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

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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 seminconductors promise record conversion efficiencies as they are characterized by very large second-order nonlinear coefficients (one order of magnitude larger than $LiNbO_3$). However, only a single independent tensor element is nonzero ($\chi^{(2)}_{xyz}$ 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, $\vec{E}(\vec{r},t) = \Re\{a(z)\vec{e}_a(x,y)e^{i(\beta_a z-\omega_0 t)} + b(z)\vec{e}_b(x,y)e^{i(\beta_b z-2\omega_0 t)}\}$, propagating in a III-V nanowaveguide along the z direction. $\vec{e}_{a,b}(x,y)$ are the spatial distributions of the electric field in the transverse plane, normalized such that the field amplitudes a,b are expressed in $\sqrt{\mathrm{W}}$. In the case of negligible propagation loss and pump depletion, the second harmonic power along the waveguide is $|b(z)|^2 = |\kappa|^2|a(0)|^4 z^2 \mathrm{sinc}^2(\Delta\beta L/2)$ where $\Delta\beta = 2\beta_a - \beta_b$ and κ is the effective nonlinearity. When the propagation direction is aligned with a crystallographic axis, it reads:

$$\kappa = \frac{\omega_0 \varepsilon_0}{2} \int \chi^{(2)}_{xyz} \left(e_b^{*x} e_a^y e_a^z + e_b^{*y} e_a^x e_a^z + e_b^{*z} e_a^x e_a^y\right) dA. \qquad (1)$$

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 $\kappa = 75(\sqrt{\mathrm{W}}\mathrm{m})^{-1}$, corresponding to a conversion efficiency of $50\%/(\mathrm{Wcm}^2)$.

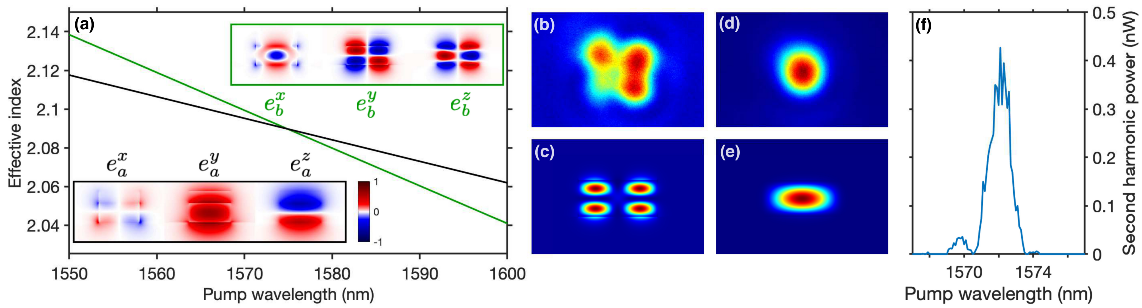

Fig. 1. (a) Simulation of the effective indices of a pump mode (black) and a SH mode (green). The spatial distribution of the different electric field components is shown as inset. (b-c) Measured and computed spatial distribution of the intensity of the SH at the output of the waveguide. (d-e) Measured and computed spatial distribution of the intensity of a 775 nm TM fundamental wave for comparison. The field of view for theoretical modes is 1.5 μm x 1 μm. (f) Second harmonic power collected at the output of the waveguide as a function of the pump wavelength.

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 [$1\bar{1}0$]. 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 sinc^2-shaped transmission around 775 nm is shown in Fig. 1(c). From the experiment, we estimate a maximum experimental conversion of 0.2 %/W/cm^2 with pump at 1572 nm, in good agreement with the computed phase mathing 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 antisymetric 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

1. C. Wang, *et al.*, "Ultrahigh-efficiency wavelength conversion in nanophotonic periodically poled lithium niobate waveguides", Optica, **5**, 1438 (2018).
2. L. Chang, *et al.*, "Heterogeneously Integrated GaAs Waveguides on Insulator for Efficient Frequency Conversion", Laser & Photonics Reviews **12**, 1800149 (2018).
3. D. Duchesne, *et al.*, "Second harmonic generation in AlGaAs photonic wires using low power continuous wave light", Opt. Express **19**, 12408 (2011).
4. U. Dave, "Nonlinear properties of dispersion engineered InGaP photonic wire waveguides in the telecommunication wavelength range", *et al.*, Opt. Express **23**, 4650 (2015).

Nonlinear Optics (NLO) Topical Meeting

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Waikoloa Beach, Hawaii, USA

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Monday, 15 July

Naupaka III

19:30 -- 21:30

NM3A • New concepts II

Presider: Ray-Kuang Lee; National Tsing Hua Univ., Taiwan

NM3A.1 • 19:30

Third-Order and Fifth-Order Optical Nonlinearities by Two-Dimensional Excitonics, Wei Ji[1]; *[1]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 di-chalcogenides, 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 crossings , Shreesha Rao D. S.[1], Etienne Genier[2], Rasmus D. Engelsholm[1], Ivan B. Gonzalo[1], Binbin Zhou[1], Patrick Bowen[2], Peter M. Moselund[2], Thibault Sylvestre[3], John M. Dudley[3], Morten Bache[1], Ole Bang[1,2]; *[1]Dept. of Photonics Engineering, Danmarks Tekniske Universitet, Denmark; [2]NKT Photonics A/S, Denmark; [3]Institut FEMTO-ST, CNRS-Université de Franche-Comté, France.* We demonstrate surprising effects of technical pump laser fluctuations on the noise of a normal-dispersion fs-pumped supercontinuum and how the noise varies with power in fibers with a zero-dispersion at longer wavelengths.

NM3A.3 • 20:00

Beam Deflection Measurements of Transient Nonlinear Refraction in Air in the Mid-IR, Salimeh Tofighi[1], Natalia Munera[1], Munan Gao[1], David J. Hagan[1], Eric Van Stryland[1]; *[1]Univ. of Central Florida, CREOL, USA.* Using the Beam Deflection Technique, the bound-electronic and nuclear reorientation

Naupaka V

19:30 -- 21:30

NM3B • Integrated Nonlinear Optics

Presider: Majid Ebrahim-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 Poulvellarie[1], Utsav Dave[6], Koen Alexander[2], Charles Ciret[5], Fabrice Raineri[4], Sylvain Combrié[3], Alfredo De Rossi[3], Gunther Roelkens[2], Simon-Pierre Gorza[1], Bart Kuyken[2], François Leo[1]; *[1]OPERA-photonique, Université libre de Bruxelles, Belgium; [2]Photonics Research Group, Ghent Univ.-IMEC, Belgium; [3]Thales Research and Technology, France; [4]Laboratoire de Photonique et de Nanostructures, France; [5]Laboratoire de Photonique d'Angers, Université d'Angers, France; [6]Columbia Univ., USA.* 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 Microcavity Brillouin Laser, Jianfan Yang[1], Tian Qin[1], Wenjie Wan[1]; *[1]Shanghai Jiao Tong Univ., China.* We experimentally observe light, sound and microwave induced modulation in an optomechanical microcavity Brillouin laser system. Unique applications as dual-channel communication