Second Harmonic Generation Induced by Longitudinal Components in Indium Gallium Phosphide Nanowaveguides

Nicolas Poulvellarie,1,2,∗ Utsav Dave,3 Koen Alexander,2 Charles Ciret,4 Fabrice Rainieri,3 Sylvain Combrès,6 Alfredo De Rossi,6 Gunther Roelkens,2 Simon-Pierre Gorza,1, Bart Kuyken,2 and François Leo4

1 OPERA-Photonique, Université libre de Bruxelles, Brussels, Belgium
2 Photonics Research Group, Ghent University-IMEC, Ghent, Belgium
3 Department of Electrical Engineering, Columbia University, New York, USA
4 Laboratoire de Photonique d’Angers EA 4404, Université d’Angers, Angers, France
5 Laboratoire de Photonique et de Nanostructures, CNRS-UPR20, Marcoussis, France
6 Thales Research and Technology, Palaiseau, France
∗ Email: Nicolas.Poulvellarie@ulb.ac.be

Abstract: We experimentally demonstrate second harmonic generation in Indium Gallium Phosphide waveguides by mixing transverse and longitudinal components of the optical fields. We confirm the excitation of an antisymmetric second harmonic mode through modal imaging.

OCIS codes: (130.3120) Integrated optics devices; (190.4223) Nonlinear wave mixing

1. Introduction

Integrated photonic circuits are revolutionizing nonlinear optics as they allow for strong confinement in materials with elevated nonlinear indices. While third order nonlinear interaction have been the most studied by far, novel integrated platforms such as lithium niobate [1] or III-V semiconductors on-insulator [2] are renewing interest in second-order nonlinear processes such as second harmonic generation. III-V semiconductors promise record conversion efficiencies as they are characterized by very large second-order nonlinear coefficients (one order of magnitude larger than LiNbO3). However, only a single independent tensor element is nonzero (χ(2)xyz and permutations). Previous demonstrations of second harmonic generation used waveguides that are rotated by 45° with respect to the crystallographic axes in order to split the main transverse component along two directions [2, 3]. Conversely, we show here that the strong longitudinal component of the pump mode can be leveraged to efficiently generate a second harmonic wave in a waveguide aligned with a crystal axis.

2. Theory

We consider a pump optical mode and its second harmonic, \( \vec{E}(r,t) = \mathcal{R}\{a(z)e_a(x,y)e^{i(\beta_a z - \omega_a t)} + b(z)e_b(x,y)e^{i(\beta_b z - 2\omega_b t)}\} \), propagating in a III-V nanowaveguide along the \( z \) direction. \( e_{a,b}(x,y) \) are the spatial distributions of the electric field in the transverse plane, normalized such that the field amplitudes \( a, b \) are expressed in \( \sqrt{W} \). In the case of negligible propagation loss and pump depletion, the second harmonic power along the waveguide is \( |b(z)|^2 = |a(0)|^2 \frac{\pi^2}{2} \text{sinc}^2(\Delta \beta L/2) \) where \( \Delta \beta = 2\beta_a - \beta_b \) and \( \kappa \) is the effective nonlinearity. When the propagation direction is aligned with a crystallographic axis, it reads:

\[
\kappa = \frac{6\hbar \varepsilon_0}{2} \int \chi^{(2)}_{xy\zeta} \left(e_b^* e_a e_b^* e_a + e_b^* e_a e_b^* e_a + e_b^* e_a e_b^* e_a\right) dA. \tag{1}
\]

Importantly the effective nonlinearity would vanish in this case for purely transverse modes. But in high index contrast waveguides, optical modes are known to display large longitudinal components. We compute the modes of a 680 nm wide, 320 nm thick Indium Gallium Phosphide nanowaveguide. Our simulations predict phase matching between a quasi transverse fundamental pump mode around 1575 nm and a higher order second harmonic mode. The effective indices as well as the different electric field component are shown in Fig. 1(a). We readily note the field components of a same mode have very different spatial distributions. Moreover, most have non-negligible amplitudes, confirming the need for full vectorial modeling in order to predict nonlinear coupling in III-V nanowaveguides. We compute an effective nonlinearity \( \kappa = 75(\sqrt{W}m)^{-1} \), corresponding to a conversion efficiency of 50%/Wcm².
3. Experimental results

To confirm these theoretical predictions, we fabricated 1.5 mm long InGaP waveguides. We follow the process described in [4] but we rotate the epitaxial stack by 45° before bonding it to the silicon-on-insulator wafer. This is because the cleave directions for III-V semiconductors grown on (100) substrate are [110] and [110]. Following the rotation, waveguide facets cleaved along the silicon [011] direction are aligned with a crystallographic axis of the indium Gallium Phosphide layer. We launch a 3 mW telecom band pump in the waveguide through a lensed fiber and collect the second harmonic by use of a high NA (0.9) objective. The sinc²-shaped transmission around 775 nm is shown in Fig. 1(c). From the experiment, we estimate a maximum experimental conversion of 0.2 %/W/cm² with pump at 1572 nm, in good agreement with the computed phase matching wavelength. The experimental efficiency however is around 2 orders of magnitude less than the theoretical prediction. This is likely due to strong propagation losses at the second harmonic but could also be because of low collection efficiency or waveguide inhomogeneities. Further experimental investigations are ongoing to shed light on this discrepancy. Next we imaged the second harmonic mode in a microscope arrangement with a nominal magnification of 416. We find good agreement with the theoretical Poynting vector intensity [Fig. 1(c)], confirming the excitation of the predicted antisymmetric higher order mode. To calibrate our imaging system, we injected 775 nm light through the lensed fiber to excite a fundamental mode around the SH wavelength [See Fig. 1(d),(e)].

4. Conclusion

We experimentally observed second harmonic generation through mixing of transverse and longitudinal field components in an Indium Gallium Phosphide nanowire. Not only does it demonstrate the vector nature of the propagating waves, it also allows to excite higher order modes with different symmetries.

References

Nonlinear Optics (NLO) Topical Meeting

15 - 19 July 2019
Waikoloa Beach Marriott Resort & Spa
Waikoloa Beach, Hawaii, USA

Table of Contents

Program Committee ........................................................................................................ 2
General Information ...................................................................................................... 3

Nauplica III

NM3A • New concepts II
President: Ray-Kuang Lee, National Tsing Hua Univ., Taiwan
NM3A.1 • 19:30
Third-Order and Fifth-Order Optical Nonlinearities by Two-Dimensional
Electronics, Wei L. H. National Univ. of Singapore, Singapore. We present our
two-dimensional excitonic models to quantitatively predict the giant optical
nonlinearities in terms of Two- and Three-Photon Absorption, for monolayer
transition-metal dichalcogenides, or layered organic-inorganic hybrid
perovskites. Our models are in agreement with the experimental
measurements, within one order of magnitude.

NM3A.2 • 19:45
Femtosecond supercontinuum generation with noisy pumps in normal
dispersion fibers with zero crossing, Shreeda Roy O. S., Etienne Germain,
Rasmus D. Engellohn, Ivan B. Goral, Bibin Zou, Patrick Bowers, Peter
M. Moselund, Thibault Sylvester, John M. Dudley, Morten Bache, Ole
Barany

NM3A.3 • 20:00
Beam Deflection Measurements of Transient Nonlinear Refraction in Air in the
Mid-IR, Salimah Tofghi, Natalia Munera, Munen Gao, David J. Hager, Eric
Van Straylight, Univ. of Central Florida, CRQOL, USA. Using the Beam
Deflection Technique, the bound-electronic and nuclear orientation

Naupaka V

NM3B • Integrated Nonlinear Optics
President: Majid Ebrahimi-Zadeh; ICFO-Institut de Ciencies Fotoniques, Spain
NM3B.1 • 19:30
Withdrawn

NM3B.2 • 19:45
Second Harmonic Generation Induced by Longitudinal Components in Indium Gallium
Phosphide Nanowaveguides, Nicolas Pichaud-Rivard, Ugo David, Irois Alexandre, Charles Pret, Fabrice Hainer, Sylvain Cornillet, Alfredo De Rossi, Guenter Ruester, Simon-Pierre Gorre, Bert
Kublt, Francois Lejeune, CPERD, Physique, Université Libre de Bruxelles, Belgium; Photonics Research Group, CPERD Physique, Université Libre de Bruxelles, Belgium; Photonics
Research Group, CNRS, France; Laboratory of Photonic and Nanostructures, France; Laboratory de Physique d’Angers, Université d’Angers, France; Laboratory of Photonic and Nanostructures, France. We experimentally demonstrate second harmonic generation in Indium Gallium Phosphide waveguides by mixing transverse and longitudinal
components of the optical fields. We confirm the excitation of an antisymmetric second
harmonic mode through modal imaging.

NM3B.3 • 20:00
Light, Sound and Microwave Induced Modulation in Microwavy Brillouin Laser, Jianfan Yang, Tan Qin, Wenjie Wen, Shanghai Jiao Tong Univ., China. We experimentally
observe light, sound and microwave induced modulation in an optomechanical
microwavy Brillouin laser system. Unique applications as dual channel communication