Chapter 8

Widely Tunable Quantum-Dot Source Around 3 μm

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Abstract

We propose a widely tunable parametric source in the 3 μm range, based on intracavity spontaneous parametric down conversion (SPDC) of a quantum-dot (QD) laser emitting at 1.55 μm into signal and idler modes around 3.11 μm. To compensate for material dispersion, we engineer the laser structure to emit in a higher-order transverse mode of the waveguide. The width of the latter is used as a degree of freedom to reach phase matching in narrow, deeply etched ridges, where the in-plane confinement of the QDs avoids non-radiative sidewall electron-hole recombination. Since this design depends critically on the knowledge of the refractive index of $In_{1-x}Ga_xAs_yP_{1-y}$ lattice matched to InP at wavelengths where no data are available in the literature, we have accurately determined them as a function of wavelength (λ = 1.55, 2.12 and 3 μm) and arsenic molar fraction (y = 0.55, 0.7 and 0.72) with a precision of $\pm 4 \times 10^{-3}$. A pair of dichroic dielectric mirrors on the wave-guide facets is shown to result in a continuous-wave optical parametric oscillator (OPO), with a threshold around 60 mW. Emission is tunable over hundreds of nanometers and expected to achieve mW levels.

Keywords: quantum dots, laser diode, near infrared, InGaAsP, tunable source, OPO

1. Introduction

The tunability of currently available integrated sources is limited to a few tens of nanometers at most, via temperature or current control. While this is not a problem for most applications, certain fields like wavelength division multiplexing and spectroscopy are in demand of sources with broader tunability and choice of spectral range. Spectroscopy, especially, requires wide-band, continuously tunable sources with narrow emission lines. The 2–4 μm wavelength interval is of particular interest since it contains various peaks of atmospheric and hydrocarbon molecules, with important applications in environmental monitoring, security, and medicine [1–4]. This spectral region is at the frontier between the emission ranges of diodes and quantum cascade lasers (QCLs), and to date most existing sources around 3 μm, such as short-wavelength QCLs [5, 6] or GaSb diodes [7], are only available in laboratories. Interband cascade lasers (ICLs) are the only sources commercially available in this wavelength range, albeit at a high price [8–10]. Moreover, the tunability range of all these devices is limited to a few tens of nanometers. As a consequence, individual laser diodes are used for each spectroscopic line of absorption, which increases the price of a complete diagnosis based on several lines. In this context, nonlinear optics offers a solution for widely wavelength tunable sources, bulky tabletop optical parametric oscillators (OPOs) being commonly used to provide high-quality, tunable beams. Most miniaturized OPOs have been demonstrated in $LiNbO_3$ [11, 12], but an OPO threshold has been achieved in a GaAs micrometric waveguide [13] with a potential span of 500 nm. Like GaAs, InP is an attractive material for its high $\chi^{(2)}$ and mature technology, especially for emission at 1.55 μm.

Here we report on the design of an InGaAsP/InP QD laser diode emitting at 1.55 μm, optimized for intracavity spontaneous parametric down conversion (SPDC) around 3.11 μm via modal phase matching. The use of QDs is justified by the choice of narrow, deeply etched structures insofar they have been shown to trap carriers and limit surface recombination [14], and narrow-ridge, low-threshold InAs/InP QD lasers have already been demonstrated [15]. In order to estimate the phase mismatch accurately, a precise knowledge of the refractive indices is critical at pump, signal, and idler wavelengths. While the index of InGaAsP lattice matched to InP is well known at 1.55 μm [16–20], to date only one publication deals with its measurement at longer wavelengths [21], and none exists at 3 μm. This makes it crucial to accurately characterize its refractive index up to 3.14 μm, outside of the scope covered by literature data.

2. Tunable source design

2.1. Laser diode design

We propose a 1.55 μm source optimized for SPDC around 3.11 μm. This design results from back-and-forth optimizations between optical and electrical simulations, to jointly facilitate electron-hole injection, increase the conversion efficiency, and reduce losses. The conduction band and composition profile of this structure are shown in **Figure 1**. To compensate for the material dispersion, the laser diode is conceived so as to favor lasing on the TE_{20} mode (the second order in the direction of growth). To achieve this, the refractive index kept small in the center of the waveguide. As a consequence, the TE_{20} mode confinement inside the active area is stronger than for the TE_{00} mode. **Figure 2** shows the modes TE_{00} and TE_{20} supported by the waveguide at a wavelength of 1.55 μm. In order to achieve an efficient electron injection despite the conduction band increase in the core center, we reduce the series resistance with two strategies. Firstly, we introduce compositional gradients at the interfaces. Secondly, the waveguide core is only lightly doped. **Figure 3** depicts the conduction band and doping profile of the structure. An electrical simulation of this device using the software Nextnano yields a transparency current of 26 A/cm^2 at the transparency threshold.

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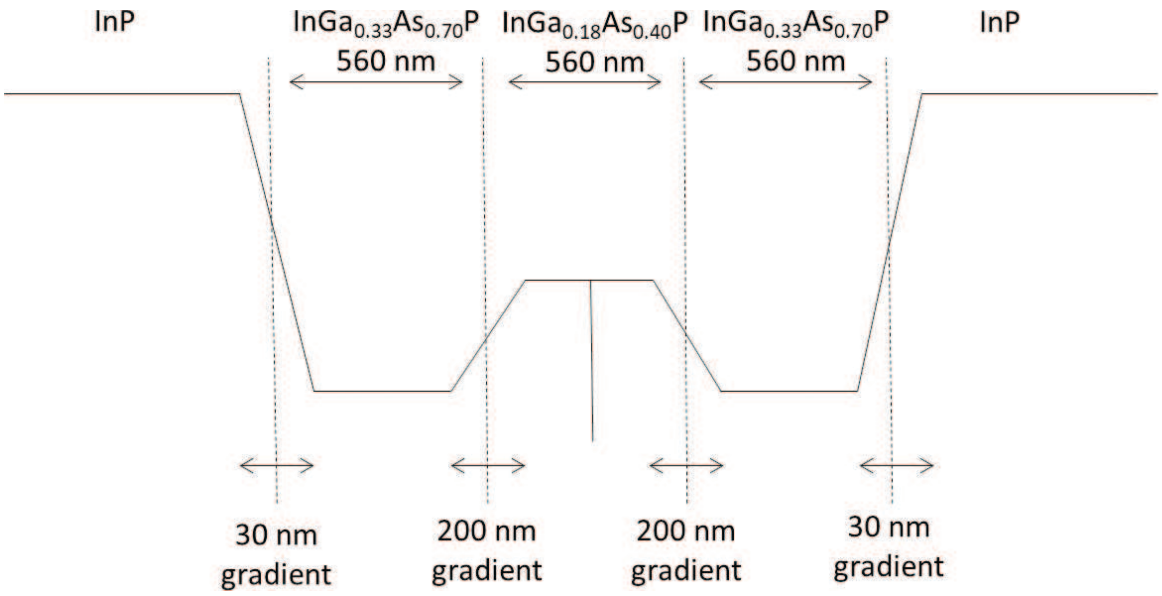

Figure 1. Conduction band and composition profile of the structure.

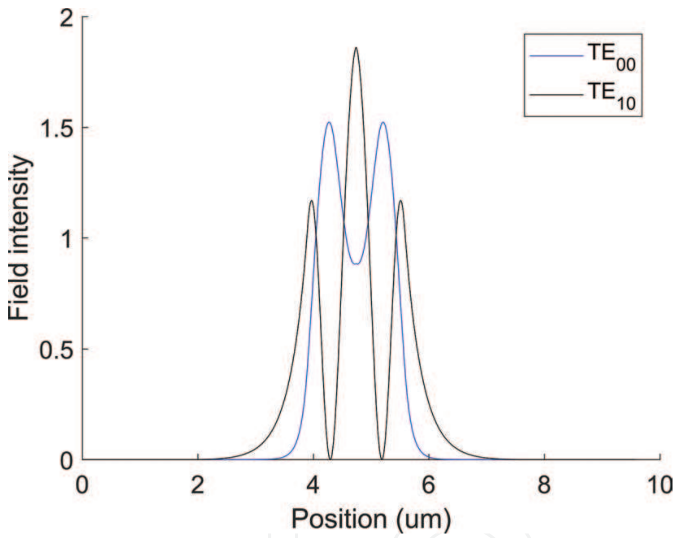

Figure 2. The first two even modes supported by the waveguide at $\lambda = 1.55$ µm.

2.2. Nonlinear properties

To achieve Type-II phase matching despite the error bars on the dispersion model and the fabrication tolerances, we use the ridge width as a crucial degree of freedom. **Figure 4** shows the phase mismatch at degeneracy vs. ridge width and pump wavelength, defined as

$$\Delta n = n\,(TE_{20}, 1.55\ \mu m) - \left[n\,(TE_{00}, 3.11\ \mu m) + n\,(TM_{00}, 3.11\ \mu m)\right]/2 \qquad (1)$$

where the refractive indices are provided by our experimental data, presented in Part 2, and an interpolation of literature data [20]. By changing the ridge width from 3 to 7 µm, we are able to achieve phase matching for pump wavelengths of 1.50–1.60 µm. Furthermore, a variation in phase mismatch of ±0.02 can be compensated for by setting the correct ridge size. The ridge width thus acts as a gross parameter to meet the phase-matching condition, which can be set after wafers have been grown and characterized.

During operation, temperature provides a supplementary degree of freedom to tune the pump wavelength and reach a wide range of frequencies. **Figure 5** shows the wavelengths

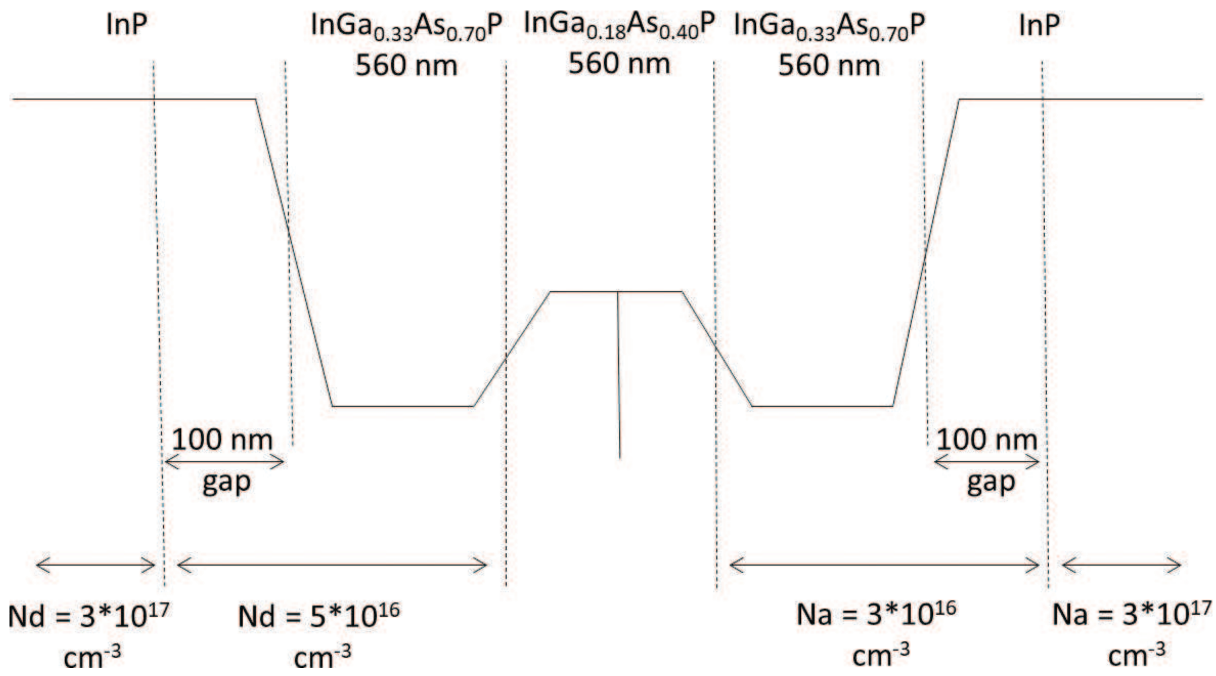

Figure 3. Conduction band and doping profile of the structure.

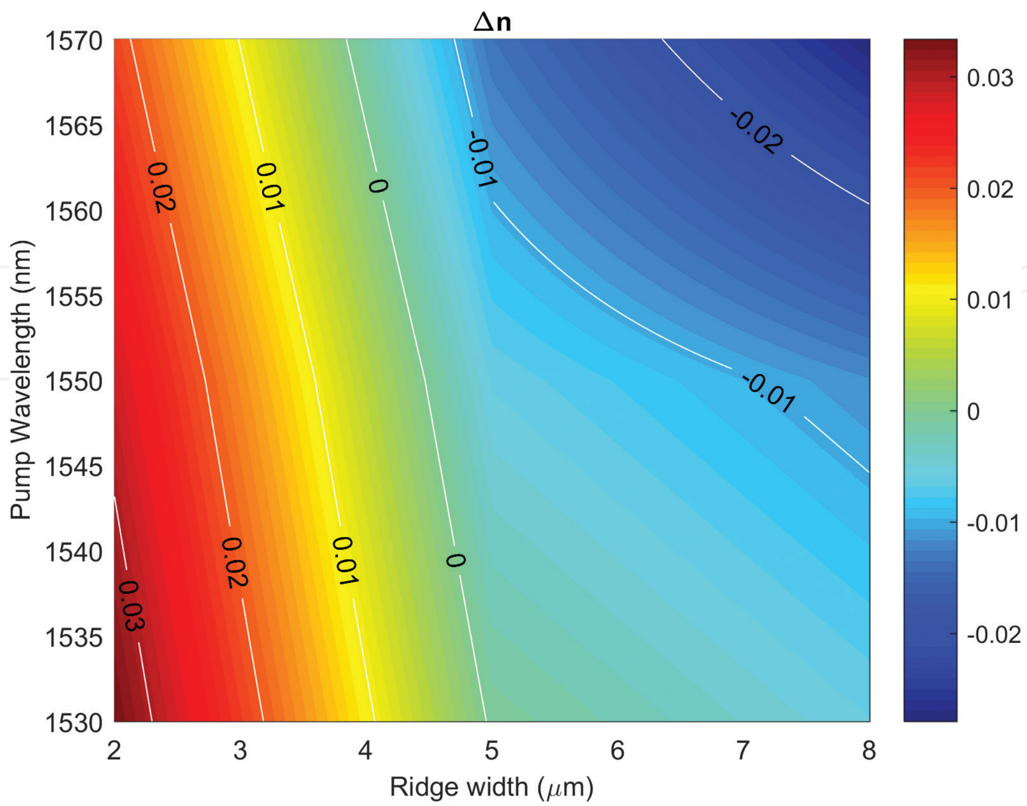

Figure 4. Phase mismatch in a deeply etched structure vs. ridge width and pump wavelength.

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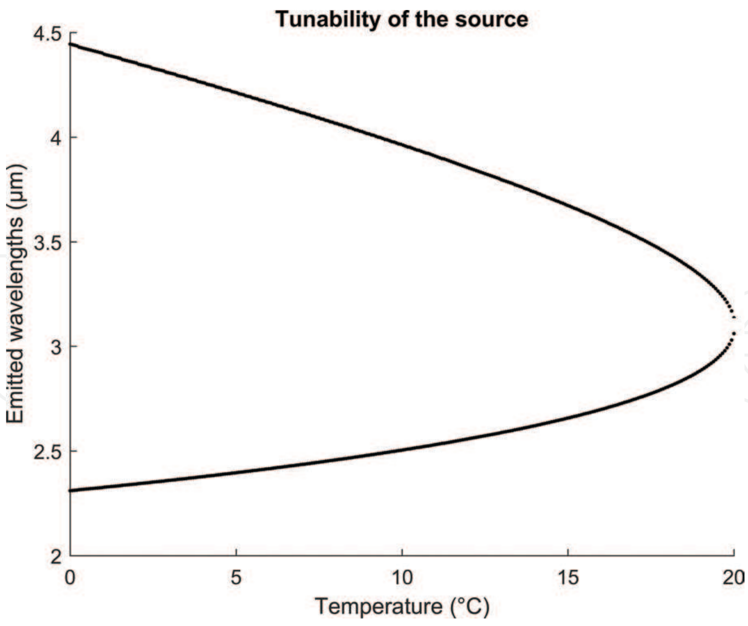

Figure 5. Emitted wavelengths for a device of ridge width 3.3 µm, emitting at 1.55 µm at 20°C.

of signal and idler emitted beams, for a source of ridge width 3.3 µm, emitting at a pump wavelength of 1.55 µm at 20°C. The dependency of quantum dots wavelength emission with temperature was assumed to be 0.5 nm/K from [22].

Figure 6 shows the profiles of the interacting modes, at a pump wavelength of 1.55 µm and signal and idler 3.11 µm. The expected conversion efficiency at a pump wavelength of 1.55 µm is 240% W^{-1} cm^{-2}. For an intracavity power of 100 mW, this corresponds to a parametric gain of 0.5 cm^{-1}. Since common InP QD lasers at 1.55 µm emit up to 20 mW outside the cavity without facet coatings [23], the above hypothesis on the intracavity power is very reasonable. The losses experimented by the mode at 3.11 µm are mainly expected to stem from free-carrier

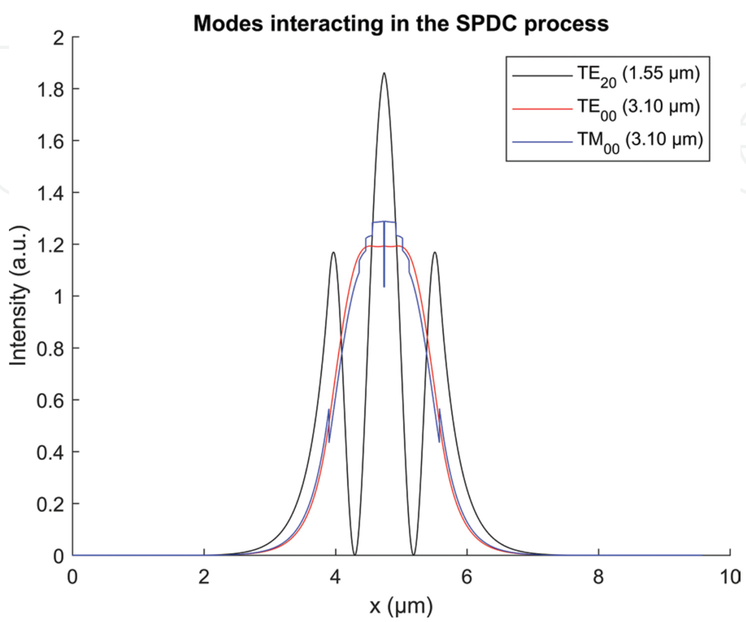

Figure 6. Field intensity of the three interacting modes in the SPDC process, at a pump wavelength of 1.55 µm.

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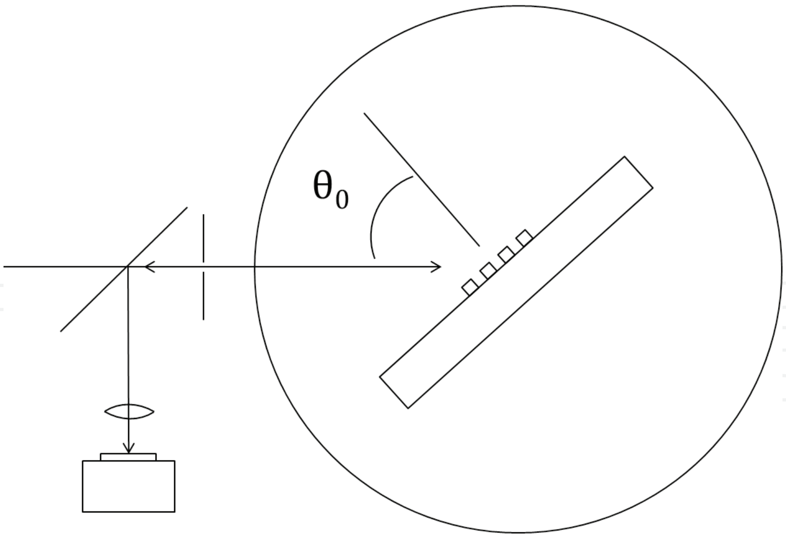

Figure 11. Optical setup for measuring the grating period.

3.4. Results

A typical result of coupling measurement is shown in **Figure 12**. The position of the peaks is determined with a precision of 0.01°. Since the effective indices are a function of material index and thickness of the guiding layer, each measured value corresponds to a range of possible {material index, thickness} pairs. This is represented in **Figure 13**, where one line corresponds to the space of parameters that minimize the difference between measured and theoretical indexes. Since more than one effective index is measured, it is possible to determine the right pair {material index, thickness}, at the crossing point. **Figure 14** shows the average difference between measured and effective indices. Waveguides support three modes at 1.55 μm, two at

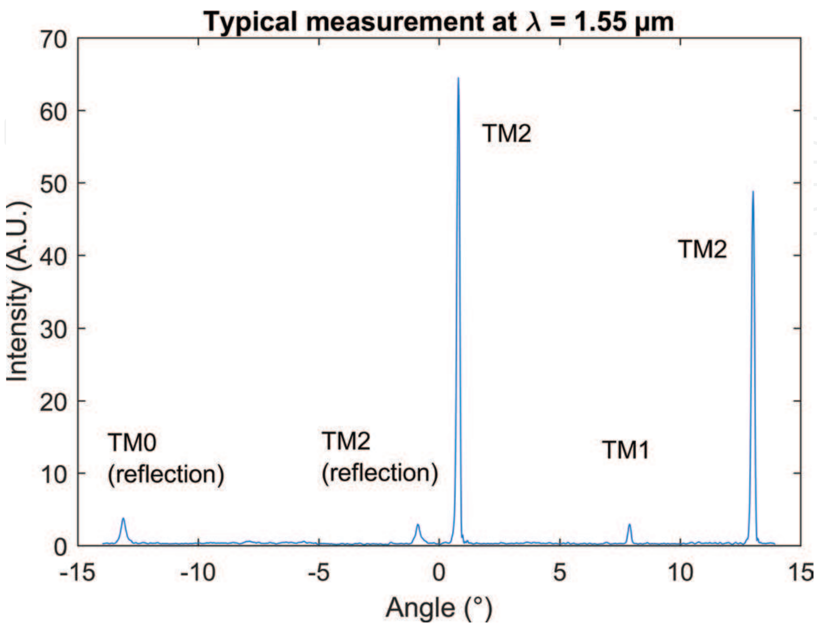

Figure 12. Determination of the refractive index and thickness for a slab of $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ at λ = 1.55 μm. Each line shows the possible range of data corresponding to the measured value of the effective index of a given waveguide mode.

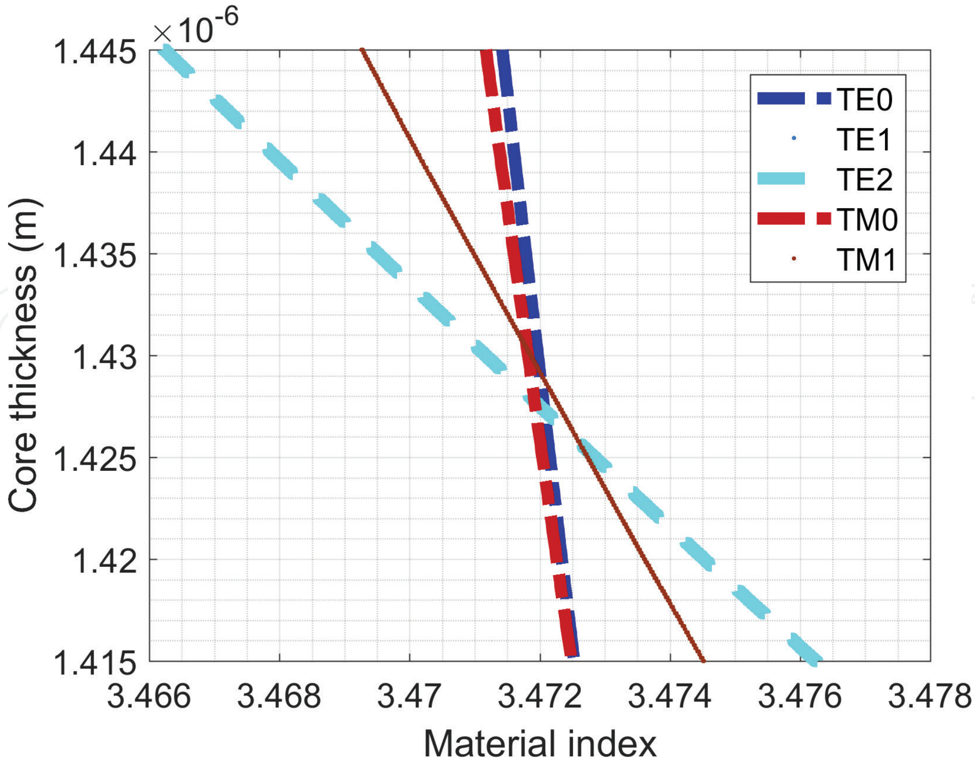

Figure 13. Coupling measurement into a slab of $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ on InP at a wavelength of 1.55 μm.

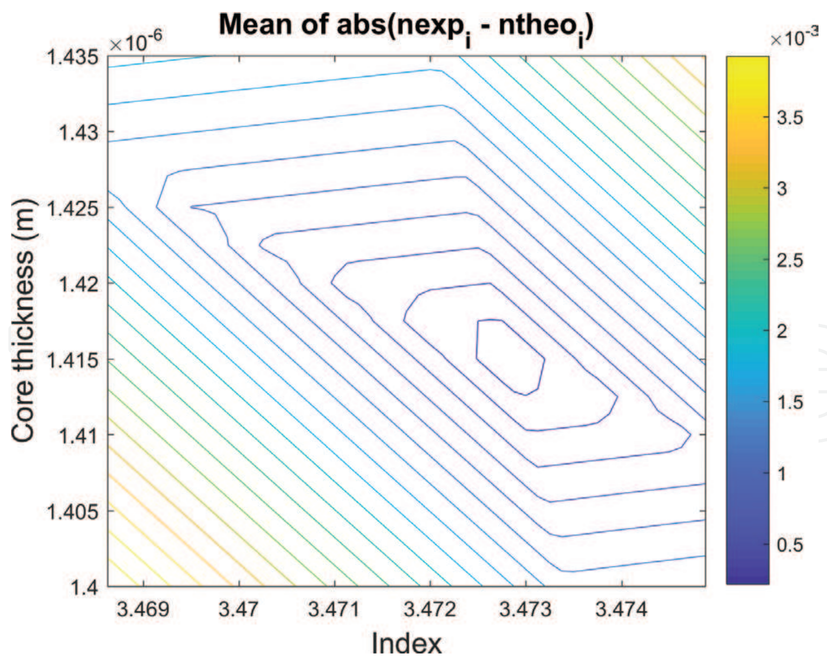

Figure 14. Determination of the refractive index and core thickness for a slab of $In_{0.67}Ga_{0.33}As_{0.72}P_{0.28}$ on InP at a wavelength of 1.55 μm. This figure shows the mean difference between calculated and measured effective indices. Area width gives an estimation of the error.

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2.12 μm, and one at 3.14 μm. In order to derive the effective index at 3 μm, the guide thicknesses were estimated from the data at 1.55 μm (**Table 1**).

Figures 15–17 show the measured refractive indices as a function of As fraction, at wavelengths of 1.55, 2.12, and 3.14 μm. The data at 1.55 μm was compared to the model presented in [20]. At 2.12 and 3.14 μm, no model being available in the literature, we trace the data against a linear regression versus the molar fraction of As(y). The refractive index of InP from [24] was taken into account. **Figure 18** shows the refractive index versus wavelength, against a one-oscillator fit calculated from the Afromowitz model [25]. The fit parameters are presented in **Table 2**.

#	PL peak (μm)	da/a0	xGa	yAs	N (λ = 1.55 μm)	N (λ = 2.1 μm)	N (λ = 3.11 μm)
1	1.395	−0.0025	0.33	0.72	3.470		3.348
2	1.395	+0.002	0.33	0.72	3.472		3.349
3	1.395	n.m.	0.33	0.72		3.384	
4	1.346	n.m.	0.35	0.70	3.445		3.333
5	1.346	−0.0017	0.35	0.70	3.444		3.330
6	1.346	n.m.	0.35	0.70		3.370	
7	1.266	n.m.	0.24	0.55	3.391		3.289
8	1.266	+0.00078	0.24	0.55		3.325	

The lattice mismatch was measured by X-ray diffraction. Ga and As fraction are deduced through the model presented in [26].

Table 1. Physical properties and measured indices of the studied samples.

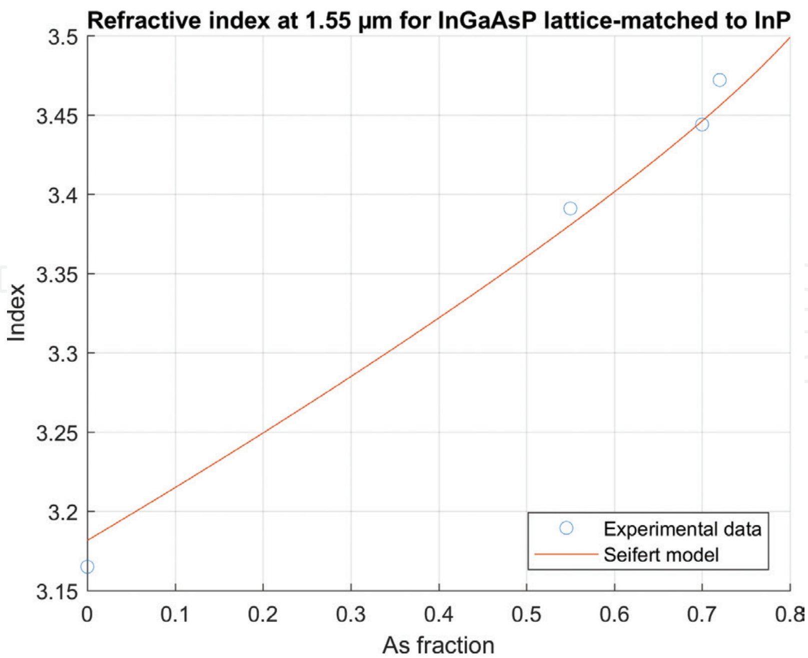

Figure 15. Refractive index measured at 1.55 μm vs. y, compared to [20].

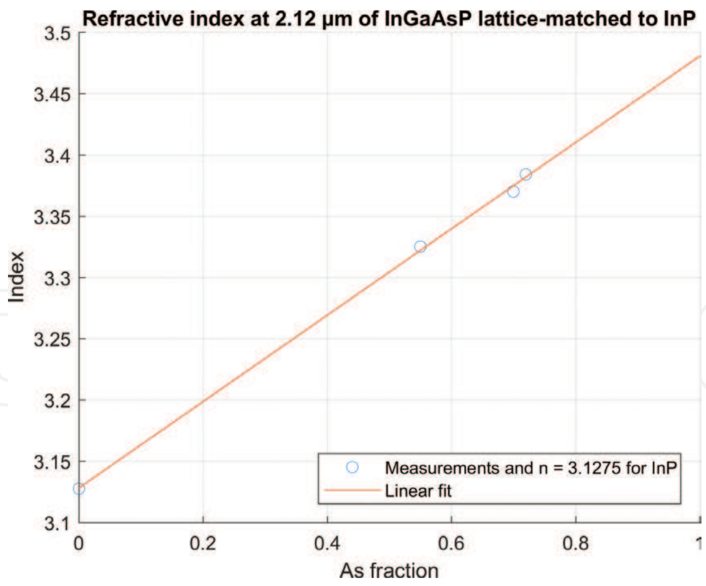

Figure 16. Refractive index measured at 2.12 μm vs. y (data plotted against a linear fit).

3.5. Discussion

The accuracy of this measurement is determined by several factors.

- Values of the grating period were determined by repeated measurements with a precision of 0.1 nm. This leads to a 0.3×10^{-3} error bar on the effective index.
- The uncertainty due to sample misalignment can be estimated at 0.5×10^{-3}. This may be explained by local variations of the resist filling factor and depth.
- In order to estimate the impact of the thin layer of photoresist on the effective indices, we performed a set of measurements on a sample covered with a thin photoresist grating. Then we etched it shallowly, removed the resist, and took a new set of data. The estimated thickness diminishes by 11 nm. This is in agreement with a profilometry of the etched grating depth, yielding 15 nm. The estimated core index is raised by 0.7×10^{-3}, a value lower than the possible variation of twice the experimental error. Thus we conclude that the resist has a negligible impact on the effective indices.
- While the laser beam alignment and position of the sample with respect to the rotating stage are adjusted in each measurement, one could point out that the axis of the rotating motor could be slightly misaligned with respect to the vertical axis and introduce a systematic error. A simple observation of the height of the beam reflection as the motor rotates indicates that the angle could be at most of 0.5 mrad. This leads, after a calculation, to an error on the effective index of 3×10^{-5}.
- Finally, incertitude on the composition is the most important. It is determined by the photoluminescence and lattice mismatch of the samples, with a precision of ~1%, through the model described in [26]. This corresponds to an uncertainty on the effective index of 4×10^{-3}. The deviation of our measurements with respect to literature and to a linear fit is in the range of 10^{-2} to 2×10^{-2}. This is in agreement with the observed variations of index due to the lattice mismatch observed in [16].

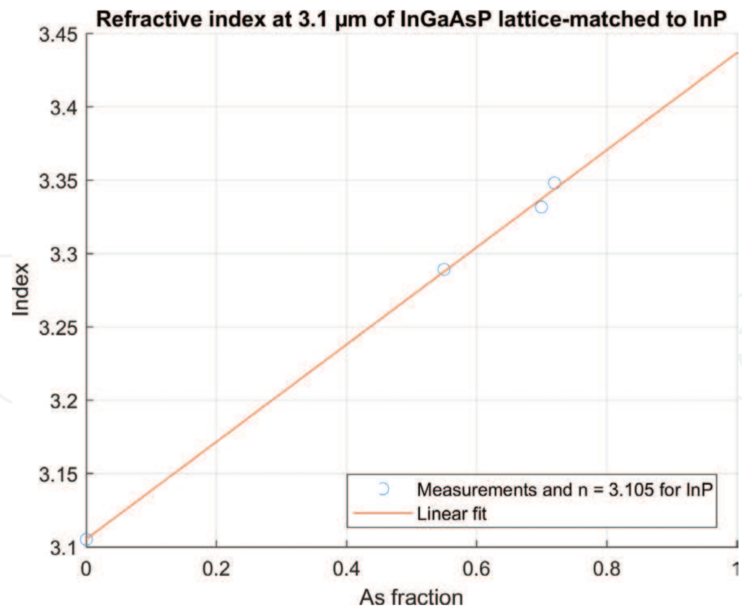

Figure 17. Refractive index measured at 3.14 μm vs. y (data plotted against a linear fit).

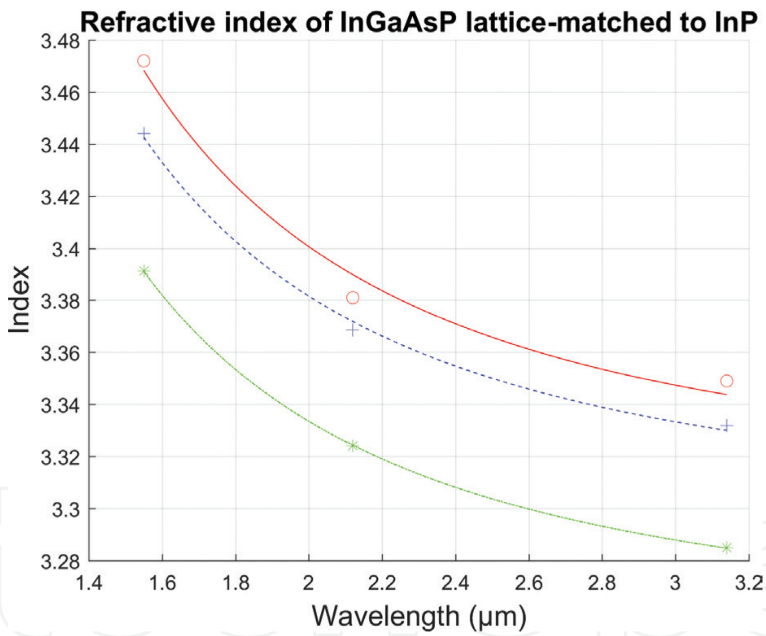

Figure 18. Refractive index of InGaAsP lattice matched to InP vs. wavelength for y = 0.72, 0.70, and 0.55. A one-oscillator fit (Afromowitz model) is added.

yAs	a	b
0.72	−0.0156	0.1007
0.70	−0.0144	0.1014
0.55	−0.0143	0.1044

Table 2. Parameters of the Afromowitz model inferred from the index measurements: a and b are extracted by a linear regression from $(n^2–1)^{-1} = a\,E^2 + b$, where E is the wavelength energy in eV.

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