

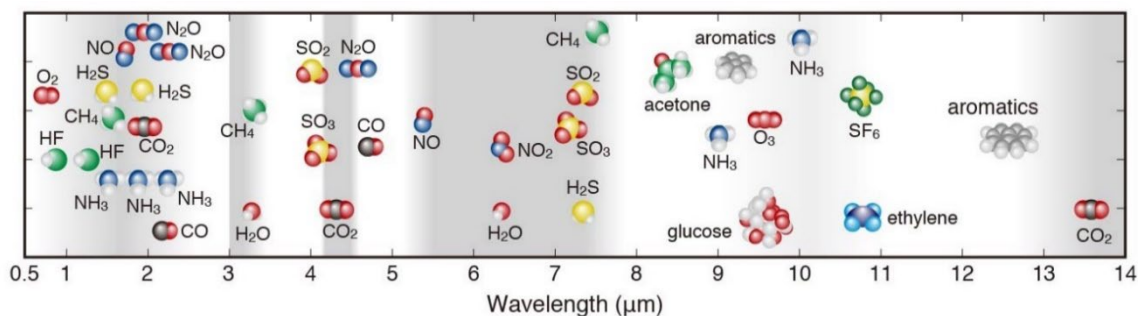
# **Non-Dispersive Infra-Red (NDIR) Sensors – Theory of Operation**

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## NON-DISPERSIVE INFRA-RED (NDIR) SENSORS

NDIR gas sensors work by detecting the amount of light that is absorbed by the target gas. Gases absorb light energy at different wavelengths, depending on the chemical bonds in the gas. The amount of energy absorbed by the target gas is proportional to the concentration, as described by the Beer-Lambert Law.



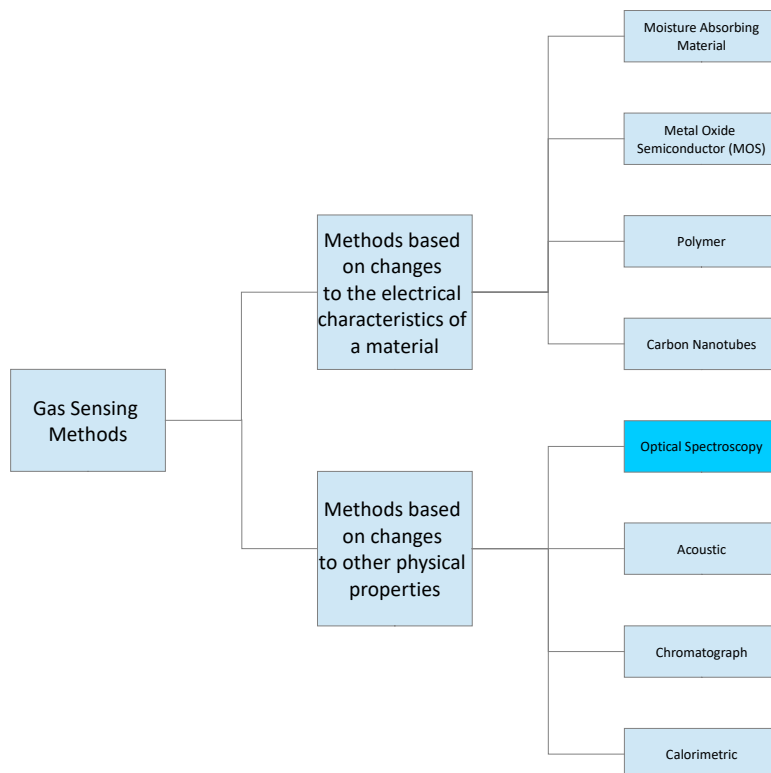
**Figure 1: Gas Absorption Wavelength**

## GAS SENSOR TYPE REVIEW

There are many different techniques that can be used to detect the presence of a gas or to measure the concentration of gas. Most people acknowledge the first proper gas detector was the Davy lamp, invented by Sir Humphrey Davy in 1815. The industrialisation of Britain in the 19<sup>th</sup> century drove a huge expansion in mining for coal and other raw materials. Prior to the Davy lamp, burning torches were used that would dim or go out in the absence of oxygen or burn brighter in the presence of methane. Alternatively, poor unfortunate canaries were carried down into the mines, and would stop singing if methane, carbon monoxide or carbon dioxide levels began to rise.

The Davy lamp was designed to detect methane, where the height of a calibrated oil flame was used to determine methane gas concentrations. The flame was protected behind a glass barrier and a metal mesh flame arrestor to prevent it causing an explosion. It was not until the 20<sup>th</sup> century when other technologies began to transform the gas sensor market.

The 20<sup>th</sup> century saw the invention of thermal conductivity sensors in the 1920's and chemical resistive sensors in the 1950's. Nowadays, there are a plethora of gas sensor types, including the aforementioned electro-chemical and thermal conductivity sensors, pellistors, acoustic, metal oxide semiconductor (MOS) and many others.



**Figure 2: Gas Sensing Methods**

All gas sensing technologies have their strengths and weaknesses, and no one method will suit all requirements. The common ones are noted below.

### **Methods based on changes to the electrical characteristics of a material**

Electro-chemical sensors measure the current produced by a chemical reaction with the target gas. Gas diffusion is limited by a small hole, and the current is proportional to the gas concentration. They are similar to a battery and have a finite life, require a reactive gas and selective chemistry. They are the favoured option for low concentrations of toxic gasses.

Thermal conductivity sensors use the thermal coefficient of the sample gas to infer a level of target gas, where a metal element is heated by constant power and the temperature change induced by the target gas is proportional to concentration, often arranged in a Wheatstone bridge configuration. They are frequently used for high concentrations of inert gases but are not selective.

Pellistors are another type of sensor that uses a catalyst to burn a flammable gas, where increased heat is proportional to the target gas present. This type of sensor requires a flammable gas, is very cheap but high power and susceptible to poisoning of the catalyst, and not very selective.

## Methods based on changes to other physical properties

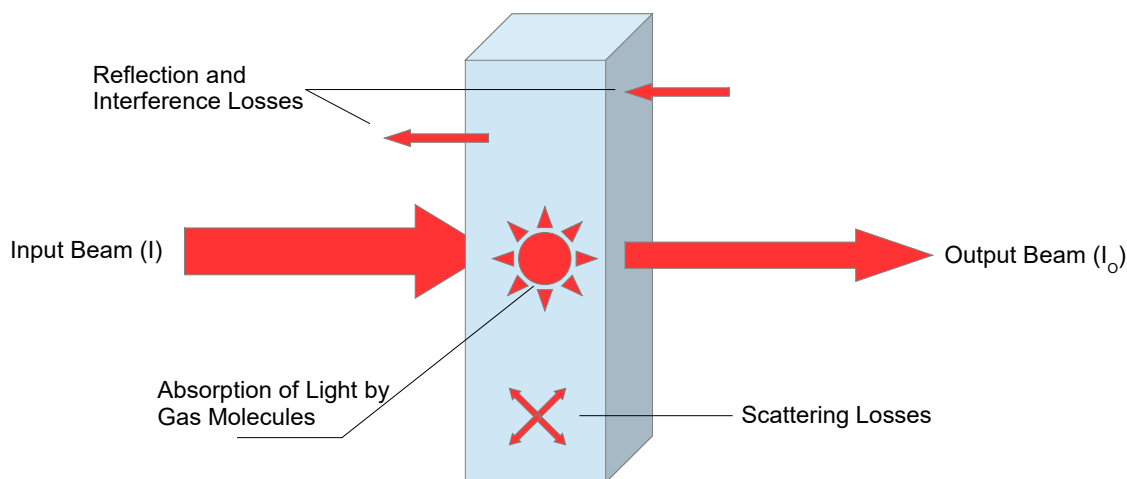
NDIR sensors use the spectral absorption properties of gas, where the amount of light absorbed is proportional to gas present. However, not all gases absorb or absorb light strongly enough to allow practical implementation of a sensor.

Acoustic sensors operate in an equivalent manner to NDIR sensors, where gas is excited by high frequency IR, and sensitive microphone picks up sound proportional to the amount of gas present. This type of sensor is generally thought of working best in relatively high concentrations of the target gas.

NDIR sensors and in particular solid-state infra-red LED based optical sensors have many benefits that make them suitable for a broad range of applications. NDIR sensors measure gas concentration directly and do not infer a measurement through a change in the properties of another material, such as a chemical element, semiconductor, or metal.

## THE BEER-LAMBERT LAW

As light passes through a gas medium, some of the light is attenuated due to absorption, reflected losses, interference, and scattering. To derive the Beer-Lambert Law requires the manipulation of several formula.



**Figure 3: Incident Light on a Medium**

Lambert derived a relationship between the decrease in intensity of a monochromatic light passing through a homogeneous medium of path length  $dx$  and the intensity of light  $I$ .

The rate of decrease in the intensity of the light passing through the distance of the gas path ( $x$ ) is directly proportional to the intensity of the incident light.

$$-\frac{dI}{dx} \propto I$$

Where  $dI$  is a small decrease in intensity of light upon passing through a small distance  $dx$  and  $I$  is the intensity of the monochromatic light just before entering the medium. Re-arranging the above equation gives the following.

$$-\frac{dI}{dx} = aI$$

Where  $-\frac{dI}{dx}$  is the rate of decrease of intensity with path length, and  $a$  is called the absorption coefficient.

Integration of the above equation gives the following.

$$\ln I = ax + C$$

Where  $C$  is the constant of integration. At  $x = 0$ ,  $I = I_0$ . Therefore,  $C = -\ln I_0$ .

By substitution, we get the following.

$$\ln \frac{I}{I_0} = -ax$$

Or.

$$I = I_0 e^{-ax}$$

$$\log \frac{I}{I_0} = \frac{-a}{2.303} * x$$

$a' = a/2.303$  is called the extinction coefficient and  $-\ln \frac{I}{I_0}$  is called the absorbance of the medium.

Absorbance is normally represented by the letter  $A$ .

Beer extended Lambert's Law to show that when light passes through a solution of a given thickness, the proportion of light absorbed by the solution is dependent on both the intensity of the light  $I$  and the concentration  $c$  of the solution.

$$-\frac{dI}{dx} \propto I * c$$

Or.

$$-\frac{dI}{dx} = b * I * c$$

When  $c$  is expressed in mol/L,  $b$  is called the molar absorption co-efficient. This equation may be rearranged to give the following.

$$\log \frac{I}{I_0} = \frac{-b}{2.303} * c * x$$

The Beer-Lambert Law equation is classically shortened as follows.

$$\log \frac{I}{I_0} = A = \epsilon * c * x$$

Where  $A$  is absorbance

$\epsilon$  is molar extinction coefficient ( $= -b/2.303$ ), and is dependent on the nature of the absorbing medium as well as on the wavelength of the incident light

$c$  is concentration

$x$  is the thickness of the light path

### Beer-Lambert Law Non-Linearities

Whilst this general equation looks nice in principle, it hides several assumptions that in most real-life conditions are not valid. Whilst the Beer-Lambert Law looks nominally linear,  $\epsilon$ ,  $c$  and  $x$  are not true constants, especially as the concentration increases.

### Monochromatic Light

The law assumes the radiation source is a single wavelength, such as generated by a single mode laser. However, in most gas sensors, the light source is unlikely to be a true single wavelength.

Hence, in real life instruments, the transfer function is non-linear due to the bandwidth of the source. As the bandwidth reduces, the transfer function becomes increasingly linear.

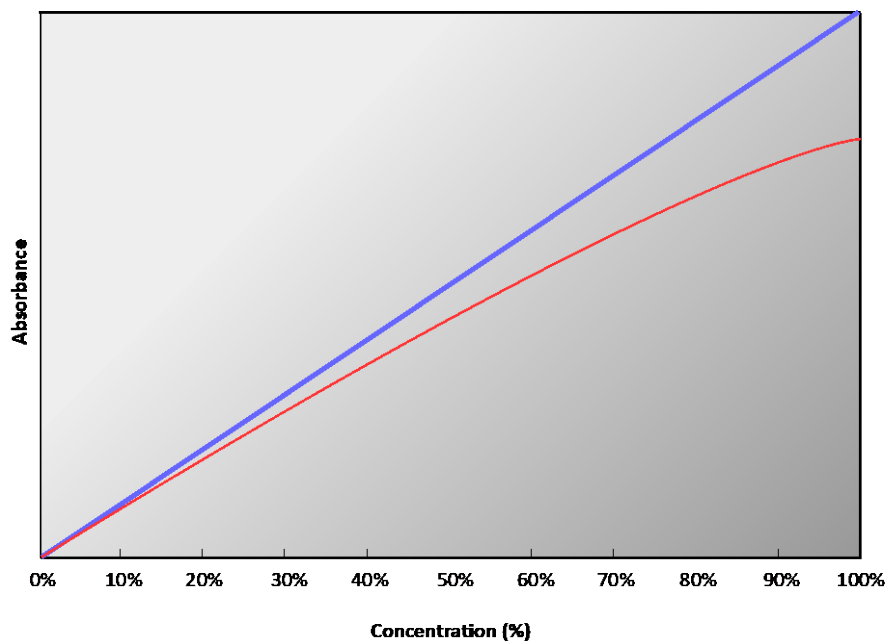
## Gas Absorption

Beer-Lambert assumes the target absorbent is distributed homogeneously in the light path and acts independently. It also assumes that light is only absorbed by the target gas. However, in real life, there will be reflective and interference losses. Most gas sensors assume the losses are constant so are eliminated from gas concentration calculations.

## Optical Path Length

The optical path length in real life is clearly not a constant. The path length from source to detector will be a function of the wavelength of the light. The light is not a point source but will have finite dimensions with multiple path lengths to the detector. There will also be deviations due to scattering, reflections, and interference.

The Beer-Lambert Law becomes increasing non-linear as the concentration increases.





## IMPLEMENTATION OF A REAL-WORLD GAS SENSOR

The Beer-Lambert Law is a good proxy for the relationship between gas concentration and light absorption. However, for a real-world gas sensor implementation, this foundation needs to be supplemented to overcome its limitations.

At GSS, the precise relationship between the light intensity and gas concentration is characterised for each individual sensor. The native transfer function of how absorption increases with gas concentration is calculated for each GSS sensor by exposing it to multiple gas concentrations at multiple temperatures. Once the native transfer function is known, a series of corrections are calculated and uploaded to each sensor to linearise them.

## CONCLUSION

GSS has developed a technique to linearise its gas sensors to overcome the real-life limitations of the Beer-Lambert Law. Each sensor is individually linearised by exposure to the target gas over its functional operating range and specific corrections are uploaded to each sensor to ensure linear operation for the life of the sensor.

For more information on GSS gas sensors, please contact your local GSS sales representative. Contact details can be found on our web site, [www.gassensing.co.uk/contact](http://www.gassensing.co.uk/contact).

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