Artificial Lighting Interference on Free Space Photoelectric Systems

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***Abstract*—Artificial lighting is a main source of interference on free space photoelectric systems for communication applications. This work presents digital measurements and numerical analysis of the time and frequency characteristics of artificial lighting interference using Welch Power Spectral Density estimate and spectrogram with Short Time Fourier Transform. Measurements of time waveforms and spectra of incandescent lamps, tubular and compact fluorescent lamps with conventional and electronic ballasts, as well as Light Emitting Diodes are discussed and compared to other works.**
***Keywords* — artificial lighting, optical interference, photoelectric systems, measurements, time frequency analysis**

I. Introduction

Incoherent free space photoelectric systems are widely used in consumer and industrial electronics to realize low-cost communication. Examples are applications like the Infrared Data Association (IrDA) standard and infrared remote controls. Recently, the National Science Foundation (NSF) launched the Smart Lighting Engineering Research Center (ERC) which focuses, among other topics, on free space optical communication [1].

In general, incoherent free space photoelectric systems are based on intensity modulation with Direct Detection (IM/DD) using a Light Emitting Diode (LED) as transmitter and a photodiode as receiver [2]. The transmitted information is represented by an intensity modulated optical power. The receiver works as an energy detector, collecting and converting optical power to electrical current.

Despite optical filtering, incoherent free space photoelectric systems are more or less sensitive to optical interference of the same wavelength as the main system. Important sources of visible optical interference are ambient light (sun light), artificial lighting and light from other free space photoelectric systems (multi user access of the optical medium). Major sources of artificial lighting found in consumer and industrial applications are incandescent lamps, fluorescent lamps with reactive ballasts, fluorescent lamps with electronic ballasts and LEDs.

The scope of this work is the analysis of artificial lighting interference in time and frequency domain as a basis for works on robust optical transmission and receiving schemes. This work does not focus on the optical spectrum in a coherent sense (wavelength domain). Here the spectrum of an optical interferer is the spectrum of the optical power after conversion in the photodiode. There has been some work concerning optical interference in the context of wireless infrared communication [3], and in the context of infrared remote controls [4]. This work gives an extended analysis and characterization of artificial lighting interference and adds new results concerning the time frequency behavior of interference sources.

The remainder of the paper is organized as follows. In section II, measurement setup and equipment are presented, followed by the measurement results and analysis of each type of lamp. Section III concludes the paper.

II. Measurements

A. Measurement Setup

To prevent Electromagnetic Interference (EMI) in order to focus on pure optical interference, the light of the examined lamps was captured over an optical plastic waveguide to a photoreceiver (10 MHz NFO-2051-FS) within a shielded metal box. Several measurements with all combinations with and without EMI and optical input have been taken to make sure only optical interference was captured. No optical filter was used for measurements. After the photodiode, the photoreceiver converts and amplifies the received photocurrent with a three-stage transimpedance amplifier and additional analog low and high pass filters to the output voltage. All measurements were taken with 220 V 50 Hz and under thermal equilibrium. Long term measurements have been taken, finding changing frequency characteristics within the first ten minutes after startup of the lamps.

The output of the photoreceiver was then digitized with a 5 GS/s digital sampling oscilloscope Tektronix TDS5054B with a memory of 16 MS. The digital data then was exported to a computer and analyzed numerically in time and frequency domain, using the Welch Power Spectral Density (PSD) estimate [5] and the spectrogram based on Short Time Fourier Transform (SFFT). To reduce influences of ambient sun light and dynamic range, all measurements were taken with AC-coupling (Alternating Current). All PSDs are normalized to 0 dB/Hz maxima, the time signals are normalized to their maximum amplitude in volts.

B. Incandescent Lamp

Several incandescent lamps with tungsten filament of different power and manufacturers were measured and analyzed, showing uniform time and frequency characteristics. Measurement results are almost identical to ones taken in [3], hence results are interpreted here without displaying the figures.

The time waveform of the received optical power is a $100\,\mathrm{Hz}$ sinusoid. The Welch Power Spectral Density estimate shows a main peak at $f = 100\,\mathrm{Hz}$ followed by harmonics every $100\,\mathrm{Hz}$ with a decay of $60\,\mathrm{dB}$ per decade, reaching $-80\,\mathrm{dB}$ at $2.5\,\mathrm{kHz}$.

Considering the power supply frequency of $f_{ps} = 50\,\mathrm{Hz}$ the emitted optical power of the tungsten filament should be proportional to $|\sin(2\pi f_{ps}t)|$ in addition with the afterglow of the filament, witch results in an additional low pass filtering. Using fourier series decomposition [6]:

$$|\sin(2\pi f_{ps}t)| = \frac{2}{\pi} - \frac{4}{\pi}\sum_{K=1}^{\infty}\frac{\cos(4\pi k f_{ps}t)}{(2k)^2 - 1} \qquad (1)$$

the spectrum only shows even harmonics of the $50\,\mathrm{Hz}$ fundamental. The spectrum of a pure $|\sin|$ shows a decay of $40\,\mathrm{dB}$ per decade, the observed decay of $60\,\mathrm{dB}$ per decade can be explained by filament afterglow. With this interpretation, the $100\,\mathrm{Hz}$ main peak of the incandescent lamp is the second harmonic of the $50\,\mathrm{Hz}$ fundamental (first harmonic).

C. Fluorescent Lamp with Reactive Ballast

Several fluorescent lamps with conventional (reactive) ballasts were analyzed, involving tubular lamps with different colors, powers with external ballasts and compact fluorescent lamps with built in conventional ballasts. All lamps showed similar time and frequency characteristics, corresponding with the results in [3]. When turned on, strong EMI could be observed for a few seconds without shielding.

Near the electrodes of a fluorescent lamp with reactive ballast, high frequency oscillations can be observed, also described by [4]. This phenomenon is called anode oscillations, see [7] for detailed theoretical background. Fig.1 shows the time waveform and spectrum of the anode oscillation of the $18\,\mathrm{W}$ tubular fluorescent lamp Philips Master TL-D Super 80 18W/840 driven by an Tridonic Atco EC 18 C501 K ballast. Due to AC power supply voltage, each electrode serves as an anode and a cathode. Anode oscillations can be observed during the anode half wave of the electrode at the first $10\,\mathrm{ms}$ (anode phase). The time signal of the cathode half wave (cathode phase) is best described by a slightly distorted fully rectified $50\,\mathrm{Hz}$ sinusoid. The Welch Power Spectral Density estimate shows a $50\,\mathrm{Hz}$ fundamental with even and odd harmonics with a decay of $50\,\mathrm{dB}$ per decade in lower frequencies up to $1\,\mathrm{kHz}$ and High Frequency (HF) components with a decay of $20\,\mathrm{dB}$ per decade reaching $-80\,\mathrm{dB}$ at about $200\,\mathrm{kHz}$. Although anode oscillations are only a small amount of the total optical power of the lamp, HF components still can be crucial for the reliability of photoelectric applications under certain configurations.

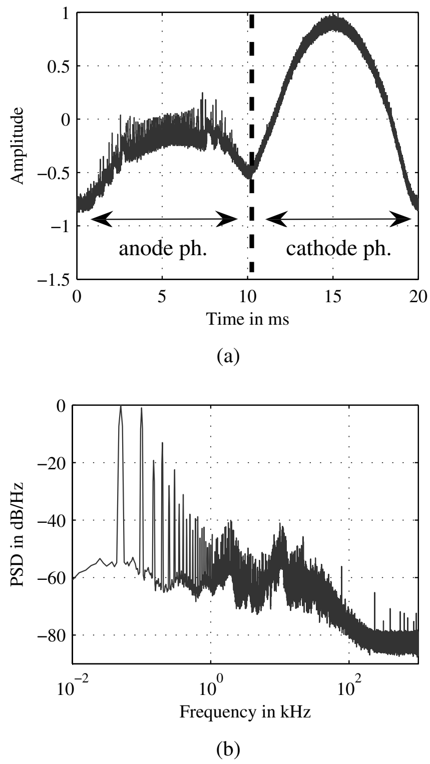


Fig. 1. Anode oscillations of fluorescent lamp Philips Master TL-D Super 80 18W/840 driven by an Tridonic Atco EC 18 C501 K reactive ballast: (a) Time Waveform (b) Welch Power Spectral Density Estimate

D. Fluorescent Lamp with Electronic Ballast

Beside classical electromagnetic ballasts, fluorescent lamps can be operated with electronic ballasts, which offer a better energy efficiency and advanced functionality like dimming or remote control. There are many different kinds of ballast circuits, whereas essential parts are a rectifier to convert AC power supply voltage to DC (Direct Current), a high frequency DC/AC converter and additional filters for limiting and smoothing harmonic distortion. Todays ballasts operate at frequencies between 30 to $100\,\mathrm{kHz}$ to avoid audibility and optimize transistor and ferrite coil losses. According to [8], electronic ballast operate up to $500\,\mathrm{kHz}$.

Time and frequency characteristics of the optical power emitted by fluorescent lamps driven by electronic ballasts are strongly dependent on the ballast. Some dependences using different lamps with the same ballast was observed, but within our measurements, the general character was determined by the particular ballast. Several different ballasts, lamps as well as compact fluorescent lamps have been tested, resulting in a large variety of time frequency properties. One example is the $23\,\mathrm{W}$ compact fluorescent lamp Osram Dulux EL 23 presented in Fig. 2. The time waveform is a distorted $50\,\mathrm{Hz}$-sinusoid with dominant even harmonics in addition to strong HF components. The PSD shows a Low Frequency (LF) and a HF region. In the LF region, there is a $50\,\mathrm{Hz}$ fundamental with even and odd harmonics with a decay of $50\,\mathrm{dB}$ per decade

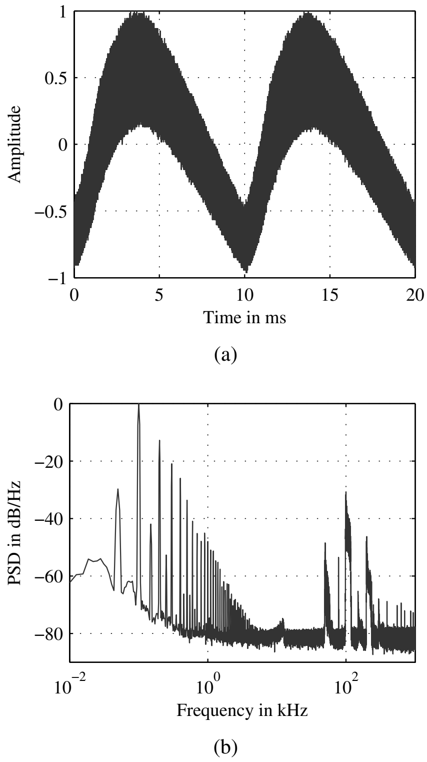


Fig. 2. Compact fluorescent lamp Osram Dulux EL 23 with electronic ballast: (a) Time Waveform (b) Welch Power Spectal Density Estimate

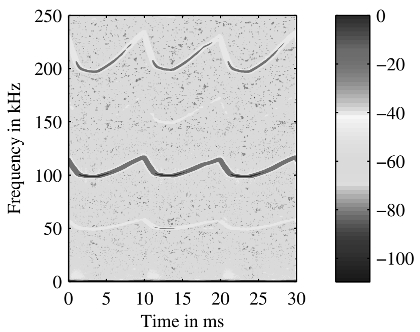


Fig. 3. Spectrogram of compact fluorescent lamp Osram Dulux EL 23 using Short Time Fourier Transform

reaching -80 dB at 4 kHz. In the HF region three strong signal components with several tens of kHz bandwidth each can be seen with a lower band edge at 50 kHz, 100 kHz and 200 kHz as well as several weak harmonics.

Further analysis of the HF components with the spectrogram method based on a windowed Short Time Fourier Transform is shown in fig. 3. With conventional fourier analysis, all information about time dependent spectrum characteristics is lost by averaging over the whole time interval. The spectrum of fig. 2(b) corresponds to a time signal with a duration of 3.2 s. In the time frequency plane it can easily be seen, that the HF components are not broadband signals, but modulated narrowband signals with period of 10 ms, which corresponds

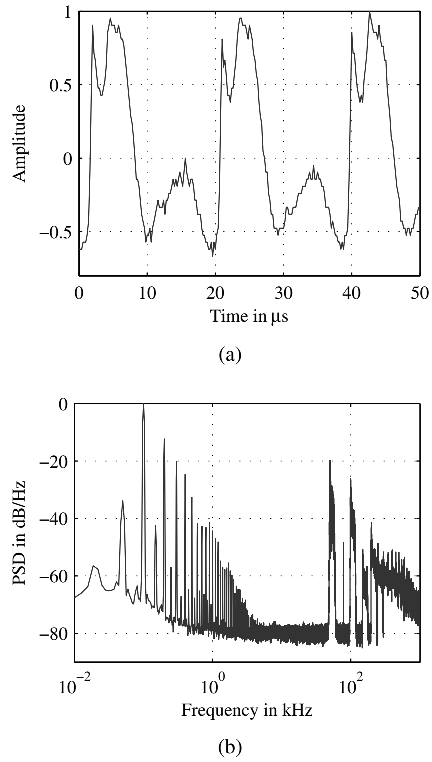


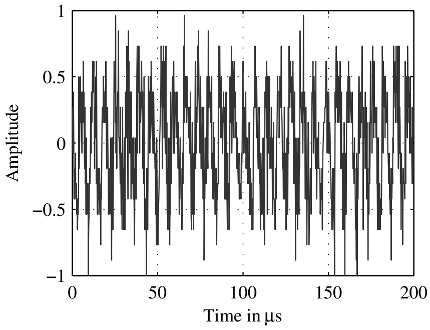
Fig. 4. Anode oscillations of compact fluorescent lamp Osram Dulux EL 23 with electronic ballast: (a) Time Waveform (b) Welch Power Spectal Density Estimate

to the rectified 50 Hz power supply voltage.

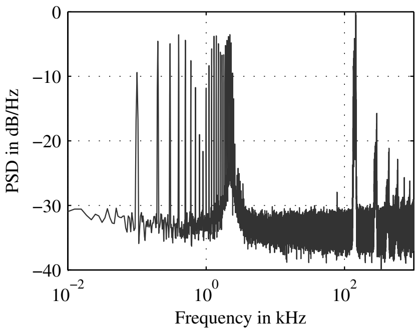
In fig. 2(b), the current power of the modulated narrowband HF component is averaged over the modulation bandwidth. Computing the instantaneous power of the HF components results in -29.9 dB for the 50 kHz component, -5.2 dB for the 100 kHz component, -38.9 dB for the 150 kHz component and -19.4 dB for the 200 kHz component. So it is notably, that the HF components are stronger than most LF harmonics.

Like at the fluorescent lamps with conventional ballasts, the behavior of the light near the electrodes was analyzed. Fig. 4 shows time and frequency characteristics measured directly over the electrode with an effect similar to anode oscillations. Due to HF modulation, the time waveform shows a period length of 20 μs, which corresponds to a switching frequency of the electronic ballast of 50 kHz. The spectrum shows a main peak at 100 kHz through rectification with an increase at high frequencies compared to fig. 2(b).

The LF and HF region are typical for all fluorescent lamps driven by electronic ballasts and were found in all measurements in different varieties. In the LF region different combinations of even and odd harmonics of the the 50 Hz fundamental were found. In the HF region different characteristics were observed, including some ballasts with no shifting HF frequencies. The electronic ballasts showed operating frequencies up to 117 kHz.



(a)



(b)

Fig. 5. 7 W Light Emitting Diode Philips Master LED E27 A55 MV bulb lamp: (a) Time Waveform (b) Welch Power Spectal Density Estimate

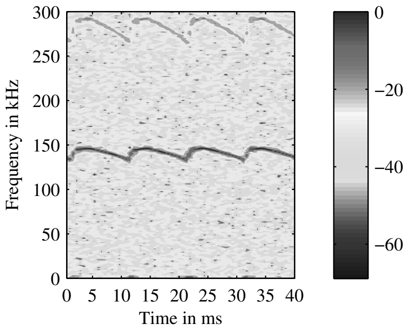


Fig. 6. Spectrogram of 7 W Light Emitting Diode Philips Master LED E27 A55 MV bulb lamp using Short Time Fourier Transform

E. Light Emitting Diodes

Steady improvements in high power light emitting diodes together with unique features like instant color variability are now opening the market of artificial lighting to this technology. Due to low driving voltages, LEDs need to be operated with some kind of ballast. For artificial lighting applications powered by a 220 V power supply voltage, HF electronic ballasts provide benefits concerning optical flickering, audability and energy efficient voltage transformation. Several different LED lamps for artificial lighting were tested. All were driven by a high frequency electronic ballast. Time and frequency characteristics of the LED light strongly depends on the used ballast. A huge variety of different time waveforms was observed. As an interesting example, measurements of the 7 W Philips Master LED E27 A55 MV bulb lamp are presented.

The time and frequency characteristics of the LED are shown in fig. 5. The time signal shows HF oscillations. The displayed measurements were taken with AC-Coupling. DC-coupled measurements for comparison showed a large DC component of the light more then 30 dB stronger than the HF components. The spectrum again shows a LF region up to 2 kHz with no clear decay like the other lighting types and a high frequency region starting at more then 100 kHz with a decay of about 30 dB per decade reaching -30 dB at 1 MHz.

Fig. 6 shows the spectrogram of the LED signal. Note that the frequency scale is linear, so the LF region cannot be seen in detail. The HF components at around 140 Hz and 280 Hz are changing their instantaneous frequency with a period of 10 ms, which corresponds to the rectified 50 Hz power supply voltage.

III. Conclusion

This paper presents digital measurements and numerical analysis of important sources of artificial lighting interference. Classic artificial lighting devices like incandescent lamps and fluorescent lamps geared by reactive ballasts show similar time frequency characteristics each over different lamps. Newer artificial lighting devices like fluorescent lamps geared by electronic ballasts and LED lamps also geared by electronic ballasts show a large variety of time frequency characteristics dependent on the mode of operation of each ballast. The spectra of these devices show either LF components within several hundred Hz, HF components with harmonics up to several hundred kHz or a combination of both as well as time dependent frequency characteristics.

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