Modal Phase Matching in GaAs/AlGaAs Waveguides: Second Harmonic Generation With Femtosecond Pulses Near 1.5 μm

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Plan for the talk

- → Introduction
- → Phase-matching Techniques (BPM, QPM, MPM)
- → Sample + Experiment
- → Results and Discussion
- → Conclusions

INTRODUCTION

GaAs-based devices:

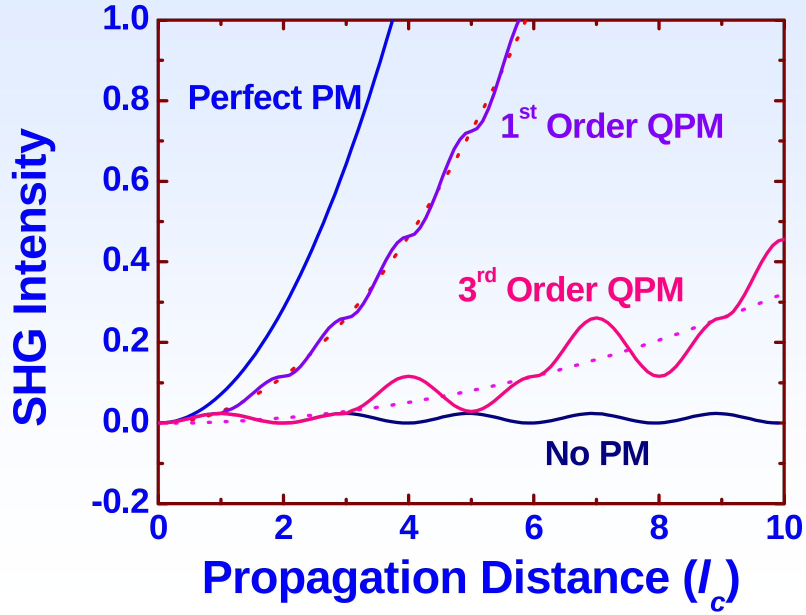
- ✓ Large nonlinear coefficients [d_{14}~170 pm/V @ 2 μm]
- ✓ d^2/n^3 (figure-of-merit) ~10 times * $LiNbO_3$.
- ✓ Broad transparency (0.9-17.0 μm)
- ✓ High laser-damage threshold
- ✓ Integrability
- ✓ No photo-refractive effect (Room temperature operation)

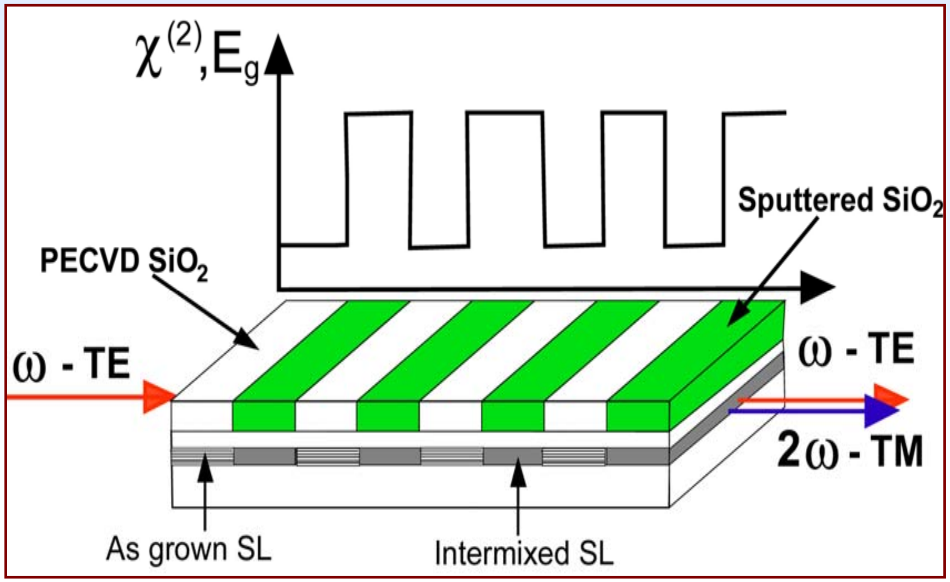
X Lack of intrinsic birefringence → Problem with phase matching

Solution:

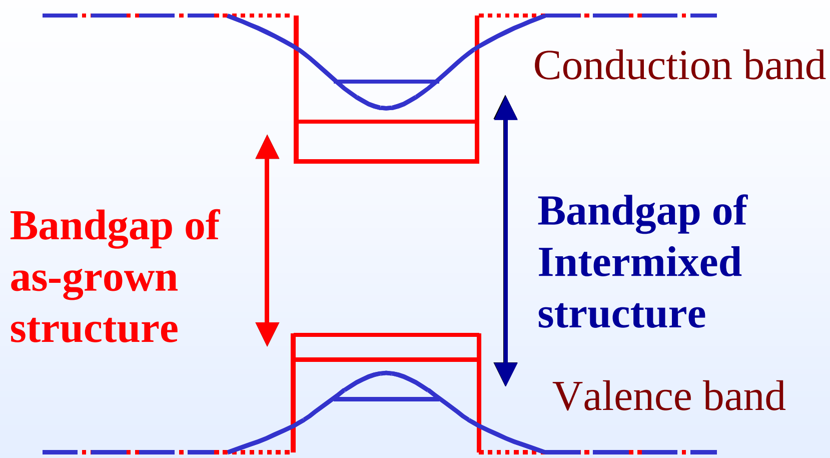
- ➢ Quasi-Phase Matching (QPM)
- ➢ Form Birefringence Phase Matching (BPM)
- ➢ Modal Phase Matching (MPM)

I QPM





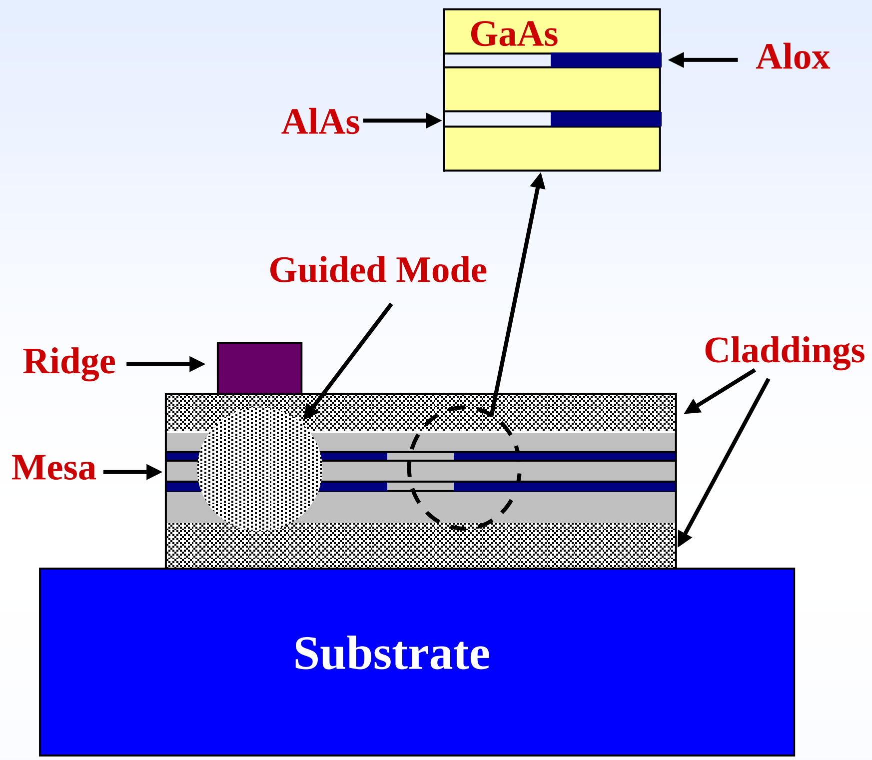
Quantum Well Intermixing (QWI)



- ✓ Demonstrated QPM SHG using femtosecond pulses @ 1.55 µm.
- ✓ (Domain disordering QWI): ~25 nW SHG power in 3rd order QPM
- ✓ (Ion-implantation induced intermixing): ~10 µW in 1st order QPM for ~50 mW of input power

II BPM

- TE and TM waves experience different refractive indices at the interfaces for tangential and normal fields.
- The strong refractive index contrast between semiconductor (n ~3.4) and the Alox (n ~1.6) results in a Form Birefringence.
- First demonstration of SHG using femtosecond pulses near 2.0 μm
- ~650 μW maximum SHG power in a 1-mm waveguide for 50 mW of pump power (>1000%W^{-1}cm^{-2})



$$n_{TE}^2 = \frac{h_1 \cdot \varepsilon_1 + h_2 \cdot \varepsilon_2}{h_1 + h_2} \qquad \frac{1}{n_{TM}^2} = \frac{h_1/\varepsilon_1 + h_2/\varepsilon_2}{h_1 + h_2}$$

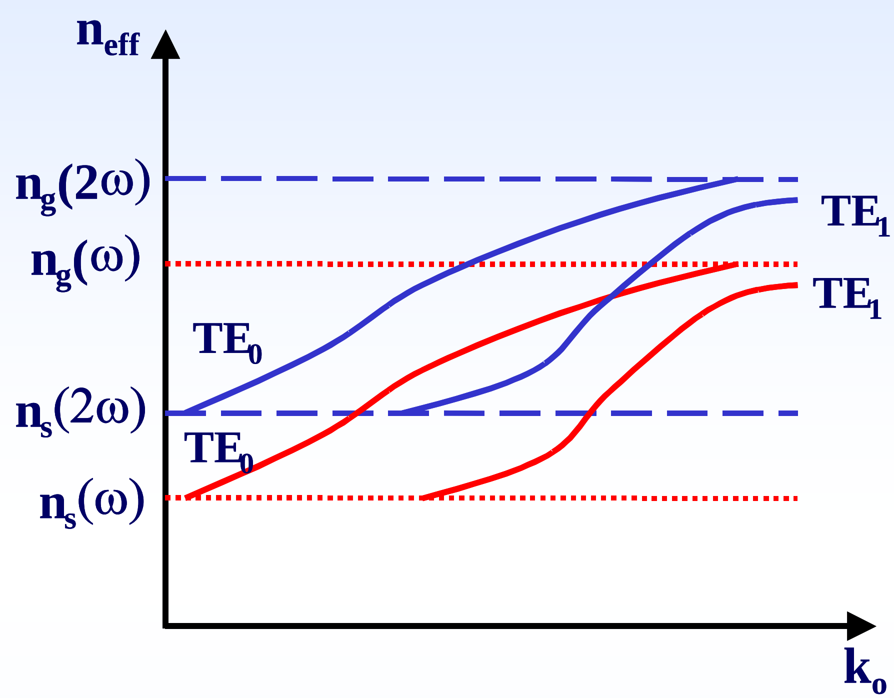
MODAL PHASE MATCHING

- Exploitation of modal dispersion to compensate material dispersion
- Direct + simple approach; Studied in polymer waveguides
- <u>Main restriction: Mode overlap</u>
- Previous reports in semiconductor waveguides:

a) SHG @ ~10.0 μm [APL <u>19</u>, 266, (1971)]

b) SHG @ ~2.0 μm [APL <u>25</u>, 238, (1974)]

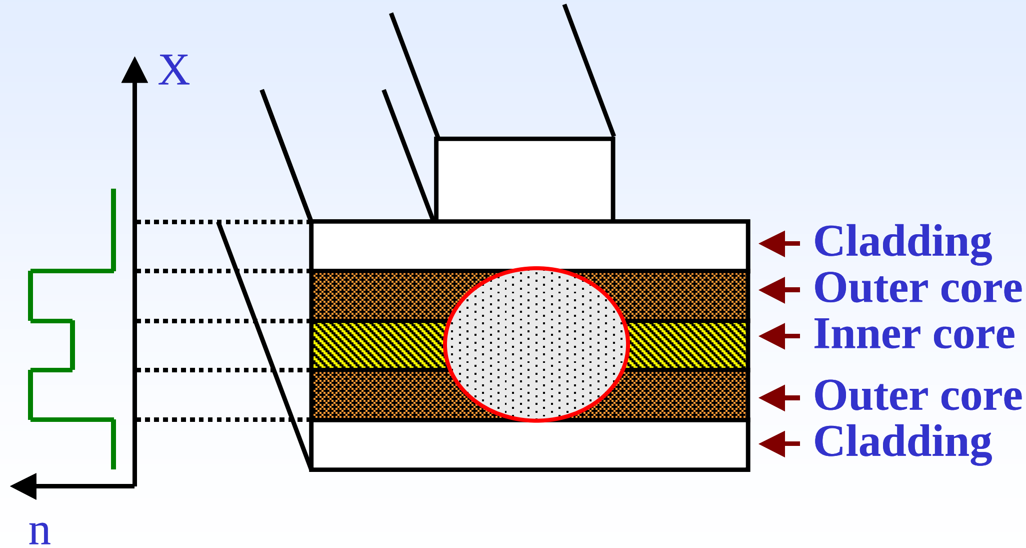
- Type II: $TE_0 + TM_0 \rightarrow TE_2$
- Type I: $TE_0 \rightarrow TM_2$



$$P_2(L) = \frac{\varepsilon_0^2 \omega^2 P_1^2(0) d_0^2 L^2}{4} \left| \frac{1}{L} \int_0^L dz\, d(z) e^{i\Delta\beta z} \right|^2$$

$$\left| \iint dx dy\, d_{ijk}(x,y) e_{1j}(x,y) e_{1k}(x,y) e_{2i}^*(x,y) \right|^2$$

MODE OVERLAP OPTIMIZATION STRATEGY:



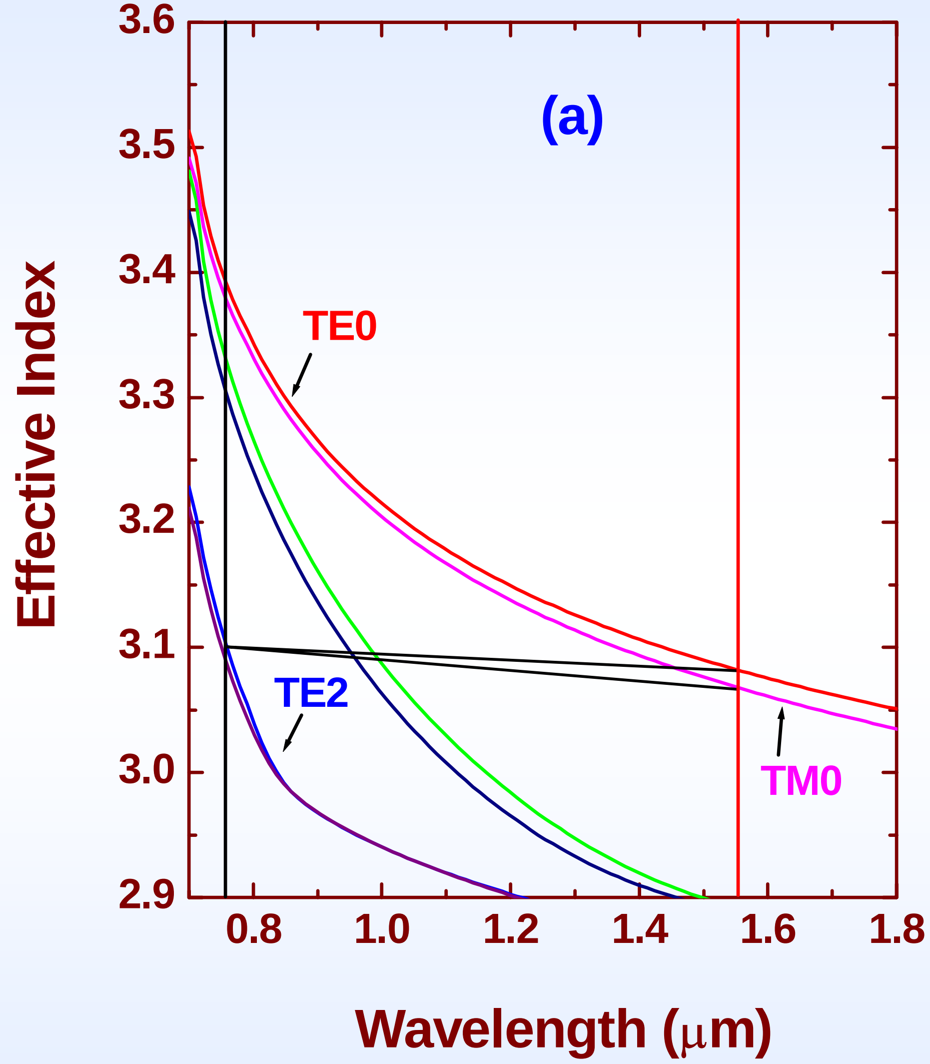
- **M-type waveguide approach**
- **Proper M-waveguide design leads to significant increase in overlap:**

$LiNbO_3$ (Chowdhury, McCaughan)
[IEEE PTL 12, 486 (2000)]

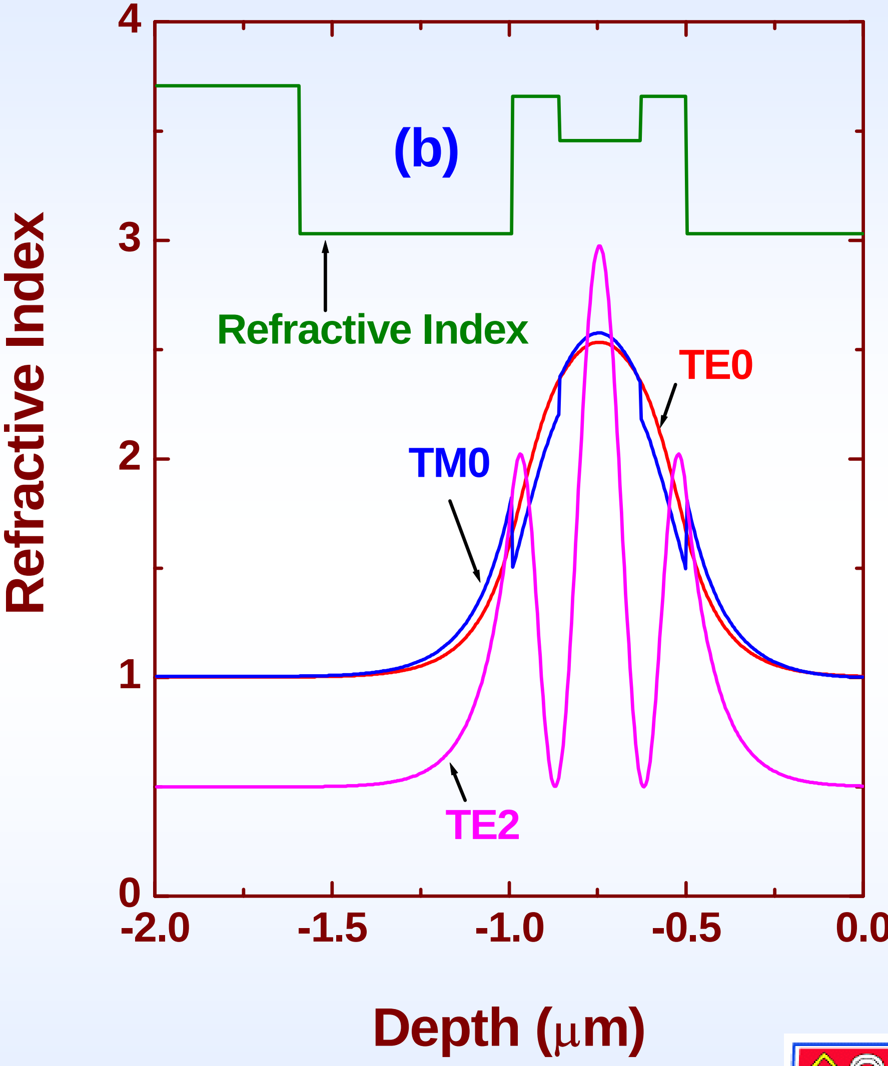
GaAs (Oster, Fouckhardt)
[IEEE PTL 13, 672 (2001)]

Structure design:

1) **Cladding: 1000 nm $Al_{0.98}Ga_{0.02}As$**
2) **Outer core: 130 nm $Al_{0.25}Ga_{0.75}As$**
3) **Inner core: 260 nm $Al_{0.5}Ga_{0.5}As$**
4) **Both Type I and II possible**
   Mode overlap optimized for type II

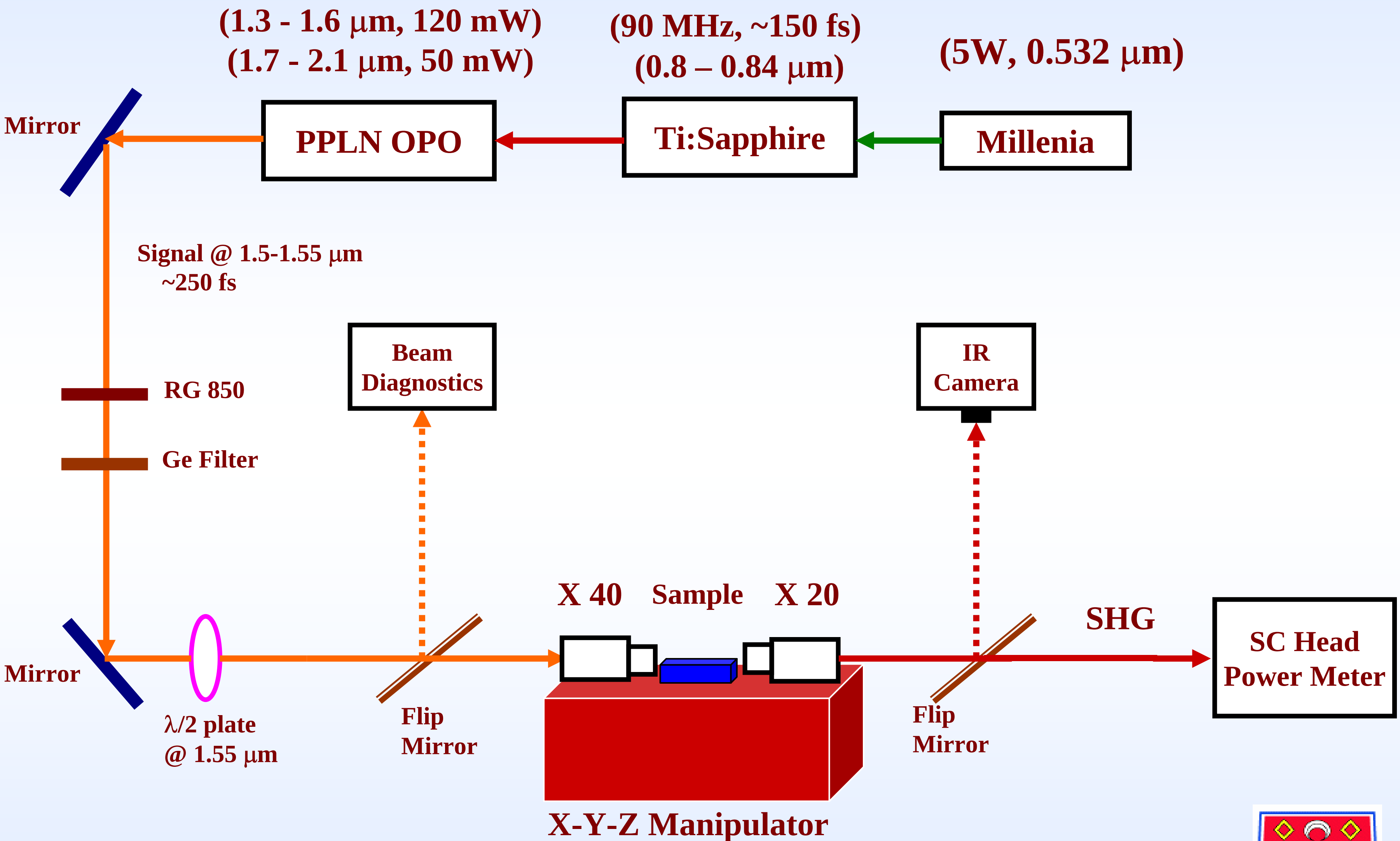


(a)
Effective Index
Wavelength (μm)
TE0
TE2
TM0
3.6
3.5
3.4
3.3
3.2
3.1
3.0
2.9
0.8
1.0
1.2
1.4
1.6
1.8

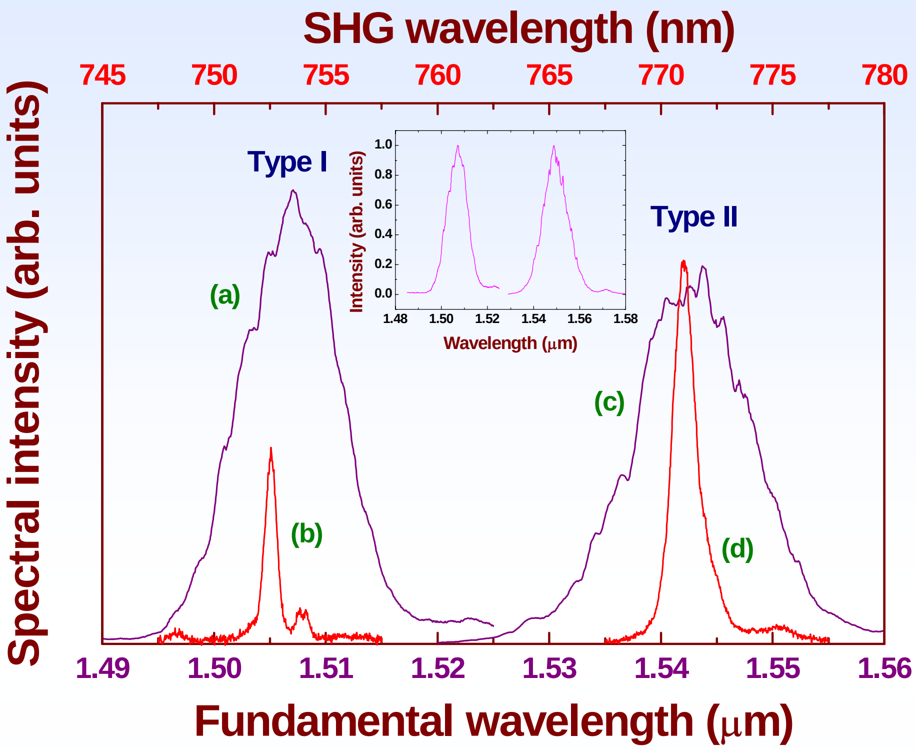


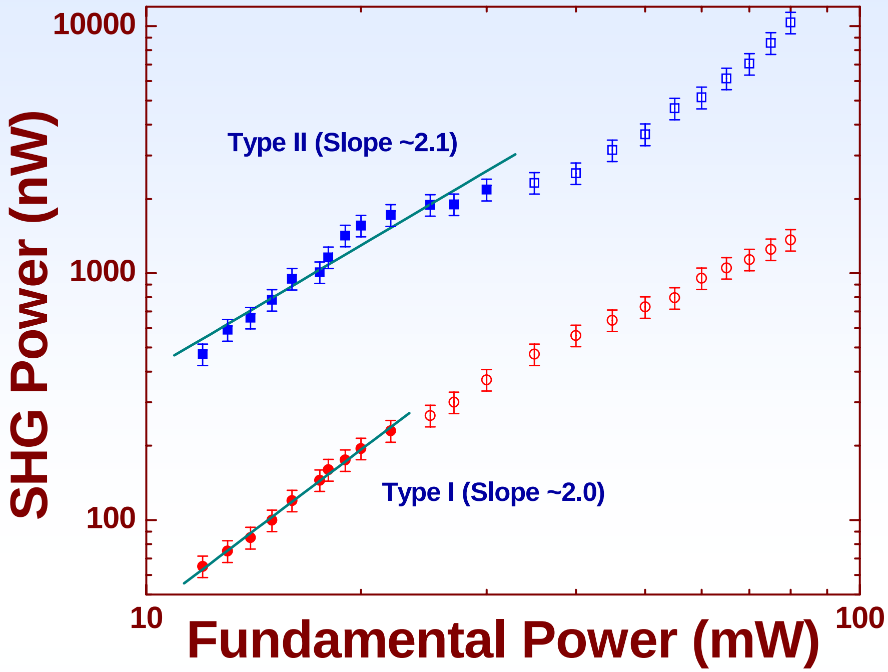
(b)
Refractive Index
Depth (μm)
TE0
TM0
TE2
4
3
2
1
0
-2.0
-1.5
-1.0
-0.5
0.0

EXPERIMENT


(1.3 - 1.6 μm, 120 mW)
(1.7 - 2.1 μm, 50 mW)
(90 MHz, ~150 fs)
(0.8 – 0.84 μm)
(5W, 0.532 μm)
Mirror
PPLN OPO
Ti:Sapphire
Millenia
Signal @ 1.5-1.55 μm
~250 fs
Beam
Diagnostics
IR
Camera
RG 850
Ge Filter
X 40
Sample
X 20
SHG
SC Head
Power Meter
Mirror
λ/2 plate
@ 1.55 μm
Flip
Mirror
Flip
Mirror
X-Y-Z Manipulator

RESULTS





- Optical Loss (Scattering technique)

1.55 μm:

* ~2.7 cm^{-1} for TE
* ~3.5 cm^{-1} for TE+TM

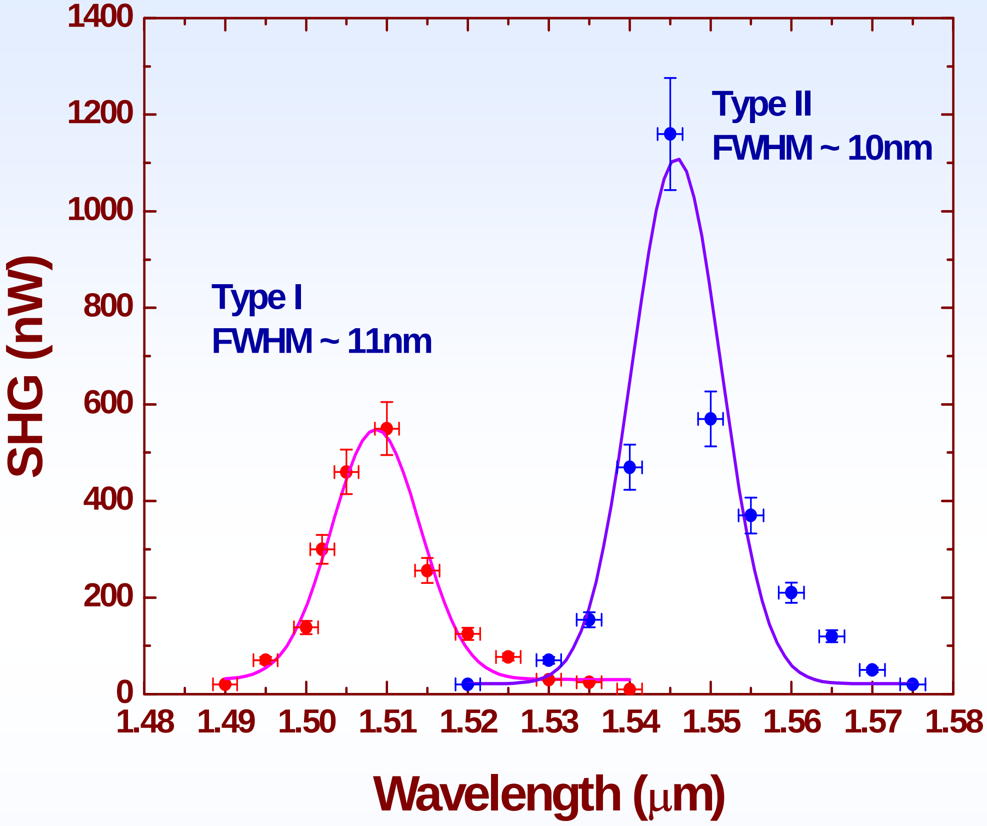
0.82 μm:

* ~1.1 cm^{-1} for TE
* ~1.0 cm^{-1} for TM

→ Type I : ~1.505 μm

→ Type II: ~1.540 μm

→ Indication of SHG saturation at high power levels



FWHM Bandwidth

1. Type-I ~11 nm
2. Type-II ~10 nm

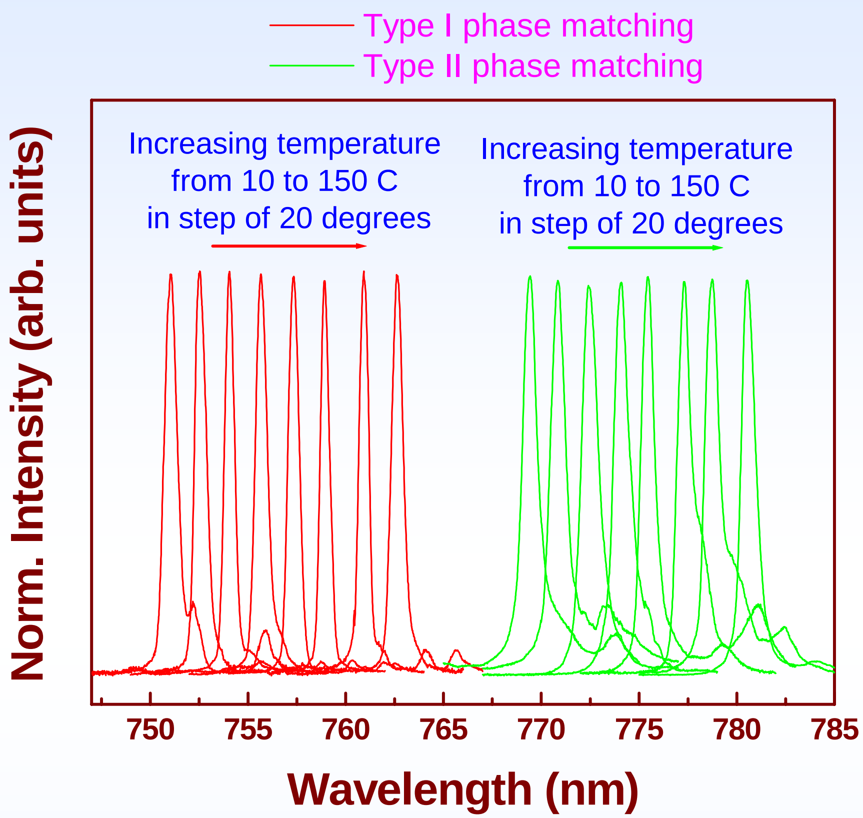
- Maximum SHG power ~10.3 µW for input power of ~65 mW (Type-II).
- ~2.6 µW for Type-I

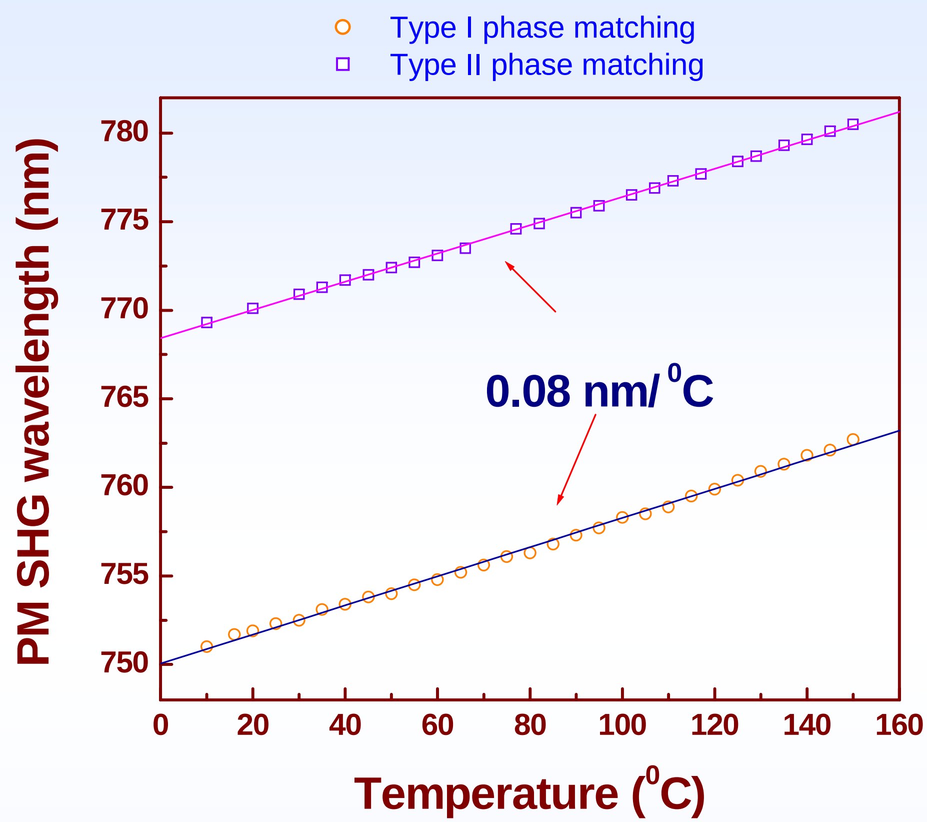
→ **Overall device efficiency 0.015 % (II)**

- Estimated coupling efficiency ~30 %. Collection efficiency (third-order SHG) ~30 %.

- Hence, ~30 µW of SHG power was generated inside the waveguide for <20 mW of coupled input power,

→ **Internal device efficiency ~0.15% (II)**





- **Temperature tuning available at a rate of ~ 0.08 nm/ ^{0}C**

Comparison with other waveguides

PSN GaAs (SHG) : ~0.1 % (Internal, P_{out} / P_{in}) @ 2.0 μm (OL 26, 1984, 2001)

AlGaAs (QPM/SFM) : ~810 %/Wcm^2 @ 1.54 + 1.575 μm (JJAP 37, 823, 1998)

PPLN (QPM/SHG) : ~150 %/Wcm^2 @ 1.55 μm (OL 27, 179, 2002)

Polymer (MPM/SHG) : ~245 %/Wcm^2 @ 1.5 μm (JOSAB 17, 412, 2000)

$MgO:LiNbO_3$ (QPM/SHG) : ~1200%/Wcm^2 @ 0.867 μm (OL 22, 1217, 1997)

GaAs/AlAs (QPM/SHG) : ~0.07 % Internal @ 1.55 μm (OL 28, 911, 2003)
~1.2 %W^{-1}cm^{-2} Normalized

GaAs/Alox (BPM/SHG) : ~20 % Internal @ 2.01 μm (OL 26, 1785, 2001)
>1000 %/Wcm^2 Normalized

GaAs/AlAs (MPM/SHG) : >0.15% Internal @1.55 μm
~ 2 %W^{-1}cm^{-2} Normalized

CONCLUSIONS

- **First demonstration of MPM in semiconductor waveguides using femtosecond pulses**

- **Type I phase matching near 1.505 μm**
  Maximum SHG ~2.6 μW
  Phase Matching Acceptance Bandwidth ~11 nm

- **Type II phase matching near 1.545 μm**
  Maximum SHG ~10.6 μW
  Phase Matching Acceptance Bandwidth ~10 nm

- **Overall device efficiency ~0.015 %**
  Internal device efficiency ~0.15%

THANK YOU……