PHOTONICS

5b Optically powered sensors and sensory systems 1 part

Dr.h.c . Prof. RNDr. Ing. Ján Turán, DrSc.
KEMT FEI TUKE

Summary

- Advantages of Microelectronic Sensors
- Advantages of Fiber Optics and partially Fiber Optic Sensors
- Optically Powered Sensors (OPS)

  Fiber optic powered sensors (FOPS)

  basic block scheme and generalized architectures
- OPS system power budget model
- OPS industrial applications
- Optically powered industrial barometric system
- OPS Products

Advantages of microelectronic sensors

- Simplicity of implementation (well understood techniques)
- Simple construction
- Easy and low powering
- Low cost
- High accuracy (with possible embedded data processing, intelligence)
- Possibility of miniaturization and integration
- Output signal is easy to evaluate (frequency, digital outputs)
- Output information can be simply evaluated by microcomputer or signal processor

Disadvantages of microelectronic sensors

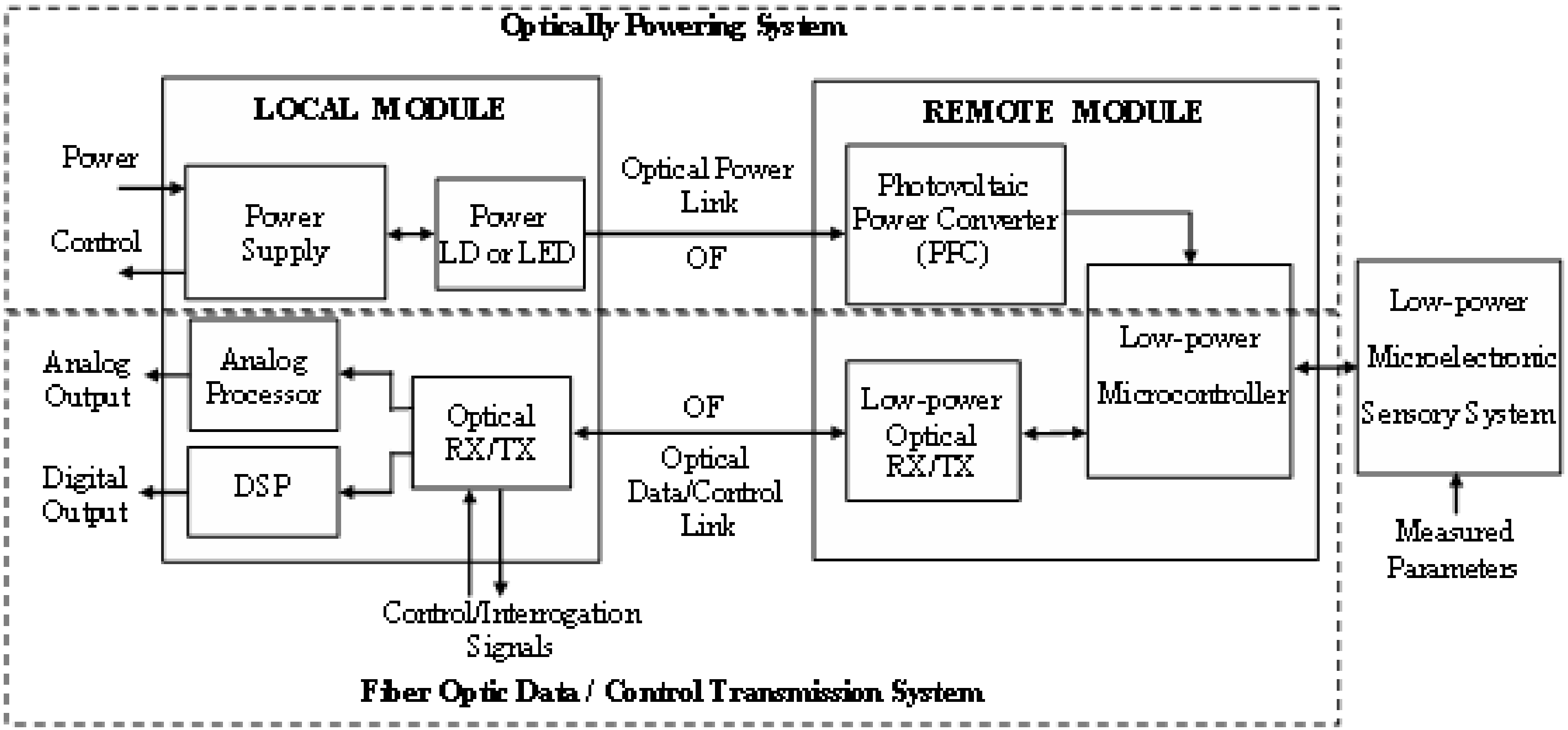
- **Electrical transmission of information and powering, i.e. they are not tolerant to EMI**
- **Data transmission rate is very low**
- **Cannot be used in explosive, corrosive, high-voltage or high-current environment**
- **Cannot be used for sensing in gasoline, mining or electrical power industry**

- OPS can solve the disadvantages of microelectronic sensors, by hybridization of fiber optic and microelectronic technologies.
- The basic principle of this sensory systems is using optical fibers for transmission of control and measurement information, as well as for optically powering of remote microelectronic sensory system.

Advantages fiber optic and partially Fiber Optic Sensors

- Immunity to electromagnetic interference (EMI)
- Low thermal and mechanical inertia
- More sensitive than others sensors
- Can be used in: electrically noisy, corrosive, explosive, high-voltage, high-current, or high-temperature environments
- Use of fiber optic telemetry systems exhibit some advantages of fiber optic communication systems, providing telemetry over long distances and the possibility of control, interrogate or multiplexing many sensors or sensors for different measured into a single system

Optically Powered Sensors



Basic block scheme of OPS system

Optically Powered Sensors

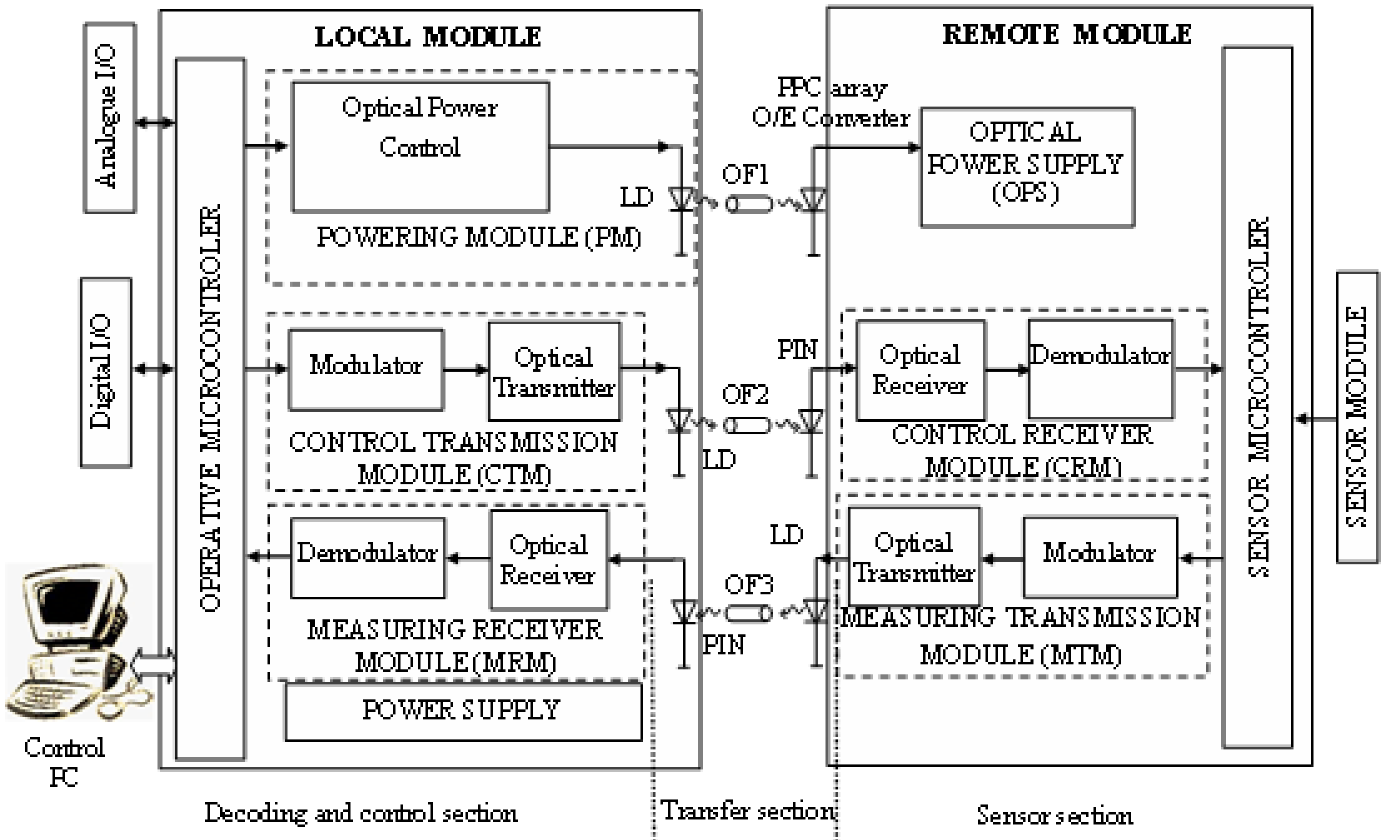
Possible architectures of OPS systems can be classified according to the number of OF used

- **OPS systems with three OF**
- **OPS systems with two OF**
- **OPS systems with one OF**

Multiplex of optical powering and optical transmission

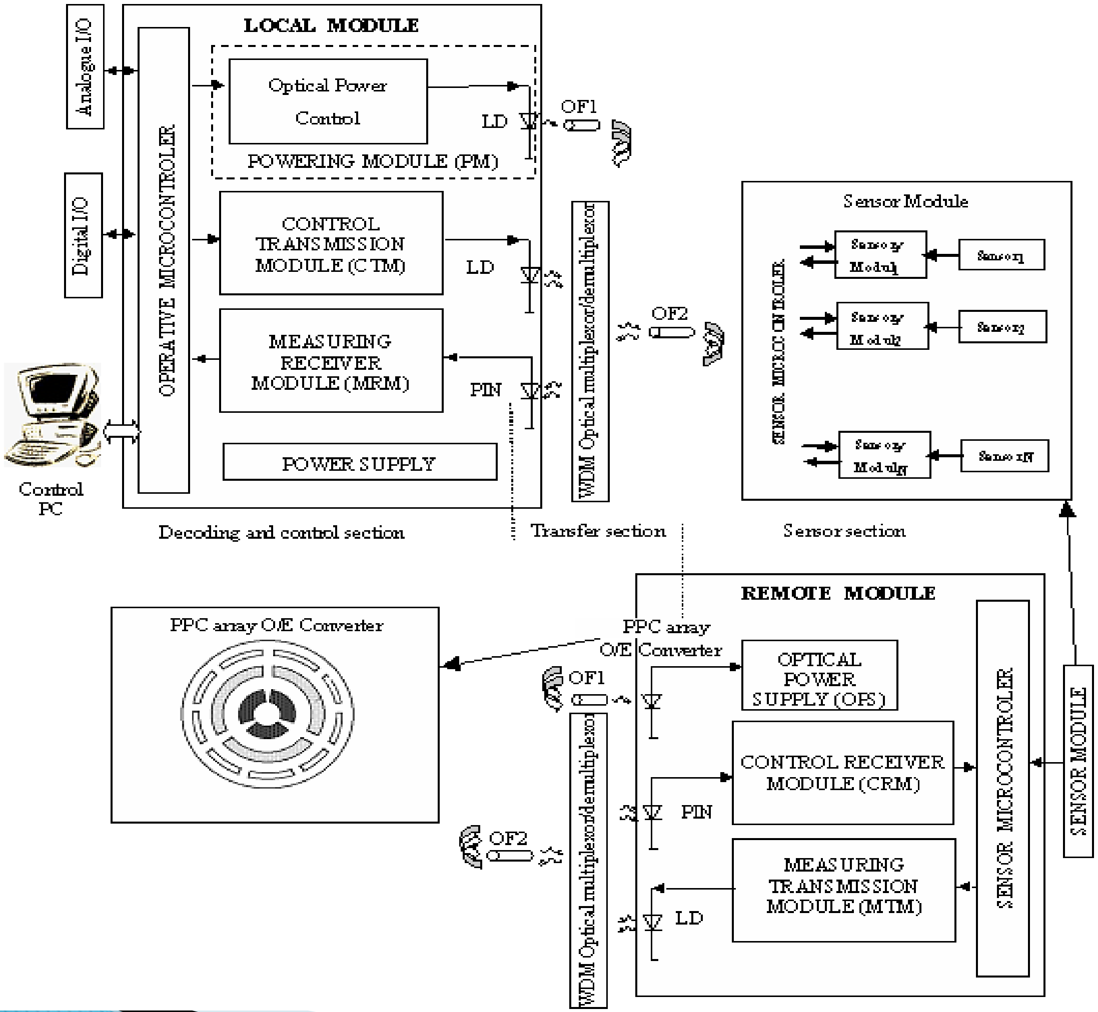
- **Space multiplex**
- **WDM**
- **Both**

Optically Powered Sensors



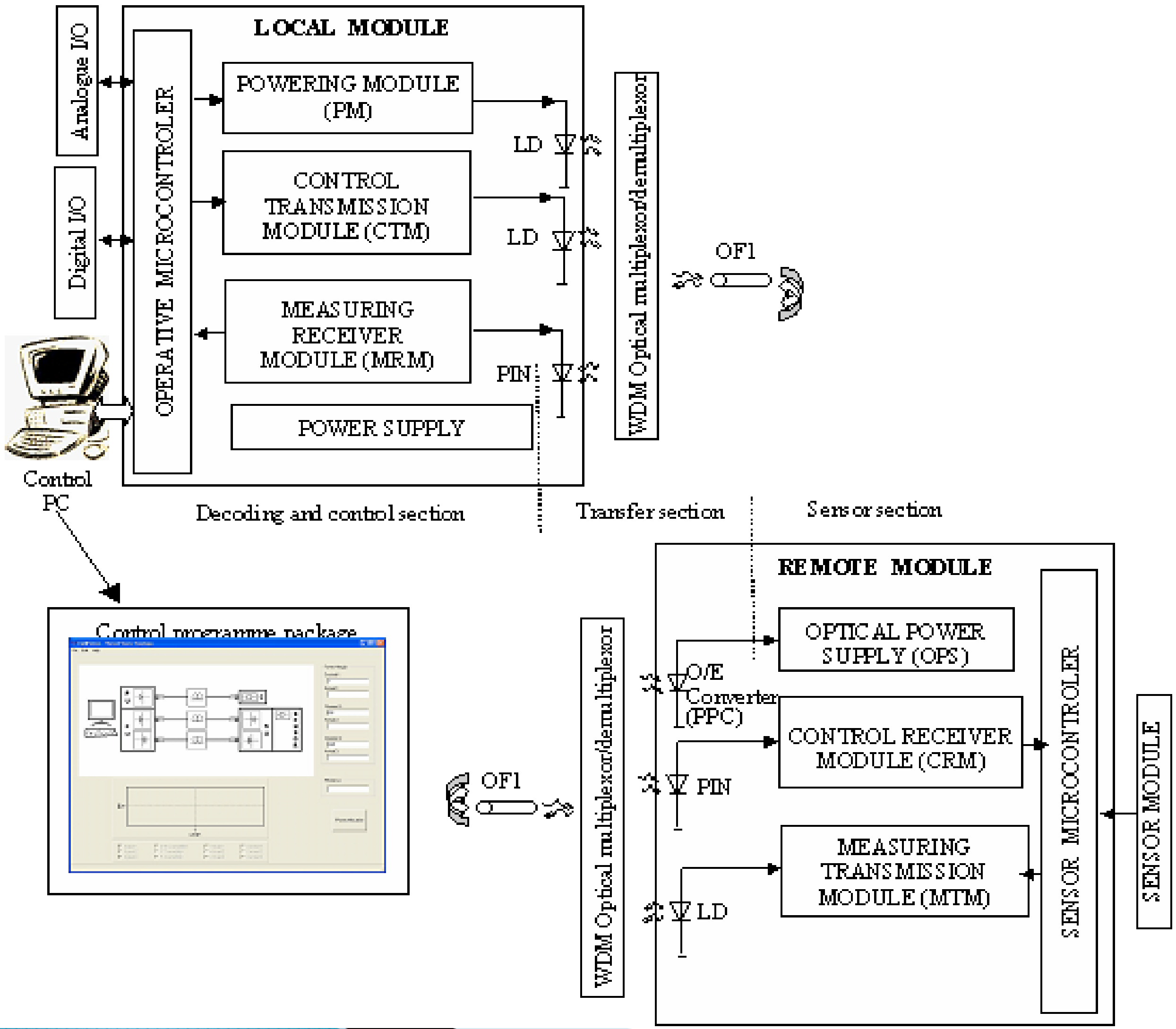
OPS system with three OF

Optically Powered Sensors



OPS system with two OF

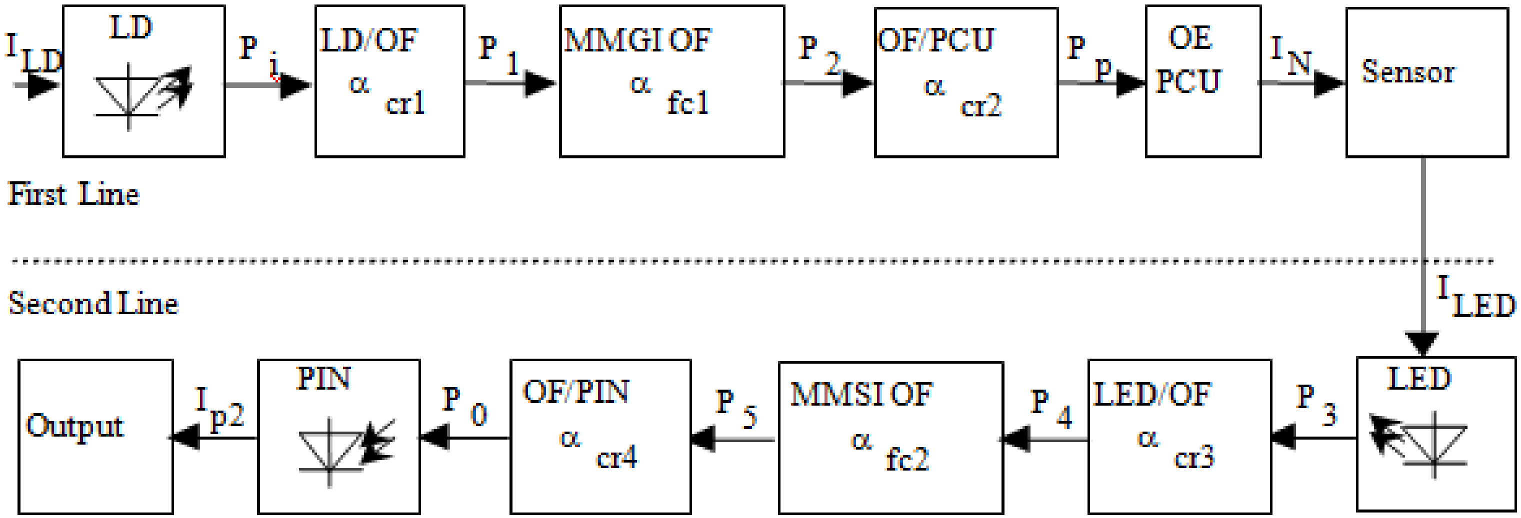
Optically Powered Sensors



OPS system with one OF

OPS system power budget model

Power transmission in OPSS can be modelled as two independent optical lines. The first one is used for the powering of the Remote Module and the second one is used for the transmission of the measuring optical signal from the Remote Module to the Local Module.



Signal transfer path of in OPSS

OPSS power budget model

Total loss C_L may be expressed in the form

(1)

$$C_L = \alpha_{fc1} L_1 + \alpha_{fc2} L_2 + \alpha_{cr1} + \alpha_{cr2} + \alpha_{cr3} + \alpha_{cr4} + \alpha_s$$

L_1, L_2 is length of used optical fibres; α_s is equivalent loss due to power consumption of the sensor. The power balance for both optical lines is

(2)

$$P_i(dB) = P_0(dB) + C_L(dB) + M_a(dB)$$

where P_i is input power, P_0 is output power, C_L is total line attenuation and M_a is system safety margin. Using (1) expression (2) can be write in the form

(3)

$$P_i = P_0 + \alpha_{fc1} L_1 + \alpha_{fc2} L_2 + \alpha_{cr1} + \alpha_{cr2} + \alpha_{cr3} + \alpha_{cr4} + \alpha_s + M_a$$

This equation describes general power balance for modelled OPSS.

OPSS power budget model

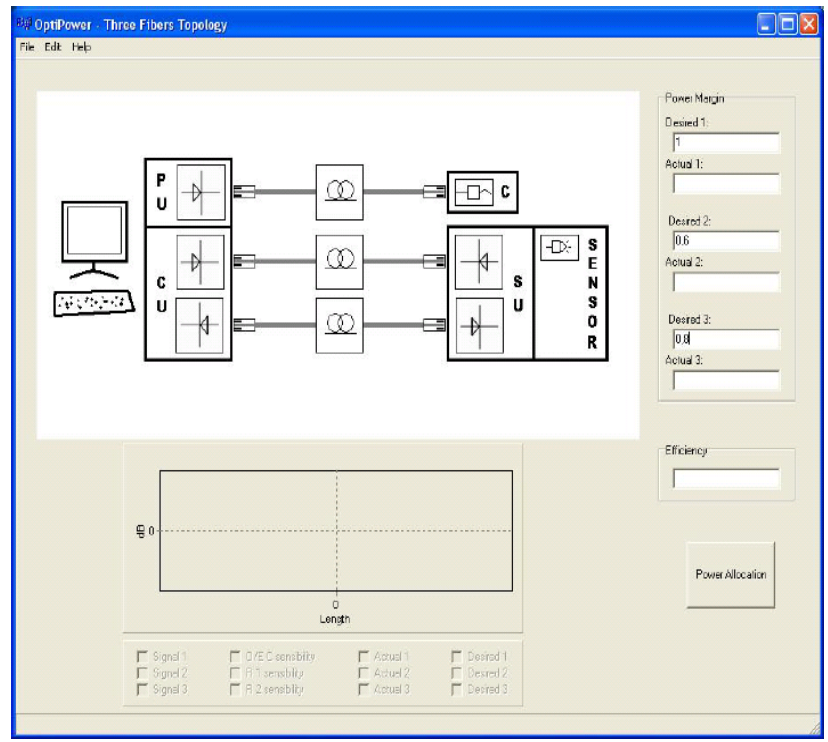
Table 1

Power balance of OPSS

I_{p2}	3.47 nA		I_N	30 µA	
P_0	6.3 nW	-52.0 dBm	P_N	45 µW	-13.4 dBm
α_{cr4}		0.8 dB	η	15%	
P_5	7.6 nW	-51.2 dBm	P_P	300 µW	-5.22 dBm
α_{fc2}		10 dB	α_{cr2}		0.8 dB
P_4'	75.85 nW	-41.2 dBm	P_2'	360 µW	-4.42 dBm
M_{a2}		7 dB	M_{a1}		6 dB
P_4	380 nW	-34.2 dBm	P_2	1.43 mW	1.58 dBm
α_{cr3}		12.4 dB	α_{fc1}		2 dB
P_3	6.6 □W	-21.8 dBm	P_1	2.28 mW	3.58 dBm
P_{LED}	0.47 mW	-3.28 dBm	α_{cr1}		3 dB
P_{LEDm}	43 mW	+16.3 dBm	P_i	4.5 mW	6.6 dBm
			I_{LD}	146 mA	

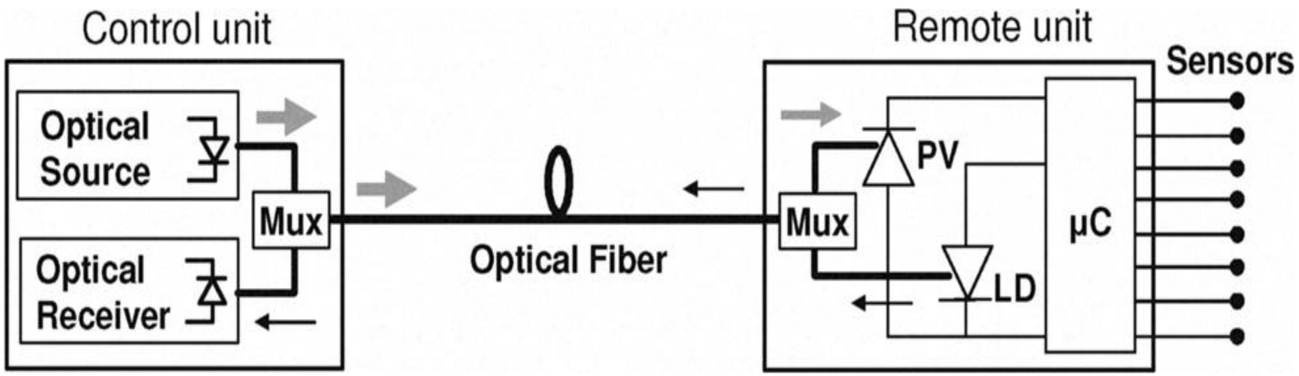
OPSS power budget model

"OptiPower" programme package for OPSS power budget modelling was developed at KEMT FEI TUKE

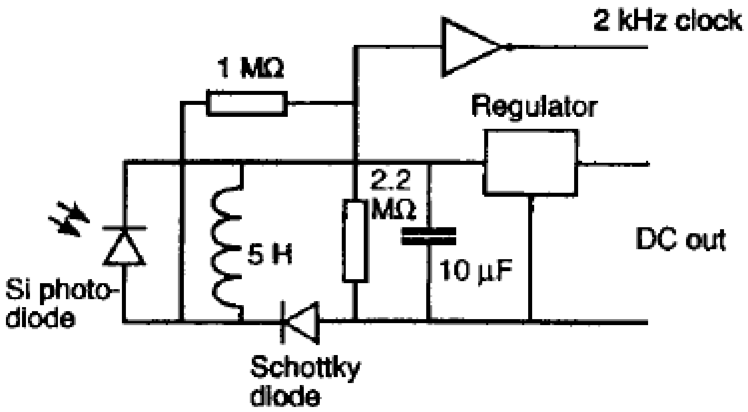


OptiPower opening screen and primary menus

Fiber powering sensory system

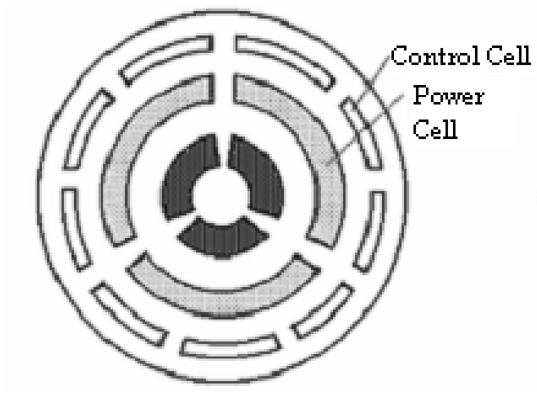


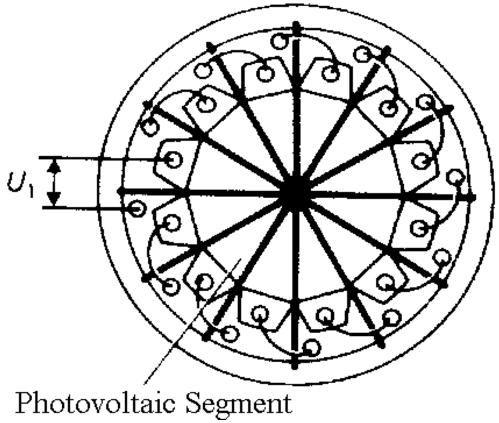
- Power LD at 810 nm
  - Normally used for medical applications
  - Maximum power between 2 or 3 W
- Other options Fiber Lasers at 1480 nm and 980 nm
  - Maximum output power less than 500 mW
- Optical receiver is PIN PD followed by transimpedance amplifier
- 2 MM OF with core diameter of *50 or 62.5 µm*
- SM OF can be used if energy transmission is at 980 nm and 1480 nm



Simple PPC circuit
Peak optical power of 2 mW
Delivered to PPC
Electrical power 160 µW
after conversion to 2.5 V

- **Light wavelength from near infrared region (800-1000 nm)**
- **Loss in OF low**
- **Permits use Si or GaAs PPC**
- **Terminal voltage for Si PPC is 0.4-0.5 V, for GaAs PPC 0.6 V**
- **Voltage from a single PPC is too small to be of direct use to power an electronic circuit - necessary to use either an array of PPC in series, or some form of upconversion**
- **Disadvantage of D.C.-D.C. power converter - requires inductance or transformer (relatively bulky) and hazard for system in flammable or explosive atmosphere**





PPC array

- GaAs based PPC at 810 nm with 35% efficiency
- Cheap Si PPC at 810 nm with 15% efficiency
- For 1480 nm InP PPC
- Standard voltage outputs: 2.8, 3.3, 5, 10 V DC

Maximum distance reached by a PPSS

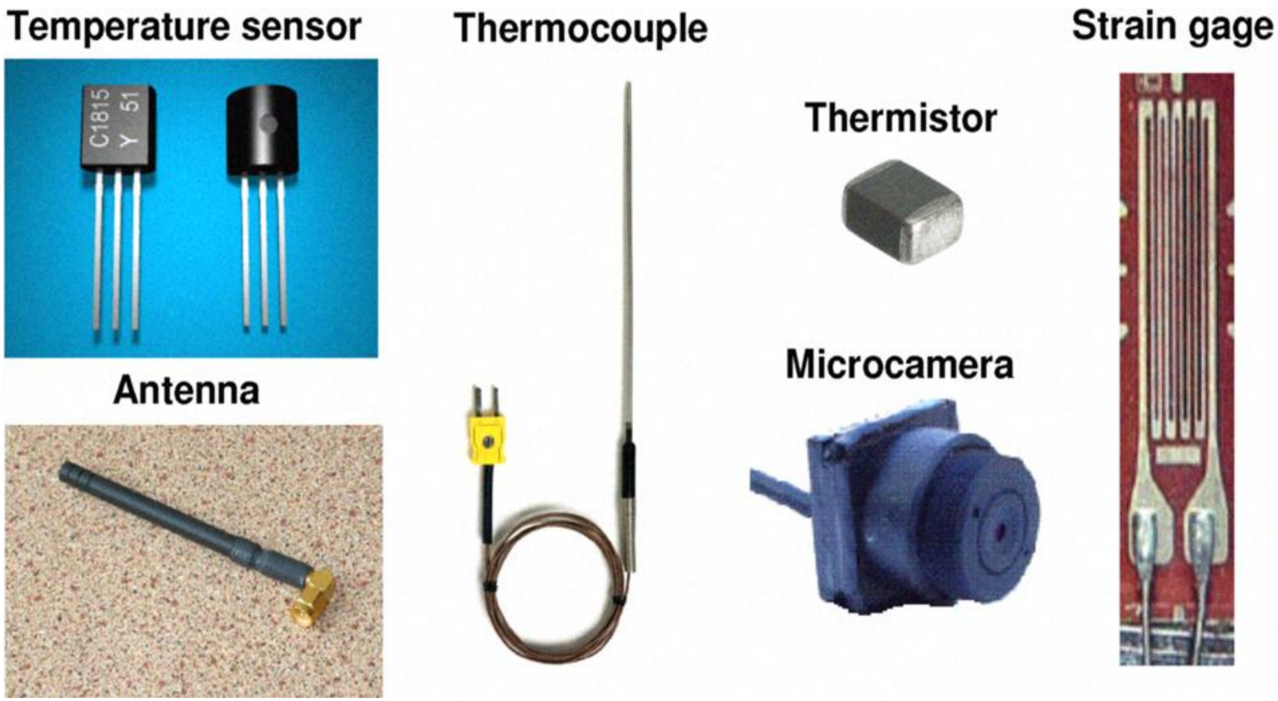
Example 1

- 2 W (33 dBm) LD source at 810 nm
- OF attenuation of 3 dB/km
- Optical power in PPC must be
  27 dBm for GaAs PPC with
  35% efficiency
  30 dBm for Si PPC with 15% efficiency
- Maximum distance will be of 2 km and 1 km, resp.

Example 2

- For two 0.5 W (30 dBm) LD at 1480 nm
- One InP PPC
- OF attenuation of 0.27 dB/km
- Maximum distance will be 11 km

Typical microelectronic sensors available on market



PPSS bandwidth

- Bandwidth for PPSS is measured in terms of bit rate of microcontroller
- Bit rate as low as 9600 BPS can transmit the information of 16 electronic analog sensors coupled to the microcontroller in few milliseconds
- Bit rate can be turned faster and more complex circuits
- This increase in the system power consumption

PPSS safety in explosive environment

- Sensing in explosive environments
  petroleum storage, natural gas production and
  oil and flammable gas reservoirs
- Power carried by FO can induced explosion in this applications
- Explosion depends on power level density in fiber core,
  explosive particle material size and ignition time
- Optical flux of 10^{-7} W/m^2 *can induce an* ignition of flammable gas
- For SM OF of 9 µm core diameter critical optical power is ~ 6 µW
- For MM OF of 62.5 µm core diameter critical optical power is ~ 300 µW
- For typical values carried by OF in PPSS techniques
  the critical values are far outweighed
- Induced explosion will only occur if the optical cable is broken and
  the fibers are exposed to the flammable material

Typical cost for a PPSS

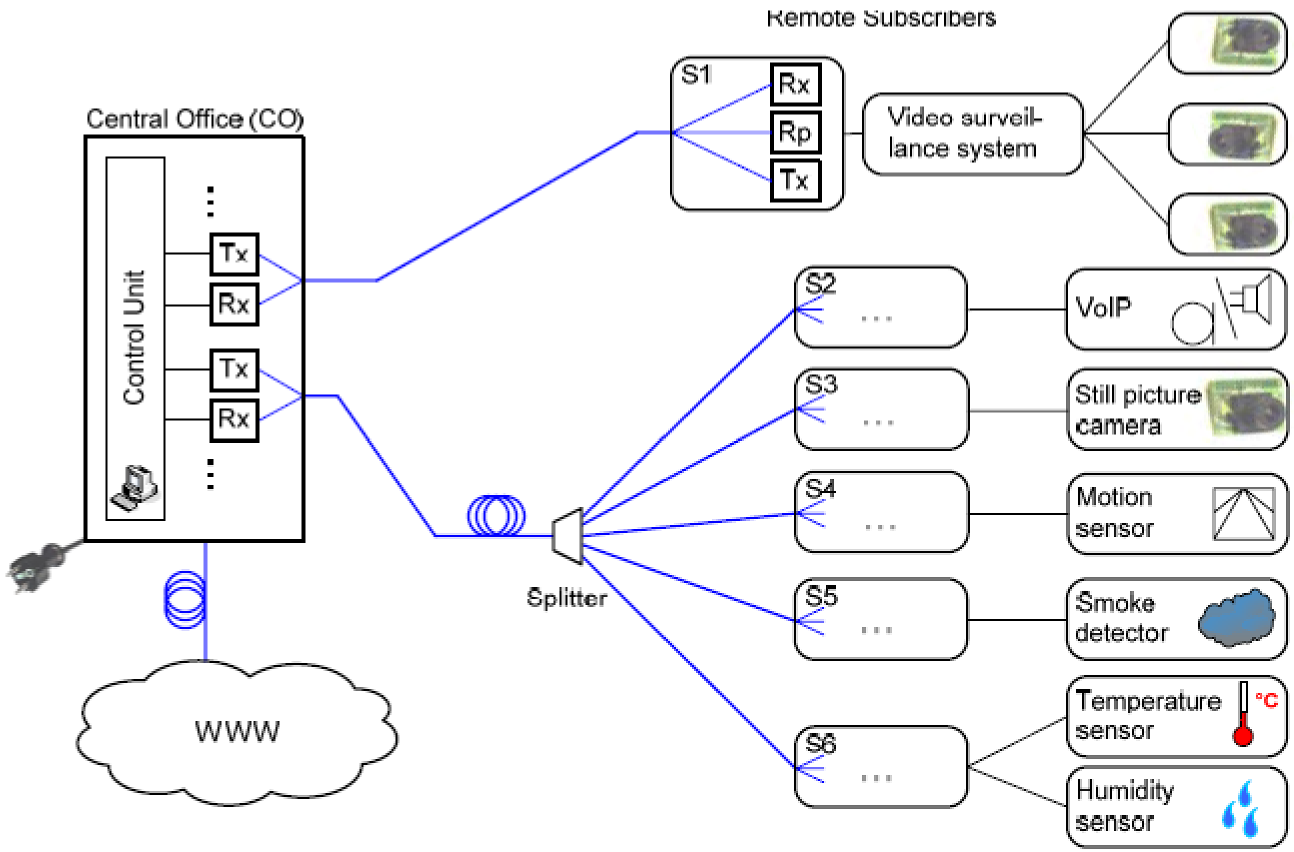
- For PPSS the main cost
  - For control unit is the high power LD
  - For remote unit is the PPC
- The cost for these two units is around 1.5 K U$
- Electronic sensor for temperature or strain measurements costs around 5 U$

OPSS indicate their usefulness for monitoring, control and metering in various industrial applications

- **Temperature Sensors**
- **High-voltage and High-current Sensors**
- **Home Automation Sensors (temperature, humidity, pressure, illumination and obtrusive detection)**
- **Oil Tank Liquid Level Sensors give a accurate and safe solution in petrochemical industry for monitoring fuel tanks, fuel leakage, etc.**
- **Sensors of Mechanical Variables (position, angle, strange, pressure, force, vibrations, proximity, etc.)**
- **High Frequency Electromagnetic Field Sensors (E and H)**
- **Remote Gas and Coal Mines Monitoring Sensors**

Optically powered industrial atmosphere quality monitoring sensory system

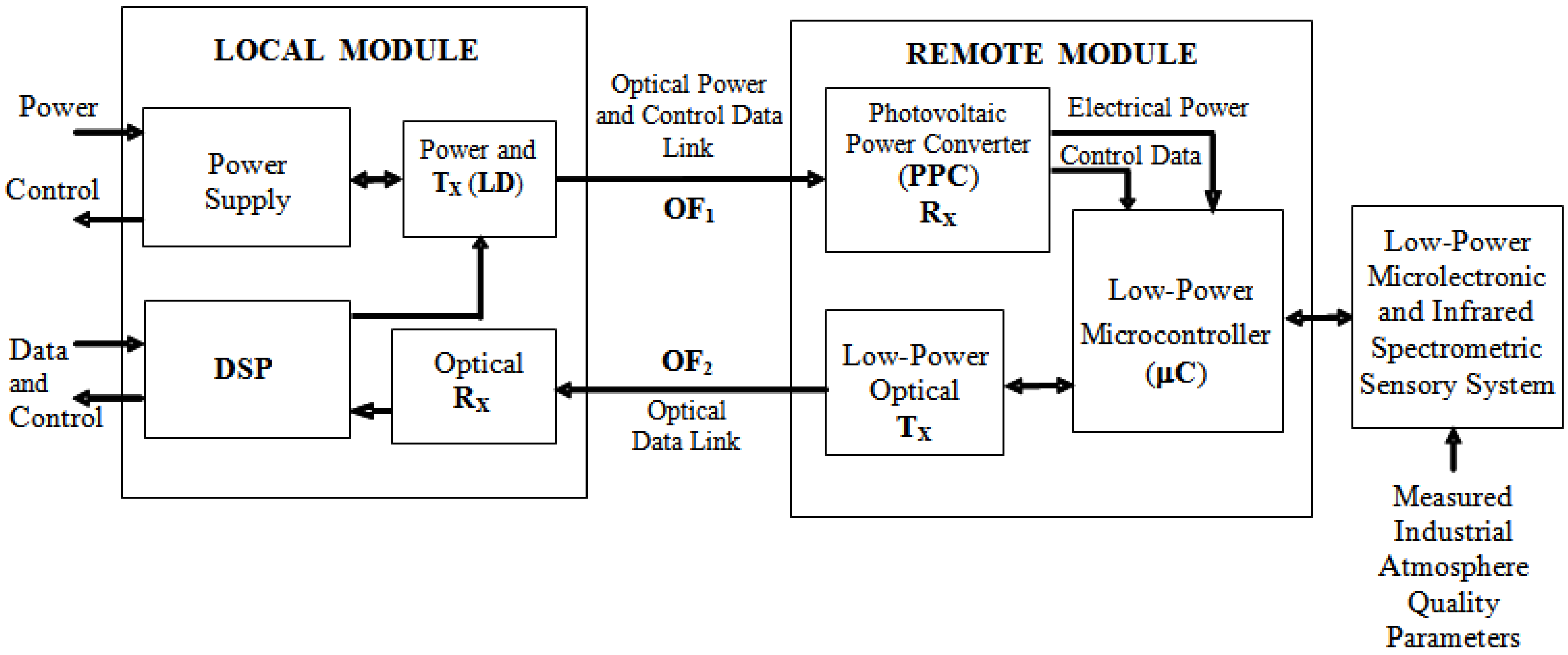
Industrial atmosphere quality monitoring systems (i.e. systems to monitor air (or other gas content - methane, other hydrocarbons or carbon dioxide) temperature, pressure, humidity) are used in various control and monitoring systems in mines, chemical plants, petrochemical industry, explosive production, weapon liquidation workshops, etc.



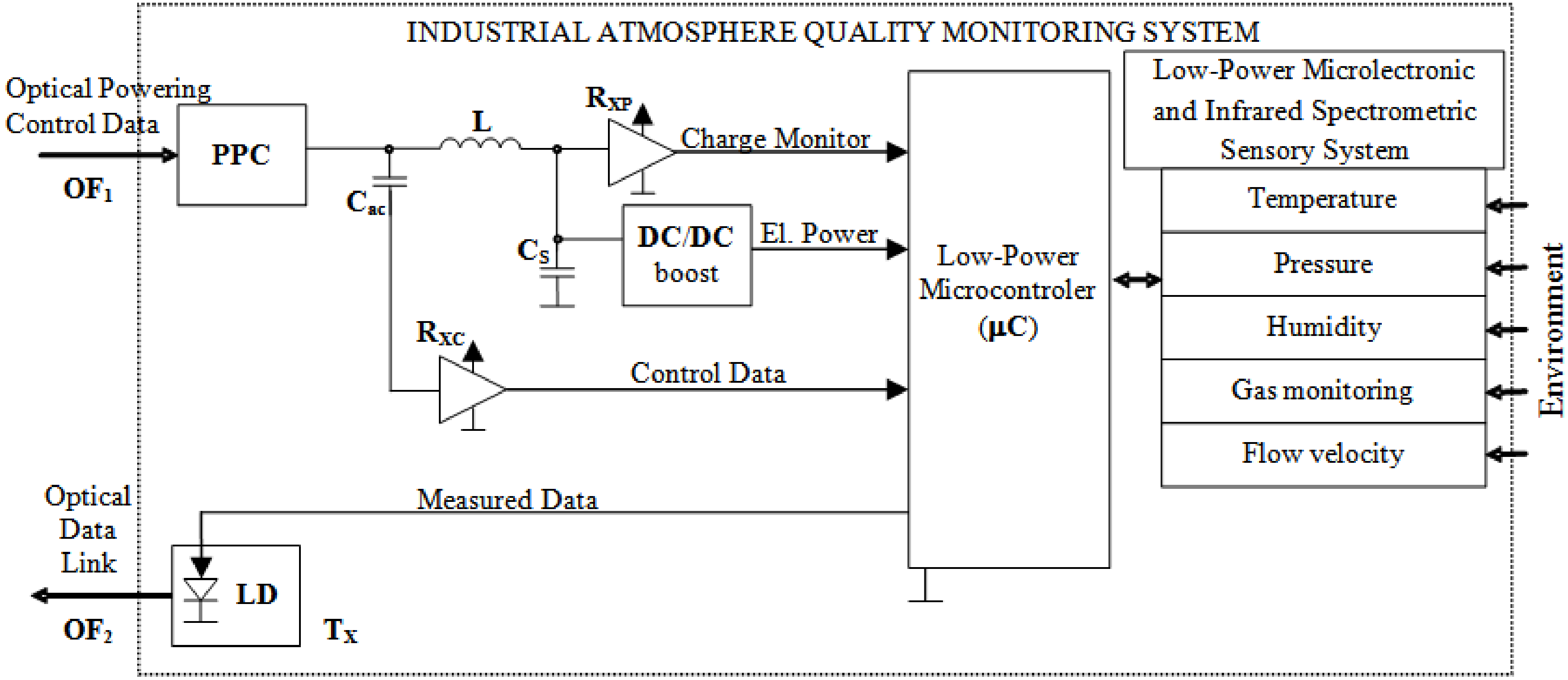
Photonic network with optically powered subscribers.

Optically powered industrial atmosphere quality monitoring sensory system (OPAQMS) develeoped at KEMT FEI TUKE

Architecture of OPAQMS with two OFs



Optically powered industrial barometric system



Remote module system design

OPAQMS basic parameters

- Optical power delivery fiber - OF_1
  - Wide core (200 μm) SI-MM low-cost OF
  - Attenuation α_{fc} = 2 dB/km (at λ=850 nm)
- OF_1 is powered with AlGaAs LD P_o = 500 mW
- PCC commercial unit GaAlAs with up-to 50 % efficiency
- Low-power optical data link at λ = 1310 nm
- SI-SM fiber - OF_2 (α_{fc} = 0,4 dB/km)
- Maximum distance from the Local Module to Remote Module may be up-to 500 m
- In experiments 300 m fiber - OF_1 and OF_2 is used

OPAQMS basic parameters

1. **Temperature:**

Range: - 40,…, + 60ºC

Accuracy: ± 0,2ºC

2. **Humidity:**

Range: 0,…, 100 % RH

Accuracy: ± 1,0 % (0,…, 90 %) RH
± 1,7 % (90,…, 100 %) RH

3. **Pressure:**

Range: 50,…, 1100 hPa

Accuracy: ± 0,2 hPa

OPAQMS basic parameters

4. Gas content monitoring sensory system:

4.1 Hydrocarbon channel

Methane measuring range: 0,…, 100 % volume

Hydrocarbon (Butane, Pentane, Ether, Propane, Ethylene, Hexane, Propylene, Cyclopentane) measuring range: 0,…, 100 % LEL equivalent

Resolution: 0,01 % up to 10 % nether content
0,1 % from 10 % nether content

Accuracy: ± 2 % of full scale at 20 ºC

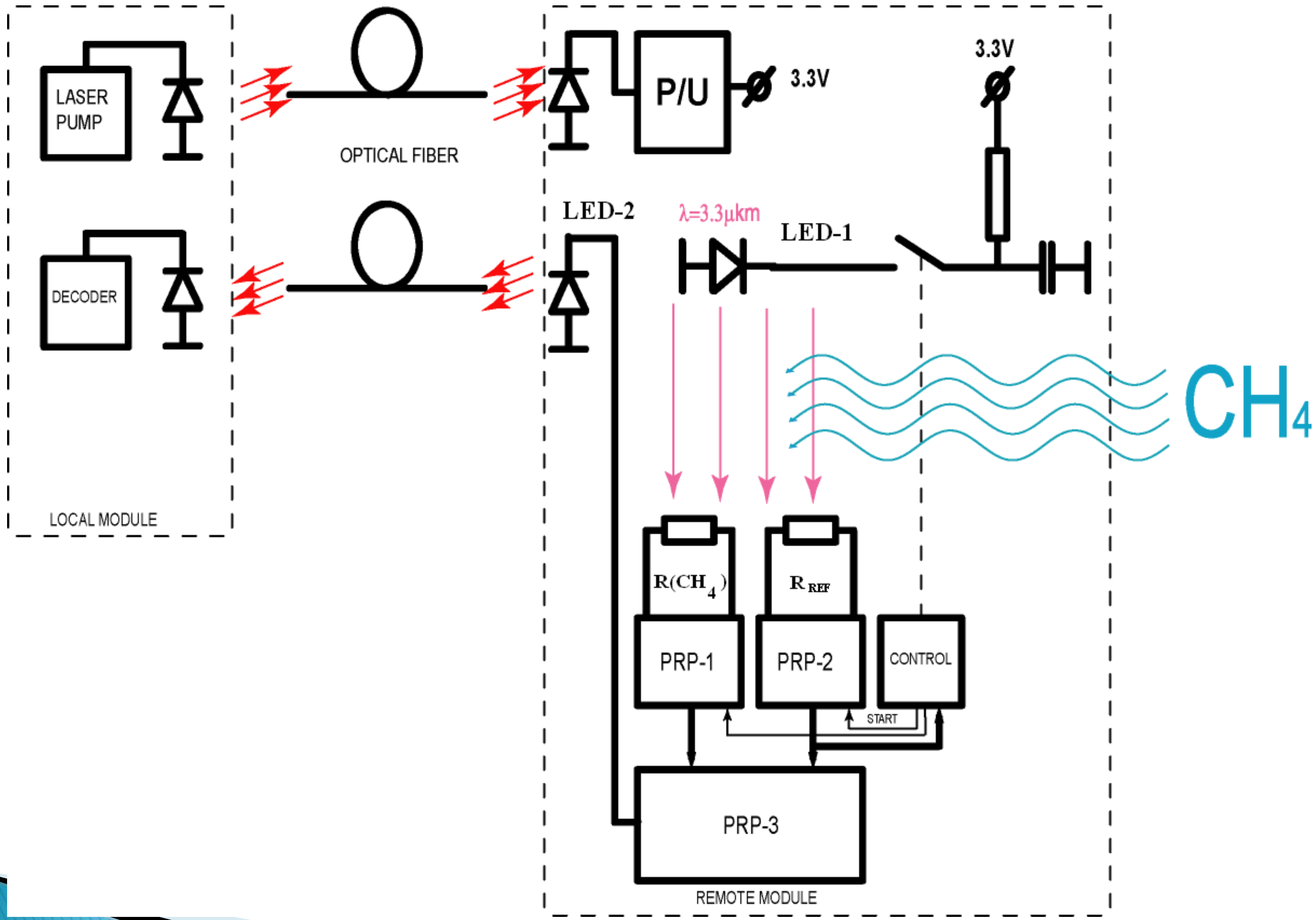
4.2 Carbondioxide channel

Measuring range: 0 - 5 %, 0 - 4 % volume CO_2

Resolution: 0,01 % volume CO_2

Accuracy: ± 2 % of full scale at 20 ºC

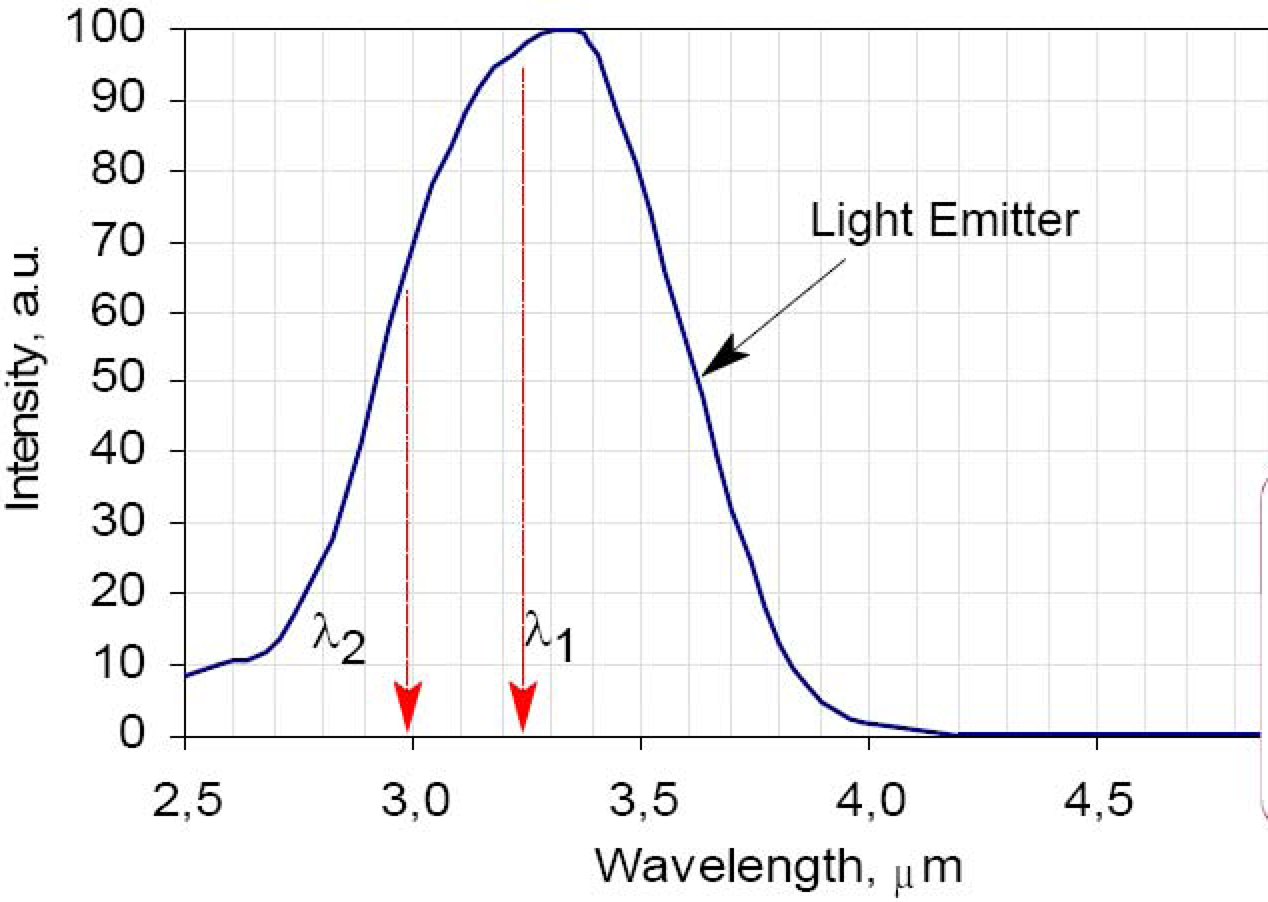
Optically powered Methane sensor

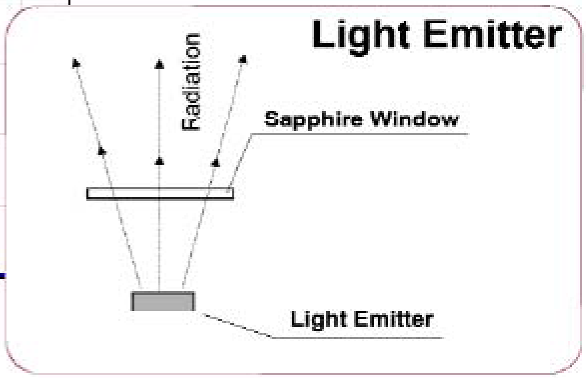


Optically powered Methane sensor

- Optical source LD at 808 nm
  widely used for Nd: YAG punping
- PPC AlGaAs PD at λ=0.81 μm,
  V= 1,23 V, R= 0,40- 0.45 A/W, FF=80-85 %
- DC converter output voltage 3.3 V
- PPC total efficiency 30 %
- Primary CH_4 transducer
  Commercial optoppair OPR1-320
- Two photoresistors R(CH_4) and R_{ref}
  receiving 3.3 μm radiation from LED-1
- Two preprocessors PRP-1 and PRP-2
- CONTROL – Remote Module management
- MM OF 62,5/125 μm
- PRP-3 power safety management

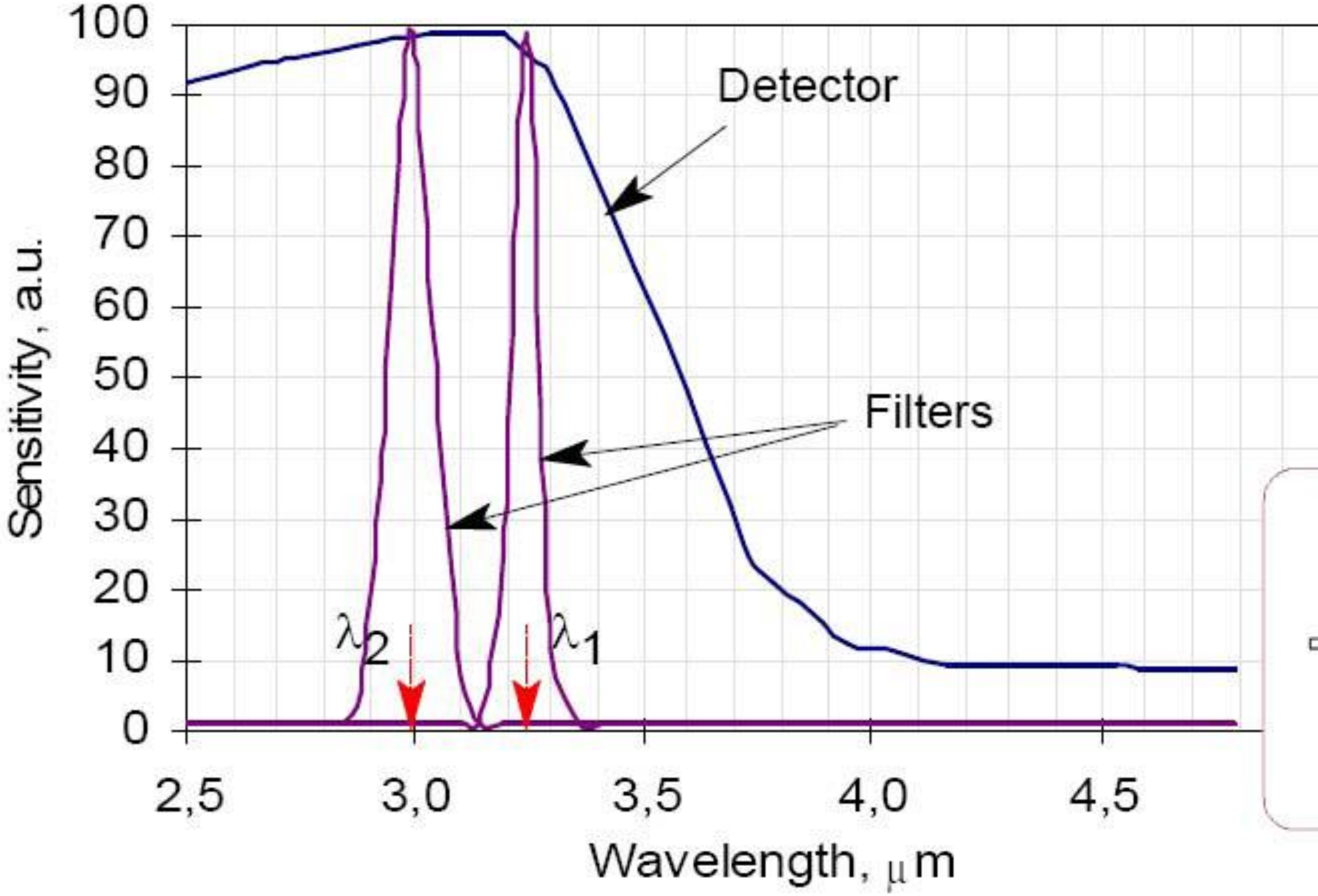
Optically powered Methane sensor – Remote module

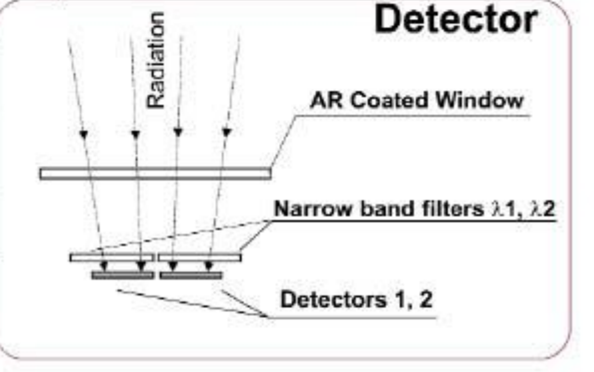




Spectral response of LED-1

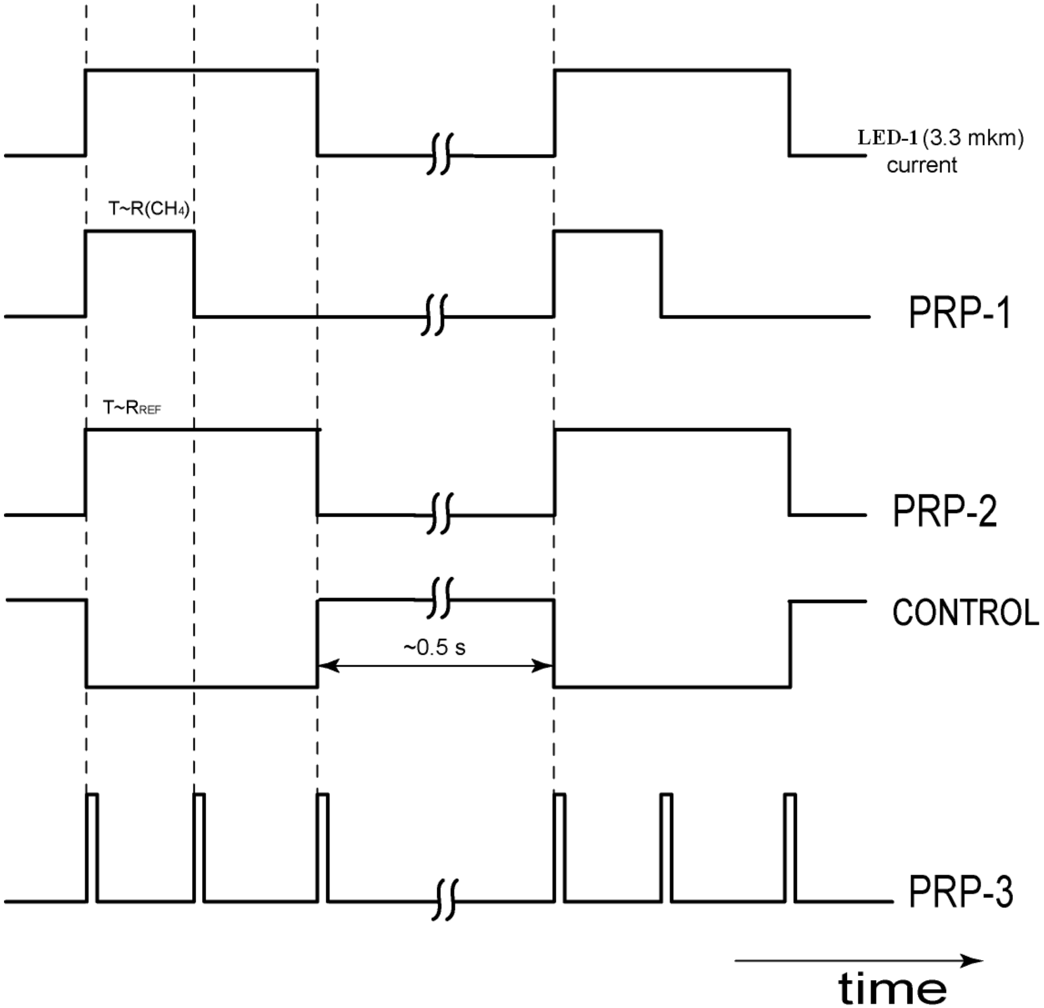
Optically powered Methane sensor – Remote module





Spectral response of PD with two narrow band optical filters.

Signal diagram of the Remote Module



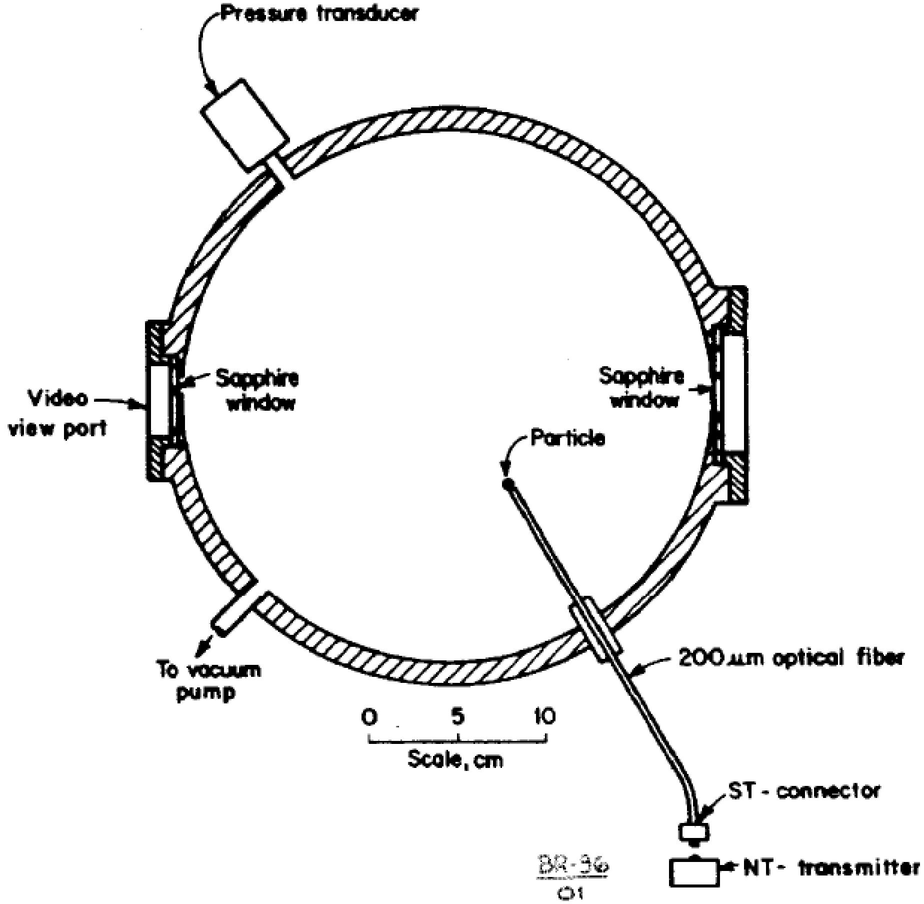
Optically powered Methane sensor

- Full measurement cycle 2 times per second
- Remote Module power consumption 3 mW
- Optical power in OF 10 – 12 mW

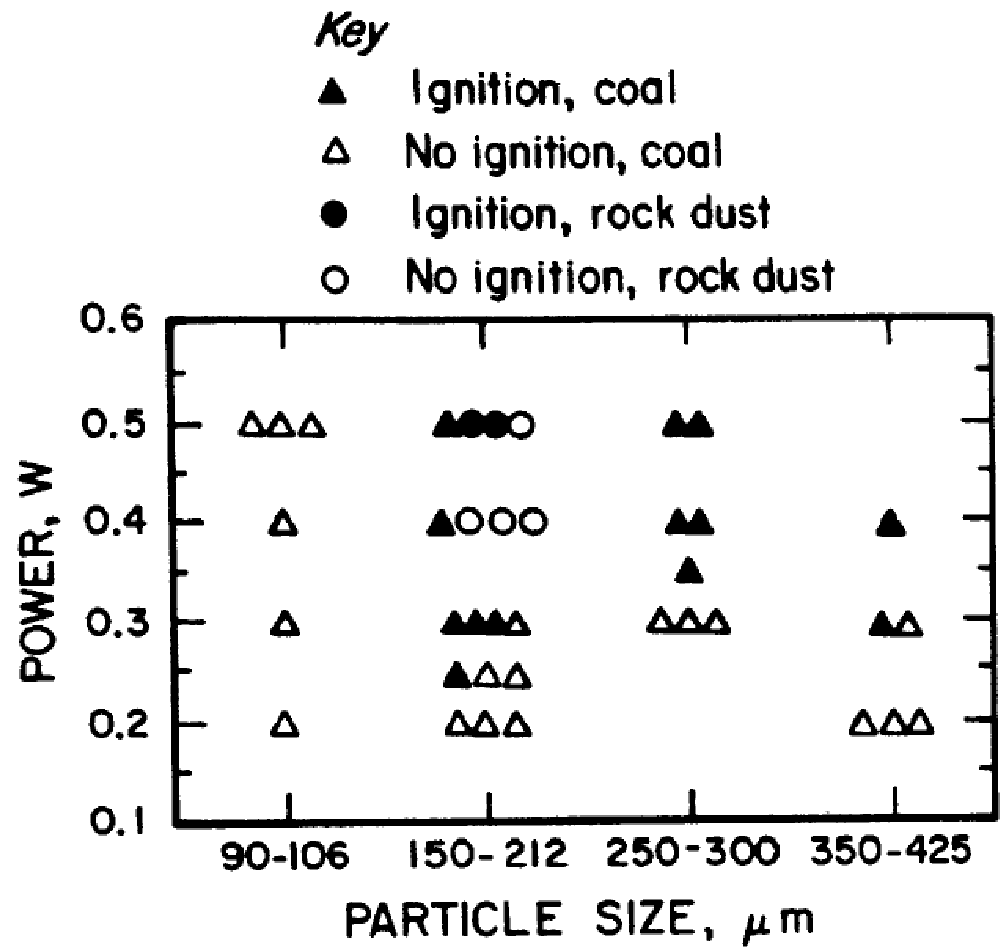
  Not exceeded the explosion safety threshold
- Injection current for LED-2 20-30 mA
- LED-2 output optical power 2 mW
- For long haul data transmission LD can be used
- Sensory system have 1 % accuracy, 0.5 minimal detection level in 0-100 % (volume parts) measurement range

Flamability and ignibility of H_2, CH_4 and CS_2

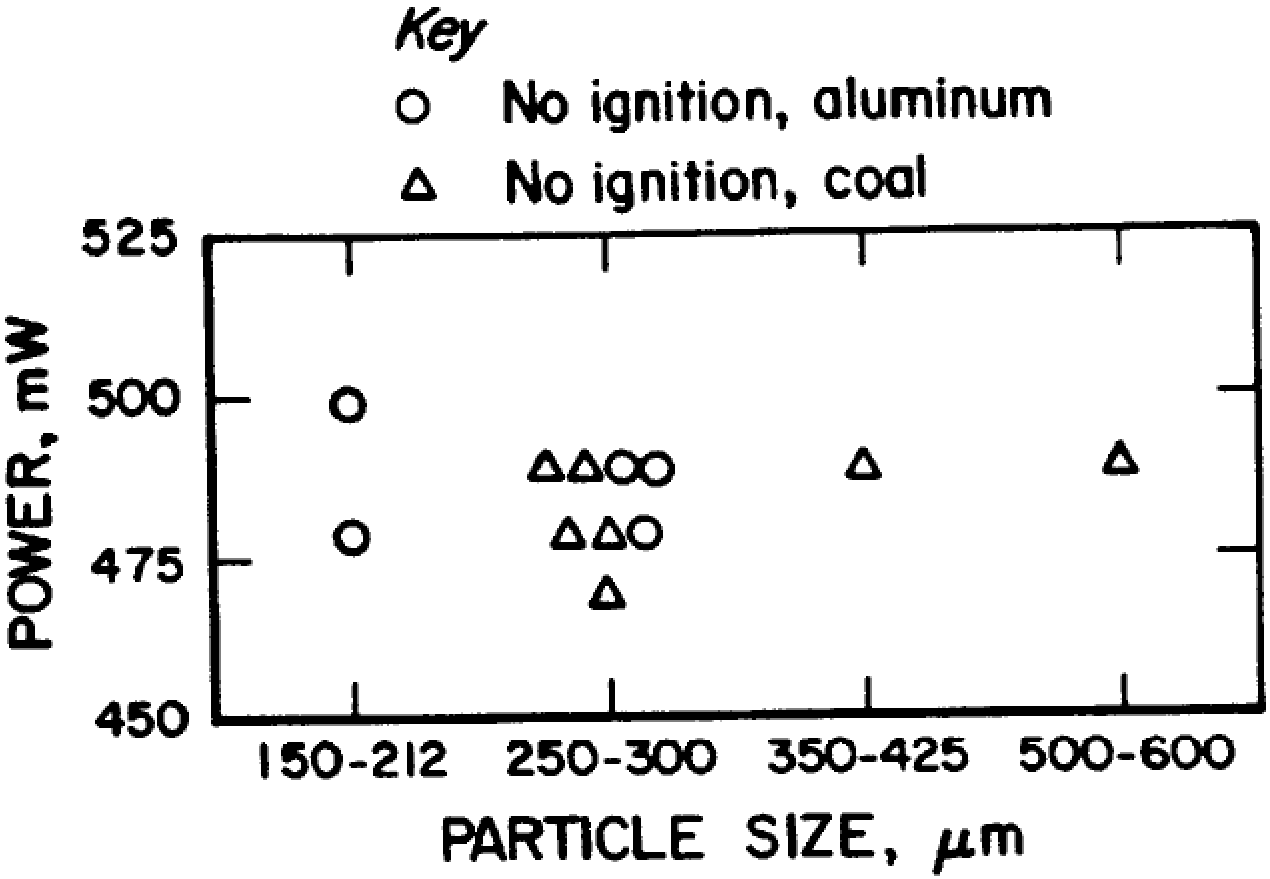
GAS	Flamable range	Stoichiomeric value	Electric spark ignition energie [mJ]	Autoignition temperature [^0C]
H_2	4 - 75 %	29.5 %	0.017	500 - 520
CH_4	5 – 15 %	9.4 %	0.30	600 - 630
CS_2	1.3 – 50 %	6.5 %	0.015	100



Cross section of FO powered ignition test chamber.



Data for ignition tests in 15 % H_2 in air, Laser with 200 µm OF, coal and rock particles used.



Data for ignition tests in 10 % CH_4 in air, Laser with 200 μm OF, coal and aluminium particles used.

EC Reprot results

CW Laser device radiating in visible and near visible region are not hazardous either:

a) Radiated power is less than 35 mW,
b) Peak radiation flux is less than 5 mW/mm^2

In tests CS_2 - air as model explosive gas was used

US Reprot results

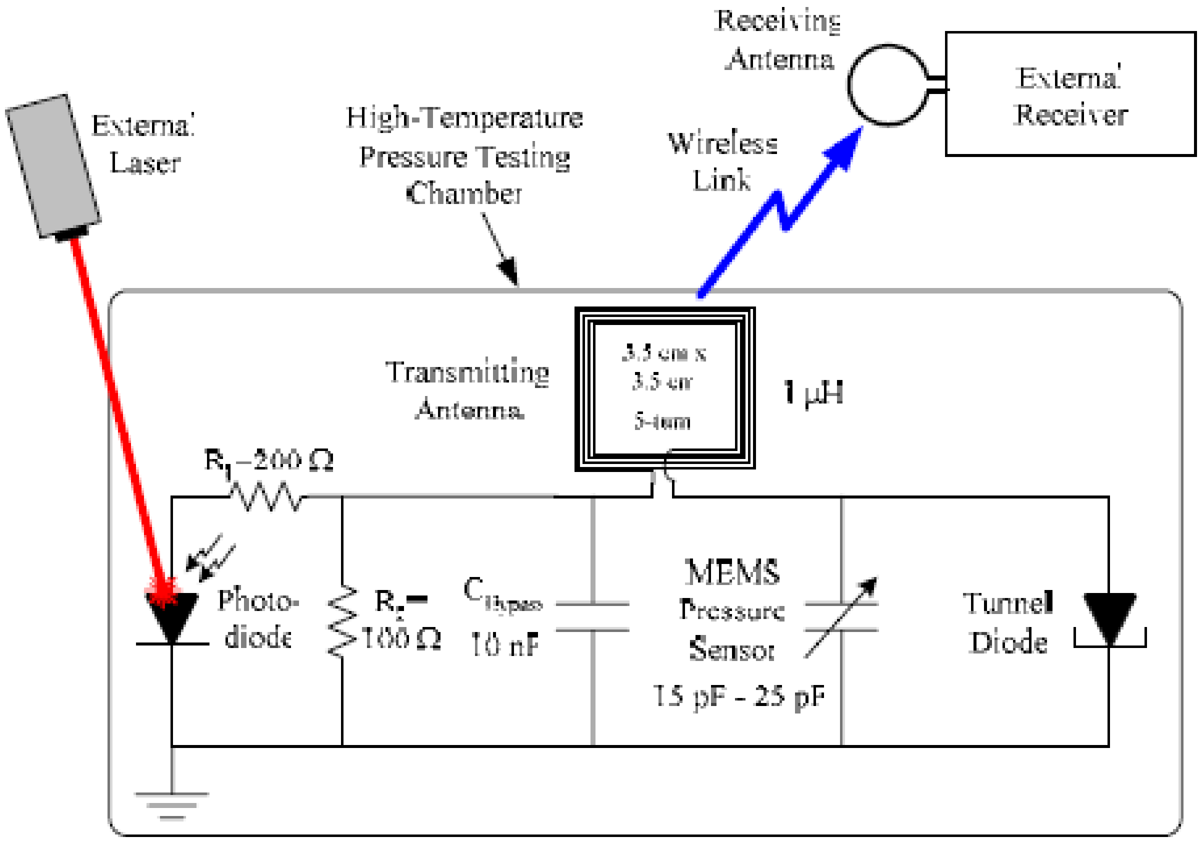
a) Min. ignition power 250 mW, 15 % H_2-air, coal particle – 150-212 µm

a) Min. ignition power 500 mW - 15 % H_2-air, rock dust particle

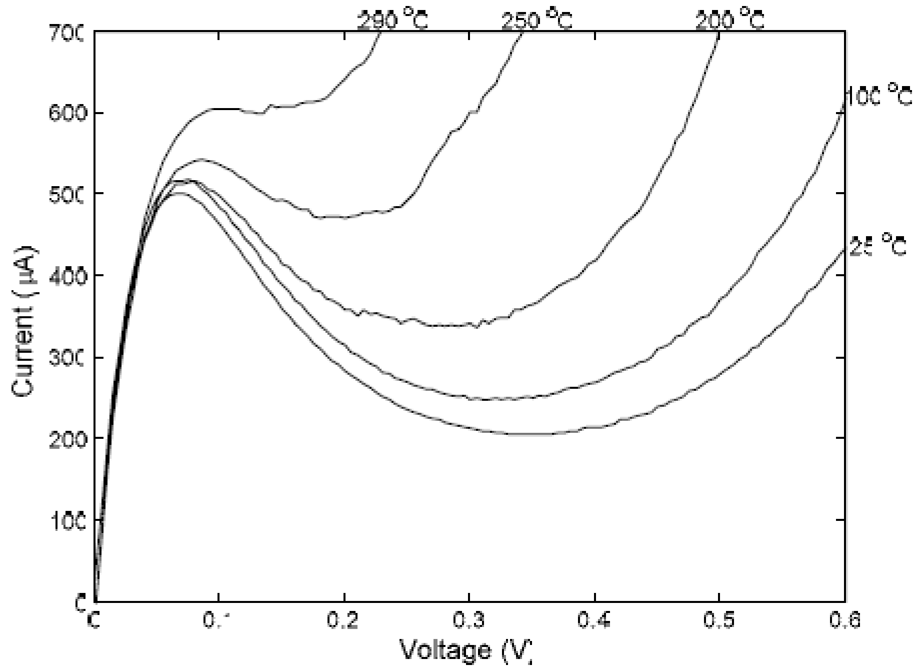
a) No ignition to 500 mW - 10 % CH_4 -air, coal or aluminium particle

In tests H_2, CH_4 and CS_2 - air as model explosive gas was used

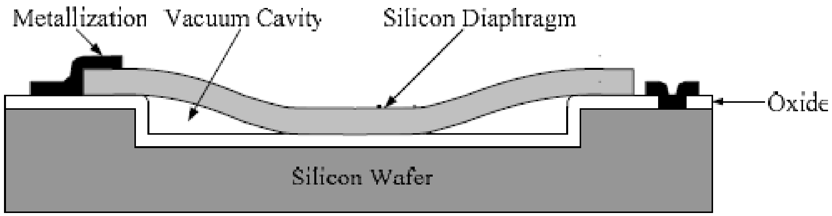
OPTICALLY POWERED HIGH TEMPERATURE PRESSURE SENSING AND TELEMETRY SYSTEM



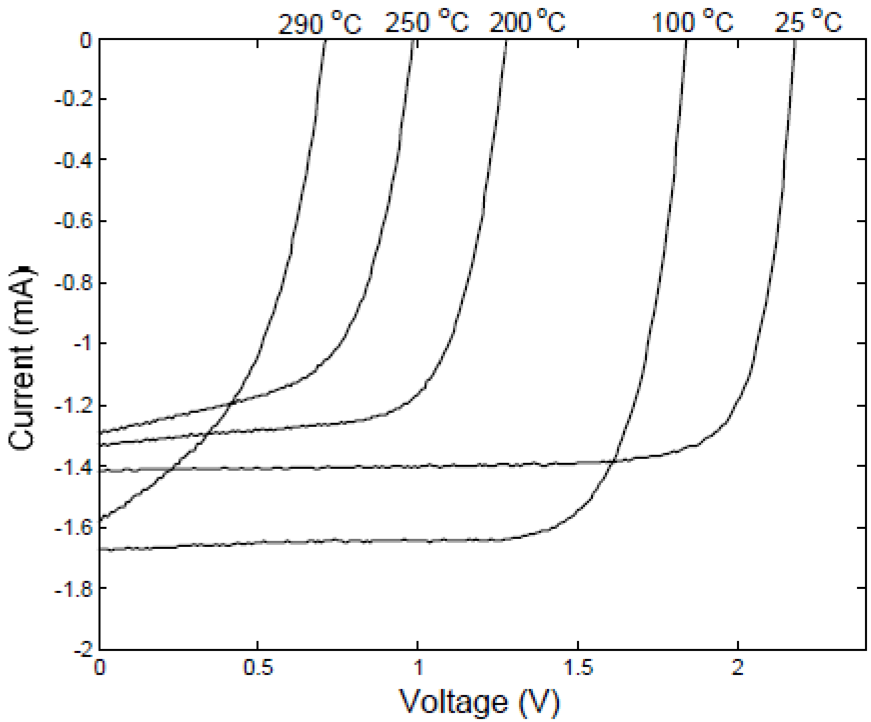
1 atm measured at 250 °C, with an SNR of at least 10 dB over telemetry distances of 1.5 m



3 mm x 4 mm GaAs photodiode PPC measured over a temperature range from 25 °C to 290 °C with an 8 mW laser beam



- MEMS touch-mode silicon capacitive pressure sensor
- Capacitance values ranging from 15 pF at 2 psi to 25 pF at 32 psi (absolute pressures)
- Series resistance of 25 Ω



- The tunnel diode exhibits negative resistance characteristics up to 250 ^{0}C
- Voltage and current bias levels of approximately 120 mV and 500 µA correspond to a power consumption of 60 µW

Conclusions

Main application areas of OPSS

- **High voltage technology**
- **Medicine**
- **Power electronics**
- **Military, avionic and aerospace systems**

Fiber optically powering technology

will be spread in the wide range of commercial applications

- **EMC**
- **Nanotechnology**
- **Communications**
- **Robotics**
- **Intelligent manufacturing systems,**
- **Automotive industry**
- **Surveillance system**

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