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Short Communication

Differential measurements of light power variations through Si photodiodes in a bridge configuration for high-sensitivity chemical/biological optical sensing

Andrea De Marcellis*, Elia Palange

Department of Industrial and Information Engineering and Economics, Via G. Gronchi 18, University of L'Aquila, I-67100 L'Aquila, Italy

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ABSTRACT

This paper reports on a new optoelectronic technique based on the differential measurement of currents for the detection of small variations of the molar concentrations of chemical and biological substances by measuring changes of light power through two Si-photodiodes used in a bridge configuration. The solution exhibits high sensitivity, linear response and allows for the compensation of the initial bridge unbalance without changing its elements so optimising the output signal amplification and detection resolution. The proposed optoelectronic approach allows obtaining unique performances with respect to those ones achievable by using the standard synchronous demodulation technique for amplitude and phase measurements implemented by lock-in amplifiers. Moreover, the overall optoelectronic apparatus is simple and suitable for portable integrated sensor systems. Its main performances have been experimentally evaluated through a prototype PCB employing off-the-shelf components demonstrating the capability to detect light power variations with a settable maximum sensitivity of 300 mV/nW with a resolution of about 3 pW. Furthermore, a comparison with amplitude measurements based on the standard synchronous demodulation technique performed by lock-in amplifiers has demonstrated that the proposed optoelectronic system allows for a sensitivity enhancement of 2.9×10^4. As a case example, the optoelectronic system has been employed to determine variations of the molar concentration of a Rhodamine B solution diluted in ethanol with a resolution of about 5 pM by performing optical absorption measurements.

1. Introduction

Optical techniques are widely used to detect the presence of chemical and biological substances since the measurements are non destructive and can also be performed at distance from the sample under analysis [1]. Nowadays, functionalised surfaces composed of 2D-array of metal nanoantennas demonstrated the properties to enhance the optical response of substances adsorbed on these structures also at very small molar concentrations. Thus, they act as plasmonic sensors able to characterise, identify and probe chemical, biological and physical modifications of substances, cells and organelles by using different optical transduction techniques such as Surface Enhanced Raman Scattering (SERS), Surface Enhanced InfraRed Absorption (SEIRA) and Surface Plasmon Resonances (SPR) [2–10]. Nevertheless, independently from the optical technique employed for the target recognition, the light beam interacting with the sample under analysis is detected by PhotoDiodes (PDs) that generate photocurrents proportional to the number of photons (i.e., the light power) impinging on their sensitive area. However, progresses in employing the plasmonic chemical and biological sensors have been focussed to implement new optical schemes and/or nanostructured metal and semiconductor interfaces to enhance the response from the analyte to be detected. For example, a 295 ng/cm^2 surface coverage of neutravidin molecules corresponding to 4.9×10^{-12} moles/cm^2 has been measured by using the SPR technique [10] and a sensitivity detection limit for human immunoglobulin of the order of 20 fgmL^{-1} has been reported using specific carriers in SERS experiments [11]. Nevertheless, these results, as many others that can be found in literature, have been achieved without any special efforts to improve sensitivity and resolution of the light detection techniques. In the case of small and noisy signals due, for example, to

* Corresponding author.
E-mail address: andrea.demarcellis@univaq.it (A. De Marcellis).

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low molar concentration of the targets, the standard optoelectronic detection approach is based on the in-phase synchronous demodulation technique implemented by lock-in amplifiers to improve the signal-to-noise ratio [11–16]. Generally, this technique is used to detect the amplitude of electrical signals at a fixed modulating frequency and the achieved sensitivity and resolution depend and are limited by the selected full-scale needed for each specific measurement. To overcome this constraint, recently it has been demonstrated that variations of light power deriving from any interaction with matter, can be measured by evaluating the phase shift between the electrical signal generated by a PD (i.e., the input signal) and a suitable reference signal at a specific modulating frequency [17,18]. This approach presents the advantage to be independent from the amplitude of both the input and reference signals and does not suffer of any full-scale limitations. Even if the reported experimental results demonstrate the capability to obtain sensitivities and resolutions much higher than those ones achievable by using the standard synchronous demodulation technique, the achievement of the best operating conditions for the phase shift technique must be properly adjusted as a function of the value of the light power impinging on the PD and of the wavelength [19,20].

This paper reports on a new optoelectronic detection technique that uses two PDs in a Wheatstone bridge configuration combined with differential measurements of the generated photocurrents through a conditioning electronic circuit employing only three Operational Amplifiers (OAs). More in general, Wheatstone bridge is a widely used sensor conditioning circuit that typically detects small resistance changes with good linearity through voltage differential measurements [21–23]. However, in order to perform accurate measurements with high sensitivity and resolution, it is fundamental to zeroing the initial bridge unbalance condition by regulating its elements, adding further components or implementing auto-calibration techniques [24–27]. Alternative complex solutions perform a current subtraction between only two sensing elements with the reduction of the bridge components and sensitivity that result not suitable for standard/commercial bridge configurations [28–31]. The presented optoelectronic architecture allows for the initial bridge balance simply through external voltages so avoiding any full-scale limitations and achieving very high detection sensitivities and resolutions of light power variations [32]. Furthermore, the response of the proposed optoelectronic system is independent from the kind of PDs employed for the measurements as well as from the value of the light power to be detected and the dependence from the light wavelength can be easily overcome by using calibrated PDs.

2. Implementation of the proposed optoelectronic detection technique

The differential measurements of light power variations have been accomplished by implementing the experimental set-up reported in Fig. 1. A continuous wave p-polarised laser beam (emission wavelength and power equal to $\lambda = 543.5$ nm and 5 mW, respectively) is suitable attenuated by a neutral density filter (optical density ND = 2) and is split in two different optical paths: the signal path containing a cuvette with the sample under analysis and the reference path that takes into account for only the changes of the laser power during the measurements. The laser power of the beams travelling along the two optical paths is detected by two commercial Si-PDs: PD_S and PD_R that indicate the signal and reference photodiodes, respectively. These PDs generate the photocurrents i_S and i_R proportional to the light power impinging on their sensitive area. The electronic conditioning circuit operates a differential measurement of these photocurrents by amplifying and converting them into voltages and providing a single-ended DC output voltage V_{OUT}. Thus, the latter signal is proportional to the variations of the light power of the laser beam passing through the cuvette containing the chemical/biological substance under analysis and is automatically normalised to the random variations of the laser power detected by PD_R in the reference path.

Fig. 2 reports the implementation of the overall optoelectronic conditioning circuit for the differential photocurrent measurements. The circuitry has been developed on a prototype PCB employing commercial discrete components: PD_S and PD_R are Si-PD VTB8440B by PerkinElmer Optoelectronics; OA_1–OA_3 are operational amplifiers LF411 by Texas Instruments powered at ±15 V. The bridge is DC biased through $V_{BIAS} = 2$ V, R_A and R_B are fixed resistive loads. The main output signals of the Wheatstone bridge are the currents $i_{OUT1} = i_B - i_S$ and $i_{OUT2} = i_A - i_R$ that are converted into voltages V_{OUT1} and V_{OUT2} by OA_1 and OA_2 in a transimpedance configuration with the feedback resistors R_1 and R_2. The two voltages V_{OUT1} and V_{OUT2} are then differentially amplified by OA_3 in a differential-to-single-ended configuration so providing the circuit main output voltage V_{OUT}. Moreover, the external control voltages V_{OFF1} and V_{OFF2} allow initially to balance the Wheatstone bridge zeroing its output currents i_{OUT1} and i_{OUT2} by imposing suitable voltage values at the A and B nodes. Finally, a further external control voltage V_{OFF3} allows achieving $V_{OUT} = 0$ to zeroing the overall offset due to the initial bridge unbalance condition.

3. Experimental results

The electrical and optical characterisation of the optoelectronic conditioning circuit as a function of the gain of OA_3 is shown in Fig. 3 demonstrating a linear dependence of the output voltage V_{OUT} as a function of the light power (linear correlation coefficient R = 0.998). The experimental results have been achieved by setting $R_A = R_B = R_1 = R_2 = R_4 = R_6 = 100\,k\Omega$ and by replacing the cuvette in Fig. 1 with a linear polariser (LPVISB050-MP2 by Thorlabs with a polarisation extinction ratio greater than 10,000:1) that permits to continuously vary the laser beam power in the signal path by rotating its transmission axis. As shown in Fig. 3, three different circuit detection sensitivities S have been achieved setting

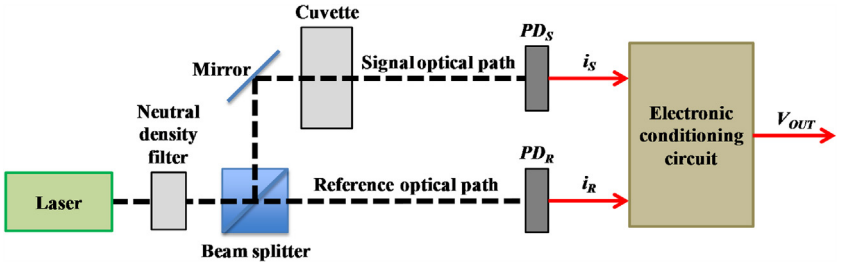

Fig. 1. Optical experimental set-up for the differential measurements of light power variations.