# Paracetamol concentration-sensing scheme based on a linear cavity fiber laser configuration

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ABSTRACT

A paracetamol concentration-sensing scheme based on a linear cavity fiber laser configuration is demonstrated experimentally. The laser cavity has a fiber sensor at one end, that allows refractive index measurements. The refractometer consists of a cleaved fiber tip combined with an FBG functioning as a reflecting mirror. The combination of a fiber loop mirror at the other end allows to reflect all the light from the FBG and refractometer, forming a linear cavity. By measuring the intensity variation of the Fresnel reflection at the fiber-to-liquid interface, the measured concentration is linear and have a concentration sensitivity of $[(-8.74 \pm 0.34) \times 10^{-5}]$ μW/(g/kg), over a range of 52.61 to 219.25 g /kg, and with a resolution of 2.77 g/kg.

The results obtained present high stability and prove the potential of the fiber laser system to performed real-time measurements of concentration, in a non-invasive way.

*Keywords:* paracetamol, concentration, linear cavity, fiber laser, fiber tip.

## 1. Introduction

In the several past years, Refractive Index (RI) measurement has performed an important role in several processing industries, such as pharmaceutical, chemical, biological, medical, foody industry and environmental [1, 2]. The growth of research and development in this field is driven by the need for quality control, which is often required by the end consumer.

Optical fiber sensors are a promising tool for RI sensing, due to their desirable features, such as reduced dimensions, compatibility, and high degrees of integration, which allow to provide real-time measurements in a non-invasive and non-destructive way [3, 4].

Different configurations and mechanisms of fiber optic RI sensors have been proposed and developed in the last years – Table 1. They are sensitive to the RI variations in the surroundings of the fiber surface and these variations modify the light propagation, which cause changes in the transmission or reflection spectra [5, 6]. The refractometric sensors work on the principle of either wavelength modulation (Fiber Bragg gratings (FBGs), Long Period

Gratings (LPGs) and modal interferometers) or intensity modulation [7]. However, in several cases, intensity sensors are preferred. Despite of the high sensitivities of wavelength-modulated sensors, the wavelength processing depends on complicated technology/instruments and their measurement ranges are limited by high cross response to temperature and RI [7, 8].

**Table 1**
Different configurations of refractometric sensors reported in literature.

| Year | Range (RIU) | Modulation | Sensing head | Applications | Ref |
|---|---|---|---|---|---|
| 2007 | 1.333 – 1.390 | Wavelength | Photonic bandgap fibers | Determination of concentration | [9] |
| 2008 | 1.310 – 1.350 | Wavelength | Tilted Fiber Bragg Grating | Detection and quantification of biomolecules in real-time | [10] |
| 2008 | 1.333 – 1.404 | Wavelength | Fabry-Pérot interferometer | Biochemical sensing | [11] |
| 2013 | 1.330 – 1.360 | Intensity | Combination of two reflectors fibers: transmitting fiber and receiving fiber | Measurement of salinity | [12] |
| 2014 | 1.330 – 1.360 | Wavelength | Bent fused biconical tapers | Refractometry - biosensing | [13] |
| 2019 | 1.363 – 1.395 | Intensity | Multimode cleaved fiber tip | Detection of crystallization process | [14] |
| 2019 | 1.300 – 1.340 | Wavelength | Looped fiber taper | Biological and chemical sensing in water-based solutions | [15] |
| 2020 | 1.335 – 1.380 | Wavelength | Cleaved taper, single mode fiber and spherical structure (Mach-Zehnder interferometer) | Biomedicine and physical engineering applications | [16] |
| 2022 | 1.300 – 1.390 | Intensity | Fiber tip | Measurement of refractive index | [3] |
| 2022 | 1.332 – 1.348 | Wavelength | D-shaped fibers | Biomedical applications | [17] |

For more than a century, the measurement of concentration has been very important in processing industries for optimize the production [8]. In this way this type of refractometric sensors have been specially used to determine the material concentration.

The sensibility of the technology used in this process can substantially improve all type of refining, manufacturing, and quality control operations. For this, real-time measurements are the most appealing, because they avoid sample preparation and time delays [18, 19].

In this work, a refractometric sensor, implemented through a fiber laser design and modulated in intensity, is proposed, and demonstrated to perform paracetamol concentration measurements in liquids.

The fiber laser design proposed allows to achieve both stimulated emission (used for referencing) and Amplified Spontaneous Emission (ASE) functioning as an intensity sensor.

The sensor measures the output reading and monitor the changes of optical power at different concentrations influenced by the interaction of Fresnel's reflection produced at the interface between the fiber tip and the liquid solutions. This work offers simplicity, reliability, and continuous capability of measurement. Through of it, paracetamol

concentration measurements were performed, in real-time and in a non-invasive and non-destructive way. This represents a potential to optimize the production in processing industries: maximizing the use of reagents, avoiding the production of waste and, consequently, ensuring the cost reduction.

Other advantage of this proposed system is the possibility of multiplexing several sensor fiber tips placed in different measurement sites, without changing the interrogation system. In this way, it can be used for different applications requirements, in a simple and low-cost way, compared to other process analytical technologies.

## 2. Experimental setup

In this work a fiber laser system is proposed to performed measurements of paracetamol concentration in liquid solutions. The configuration used is presented in Fig. 1.

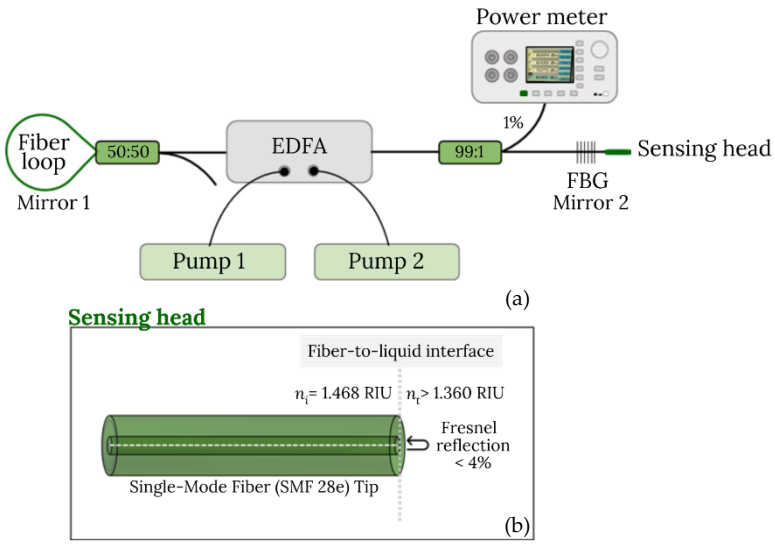


**Fig. 1.** Experimental setup of the fiber laser system for paracetamol concentration measurements.

The laser gain of the system is provided by a commercial bidirectional Erbium-Doped Fiber Amplifier (EDFA) from *MWTechnologies* – Fig. 1 (a). The bidirectional EDFA used consists of two 3-port optical circulators and two conventional EDFAs (i.e., an erbium-doped fiber and a co-directional pump). Each pump of the conventional EDFAs could be independently controlled. It is important to notice that, in the implementation of the fiber laser system, the erbium-doped fiber should be carefully fixed in a stable position to mitigate the effects of bending and polarization losses. Also, an appropriate pumping system should be chosen to ensure the laser stability.

To obtain a linear cavity, two distinct mirrors are used: a fiber loop mirror and a Fiber Bragg Grating (FBG). The use of two different mirrors allows to obtain an increase in the Amplified Spontaneous Emission (ASE), generated by the fiber tip, and, simultaneously, an increase in the stimulated emission by the FBG mirror. As it is illustrated in Fig. 1, the fiber loop mirror allows the reflection of all the light obtained from the EDFA. A portion of this light is then reflected by the FBG mirror, resulting in stimulated emission, and the remaining light is reflected by the fiber tip, which contributes to generate ASE. Having this two laser effects, stimulated emission, and ASE, it is possible to obtain a reference for the sensor implemented through this fiber laser system.

In relation to the FBG mirror used, it corresponds to a commercial grating, centered at 1567.8 nm, with a reflectivity of 97.59% and a bandwidth of 0.243 nm at −3 dB.

To acquire the laser optical power, a 99:1 optical coupler is used. In the measurements performed, 1% of the system signal is extracted to a power meter (model Agilent 8163B).

In this configuration, the sensing head corresponds to a standard Single-Mode Fiber (SMF 28e) tip, that works as an intensity sensor – Fig. 1 b. The tip is cleaved at 20 mm after the FBG, because its operating mechanism relies on the Fresnel reflection. In this way, the measurand-induced intensity variation of the Fresnel reflection at the fiber-to-liquid interface is monitored. When the light reaches the surroundings (see Fig. 1 b), it is partially reflected and, according to the liquid RI variations, the intensity of the reflected optical signal linearly changes.

Through the Fresnel equation (Equation 1) for a reflection at a normal incidence, it is possible to calculate the Reflectance, $R$, which corresponds to the ratio between the reflected light in the fiber-to-liquid interface and the incident light [20]:

$$R = (n_t - n_i/n_t + n_i)^2 \quad (1)$$

Since the RI of the fiber optic core ($n_i$=1.468 RIU) has a higher value than the RI of paracetamol liquid solutions ($n_t$> 1.360 RIU, see Fig. A.1), and according to Equation (1), less than 4% of the light guided by the fiber is reflected at the fiber-to-liquid interface monitored.

## 2.1. *Fiber laser characterization*

The fiber laser system was characterized using an optical power meter (recall Fig. 1) and an Optical Spectrum Analyzer (OSA – YOKOGAWA, model AQ6370D).

The power meter allowed to obtain the relation between optical output power and laser diode drive current, as Fig. 2 illustrates. Through these results (Fig. 2) it was possible to obtain a threshold current of 139 mA.

The output spectrum of the fiber laser system, obtained through the OSA, is shown in the inset of Fig. 2. The maximum output power level was measured with an Optical Signal to Noise Ratio (OSNR) of 54 dB and it corresponds to the FBG filter: centered at 1567.8 nm and with an output power level of −12 dBm.

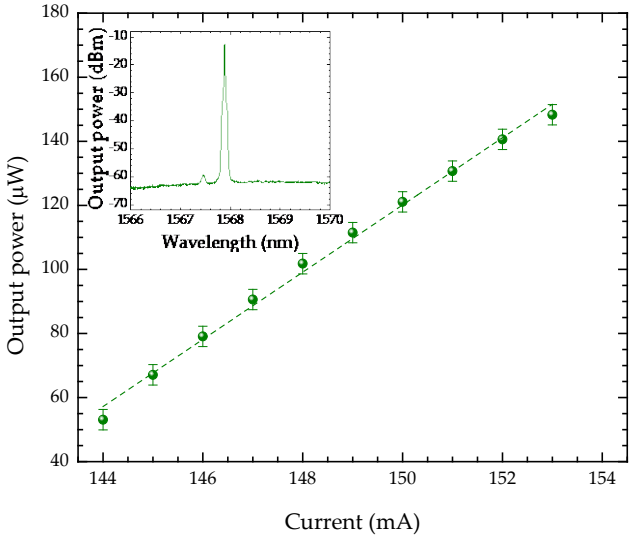


**Fig. 2.** Relation between optical output power and laser diode drive current. Inset: Fiber laser system output spectra.

In all the experiments performed for characterization of paracetamol concentration, it was used a pumping rate of 150 mA, which corresponds to a constant power of 120 μW (see Fig. 2).

## 2.2. *Fiber laser system for sensing applications*

Eight standard liquid solutions of paracetamol (see Appendix A) with a concentration range of 52.61 to 219.25 g /kg were measured using the laser configuration proposed. Since the laser response it is independent of the paracetamol concentration, it is suitable to used it as reference.

During the measurements, paracetamol samples were kept in a water-bath at 50°C to avoid paracetamol crystallization. The sensing head was vertically immersed in each sample and output power level was obtained using the power meter. To avoid possible contamination and the formation of paracetamol residuals around the fiber, the sensing head was cleaned with alcohol, after each measurement.

A linear sensitivity of $[(-8.74 \pm 0.34) \times 10^{-5}]$μW/(g/kg) to the variation of paracetamol concentration, with ranges of 52.61 to 219.25 g/kg, was obtained, as it is possible to see in Fig. 3.

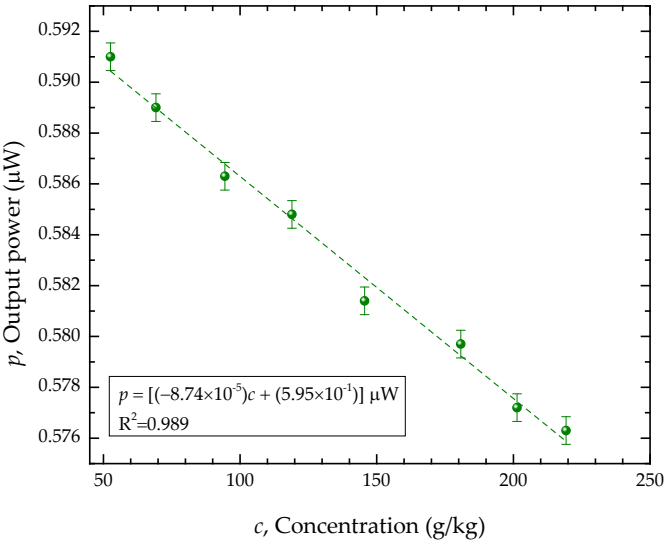


**Fig. 3.** Output power level as a function of paracetamol concentration.

The influence of temperature in the output power response of the system was analyzed. For this, the FBG mirror was immersed in a temperature-controlled water bath (the sensing head remained in contact with air).

During the water bath heating, the optical spectra of the fiber laser system were obtained through the OSA – inset of Fig. 4 a, and the output power response was obtained using an optical power meter – Fig. 4 b.

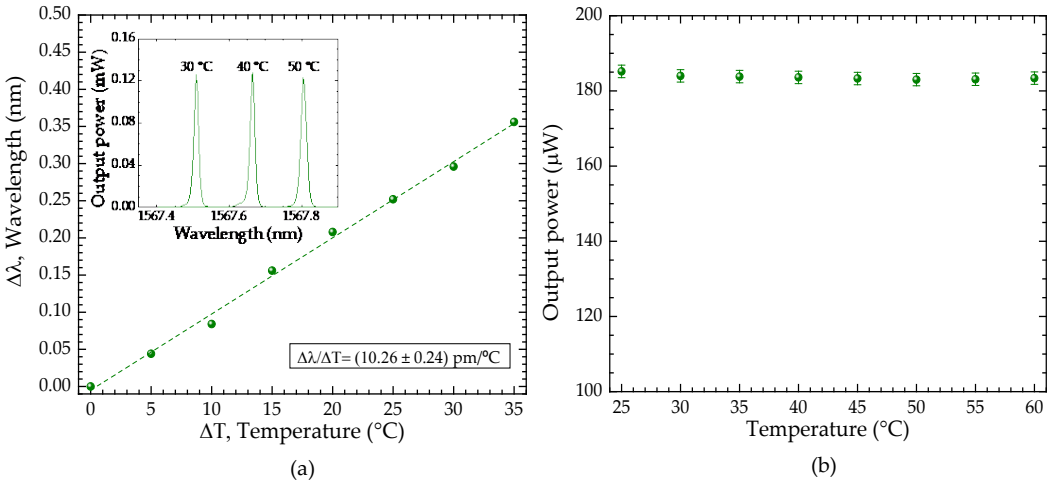


**Fig. 4.** Influence of temperature in the fiber laser system output power response. (a) variation of the FBG central wavelength as a function of temperature. Inset: output spectra, only presented in the FBG mirror spectral range. (b) integrated output power response.

The results (Fig. 4 a) show a wavelength dependence on temperature (~ 10 pm/°C) during the heating, caused by the thermo-optical effect that changes the material effective RI [21]. However, the output power response remains approximately constant (~ 0.18 mW) – Fig. 4 b. This proves that the output power response of the system is only related to the variations of paracetamol concentration.

The resolution of the system was also determined. To achieve this, it was conducted two consecutive measurements of two samples of paracetamol, with consecutive values of concentration, 52.61 g/kg, and 69.21 g/kg, respectively. The sensing head was successively immersed in the refered samples, and the sensor response was achieved using an optical power meter – Fig. 5. As previous refered, to avoid paracetamol crystallization, the samples were kept in a water-bath at 50°C and the measurements were performed at a lab environment of 20°C.

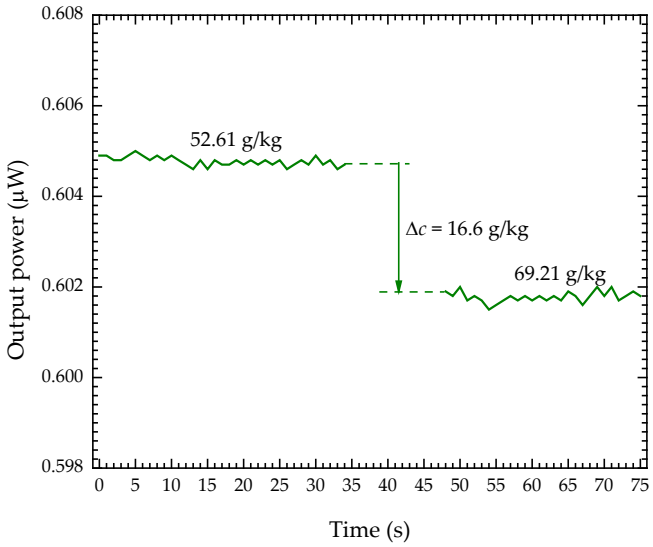


**Fig. 5.** Evaluation of system resolution.

According to the sensor response (see Fig. 5) and applying the Equation (2), the resolution of the system, i.e., the minimum value of concentration ($\delta_c$) that the system can discriminate, was calculated [14]. Table 2 presents the variables values used in the calculation of the system resolution.

$$\delta_c = 2\frac{\sigma_p \Delta c}{\Delta P} \quad (2)$$

**Table 2**
Calculation of fiber laser sensor system resolution.

| Variable | Designation | Value |
|---|---|---|
| $\sigma_p$ | maximum standard deviation of the output power | $2.5 \times 10^{-4}$ μW |
| Δc | variation of concentration | 16.6 g/kg |
| $\Delta P$ | mean displacement of output response between the two steps | $3.0 \times 10^{-3}$ μW |

A value of 2.77 g/kg was obtained for the system resolution. During this experiment, it was possible to determine the sensor's response time of $(2.91 \pm 0.63)$ s. It is important to refer that this value was also influenced by the spectral resolution of the equipment used for data acquisition (0.01 pW).

The stability of the system response during the measurements was also studied and can be seen in Fig. 6. It was used an ethanol sample with a RI of 1.3642 RIU. The sensing head was vertically immersed in the sample for 120 minutes and the output optical power level was recorded every 5 minutes using the optical power meter.

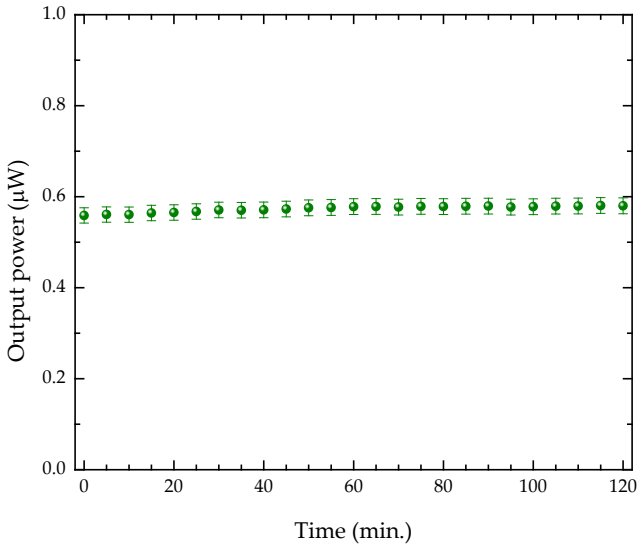


**Fig. 6.** Long-term stability evaluation of the fiber laser system.

The results (Fig. 6) show that the output power level did not change significantly at room temperature (error < 3%) over a long period of time, which proves the stability of the system response, during the measurements.

## 3. Conclusion

In this work, a fiber laser sensor system has been proposed and experimentally demonstrated to performed concentration measurements in paracetamol liquid solutions.

The sensing head of the system corresponded to a refractometric sensor capable of measuring the laser optical power as a function of the concentration with high stability.

The experimental results indicated that the optical power of the proposed system varied linearly with the concentration of paracetamol within the range of 52.61 to 219.25 g/kg, yielding a sensitivity of $[(-8.74 \pm 0.34) \times 10^{-5}]$μW/(g/kg) and a resolution of 2.77 g/kg.

The proposed fiber laser sensor system is a simple configuration, it can be easily implemented in reactors in the pharmaceutical industry, and it can be used to in-line liquid measurements of concentration for the purpose of process control in several processing industries.

## CRediT authorship contribution statement

**Liliana Soares:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing-Original draft preparation, Writing-Review & Editing. **Rosa Ana Pérez-Herrera:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing-Review & Editing. **Susana Novais:** Resources, Writing-Review & Editing. **António Ferreira:** Resources, Writing-Review & Editing, Visualization, Supervision. **Susana Silva:** Methodology, Formal analysis, Investigation, Resources, Writing-Review & Editing, Visualization, Supervision. **Orlando Frazão:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing-Review & Editing, Visualization, Supervision. All authors have read and agreed to the published version of the manuscript.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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# Appendix

## *Characterization of paracetamol liquid samples*

The paracetamol liquid samples were prepared under a controlled laboratory environment at room temperature (~20°C). Seeds of paracetamol (paracetamol (CAS number 103-90-02, min. 99% purity, supplied by Sigma-Aldrich) were dissolved in a mixture of 40% (v/v) ethanol/deionized water, producing eight standard liquid solutions of paracetamol with a concentration range of 52.61 to 219.25 g paracetamol/kg solvent, which corresponded to a RI range of 1.3642 RIU to 1.3898 RIU.

The RI of each paracetamol sample was determined using an Abbe refractometer (ATAGO, DR-A1). The measures were performed at room temperature of 19.5°C. To avoid paracetamol crystallization, during the measurements, all the samples were kept in a water-bath at ~50°C.

In Fig. A.1 a characterization of paracetamol samples is performed.

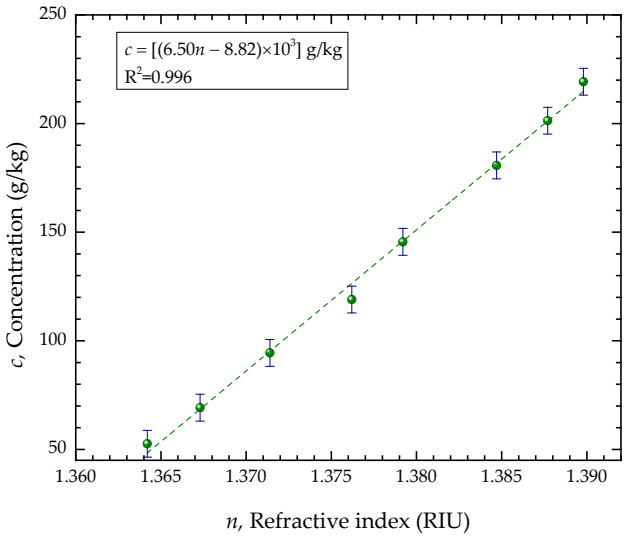


**Fig. A.1.** Characterization of paracetamol liquid samples. Concentration of paracetamol in solution as a function of RI.

As expected, with the increase of concentration, i.e., with the increase of paracetamol in solution, the RI of solutions also increases in a linearly way (correlation factor of 0.996), as consequence of the increased optical density.