Normalized Spectral Responsivity Measurement of Photodiode by Direct Method Using a Supercontinuum Laser Source

Fabiano Sanches Rocha[1], Luciana Pedrosa Salles[2], Ado Jorio[3]

Abstract—**Light detectors such as photodiodes and phototransistors are fundamental elements that compose imaging sensors and cameras devices. The photocurrent generated by photodiodes depends on the energy of light that is absorbed by semiconductor material, describing an important characteristic of this kind device. We present an optic instrumentation for measurement of normalized spectral responsivity of light detectors. The optics is composed by a single-grating monochromator, converting lens, a slit and a beamsplitter. Supercontinuum lasers provides a high-stability beam with ultra-broadband white-light spectrum. High spectral purity is achieved with only monochromator and the measurements are performed in terms of spectral power measured through a calibrated spectrometer. Uncertainties are examined at carefully for a specific confidence level considering Type A and Type B evaluations.**

Index Terms—**photodiode, experimental characterization, optical instrumentation, laser**

I. Introduction

For light detector characterization, semiconductor and chip testing applications, some technical specifications, such as capacitance, resistance, response time, quantum efficiency, sensitivity, linearity and spectral responsivity are required.

The spectral responsivity is a figure of merit that is defined as the ratio of radiant flux, P, in watts, incident on the photodetector to the photocurrent in amperes, I_{sc}, generated at the device terminals if short-circuited. Therefore, in general the responsivity is defined by

$$R(\lambda) = \frac{Isc(\lambda)}{P(\lambda)}. \tag{1}$$

This occurs when an amount of energy is absorbed by semiconductor layers sufficiently to cause an excitation of electron charges in device structure. Only photons with energy to overcome the band gap releasing electrons to move within the crystal lattice, allowing to photocurrent generation.

Lower energy photons cannot promote an electron to the conduction band through the energy gap. On opposite side, an high-energy light (short-wavelength) are not enable to diffusion in the high-deep layers of the material and determines the position of the spectral sensitivity maximum of the photodiode, i.e. a red beam penetrates deeper than a blue one [1].

The absolute spectral responsivity, $R_a(\lambda)$, is defined by equation 2 [2] where ϵ is the diode's internal quantum efficiency, λ is the wavelength in vacuum, $\rho(\lambda)$ is the directional-hemispherical reflectance and K is an constant.

$$R_a(\lambda) = \frac{[1-\rho(\lambda)]\epsilon(\lambda)\lambda}{K}. \tag{2}$$

As described in equation 2 the quantities must be obtained at each wavelength. Further, there is an complexity to determining the quantum efficiency and to measuring the specular reflectance component angle-dependent [3].

On the other hand, the relative spectral responsivity $S(\lambda)$ defined in equation 3, is given for a maximum value of normalized spectral responsivity $\max\{S(\lambda')\}$ of the photodiode, at a specific wavelength λ'. Instead, the absolute values of the spectral responsivity is not of interest to account in the measurement model [4].

$$S(\lambda) = \frac{R(\lambda)}{\max\{R(\lambda')\}} \tag{3}$$

Once the laser spot is less than the photosensitive area of the photodiode leading to the completely absorption of photons by semiconductor, the responsivity definition given by equation 1 is independent of the device dimensions. If the laser spot is larger than photosensitive area, a converging lens must be provided to prevent that the photosensitive area overfilled by beam spot [3] [5].

Essentially, to measure the relative spectral responsivity of an detector a broad spectrum light source, a monochromator, a power meter and a current meter is required. The entire detector's surface must be receives the same and known amount of optical radiation from monochromatic source. A uniformly light distribution can be accomplished using an integrating sphere [4], for instance, alternatively, polished diffusers provided a fine scattering of light and performs an effectively spatial distribution of the illumination. Even suitable for this kind application, the light uniformity across an device plane at a specific distance is dependent to the axial irradiance at the center of the object as well as the irradiance at the surface edge of the photosensitive area. Further, diffusion pattern depends on the grits that compose the diffuser well

[1]Graduate Program in Electrical Engineering, Federal University of Minas Gerais, Belo Horizonte, MG, Brazil e-mail: fabianosr@ufmg.br.
[2]Department of Electrical Engineering, Federal University of Minas Gerais, Belo Horizonte, MG, Brazil e-mail: lupsalles@gmail.com.
[3] Department of Physics, Federal University of Minas Gerais, Belo Horizonte, MG, Brazil e-mail: adojorio@fisica.ufmg.br.

as the irradiance depends on the distance that the object is placed.

In this work an optical experimental setup was implemented to measure the relative spectral responsivity of a photodiode using a supercontinuum white-laser source, a beamsplitter and a high-Resolution reflective grating. Spectral radiant power and laser linewidth was measured using a calibrated integrating sphere supported by ultraviolet (UV)/visible/near infrared (NIR) spectrometer (200-1 100 nm).

The objective of this work was extended a high spectral characterization to photonic devices such as photodiodes, pixel and phototransistors through a laser-based high stability source.

II. State of the Art Review

Some papers have suggested some techniques to measure the absolute and the normalized spectral response of light detectors. A self-calibration was the solution found by [2] using stabilized laser sources at specific wavelength supported by an absolute standard p-n junction. An optical system using a tungsten source, filters and lens was accomplished by [3] to measure the internal quantum efficiency and the spectral response of a silicon photodiode. The solution using some light-emitting diodes (LED), a single-grating monochromator and an integrating sphere have been developed in [4] to measure the normalized spectral response of a monochrome charge-coupled device (CCD).

III. Optical Set-up Description

Figure 1 shows the optical set-up used in normalized spectral response measurement procedure.

The measurement system is composed of a white laser source (SC) from 400 nm to 2 100 nm spectral band, an dielectric mirror (IRF) allows to pass the most of components between 400 to 750 nm is used to prevent damage to others optical elements from high-power infrared, a high-resolution reflective single grating (GM) with 1 800 lines/mm was placed at the optical center over a rotating platform mounted in the cage cube enabling freely rotate through of spectrum. Diffraction pattern is focusing at rectangular aperture (SL) by a 100 mm focal length lens (L2) blocking most of the wavelengths coming from diffraction grating, resulting in a narrow-band monochromatic light. Due to the large spectrum of the source, uncoated lens are employed allowing that all wavelengths between 200-1 400 nm are transmitted with same transmission factor. The collimated beam describe a high intensity profile contaminated by diffraction pattern (dark bands around main maximum) caused by scattering, thus, a diaphragm iris (IR) is placed to block the unwanted intensity fluctuations while passing the greater part of the monochromatic energy. A beamsplitter (BS) splits the beam of light in two, the first one is reflected and collected into integrating sphere (IS) to be measured by spectrometer, the second one is transmitted and focusing to the photodiode under test (PD), it is important to ensure that all energy coming from transmitted path of the beamsplitter reach at the photodiode area, therefore, a

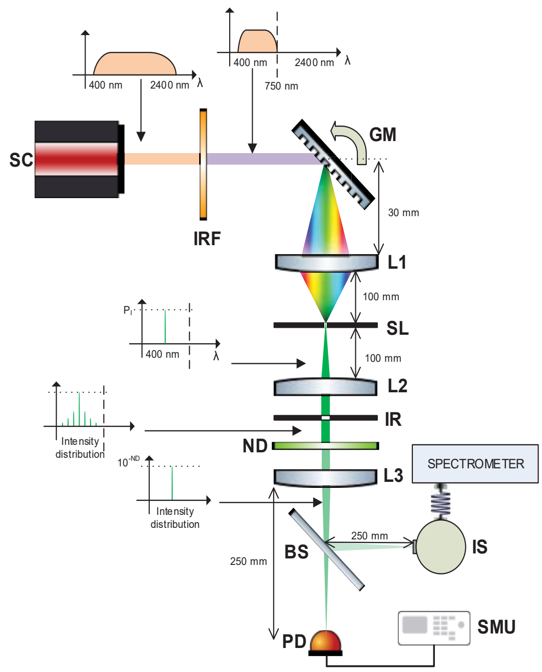

Fig. 1. Optical system: SC - Supercontinuum laser source (Fianium SC400), GM - 1 800 lines/mm reflective diffraction grating (echelle), L1/L2 - 100 mm uncoated plano-convex lens, SL - adjustable mechanical slit, IR - iris diaphragm, ND - neutral-density filter, BS - 350-1 200 nm 50:50 beamsplitter, IS - calibrated integrating sphere, PD - device under test (photodiode), SMU - source measure unit (current meter mode)

converging lens (L3) may be required. A neutral density filter (ND) reduces the light intensity to prevent the saturation of the spectrometer and photodiode.

A. *Supercontinuum laser output characteristics*

A supercontinuum light is result of nonlinear processes occurring when a laser (pump beam) propagates inside a special fiber filled with photonic crystals producing a smooth spectral continuum as shows by Fig. 2.

The optical spectral power density is obtained by integrating infinitesimal intervals distributed over a wavelength range, thus, the power of a linewidth with large bandwidth will depend on the spectral region when the power density distribution is non flat. For example, the spectral average in the dashed area is $0.74/(750-400) = 2.1$ mW/nm, however, is clearly seen in Fig. 2 at least one peak in 3.25 mW@400 nm in measurement region (dashed), meaning that a laser energy at a given wavelength can emitted with a higher power than calculated average.

The power output stability of the supercontinuum light depends on the pump laser well as fiber properties and optics. Short-term power instability leads fluctuations during the signal measurement and establish as a source of uncertainty for measurement result. Fianium SC400 manual contains the power stability tolerance information specified to be <1 %,

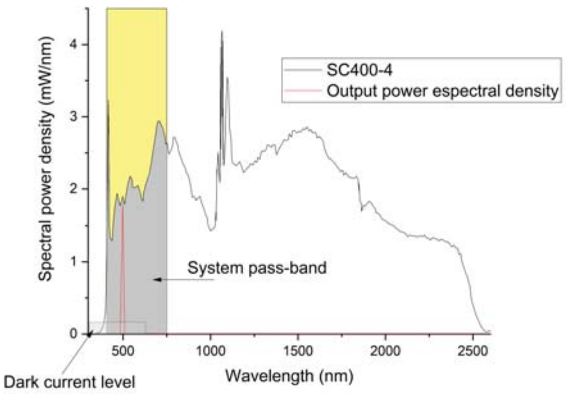

Fig. 2. Supercontinuum SC400-4 spectrum. The dashed area refers to the spectral region interested in the measurement procedure

considered as Type-B uncertainty. Moreover, since the emission characteristics of laser cavity is sensitive to temperature [6], 20 minutes is suitable to go from a cold start to operating temperature (warm-up time).

B. Spectral linewidth

The spectral purity of output depends on the focal length, slit size, f number, the optical quality of all components as well system alignment. For the optical system of Fig. 2 the resolution is about 5.0 nm (theoretical 0.86 nm) in visible region with a 1 800 lines/mm single grating, which is suitable for this application.

Note that the spectral power distributed in the linewidth that cause an excitation higher than the dark current contributes to the photocurrent generation. Thus, any contribution of irradiance low than dark current will not be in responsivity calculation, the limit is experimentally obtained reducing the power of laser and monitoring the current to closest to the dark current.

In order to check the spectral power of the linewidth, the output beam is measured by a calibrated spectrometer (Ocean Optics USB2000) with a optical resolution of approximately 0.1 nm, allowing to indirectly measure spectral irradiance once calibration process generates a file with energy response data for each pixel in the CCD, the counter processes and integration time enables to convert μJ/count into spectral power (energy/time) that achieve the photodiode through beamsplitter.

Another consideration is the output power, a smaller slit size yield a narrow spectral resolution and the lower irradiance power admitted into photodiode, on the other hand, using a larger slit size will degrade the spectral resolution.

C. Spectrometer calibration

Ocean Optics spectrometer USB2000 model has a tool that provides the measurement of spectral power with the supported by an integrating sphere. Measurements in absolute spectral power require a calibration source with known power output and a data file with energy response given in the μW/cm^2/nm units for each pixel in the CCD.

Each version of these light sources is designed to be used with specific sampling optics (e.g.) cosine corrector, integrating sphere or fiber.

Once the temperature has stabilized, the spectrometer was calibrated with the calibration lamp (HL-2000) that has a spectral range of 360-2400 nm with stability of 0.5 % and a lamp of 4.75 W. The calibration lamp is designed to be used with an integrating sphere (ISP-50-8) that has 0.98 % reflective from 400 nm to 1 500 nm.

Once calibrated, the system is able to make spectral power measurements.

D. Beamsplitter characterization

In order to minimize the error due to the beamsplitter ratio we check the reflected beam power in relation to the transmitted power at each wavelength. Readings of the reflected and the transmitted light was measured in sequence from 400 nm to 800 nm considering 20 measurement points uniformly distributed (20 nm of step). The split factor changes according to the wavelength of the incident radiation, thus, we consider the average ratio, $k = P_T/P_R = 1.15$, with associated uncertainty, $u_k = 0.001$

IV. Measurement Model

Using the responsivity definition (1) and (3), the measurement model considering all relevant quantities which may significant affect the result is given by equation 4

$$S(\lambda) = \frac{I_{ph} + \Delta_I}{[P_R + \Delta_{P_R}][1 + \Delta_L + \Delta_{SC}]/(1.15 + \Delta_k)} \cdot \frac{1}{\max\{S(\lambda')\}}, \tag{4}$$

where,

I_{ph}	- Photodiode Short-circuit current
P_R	- Reflected spectral power
Δ_{P_R}	- Repeatability of the power reading
Δ_I	- Current meter accuracy
Δ_L	- Calibration lamp stability
Δ_{SC}	- Supercontinuum stability
Δ_k	- Beamsplitter ratio repeatability
$\max\{S(\lambda')\}$	- Maximum spectral responsivity

V. Uncertainty Budget

The input quantities probability distribution are given by table I considering the measurement model given in 4. Limits of distributions were obtained from product datasheets, technical judgments and trough repeated observations.

Let $(\overline{P_{Ri}})$ is the average given by $1/n \sum_{i=1}^{n} P_{Ri}$ of a series of n indicators obtained from spectral power quantity that is reflected by beamsplitter having Gaussian distribution with $n-1$ degrees of freedom and variance s^2 [7].

TABLE I
INPUT QUANTITIES OF THE MEASUREMENT SYSTEM

Quantity	Distribution	Limits	Unit
I_{ph}	t-student	t$_4(\overline{I_{ph}^i}, u(I_{ph}^i)^2/n)$	A
Δ_{P_R}	t-student	t$_4(\overline{P_R^i}, u(P_R^i)^2/n)$	W
Δ_I	Rectangular	R(-6.0,+6.0)	nA
Δ_L	Rectangular	R(-0.75,+0.75)	%
Δ_{SC}	Rectangular	R(-0.5,+0,5)	%
Δ_k	t-student	t$_4(1.15, 2\times10^{-7})$	

VI. MEASUREMENTS RESULTS

After warm-up (about 1 hour), the spectrometer is calibrated using the HL-2000 lamp placed at integrating sphere input port, the count values are compared with data file allowing to measure the spectral power in visible region. Second, an arbitrary monochromator position is set and compared with spectrometer, 5 readings of the spectral power and current (Keithley SMU2400) with $6\frac{1}{2}$ digits and 50 pA of resolution are obtained and recorded. Then, the monochromator is set to a new wavelength and measurements are taken again.

A silicon PIN-10DFP photodiode sensor, active area 1 cm^2, with flat known responsivity are placed at transmission optic. Since the photodiode area is fully coverage by beam spot including all laser energy, the convergent lens were not used in our experiment and uncertainties due to their coating reflection and absorbing was not considered in measurement result.

The Monte Carlo method (MCM) has been implemented to propagation each input quantities (4) trough the measurement model in order to provide the estimate, uncertainty and coverage intervals. According to JCGM101 [7] the MCM require that each input quantity is associated with a probability distribution function (PDF). The set of values assigned to PDF should, in turn, coverage all possible values that can take the quantity. Figure 3 shows the measured normalized spectral responsivity as dot symbols, the error bars indicate the 95 % coverage interval of the measurement.

We see a significant offset between both spectral response caused by a non-homogeneity wavelength dependence interaction of light that reflected from the front and back surfaces of the beamsplitter and photodiode window interference.

Our measurement system is limited to the optical elements pass-band which can be easily specified for a wider range or interchanged according to a section of the spectral region.

Table II shows the absolute values measured at each of the calibration points.

TABLE II
ESTIMATE OF THE ABSOLUTE SPECTRAL POWER AND CURRENT

λ (nm)	P (μW)	I_{ph} (μA)	R (A/W)
455.7045	272.98	2.48	0.0091
492.7349	548.64	5.43	0.0099
534.4148	916.12	9.16	0.0100
588.3827	322.95	3.26	0.0101
647.0003	644.00	6.56	0.0102
696.4847	114.00	1.16	0.0102
727.3710	259.77	2.62	0.0101

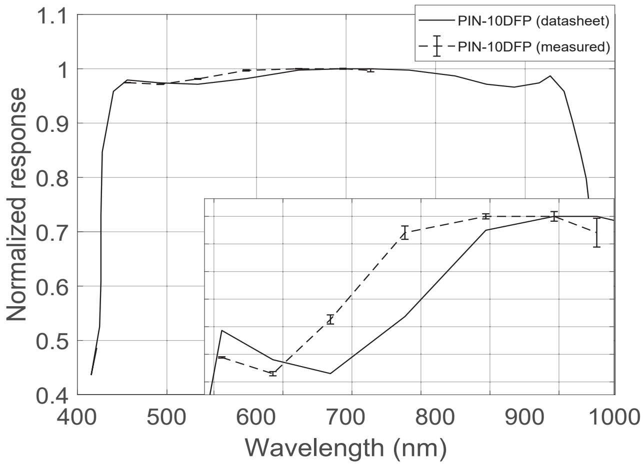

Fig. 3. Normalized spectral responsivity of PIN-10DFP given by manufacturer datasheet (continuous line). Normalized spectral responsivity of PIN-10DFP with uncertainties obtained by this spectral power measurement (dashed line) and detail of the measured region.

Table III summarizes the result at each measurement point with uncertainties well as 95 % coverage intervals.

TABLE III
ESTIMATE, STANDARD UNCERTAINTY AND ENDPOINTS OF THE SHORTEST 95 % COVERAGE INTERVAL PROVIDED BY MCM AT CALIBRATION POINTS

λ (nm)	Estimate	Standard uncertainty	95 % coverage interval ($\times10^{-3}$)
455.7045	0.0990	0.00020	[974.32, 974.55]
492.7349	0.0980	0.00010	[971.10, 971.87]
534.4148	0.0998	0.00005	[980.49, 982.14]
588.3827	0.1014	0.00003	[995.84, 998.26]
647.0003	0.1017	0.00003	[999.54, 1.00]
696.4847	0.1017	0.00003	[999.13, 1.00]
727.3710	0.1014	0.00003	[994.44, 999.66]

VII. CONCLUSIONS

Authors demonstrated a high-stability method based on the supercontinuum light as source for normalized responsivity measurement. A single grating monochromator was used as dispersive element with an adjustable slit reporting approximately 5.0 nm for the spectral resolution, make that spectral purity suitable for this application. Uncoated optics can be used to improve the spectral pass-band expansion of the instrument limited by anti reflective coating. Uncertainties are reported based on Type A and Type B evaluations, the measurement result statistics (estimate, standard uncertainty and coverage intervals) were computed through Monte Carlo Method.

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