# PIR sensor modeling and simulating using Comsol Multiphysics and its Ray Optics Module

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## Introduction

PIR (Passive Infrared) sensor is the most widely used motion sensor for occupancy detection. PIR sensor outputs a voltage corresponding to the temperature change of the sensor element. PIR sensor has two detector elements connected in series with opposite polarities. This arrangement prevents triggering to an event caused by the change of background IR.

PIR sensor was modelled and simulated using the Ray Optics Module and AC/DC Module with its electric circuit interface. The model includes the optics and the pulse shaping electric circuitry.

## Signal generation in a pyroelectric detector

Pyroelectricity is a physical phenomenon, which has been known since ancient times. However, the full understanding about it has been revealed much later. Use of the phenomena in motion and occupancy detection has started quite recently, in the last few decades.

Materials having a significant high pyroelectric effect have a crystal structure, which in normal steady state condition is already polarized. This means that positive and negative charges will be gathered on the opposite ends of the crystal. In the detector element, the crystals are oriented in such a way that there is a voltage difference over the detector element. Radiation, which will be absorbed on the detector surface, creates heating of the detector element. The generated heat reduces the level of polarization, which is measured as a voltage change over the detector element. The measured voltage has a bipolar waveform based on the polarization changes. The first positive slope is due to the steady state polarization. The following negative slope follows the reduction of the polarization. The final positive slope is explained by return to the original steady state condition.

The pyroelectric effect is observed in a material, which has a significantly high pyroelectric constant p. The most often used materials in PIR detectors are leadtitanate $PbTiO_3$ and lithium tantalate $LiTaO_3$. The thermodynamic equation for the crystal will be

$$C_Q \frac{d(\Delta T)}{dt} + G\Delta T = \varepsilon W_0 \qquad (1)$$

where $\Delta T$ is the temperature change, $C_Q$ is the heat capacity, G is the thermal conductance and $\varepsilon$ is the emissivity of the crystal. The time dependent solution for $\Delta T$ is

$$\Delta T = \frac{\varepsilon W_0}{G}\left(1 - e^{-t/t_0}\right) \qquad (2)$$

where $t_0$ is $C_Q/G$.

The current of crystal is proportional to the pyroelectric coefficient p, the active area $A_s$, which absorbs the radiation and temperature change speed versus time $d(\Delta T)/dt$.

$$I_p = pA_s \, {}^{d(\Delta T)}/_{dt} \qquad (3)$$

As the equation (3) shows, detector current is proportional to the temperature change, not the absolute temperature. The temperature change is directly proportional to the absorption of infrared radiation. Solving $d(\Delta T)/dt$ in equation (3) and writing it to equation (4) results in the equation (4).

$$I_p(t) = pA_s \frac{\varepsilon W_0}{G} e^{-\frac{t}{t_0}} \qquad (4)$$

Equation (4) shows only parameters related the pyroelectric element itself. An electric circuit is used for amplifying and shaping the signal.

## Analog signal processing of PIR sensor

After the detector, an amplifier with a bandpass filter follows. This combination amplifies the signal and reduces noise from the signal. Considering a moving human target, typical distance between the detector and the target is between 0.5-10 meters and moving speed is from 0.5 m/s (walking) to 3 m/s (running). The thermal time constant related to the detector sets the lower limit for the bandpass filtering of the signal [1].

The analog signal could be further processed in order to reveal more information on the heat source. A Fourier transformed data could give information on the spectral components of the signal. A wavelet transform of the signal shows the signal in a time-frequency domain. Wavelet transformed data can be easily applied to a classification algorithm used in machine learning methods. These methods could reveal the nature of the heat source, indicating the target to be for example a walking human, a running pet, a fire in the background or external sunlight change [2]. Measuring a distance between a source and a sensor can be one with multiple PIR sensors [3].

## PIR sensor optics

Focusing IR-radiation to the surface of a PIR sensor requires some kind of a spherical lens or lenses are used. Typically, multiple lenses are mounted on a sphere. They can be plano-convex lenses, which planar surfaces are facing outwards. Size of a single lens will be an optimized for the given size of the sphere and the size and distance of the IR source. Lens material should have a high IR transmission coefficient. A slim lens would be an ideal one. Often PIR optics is composed of numerous Fresnel lenses made of high-density polyethylene (DPE) plastics having the refraction index of 1.54 [4]. Such optics can be manufactured fast and inexpensively in large volumes. It results in a small material thickness featuring sufficiently good IR transmission characteristics.

Use of multiple lenses means that the field of view is not uniform, but segmented. Each lens creates a cone of visibility. You can also say that a cone has two beams as there are two detectors inside a PIR sensor. This is desirable characteristics of a motion detector. The polarity and the amplitude of the signal depend on which one of the detectors is absorbing the larger part of the radiation and what is relative division between the detectors. There is a small gap in the field of view just in the middle of each segment while at that point both of the sensors are absorbing equal amount of radiation. The width of the gap gets larger when an object moves further from the sensor. This also means the time delay in the detection of a moving object is longer in case of a more distant object. Fresnel lens with grooves has even more gaps in its field of view. The way the grooves have been realized has an impact on the optical characteristics. If constant groove width is used, the grooves have variable groove depth. The lens becomes smoother in the middle and deeper near the sides. In that case, optical transmission is higher in the middle of the lens [4].

PIR optics can de optimized for various targets like for wide range, long range, vertical barrier, animal detection or animal immunity. This will be done by reducing the lens diameter in such sectors, which point in less interesting directions. In case animal immunity for example, downwards looking sectors will be depreciated. A sensor mounted on ceiling should have a wide field of view, a sensor mounted on corridor wall for detecting a passing, just a narrow field of view

## Simulation model

Comsol Muliphysics (ver. 5.3a), its Ray Optics- and AC/DC-module has been used. The Ray Optics module is a computational tool for modelling the propagation of light, showing ray tracing through the geometry, reflections, refractions and absorption at boundaries. These features are available in the geometrical optics interface. Several quantitative measures including light intensity, power, energy etc. can be calculated. The ray heating interface could solve the heating in a domain caused by radiation absorption. With the heat transfer module, all thermal issues in a PIR sensor could be simulated. In that case, it would be necessary to include the required material information and the accurate geometry of the PIR detector element as well as the thermal interface to the surroundings. As this information is difficult to obtain, the full thermal analysis has been rejected.

A major limitation is related to the ray heating interface. It can be included in a time dependent simulation, but its solution is always for the case time is indefinite. The reason behind this limitation is related to the different time scales of light propagation and heat transfer. Heat transfer is a very slow process compared with light propagation. Instead of thermal effects, one could use absorbed intensity on the detector surface ($W/m^2$) and the mathematical relationship between the intensity and the output electrical signal.

By including AC/DC-module and its electrical circuit interface, it is possible to simulate the signal shaping the external electric circuit performs. Time scale transforming for the component values of the circuit is needed. By this way, the circuit is transformed to a nanosecond scale, typical for considering light propagation.

In the conducted Multiphysics simulations, the heat point source traverses perpendicularly over the detector's field of view. Only the rays, which direct towards the detector, are included in the simulation. This keeps simulation time in reasonable limits. In this approach, the changing distance between the source and the detector must be included in the simulation.

The time dependent simulation includes numerous ray inlets. Each one of them has a specific release time. The number of rays per release has been defined. Ray direction vector components have been defined in such a way the vector always points towards the detector. The distance between the source and the detector has taken into account when setting the source power for each inlet.

In the figure below the model geometry and some of the simulation results are presented. Fig. 1 shows the CAD model. The transparent figure shows the hexagon lenses and the detector element behind it. Fig. 2 shows some of the rays refracting in the lens and reaching the detector element. Depending on the angle of incidence, some of rays hit the first some the second detector element. Fig. 2 the solid angle $\Omega_i$ and angle $\alpha$ when the source moves further from the detector. The intensity observed at the detector can be expressed using Equ. 5.

$$\frac{I_i}{I_0} = \cos(\alpha) \cdot \left(\frac{L_0}{L_i}\right)^2 \qquad (5)$$

A typical electric circuit of PIR sensor is shown in the Fig. 3. Fig. 5 shows the subtraction of the absorbed power integrals. According to the equation (3) this has to be differentiated. Fig. 6 shows the differentiated and filtered output signal of PIR sensor. Figures 5-6 are presented using normalized values.

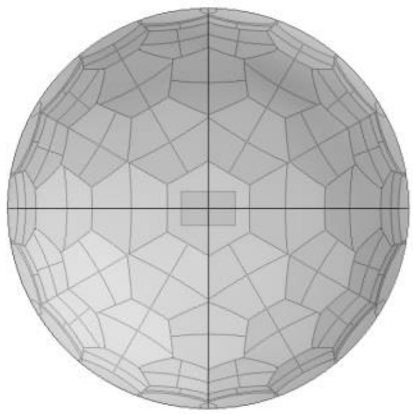

**Figure. 1.** The CAD model of the PIR sensor optics and the detector (below).

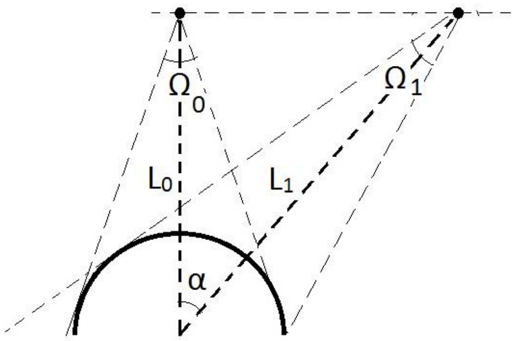


**Figure. 2.** Solid angles $\Omega_i$, angle $\alpha$ and distances between the source and the detector.

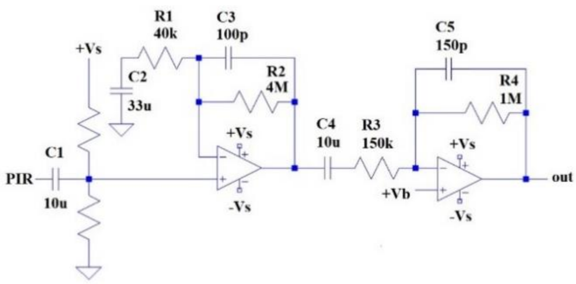


**Figure. 3.** The amplifier & shaping circuitry with typical component values.

## Simulation results

Figure 4. shows some of the simulated ray trajectories. The figure shows how the rays are collimated and hit to the detector elements.

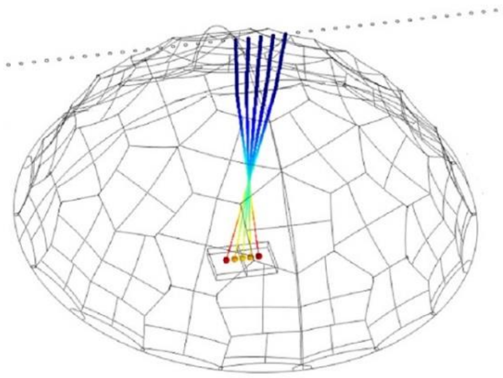

**Figure. 4.** Some of the simulated ray trajectories.

Boundary probes (bnd1 and bnd2) were defined for the detector surfaces. They were defined as integral types. Accumulating function was selected for expression gop2.wall1.bacc1.rbp_accum. In the results section global plot will be drawn showing the difference bnd2-bnd1. This is shown in Fig. 5.

If the electrical circuit interface of AC/DC Module has been included, the node voltages or branch currents could be solved. The second option is to use a separate circuit simulator and use the waveform of Fig. 5 as an input source for a derivation circuit followed by the circuit of Fig.3. The third option is to omit the derivation circuit and calculating first the differential of the waveform of Fig.5. Both x- and y-axis values are normalized ones.

Fig.6 is inverse symmetric from the center point of view, which indicates PIR sensor is able to resolve the direction the heat source approaches the sensor [5]. At the center point of the Fig. 6, the output voltage is zero. When the heat source is just ahead the sensor, both detector elements receive equal amount of radiation resulting zero output.

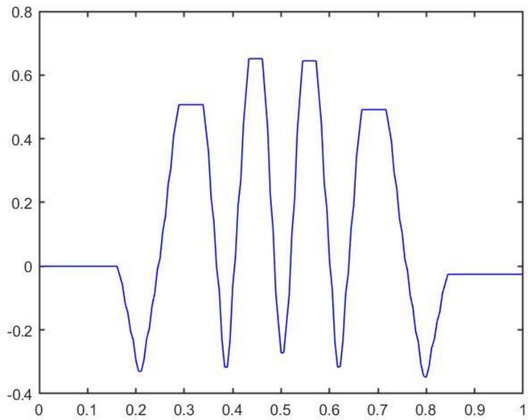


**Figure. 5.** Subtraction of the absorbed IR-powers $P_2$-$P_1$ (y-axis) versus time (x-axis).

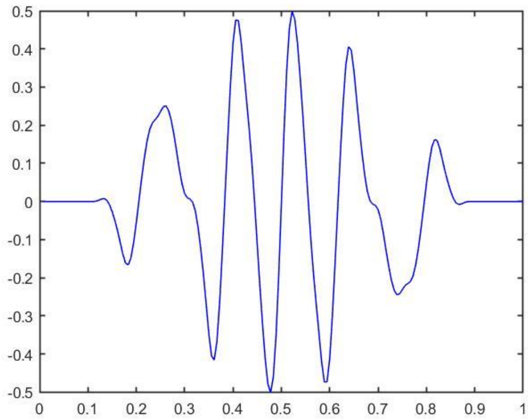


**Figure. 6.** Output voltage (y-axis) versus time (x-axis).

## Conclusions

A short introduction to PIR sensors has been presented. A CAD model for a typical PIR sensor has been created. A case where heat point source traverses over the sensor field of view has been simulated. Analog signal shaping circuit has been included in the model. Results show a 3D ray trajectory plot and output voltage waveform of the sensor.

## References


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