Efficient sensings of temperature, refractive index, and distance measurement using the cubic-nonlinear optoelectronic oscillators

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Abstract
In this work, we use the cubic-nonlinear optoelectronic oscillator (CNOEO) in three different configurations to successfully perform the sensings of temperature, refractive index, and distance measurement with high precision. From our results, the use of the CNOEO through the variation of the values of the cubic-nonlinear parameter increases the sensitivity of the different sensings and the measurement carried out compared to the results obtained with the standard OEO which is a particular CNOEO featuring a cubic-nonlinear parameter equal to zero.

Keywords Optoelectronic oscillator (OEO) · Oscillation frequency · Temperature sensing · Refractive index sensing · Distance measurement

1 Introduction
Optoelectronic oscillators (OEOs) have inspired numerous applications and technological aims such as ultra-stable microwave generation, neuromorphic computing, signal processing, photonic integration circuits, random numbers generation, and chaos communications (see Larger 2013; Chembo et al. 2019; Hao et al. 2020; Talla Mbé et al. 2021 and references therein for a comprehensive review). Recently, the scope of technology and applications has widened to incorporate sensing, measurement, and detection (Zou et al. 2016; Yao 2017; Wu et al. 2018) owing to the fact that typically, an OEO is a high-Q device capable of producing microwave signals with ultralow phase noise and high frequency (Zhang et al. 2018). Indeed, with OEOs it is possible to carry out the measurement or
sensing of length, refractive index, temperature, angular velocity, load, strain, low-power RF signal, magnetic field, amongst others (see Zhang et al. 2018, 2021; Liu et al. 2019; Zhu et al. 2019; Xie et al. 2019; Xu et al. 2019; Ming et al. 2021; Zhang et al. 2020; Feng et al. 2019 and references therein). For this purpose, several architectures were proposed for the efficiency of the method. For instance, the authors of Feng et al. (2019) achieved a strain-insensitive temperature sensor with a sensitivity of 1.00745 MHz/°C based on an optoelectronic oscillator incorporating both the phase and the intensity optical modulators. Besides, Zhang et al. achieved a sensitivity of the angular velocity of 51.8 kHz/(rad/s) using an OEO incorporating a Sagnac interferometer (Zhang et al. 2018).

The fundamental principle of using OEO for optical metrology is to code the quantity to evaluate, such as temperature, strain, transverse load, refractive index, and more, to the frequency shift of oscillating signal of OEOs. Two mechanisms are possible (Feng et al. 2019): The first one consists of using the band-pass of the microwave photonic filter both as an oscillation frequency selection element as well as a sensing/measurement element. Even if it gives high sensitivity for optical metrology, it is not easy to implement experimentally. The second one known as the time-delay mechanism is quite easy since it relies on the direct change in the oscillator’s loop when affected by the quantity to sense, detect, or measure.

Thus, this latter technique is the most developed one (Chembo et al. 2019). Following this, an OEO with optimal frequency could play an important role in sensing and measurement processes. Recently, an OEO displaying dynamics predominated by high-frequency limit-cycle oscillations was proposed (Talla Mbé et al. 2019). Such dynamics were made possible by substituting the standard band-pass filter in the electrical path of the standard OEO with a cubic-nonlinear band-pass filter. The oscillator is known as the cubic-nonlinear optoelectronic oscillator (CNOEO) and has not yet been used for sensing and measurement.

In this paper, we theoretically aim to increase the sensitivity of the sensor/measurer-based OEOs using the CNOEO. The distance measurement and two main sensings are investigated, namely, the temperature and the refractive index. The paper is organized as follows: In Sect. 2, the cubic-nonlinear optoelectronic oscillator (CNOEO) is presented. Applications to temperature, refractive index sensings, and the distance measurement are discussed in Sects. 3, 4, and 5, respectively. Finally, a conclusion is given in Sect. 6.

2 The cubic-nonlinear optoelectronic oscillator (CNOEO)

The CNOEO used for this work is displayed in Fig. 1a (Talla Mbé et al. 2019). The CNOEO is made up of a laser diode, a polarization controller (PC), a Mach-Zehnder modulator (MZM), an optical delay line, a photodiode (PD), a cubic-nonlinear band-pass filter (CNBPF), a voltage subtractor (VS), an amplifier (Amp), a microwave coupler (MC), and an oscilloscope to visualize the oscillating signal. The CNBPF is made of an inductor, a resistance, and a nonlinear capacitor (NC). The structure of the nonlinear capacitor is shown in Fig. 1b: an operational amplifier (U), two capacitors $C_{1,2}$, one resistor $r$, and eight junction diodes can be identified. The functioning of the CNOEO will be specifically given for each application treated in this paper. Detailed explanations of the main CNOEO can be found in Talla Mbé et al. (2019), Kamaha et al. (2020). Nevertheless, it is important to notice that the dynamics of the CNOEO is governed by the following integro-delay differential equation (Talla Mbé et al. 2019; Kamaha et al. 2020):
where the parameters are expressed in terms of the components of the system of Fig. 1 as follows:

\[
\begin{align*}
\mu &= \frac{L}{R}, \\
\eta &= \frac{n_o V_o}{6} \left( \frac{1}{2i_o R C_2} \right) \frac{1}{R} \left( \frac{2V_{\text{ref}}}{xG} \right)^2, \\
\beta &= \frac{xG \eta}{2V_{\text{ref}}}, \\
\frac{1}{\theta} &= \left[ \frac{1}{C_1} - \frac{n_o V_o}{2i_o R C_2} \right] \frac{1}{R} \\
x(t - \tau) &= \frac{V_{\text{ref}}}{2V_{\text{adc}}}, \\
\phi &= \frac{V_B}{2V_{\text{adc}}},
\end{align*}
\]

In the set of Eq. (2), \( \mu \) is the high cut-off time, \( \theta \) the low cut-off time, \( \tau \) the time-delay, \( x \) the dimensionless dynamical variable of the system, \( n_o = 4 \) the number of junction diodes in series and whose characteristics are the thermal voltage \( V_o = 25 \text{ mV} \) and inverse saturation current \( i_o = 5 \text{ \mu A} \). \( \eta \) is the cubic-nonlinear coefficient. \( V_{\text{ref}}, V_{\text{adc}} \), and \( V_B \) are the radio-frequency (rf), the direct-current (dc) half-wave voltages, and the bias voltage of the Mach-Zehnder modulator, respectively. The gain of the
amplifier is $G$, the sensitivity of the photodiode $S$, and $P$ is the power of the laser diode. The values of these parameters are taken compatible with the experiment (Talla Mbé et al. 2019; Kamaha et al. 2020): $V_{\text{rf}} = 3.8 \text{ V}, V_{\text{dc}} = 5 \text{ V}, R = 2.5 \text{kΩ}, r = 300 \text{ Ω}, L = 0.1 \text{ mH}, C_1 = 270 \text{ pF}, C_2 = 9.15 \text{ nF}, S = 4.75 \text{ V/mW}$.

When using OEOs for sensings, detections, and measurements, the oscillation limit-cycle frequency plays a fundamental role since the principles are based on the variation of this frequency recorded on an oscilloscope (Chembo et al. 2019). It was demonstrated that due to the cubic-nonlinear term $u\left(\frac{\int_0^t x(t)dt}{\alpha}\right)^3$ in Eq. 1, CNOEO features limit-cycle oscillations of higher frequency $f_{\text{osc}}$ compared to the standard OEO, yielding (Talla Mbé et al. 2019; Kamaha et al. 2020):

$$f_{\text{osc}} = f_{\text{sd}} \left(1 + \frac{3\rho y_{\text{st}}^2}{\alpha}\right)^{\frac{1}{2}},$$

where $f_{\text{sd}}$ is the oscillating frequency of the standard OEO, $\rho = u\mu^3$ the cubic-nonlinear parameter, and $\alpha = \frac{t}{\delta}$ the cut-off times ratio. For a delay line of $656 \text{ m}, f_{\text{sd}} = 304.8 \text{ kHz}$. Considering the following variable $y = \int_0^t x(t)dt, y_{\text{st}}$ denotes the corresponding fixed point of our system. It is important to note that the CNOEO is identified by $\rho \neq 0$, whilst for the standard OEO, $\rho = 0$. Experimentally, $\rho$ can be turned through the gain $G$ of the amplifier [see Eq. (2)]. The next sections (Sects. 3, 4 and 5) deal with some sensings and one measurement using the CNOEO.

3 Temperature sensing using CNOEO

3.1 Circuit and principle of temperature sensing using a CNOEO

The setup for temperature sensing is given in Fig. 2. As in Zou et al. (2016), Zhu et al. (2014), the single-mode fiber (SMF) is the temperature sensor. Indeed, the SMF is

![Fig. 2 Setup of the temperature sensing using a CNOEO. SMF single-mode fiber](image)
subjected to different temperatures by heating or cooling as shown in Fig. 2. The variation of temperature consequently modifies the total time-delay $\tau$ of the CNOEO which is given by:

$$\tau = \tau_{op} + \tau_1,$$

with $\tau_{op}$ being the proper time-delay of the SMF which corresponds to the time needed by light to travel through the SMF and $\tau_1$ is the time-delay of the remaining path of the CNOEO’s loop, including both the electrical and optical paths. Noting that each time-delay $\tau_{op}$ and $\tau_1$ is related to a length $l_{op}$ and $l_1$, through the speed of the signal in the SMF and other paths of the CNOEO loop, respectively. Thus, the frequency is a function of the total length $l = l_{op} + l_1$ and the refractive index $n$, and yields (Zhu et al. 2014):

$$f = \frac{c}{2\pi nl}$$

Equation (5) gives the frequency of the signal recorded at the oscilloscope. Indeed, the frequency $f$ is a sum of the nominal value $f_{osc}$ [see Eq. (3)] and the variation $\Delta f$ due to the variation of temperature ($\Delta T$) sensed by the SMF; that is:

$$f = f_{osc} + \Delta f$$

In OEOs, the length $l$ and refractive index $n$ of the SMF are the two parameters that vary with the temperature. Differentiating Eq. (5) with respect to $n$ and $l$, and assuming that $l_{op} \gg l_1$, the variation of the frequency $\Delta f$ due to heating/cooling yields:

$$\Delta f = -f_{sd} \frac{l_{op}}{l} \left( \alpha_1 + \xi \right) \left( 1 + \frac{3\rho y'^2}{\alpha} \right)^{\frac{1}{3}} \Delta T$$

In Eq. (7), $\Delta f$ is the variation of the frequency recorded by the oscilloscope, $\Delta T$ the variation of the temperature, $\alpha_1$ the expansion coefficient, and $\xi$ the thermo-optic coefficient of the SMF (Zhu et al. 2014). $\Delta T$ also characterizes the temperature sensitivity and precision; small values of $\Delta T$ means that our system can detect a slight temperature change.

### 3.2 Results of temperature variation sensing

Figure 3 shows the variation of the temperature $\Delta T$ against the variation of the recorded frequency in the oscilloscope $\Delta f$ [see Eq. (7)]. Figure 3 presents 5 plots obtained by varying $\rho$. Each plot of Fig. 3 is a linear variation with a positive slope which decreases as the cubic-nonlinear parameter $\rho$ increases. From up to down, the curves are obtained for $\rho = 0$, $\rho = 2.0 \times 10^{-9}$, $\rho = 1.48 \times 10^{-8}$, $\rho = 4 \times 10^{-7}$, and $\rho = 1.39 \times 10^{-4}$. It can be noticed that for a given variation of the frequency recorded in the oscilloscope, the value of the change in temperature sensed by the SMF decreases with the increase of the cubic-nonlinear parameter $\rho$ (see Fig. 3). Some cases are illustrated in Table 1. For instance, for a recorded value of $\Delta f = 1050$ Hz, the standard OEO displays a variation of the temperature of $\Delta T = 229.6$ °C which is less precise compared to $\Delta T = 159.3$ °C, $\Delta T = 110.5$ °C, $\Delta T = 60.58$ °C, and $\Delta T = 22.24$ °C obtained with the CNOEO when the cubic-nonlinear parameter is increasingly monitored to the values $\rho = 2.0 \times 10^{-9}$, $\rho = 1.48 \times 10^{-8}$, $\rho = 4 \times 10^{-7}$, and $\rho = 1.39 \times 10^{-4}$, respectively. Noting that the higher precision (smaller value of $\Delta T$) is obtained with the higher value of $\rho$; that is
$\Delta T = 22.24 ^\circ C$ for $\rho = 1.39 \times 10^{-4}$. A similar example showing the decrease of $\Delta T$ when $\rho$ grows is obtained for $\Delta f = 1500$ Hz (see Table 1).

Figure 4 displays the variation of the temperature against the length ($l$). It is also the plots of 5 graphs obtained for different values of $\rho$ as that shown in Fig. 3. But, it is an inverse variation (as Eq. (7) demonstrates) which values decrease as the cubic-nonlinear parameter $\rho$ is being increased (see Fig. 4). Table 2 shows one numerical illustration.

Here, one still observes the same sensitivity of $\Delta T$ as $\rho$ increases. For example, when $l$ is equal to 1000 m, $\Delta T = 288.6 ^\circ C$ for the standard OEO ($\rho = 0$), whereas it is significantly

![Graph 3](image3.png)

**Table 1** Corresponding values of $\Delta T$ at fixed $\Delta f$ for different values of $\rho$

| Nonlinear parameter ($\rho$) | $\Delta f$ (Hz) | $\Delta T$ ($^\circ C$) | $\Delta f$ (Hz) | $\Delta T$ ($^\circ C$) |
|-----------------------------|-----------------|------------------------|-----------------|------------------------|
| $\rho = 0$                  | 1050            | 229.6                  | 1500            | 328                    |
| $\rho = 2.0 \times 10^{-9}$ | 1050            | 159.3                  | 1500            | 227.6                  |
| $\rho = 1.48 \times 10^{-8}$| 1050            | 110.5                  | 1500            | 157.8                  |
| $\rho = 4.0 \times 10^{-7}$ | 1050            | 60.58                  | 1500            | 86.54                  |
| $\rho = 1.39 \times 10^{-4}$| 1050            | 22.24                  | 1500            | 31.78                  |
reduced to $\Delta T = 76.16 \, ^\circ\text{C}$ for $\rho = 4 \times 10^{-7}$ and to $\Delta T = 27.96 \, ^\circ\text{C}$ for $\rho = 1.39 \times 10^{-4}$. Thus, this demonstrates the fact that $\rho$ increases the sensitivity of our CNOEO as a temperature sensor.

4 Refractive index sensing using a CNOEO

4.1 Circuit and principle of refractive index sensing using a CNOEO

Based on Wang et al. (2014), the proposed setup used for the refractive index sensing is shown in Fig. 5. The liquid whose refractive index $n_x$ is to determine is inserted in the glass cell of diameter $d_x$. The light from the optical delay line passes through the first free space, then the glass cell, and after, the second free space. It hits the target and is reflected again to the same path. The extra time-delay due to the liquid will cause a variation of the oscillation frequency recorded on the oscilloscope. This oscillation frequency will be used to evaluate the refractive index $n_x$. Indeed, the total time-delay $\tau$ of the signal to come to completion is the sum of the electrical time-delay ($\tau_e$) and the optical time-delay ($\tau_{opt}$) given by Pham et al. (2014):

$$\tau = \tau_e + \tau_{opt}$$  \hspace{1cm} (8)

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Table 2 Corresponding values of $\Delta T$ at fixed $l$ for different values of $\rho$

| Nonlinear parameter ($\rho$) | $l$ (m) | $\Delta T$ ($^\circ\text{C}$) |
|-----------------------------|--------|--------------------------|
| $\rho = 0$                  | 1000   | 288.6                    |
| $\rho = 2.0 \times 10^{-9}$ | 1000   | 220.3                    |
| $\rho = 1.48 \times 10^{-8}$| 1000   | 138.9                    |
| $\rho = 4 \times 10^{-7}$  | 1000   | 76.16                    |
| $\rho = 1.39 \times 10^{-4}$| 1000   | 27.96                    |

---

Fig. 5 Setup of the refractive index sensing using a CNOEO. $l_{a1}$ is the first free space distance of refractive index $n_{a1}$, $l_{a2}$ the second free space distance of refractive index $n_{a2}$, $d_x$ represents the diameter of the glass cell of refractive index $n_x$. 
Let us note the length of the free space \( l_a = l_{a1} + l_{a2} \) with the refractive index \( n_a = n_{a1} = n_{a2} \), which is the refractive index of air. The mathematical expression of \( \tau_{opt} \) is given below:

\[
\tau_{opt} = \frac{n_1 l_0}{c} + \frac{2n_a l_a}{c} + \frac{2n_x d_x}{c},
\]

where \( l_0 \) is the total length of the optical delay line in Fig. 5, \( n_1 \) its refractive index, and \( c \) the speed of light in the vacuum. In Eq. (9), 2 accounts for the round trip of light in the media of refractive indexes \( n_{a1}, n_x \), and \( n_{a2} \) (see Fig. 5). Equation (8) becomes (Nguyen et al. 2010):

\[
\tau = \tau_c + \frac{n_1 l_0}{c} + \frac{2n_a l_a}{c} + \frac{2n_x d_x}{c}
\]

Let us consider \( n_1 L_1 = n_1 l_0 + c\tau_c \). It implies that Eq. (10) becomes

\[
\tau_c = n_1 L_1 + 2n_a l_a + 2n_x d_x
\]

By definition, the oscillation frequency \( f_{osc} = \frac{k}{\tau} \), with \( k \) an integer standing for the mode number (\( k = 1 \) for the fundamental mode) (Pham et al. 2014; Nguyen et al. 2010). Thus,

\[
f_{osc} = \frac{kc}{n_1 L_1 + 2n_a l_a + 2n_x d_x}
\]

Differentiating Eq. (12), the variation of frequency is given by:

\[
\Delta f_{osc} = -\frac{2f_{osc}.FSR.d_x}{c} \Delta n_x.
\]

Equation (13) is similar to the one obtained by Nguyen et al. (2010). Here, \( FSR \) is the free spectral range which expression is given by:

\[
FSR = \frac{c}{n_1 L_1 + 2n_a l_a + 2n_x d_x} = \frac{1}{\tau}
\]

After the substitutions of \( FSR \) and Eq. (3) in Eq. (13), one obtains the mathematical expression of the variation of the refractive index given below:

\[
\Delta n_x = -\frac{n_1 l_0 + c}{f_{osc}} \left( 1 + \frac{3\rho^2 a}{\rho_a^2} \right)^{-\frac{1}{2}} + 2n_a l_a + 2n_x d_x \frac{\Delta f_{osc}}{2f_{osc}.d_x}
\]

Finally, the refractive index \( n_x \) of the liquid is computed through:

\[
n_x = n_a + \Delta n_x
\]

### 4.2 Results of refractive index variation sensing.

Figure 6 plots the variation of the refractive index against the optical length \( (l_0) \). It can be seen that the variation of the refractive index \( \Delta n_x \) reduces as one keeps on increasing \( \rho \) for a given value of optical length \( l_0 \). This variation is very small since it is in the order
of five digits showing then the high sensitivity of our system. That sensitivity is more accurate when the cubic-nonlinear parameter $\rho$ becomes more important. From up to down, the curves are obtained for $\rho = 0$ (standard OEO), $\rho = 2 \times 10^{-9}$, $\rho = 1.48 \times 10^{-8}$, and $\rho = 1.39 \times 10^{-4}$.

In Fig. 7, we also show the variation of the refractive index $\Delta n_x$ against the variation of the frequency $\Delta f_{osc}$ [see Eq. (15)]. Here also, one remarks that with higher values of the cubic-nonlinear parameter $\rho$, higher precision $\Delta n_x$ in the values of the refractive index are obtained. Moreover, $\Delta n_x$ is reduced to the order of 8 digits.
5 Distance measurement using a CNOEO

5.1 Circuit and principle of distance measurement using a CNOEO

When using an OEO for distance measurement, the distance to evaluate \( l_a \) is the length within the OEO and a target, as shown in Fig. 8 (Zou et al. 2016; Wang et al. 2014). The principle is as follows: the light from the optical delay line travels through the free space to the target. The target reflects the light to regain the optical path of the CNOEO. This induces an additional time-delay

\[
\tau_A = \frac{2n_a l_a}{c},
\]

with \( n_a \) and \( l_a \) being the refractive index of air and the distance to measure, respectively. As a result, the oscillation frequency changes and is read by the oscilloscope. The total time-delay \( \tau \) of the system of Fig. 8 is the sum of the reference time-delay (\( \tau_R \)) and the additional time-delay (\( \tau_A \)) given by Wang et al. (2014):

\[
\tau = \tau_R + \tau_A
\]

where

\[
\tau_R = \frac{1}{f_R}
\]

with \( f_R \) representing the reference frequency. Substituting Eq. (16) and (18) in Eq. (17) gives Wang et al. (2014):

\[
\tau = \frac{2n_a l_a}{c} + \frac{1}{f_R}
\]

From Eq. (19) and applying \( \tau = \frac{1}{f_{osc}} \), \( l_a \) is given as follows:

\[
l_a = \frac{c}{2n_a} \left( \frac{1}{f_{osc}} - \frac{1}{f_R} \right)
\]

![Fig. 8 Setup of the distance measurement using CNOEO. \( l_a \) is the distance to determine](image-url)
where $f_{osc}$ is the fundamental frequency of the CNOEO which is determined by the total group delay of the loop $\tau$ read from the oscilloscope [see Eq. (3)]. Any N-th frequency mode is harmonic of that fundamental frequency and given by $f_N = Nf_{osc}$. Thus $l_a$ yields:

$$
\frac{\Delta l_a}{l_a} = \left| \left( \frac{2n_a l_a + c \tau_R}{n_a l_a} \right) \left| \frac{\Delta f_N}{f_N} \right| \right|
$$

(22)

Equation (22) is similar to the one obtained by Wang et al. (2014) but with different expression of $f_N = Nf_{osc}$ [see Eq. (3)].

### 5.2 Results of distance measurement

Figure 9 displays the precision of the distance measured in terms of the variation of the frequency. It can be observed that highly nonlinear CNOEO contributes to obtaining the distance measured with higher precision. That is the standard OEO displays a distance measurement with a large error from the nominal value as $\Delta l_a$ is great. However, a CNOEO featuring an important value of the cubic-nonlinear parameter $\rho$ will rather display a distance measured which value is closer to the nominal one as the precision $\Delta l_a$ is smaller (see Fig. 9). For instance, for a variation in frequency $\Delta f_N = 0.04$ Hz, the standard OEO ($\rho = 0$) gives a precision of $\Delta l_a = 3 \times 10^{-10}$ m while using a CNOEO with cubic-nonlinear parameter $\rho = 1.39 \times 10^{-4}$, the precision drops considerably to $\Delta l_a = 2.12 \times 10^{-13}$ m. That is a spanning of about three orders of magnitude.

![Figure 9](image-url)
6 Conclusion

In this work, we have carried out a comparative study of temperature sensing, refractive index sensing, and distance measurement using both the standard and the cubic-nonlinear optoelectronic oscillators. For each of these sensings and the measurement, we have proposed an appropriate setup as well as the analytical expression of the sensing/measurement quantity. It globally comes out that the cubic-nonlinear optoelectronic oscillator (CNOEO) is more sensitive; that is higher precisions in the sensings and the measurement are achieved with the CNOEO than using the standard optoelectronic oscillator. Such precisions become sharper as the values of the cubic-nonlinear parameter become larger. With the CNOEO, results that span several orders of magnitude have been recorded compared to those with the standard OEO. Further investigations will focus on using other novel architectures of OEO (Chengui et al. (2016), Chengui et al. 2018, Kouayep et al. (2020), Nguewou-Hyousse and Chembo (2020)) for other metrological quantities such as strain, load, angular velocity, and more.

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