A CMOS INTEGRATED INFRARED RADIATION DETECTOR FOR FLAME MONITORING

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ABSTRACT

This paper presents an integrated infrared radiation detector for flame monitoring applications, fabricated in CMOS technology. The system discriminates the radiation of the flickering flame in an oil burner from the steady background radiation generated by the furnace by considering only the harmonic components of the infrared signal in the band from 50 Hz to 250 Hz. In order to maximize the flexibility and the robustness of the system, most of the signal processing is performed in the digital domain. Experimental results on an integrated prototype, confirming the validity of the proposed approach, are reported.

1. INTRODUCTION

Nowadays the regulations and the requirements concerning security in domestic and industrial apparatus are becoming more stringent and severe. In particular gas and oil burners require necessarily flame monitoring systems, in order to detect the presence of the flame and avoid dangerous leakages of gas or oil. Very simple and cheap ionization probes are typically used in gas burners, in view of the relatively clean environment. These sensors, however, degrade very quickly in oil burners because of the dirt combustion residues. Other available flame detectors placed inside the furnace of oil burners [1], including thermocouples, microphones and video cameras, provide a low signal-to-noise ratio and easily degrade in the hostile furnace ambient. By contrast, flame monitors based on radiation detection [2, 3, 4] can be placed outside the furnace, in a less harsh and polluted environment, thus increasing significantly its long-term stability and reliability of the system.

In particular, silicon infrared (IR) sensors (photodiodes) can be fabricated using the standard CMOS layers, thus allowing the integration of complex signal processing functions on the sensor chip at very low cost. Of course, in the IR region of the spectrum (from 800 nm to 1000 nm), the emission intensity of the flame is at least one order of magnitude lower than the emission intensity of the furnace. The IR radiation power produced by the furnace, however, is concentrated at DC (or at least at very low frequency), while the unavoidable flickering of the flame spreads the IR radiation power of the burning oil in a frequency band ranging from 50 Hz to 250 Hz. It is, therefore, possible to detect the presence of the flame with a large signal-to-noise ratio by monitoring the IR radiation in this frequency band, while suppressing the large DC component. Thanks to the CMOS compatibility of IR photodiodes, the additional hardware required to perform the filtering can be integrated on the sensor chip, thus making the resulting microsystem very convenient in terms of cost and performance.

2. INTEGRATED PHOTODIODE

The cross-section of a CMOS compatible IR photodiode is shown in Fig. 1. The active junction of the diode (n-well/p-substrate) is sufficiently deep to allow the generation of electron/hole pairs due to IR radiation [5, 6].

![Figure 1. Cross-section of the CMOS integrated photodiode](image)

The responsivity of a photodiode at wavelength \( \lambda \) is defined as

\[
R(\lambda) = \frac{I_{ph}(\lambda)}{\Phi(\lambda)},
\]

where \( I_{ph}(\lambda) \) denotes the generated photocurrent and \( \Phi(\lambda) \) the corresponding incident radiation power. Therefore, the
generated photocurrent can be expressed as

$$I_{ph} = \int_{\lambda_1}^{\lambda_2} \Phi(\lambda) s(\lambda) d\lambda.$$  

(2)

In order to determine the expected photocurrent in flame monitoring applications, the responsivity of the photodiode used in the proposed system has been measured (Fig. 2). From the measurements we obtained an effective photocurrent $I_{ph}$ of the order of few tens of $\mu$A. It is worth to note from Fig. 2 that the integrated photodiode shows a large responsivity also in the visible region of the spectrum, as expected. This additional information may be useful in flame monitoring applications, however, if necessary, it can be removed by placing an optical filter on top of the sensor.

![Figure 2. Measured spectral responsivity of the integrated photodiode](image)

**3. SYSTEM DESCRIPTION**

The most important specifications of an IR radiation detector for flame monitoring are summarized in Tab. 1. In view of the low frequency of the considered signals, a digital implementation of the filters, which does not require external components to realize large time constants, is preferable with respect to a classical analog solution and, in addition, it is more flexible and easily programmable.

The block diagram of the proposed IR detector is shown in Fig. 3. The system consists of an integrated inversely biased IR photodiode, a readout circuit, an analog-to-digital converter (ADC), the digital filters, a digital signal processing circuit and a feedback loop with digital-to-analog converter (DAC) for suppressing the DC component of the IR signal.

The readout circuit for the integrated photodiode has two main functions: provide a suitable biasing voltage for the diode and transform the diode current into a voltage. Both of these tasks are accomplished by an operational amplifier with resistive feedback. The used operational amplifier is based on a standard two-stage class AB structure. The feedback resistor $R$ and the biasing voltage $V_b$ are external, in order to allow sensitivity and operating point adjustments.

The current generated by the photodiode, transformed into a voltage and amplified, is converted into the digital domain by an 8-bit resistor-string-based successive approximation ADC with sampling frequency $F_{S} = 32$ kHz. The resulting digital word is then down-sampled (decimated) with $F_{S} = 1$ kHz, in order to reduce the complexity of the subsequent digital filtering section. The output word of the decimator is delivered either to the feedback loop and to a digital band-pass filter. The feedback loop extracts the DC component of the signal with a digital accumulator and subtracts it directly from the sensor signal by means of an 8-bit current mode DAC (binary weighted current sources). At the same time, the band-pass filtered signal is delivered to the digital signal processor, whose block diagram is shown in Fig. 4, where it is rectified, accumulated and compared with a programmable threshold, in order to produce an output bit representing the status of the flame.

The block diagram of the decimating filter is shown in Fig. 5. The filter consists of two accumulators sampled at $F_{S} = 32$ kHz followed by two differentiators sampled at

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>CMOS</td>
</tr>
<tr>
<td>Power Supply</td>
<td>5 V</td>
</tr>
<tr>
<td>Frequency Band</td>
<td>50 Hz + 250 Hz</td>
</tr>
<tr>
<td>Radiation Wavelength</td>
<td>800 nm + 1000 nm</td>
</tr>
<tr>
<td>Output Signals</td>
<td>Digital</td>
</tr>
<tr>
<td>Flame Presence</td>
<td>1 Bit</td>
</tr>
<tr>
<td>Flame Intensity</td>
<td>8 Bits</td>
</tr>
<tr>
<td>DC Component Suppression</td>
<td>−40 dB</td>
</tr>
<tr>
<td>High Frequency Rejection</td>
<td>−30 dB</td>
</tr>
<tr>
<td>Flame Detection Threshold</td>
<td>Programmable</td>
</tr>
</tbody>
</table>

**Table 1.** Specifications of the IR detector for flame monitoring

![Figure 3. Block diagram of the infrared radiation detector](image)
$F_{SL} = 1$ kHz \[7, 8\] and implements the $z$-domain transfer function

$$H_D(z) = \left(\frac{1 - z^{-D}}{D(1 - z^{-1})}\right)^2,$$

(3)

where $D = 32$ is the decimating factor.

The digital band-pass filter, whose block diagram is shown in Fig. 6, is obtained by cascading a high-pass filter with $z$-domain transfer function

$$H_{LP}(z) = 1 - z^{-3}$$

(4)

and a five-tap FIR low-pass filter. The coefficients $A, B$ and $C$ have been approximated with powers of 2 ($A = -2^{-9}$, $B = -2^{-5} - 2^{-7} - 2^{-8}$ and $C = 2^{-1} + 2^{-5}$), in order to replace the expensive multipliers with simple shift registers and adders [9]. The resulting transfer function

$$H_{LP}(z) = Az^{-5} + Bz^{-4} + Cz^{-3} + Cz^{-2} + Bz^{-1} + A,$$

(5)

is graphically shown in Fig. 7.

4. EXPERIMENTAL RESULTS

The proposed integrated IR detector has been integrated in a standard 0.8 \( \mu \)m double-poly, double-metal CMOS process. The microphotograph of the chip is shown in Fig. 8. The total die area, including pads is 3.7 mm \( \times \) 2.5 mm, while the IR photodiode area is 800 \( \mu \)m \( \times \) 800 \( \mu \)m.

The measured operational amplifier output voltage ($V_{ADC}$) as a function of the diode photocurrent ($I_{ph}$) with and without the DC cancellation feedback loop is shown in Fig. 9. It can be observed that the feedback loop attenuates the DC component more than 30 dB, thus avoiding the saturation of the operational amplifier. The residual DC component is then removed by the digital band-pass filter.

Fig. 10 and Fig. 11 show the measured transient behavior of the system digital output (Output) and of the operational amplifier output voltage ($V_{ADC}$) when the flame is turned off and when the flame is turned on, respectively. To perform these measurements, the flame has been emulated with an IR diode operated at 50 Hz.

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5. CONCLUSIONS

This paper presented a fully integrated infrared radiation detector for flame monitoring applications. The system discriminates the flickering flame radiation from the steady background radiation generated by the furnace by considering only the harmonic components of the infrared signal in the band from 50 Hz to 250 Hz. This solution allows a large signal-to-noise ratio to be obtained although the flame radiation is lower than the background radiation. In order to maximize the flexibility and the robustness of the system, most of the signal processing is performed in the digital domain. Experimental results obtained from an integrated prototype demonstrate the validity of the proposed approach.

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