Application Note DESA1: Infrared Sensor Preamplification

This application note discusses the power and drive requirements of an infrared sensor and the preamplification of the infrared sensor signals. A suggested sensor drive and preamplifier circuit is shown and the component sections are discussed. This application note is intended as a general guide to interfacing infrared sensors to external circuitry.

An infrared gas sensor comprises a radiation source and a radiation detector housed within an optical arrangement into which target gas diffuses. The radiation detector is a dual detector containing 2 detector elements that respond to radiation emitted by the radiation source. One detector element (the active) responds to radiation of wavelengths emitted by the radiation source that are absorbed by the target gas. The other detector element (the reference) responds to radiation emitted by the radiation source that is not absorbed by target gas. The radiation detector therefore provides an active signal (affected by target gas) and a reference signal (unaffected by target gas). The reference signal is used to compensate for changes in radiation intensity caused either by the radiation source (e.g. through ageing) or by changes in the optical characteristics of the optical arrangement (e.g. through neutral density contamination).

The radiation detector is a pyroelectric detector and therefore responds to <u>changes</u> in incident radiation, unlike a photometric detector that responds directly to incident radiation. The radiation is therefore chopped in order to generate changes in incident radiation at the detector. This chopping is achieved by pulsing the radiation source, which is a low power filament lamp. The lamp is typically driven by a square wave supply, which should be of a constant frequency and ideally a constant 50% duty cycle. Typical operating frequencies are in the range 2.0Hz – 4.0Hz, where the pyroelectric detector response is close to optimum.

The detector signals comprise a DC voltage pedestal upon which is superimposed a small oscillating signal in sympathy with the lamp chopping. It is important that the preamplifier gain be optimised for the frequency range of the lamp chopping. If the preamplifier AC response is optimised at higher frequencies then some differentiation of the signals occurs and this shows itself as a distortion in the signals. Typically the signals should have a sinusoidal shape. Any differentiation will show as a peak response decaying to a lower value before the next half cycle occurs. The larger the difference between the preamplifier frequency response and the chopping frequency the more this decay and distortion appears.

In the presence of target gas the active oscillating signal reduces as the target gas absorbs radiation detected by the active element, whereas the reference oscillating signal remains constant. In order to accurately monitor the signals there must be some amplification of the small oscillating signal without amplification of the DC voltage pedestal. The resulting signals can then be read directly via an A/D converter for example and used to obtain a measure of the target gas concentration. This is discussed in Clairair Application Note DESA2: Infrared Sensor Signal Extraction.

A suggested Infrared sensor preamplifier is shown below in Fig. 1 where both active and reference preamplifiers are essentially identical. In practice one may wish to adjust the individual signal gains to suit the target circuit. A simple means of chopping the source is shown where the input to the chopping is a digital signal of 50% duty cycle at the operating frequency. Each component part of the suggested circuit is explained below.
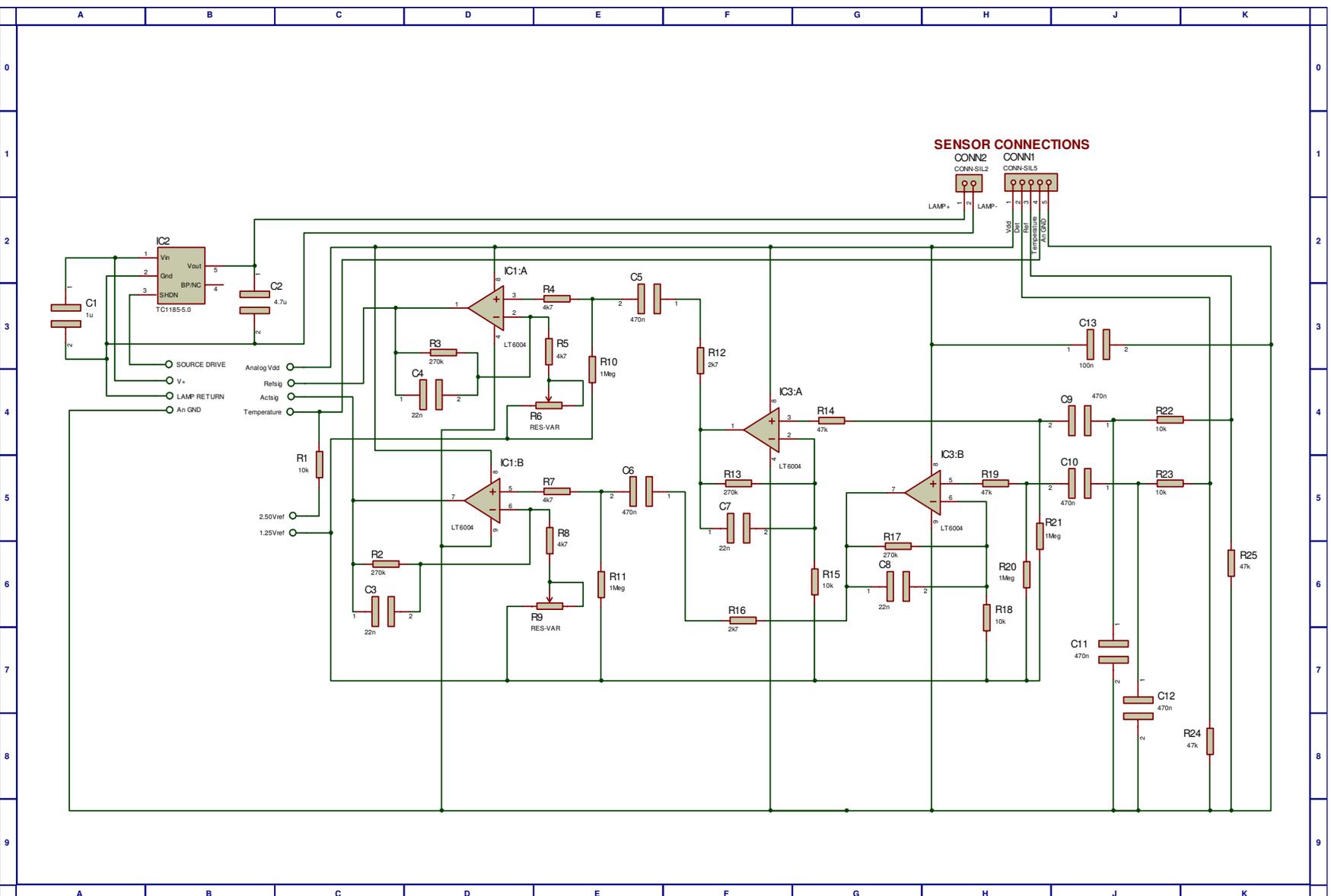
Fig.1: Suggested IR sensor preamplifier circuit

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1) Sensor connections:

The sensor connections are comprised of 2 connectors, CONN1 and CONN2. They are separated to indicate that the lamp supply on CONN2 should be tracked separately from any other tracks to avoid lamp current generating noise in the amplifier circuit. Adopting a constant current regime for the lamp circuitry can also dramatically reduce lamp-switching noise. A suggested circuit to maintain a constant current for the lamp circuit and also provide the voltage references for the preamplifier circuit are shown in Fig. 2.

1a) Source drive:

The sensor source is driven directly from IC2, which is controlled by a source drive signal to turn IC2 on and off. There are many different regulator ICs with shutdown available and transistor switches to a regulated supply can also be used. The source drive signal should be a stable 50% duty cycle square wave with a frequency of typically 3Hz. Lower frequencies (down to 2Hz) will give larger sensor signals and higher frequencies (up to 4Hz) will give lower sensor signals. This is a characteristic of the pyroelectric detector contained within the sensor. The frequency response of the preamplifier is centred around 3Hz but will maintain the gain over the range 2Hz -4Hz to within 1% with negligible distortion of the signals. It is suggested that the sensor source be powered at 5V, lower voltages (down to 2.5V) can be used and the signal from the sensor will reduce as the source voltage reduces. It is important that the voltage drive to the lamp be stable and well regulated. It is also important that the duty cycle be an accurate 50% and does not vary, as any variations will show as cycle-to-cycle changes in the sensor signals. The lamp current returns via the LAMP RETURN connection and it is important that this be segregated from the amplifier tracking, ultimately returning to 0V at the incoming supply.

The lamp is rated at 5V, 60mA but there will be an inrush current whenever the lamp is turned on of up to 120mA. This inrush current can be reduced by supplying the lamp with a low voltage (less than 0.5V) during the off period in order to keep the lamp coil warm. This will reduce contrast and result in a reduction in sensor signal size but will extend the life of the lamp. Alternatively the LAMP RETURN connection can be made to a constant current point as shown in Fig.2 which, although drawing current continuously, removes current pulses at the expense of a slower lamp heating time.
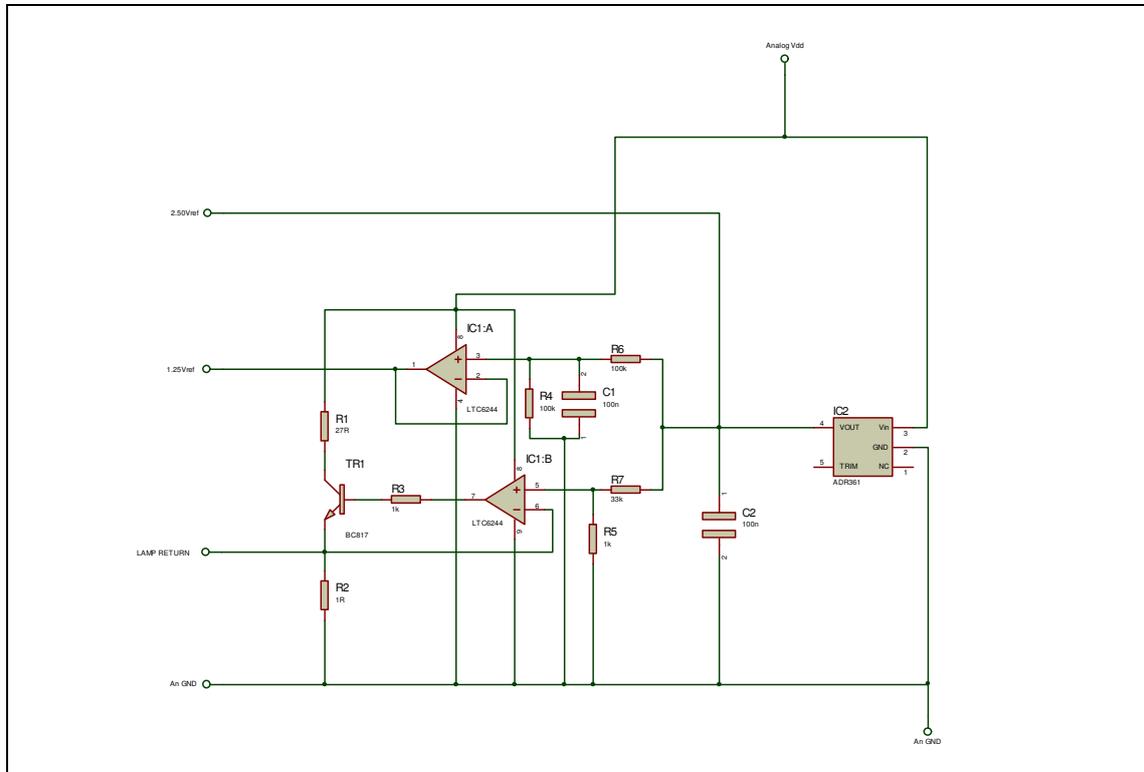

Fig.2: Suggested IR source constant current circuit and reference generator.

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The supply current to the complete circuit will reflect the source drive current and if a number of circuits are connected to the same power supply via a common power cable there can be phasing of current demand from the supply that is likely to show as low frequency seemingly random ripple on the final output signals. This can also be removed by returning the LAMP RETURN connection to a constant current point as shown in Fig.2.

1b) Sensor power:

The power supply to the sensor is derived from the circuit analogue Vdd and the circuit analogue ground. The Vdd supply should be well regulated and the analogue ground should be segregated from any digital ground.

1c) Temperature signal:

The temperature signal is derived from an internal 3k NTC thermistor, which is connected between the temperature pin of the sensor and the analogue ground pin of the sensor. It is suggested the temperature connection be to a 2.50V reference via a 10k resistor, the subsequent voltage at the temperature pin of the sensor then being dependent on the thermistor resistance. The thermistor has a beta value of 3450 +/- 3.5% and a resistance of 3.0kΩ +/-5% at 298°K. The change in resistance of the thermistor with temperature can be modelled with a 10k resistor in series to a 2.5V reference to generate a voltage/temperature relationship such as:

Temperature (°K) $= beta / (\ln \{ R_{thermistor}[T°K] / R_{thermistor}[298°K] \} + beta / 298)$

where $R_{thermistor}[T°K]$ is the thermistor resistance at temperature T°K and
$R_{thermistor}[298°K]$ is the thermistor resistance at 298°K

Temperature (°K) $= 3450 / (\ln \{ 10 \times V_{temp} / (3 \times (2.5 – V_{temp})) \} + 11.577181)$

where V_{temp} is the voltage appearing at the temperature pin of the sensor.

1d) Active and reference signals:

These are the active and reference signal outputs from the sensor. The signals should be loaded to analogue ground via 47k resistors (R24 and R25 in the attached circuit) although if a -5V supply is available in the circuit they can be connected to -5V via 390k resistors. The active and reference signals comprise a DC voltage pedestal on which is superimposed the low level AC signal which we need to amplify, this AC signal being in sympathy with the source drive. The load resistors set the current draw from the signal outputs in the region of 15 - 30 micro amps. It is important that the analogue ground here and within the preamplifier circuit be clean and noise free.

2) Signal amplification:

There are a number of variations on low frequency AC amplifiers, some give better performance than others when used for amplifying the signals from IR sensors. In particular, tolerance to noise pickup and temperature variations are very important. Fig. 1 shows a suggested 2-stage amplifier.

2a) First stage:

This is an AC coupled non-inverting amplifier. The sensor signals pass through initial high frequency filtering formed by R22/C11 (reference) and R23/C12 (active); this is to reduce high frequency interference that may be picked up in the cable between the circuit and the sensor. Any noise induced at the sensor cable will otherwise be subject to amplification. The signals are then AC coupled via C9/R21 (reference) and C10/R20 (active) to a 1.25V reference voltage. This reference is chosen as the mid scale point of a 2.5V referenced A/D converter into which the outputs can be digitised. If a different A/D reference voltage is used then it should be divided by 2 and that level used for the reference point of the amplifiers. This allows the signals to swing equally above and below the reference voltage. If the amplified signals exceed the reference voltage they will clip both against analogue ground and the A/D reference. If an amplifier reference voltage is used which is not half the A/D reference level then care must be taken that the amplified signals do not clip either analogue ground or the A/D reference. Note that if only one of these limits is reached then such clipping can avoid detection since the A/D result does not reach maximum counts.

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The gain of the first stage is set by R13/R15 (reference) and R17/R18 (active), the frequency response being set by the AC coupling and C7 (reference) and C8 (active). The first stage gains are set to a nominal value of 28, varying a little with frequency and centred at around 27.8.

2b) Second stage:

The outputs of the first stage are AC coupled to the second stage via R12 (reference) and R16 (active). The second stage is essentially the same circuit as the first stage but with a variable gain element shown as R5/R6 (reference) and R8/R9 (active). It is advisable to have a means to adjust the gain in order to obtain the maximum signal size in zero grade air without the signals getting too close to analogue ground or the A/D reference voltage at their minimum and maximum values. A digital potentiometer with EEPROM data storage is recommended, the digital potentiometer being controlled by a circuit processor and the start-up value loaded directly from the EEPROM within the digital potentiometer. Note that changing the gain of the second stage as per the suggested circuit does not affect the frequency response of the second stage. The outputs of the second stage then form the active and reference signals that can be connected directly to an A/D converter.

3) Signal conversion:

A typical change in signal for a hydrocarbon sensor monitoring methane is 10% when exposed to 100%lel methane. In order to resolve to 1%lel methane a change in signal of less than 0.1% must be measured which requires a minimum 12 bit A/D resolution. The active signal size should be optimised by the second stage gain adjustment such that the peak of the signal in zero gas is at least 90% of the A/D reference level and the trough is not greater than 10% of the A/D reference level. The effect of temperature on the gain circuits can be roughly balanced by using the same gain setting for the reference as for the active, although the effect is minor compared to the effects of temperature on the detector itself. Therefore the reference gain can be set to the same as the active gain or it can be set to optimise the reference signal such that the peak of the signal in zero gas is at least 90% of the A/D reference level and the trough is not greater than 10% of the A/D reference level.

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Application Note DESA2: Signal extraction

This application note discusses the means to extract the target gas concentration from the output signals of an infrared sensor preamplifier. The mathematics is discussed along with means to compensate for temperature and cross-referencing. The expressions to extract the concentration are given along with a programming guide.

1) Signal waveforms and entry values:

The signals resulting from amplification as discussed in application note DESA1 should appear as an approximate sine wave, one signal for the active and one signal for the reference. The meaningful signal is related to the integrated charge generated by the detector for each channel during each on-off cycle of the lamp. So we need to extract firstly a measure we can use. This measure can simply be the peak-to-peak measurement or it can be the integrated area within the waveform or it can be the RMS equivalent of the waveform. Whichever method is used results in a value for the active signal strength and a value for the reference signal strength. This measure should be taken every on-off cycle of the lamp. Figure 1 shows typical sample waveforms, the relationship between the waveforms and the lamp cycle plus the peak to peak and integrated area measures as examples.

Figure 1: Sample waveforms
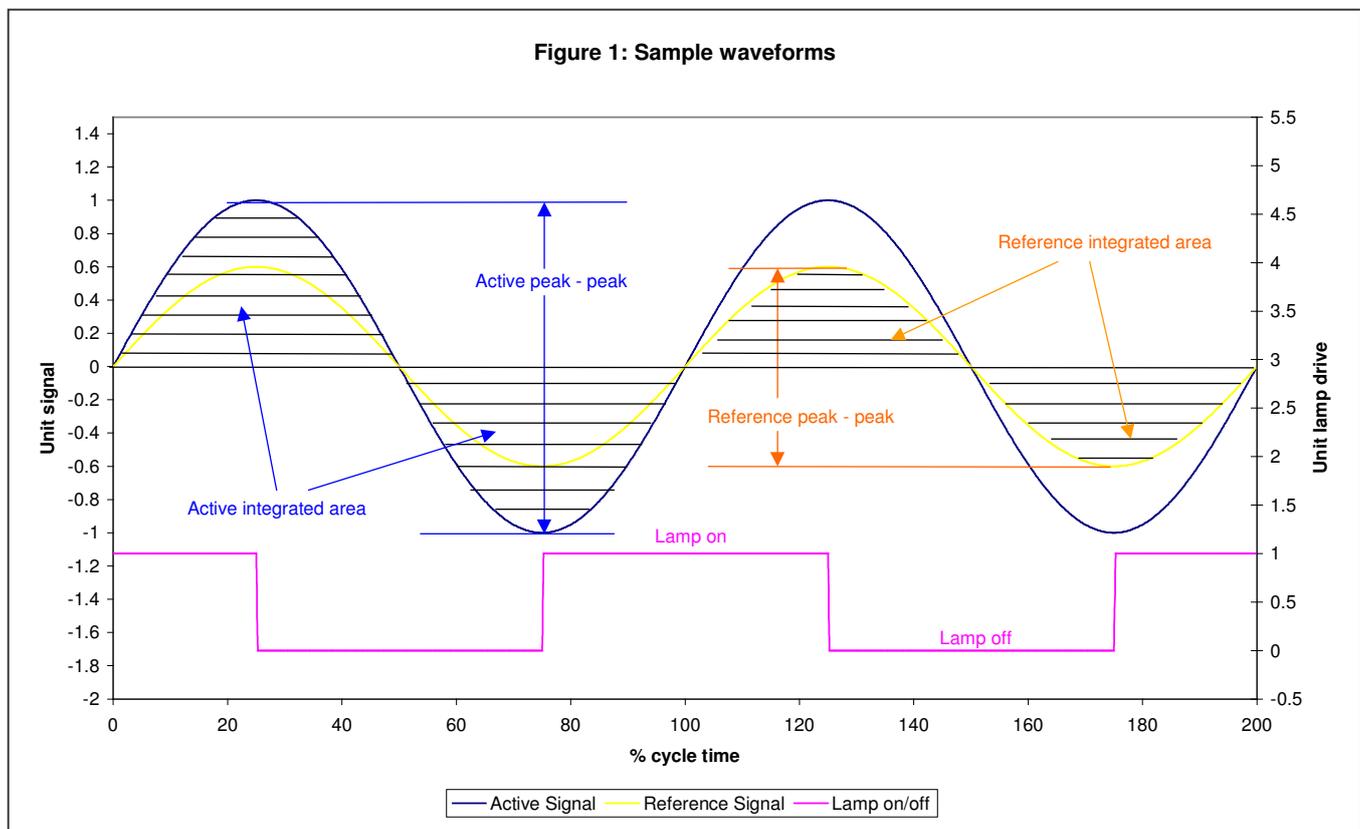
For each cycle a new measure of the active and reference signal strengths should be taken. This measure can be the new peak to peak value, the new integrated area value or the new RMS value, whichever method is chosen depends on the software approach being taken.

In the presence of target gas the active signal strength will reduce and this is the basic detection means. The reference signal strength is used to compensate for changes in incident radiation, changes in optical transmission and any changes in responsivity of the detectors due to temperature. It is the ratio of active signal strength to the reference signal strength that is used to extract the gas concentration in the mathematics routines.

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2) <u>Basic equations to extract gas concentration:</u>

The Beer-Lambert law describes the absorbance of radiation as a function of the gas concentration and is expressed as $A = \varepsilon c l$ where A is absorbance (dimensionless), $\boldsymbol{\varepsilon}$ is the extinction coefficient for the wavelength being absorbed, c is the gas concentration and l is the pathlength. The absorbance, A, is related to the intensity of radiation by $A = -\log(I/I_0)$, where I is the intensity of radiation in the presence of target gas and I_0 is the intensity in the absence of target gas. This law holds for a single wavelength since the extinction coefficient changes with wavelength in accordance with the spectrum of the target gas.

The detectors consist of an active channel and a reference channel. Each channel has a passband infrared filter in order that the channel only responds to wavelengths of radiation that pass through the filters. Therefore the detectors see a band of wavelengths, each wavelength having its own extinction coefficient from the target gas and its own transmission through the passband filter. Consequently this distorts the Beer-Lambert law relationship between intensity and gas concentration, modifying it in general terms from $I/I0 = \exp\{-\varepsilon c l\}$ to:

$$1 - I/I_0 = s * (1 - \exp\{-a * [c]^b\})$$

where s represents a span value, a is an exponential constant for a given target gas and range related to εl, c remains as the gas concentration and b is a power term. The span value represents the maximum reduction in intensity expected for a given target gas while the exponential and power term constants are derived empirically from measurements of the intensity as a function of gas concentration.

The ratio of active to reference signal should be normalised in order to get a value for I/I_0 which is within the range 0 to 1. In order to do this, measures of the active and reference signals are taken in the absence of target gas and the ratio of these signals is then stored as a zero value. So zero = $I_{active}/I_{reference}$ in the absence of target gas where I_{active} is the active signal value and $I_{reference}$ is the reference signal. The normalised value of I/I_0 is then obtained for each lamp cycle from:

$$I/I_0 = I_{active}/(zero * I_{reference})$$

The resulting modified form of the relationship is then given by:

$$1 - I_{active}/(zero * I_{reference}) = span * (1 - \exp\{-a * [concentration]^b\})$$

Rearranging the expression allows us to extract the gas concentration from:

$$[concentration] = (-\ln\{1 - [(1 - I_{active}/(zero * I_{reference}))/span]\}/a)^{(1/b)}$$

If we denote absorbance as being equal to $(1 - I_{active}/(zero * I_{reference}))$ then:

$$[concentration] = (-\ln\{1 - (absorbance/span)\}/a)^{(1/b)}$$

For each cycle of the lamp a new reading of I_{active} and $I_{reference}$ is used to update the calculation. The parameters required in addition to the active and reference signal sizes are the zero (found from calibration), the span (also found from calibration), the exponential constant a and the power term constant b.

The value for span can be found by measuring the active and reference signals when the sensor is exposed to a known target gas concentration, calculating the absorbance and then using the rearranged form:

$$Span = absorbance / (1 - \exp\{-a * [concentration]^b\})$$

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3) Temperature compensation:

Temperature can make several possible contributions to the signals. The responsivity of the detectors changes with temperature and this is approximately compensated by the inverse temperature characteristic of the on-chip FETs within the detector. In addition, the effect of temperature on capacitance values within the preamplifier can change the frequency response and the subsequent gain. The suggested circuit in DESA1 is balanced to give a plateau response in the frequency range of interest so this effect should be minimal. However, if other circuit arrangements are used then care should be taken to ensure the gain is not affected significantly by temperature. Finally, the ideal gas law has an absolute effect on the relationship between the gas concentration and temperature, as given by the ideal gas law relationship:

$$PV = nRT$$

Where P = pressure, V = volume of the sensor, n = number of moles of gas inside the sensor, R = Ideal gas law constant and T = absolute temperature.

The sensor effectively monitors the number of moles of gas within the optical path and therefore this is affected by both pressure and temperature, where we assume the volume of the sensor remains constant. This ideal gas law effect is normally compensated in software by applying ideal gas law correction, at least for temperature.

Temperature correction is typically applied to both the zero and to the span. Note that ideal gas law correction can be incorporated in the span temperature compensation if desired, otherwise it is applied to the final concentration value. The general expression for zero temperature compensation is:

$$Z_{corr} = Z_{cal} * (1 + \alpha * (T - T_{cal}))$$

Where Z_{corr} is the temperature compensated zero result, Z_{cal} is the zero value when calibrated, α is the temperature compensation factor, T is the absolute temperature inside the sensor and T_{cal} is the absolute temperature inside the sensor when the zero was calibrated. It is advisable to have 2 temperature compensation factors, one for temperatures greater than the calibration temperature and one for temperatures less than the calibration temperature.

A similar expression is used for the span temperature compensation:

$$S_{corr} = S_{cal} * (1 + \beta * (T - T_{cal}))$$

Where S_{corr} is the temperature compensated span result, S_{cal} is the soan value when calibrated, β is the temperature compensation factor, T is the absolute temperature inside the sensor and T_{cal} is the absolute temperature inside the sensor when the span was calibrated. Again, it is advisable to have 2 temperature compensation factors, one for temperatures greater than the calibration temperature and one for temperatures less than the calibration temperature.

Finally, the ideal gas law correction for temperature can be applied to the final calculated concentration according to:

$$[concentration]_{corr} = [concentration] * T / T_{cal}$$

where [concentration] is the calculated resulting gas concentration, T is the absolute temperature in Kelvin, T_{cal} is the absolute temperature in Kelvin when the span was calibrated and $[concentration]_{corr}$ is the ideal gas law corrected concentration value.

The above expressions and means of compensation are summarised below in the form of a typical software algorithm.

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APPLICATION NOTE

4) <u>Example concentration calculation software routine:</u>

```
//-------------------------------------------------------------------------
// FUNCTION NAME: float GetConcentration(void)
//
// DESCRIPTION:
// Calculates the gas concentration from measured active, reference and temperature values measured during one full lamp on – lamp off cycle
// using the expression:  Concentration = ( -ln(1-Absorbance/span)/exponent )^(1/powerterm)
//-------------------------------------------------------------------------
//
// Entry requirements:
//       Active_Cycle:              Value of the active signal (float)
//       Reference_Cycle:           Value of the reference signal (float)
//       Temperature_Reading:       Value of the current temperature in Kelvin (float)
//       Zero_Value:                Value of the zero determined during calibration (float)
//       Span_Value:                Value of the span determined during calibration (float)
//       Zero_Temperature:          Temperature in Kelvin when zero calibrated (float)
//       Span_Temperature:          Temperature in Kelvin when span calibrated (float)
//       Positive_Zero_Tempcomp:    Value of the temperature correction factor for zero if temperature > when calibrated (float)
//       Negative_Zero_Tempcomp:    Value of the temperature correction factor for zero if temperature < when calibrated (float)
//       Positive_Span_Tempcomp:    Value of the temperature correction factor for span if temperature > when calibrated (float)
//       Negative_Span_Tempcomp:    Value of the temperature correction factor for span if temperature < when calibrated (float)
//       Exponent:                  Linearity exponent constant (float)
//       Powerterm:                 Linearity power term constant (float)
//       IdealGasLaw:               Switch for applying ideal gas law temperature correction (integer)
//
// Exit result:     Concentration (float)
// Side effects:    none
//-------------------------------------------------------------------------

float GetConcentration(void)
{
// local variables:
        float temp_comp_ratio = 0;
        float absorbance = 0;
        float temp_comp_span = 0;
        float value = 0;
        float Concentration = 0;

// Calculate the absorbance from the temperature compensated normalized_ratio:

        temp_comp_ratio = Active_Cycle / ( Reference_Cycle * Zero_Value ); Get normalised ratio

        if (Temperature_Reading > Zero_Temperature)
                {
                temp_comp_ratio = temp_comp_ratio * (1 + Positive_Zero_Tempcomp * (Temperature_Reading - Zero_Temperature ));
                }

        else if (Temperature_Reading < Zero_Temperature)
                {
                temp_comp_ratio = temp_comp_ratio * (1 + Negative_Zero_Tempcomp * (Temperature_Reading - Zero_Temperature ));
                }

//Get absorbance value:

        absorbance = (1 - temp_comp_ratio);

// Calculate SpanCorrection:

        temp_comp_span = Span_Value ;

        if (Temperature_Reading > Span_Temperature)
                {
                temp_comp_span = temp_comp_span * (1 + Positive_Span_Tempcomp * (Temperature_Reading - Span_Temperature));
                }

        else if (Temperature_Reading < Span_Temperature)
                {
                temp_comp_span = temp_comp_span * (1 + Negative_Span_Tempcomp * (Temperature_Reading - Span_Temperature));
                }
```

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```
// Calculate the value for conversion:

        if (temp_comp_span != 0)
                {
                value =  absorbance / temp_comp_span;
                }

        else
                {
                value = 0;
                }

        if(value > 0)
                {
                        sign = POSITIVE;
                }
        else if (value < 0)
                {
                        sign = NEGATIVE;
                        value = fabs(value);
                }
        else
                {
                // If here then value = 0 so return result = 0:
                Concentration = 0;
                return(Concentration);
                }


// Calculate the concentration using the expression Concentration = ( -ln(1-Absorbance/span)/exponent )^(1/powerterm):

        value = - log(1 - value);

        value = pow((value / Exponent), (1 / Powerterm));

        if(sign == NEGATIVE)
                {
                value = -value;
                }

// Apply ideal gas law temperature correction if required:

        if(IdealGasLaw == TRUE)
                {
                Concentration = value * ( Temperature_Reading / Span_Temperature )
                }
        else
                {
                Concentration = value;
                }

//Return new concentration result:

        return(Concentration);
}


//-------------------------------------------------------------------------
//
//        End of routine
//
//-------------------------------------------------------------------------
```

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