Efficient second harmonic generation in birefringently phase-matched GaAs/Al_2O_3 waveguides using femtosecond pulses at 2.01 μm

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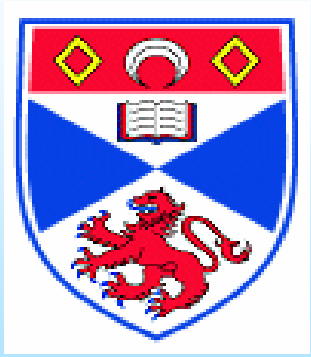


Plan for the talk

- Introduction
- GaAs/Alox waveguides
- Experiment
- Results and Discussion
- Conclusions

INTRODUCTION

GaAs/AlGaAs based waveguides are attractive because of their

1. **Large second order coefficients [$\chi^{(2)}$ ~ 240 pm/V for GaAs at 1.0 μm]**
2. **Broad infrared transparency (0.9-17.0 μm)**
3. **High laser-damage threshold**
4. **Integrability with semiconductor laser sources**
5. **No photo-refractive effect (Room temperature operation)**

Lack of intrinsic birefringence → Problem with phase matching

Solution:

(a) Quasi-Phase Matching (QPM) or

(b) Birefringence Phase Matching [Selective oxidation of AlAs layers to form Aluminium Oxide (Alox)].

- **Artificial birefringence can be engineered by piling up thin layers of materials of different indices of refraction.**
- **TE and TM waves propagating in the structure experience different refractive indices due to the continuity relations at the interfaces of the multi-layers for tangential and normal fields.**
- **The amount of birefringence available depends on the thickness of the layers and the index contrast. For the GaAs/AlAs system the index contrast is not enough to phase match interesting interactions.**
- **Selective oxidization of the AlAs layers, to form Alox was proposed as a method to introduce a useful index contrast. [Nature 391, 463 (1998)]**
- **The strong refractive index contrast between semiconductor (n ~3.4) and the Alox (n ~1.6) results in a form birefringence strong enough to phase match the SHG process.**

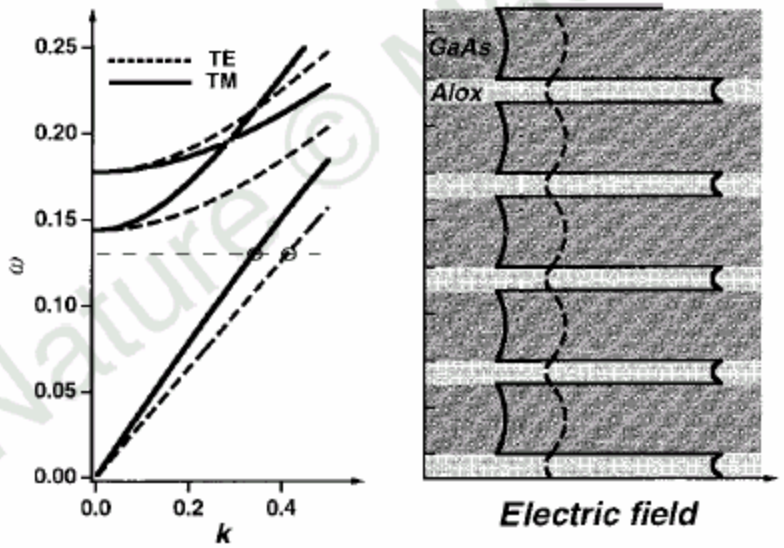


Figure 1 Dispersion relation for an in-plane propagation in a periodic composite material of period d. The material consists of 25% of Alox (refractive index $n \approx 1.6$; see text) and 75% of GaAs ($n \approx 3.5$), for TM modes (full line) and TE modes (dotted lines). The physical origin of form birefringence appears in the mode wavefunction, pictured on the left for a frequency $\omega = 0.13(2\pi/d)$ (corresponding to the open circles in the dispersion relation). These Bloch waves have been calculated using standard periodic multilayer theory[10]. The direction of propagation is perpendicular to the plane of the figure. Due to the continuity of the electric displacement ϵE normal to the layers, the TM mode (solid line in both panels) has a significant overlap with the low-ϵ layer (Alox, shown in light grey in the right panel), and a lower average dielectric constant. The continuous TE electric field (dotted line in both panels) has a higher value in GaAs (dark grey, right panel), and a higher average dielectric constant.

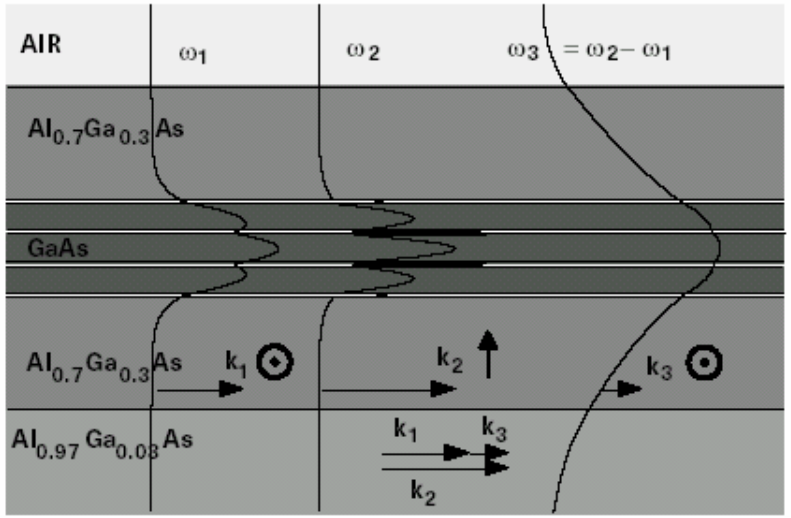
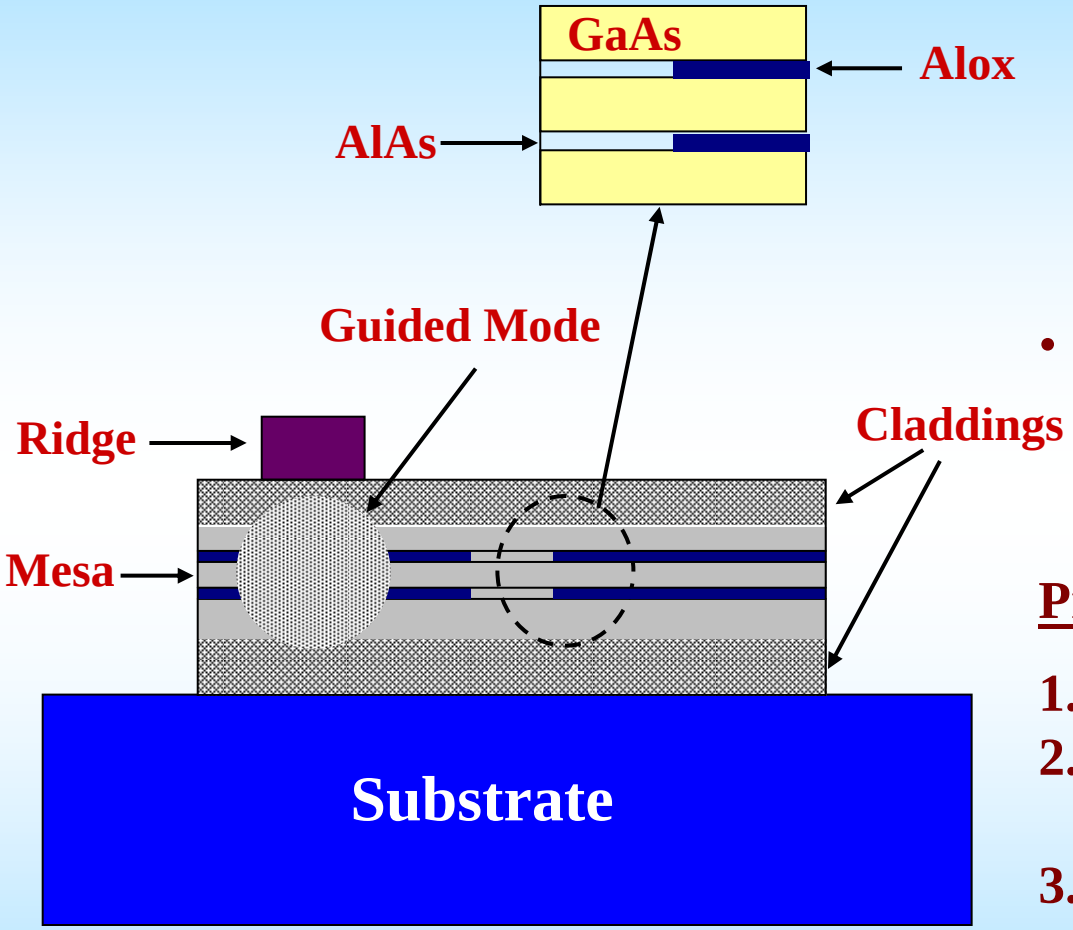


Figure 2 Difference frequency generation (DFG) process in the sample. Here ω_1 and ω_2 are the pump frequencies of wavelengths 1.32 μm and 1.058 μm, respectively, and ω_3 is the frequency difference of wavelength 5.3 μm. Three periods of the composite material GaAs (325 nm)/Alox (40 nm) constitute the core of the waveguide. The birefringence of the composite material was engineered to compensate for the dispersion arising from both the natural dispersion in bulk GaAs and the optical confinement dispersion in the waveguide. The sample was grown by molecular beam epitaxy on a GaAs (100) substrate and consists of: 2,800 nm $Al_{0.97}Ga_{0.03}As$; 1,500 nm $Al_{0.70}Ga_{0.30}As$ (waveguide cladding layers), three periods of birefringent composite material (40 nm Alox; 325 nm GaAs) × 3 and 40 nm Alox; 1,500 nm $Al_{0.70}Ga_{0.30}As$ and a final 30-nm GaAs cap layer. The oxidation process is described in detail in ref. 15. The three modes involved in the DFG process are pictured together with their polarization (↑ for TM, ⊙ for TE). The higher overlap of the TM mode with the low-refractive-index Alox layers is apparent, which is the origin of form birefringence. The arrows indicate the "phase matching" momentum conservation. $\mathbf{k}_1 + \mathbf{k}_3 = \mathbf{k}_2$, where $\mathbf{k}_i$ indicates the wavevector of the wavenumber i.

GaAs/Alox Waveguides



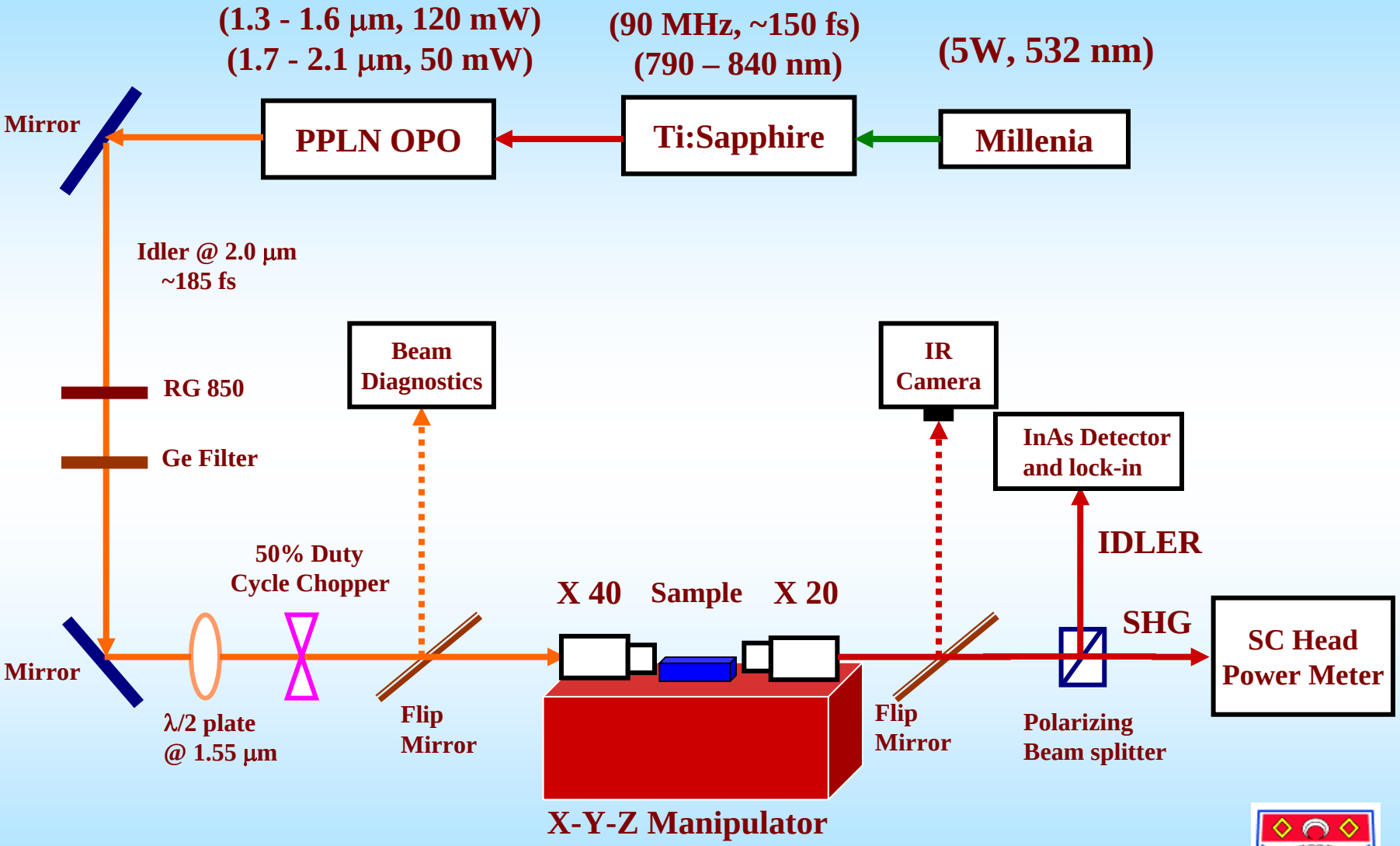
Structure

- (GaAs <001> substrate non intentionally doped) / 1000 nm $Al_{0.92}Ga_{0.08}As$ / 1000 nm $Al_{0.7}Ga_{0.3}As$ / 4 x (50 nm AlAs / 250 nm GaAs) / 50 nm AlAs / 1000 nm $Al_{0.7}Ga_{0.3}As$ / 30 nm GaAs.
- Alloys composition and layer thickness designed to have SHG wavelength phase matched around 1.0 µm

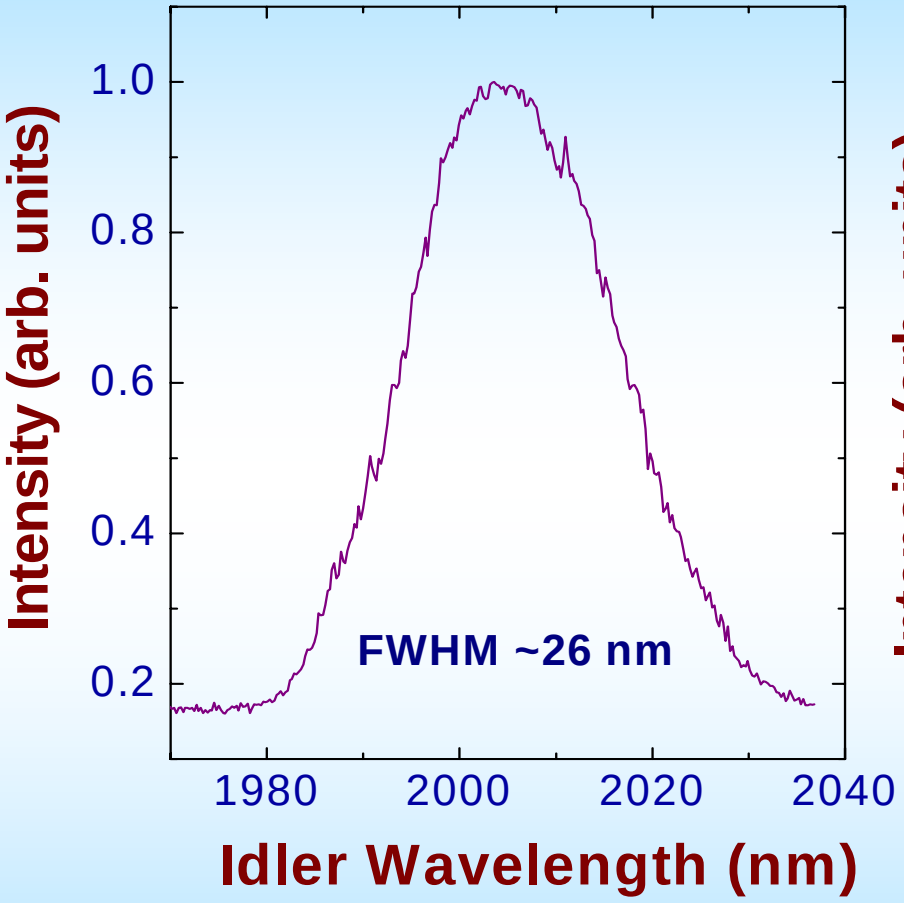
Process steps

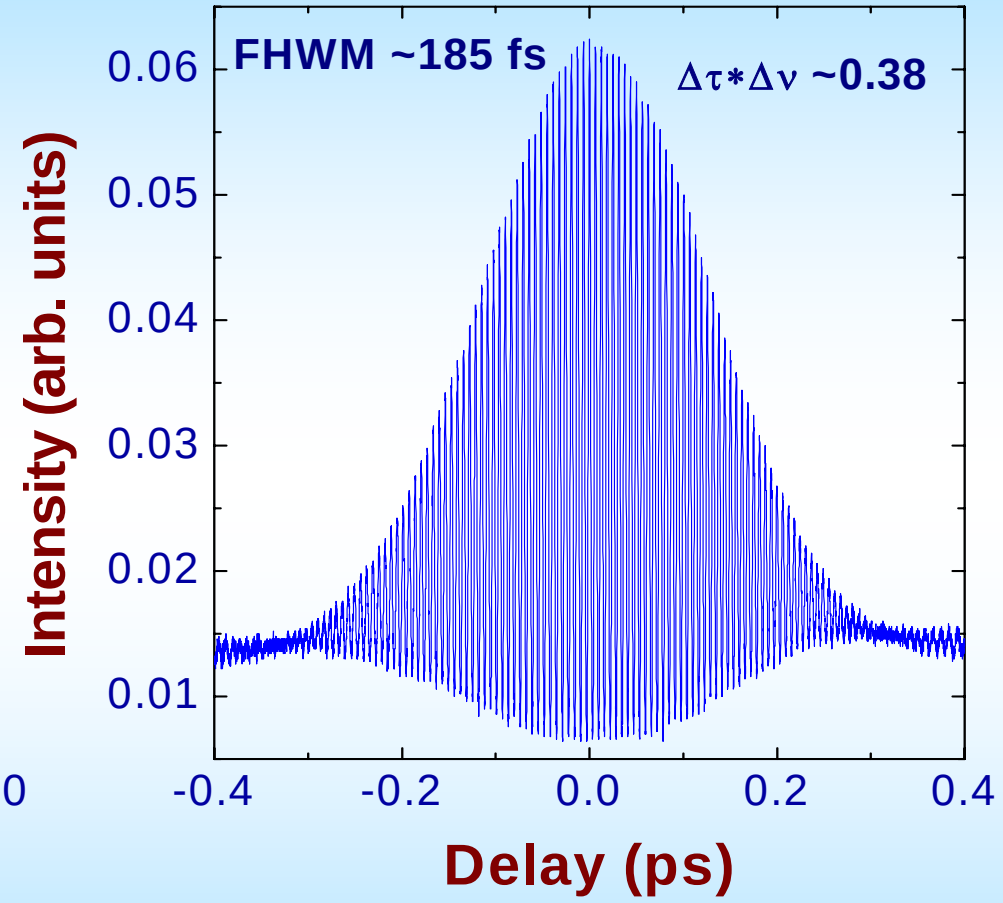
1. Ridge etching (optical confinement)
2. Mesa etching (to allow lateral oxidation)
3. Oxidation
4. Annealing (interface quality)

EXPERIMENT

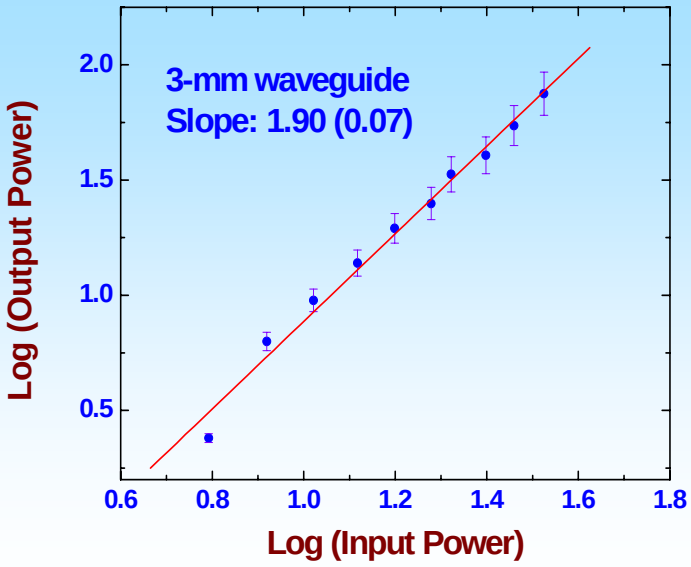

(1.3 - 1.6 μm, 120 mW)
(1.7 - 2.1 μm, 50 mW)
(90 MHz, ~150 fs)
(790 – 840 nm)
(5W, 532 nm)
Mirror
PPLN OPO
Ti:Sapphire
Millenia
Idler @ 2.0 μm
~185 fs
Beam Diagnostics
IR Camera
RG 850
Ge Filter
InAs Detector and lock-in
IDLER
50% Duty Cycle Chopper
X 40
Sample
X 20
SHG
SC Head Power Meter
Mirror
λ/2 plate @ 1.55 μm
Flip Mirror
Flip Mirror
Polarizing Beam splitter
X-Y-Z Manipulator

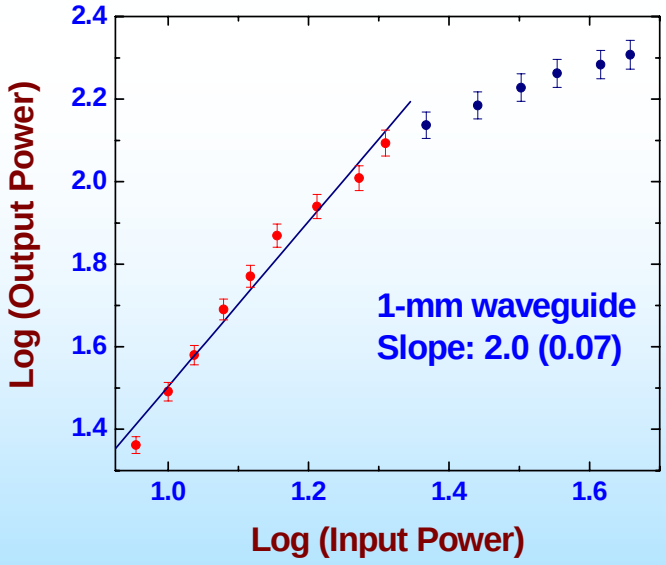
Fundamental (Idler) Pulses





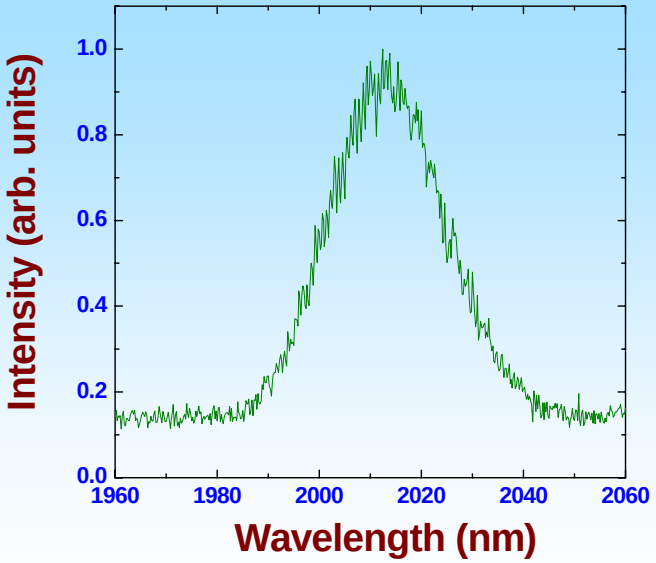
RESULTS AND DISCUSSION

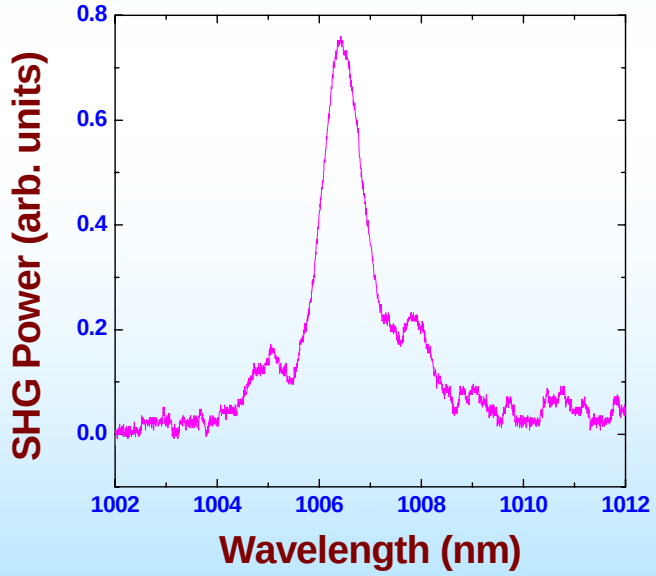




Input Idler Characteristics

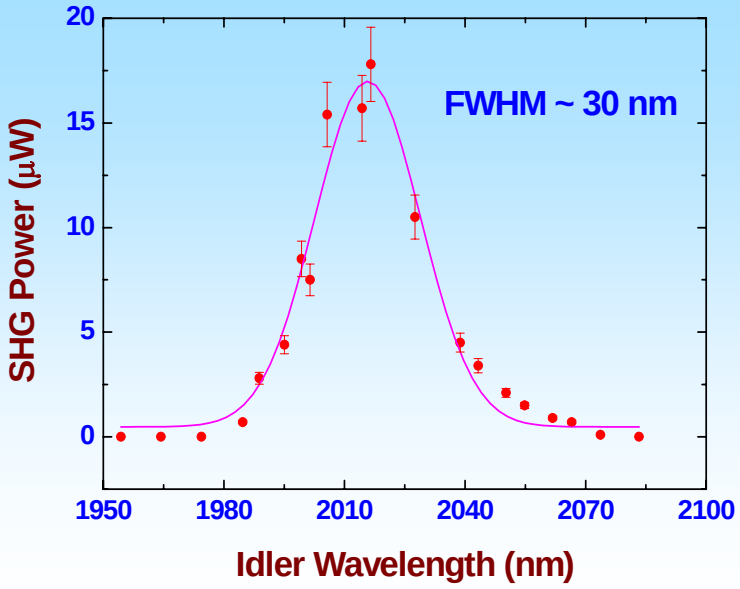
- Near-transform limited pulses (~185 fs) with 90 MHz repetition rate
- Idler tunable in the 1.7–2.1 μm range, with average power levels of ~50 mW
- Type–I phase matching: Input TE polarization → TM polarized output.
- Quadratic behaviour of SHG output vs input power as expected. Saturation behaviour in the shorter sample at higher input intensities, possibly due to multi-photon absorption.

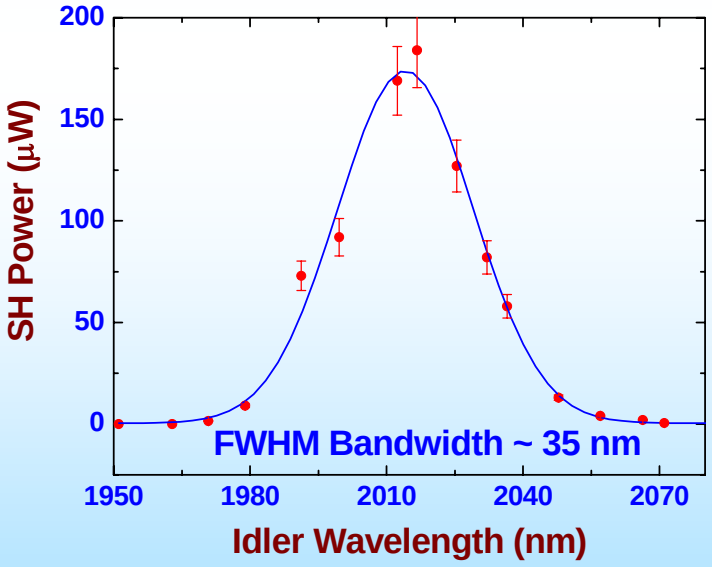




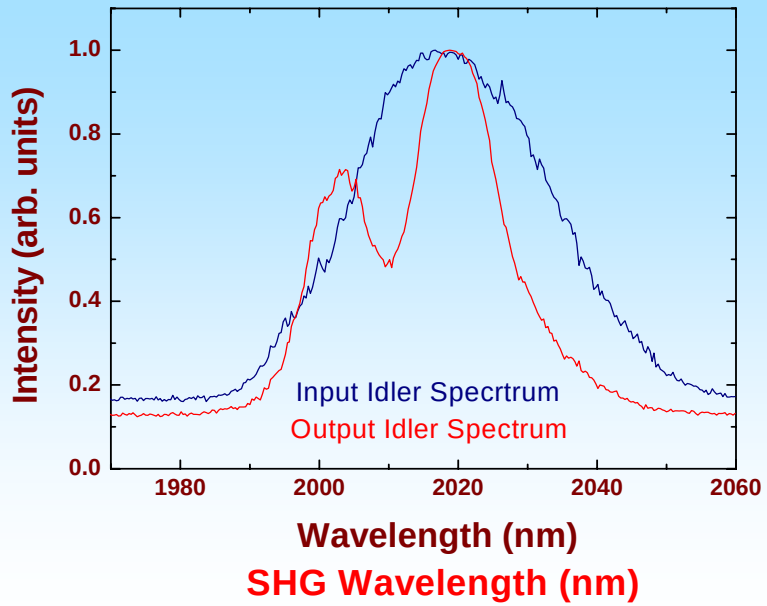
Idler and SHG spectra

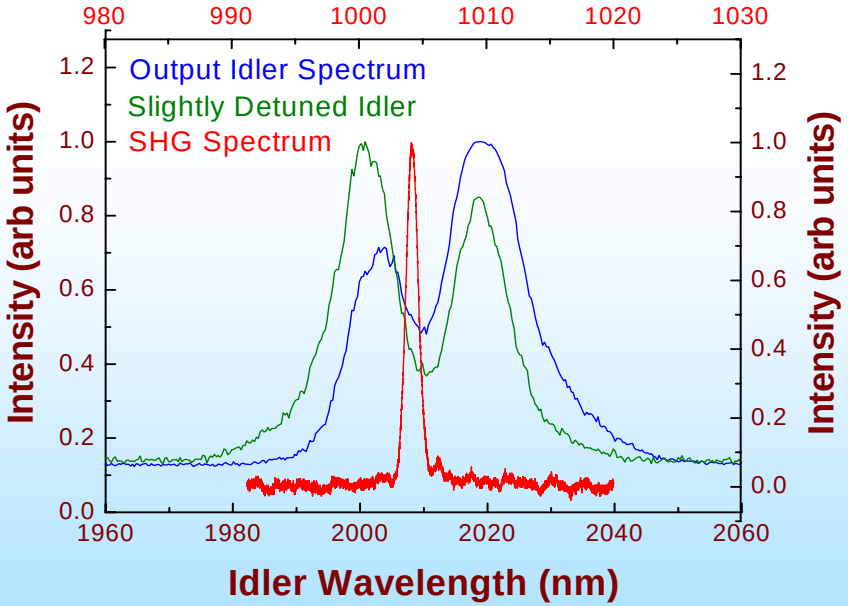
- Maximum observed SHG power ~650 μW for 1-mm waveguide and ~380 μW for 3-mm waveguide with input power of ~50 mW
- Overall efficiencies (P_{SHG}/P_{IDLER}) of 0.78 % (3-mm waveguide) and 1.3% (1-mm waveguide)
- Taking into account the facet reflectivity, transmission losses (~1 cm^{-1}), geometrical coupling factor we estimated the launched power ~5 mW. Considering the duty cycle and the actual interaction length (due to GVM), we extract a normalized conversion efficiency of >1000 $\%W^{-1}cm^{-2}$ for the 1-mm waveguide.





- Transmitted idler FWHM was ~26 nm and generated SHG FWHM ~0.95 nm (3-mm) and ~1.3 nm (1-mm)
- Tuning curve (SHG output versus fundamental/idler wavelength) shows a peak around 2.0 μm. FWHM of the tuning curve ~30 nm for 3-mm waveguide, and ~35 nm for 1-mm waveguide
- Pump depletion measurements (using InAs detector and a lock-in amplifier combination) in the 1-mm sample indicate about 40% of the total input pump power was depleted (converted to SHG and other loss mechanism).





- **The spectra of the transmitted idler recorded on and off-resonance also showed depletion, supporting our argument. Within the phase-matching bandwidth the depletion was greater than 80%.**

- **Any spectral shift within the pump bandwidth resulted in no shift in the position of the dip in the transmitted pump spectrum or in the position of the peak in the SHG spectrum.**

Comparison with other waveguides

PPLN waveguides : 150 % /W cm^2 at 1.55 μm (OL 27, 179, 2002)

APE PPLN waveguides : 40 % /W cm^2 (IEICE Trans. Elec. E83C, 869, 2000)

$KNbO_3$ waveguides : 30% /W cm^2 at Ti:Sapphire wavelengths

PSN GaAs waveguides : 0.1 % (Internal, P_{out} / P_{in}) at 2.0 μm

QPM GaAs AlAs : 0.02 % (Internal, P_{out} / P_{in}) at 1.55 μm (OL 25, 1370, 2000)

Polymer waveguides : 0.05 % /W cm^2 at 1.5 μm (APL 68, 1183, 1998)

$MgO:LiNbO_3$ waveguides : 1000% /W at 772 nm (JJAP 40, 1751, 2001)

THIS WORK (BPM GaAs/Alox) : 20 % Internal and >1000 /W cm^2 normalized, at 2.01 μm

CONCLUSIONS

- First demonstration of SHG in birefringent GaAs/AlGaAs waveguides using femtosecond pulses.
- Usable SHG powers of ~650 μW for 1-mm waveguide and ~390 μW for 3-mm waveguide. (With an input of ~50 mW). FWHM of SHG ~0.95 nm (1-mm waveguide) & ~1.3 nm (3-mm waveguide). Input pulses had a FWHM of ~26 nm.
- Phase matching peak around 2.0 μm with SHG generated around 1.0 μm
- A normalized conversion efficiency >1000 $\%W^{-1}cm^{-2}$ was achieved for the 1-mm waveguide.