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AN2042

PSoC® 1 - Multifunctional Optical Sensor

Author: Viktor Kremin
Associated Project: Yes
Associated Part Family: CY8C27443
Software Version: PSoC© Designer™ 5.1
Related Application Notes: None

AN2042 explains how to design applications with optical sensors. The application note elaborates on the sensor flowchart and gives a step by step procedure to implement the sensor flowchart inside PSoC.

Introduction

Optical sensors, which are based on detection of light beam interruption, are widely used in practice. These sensors are installed in automatic door opening systems in the shops, garages and private apartments. They are used in a variety of applications. Identifying unauthorized object access, measuring liquid level in tanks, position of the movable part are few of those examples.

These sensors typically consist of light source (bulb lamp, infrared or red LED, or even semiconductor laser, depending on the application type), photodiode for reception of light beam and threshold electronic circuit, which compares photodiode signal level with reference signal and turns-on the corresponding executive part. The primary drawback of this approach is the sensor noise and poor sensitivity, which might result in false detection. However, these drawbacks can be eliminated by using a modulated light and involving correlation techniques to make decisions on the presence and absence of an object between light source and receiver.

The PSoC® microcontroller optical sensor is free from these drawbacks and is characterized by excellent sensitivity, which allows decreasing light emitting power. This reduces sensor current consumption and improves resistance to various external light and electromagnetic noise signals.

The discrete component approach for building a sensor signal processing part requires a substantial number of passive and active components, which are not cost effective. The proposed signal processing scheme is universal and can be used for building several types of non-optical sensors as described below in the sensor applications' section.

The heart of the sensor is Cypress PSoC microcontroller. PSoC enables the user to build the sensor with minimum number of external components. This reduces the cost of the solution.

The following table summarizes the main sensor characteristics.

Table 1. Main Characteristics for the Sensor

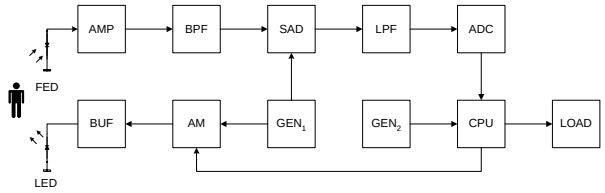
Item	Item Value
Operation Range (dependent on the light source type): Infrared or red emitting diode with focus lens, narrow beam Red semiconductor laser, radiation power less than 1 mW. Detection movable persons via scattering reflected light.	 Up to 5-15 m Up to 100-150 m Up to 2 m
Power Consumption	75 mA
Sensor Outputs	Alarm LED and relay with normal closed and normal open contact pairs.
Threshold Value	Automatically adjustable.
Alarm Conditions (DIP switches programmable)	Input signal level changed, level decreased, level increased, threshold mode.
Sensor Response Time	0.1 s

The Sensor Flowchart

Figure 1 depicts the sensor block-diagram. The sensor operates in the following way:

The generator **GEN_1** is forming continuous carrier signal, which is routed to the amplitude modulator (AM). The amplitude modulated carrier signal is routed to light emitting diode (LED) via buffer amplifier (BUF). The LED light is reaching the photodiode FED and is being converted into electric signal.

Figure 1. Sensor Block Diagram



The photodiode signal is amplified by input amplifier (AMP) and is filtered by band-pass filter (BPF). The filter center frequency is selected equal to carrier frequency of **GEN_1**. The filter output signal is amplitude demodulated by synchronous amplitude demodulator (SAD). The low-pass filter (LPF) removes the high-frequency products from demodulator output signal. The analog-to-digital converter (ADC) is sampling the low-pass filter output signal. ADC samples are processed by the central processor CPU. The generator **GEN_2** is forming periodic processor interrupts for creating low-frequency modulation signal, which is used for controlling the AM as well as for additional service purposes.

The processor performs the digital correlation between ADC data stream and modulation signal, for detection of received FED signal amplitude changing. The calculation results are used for controlling the external load.

Note: All sensor blocks are implemented in the PSoC chip internals except the external LED, buffer BUF and load driver.

The proposed sensor signal-processing scheme is characterized by high immunity to external light signals and various electric noises that may be encountered in harsh industrial systems.

The Sensor Hardware

We suggest first to examine the detailed circuit diagram then go to chip configuration internals. This approach will simplify the understanding of sensor operation.

The Sensor Schematics

The complete sensor schematic is represented on Figure 2 and Figure 3. Figure 2 displays the LED buffer, load controller and power regulator and Figure 3 depicts the processor.

Figure 2. Sensor Schematic; Interface

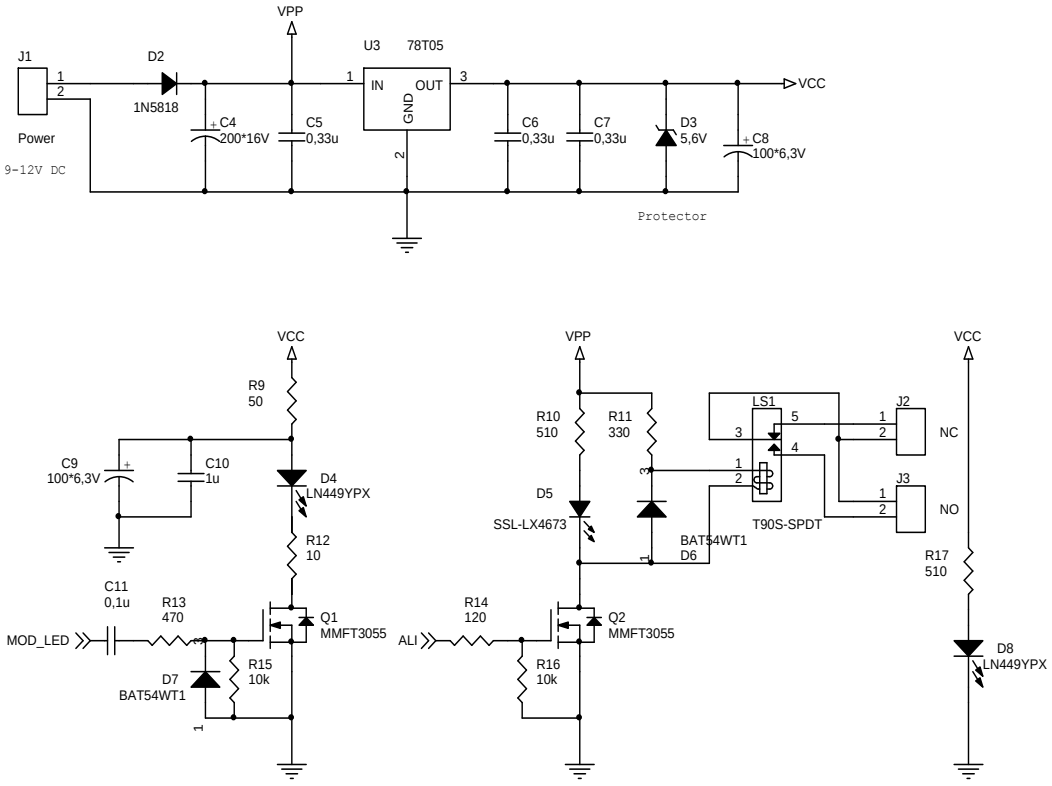
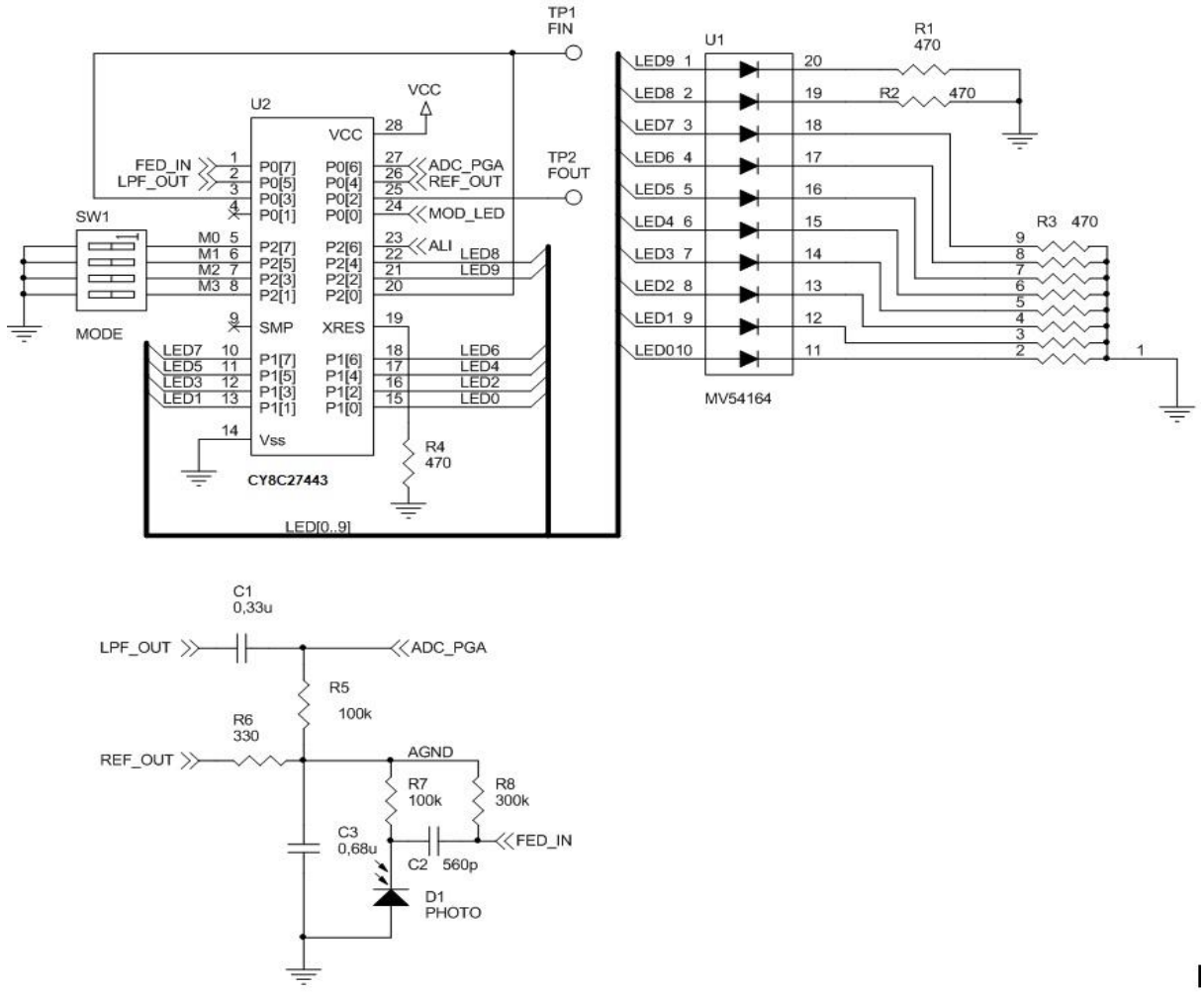


Figure 3. Sensor Schematic; CPU



The LED drive signal via network $C_{11}R_{13}R_{15}D_7$ is reaching the gate Q_1 MOSFET. This circuit blocks possible DC component and protects power LED or semiconductor laser from potential CPU instabilities, which might produce constant high output level and thermally damage light emitter. The filter $R_9C_9C_{10}$ suppresses the LED current pulses' influence on sensor supply. The driver can serve several power LEDs or semiconductor laser diode, depending on application operation range demands.

The load driver is MOSFET Q_2, which controls the relay LS_1 for switching of external loads. LED D_5 provides an indicator for the relay switching. Depending on the application type, the Q_2 can serve other load types, for example serve as power open-drain switch. The power supply consists of a conventional linear regulator U_3. D_2 protects sensor electronics under reverse power condition. The sensor can be powered from non-stabilized 7-12 V DC/AC supply with maximum current of 100 mA.

The reference analog ground *AGND* is routed from the PSoC internal reference and output buffer and filtered by R_6C_3 low-pass filter, which suppresses reference noise. The high-pass filter C_1R_5 blocks DC component from switched capacitor low-pass filter before bringing to ADC. The C_1R_5 filter cut-off frequency is selected near 5 Hz and is well below the amplitude modulation frequency. The modulation frequency is set to 300 Hz and is divisible to AC mains frequency for both American and European standards. This additionally reduces the AC mains noise influence on sensor behavior. The carrier frequency is set as 15 kHz and is divisible for amplitude modulation frequency by factor 50.

R_7 provides the photodiode reverse bias level; the high-pass filter C_2R_8 blocks the low-frequency noise signals from external light or inducted by AC mains. The second function of this filter is the correction of phase delay originated in the internal band-pass filter. The C_2R_8 filter cut-off frequency is set at 1 kHz to provide suitable phase shift.

The bar-graph display U_1 is intended for visualizing the received signal level and allows adjusting the LED and FED relative attitudes for reaching the maximum level of received signal. This display is particularly useful when invisible infrared laser or transmit LED is used.

The DIP switches SW_1 are assigned for setting sensor operation mode. The switches allow having one software version for wide range of applications and in some cases eliminates application-specific software adaptation. Supported sensor modes are described ahead in The Sensor Software section.

The Chip Internals

The total chip interconnection is presented on Figure 4. The photodiode amplifier is implemented on ACB00, Continuous Time (CT) block, which is configured as programmable gain amplifier (PGA). The amplifier output signal, routed to P0[3] port pin, is externally connected with input of band-pass filter via pin P2[0]. PSoC routing and placement limitations prohibit this connection internally.

The band-pass filter output is routed via LPF_PGA to input of the synchronous amplitude demodulator. The amplitude modulation capability of block ASC10 is used for demodulator operation. The demodulator reference signal is generated by the timer and delivered to the modulator via *Global Output Bus 0*. The demodulator is combined with low-pass filter and is placed on ASC10 and ASD11 switched capacitor analog blocks. The filter output signal is routed via internal buffer to P0[5].

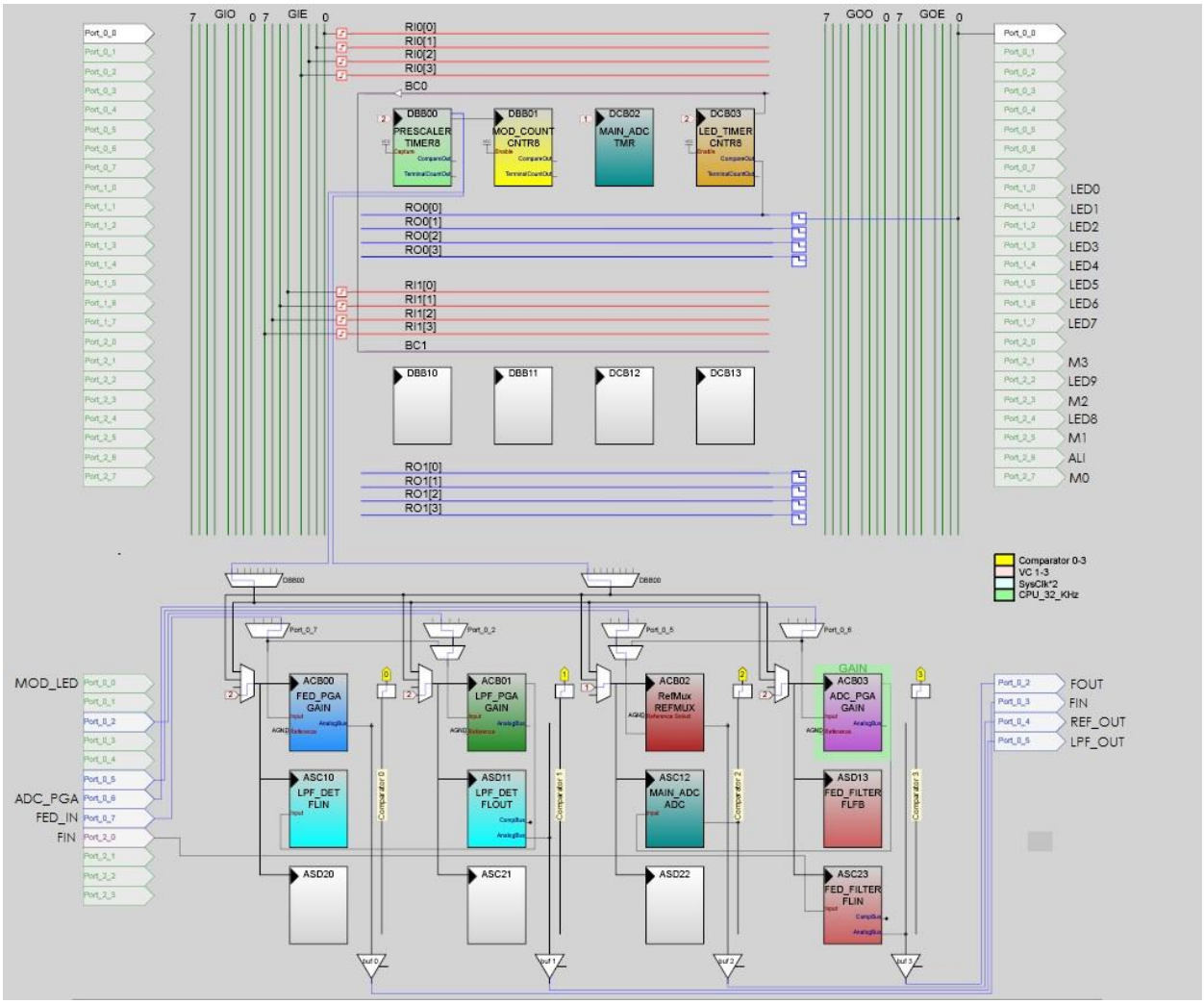
The low-pass filter signal via external offset blocking high-pass filter is routed to ADC input via port P0[6] and ADC_PGA. The 11-bit Sigma-Delta ADC is sampling the filter output signal and is characterized by good accuracy and relatively low CPU overheads. The ADC sampling rate is near 16 times higher than frequency of modulation signal, adequate for good waveform resolution.

The reference generator is placed into ACB02 CT block. The reference output signal is routed to P0[4] pin. The reference value is $V_{cc}/2$ and is used as bias for PGAs and filters.

PRESCALER and MOD_COUNT generate the periodic interrupt signal used for amplitude modulation of LED signal. The interrupt frequency is four times higher than modulation frequency and is set to 1200 Hz. LED_TIMER forms the carrier signal for LED emitter and synchronous amplitude demodulator. The carrier frequency is set as 15 kHz.

The LED_TIMER output is routed via *Global Output Bus 0* to P0[0] pin which controls the LED driver. The LED signal amplitude modulation possibility is implemented on-the-fly changing of port P0[0] function in the software interrupt routine. The P0[0] port pin function is alternating between standard CPU port and Global Output. The switching is being performed by toggling the corresponding bit in the PORT0 global select register (PRT0GS). The synchronous amplitude demodulator reference signal is active continuously.

Figure 4. PSoC Internals



The clocking scheme has the following advantages:

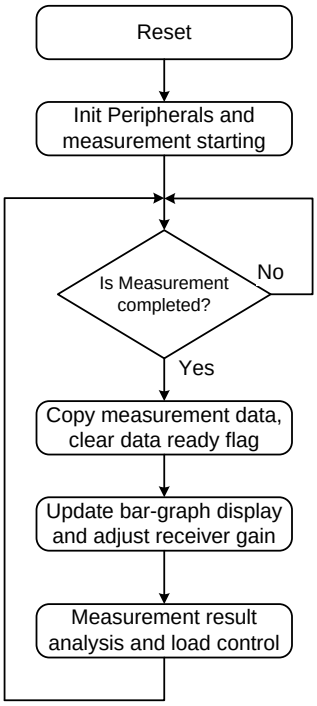
- single reference clock source eliminates low-frequency beating in the generated signals and minimizes jitter;
- the same clock frequency for both low-pass and high-pass filters minimizes the influence of frequency transformation products;
- filters' clock frequency is multiple of carrier and modulation frequencies.
- The Sensor Software

The sensor performs the continuous photodiode signal level measurement to make decisions concerning presence or absence of an object between light source and detector. Software algorithms are also implemented for dynamically adjusting the sensor blocks' parameter values, load, and bar-graph display controlling and processing of supplementary service operations. Let us describe the data processing algorithms and features of implementation in detail.

The sensor software is implemented using the interrupt-main loop programming technique. The real-time data collection and processing algorithms are implemented in the interrupt routines. The data analysis, load, and bar-graph display control functions are implemented in the main software loop.

Figure 5 depicts the main loop structure.

Figure 5. Main Loop Structure



The main loop is quite simple. After reset, we initialize all the peripheral devices first and enable the start of data collection. Second, we wait until measurement is complete, copy results and clear the data-ready flag. Next measurement cycle starts automatically after completing the previous one without any delay. Third, we display the level of photo detector signal and adjust the receiver gain level, if necessary. Last, we perform the measurement results' analysis, switch the load if alarm condition is detected, and start waiting for new measurement results. Note the configuration DIP switches are read after each measurement completes allowing dynamic changes to the sensor settings.

Figure 6. Modulation Waveforms

The photodiode receiver signal level measurement is based on correlation techniques to obtain better noise resistance. The software algorithm performs the cross-correlation function values' calculation. The presence of resonance band-pass filter together with low-pass filter produces some phase shift between modulation signal and measured photodiode-detector, envelope-signal samples. For elimination of the influence of this phase shift, the quadrature correlation has been used. The sensor calculates the two cross-correlation function values for zero shift time; first correlates the photodiode envelope signal with modulation signal and the second correlates the envelope signal with quadrature shifted modulation signal. Later, we shall combine these values into a single value to determine the useful signal level of the photodiode detector.

The following equations reflect this approach:

$$B_{\mathrm{R}} = \int_0^{T_i} U_{env}(t) M_{\mathrm{R}}(t)\, dt \qquad \text{Equation 1}$$

$$B_{\mathrm{I}} = \int_0^{T_i} U_{env}(t) M_{\mathrm{I}}(t)\, dt \qquad \text{Equation 2}$$

Where:

- U_{env} – envelope signal from the switched capacitor low-pass filter, which is sampled by ADC
- B_{R} and B_{I} – the value of cross-correlation functions
- M_{R} – centered modulation signal
- M_{I} – quadrature shifted, centered modulation signal
- T_i – Integration time, must be multiple to modulation period for better accuracy. These integrals can be replaced by integration sums as described ahead:

$$B_{\mathrm{R}}^{d} = \sum_{j=0}^{N_s} U_{env}^{j} \cdot M_{\mathrm{R}}^{j} \qquad \text{Equation 3}$$

Where:

- U_{env}^{j}, M_{R}^{j}, M_{I}^{j} – the values of corresponding signals for time t_i.

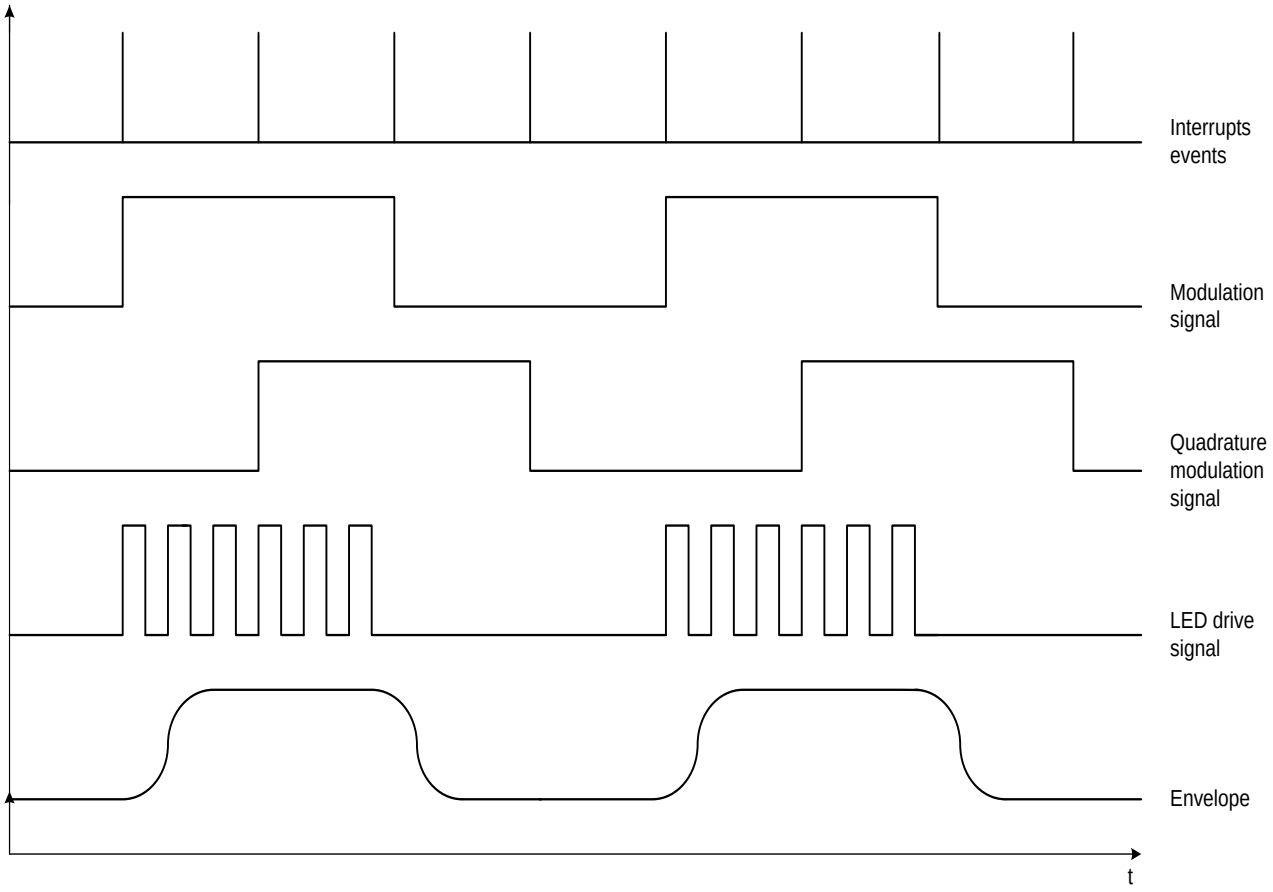
The discrete functions of modulation signal M_{R}^{j} and M_{I}^{j} can take only two values; +1 and -1 for replacing complicated multiplication operation by less expensive addition and subtraction.

Figure 6 .illustrates the time dependence for processor-interrupt events, modulation signal, quadrature shifted modulation signal, LED drive signal, and demodulated photodiode envelope signal. Note that the interrupt rate is four times higher than the modulation signal frequency for quadrature signal generation.

To implement this technique in the software, two interrupt routines are used. The first interrupt routine is called when ADC sample is prepared for reading and processes the sample value by recurrent calculation of integration sums from Equations 3 and 4. This routine compares the ADC sample value with the current maximum and minimum sample values and updates it, if necessary. These values are used for ADC swing calculation after the measurement cycle has been completed.

The second routine is called by timer interrupt and serves several functions. First, it generates the quadrature modulation signal, controlling the duration of measurement cycle to be equal to desired modulation signal period numbers, initializes a new one after the previous has been completed, and controls the duration of load-switching time.

Figure 6. Modulation Waveforms



The sensor can be installed into various applications which are characterized by different operation ranges, various light emitter and receiver types, different environment conditions (open air, fog, liquid, etc.) and, moreover, the operation conditions can be varied during sensor use. As a result, the photodiode signal level can be varied in the wide bounds correspondingly. The high signal level can saturate the sensor input stages and the low-level signal cannot be analyzed accurately. Both these situations reduce the sensor sensitivity. To extend the sensor's dynamic range, an Automatic Gain Control (AGC) loop is implemented in the sensor.

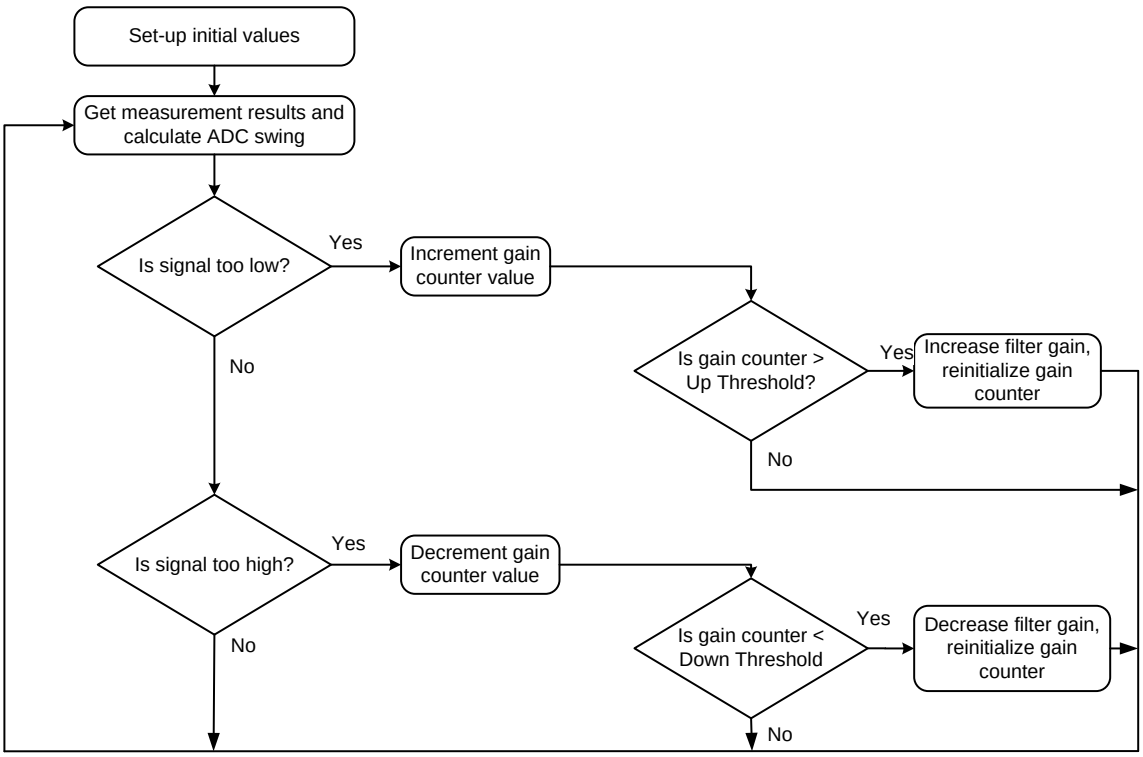
The AGC subsystem analyzes the ADC swing and adjusts the receiver gain for maximum ADC input range utilization. The gain variation is done by changing the band-pass-filter gain level. To change the filter gain, only the filter's input capacitor value is altered. Figure 7 illustrates the AGC operation. Alternatively, the gain switching of input PGA can be used for AGC implementation.

We suggest the following algorithm of AGC operation: If ADC input signal range is lower than some threshold value, we increment the gain loop counter. If gain loop counter has reached the upper predefined value, we increase the gain by setting the next gain level, if possible, and reinitialize the gain counter to some middle value. If the signal range is bigger than a set threshold value, we decrement the gain loop counter. If the gain loop counter has reached the lower limit, we decrease the gain of filter or PGA (depending on AGC implementation), if possible, and initialize the gain counter to some middle value. By accordingly defining the gain loop counter upper and lower threshold values together with the proper initial value, we can adjust the AGC transient time, and the non-symmetric AGC behavior can be implemented easily for special applications.

Note: For some applications, the ACG system can be turned off after the sensor has been installed and the optimal gain is determined and stored in the processor nonvolatile Flash memory. The examples of these applications are industrial position sensors, level detectors, when the light beam can be blocked for a long time and permanent operational AGC is not effective. Opposite, in the security or automatic door opening sensors the light beam is presented for most of the time and the constant AGC operation mode is preferred.

The 10-line, bar-graph display is updated after measurement cycle completion and the current ADC range is calculated. The filter gain level is accounted into signal level calculation of course, but bar-graph display can be used for visualization ADC signal level only.

Figure 7. AGC Operation



As explained earlier, the sensor performs photo detector signal-level analysis for load controlling. The load can be turned on, if the following events are detected:

- any directions in input level changes;
- Level has been decreased;
- Level has been increased.

The active events' combination detection is determined by DIP switches, which are listed in Table 2.

.Table 2. DIP-Switch Functions

Switch	Function in On/Off State
1	Activate detection of level increasing events (ignore in a threshold mode)
2	Activate detection of level decreasing events (ignore in a threshold mode)
3	High/low sensor sensitivity
4	Operational mode selector threshold detection/event detection

Note: The current version of data analysis algorithms can be used for event and threshold detection modes. The demanded mode is selected by corresponding DIP switch.

For detection of level changing events the dedicated digital high-pass filter is used. The filter transfer equation is following:

$$y_i = x_i - \frac{1}{N}\sum_{j=1}^{N} x_{i-j} \qquad \text{Equation 4}$$

Where:

- N – filter order
- x_i – input signal level estimation, which is calculated from the following formula:

$$x_i = \left|B_{\mathrm{R}}^{d_i}\right| + \left|B_{I}^{d_i}\right| \qquad \text{Equation 5}$$

Where:

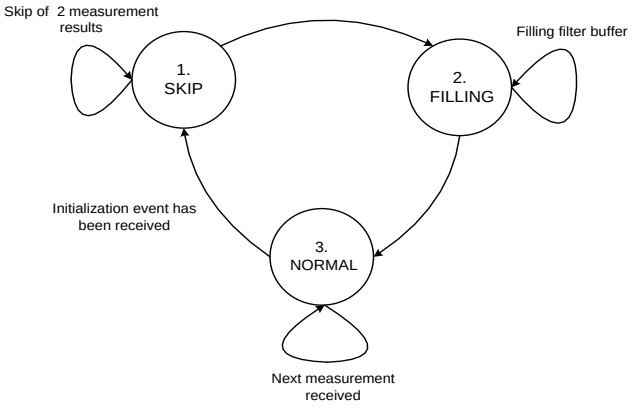
- $B_{\mathrm{R}}^{d_i}$ and $B_{I}^{d_i}$ are the integral sums from Equations 3 and 4.

The pure quadrature estimation may be more accurate, but because relation between $B_R^{d_i}$ and $B_I^{d_i}$ is not changing substantially during sensor operation (it is determined essentially by duration of transient time in band-pass filter, low-pass filter, and ADC decimator delay), the simplified estimation (6) is suitable completely for this purpose. If N in Equation 5 is equal power of two, the complicated division operation can be replaced by binary shifting for integer numbers x_i. In the sensor filter implementation software we have selected $N = 8$. The digital filter is implemented in such a way that only one addition and two subtractions together with one shift operation are needed for next y_i calculation. The circular data buffer is used for storing x_i values. The sensor threshold value is determined by sum component in Equation 5 and automatically adjusts accordingly to input signal level.

For elimination of false alarms, the filter must be initialized properly after the power-up or each time when receiver gain is changed. To this purpose, a dedicated state machine has been implemented. The machine operation algorithm is quite simple; if initialization event is received, we skip two measurement results, thus starting the filling of the digital filter buffer. When the buffer is filled completely, we start to analyze the filter output signal for detection of alarm conditions. Typically, the sensor automatically selects appropriate gain level after the power-up and keeps the constant gain afterwards. For the selected modulation frequencies and measurement duration in this example, the total sensor transient time after gain change is near 1 s. The bubble diagram in Figure 8 illustrates the machine states.

If threshold detector mode is selected, the analysis software operates in a different way; the AGC system is turned-off and a threshold value is calculated from the arithmetic mean of last eight samples when AGC was active. To do it, the sum from Equation 5 is used. As result, the user must first “teach” the sensor by turning on event detection mode after sensor installation then switching the threshold detector mode by toggling the corresponding DIP switch. Note, the non-volatile gain storage can be added simply via present Flash API functions.

Figure 8. State Machine Bubble Diagrams



Sensor Applications

Let us consider the following sensor applications:

1. **Direct Beam Interrupt Detector**
   Detection of light beam breaks in automatic door opening systems for garages, apartments, shops. For this application type the light emitter and photo detector can be located on the door-frame opposite sides or three surfaces-corner reflectors can be used.

2. **Reflected Light-Intensity Detection**
   The high-sensor sensitivity allows receiving reflected scattered light. The moving objects may change the reflected light level that the sensor will detect. This effect can be used to build security sensors, various proximity sensors, or automatic door opening systems. The LED buffer power reserve allows users to control several LEDs. For example, the sensor can be installed in wash-stands, dryers, and similar applications.

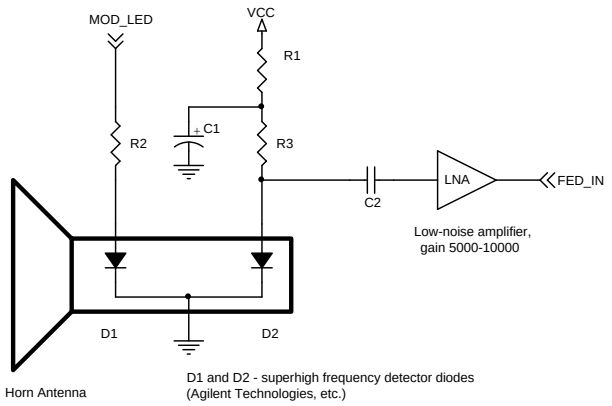
Non-Optical Applications

The proposed signal-processing scheme is universal and can be used for applications where detection of modulated signal amplitude-change is needed. We suggest taking into account two types of such applications.

1. **Capacitance-Based Level Detectors**
   The LED-photodiode pair can be replaced by a capacitance sensor. The changing of capacitance will be disclosed by the sensor and can be used to design liquid, loose materials level sensors, hydrometers, or capacitance-based position detector sensors.
2. **Super-High Frequency Radiation Detector**
   The proposed device can be used for building the high-sensitivity, low-cost device which can be used for microwave oven-leakage testing, field microwave antenna testers, microwave level measuring, and proximity sensors or even car driver information systems about active police speed measurement devices, etc. The device operation range can be 5-20 GHz and is determined by horn antenna dimensions, as well as the detector diodes' operational frequency.

The simplified device schematic is illustrated below:

Figure 9. Simplified Schematic of Super-High Frequency Radiation Detector



The sensor operation is based on the modulation of super-high frequency radiation absorption level by forward bias varying the first detector diode. This effect causes the modulation of DC level from the second detector diode, if microwaves are present. The small signal with amplitude of typically 5-20 μV is amplified by external low-noise amplifier and goes to the input of internal PSoC band-pass filter. The following signal-processing scheme is completely the same as described above.

Notes: Please take into account that internal synchronous amplitude demodulator is the phase sensitivity circuit and analyze the carrier phase shift budget. The modulation signal phase shift is not important because quadrature correlation is applied. Secondly, please carefully calculate the antenna waveguide dimensions and detector diode positions according to operational wavelength.

Summary

The multi-functional sensor that is presented can be used for building various intelligent devices. The software sources, schematics, and board layout examples simplify sensor adaptation for concrete application demands. The associated project includes full schematic and board layout files, as well as the Gerber files in Cadence Orcad® 9.2. Note that the layout was performed for components on the hand, using smaller footprints allow users to build sensors with noticeably smaller dimensions

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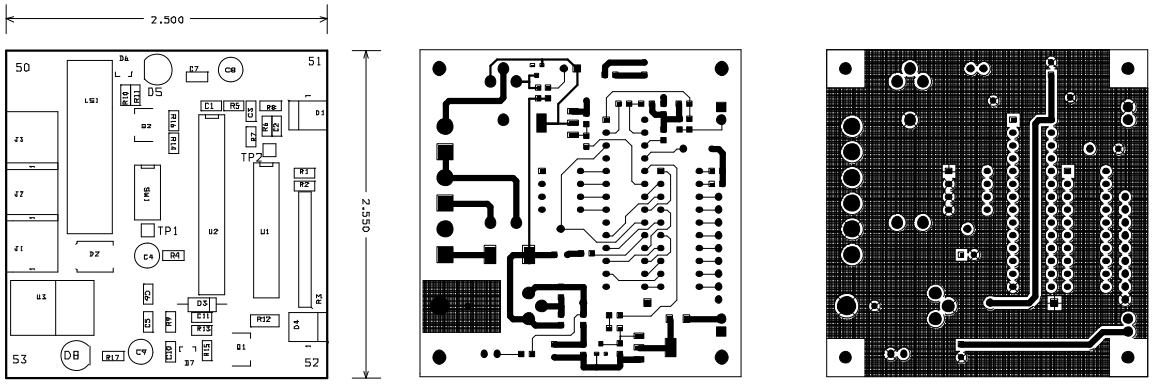
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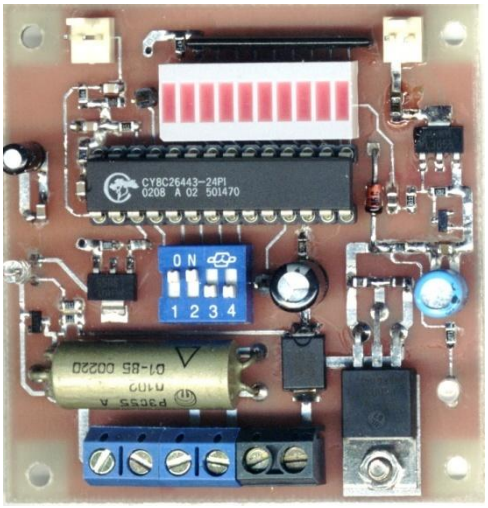
Appendix

Figure 10. Component-Placement and Board-Layout Layers



Component labels | Top layout layer | Bottom layout layer

Figure 11. Sensor; Actual Size



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**	1532004	YARD_UKR	10/02/2007	New Spec.
*A	3282541	YARD_UKR	06/15/2011	Updated to latest PSoC Designer. Updated the document as per new template.
*B	4471379	RKRM	08/11/2014	Updated the abstract. Updated the introduction to modify the structure. Updated the contents to improve clarity.

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