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Demonstration of optical nonlinearity in InGaAsP/InP passive waveguides

Shayan Saeidi[a], Payman Rasekh[a,1], Kashif M. Awan[a,1], Alperen Tüğen[b], Mikko J. Huttunen[c], Ksenia Dolgaleva[a,d,*]

[a] *School of Electrical Engineering and Computer Science, University of Ottawa, Advanced Research Complex, 25 Templeton St., Ottawa, Ontario, K1N 6N5, Canada*
[b] *Electrical and Electronics Engineering Department, Middle East Technical University, 06800, Ankara, Turkey*
[c] *Laboratory of Photonics, Tampere University of Technology, FI-33100, Tampere, Finland*
[d] *Department of Physics, University of Ottawa, Advanced Research Complex, 25 Templeton St., Ottawa, Ontario, K1N 6N5, Canada*

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ABSTRACT

We report on the study of the third-order nonlinear optical interactions in $In_xGa_{1-x}As_yP_{1-y}$/InP strip-loaded waveguides. The material composition and waveguide structures were optimized for enhanced nonlinear optical interactions. We performed self-phase modulation, four-wave mixing and nonlinear absorption measurements at the pump wavelength 1568 nm in our waveguides. The nonlinear phase shift of up to 2.5π has been observed in self-phase modulation experiments. The measured value of the two-photon absorption coefficient α_2 was 19 cm/GW. The four-wave mixing conversion range, representing the wavelength difference between maximally separated signal and idler spectral components, was observed to be 45 nm. Our results indicate that InGaAsP has a high potential as a material platform for nonlinear photonic devices, provided that the operation wavelength range outside the two-photon absorption window is selected.

1. Introduction

There has been much research effort directed towards the realization of nonlinear integrated optical devices because of their potential in all-optical signal processing [1–5]. Among different materials that have been studied for this purpose [6–10], III-V semiconductors stand out as a viable choice for passive nonlinear optical devices for two main reasons. First and most important, both active and passive integrated optical devices can potentially be combined essentially on the same material platform. This is achievable through a careful design and advanced fabrication methods, such as multilayer epitaxy and vertical tapering [11,12]. Second, III-V semiconductors can exhibit strong optical nonlinearities accompanied by minimal nonlinear absorption achievable through a proper selection of the material composition and operation wavelength [13–15].

So far, studies of nonlinear photonic devices based on III-V semiconductors have been centered around gallium arsenide (GaAs) and related compounds such as aluminium gallium arsenide (AlGaAs) [13,14,16]. The range of bandgap energies associated with various material compositions of $Al_xGa_{1-x}As$ permits the use of this compound for passive nonlinear optical devices operating at the communication C-band around 1550 nm. We recently showed that there exist other interesting representatives of the group III-V that can potentially satisfy the need for nonlinear optical devices at other wavelengths [17,18]. A variety of ternary and quaternary III-V compounds with different bandgap wavelengths can form a group of nonlinear photonic materials capable of covering the entire spectral window from ultraviolet to infrared. The present study is focused on the experimental demonstration of the nonlinear optical performance of indium gallium arsenide phosphide ($In_xGa_{1-x}As_yP_{1-y}$) integrated optical waveguides on indium phosphide (InP) substrate (we refer to them as InGaAsP/InP for conciseness).

In order to maximize the occurring nonlinear optical interactions, one needs to minimize the linear and nonlinear propagation losses in waveguides. When semiconductor waveguides are transparent to the selected operation wavelength, the linear propagation loss is mostly due to scattering off from imperfections, such as epitaxial defects and waveguide surface roughness. This loss can be minimized by improving the fabrication, and can be achieved, for example, through the reduction of growth defects and plasma-induced etch roughness [19]. The dominant nonlinear loss mechanism is two-photon absorption (TPA) which can strongly contribute to the overall loss of the integrated

* Corresponding author. School of Electrical Engineering and Computer Science, University of Ottawa, Advanced Research Complex, 25 Templeton St., Ottawa, Ontario, K1N 6N5, Canada.

E-mail address: ksenia.dolgaleva@uottawa.ca (K. Dolgaleva).

[1] The authors 2 and 3 have made equal contributions to this work.

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optical device and, hence, influence the nonlinear optical performance of the device [13,20]. In general, given a specific wavelength range of interest, it is desirable to work with the semiconductor material with the bandgap wavelength less than half of the operational wavelength. This translates into the requirement for the bandgap energy to be more than twice the photon energy, in order to minimize TPA [21,22]. For InGaAsP, the TPA cannot be entirely eliminated at the telecom wavelengths because the bandgap energies of the entire range of InGaAsP compositions are near the operational photon energy at 1550 nm (which corresponds to 0.8 eV). TPA coefficient of InGaAsP multi-quantum-well waveguides has been reported to be ~ 60 cm/GW at 1.55 μm [23], which is a relatively large value. On the other hand, InGaAsP is a well established material platform for semiconductor lasers [24,25]. This motivates one to consider the possibility of combining InGaAsP passive nonlinear optical waveguides on the same chip with InGaAsP laser sources with the potential of extending the operation ranges of the latter to longer wavelengths.

In this study, we demonstrate the potential of InGaAsP/InP waveguides for nonlinear photonic devices on-a-chip. The optimal operation wavelength range for InGaAsP passive nonlinear optical devices is at 2 μm and at longer wavelengths, as dictated by the range of its band-gap energies for various compositions that are still lattice-matched to InP substrate [18]. However, the experimental studies reported in the present work have been performed in the wavelength range between 1540 and 1590 nm. This range was chosen because some InP-based laser sources operate in this wavelength range [24,25], and it is thus both interesting and important to study nonlinear optical performance of our InGaAsP/InP devices at these wavelengths.

Our InGaAsP/InP strip-loaded waveguides were designed specifically in a way to maximize optical nonlinearity while keeping the propagation loss relatively low [18]. On the other hand, a waveguide structure fully optimized for efficient nonlinear optical interactions would require dispersion management [26,27] (see Ref. [18] for the corresponding designs in InGaAsP). Such dispersion-managed III-V semiconductor waveguides, frequently termed "nanowires" due to their superior compactness, require deep etching which makes fabrication of such structures a more challenging task.

In the present study, we focus on the "lower-risk" structures, the shallow-etch InGaAsP/InP strip-loaded waveguides with the material composition and geometry optimized for a minimization of the effective mode area of the fundamental TE and TM modes. The goal of this design is to minimize the sensitivity of the guided modes to the fabrication imperfections while still achieving a higher efficiency of the nonlinear optical interactions, despite the presence of full material dispersion.

Here, we report on the measurement of TPA coefficient and on the observation of self-phase modulation (SPM) and four-wave mixing (FWM) in such waveguides. The most similar waveguide structures studied to date were InGaAsP multi-quantum-well rib waveguides demonstrating the nonlinear phase shift of up to $\sim 2.5\pi$ acquired through SPM at the coupled-in peak power of 3.8 W [23]. This value compares well with the nonlinear phase shift of π reported in silicon waveguides at 60 W coupled-in peak power [28], which demonstrates the higher potential of such devices for nonlinear optical interactions compared to that of silicon waveguides. InGaAsP/InP waveguides in the present study differ from the devices reported in Ref. [23] by the geometry and by the fact that no quantum-well intermixing was performed.

2. Waveguide design and fabrication

The design of our InGaAsP/InP waveguides has been performed with the use of Lumerical Mode Solutions [see Fig. 1 (b) for an example of a mode pattern]. The detailed description of the design process is provided in Ref. [18]. The key aspects of this design were ensuring a single-fundamental-mode operation, and the minimization of the effective mode area through a proper selection of the material composition and waveguide dimensions. In Fig. 1 (a), we show the structure of the designed waveguide. This waveguide has relatively large dimensions compared to those of more compact "deeply etched waveguides" [18]. It also requires a relatively shallow etch depth, and it is known in reports as a *strip-loaded waveguide* [13]. The fundamental modes in such waveguides are well confined within the guiding layer [see Fig. 1 (b)]. Therefore, the optical field does not "see" much of the fabrication imperfections, and the propagation loss is thus relatively low. The composition of the guiding layer was selected to be $In_{0.63}Ga_{0.37}As_{0.8}P_{0.2}$ with the corresponding refractive index of 3.58 at 1550 nm [29]. The refractive index of InP claddings was 3.17 [30], resulting in the index contrast of 0.41 at 1550 nm between the core and claddings. The minimal effective mode area achievable with our design was around 1.7 μm^2 at 1550 nm for a 1.7-μm-wide waveguide. The designed waveguide can potentially operate at a broad range of wavelengths spanning from the telecom C-band to around 3 μm [18].

We fabricated the waveguides using standard lithographic and etching procedures. First, the wafer was commercially grown through metalorganic chemical vapor deposition. Our target etching depth was 0.9 μm. Initial trials with electron beam resists showed that InP etching selectivity is low compared to that of the electron beam resists, hence, a hard mask was required. The wafer was first coated with 300 nm of silica using plasma-enhanced chemical vapor deposition. A 40-nm-thick layer of chromium was deposited on top of the silica layer by electron beam evaporation. The patterning of the coated wafer with waveguides was performed with a 100-kV Jeol 9500 electron beam lithography system. We used hydrogen silsesquioxane (HSQ) as the electron beam resist. Following the simulation results, we chose the waveguide width to be around 1.7 μm. Waveguide patterns were produced with the widths ranging from 1.1 to 2.1 μm, with a step size of 0.1 μm, in order to ensure that there is at least one width that corresponds to the design. In addition, operating with a range of waveguide widths can help one to experimentally verify that 1.7-μm-wide waveguide has, indeed, the best experimental performance. After patterning and developing the resist, we used the HSQ mask to transfer the pattern into the chromium layer by inductively-coupled plasma reactive-ion etching.

Next, the etching of the silica layer was performed, and the waveguide pattern was transferred into the silica. Finally, the silica mask was used to transfer the waveguide pattern to InP layer. Etching InP/InGaAsP was performed using a gas mixture of CH_4, H_2 and Cl_2 at respective 4, 7 and 8 sccm (standard cubic centimeter per minute). The inductively coupled plasma source power was set to 2000 W, and the reactive-ion etching was performed at 65 W with a pressure of 4 mT for 82 s. The sample was then cleaved on both sides; the resulting waveguides were 8 mm long. The scanning electron microscope (SEM) image of the fabricated waveguide cross-section is shown in Fig. 1 (c).

It must be noted here that InP etching is very challenging due to its temperature dependency. For this work, we did not have access to an etching system that supports wafer heating. To overcome this hurdle, we developed a plasma-heated etching process, where the wafer is heated by the plasma itself. This is not well-controlled and stable, hence, roughness is visible on the etched surface.

3. Optical characterization

3.1. Loss measurement

The first step in assessing the performance of an integrated optical device is the propagation loss measurement. The overall (total) loss that includes all possible loss contributions, L_t, can be obtained by taking a ratio between the measured optical power at the output and at the input to the waveguide. The overall loss value was measured to be around 18 dB. This value is comprised of the propagation loss L_{prop}, the coupling loss due to the mode size and shape mismatch between the free-space focused laser beam and waveguide mode L_{coupl}, and the Fresnel reflection loss L_{ref}: