a graphics display of mine's extent is superimposed with MSP node information. Each MSP node location is tagged with methane levels being sensed at that node. This Methane Distribution Map can be provided to any desired user point in the network; e.g. a display in the elevator or a display with mining team supervisor.

4.7 Fabrication Procedures

The fabrication processes and procedures were developed for building WOFSNet sensing structures and modules. For confining the laser outputs in waveguides, a set of masks was designed to process the integrated sensors by bulk micromachining. The MSP and Host module PCBs with surface mount components were also assembled.

4.7.1 Sensor Processing and Fabrication Iterations

Basically two different forms of optical structures for interacting methane and laser output were developed. These structures are like optical fibers minus their cladding. These structures were fabricated by a micro-molding process using sol-gel method.

Sol-gel process is a rapidly emerging field in which optically transparent glass like material is formed by the hydrolysis and polymerization of metal alkoxides or metalorganic compounds at room temperature [1]. Sol-gel derived glass contains interconnected pores formed by the three dimensional network of SiO_2. The silica glass formed by this method is a nanoporous matrix. Compared with polymers, sol-gel matrices are more resistant to aggressive environments. Moreover, in sol-gel process the porosity can be tailored to ensure faster diffusion of the gas species to be sensed into the optical medium [2]. In a typical sol-gel process, the precursor chemicals such as metal alkoxide, water, and a suitable solvent (e.g., ethanol) is mixed in stoichiometric proportions. For this project, the precursor monomer used to prepare nanoporous active optical medium is tetra ethyl ortho silicate (TEOS), which is mixed with the deionized water at a specific molar ratio. The above mixture is then sonicated for five minutes, which initiates the polymerization reaction. About 60 μL of 0.04 molar HCl is added to the reaction mixture followed by a gentle mixing with a stirrer for few minutes, which catalyzes the

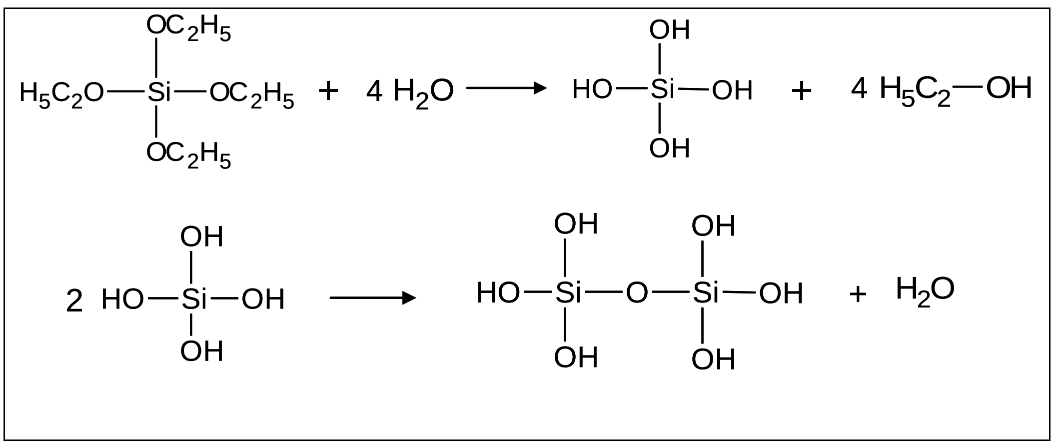


Figure 4.7.1-1: Sol-Gel Process - Hydrolysis and Polymerization Reaction Steps

polymerization reaction further. A colloidal sol is formed by the hydrolysis of the precursor mixtures, which results in the formation of silanol groups (Si-OH) and the silanol groups react further to from siloxane polymers (Si-O-Si) in the condensation reaction. Consequently three-dimensional randomly interconnected porous silica with water and ethanol molecules filling the pores is formed. A homogenous distribution of the reagents is obtained with highly interconnected pores in the glass matrix having pore dimension ~ 4 - 10 nm in diameter.

4.7.1.1 Optical Fiber Structure

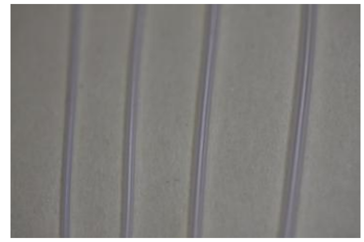


Figure 4.7.1.1-1: Teflon Tubes as Forms

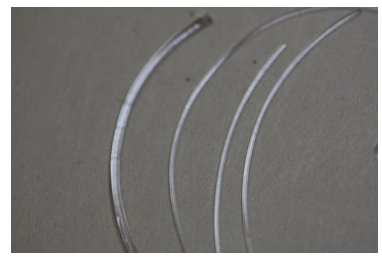


Figure 4.7.1.1-2: Sol-Gel Fibers

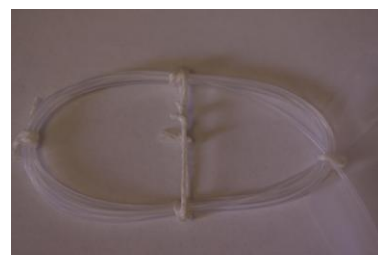


Figure 4.7.1.1-3: Oval Shaped Tube Bundle for Sol-Gel Filling

The freshly prepared sol is then injected into Teflon tubes, shown in Figure 4.7.1.1-1, used for insulating hookup wire. Different diameter tubes in different lengths were used. The smallest diameter tube used for injection filling was of 30 gage (255µm in diameter). The sol-gel solution was kept in the tubes for 2 days at the room temperature for gelation process. The gelation process can be accelerated at elevated temperatures. The gelation process can also be optimized with the amount of catalysts added to the sol-gel solution during the polymerization reaction. The gels that are formed are slightly contracted inside the tubes and do not adhere to tube walls. They are removed from the tubes by pealing, and air-dried for several hours. The solvent from the pores dries out leaving a porous silica form of the sol-gel sensor element. The sol-gel form has the same curved shape as the Teflon tubes injection filled with, as shown in Figure 4.7.1.1-2. As expected the large diameter fiber forms (due to higher skin stresses) were difficult to handle as they broke easily with slight bending. On the other hand small diameter fiber forms were much easier to handle and more flexible. This lead the requirement that tubes have to be shaped in the desired sensor shape prior to injection filling with gel. The oval shaped bundle with long fiber length, shown in Figure 4.7.1.1-1, was used in some MSP assemblies (For example see Figure 1.4-1(e)). Thereafter, these sensing structures are kept at room temperature for further applications. The steps of sol-gel fiber structure

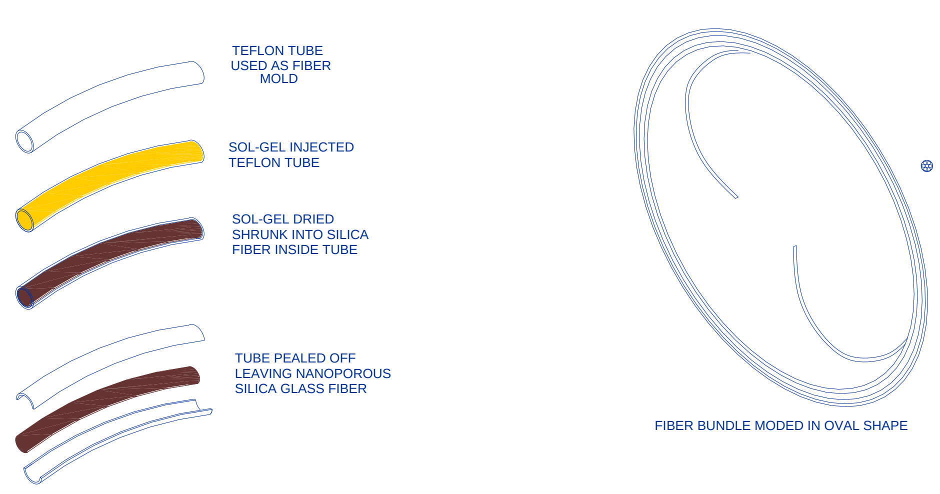


Figure 4.7.1.1-4: Steps for Forming Fiber Sensing Structures

forming are pictorially illustrated in Figure 4.7.1.1-4.

The sensor element prepared through sol-gel process has several advantages over conventional polymer supports. Firstly, sol-gel matrices are more resistant than their polymer counterparts to aggressive environments such as coal mines and chemical process industries. Polymer active core fiber sensor element will suffer degradation when exposed to environments that contain organic vapors or, even, to slightly elevated temperatures. Secondly, most of the organic polymer matrices are photo chemically and thermally unstable, whereas the sol-gel offers better stability at adverse conditions. The nanoporous structure formed by the sol-gel process turns into individual reaction centers useful for detecting diffused methane gas into the pores.

4.7.1.2 Rectangular Waveguide Channels

The rectangular waveguides could be built in either bulk micromachined molds in <110> wafers or the molds made in thick negative photoresist. The processing steps used in both methods are explained the following sub-sections.

4.7.1.2.1 Bulk Micromachined Molding Method

The steps required in this type of technology are shown in Figure 4.7.1.2.1-1(a).

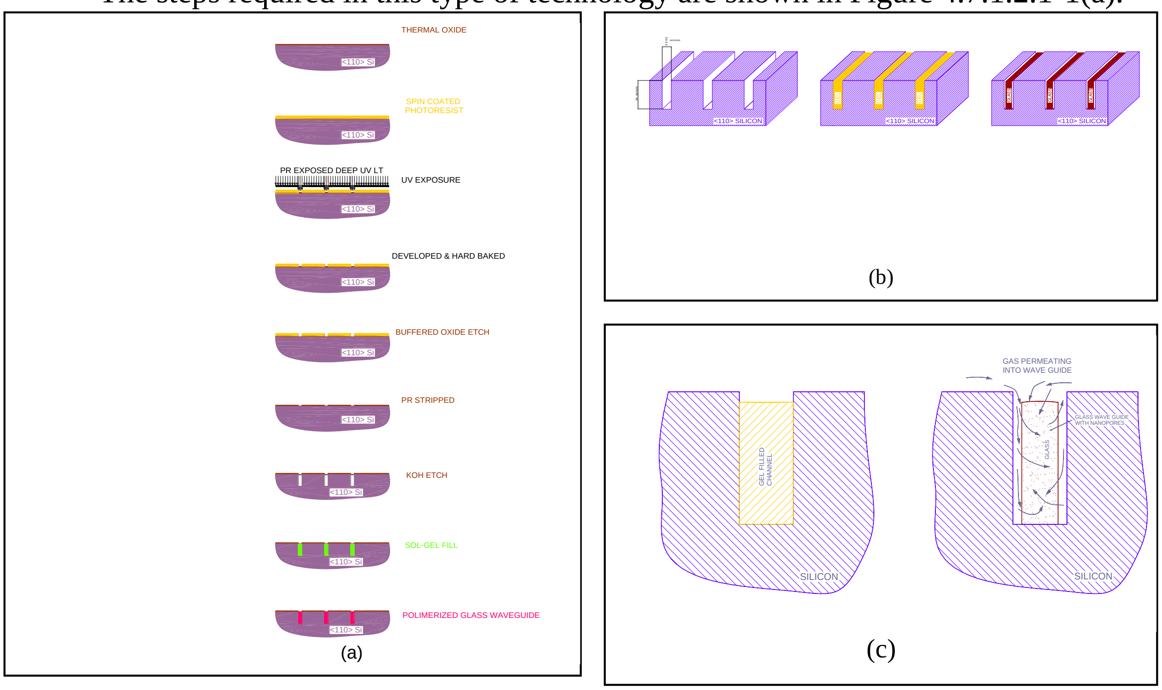


Figure 4.7.1.2.1-1: Bulk Micro-machined Molds for Channel Waveguids

As illustrated in part (a) of the above figure, the process begins with a <110> single sided polished wafer. About two micron thick thermal oxide is grown on the wafer. The wafer is spin coated with a thin positive photoresist (PR), and softbaked. A mask with channels oriented parallel to (111) directions of the wafer is used to expose the PR. Then the PR is developed and hardbaked. At this point, the thermal oxide is visible in developed regions of the PR. This oxide is etched using a buffered oxide etch (BOE). Next the PR is stripped and wafer is cleaned. Now there is a pattern in the thermal oxide for the channels. KOH is used to etch the silicon through this pattern which forms the rectangular waveguides with high aspect ratio (50:1). As shown in part (b) of the figure, channels with 10µmX300µm cross-section can be routinely etched. Since a wafer contains a multiple of the sensor chips, it is diced to separate the chips.

The channels in these devices are filled with the sol-gel produced by the method described earlier for filling the Teflon tubes, and allowed to dry for a few days. At that point the sol-gel gets polymerized into porous glass, and shrinks away from the side walls of the channels as shown in part (c) of the figure above. By placing a multiple of these channels in parallel, one can obtain a large optical region to interact with methane gas. This interaction of the gas with optics through the nanopores in the waveguide medium is also depicted in part (c) of the figure. The sensor chip for the MSP was designed using this processing technology.

4.7.1.2.2 Negative PR Molding Method

The steps required in this type of technology are shown in Figure 4.7.1.2.2-1. Rather than using crystallographic planes of the wafer for making molds for the waveguides, this method employs a negative photoresist for the molds.

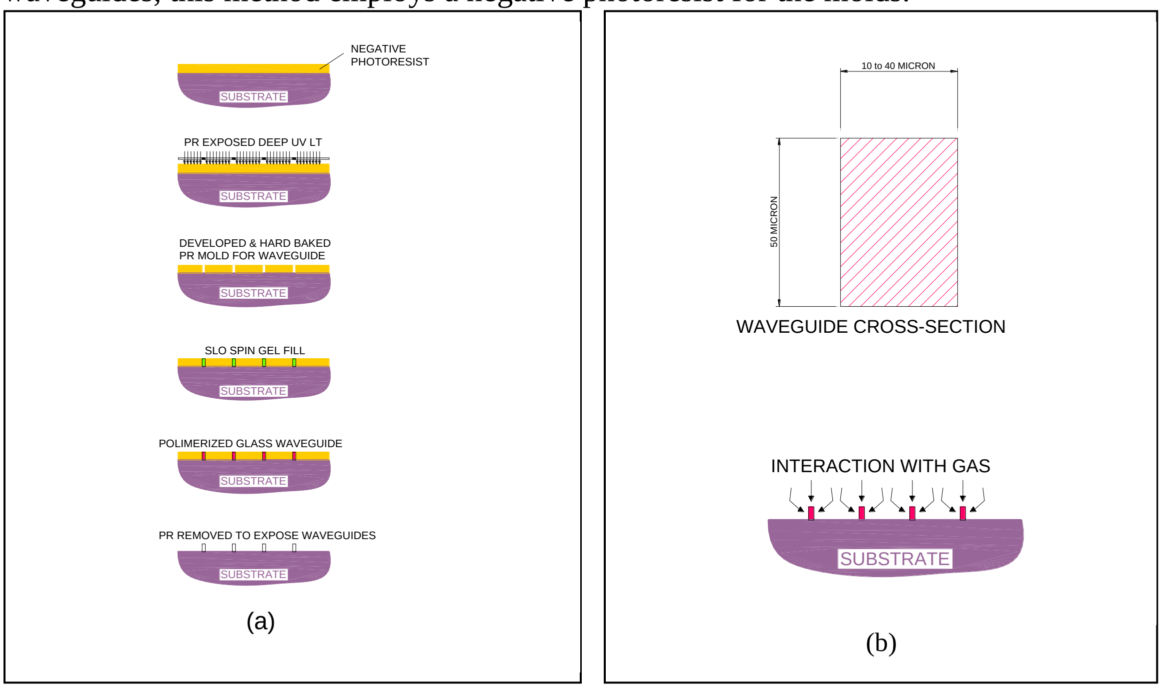


Figure 4.7.1.2.2-1: Negative PR Molds for Channel Waveguides

As illustrated in part (a) of the above figure, the process begins with any single sided polished wafer. A thick layer of Waddan's proprietary negative PR is spin coated at slow speeds on the wafer (depositing up to 50µm thick coatings), and slow ramp softbaked to avoid developing any cracks. A mask with the waveguide patterns is used to expose the PR for long durations. The PR is developed and hardbaked. The waveguide mold pattern is formed in this hardened PR. The sol-gel is filled into the PR mold pattern using a *slow speed ramp and fill spin process*. As before the sol-gel is dried for a few days, and the polymerized glass channels (10µmX50µm) are formed. The wafer is diced to separate the devices. For protection of the channels, the PR is left on the devices. It is stripped, revealing the glass waveguide pattern as depicted in part (b) of the above figure, just before assembling the sensor on to the MSP board. The methane gas interaction takes place on three faces of these waveguide channels. Processing of sensor chips using this method has been deferred until Phase II of the project.

4.7.1.3 Micromachined Sensor Chips for MSP

The first design iteration of the micromachined sensor chips was completed during Phase I for developing a realistic MSP form factor. The mask utilized for waveguide patterns is shown in Figure 4.7.1.3-1. The steps described in Section 4.7.1.2.1 were used to process the chips. Four different channel widths, from 10 to 40 microns, are designed in the same mask. Thus, each 76mm wafer yields four chips of different waveguide widths. After evaluation, only one width will be selected for the second design iteration. As can be seen from the mask, the device design is symmetrical about its mid-plane. If only half of the device yields the desired sensitivity, an additional dicing cut along the plane of symmetry would double the sensor yield of the wafers. Some of the sensor chips produced by using the mask are shown in Figure 4.7.1.3-2(a) and (b).

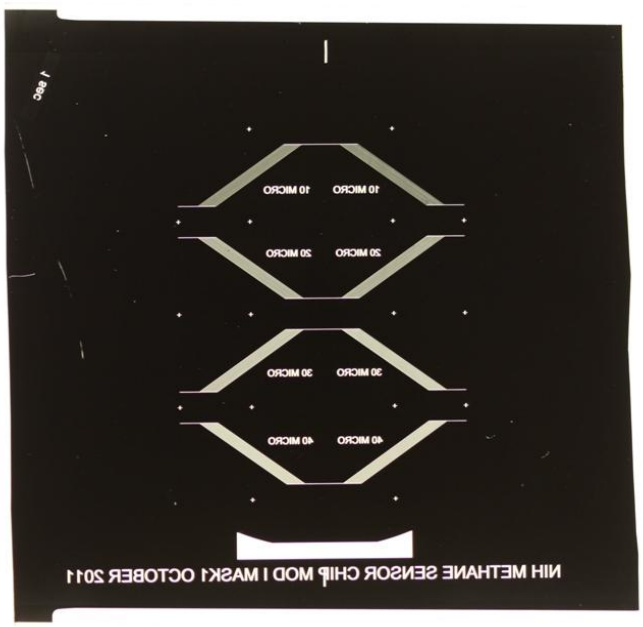


Figure 4.7.1.3-1: Masks Employed for Making the MSP Integrated Sensor

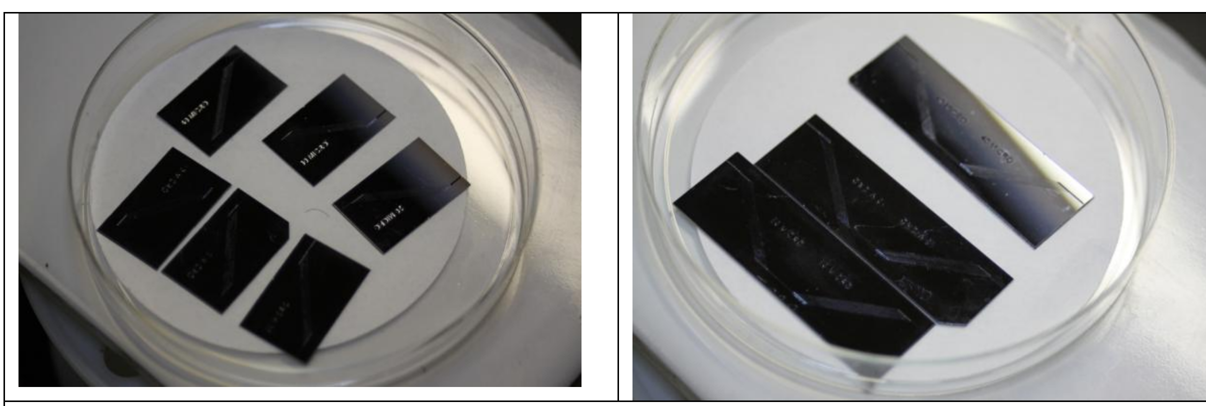


Figure 4.7.1.3-2(a): Devices Diced in Two Different Ways

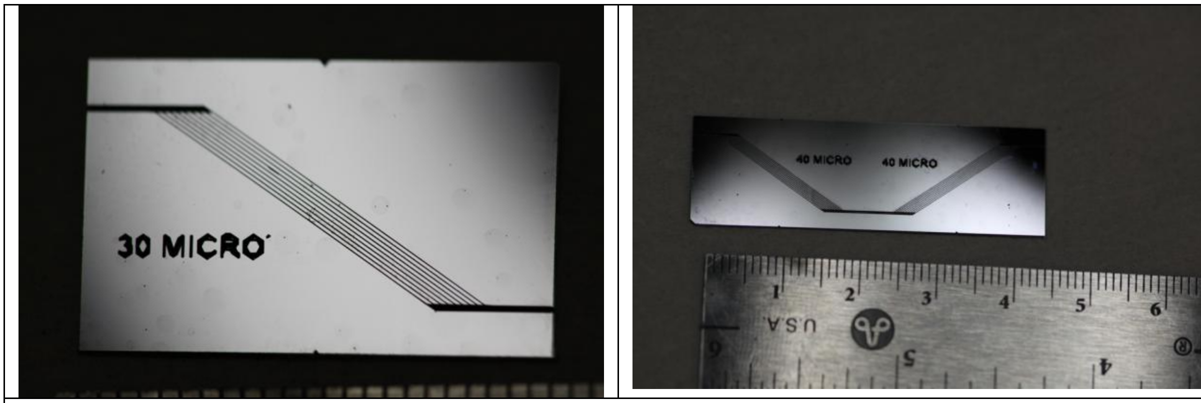


Figure 4.7.1.3-2(b): Silicon Structures for Rectangular Waveguide Sensors

4.7.2 MSP Module Packaging

The MSP Module was designed as a small (24mmX48mm) two layer board. All functions, shown in the block diagram of Figure 4.7.2-1, with design description covered in Section 4.3 were included in the MSP construction described here. The layout of the board components was developed using a board creator CAD program. A set of circuit board masks for top and bottom sides were made. Two layer copper boards were cut to a size slightly larger than their actual MSP dimensions. Aligned circuit patterns were etched on both sides of the board. Holes were drilled for vias for connecting the two layers. The copper was covered with electroless tin and the vias were filled with conductive paste. Figure 4.7.2-2(a) shows the two sides of the MSP boards in this stage.

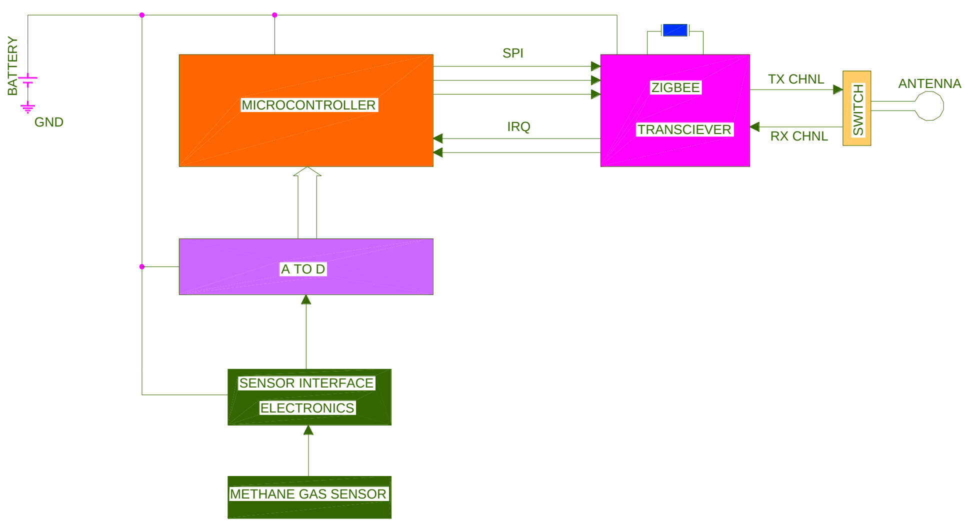
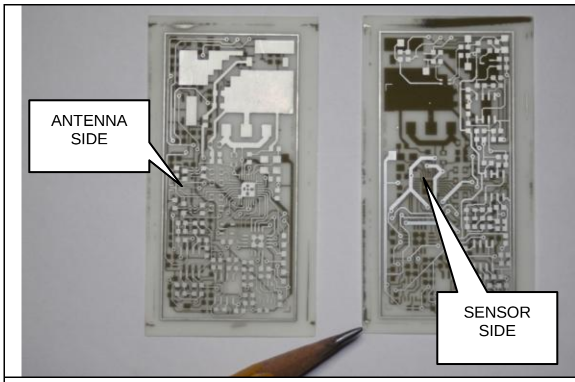
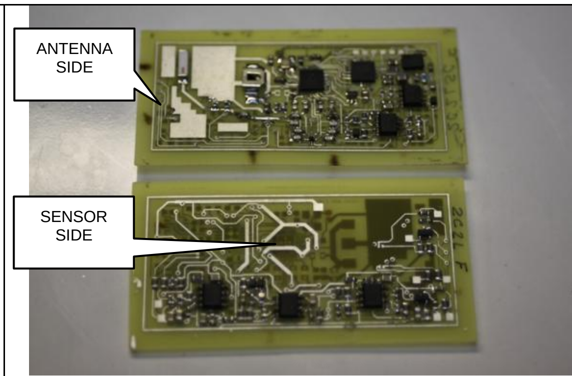


Figure 4.7.2-1: MSP Block Diagram (Phase I Design Iteration #1)

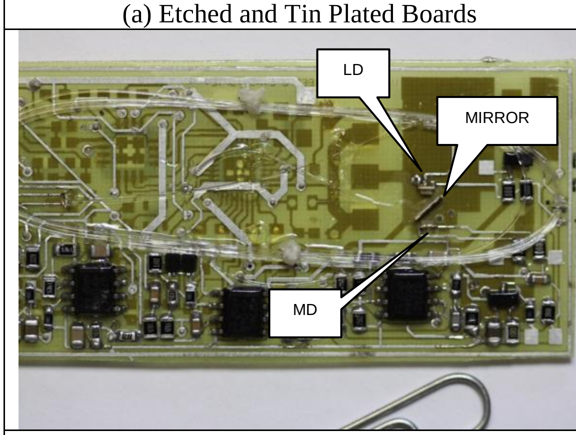
Next the boards are populated with surface mount devices (SMD) for electronics as shown in Figure 4.7.2-2(b). In Phase I, this was done by hand soldering under a microscope. This is a tedious and time consuming process, which will be replaced by a solder paste dispenser, and a computer controlled ramp and soak oven. This new soldering approach is expected to improve the assembly efficiency and the appearance of the MSP boards. As can be seen in the figure approximately 50% of the sensor side is kept free of electronics where optical sensor components are mounted.



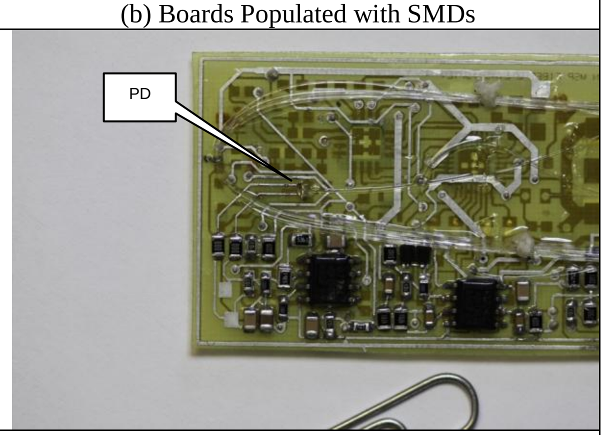
(a) Etched and Tin Plated Boards



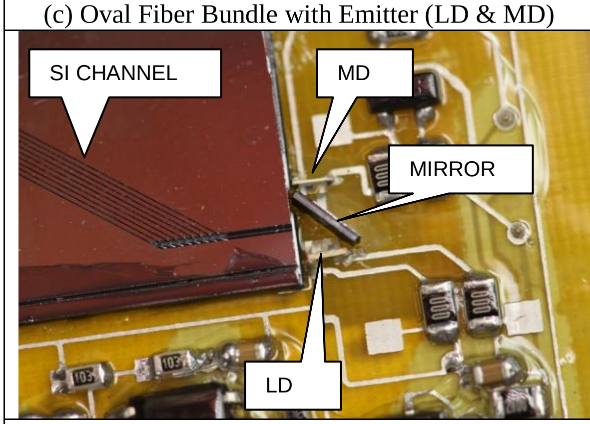
(b) Boards Populated with SMDs



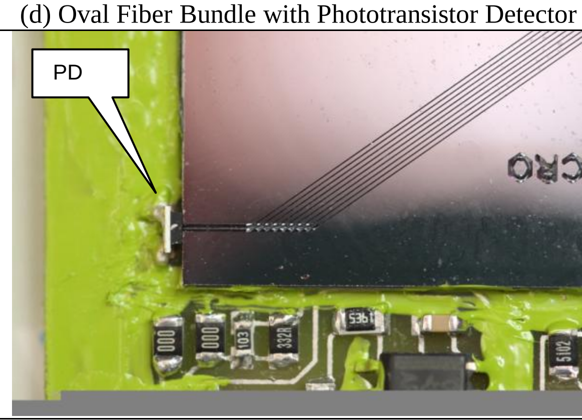
(c) Oval Fiber Bundle with Emitter (LD & MD)



(d) Oval Fiber Bundle with Phototransistor Detector



(e) Silicon Waveguide with Emitter (LD & MD)



(c) Silicon Waveguide with Phototransistor Detector

Figure 4.7.2-2: MSP Fabrication Process

Figures 4.7.2-2(c) and (d) show the sensor side of an MSP that employs an oval fiber bundle as sensor mounted in place. On the emitter side, the output of a LD is directed by an almost totally reflecting mirror (97%) into a lens that focuses the light into one end of the fiber bundle. The small portion of the light passing through the mirror is detected by an MD, which feeds back its output to the laser drive circuit. To avoid cooling requirements, the LD output is controlled and stabilized at 50% of its peak emission efficiency. At the exit end of the fiber bundle, a phototransistor is employed as the detector. Optical alignment procedures will be developed during Phase II of the effort. Figures 4.7.2-2(e) and (f) show the sensor side of an MSP that employs micromachined waveguide sensor mounted in place. As before the emitter side has an LD, an MD and a mirror; and the detector side has a phototransistor. The components are edge mounted. Details of component locations for various MSP functions are shown in Figure 4.7.2-3 below. As mentioned earlier, the board shown in the figure was successfully hand assembled. It can be further miniaturized using automatic component placement and assembly methods. A programming station with a laptop, and a fixture with spring loaded pins will be used for programming the MSP microcontroller via the BDM interface shown in the figure.

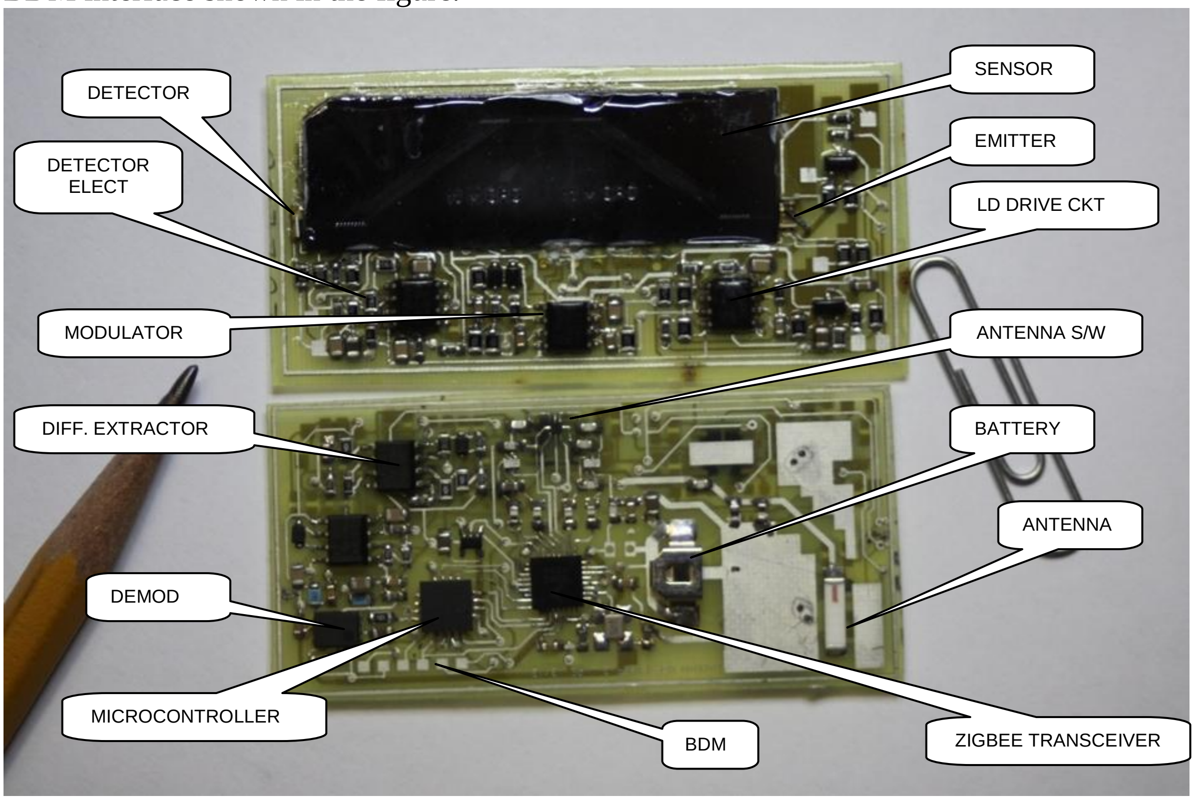


Figure 4.7.2-3: MSP Functional Details

4.7.3 Host Module Packaging

This module is fabricated using the same process as described in the previous section for MSP. However, in this case the size and shape are of little importance. As long as it has the USB connector to interface with a PC, the packaging requirements are met. An early version of the Host module is shown in the photo of Figure 4.7.3-1.

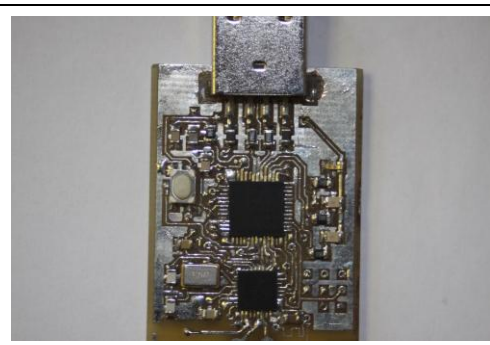


Figure 4.7.3-1: Host Module with MC13193

4.7.4 WOFSNet Programming and Eval Station

The MSP and the Host modules as described in Sections 4.7.2 and 4.7.3 are of little use without the proper programming of the microcontroller in each case. These microcontrollers have to be loaded with appropriate firmware. These programs will be developed with the help of a software tool called Codeworrier obtained from Freescale

Semiconductors. The station used for programming these microcontrollers through the BDM interface will also serve as the Eval station for these modules. These stations will be developed in Phase II.

4.8 WOFSNet Testing

This testing is divided into two parts—the first deals with testing the optical sensing medium and the second deals with wireless data transfer process.

4.8.1 Nanoporous Optical Fiber as Methane Sensor

For these tests, a gas test station was constructed in a well ventilated chamber. A blower attached to test compartment removed and dispersed the gases to the atmosphere. Plenty of nitrogen was available for purging the test apparatus and test environment. The porous optical medium in the form of round fibers was used for testing the sensing hypothesis. Large diameter fibers, although convenient from the view point of optical alignment, broke easily. The Teflon tubes used were curved to begin with, thus, formed the fibers also in their shape. Any alteration of that shape imparted skin stresses in the fiber and cracked them. It should be noted that it is not a serious problem, because the shape of the Teflon tubes can be changed by a heat gun. The tube can be held straight by applying some heat prior to injection filling with sol-gel. However, in the current tests smaller diameter fibers were employed after cleaving and polishing their ends (to reduce the scattering losses). Light from the laser diode was focused into the fiber using a small lens salvaged from the head of a DVD ROM drive. The detector had a large area, thus, required no alignment with respect to the test fiber.

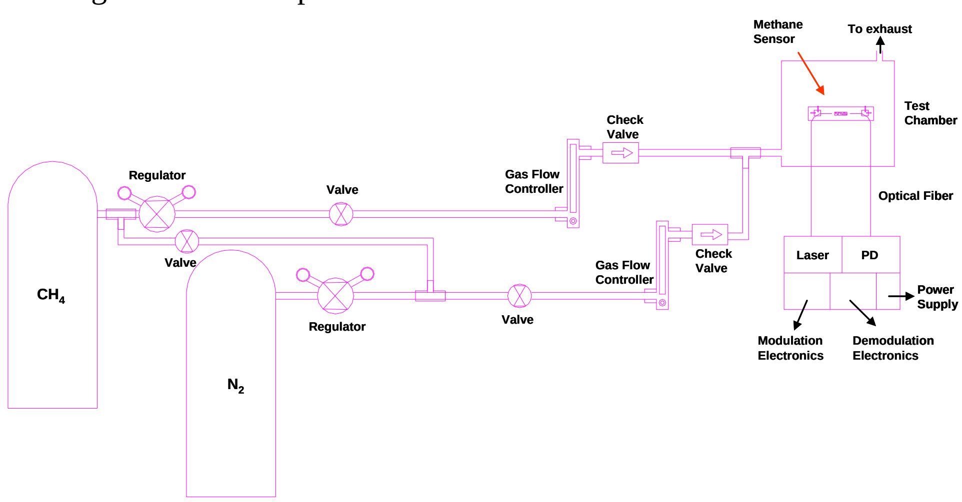
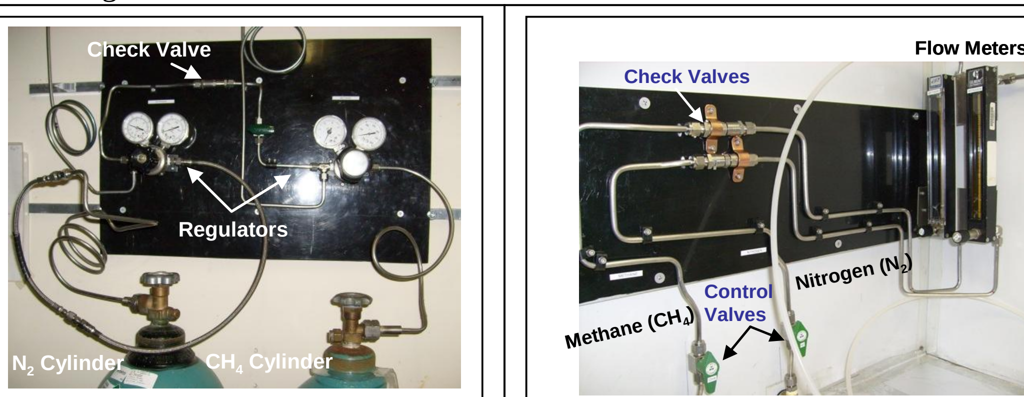


Figure 4.8.1.1-1: Planned Layout of the Test Station

4.8.1.1 Test Station Layout

The layout of the test station was planned as shown in Figure 4.8.1.1-1. Two gas bottles are used—one has pre-purified nitrogen, and the other contains certified 5% methane cut with nitrogen. Each bottle is fitted with its own 2-stage regulator. For purging the methane regulator, a plumbing line of regulated N_2 is connected before the methane regulator. The two gases are routed to their flow controllers. The check-valves shown after the flow controllers are provided to prevent any back flow of the gases. The gases are sent into a Gas Sensing Box (GSB), to be described in the next section. The outlet of the GSB is connected to an exhaust blower.

The actual plumbing of the test station set-up and its hookup with the GSB is shown in Figures 4.8.1.1-2.



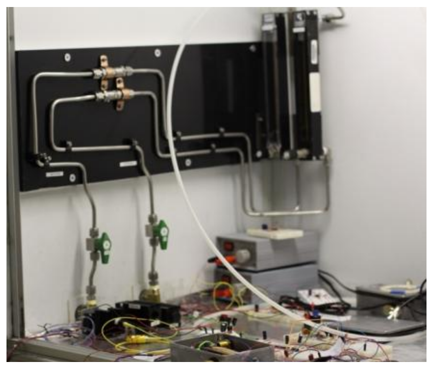


Figure 4.8.1.1-2: Test Station Plumbing and GSB

Various concentrations of methane gas are introduced to the GSB using gas regulators as well as gas flow controllers.

4.8.1.2 Gas Sensing Box (GSB)

A photo of the GSB is shown in Figure 4.8.1.2-1. It is a rectangular metallic box with a cover. The cover is secured with four screws, and contains gasket to seal the box. Two quarter inch gas tight tube fittings were fitted at diagonally opposite corners through drilled holes. The gas enters the GSB through one fitting and exits from the other. A small sealed tap in the side wall allows the hook up wires to pass through for electrical connections with the laser diode and the detector. For short term testing conditions, no monitoring diode or laser cooling was used inside the box. The laser was driven at current regulated conditions approximately at 50% of its peak power levels. The fiber material to be used as sensor is placed in a V-groove scribed on a flat fiberglass board. This is simply done for alignment purposes. The laser diode emitting at 1650nm

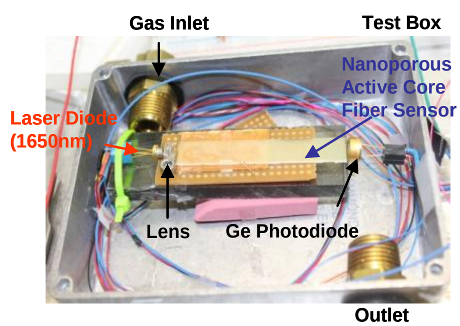


Figure 4.8.1.2-1: Gas Sensing Box

is placed on the left hand side, and directs its output into a tiny lens (from the head of a DVD). The lens is placed in such a way that it couples most of the laser radiation into the end of the sensing fiber placed in a V-groove. On the other end of the fiber, a Germanium photodiode is placed. After aligning the laser and the detector for maximum sensitivity, the box cover is closed, and a sample mixture of methane/nitrogen is introduced.

During the development testing, many different approaches for optical alignment were investigated for MSP application, and the analog electronics for the best performance (highest sensitivity with lowest noise) was developed.

4.8.1.3 Electronics and Data Extraction

The GSB involves only analog circuits. During the early part of the testing, the electronics was placed on quick changing boards, where the components can be easily replaced, and the circuit can be quickly modified. Once the electronics is firmed up a little, it is transferred to a PCB as shown in Figure 4.8.1.3-1. In future, the test station will employ only a few of these PCBs to reduce clutter and minimize noise.

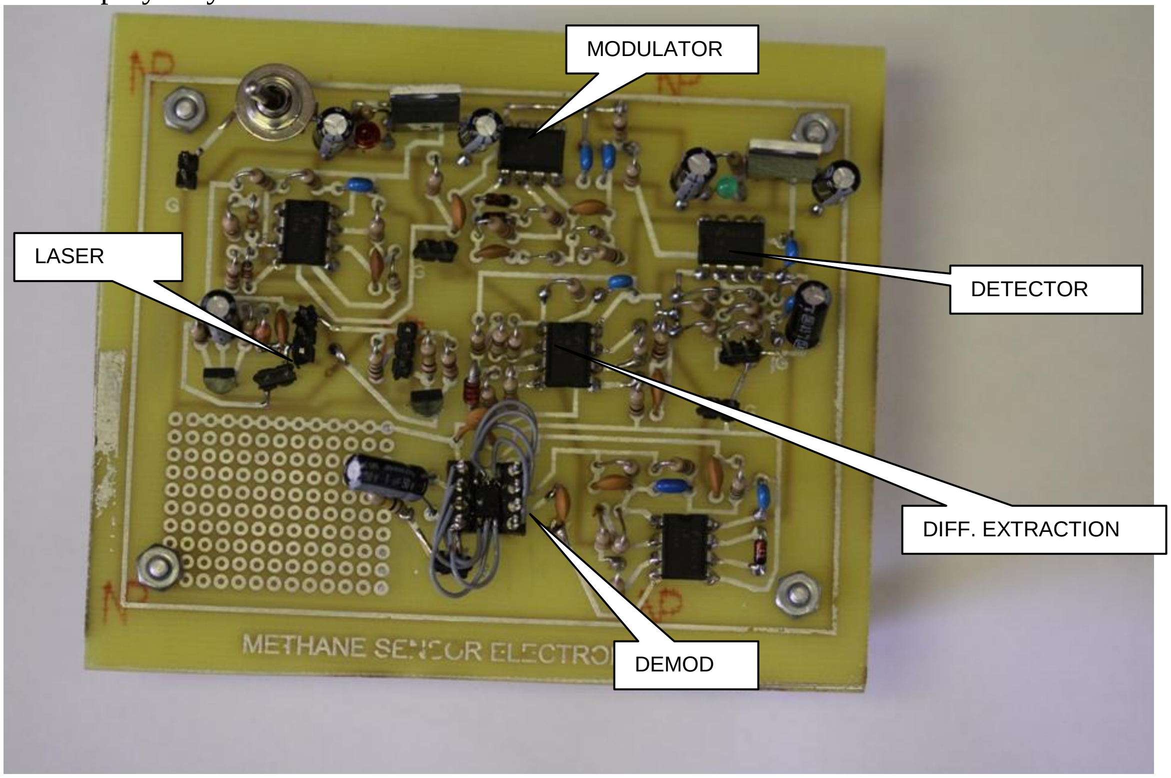
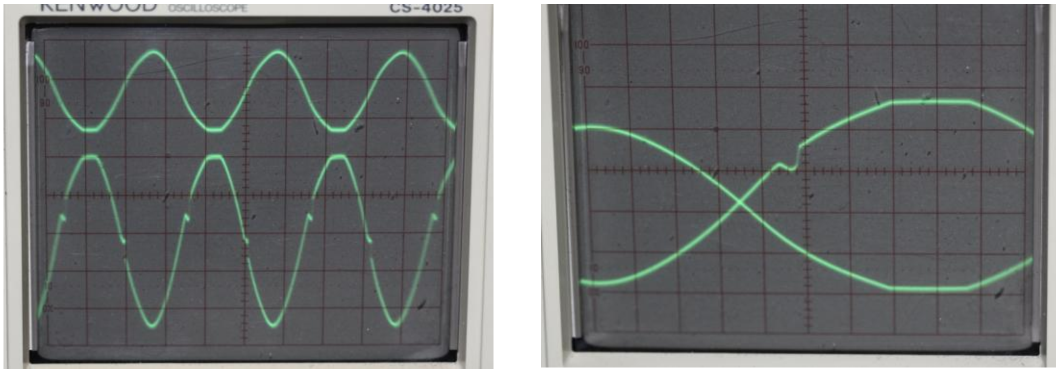


Figure 4.8.1.3-1: Test Station Electronics PCB (Rev. 1)

The electronics development began with the modulator circuit. Triangular and square wave modulation circuits were removed from consideration as they resulted in higher second harmonic noise. Pure sinusoidal modulation was preferred. The scheme that required least number of components was selected. The current circuit uses a single op amp and yields a decent sine wave which is buffered and distributed for driving the LD, for differential 2*f* signal extraction, and generation of 2*f* reference for the final demod.



Upper Trace: Sinusoidal Drive Signal
Lower Trace: Detector Output with Methane Induced Attenuation at 2*f*

Same Traces as on the Left, but at different Time Base

Figure 4.8.1.3-2: Photo of Signal Traces on a Scope After Diff Extraction (Upper Sinusoidal Modulation Trace is for Reference)

Figure 4.8.2-1: A ZigBee Network in Action

The single supply voltage for the test station electronics was provided by a 5V DC power supply. An oscilloscope was used for monitoring the signal levels at different stages of the circuit. Figure 4.8.1.3-2 shows the oscilloscope photos of the output of differential extractor stage. For comparison, the modulation signal is provided as the upper trace. The lower trace shows the methane induced attenuation in the detector output. The measure of this attenuation can be found in the delta change of the demod DC output. The demod output was measured after high frequency filtering with a multimeter. Without any methane the reading was 3.3VDC; and when methane was introduced in the GSB, the voltage dropped to 3.1VDC. Thus, a delta change of 200 millivolts was observed when the sensing fiber pores were filled with methane concentration less than 5%. The testing results show the feasibility of the gas sensing concept based upon optical porous sensing media.

4.8.2 ZigBee Network Eval Test

As per trade-off analyses, ZigBee protocol was found to be more suitable for WOFSNet application. For a quick evaluation, a kit provided by Texas Instrument was used. In Figure 4.8.2-1, a display of wireless data transfer is illustrated.

There are five measurement nodes with a built in temperature sensor. They are scattered on the table without any hardwire connection to the PC. A Host module is inserted in the USB port of the PC. The application running on the PC is alerted whenever a temp measurement node either comes into or leaves the network. The temperature measured at the nodes is displayed on the PC screen. The measurement nodes placed in different rooms still communicated with the Host. However, when placed in a location several rooms away, the link between the Host and the measurement node was broken.

5.0 COST MODEL

A spread sheet based WOFSNet cost model is being developed. Costs are divided into three major categories – nonrecurring, fabrication and part-acquisition, and test costs. This spreadsheet cost model includes the cost of all categories. The MSP and Host module costs are separated. Since a dedicated PC is not necessary for WOFSNet management, its cost is not included. The spreadsheet will be updated quarterly during the WOFSNet development. It will be linked to data from other sub-cost worksheets. Estimates at this time place the MSP and Host prices at $71 and $55 a unit respectively.

MSP MODULE (10,000 UNITS)

COMPONENT	Non-Rec Cost	Fab/Acq Cost	Test Cost	Total Costs	Recoup/Profit	Price
MC13193		$28,000		$28,000		
MC9S08QG8		$10,000		$10,000		
Sensor Optical	$100,000	$100,000	$60,000	$260,000		
Board	$10,000	$25,000		$35,000		
Misc Components		$60,000		$60,000		
Board Assembly		$150,000	$100,000	$250,000		
TOTAL COST				**$643,000**	**$6**	**$70.73**

HOST MODULE (1,000 UNITS)

COMPONENT	Non-Rec Cost	Fab/Acq Cost	Test Cost	Total Costs	Recoup/Profit	Price
MC13193		$2,800		$2,800		
MCHC908JW32		$3,150		$3,150		
Board	$10,000	$2,500		$12,500		
Misc Components		$6,000		$6,000		
Board Assembly		$15,000	$10,000	$25,000		
TOTAL COST				**$49,450**	**$5**	**$54.40**

6.0 CONCLUSIONS

The following conclusions can be drawn based upon the results obtained in Phase I:

a) The sol-gel based micromolding process can form optical sensing structures practically of any desired shape. It is limited only by the mold shape one can make for filling the sol-gel.
b) The simple test set-up used in Phase I showed the feasibility of the sensing concept. The sensor sensitivity can be greatly enhanced by increasing the gas interacting structural volume. For fibers it can be done simply by bundling longer lengths in loops. In micromachined structures, this can be achieved by enlarging the gas interactive surfaces.
c) Using the modern small scale assembly techniques, such as those used for cell phones, an MSP with a very small foot print can be built.
d) ZibBee provides the best networking for the WOFSNet. A battery operated MSP can sleep for a long time with trickle 90 μW power consumption.
e) Power management schemes can significantly extend the battery life as even during the active mode, the MSP stays awake only for 2 to 3% of the time during each measurement cycle.
f) It is feasible to manufacture a low cost WOFSNet using commercially available electronics ICs along with the sensors described in item # a) above.

g) The highly integrated ICs—one sensor support IC, one microcontroller, one regulator, one transceiver— will yield a compact device with very small foot print (30mmX30mm).
h) The estimated low price of the MSP at $75 per unit will open the door for many other gas sensing applications.
i) The system can be adapted without any mod for many commercial test applications.

7.0 RECOMMENDATIONS FOR PHASE II

On the basis of the work completed in Phase I, the following effort is recommended for Phase II:

- Test and evaluate MSP modules designed and built during Phase I
- Test and evaluate Host modules designed and built during Phase I
- Characterize the sol-gel filling process for
  - ✓ Viscosity effects
  - ✓ Surface Tension effects
  - ✓ Hygroscopy
  - ✓ Vacuum fill etc.
- Refine and process integrated sensor packages designs,
- Refine and improve MSP assembly procedures
  - ✓ Ramp and soak soldering
  - ✓ In-circuit optical alignment of the LD, MD, PD, mirrors, lenses and sensing structures,
  - ✓ Reduce the component count
  - ✓ Integrate the sensor analog circuits possibly into one IC,
  - ✓ Integrate all optics into a single IOC;
- Finalize WOFSNet design for true scale development in Phase II,
- Build and test MSP modules most promising design alternative for field testing in mining environment,
- Build BDM programming and test fixture.
- Develop host management computer software,
- Develop design and specification for a multi gas sensing network as depicted in the block diagram of Figure 7-1.

8.0 RISKS AND RISK MITIGATION PLAN

The fabrication of the sensing element employs mature and routine technology processes. Hence, its fabrication does not involve any significant risk. All other electronic ICs employed are commercial off-the-shelf devices supported by multiple vendors [4-7]. Waddan Systems has in-house full 3–inch wafer fab along with capability for hybrid manufacturing with eutectic and wire bonders. Many different test and assembly stations are available in-house for this project.

Any unforeseen risk will be mitigated by early determination and identification of the alternatives.

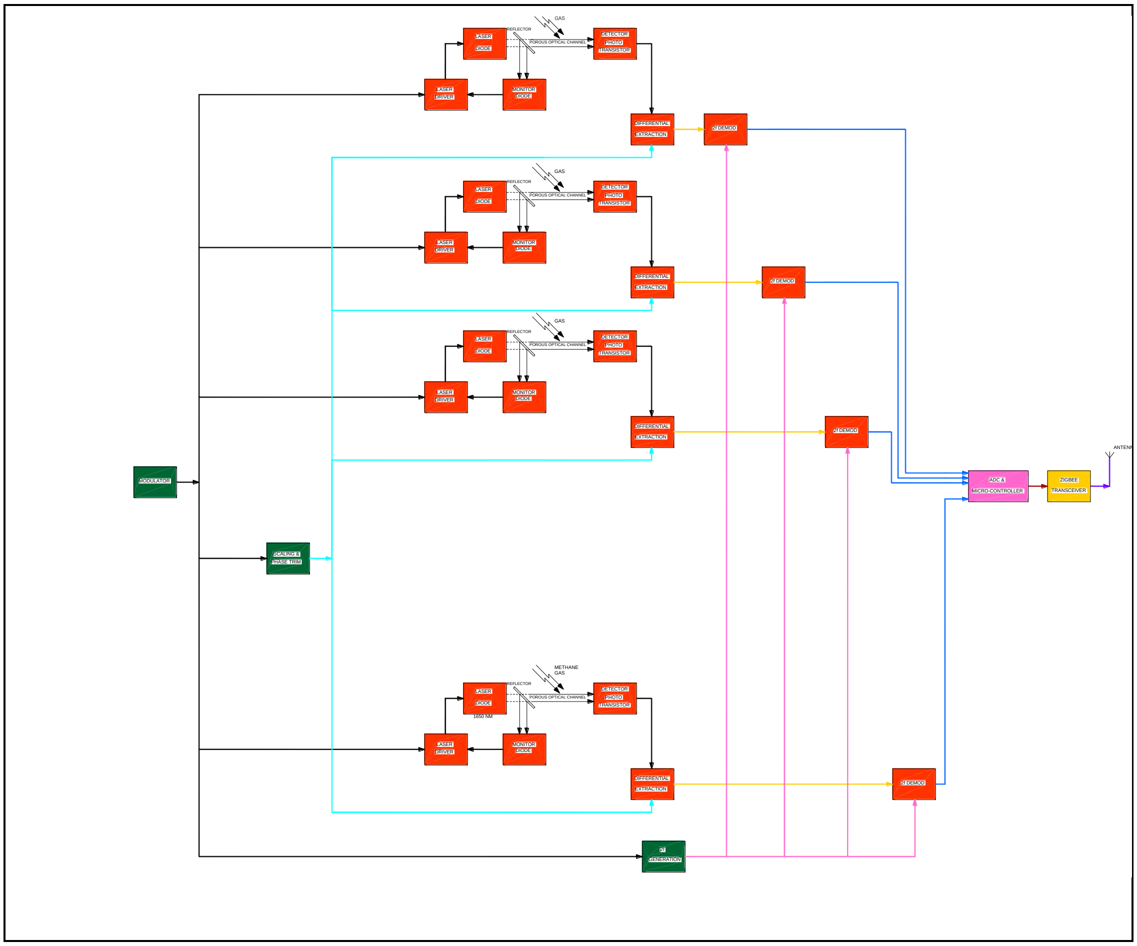


Figure 7-1: Future MSP Design for Multi Gas Sensing Network

9.0 REFERENCES

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[7] Silicon Laboratories Application Note AN222, ZigBee Development Board Hardware User's Guide.

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Appendix A
GAS MEASUREMENT THEORY

The laser based gas detection employs a basic fact that gases absorb optical radiation at unique wavelengths. These spectral gas absorption lines are very narrow and sharp. If a laser radiating at a central wavelength close to the absorption line of a gas is modulated such that its output wavelength is scanned across the absorption line of the gas, then in the presence of the gas the laser radiation is proportionally absorbed. A detector measuring the laser output measures reduced intensity every time the laser output wavelength coincides with that of gas absorption line, as shown in Figure A-1 If the laser is modulated at a frequency *f*, the laser wavelength scans across the gas absorption line twice in each cycle; thus the gas detection information is available at *2f* frequency. The amplitude of the absorption signal is proportional to the level gas distribution through which the laser light passes before being detected by the detector. This is illustrated in Figure A-2.

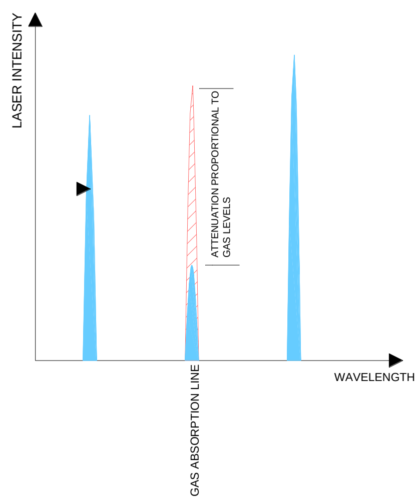

Figure A-1: Laser Radiation Absorbed at Gas Absorption Line

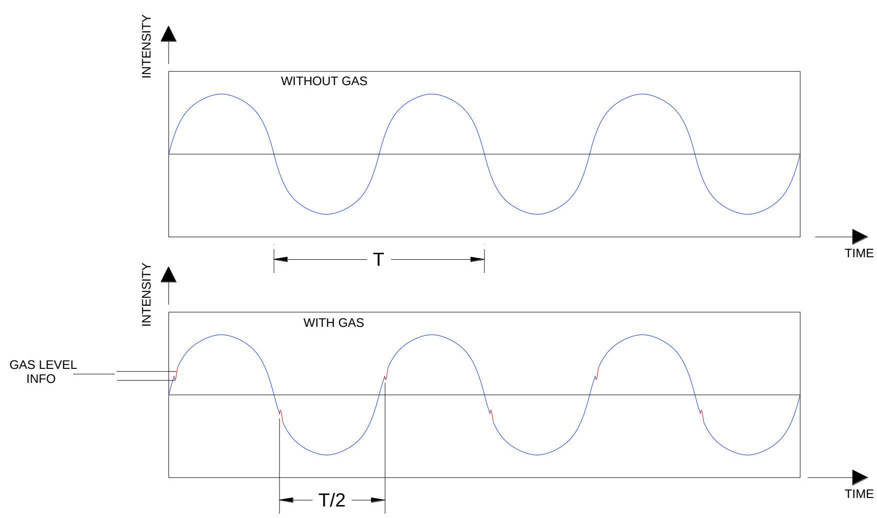

Figure A-2: Laser Radiation Affected by Gas in Time Domain

An analytical explanation of the above interactions can be provided as follows.

If the laser frequency ‘ν’ is modulated at the frequency ‘*f*’, with modulation amplitude ‘m’, then the transmitted intensity ‘I_T’ through the methane gas can be expressed as (for $m < 1$):

$$\begin{aligned} I_{T,m}(\nu) &= I_T(\nu + m\sin ft) \\ &= \left[I_T(\nu) + \frac{m^2}{4}\frac{d^2 I_T}{d\nu^2} \right] + \left[m\frac{dI_T}{d\nu} + \frac{m^3}{8}\frac{d^3 I_T}{d\nu^3} \right]\sin ft + \left[-\frac{m^2}{4}\frac{d^2 I_T}{d\nu^2} \right]\cos 2ft \end{aligned} \quad \text{(A-1)}$$

where the transmitted intensity I_T contains a DC term, a term with modulation frequency *f*, a term with twice the modulation frequency 2*f*, and so on. I_T is expanded as a series and its terms are combined (containing the first and second harmonic terms only). If phase-sensitive detection is performed at *f*, the co-efficient of the sin(*ft*) term can be extracted. Since ‘m’ is small, the coefficient of the sin(*ft*) term is essentially ‘m’ multiplied by the first derivative of the transmitted intensity (absorption). Similarly, detection at 2*f* yields the second derivative. The first harmonic signal (P_f) is proportional to the DC component of the initial laser power (I_{dc}) and AM ratio of the laser (m). $P_f \propto I_{Tdc} m$ The second harmonic signal (P_{2f}) is proportional to DC component of the initial laser power (I_{dc}), modulation depth, absorption coefficient and sample concentration. $P_{2f} \propto I_{Tdc} k \alpha_0 \times 2C$ where k is a coefficient dependent on modulation depth, α_0 is the absorption coefficient and C is the gas sample concentration. Hence, the detection at 2*f* is essential for measuring *C*. However, by making a ratio metric measurement (i.e. by dividing 2*f* signal by the *f* signal) the initial laser power gets cancelled, and one obtains a value dependent only on *C* -- the gas sample concentration.

Intuitively, if the entire output of the laser is utilized for sensing the device will be highly sensitive. This can be achieved by focusing the laser radiation via a lens into a waveguide such as a round or rectangular glass medium. However, a dense glass medium will not allow any gas to come in contact with the laser light. The gas and laser optics interaction is possible only if the glass has nano-pores that allow the permeation of the gas without much scattering loss of the laser light.

APPENDIX B

WOFSNet SCHEMATICS

On the basis of the measurement theory provided in Appendix A, the electronics for the MSP can be developed in two different ways. From equation A-1, a straight forward approach calls for the elimination of the DC and the sin(*ft*) term, and final demodulation of the 2*f* term. In the second approach, the detector output is digitized and run through a FFT algorithm, and from that ratio metric calculation are done to extract the gas sample measurement data.

In Phase I, the straight forward approach was implemented as it provides measurement transparency during the development process. Figure B-1 shows a block diagram of the measurement and the signal flow in the MSP. The schematics for all the blocks shown in Figure B-1 are provided in the succeeding Figures B-2 through B-8. Figure B-2 shows a single op amp based sinusoidal oscillator and a buffer. This circuit generates a 3 kHz sine wave output. Figure B-3 shows a circuit for laser diode (LD). No thermo-electric cooling is used, instead the laser drive is limited to produce only 50% of the LD maximum power. To maintain a stable output, approximately 3% of the LD is directed to a monitoring diode (MD) which provides a feedback to the LD driver to maintain a stable output. The modulator signal from Figure B-2 drives the laser. About 97% of the laser output is launched into a porous waveguide which is soaked in the gas sample. The light exiting the wave guide is detected by the detector circuit shown in Figure B-4. The differential extraction circuit shown in Figure B-5 removes most of the DC and 1*f* contents from the detector output. The modulator signal is scaled and phase trimmed from the detector output for the differential extraction. Figure B-6 shows a 2*f* demodulation of the differentially extracted signal. The modulator output is rectified to generate a 2*f* reference. Thus, a DC output proportional to the methane level is obtained after the 2*f* demod.

The sensed output is routed to the A/D pin# 16 of the MSP microcontroller (MC9S08QG8) which in turn is interfaced with the ZigBee wireless transceiver MC13202 (Schematics in Figures B-7 and B-8). The Rx and Tx chip antenna is connected to the transceiver via an RF switch.

The host module uses the same ZigBee wireless transceiver MC13202 which is controlled by MC68HC908JW32FC (Schematic in Figures B-9 and B-10). This microcontroller also includes a USB interface controller to communicate with a miniature host computer.

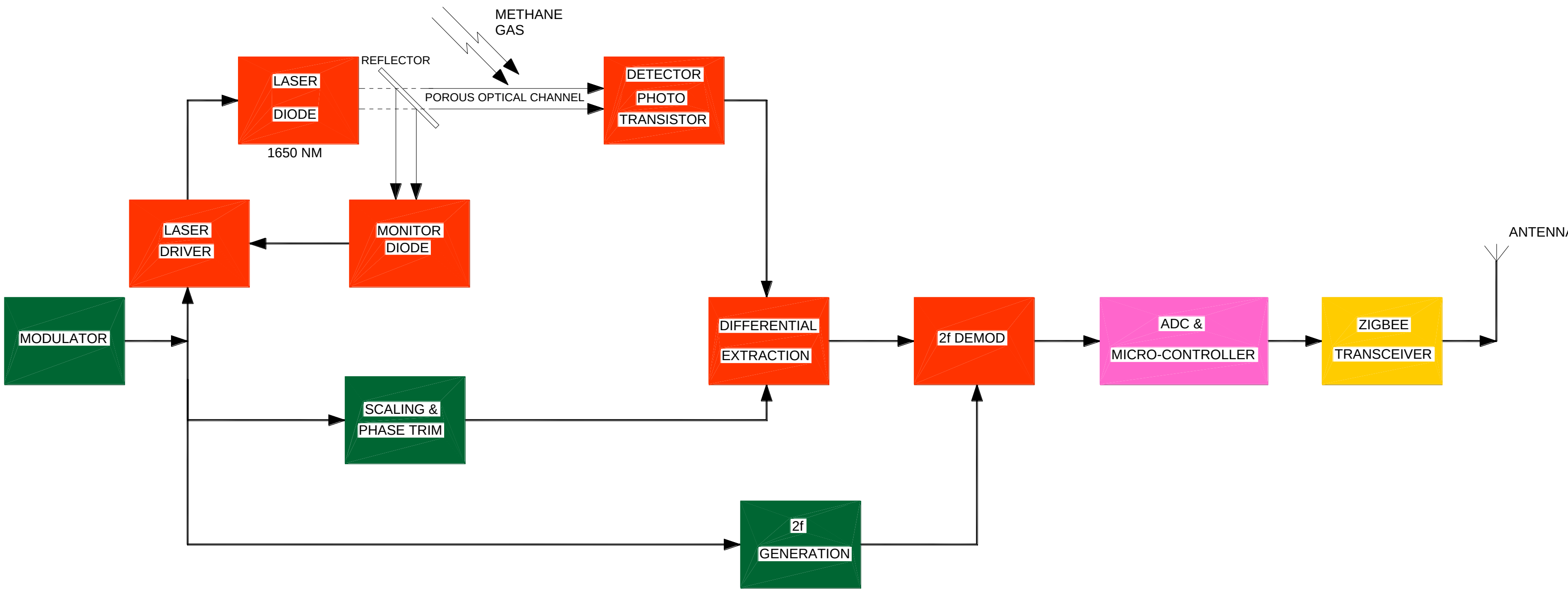

Figure B-1: BLOCK DIAGRAM OF METHANE SENSOR PACK (MSP)

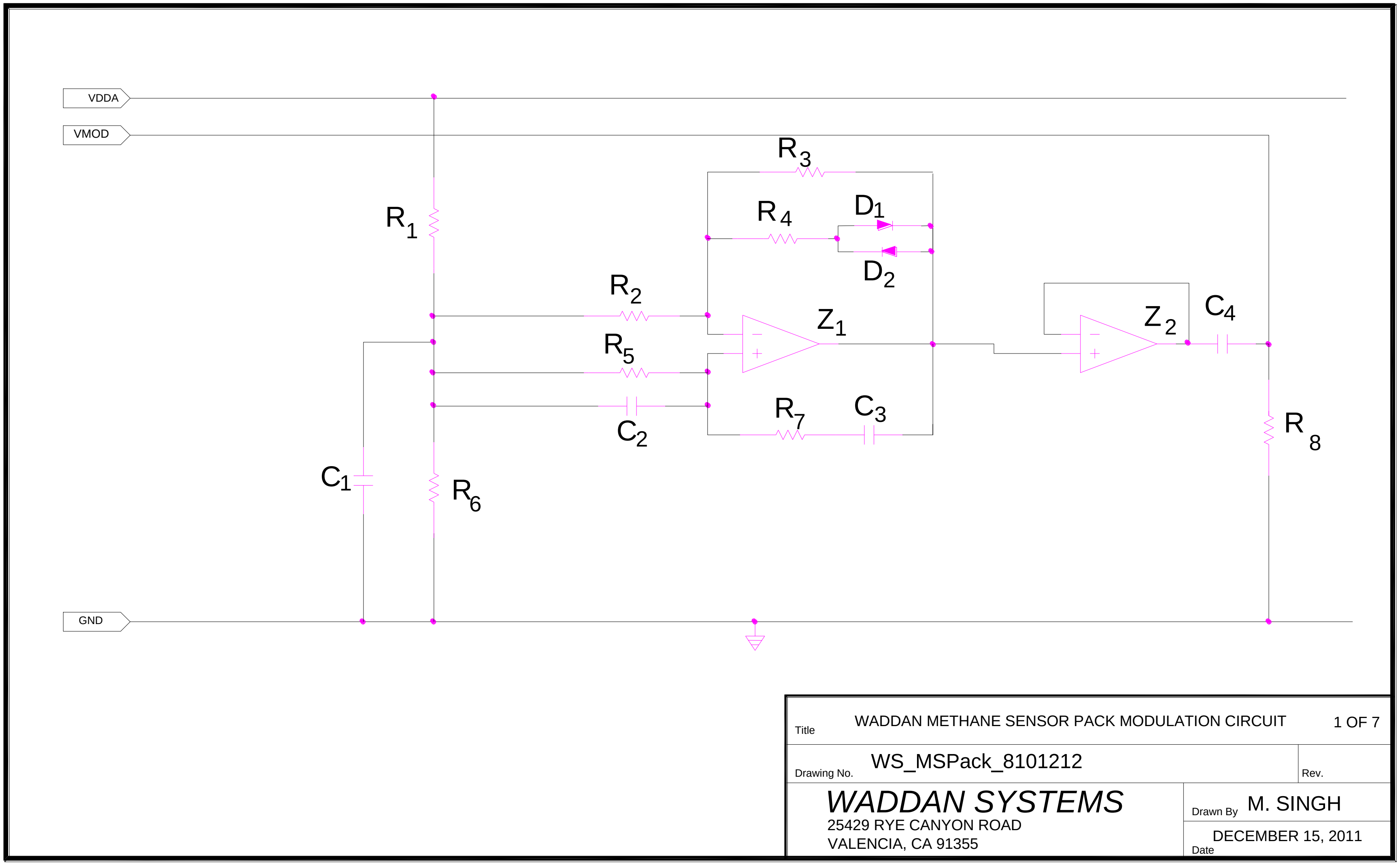

Figure B-2: SINUSOIDAL MODULATION CIRCUIT

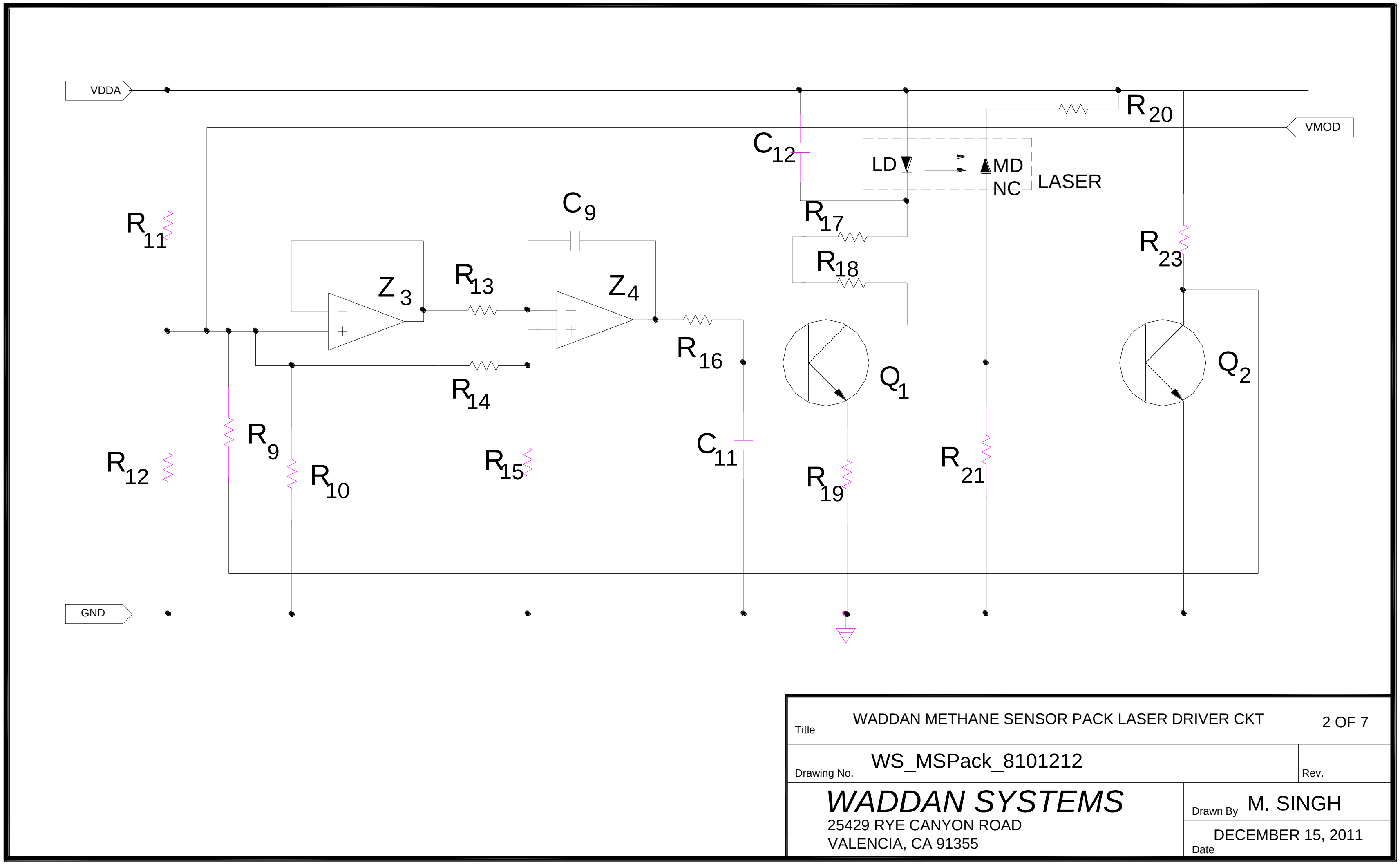

Figure B-3: LASER DRIVER CIRCUIT

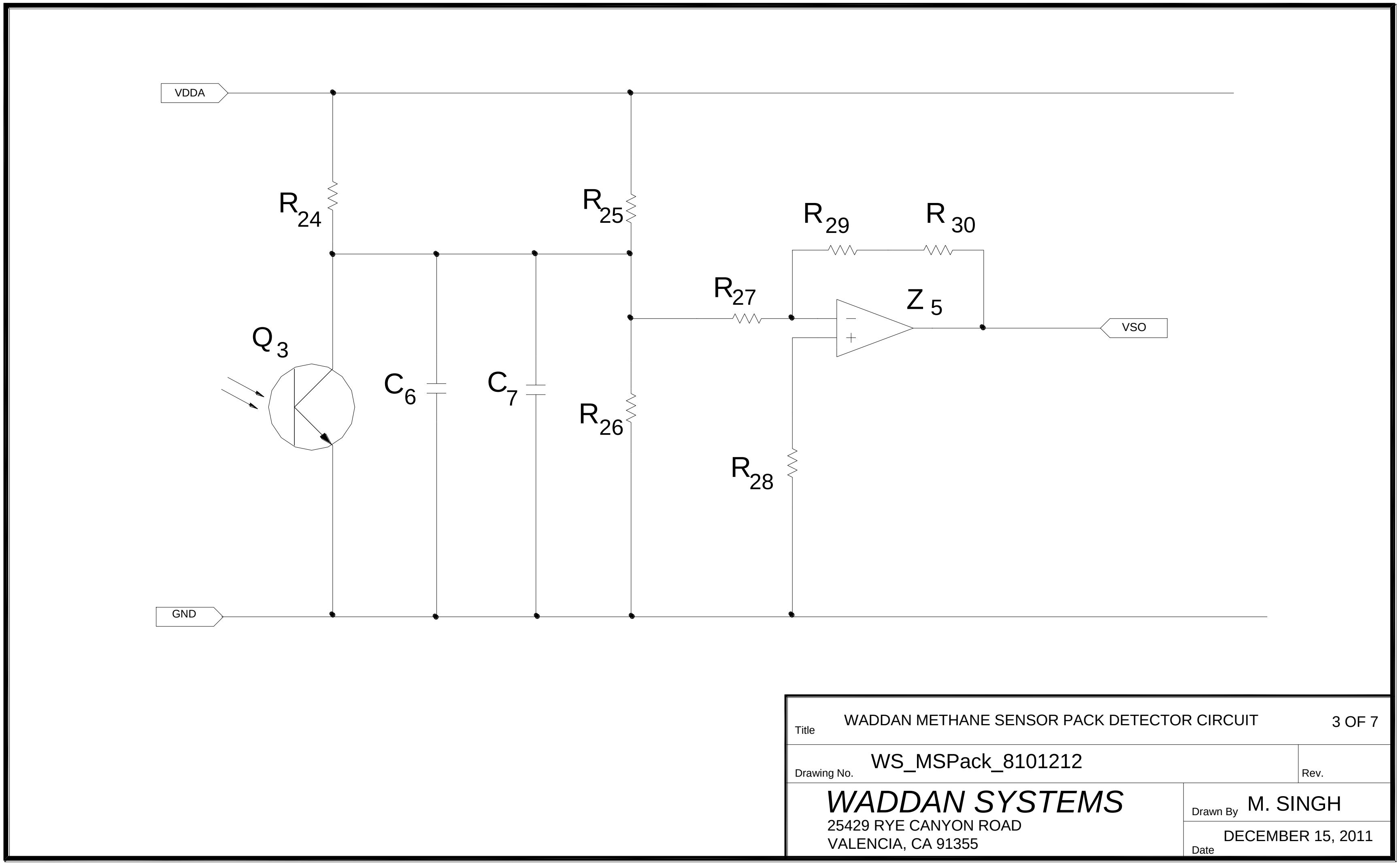

Figure B-4: OPTICAL DETECTION CIRCUIT

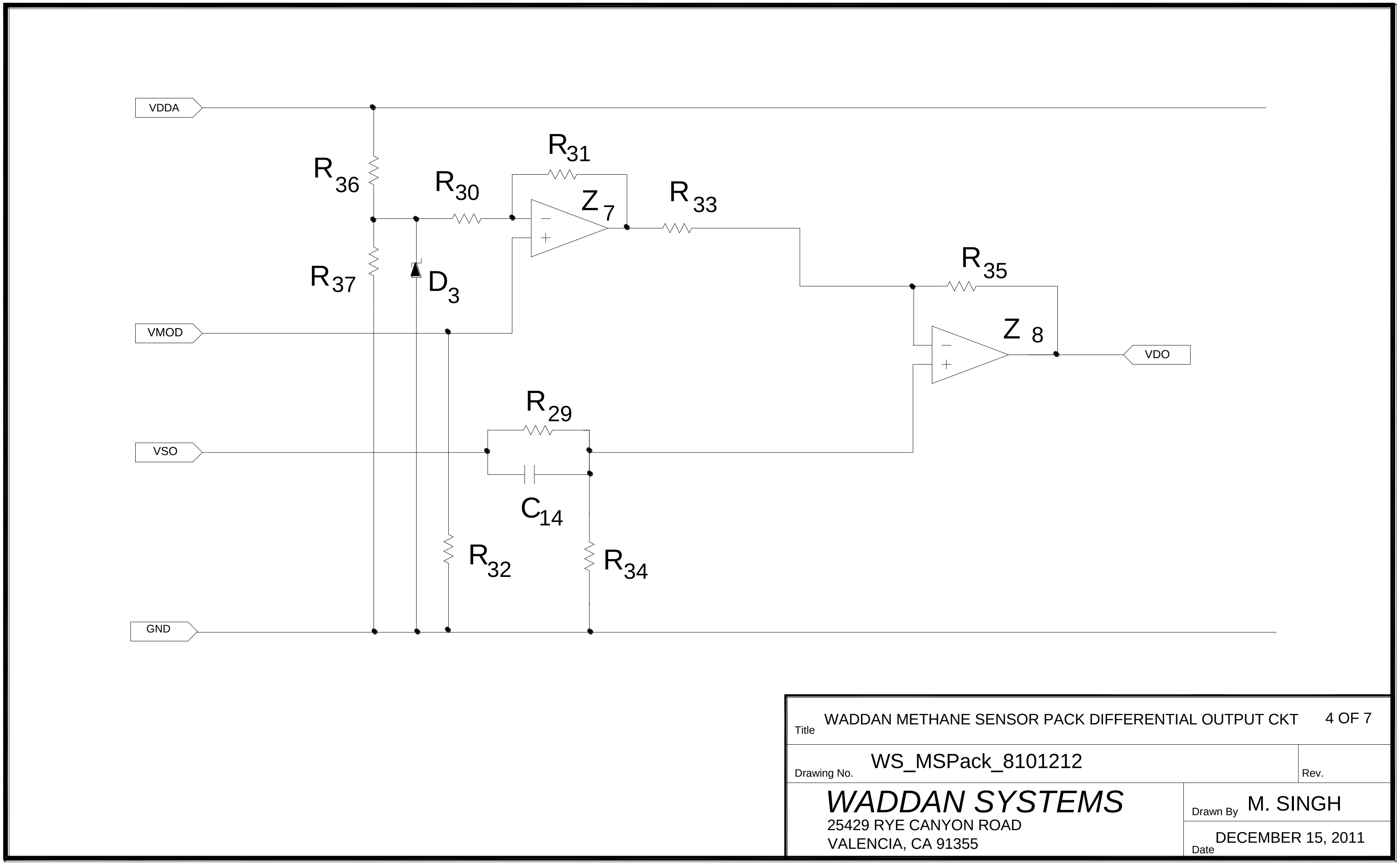

Figure B-5:DIFFERENTIAL EXTRACTION CIRCUIT

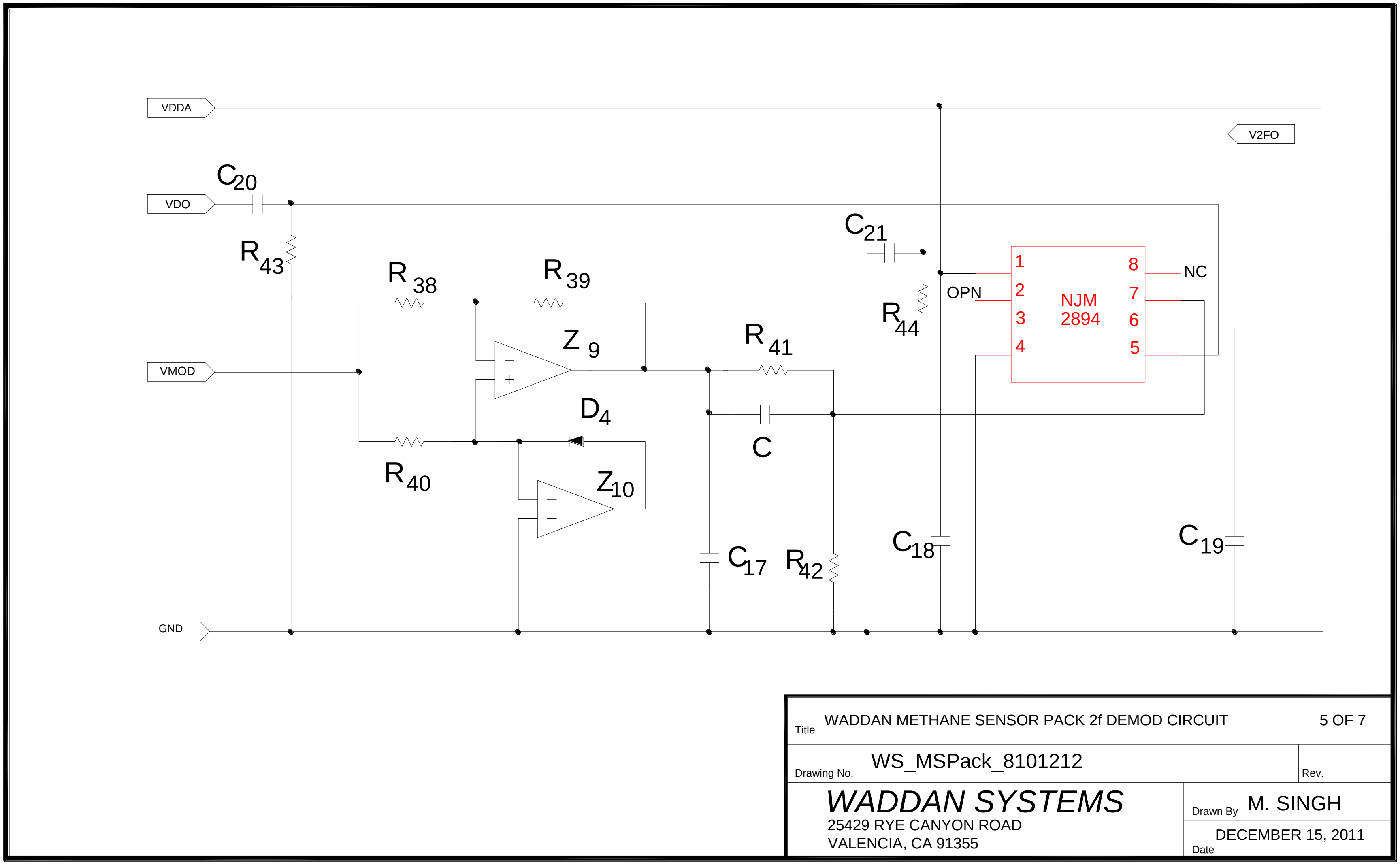

Figure B-6: 2f-DEMOD CIRCUIT

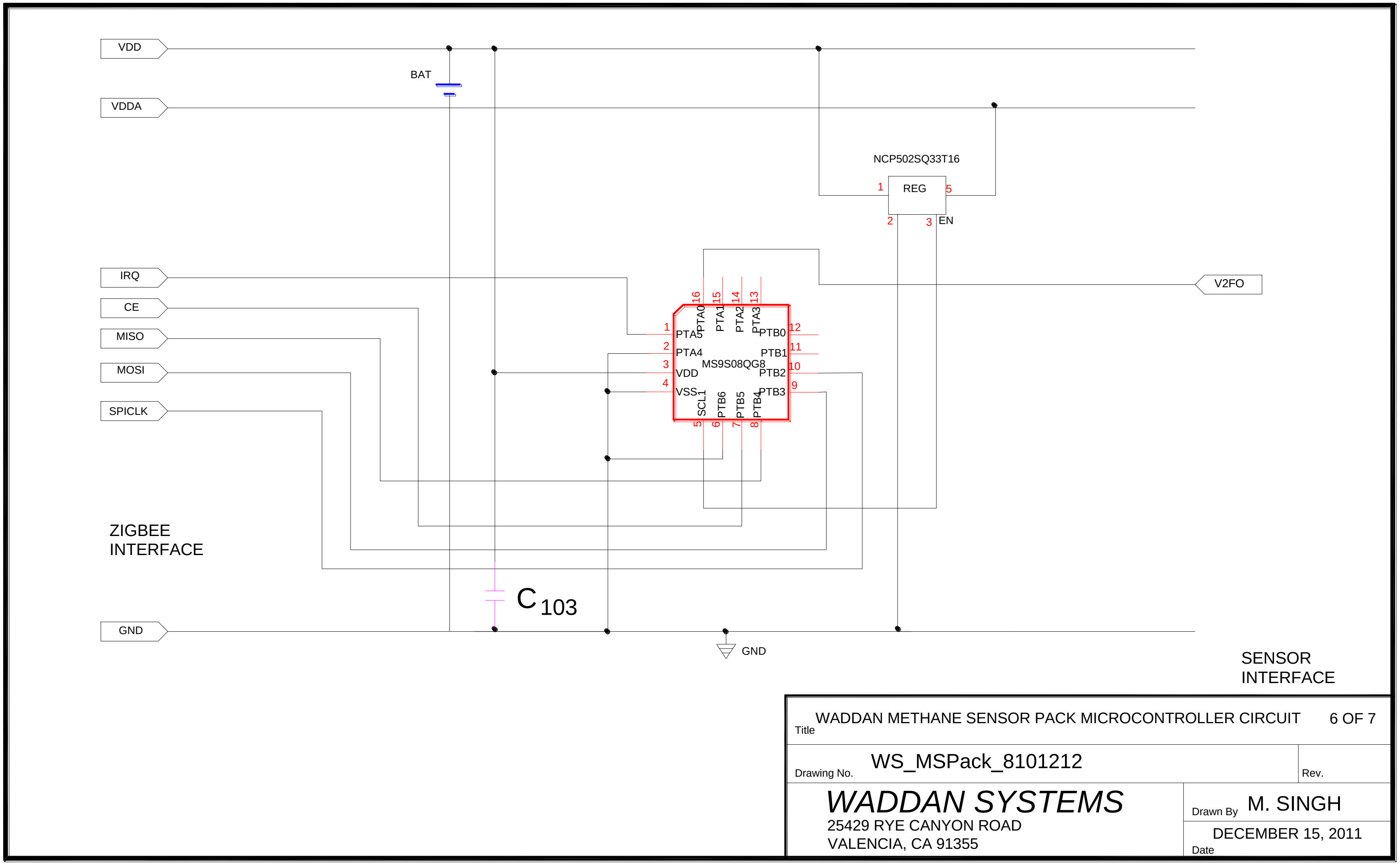

Figure B-7: MSP MICRO-CONTROLLER CIRCUIT

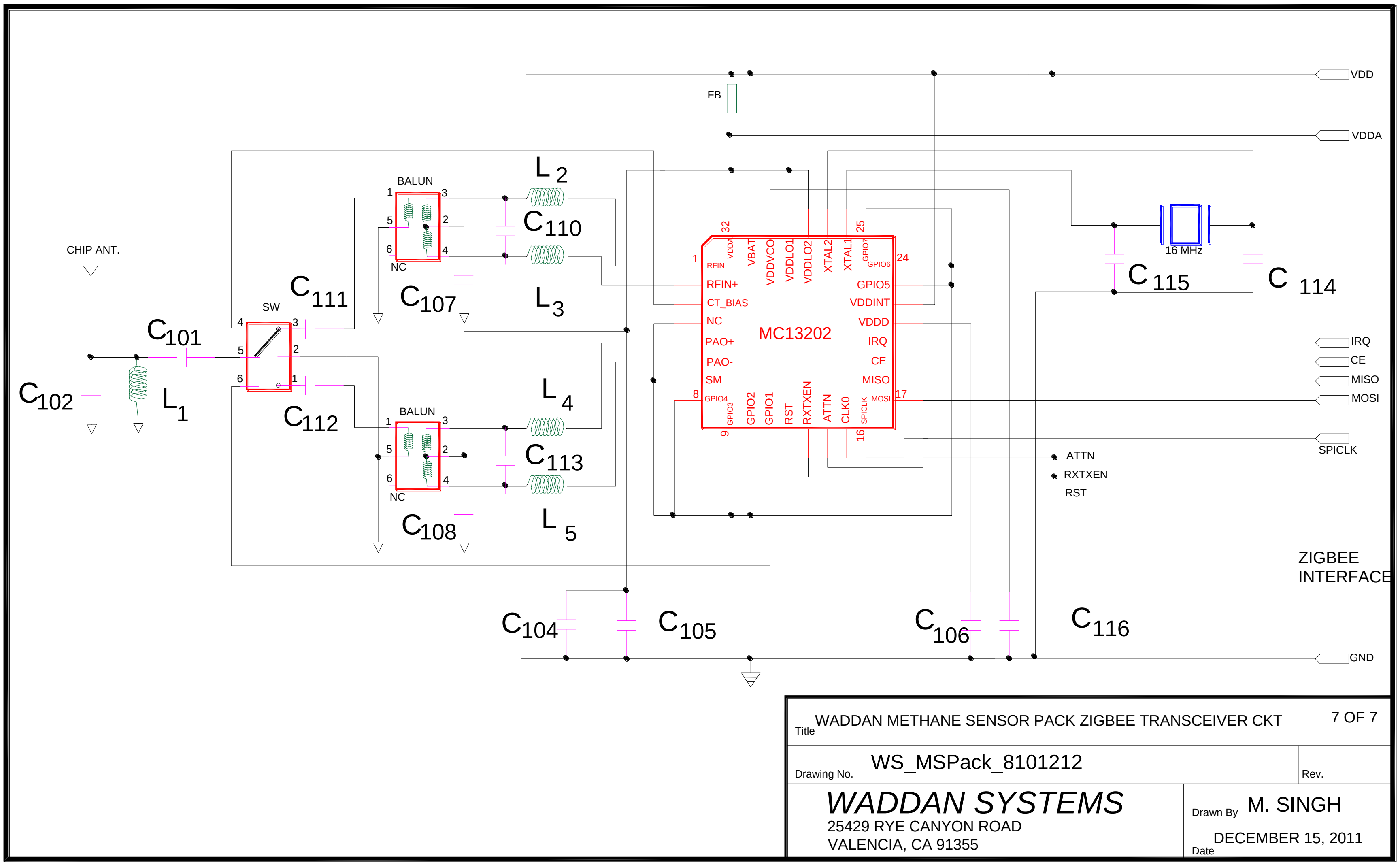

Figure B-8:MSP TRANSCEIVER CIRCUIT

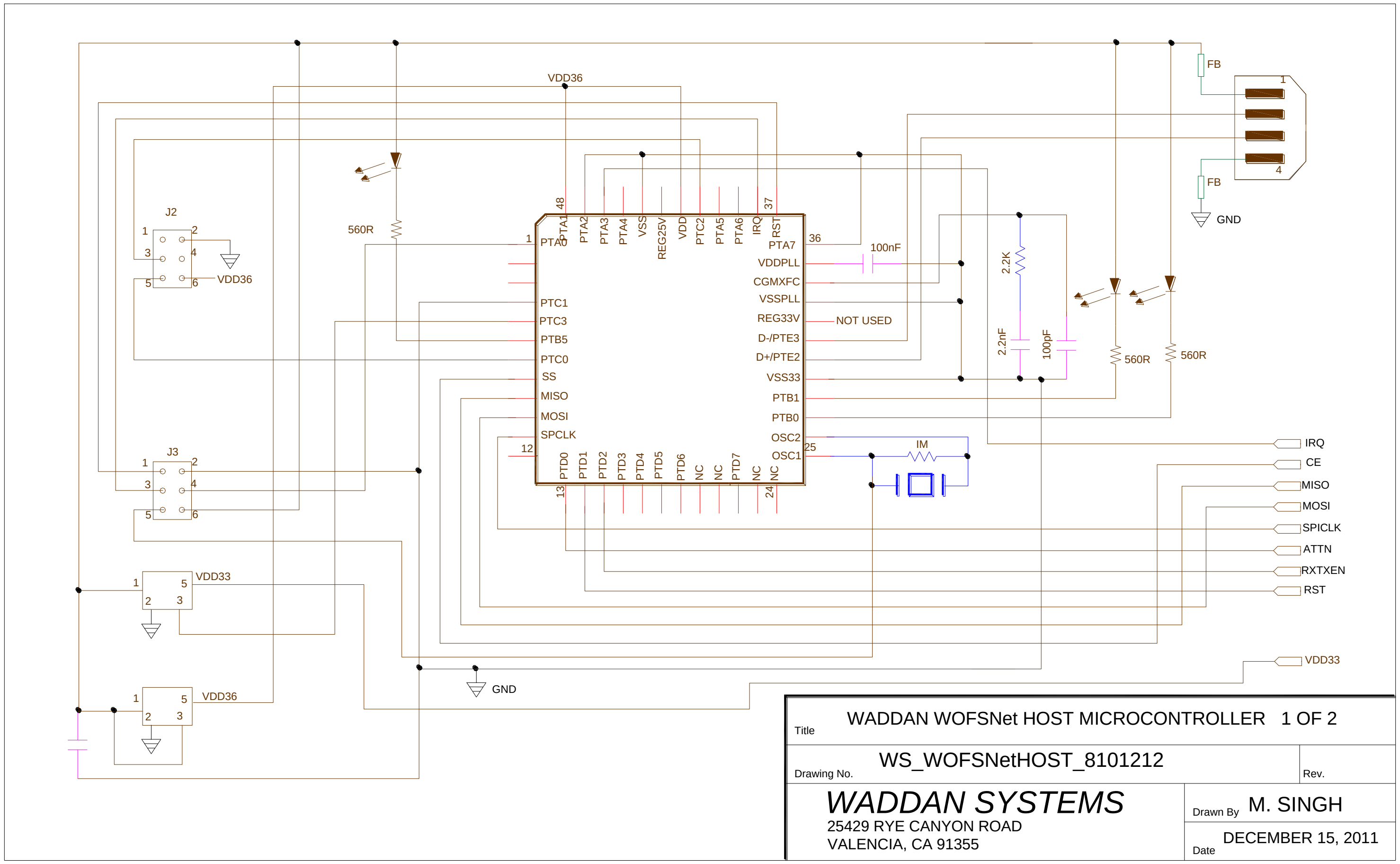

Figure B-9: HOST MICROCONTROLLER

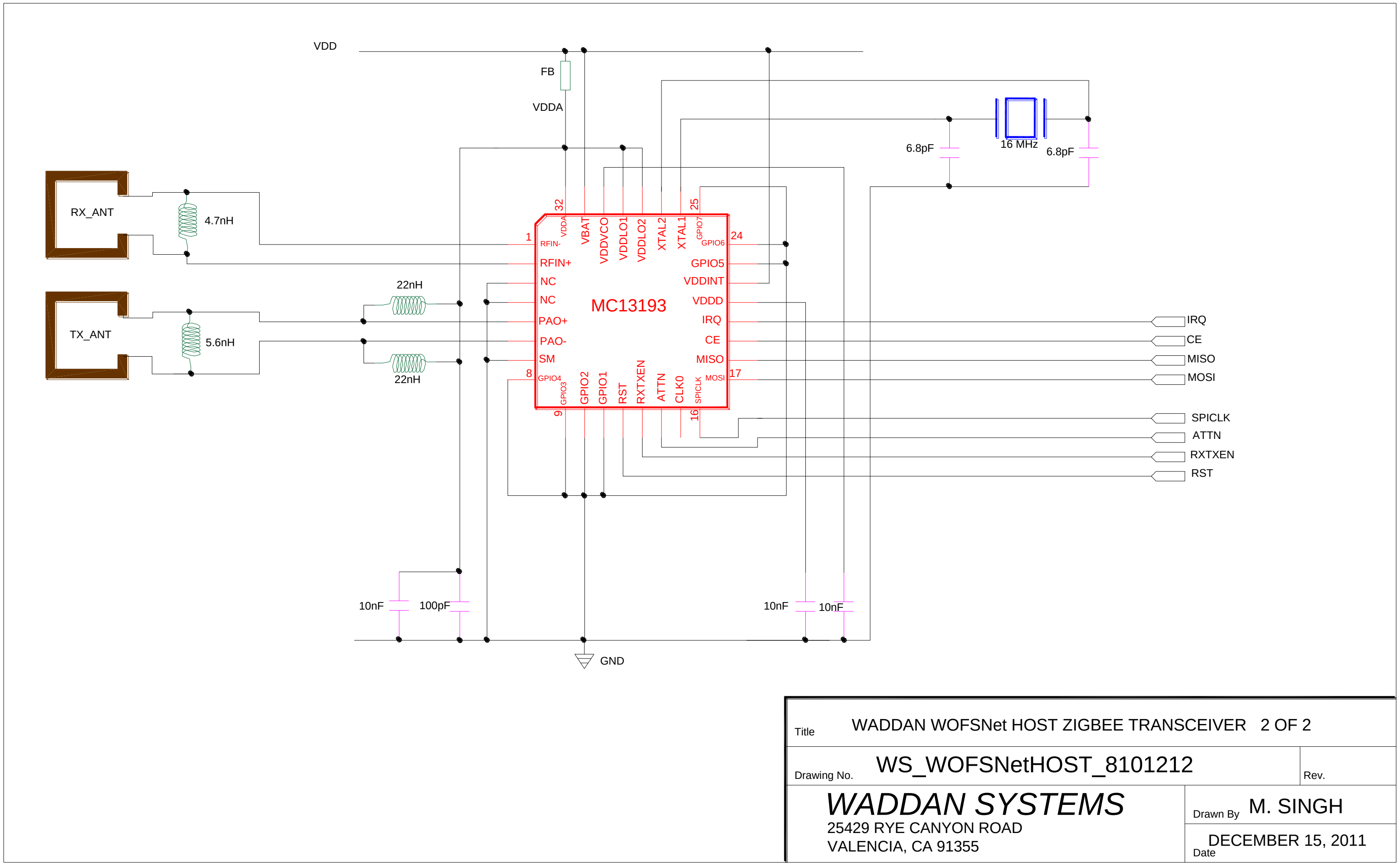

Figure B-10: Host ZigBee