# Indoor Half-Pulse L-PPM for Wireless Optical Communications: Effect of Ambient Light Noise and Flicker

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*Abstract*— **The effect of ambient radiation that includes noise and flicker voltages on half pulse L-PPM for WOC applications is studied. Photodiode responsivity and capacitance effects are investigated on flicker and noise voltages levels for indoor 4-PPM. Si p-i-n photodiodes and Si APDs are tested to find which photodetector type in most suitable for indoor WOC application. The study is focused in incandescent lamps (tungsten lamps) and fluorescent lamps.**

*Index Terms*— **Ambient radiation, noise and flicker voltage, photodiode responsivity, incandescent lamps and fluorescent lamps.**

## I. Introduction

Modern wireless optical communication (WOC) was an offshoot of the development of laser technologies in the 1960s. The main aim then was to develop communication between satellites and submarines beneath the surface of the sea. During the last 40 years, WOC has expanded to include deep space mission and terrestrial networks connected to nodes with a distance separation of 100 or 200 m at rates up to 10 Gbps. The main advantages of WOC are: 1) there are no licensing requirements, 2) no tariffs are required for its utilization, 3) there are no radiofrequency (RF) radiation hazards, 4) there is no need to dig up roads, 5) it has a large bandwidth, which enables very high data rates, 6) it is small, light, and compact and 7) it has low power consumption [1],[2].

In mobile telemetry systems, a limited transmitter complexity and small power consumption are of great importance. In such cases, digital pulse position modulation (PPM), based on intensity modulation and direct detection, is a very suitable modulation scheme, because it combines the advantages of digital transmission (easy multiplexing of sensor signals with the possibility for data compression and error correction and low-power transmitter). In the following, this modulation technique is used to address the indoor WOC characteristics [3].

In fiber optic links, the noise limiting the link performance is dependent on the components in use. Free space optical links, like RF links, have the additional constraint that optical link noise depends on the ambient environment. Receiver photodetectors are exposed to ambient optical noise in office or home environments. The system designer therefore would need to accommodate for the various sources of "**noise**" to build an optical link that is noise-immune or resistant to the ambient noise. Many works [4]-[6] studied this point in order to evaluate the effect of the ambient light sources on the performance of the indoor or outdoor wireless communications or tried to prepare solutions to enhance the performance in the presence of highly noise channel. This paper differs from these works in including the effects of studding two sources of noise (tungsten and fluorescent lamps at the same time) and in finding the most suitable type of photodiodes (p-i-n or APD) that can be used in a WOC indoor link.

The basic L-PPM architecture that used is presented in Sec. II. The mathematical model used to evaluate noise voltages generated by ambient noise sources (tungsten or fluorescent lamps) and the effect of different types of photodiodes are presented in Sec. III. Numerical results and discussion are introduced in Sec. IV. Finally, conclusion and future related works are discussed in Sec. V.

## II. Basic L-PPM Architecture

In a PPM modulator, an input word consisting of several bits is converted into the position of a pulse within a frame. This is shown in Fig. 1.

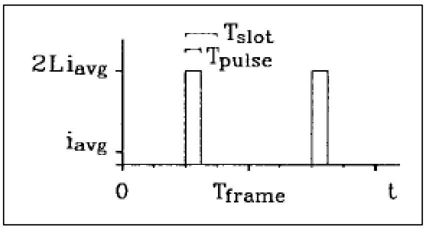


Fig.1. PPM modulation scheme [3].

The frame, with duration $T_{frame}$, is divided into L slots with duration $T_{slot}$ and only one of these slots contains an optical pulse. Since L possible pulse positions are used to code $\log_2 L$ bits of information, the bit rate is $R_b = \log_2 L / T_{frame}$. Initially, we assume the pulses to be rectangular. The height of the pulses is normalized such that the average current through the receiver photodiode is $i_{avg}$. It is an important quantity, since it depends on the transmitted optical power. Therefore, it indirectly determines the average power consumption of the transmitter and thus the battery lifetime [3].

The demodulator in our discussion is assumed to be a maximum likelihood integrate-and-dump (I&D) demodulator, i.e., a demodulator that assumes the PPM pulse to originate from the pulse interval in which most optical energy was found. For adequately designed receivers, the main source of noise is the photodetector shot-noise current caused by ambient radiation. This white-noise process is described by its double-sided spectral density $N_o = q\, I_{amb}$ $A^2/Hz$, where q is the electron charge and $I_{amb}$ is the photodiode quiescent current due to ambient radiation [3].

## III. MATHEMATICAL MODEL

### A. *Incandescent lamps (Tungsten lamps)*

Incandescent lamps suffer from flicker due to the mains frequency. The amount of infrared radiation of several standard 230 V incandescent lamps was measured and used in our work as in Ref. [3]. The detector current due to ambient light follows from

$$I_{amb} = \int_0^\infty R(\lambda) F(\lambda) IRTV d\lambda \cdot Q_v \qquad (1)$$

where R is the detector responsivity, $Q_v$ is the luminous incident flux and F is the filter transmission.

The influence of flicker and other intensity variations can be modeled after considering Fig. 2. The input signal $i_{in}$ consists of three components: the PPM signal current, a parasitic current due to ambient radiation $I_{amb}$ and the shot noise component of this latter current. The switches in the I&D filter are controlled such that the filter is integrating during the dashed intervals [3].

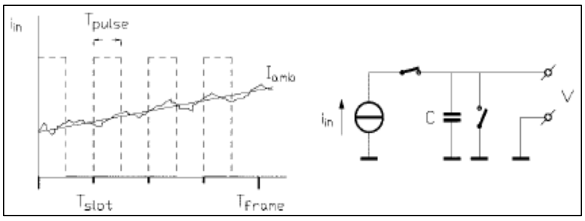


Fig.2 Signals at the receiver input and the schematic of the I&D demodulator filter [3].

In the model, we assume that the level of ambient radiation varies only slowly, compared with the PPM signal, so that its first-order derivative is satisfactory in describing its variations. Further, it is assumed that it is modulated only weakly, so that the level of shot noise is approximately constant. For incandescent lamps, these approximations are valid in almost all practical situations. The maximum slope follows from the interfering frequency and the modulation index of the lamp as

$$\left[\frac{dI_{amb}}{dt}\right]_{\max} = 2\pi m_i f_i I_{amb} \qquad (2)$$

The transfer of the I&D filter, from the input current to the output voltage at the end of an integration interval, is defined by the impulse response, h(t), and its Fourier transform, H(f), respectively, as [3]

$$h(t) = \frac{1}{C} \; if \; 0 \le t \le T_{pulse} \qquad (3)$$

$$H(f) = \frac{V(f)}{i_{in}(f)} = \frac{T_{pulse} Sinc(\pi f T_{pulse}) \exp(-j\pi f T_{pulse})}{C} \qquad (4)$$

Now, we define the flicker voltage $\Delta_i(V)$ and the noise voltage $\sigma_n(V)$ as

$$\Delta_i(V) = \frac{(L-1)T_{frame}}{L} \frac{T_{pulse}}{C} \left[\frac{dI_{amb}}{dt}\right]_{\max} (V) \qquad (5)$$

$$\sigma_n(V) = \frac{1}{C}\sqrt{N_o T_{pulse}} (V) \qquad (6)$$

In these expressions, is C the value of the capacitor in the I&D filter. In practice, $(L-1)/L \approx 1$, since only $L \ge 4$ allows for low-power transmission, and

$$T_{pulse} = \frac{T_{frame}}{2L} \qquad (7)$$

$$I_{amb} \le \frac{qL}{2\pi^2 m_i^2 f_i^2 T_{frame}^3} \qquad (8)$$

### B. *Fluorescent lamps*

Like incandescent lamps, fluorescent lamps also suffer from flicker. In lighting systems that employ a traditional inductive ballast circuit, the flicker frequency equals twice the mains frequency. Today, high-frequency ballast circuits are often used to obtain better lamp performance. In these cases, the flicker frequency is usually in the range of 40 to 100 kHz. At the same time, the modulation index is large (in the range 50% to 100%), depending on the supply frequency [3].

To investigate when lamp flicker is detrimental, the amount of infrared radiation was measured for several lamps. Since the results are approximately the same, we use the commonly used Philips 36 W tube "TL"D 83, whose intensity is described in [3]. The interfering signal can be approximated as a sine wave. The rms variations due to flicker has the form [3]

$$\sigma_i(V) = |H(f_i)| i_i(V) \quad (9)$$

where $i_i$ is the rms value of the interfering current and $f_i$ is its frequency given by

$$i_i = \frac{1}{\sqrt{2}} m_i I_{amb} \quad (10)$$

Here

$$I_{amb} \leq \frac{2q}{T_{pulse} m_i^2 \operatorname{sinc}^2(\pi f_i T_{pulse})} \quad (11)$$

## IV. Results and Discussion

### A. Incandescent lamps (Tungsten lamps)

Based on the described mathematical model, for incandescent lighting, the studied parameters include: modulation index, capacitance of I&D demodulator filter, C, frame time, $T_{frame}$, and number of data slots per frame, L. This will introduce in the following sub sections B, C, D and E.

### B. Effect of modulation index

In incandescent lighting the ripple on the intensity is almost sine shaped, with a frequency of $f_i$= 100 Hz and the modulation index of the lamp is said to equal 10-20 % [3], [7]. The parameters used to carry the simulation are L=4, $T_{frame}$ =20 μs, frequency $f_i$=100 Hz and C = 1μF. These parameters are closed to life values and give the ability to compare with [3]. These simulation parameters, especially L and $T_{frame}$, are also close to the wireless optical standardization like IrDA, created in June 1993 [8].

The effect of the modulation index, under the mentioned simulation parameters, on flicker and noise voltages for incandescent lighting in indoor half pulse 4-PPM for WOC is shown in Fig.3. The obtained results are in a fair agreement with the practical measurement based on [3]. It is clear that, the noise voltage with a low operating frequency is always larger than the flicker interfering voltage. This is mainly due to the level of infrared radiation that produces a noise exceeding (but not too much) the effect of very low modulation index with the low flicker operating frequency (100 Hz) which both control the level of flicker voltage. This is only valid in incandescent lighting.

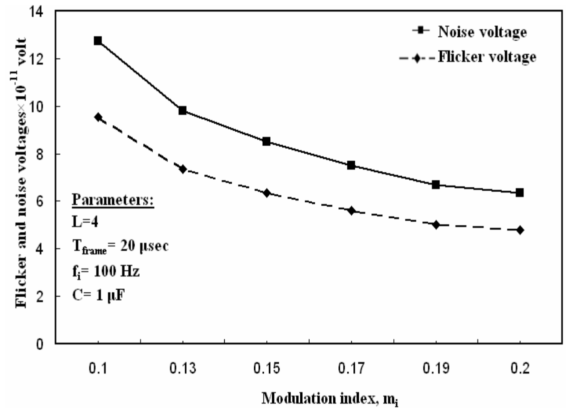


Fig..3 Effect of modulation index for incandescent lighting.

### C. Effect of demodulator capacitance

Since we are using maximum likelihood integrate-and-dump (I&D) demodulator previously described, we have to investigate the effect of its capacitance on $I_{amb}$, the current introduced in the photodiode due to the ambient radiation, for both flicker and noise voltages. This is displayed in Fig. 4 including simulation parameters which are chosen for the reasons discussed in Sec. IV-B.

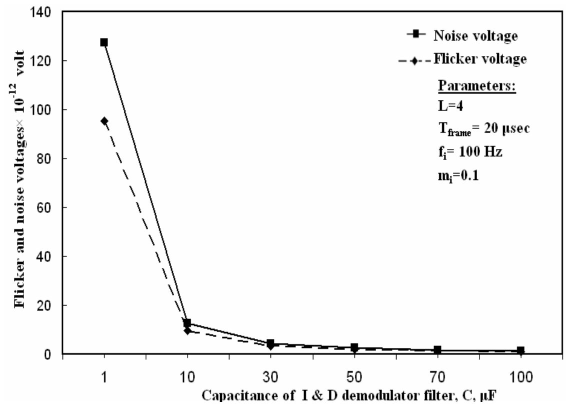


Fig.4 Effect of demodulator capacitance for incandescent lighting

The large decrease for the levels of flicker and noise voltages is due to the nature of capacitance itself. Large capacitance means large capability of storing ambient radiation including flicker. Note that with a good control for the switches that control the operation of I&D demodulator, large amount of ambient radiation can be stored in a large capacitor and isolate that radiation from detected by the receiver. However, designing such a demodulator with large capacitance makes it not suitable for integrated circuit fabrication technologies and adds a sizing problem. One has to remember that, this type of demodulator in only applicable for situations disused in Sec. III-A.

### D. *Effect of Frame time*

Figure 5 displays the variation of the flicker and noise voltages with frame time including simulation parameters. It is evident that, decreasing the frame time leads to high concentration of noise and flicker levels in a short period of data time. This will lead to a sudden increase in the generated shot noise (especially at 1 μs) and hence increasing both flicker and noise voltages. Again, for the same reasons discussed in Sec. IV-B, the level of noise voltage produced by incandescent lamps is always larger than flicker interfering voltage but not too much.

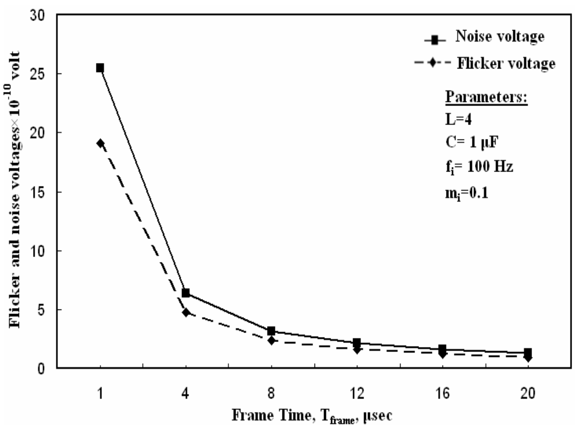

Fig.5 Effect of frame time for incandescent lighting.

### E. *Effect of number of data slots per frame*

The flicker and noise voltages are displayed in Fig. 6 with, L, the slots per frame. The increase of these voltages can be explained as follows: increasing L at low frequency and low modulation index environment makes the capacitor of I&D demodulator charges for several times to get data slots with noise and flicker and hence increasing their levels. The reason why the flicker voltage is greater than the noise voltage may considered after viewing described mathematical model, where the effect of L is more dominant for flicker voltage. Results of Fig. 6 show a good agreement with the practical measurement introduced in [3].

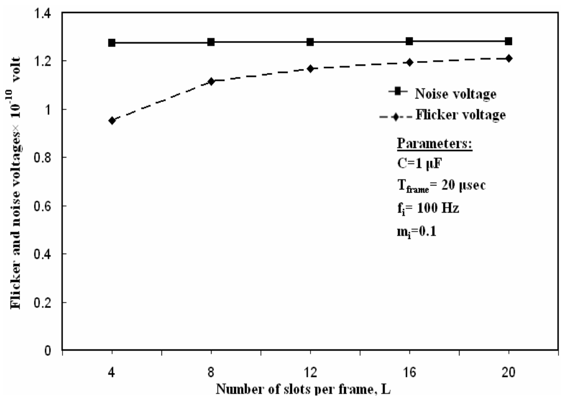

Fig.6 Effect of number of slots per frame for incandescent lighting.

### F. *Fluorescent lamps*

As indicated in Sec. III-B, studying fluorescent lighting is more complex than incandescent lighting because high-frequency ballast circuits. This will lead to omit the use of simplified model used for incandescent lighting and find $I_{amb}$ directly from (1) which will introduce new affecting parameters taking the effect of photodiode used in receivers and surrounding environment more accurately and in more details than incandescent lighting [3].

The new parameters are: the detector responsivity, R, the luminous flux incident on it, $Q_v$ , the filter transmission, F, and the photodiode effective area, $D_{area}$. In the following the IRTV for Philips 36 W tube "TL"D 83 is used since most of fluorescent lamps produce a similar spectrum and can take it as an example to study [3].

$Q_v$ was chosen to be constant (500 lm/m$^2$) through all simulation tests. This is because this illumination is typical of desktops in offices and gives ability to compare with practical measurement carried by [3]. Also filter transmission is chosen to be 100 nm centered at 900 nm. This means that we are interested only in the range of $850 < \lambda < 950$ nm. This range locates in the near IR spectrum where most commercial indoor wireless optical links including inexpensive Si photodetectors and LEDs operate. Also, the Si photodetectors has its best performance behavior in that range [2]. In the following, the effect both R and $D_{area}$ for Si p-i-n photodiodes and Si APDs on the level of flicker and noise voltages for half-pulse 4-PPM WOC is discussed and compared with [3], [5]. The parameters used to carry the simulation are introduced in each figure. Sections G, H, I, J, K, L and M will discuss the parameters that affect WOC under fluorescent lamps environment.

### G. *Effect of modulation index for fluorescent lamps*

As mentioned in Sec. III-B, the modulation index in fluorescent lighting is large and covers a wide range from 50% to 100% depending on the supply frequency [3]. The effect of modulation index is shown in Fig. 7.

Here, an opposite behavior to that observed for incandescent lighting is found. First, the flicker voltage level exceeds the level of noise voltage by so far (about $10^3$ V). Second, increasing the modulation index causes an increase in the level of flicker and noise voltages. This is because, on the one hand, the noise level is low, since the level of infrared radiation is low, while, on the other hand, the effect of flicker is large, since the modulation index is large (50% to 100%) and the flicker frequency is close to the slot rate (40 to 100 kHz). This simulation has a good agreement with [3].

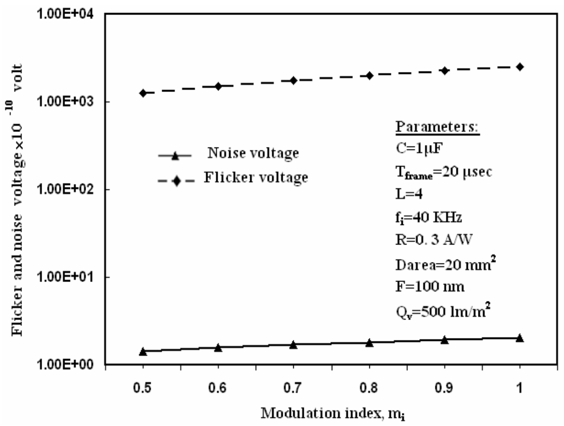


Fig.7 Effect of modulation index for fluorescent lighting.

### H. *Effect of demodulator capacitance*

It is clear, from Fig. 8, that, the levels of both flicker and noise voltages decrease with increasing demodulator filter capacitance. We believe that reasons for such decrease are similar to those mentioned in Sec. IV-C However, still the level of flicker voltage exceeds by far the level of noise and it seem impossible for the two levels to be so close at high capacitance levels as in incandescent lighting.

### I. *Effect of frame time and number of slots per frame for fluorescent lamps*

Again, in Fig. 9, an opposite behavior to that observed for incandescent lighting is obtained. In fluorescent lamps, the level of infrared radiation that produces the noise is much weaker than the effect of high modulation index and huge flicker frequency that controls the flicker voltage.

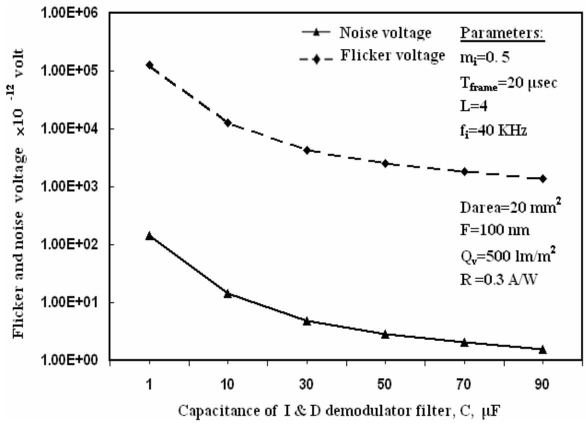


Fig.8 Effect of demodulator capacitance for fluorescent lighting

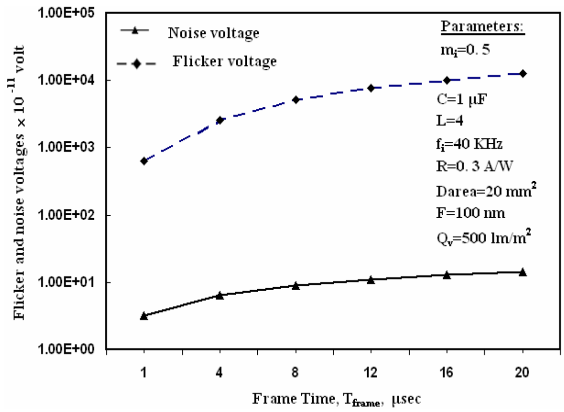


Fig.9 Effect of frame time for fluorescent lighting.

This nature is opposite to the characteristics of incandescent lighting and hence it is normal to get an opposite behavior for parameters such as the modulation index when changing frame time and number of slots per frame, Fig. 10.

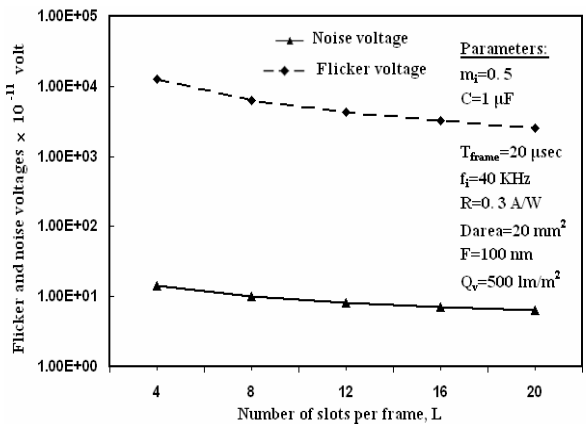


Fig.10 Effect of number of slots per frame for fluorescent lighting

This conclusion agrees with that mentioned in [3], [4]. Note the above discussed nature is not applied for the effect of demodulator capacitance since it is not a part of PPM specifications but is a part of the receiver that is independent from PPM parameters like modulation index, frame time, slot time, number of slots per frame and operating frequency.

### J. *Effect of photodiode responsivity in Si p-i-n for fluorescent lamps*

The Si p-i-n photodiodes generate at most one electron-hole pair per photon resulting in at most unity gain for the generated photocurrent and low responsivity photodiode operation [2]. It is a key parameter in photodiode models, and is taken at the central optical frequency of operation. Simulation range for responsivity is taken from 0.25 A/W to 0.5 A/W over a wide range of wavelengths from 300 nm to 1100 nm which includes the range 850 < λ < 950 nm [2]. The effect of responsivity under the mentioned parameters is shown in Fig. 11.

The responsivity represents the optoelectronic conversion factor from optical to electrical domain. This conversation (when increasing R) results in collecting more ambient noise and flicker together with the required data resulting in increasing both noise and flicker voltages.

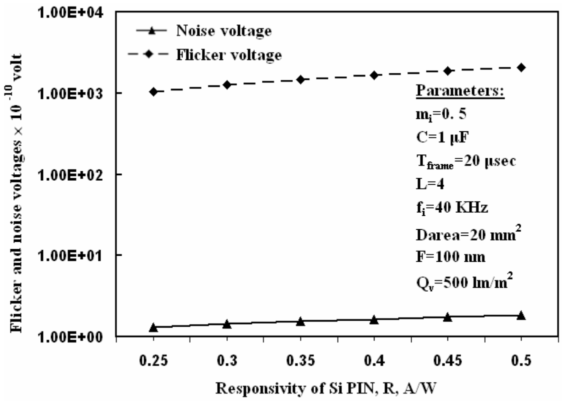


Fig.11 Effect of responsivity for Si p-i-n photodiodes for fluorescent lighting.

### K. *Effect of photodiode effective area in Si p-i-n for fluorescent lamps*

Effective area is one of the key factors in choosing an operating photodiode. In Si p-i-n a wide range of effective area are available in the markets according to application [7]. 90% of available photodiodes effective area falls in the range 2.25 to 100 mm$^2$. This is also can include about 80% of market APDs. Increasing photodiode effective area enables to collect as much radiant optical power as possible. However, this will result in an increasing photodiode internal capacitance and hence decreasing operating bandwidth and increasing collected sources of noise [2]. So, a trade off must be done to choose best photodiode suitable for the application according to available resources and surrounding environment noise sources and levels. This is in agreement with simulation results, Fig. 12.

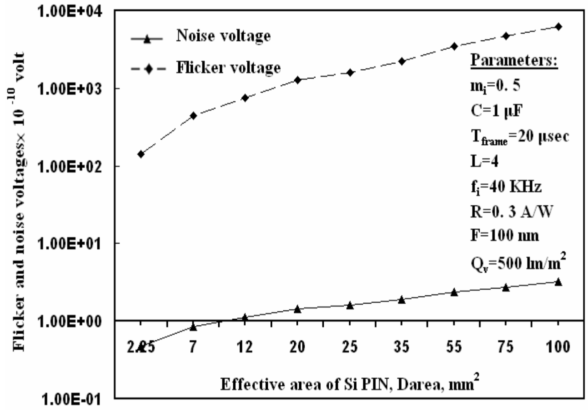


Fig.12 Effect of photodiode effective area for Si p-i-n photodiodes for fluorescent lighting.

### L. *Effect of photodiode responsivity in Si APDs for fluorescent lamps*

Avalanche photodiodes have the property of photocurrent gain of greater than unity, while p-i-n photodiodes are fixed at a unity gain. This is due to avalanche multiplication property which also reflects on the level of responsivity for each one [2]. Responsivity in Si APDs can extend to 77 A/W in the operation wavelength 400 to 1000 nm which includes our studying range [2]. Figure 13 depicts the effect of responsivity, which is in a fair agreement with that in [2].

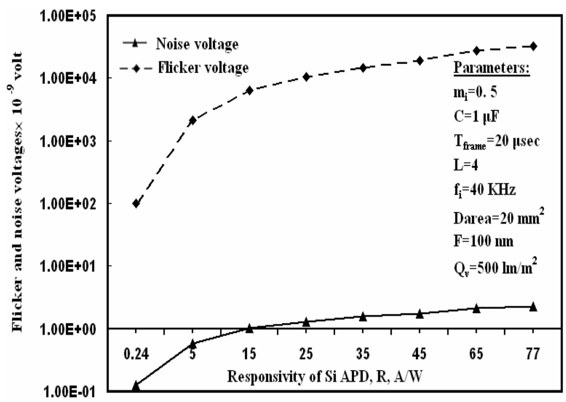


Fig. 13 Effect of responsivity for Si APDs for fluorescent lighting.

As in case of Si p-i-n photodiodes, one can say that increasing responsivity will result in more optical to electrical conversation including conversion of both flicker and noise voltages which give reason for increasing their levels with responsivity. A new-but logic-observation, here, is that the level of flicker and noise voltages in Si APDs exceeds by far the corresponding levels in Si p-i-n photodiodes. This is mainly due to the avalanche process that generates excess shot noise due to the current flowing in the device. This excess noise can degrade the operation of free space links since a majority of the noise present in the system is due to high intensity ambient light.

### *M. Effect of photodiode effective area in Si APDsfor fluorescent lamps*

The effect of photodiode effective area in Si APDs is shown in Fig. 14. Again, one can observe that the level of noise and flicker voltages in Si APDs exceeds by far the corresponding levels for Si p-i-n. So, by comparison, one can conclude that for indoor wireless optical communication application it is preferable to use inexpensive Si p-i-n photodiodes.

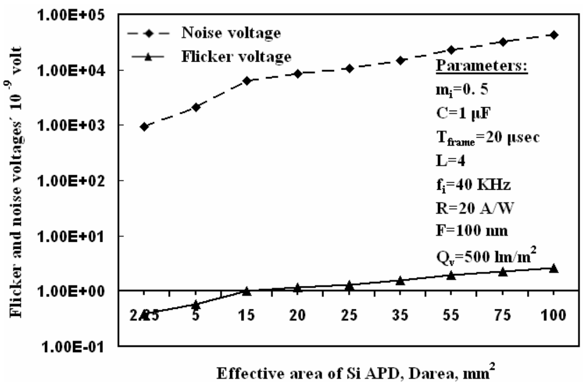


Fig.14 Effect of photodiode effective area for Si APDs for fluorescent lighting.

## V. CONCLUSION

Values of flicker and noise voltages for tungsten and fluorescent lighting in indoor environment are investigated under half pulse 4-PPM scheme. Effect of special receiver prototype is also described. The obtained results are in a fair agreement with practical observation related the level of flicker and noise voltages and indicates that effect of flicker noise voltage is dominant in fluorescent lighting while share the effect in the total noise for tungsten lighting. This study takes in to account a wide practical range of parameters to give a near practical view for the effect of such system on the operation of indoor WOC application.

The study is very important for both transmitter and receiver designers in an indoor environment since it provides them with a lot of information about levels of noise that can be collected at the receiver or added to signals after transmitter under different lighting environments.

For future directions, one suggests studying wider types of lamps with more complex demodulator types that can enhance the system performance.

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