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Strong optical field enhanced nonlinear conversion signals based on photonic crystal substrate

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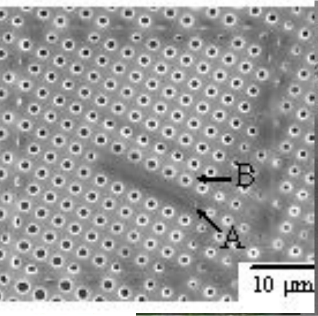
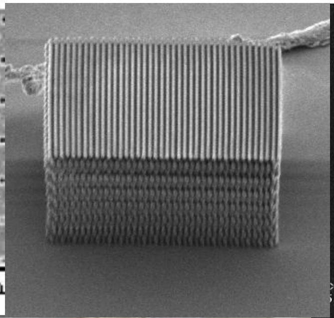
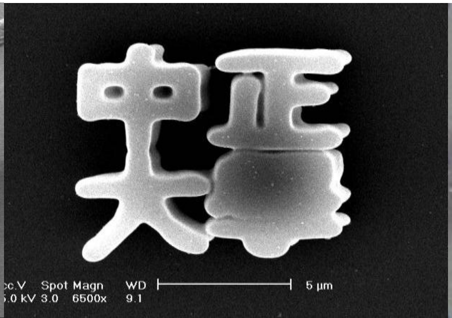
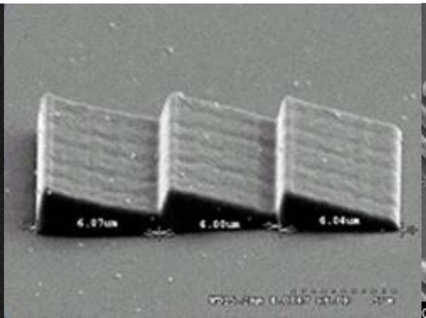
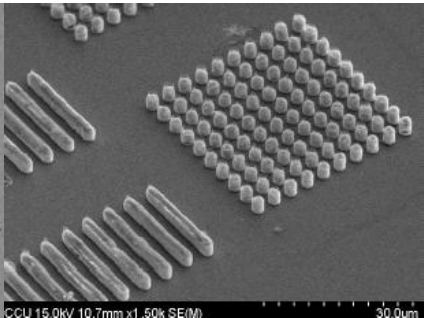
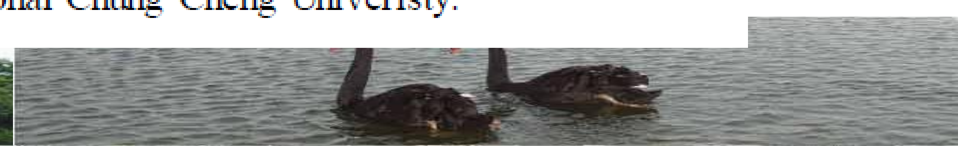


Experience:

8/2008-present	**Postdoctor:** *"Fabrication of two- and three-dimensional linear and nonlinear photonic crystals and photonic quasi crystals using multi-photon polymerization and holography techniques"* at the Nano Fabrications and Polymer Optics Laboratory, Department of Physics, National Chung Cheng University, Taiwan, under the leadership of Prof. Chia Chen Hsu.
8/2013-7/2014	**Adjunct Assistant Professor:** "General physics" in Department of Physics, National Chung Hsing Univeristy.
7/2012-8/2012	**Visiting researcher:** "'Study of second-harmonic generation of 2-dimensional nonlinear photonic crystals in azo-copolymer thin film.' at Photonics and Nanostructures Laboratory, University of British Columbia, Canada, supervised by Dr. Jeff F. Young (0.5 months).
6/2011-7/2011	**Visiting researcher:** "'Study of quasi-phase matching second-harmonic generation of 2-dimensional nonlinear photonic crystals in azo-copolymer thin film.' and 'Simulation study of photonic bandgap of circular photonic crystals by using finite-difference time-domain method'" at Photonics and Nanostructures Laboratory, University of British Columbia, Canada, supervised by Dr. Jeff F. Young (1.5 months).
1/2009-2011	**Adjunct Assistant Professor:** "General physics experiment" in Department of Physics, National Chung Cheng Univeristy.



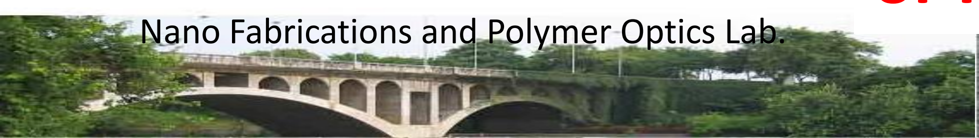
Publications in peer-reviewed international journals

1. **J. H. Lin**, H. Y. Liou, Z.-D. Wang, C.-Y. Tseng, C.-T. Lee, C.-C. Ting, H.-C. Kan, and C. C. Hsu, "Guided-mode resonance enhanced near-infrared-to-visible upconversion fluorescence in a resonant waveguide grating," Preparing to submit to Nano Lett.
2. **J. H. Lin**, J. H. Huang, H.-C. Kan, and C. C. Hsu, "*Optically manipulating guided mode resonance in an azo-copolymer waveguide grating structure inscribed with a holographic surface relief grating*," Preparing to submit to Opt. Express
3. **J. H. Lin**, C.-Y. Tseng, C.-T. Lee, J. F. Young, H.-C. Kan, and C. C. Hsu, "*Strong guided mode resonant local field enhanced visible harmonic generation in an azo-polymer resonant waveguide grating*," Opt. Express **22**, 2790-2797 (2014).
4. **J. H. Lin**, C.-Y. Tseng, C.-T. Lee, H.-C. Kan, and C. C. Hsu, "*Guided-mode resonance enhanced excitation and extraction of two-photon photoluminescence in a resonant waveguide grating*," Opt. Express **21**, 24318-24325 (2013).
5. **J. H. Lin**, W. L. Chang, H.-Y. Lin, T.-H. Chou, H.-C. Kan, and C. C. Hsu, "*Enhancing light extraction efficiency of polymer light-emitting diodes with a 12-fold photonic quasi crystal*," Opt. Express **21**, 22090-22097 (2013).
6. C.-Y. Lin, C.-S. Chang, **J. H. Lin**, C.-C. Hsu, and F. S.-S. Chien "*Optical controlled graphene-based nonvolatile ternary-logic transistor with azobenzene copolymer*," Appl. Phys. Lett. **102**, 013505 (2013).

Awards

1. Upconversion

2. Resonant waveguide grating or Photonic crystal substrate




Outline

- Introduction
  - Interaction of light and optical media !
  - Mechanisms of nonlinear signals !
  - What is photonic crystal substrate (or called resonant waveguide grating)!
  - Our motivation !
- Photonic crystal substrate
  - Enhanced two-photon photoluminescence (PL)!
  - GMR enhanced SHG and THG !
  - GMR enhanced upconversion PL !
- Conclusions

Interaction of light and optical media

Wave equation in optical media :

$$\nabla^2 \vec{E} - \frac{n^2}{c^2}\frac{\partial \vec{E}}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial^2 \vec{P}}{\partial t^2}$$

The polarization can be expressed as a power series in the incident field stregth as :

$$\vec{P} = \chi^{(1)}\vec{E} + \chi^{(2)}\vec{E}\vec{E} + \chi^{(3)}\vec{E}\vec{E}\vec{E} + \cdots$$

The polarization can be considered as a sum of a linear and nonlinear component:

$$\vec{P} = \vec{P}^{L} + \vec{P}^{NL},$$

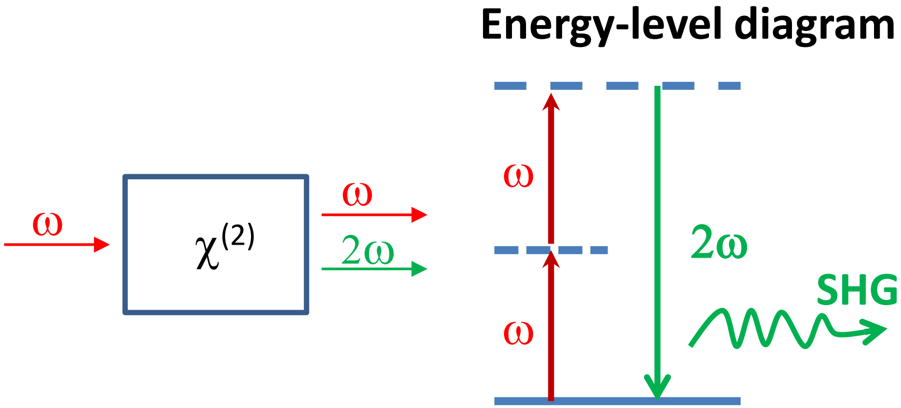
To produce nonlinear signals need multi-photon absorption !

Nonlinear signals:

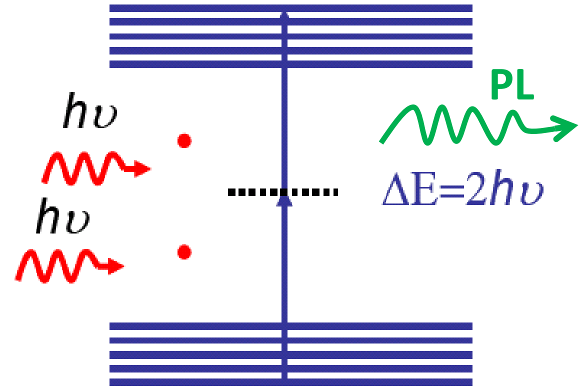
1. **Two-photon photoluminescence,**
2. **Second-or third harmonic generation.**
3. **Upconversion photoluminescence**

Mechanisms of three nonlinear signals (upconversion)

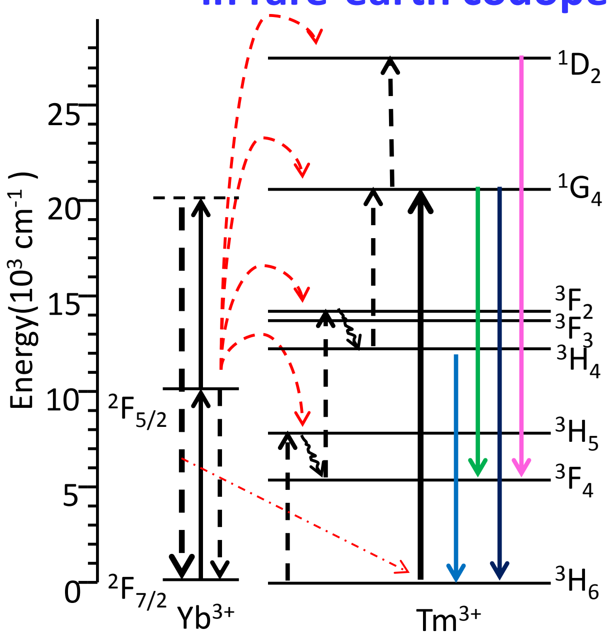
1. Geometry of second-harmonic generation (SHG)

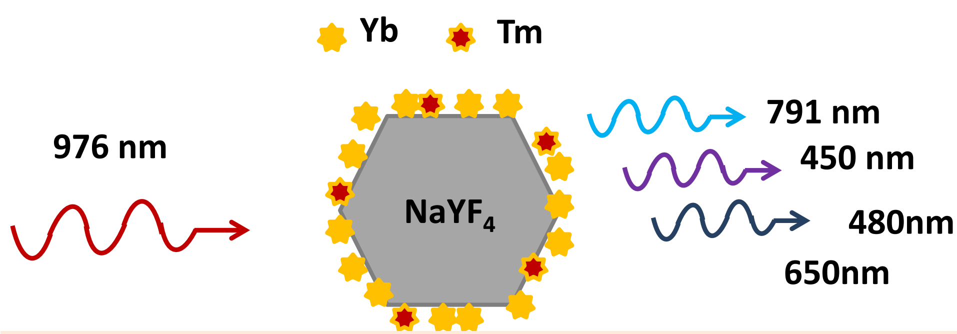


2. Energy diagram of two-photon photoluminescence (PL)



3. Energy diagram of upconversion photoluminescence in rare-earth codoped upconversion nanocrystals

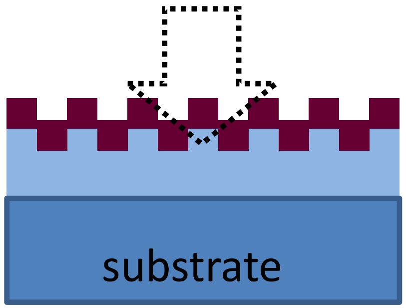




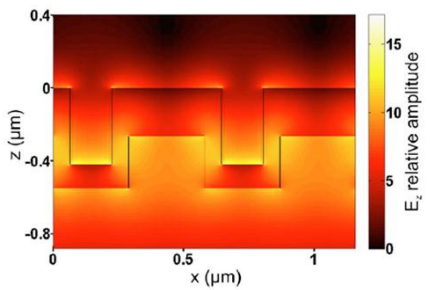
To generate nonlinear signals, higher excitation intensity is required!

What is photonic crystal substrate ?

- material with high refractive index
  e.g. Si, TiO_2 , …etc.
- material with low refractive index
  e.g. SiO_2, SU8,…etc.

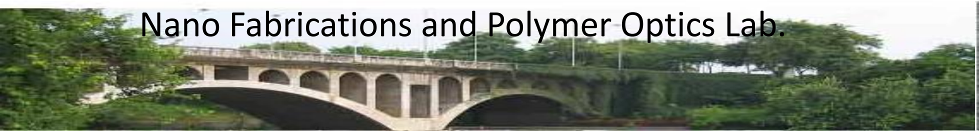


Photonic crystal substrate (resonant waveguide grating, RWG)



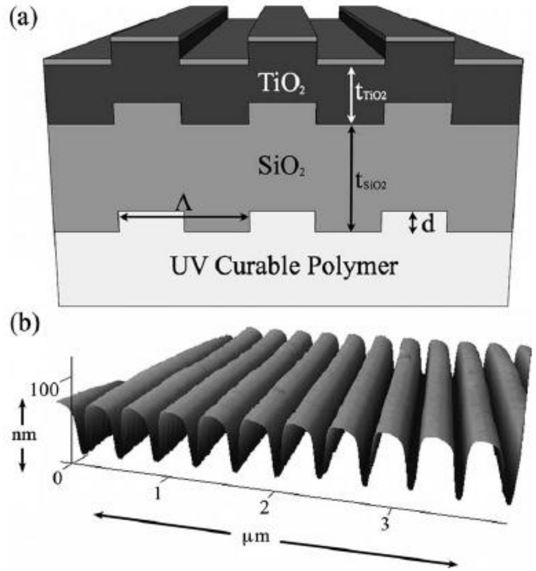
Ref. Appl. Phys. Lett. 91 111109 (2007)

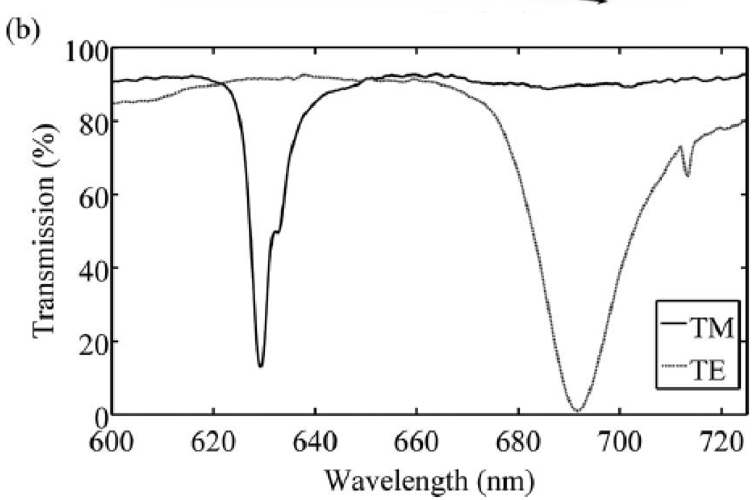
RWG can produce very sharp guided-mode resonance (GMR) !
In particular, the strong local field can be generated at the surface of RWG !
That is very interesting for nonlinear optical effect !

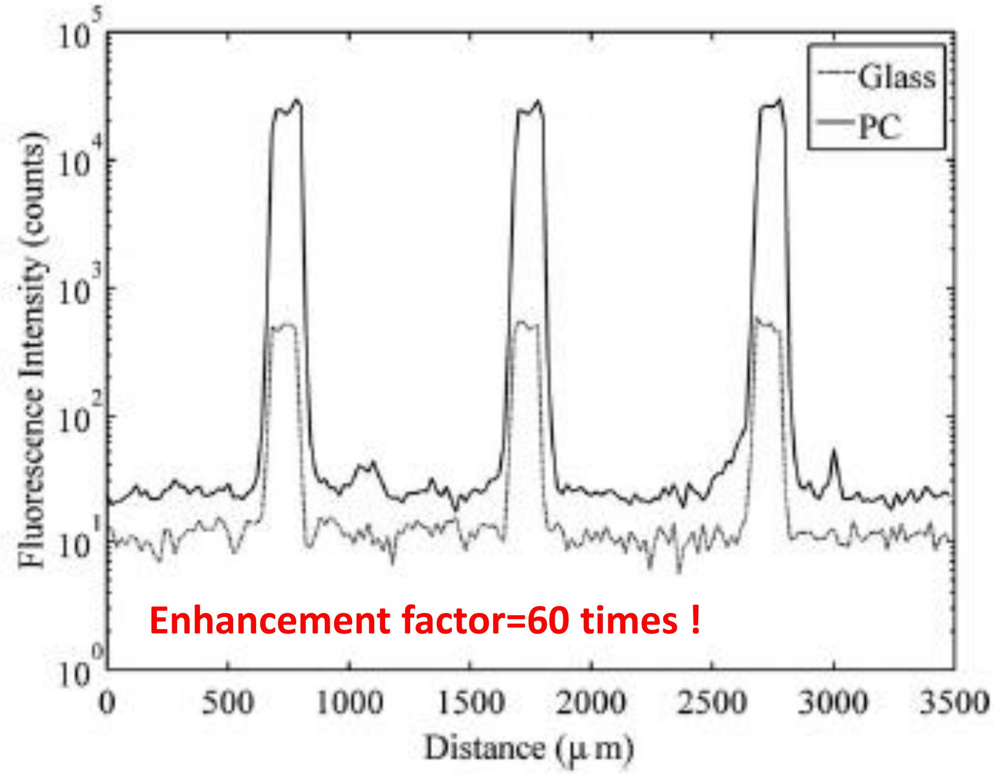


Photonic crystals filter biosensors

Photonic-crystal biosensor filter !

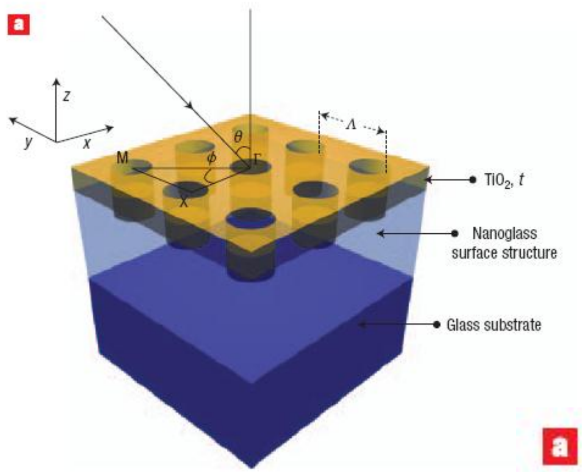


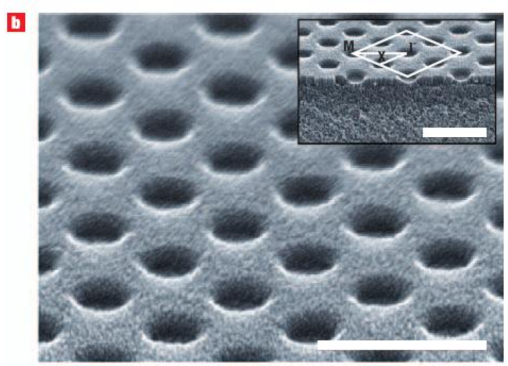




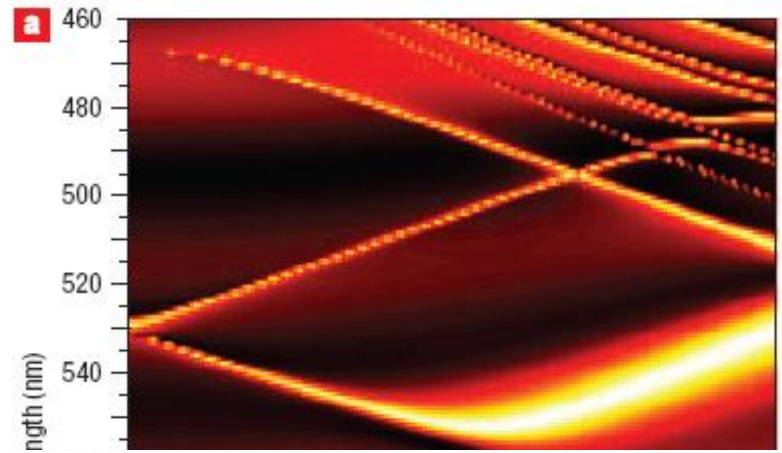
Ref. Appl. Phys. Lett. 95 021111 (2009)

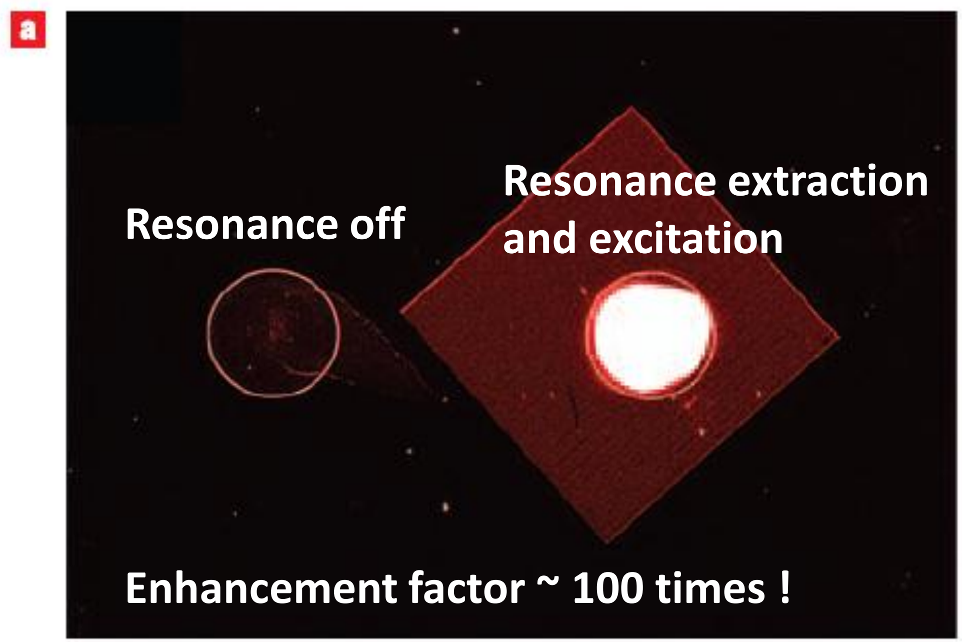
Enhanced fluorescence emission from quantum dots on a photonic crystal surface !





Ref. Nature nanotechnology 2, 515 (2007)





Motivation

To design and fabricate a RWG based on two-beam interference technique for enhancing nonlinear signals !

Two-beam interference technique

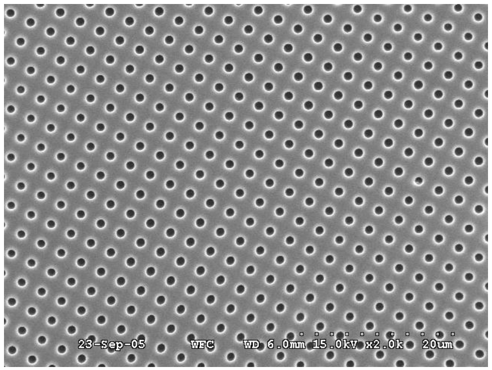
Advantage:

Fast and easy for fabricating a large grating structure.

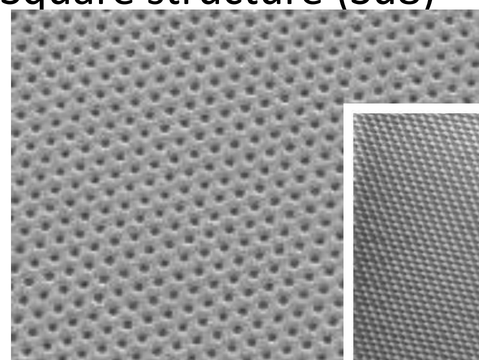
Opt. Express 14, 10746-10752 (2006)
Opt. Express **17**, 3362-3369 (2009)
Appl Opt 50, 579 (2011)

1. Fabrication of micro-nano structures

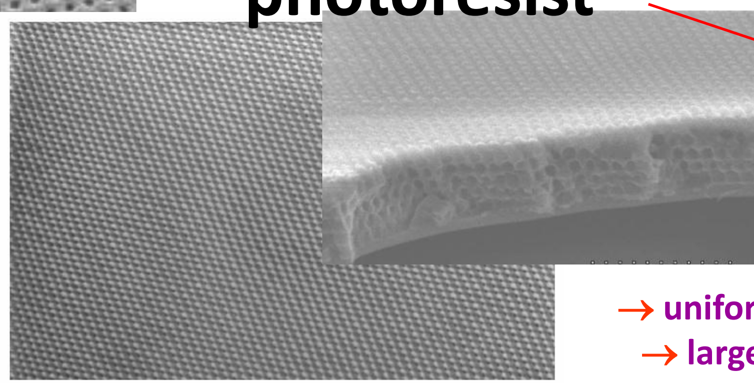
Two-beam interference technique



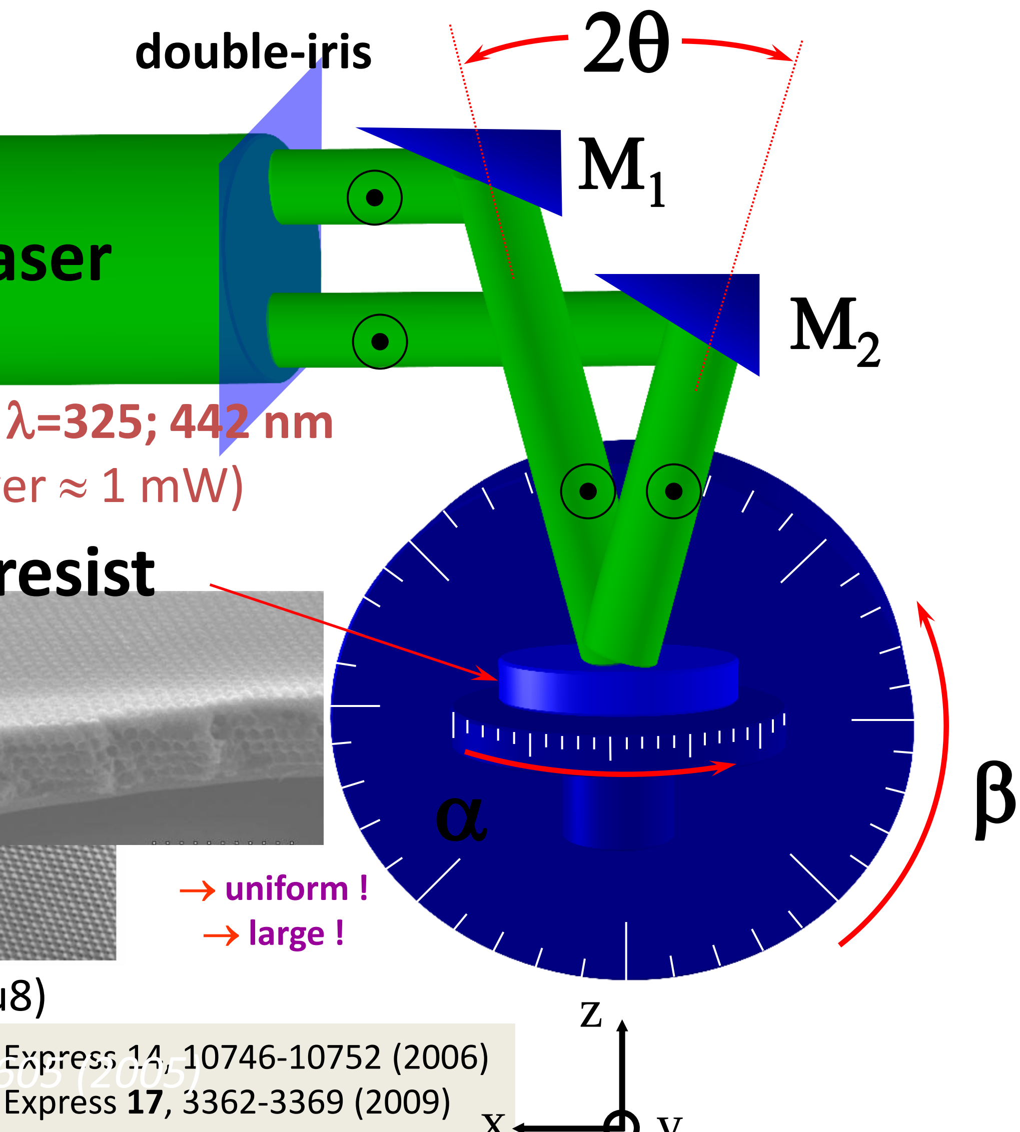
Square structure (Su8)



Hexagonal struct



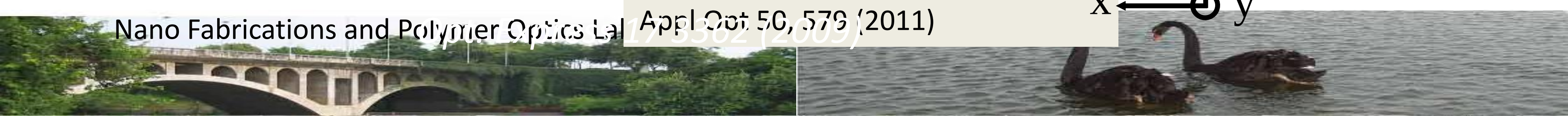
3D structure (Su8)



- He-Cd, λ=325; 442 nm (power ≈ 1 mW)

→ uniform !
→ large !

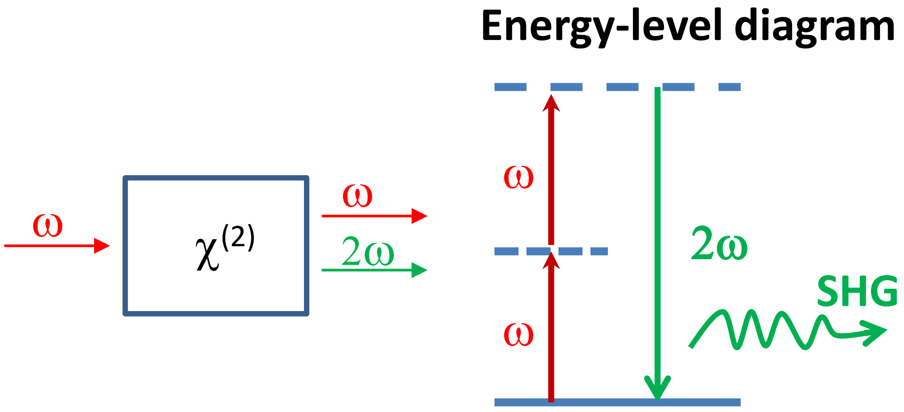
Opt. Express 14, 10746-10752 (2006)
Opt. Express **17**, 3362-3369 (2009)
Appl Opt 50, 579 (2011)



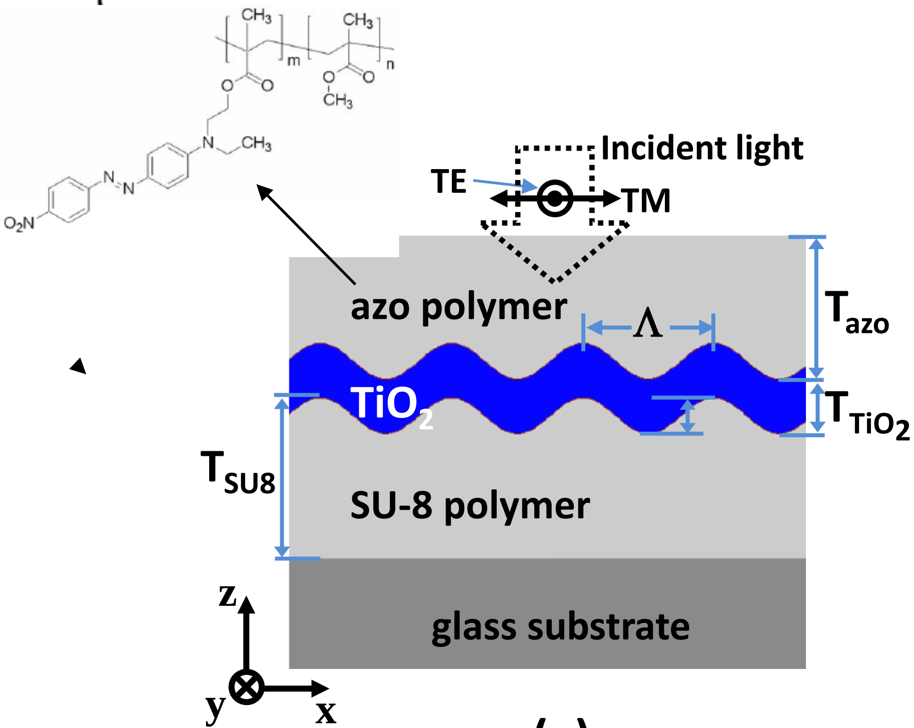
Photonic crystal substrate

➤GMR enhanced SHG and THG !

1. Geometry of second-harmonic generation (SHG)



Design and fabrication of RWG



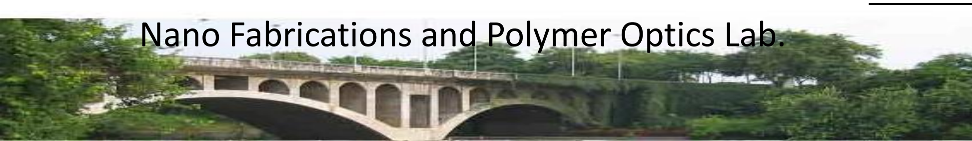
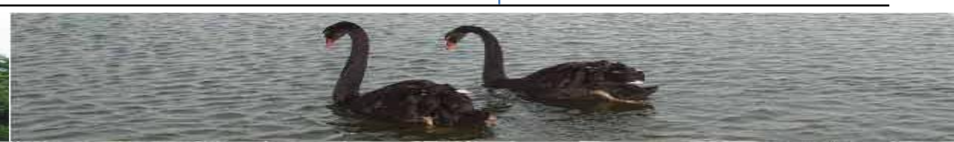
(a)

Fabrication process:

- → 1D SU8 grating structure on SU8 buffer layer was fabricated by using **two-beam interference technique** !
- → **TiO2 thin layer** was coated on the top of 1D SU8 grating layer **using E-gun evaporation** !
- → To produce second- and third-harmonic generation, an **azo copolymer thin film**, was spun-cast on the top of the TiO_2 layer with a thickness about 600nm-1um.
- → **A corona electric field poling technique** was employed to align azo- copolymer to form non-centro symmetric distribution.

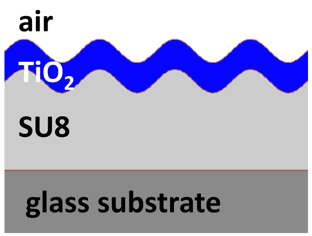
Table: sample parameters in experiment

Period=845nm Groove of grating=210 +/- 10 nm	T_SU8=950 +/- 50nm; n_SU8=1.56 at1.3 um
T_TiO2=180 +/- 10nm; n_TiO2=2.25 at 633 nm	T_azo=690+/- 10nm ; n_azo=1.53 at 1.3 um

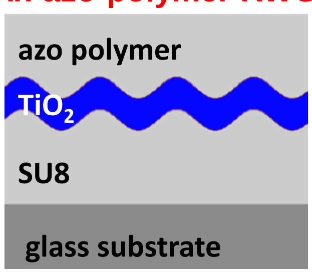
GMR in a normal RWG and an azo-polymer RWG

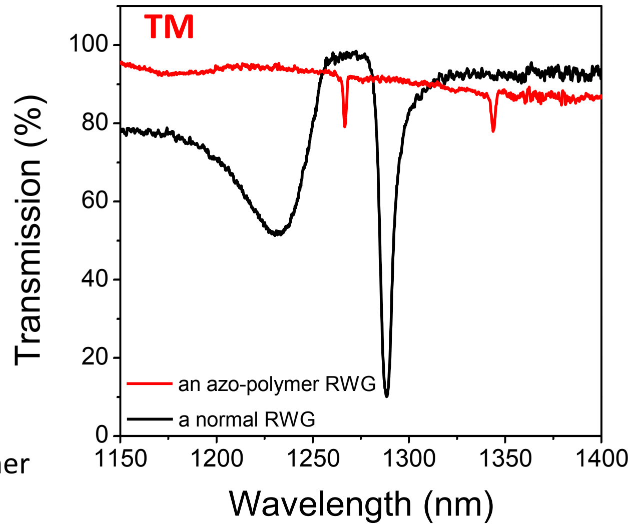
A normal RWG

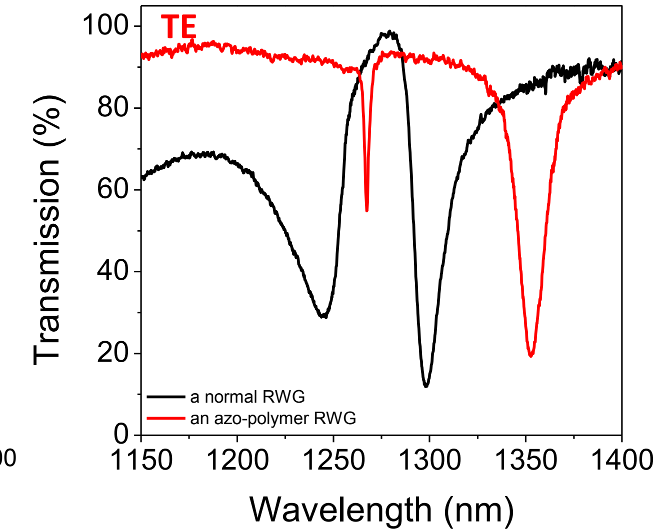


Coated
one azo polymer
and then used
corona poling

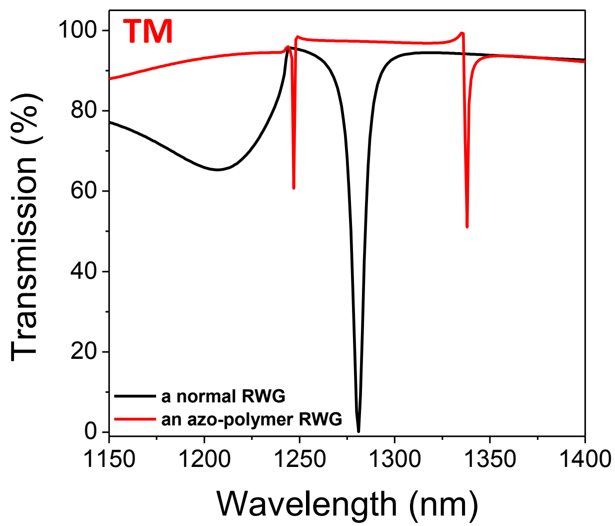
An azo-polymer RWG

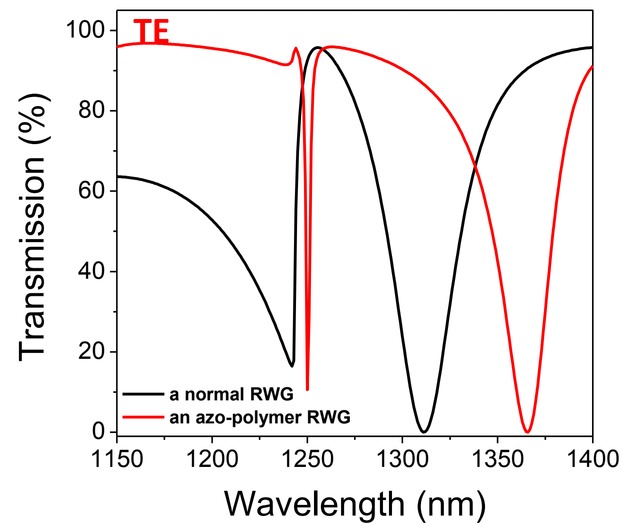


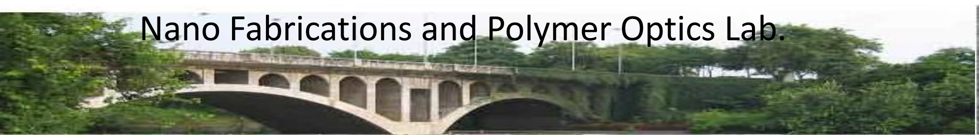




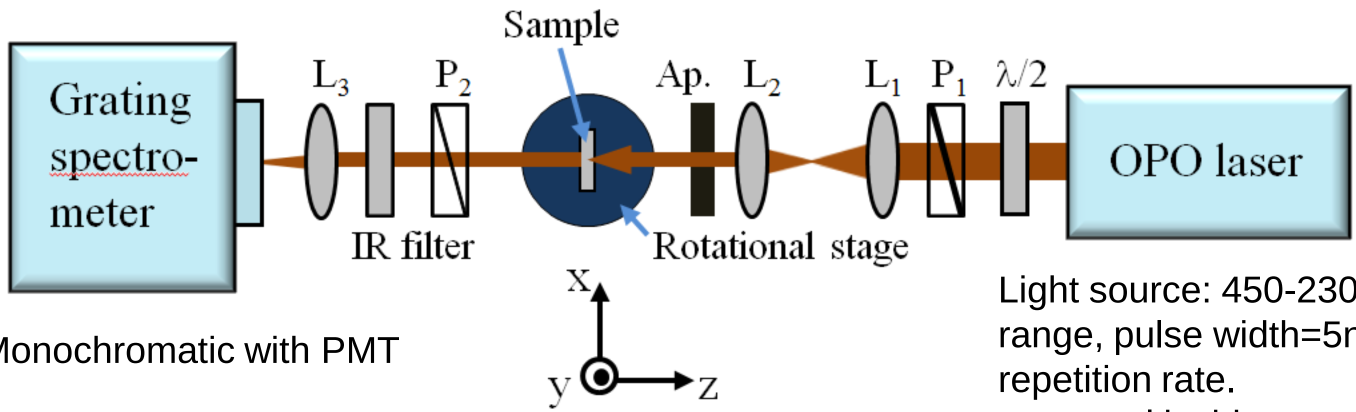
Simulation method: RCWA







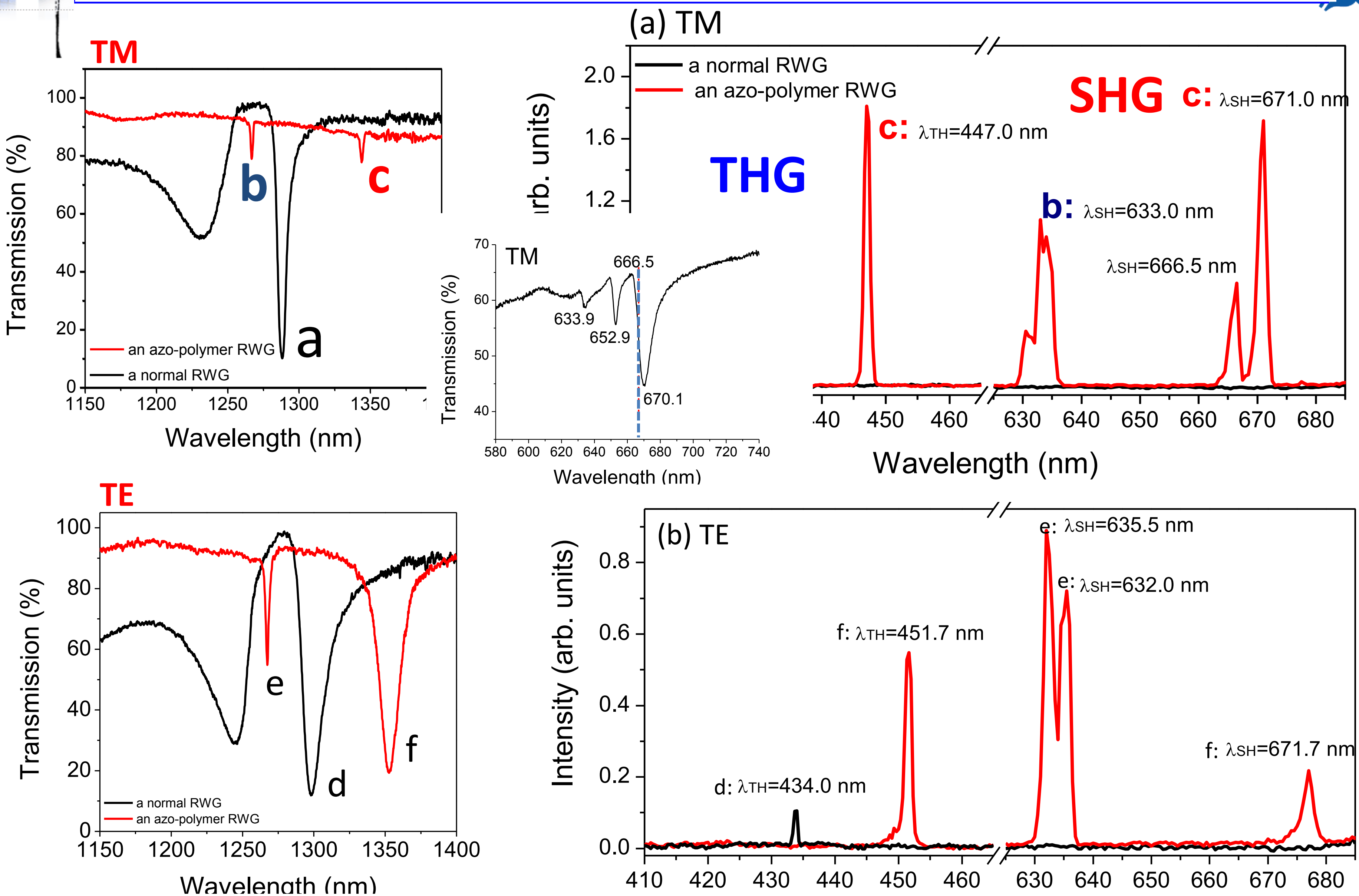

Measurement setup



Detector: Monochromatic with PMT

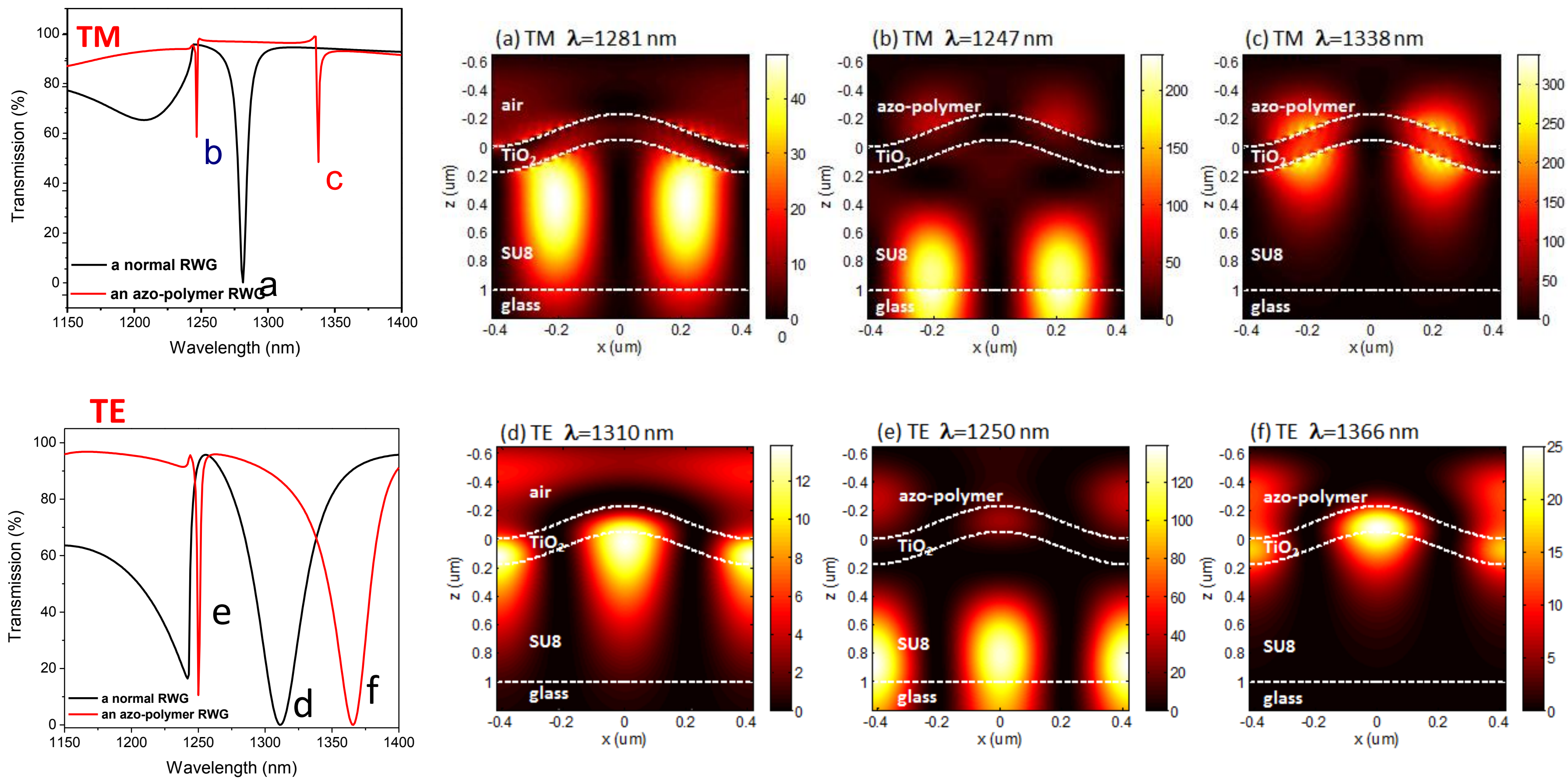
Light source: 450-2300nm wavelength range, pulse width=5ns, 10Hz repetition rate.
at normal incident

GMR enhanced SHG and THG results

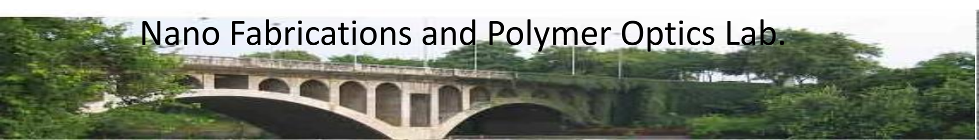


→ **Comparing with a sample without WGS, the SHG and THG output can be enhanced by 1000 times !**

Electric field profile calculations



High SHG and THG output are caused from the strong local field at the interface of an azo-polymer layer and TiO2 !

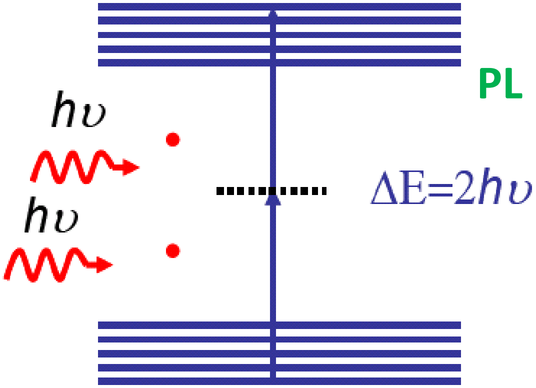


Opt. Express 22, 2790-2797 (2014)

Photonic crystal substrate

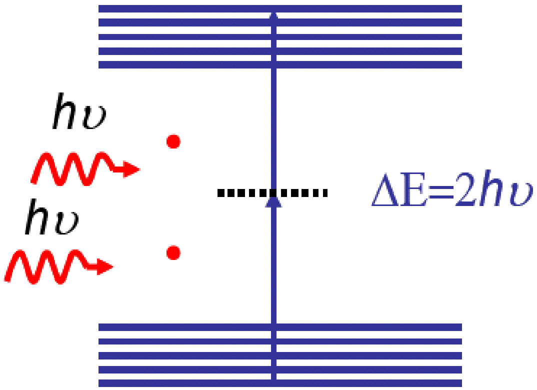
- **Enhanced two-photon PL !**

2. Energy diagram of two-photon photoluminescence (PL)



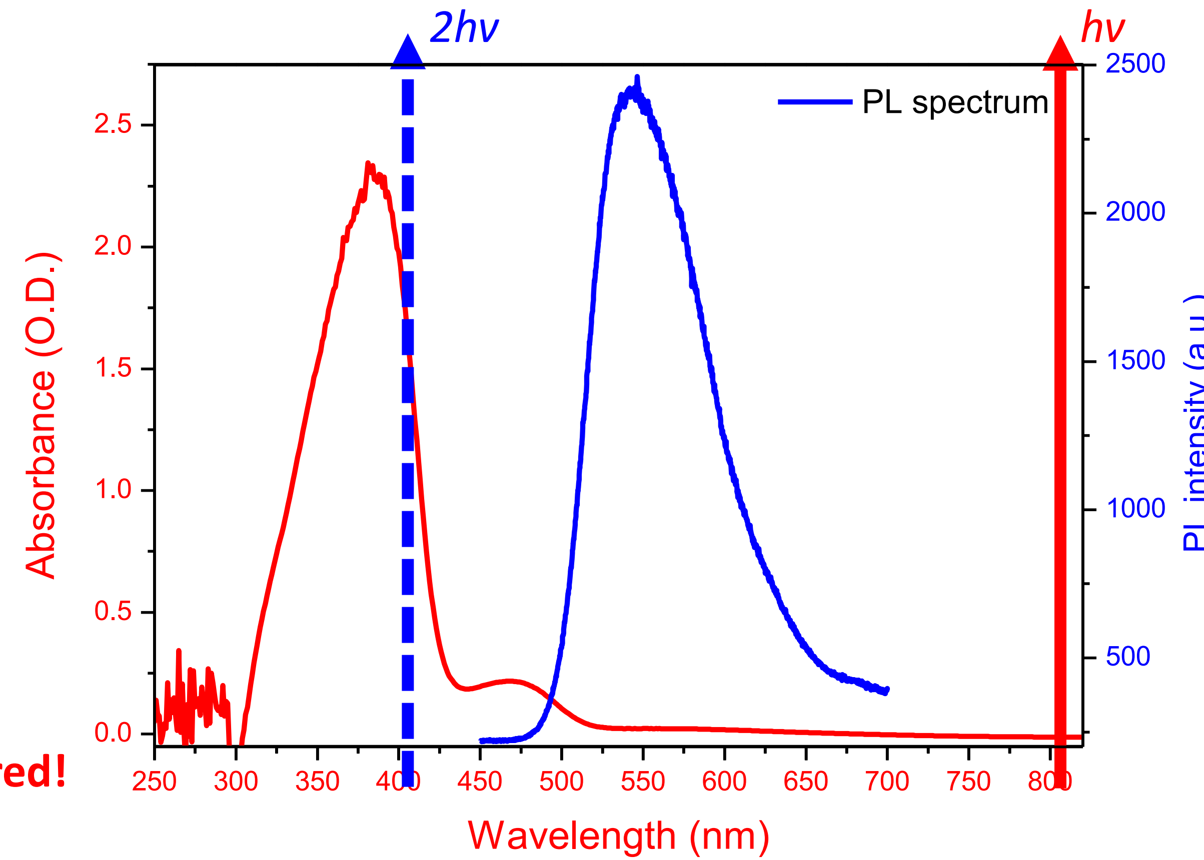
Enhanced two photon PL via RWG structures

Energy diagram of two-photon absorption effect



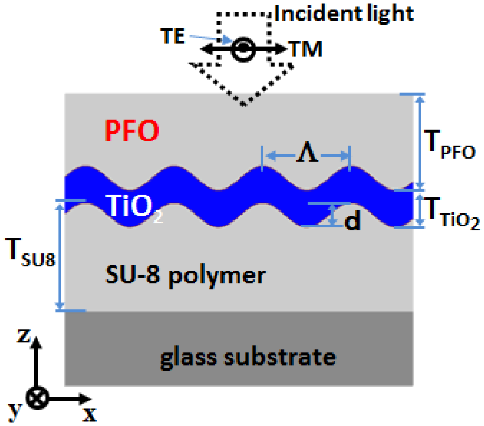
To generate PL signal, higher two-photon excitation intensity is required!

Absorption spectra and Photo-luminescence of PFO thin film

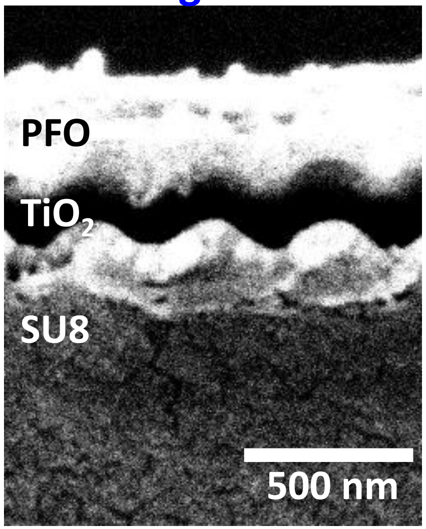


PL spectrum of PFO sample pumped by two photon excitation !

Design and fabrication of RWG with a PFO thin film

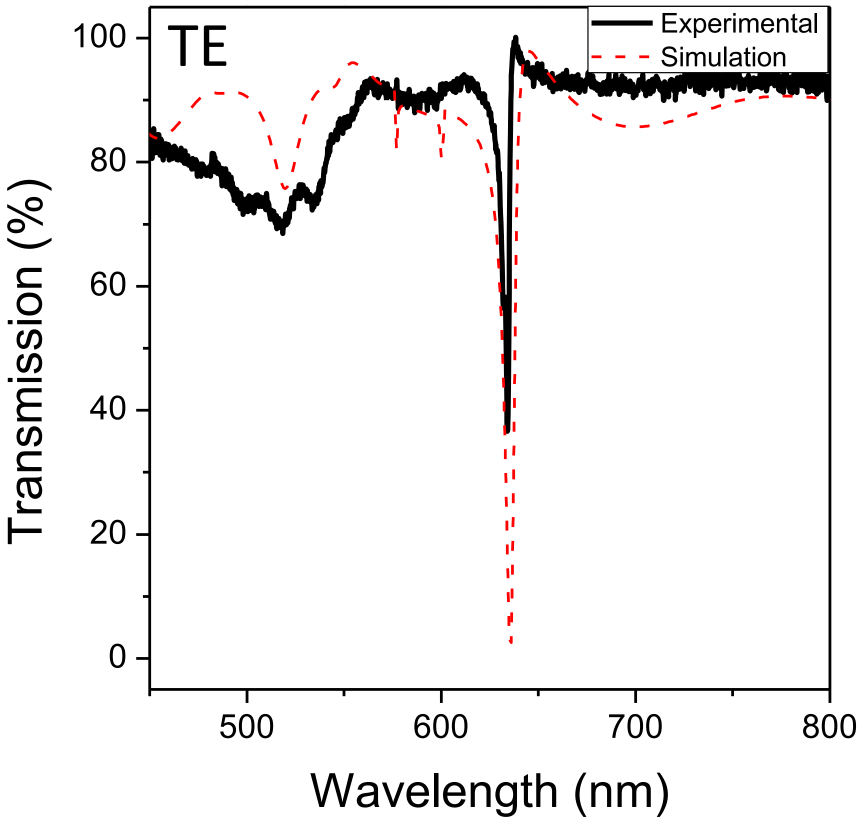


SEM image

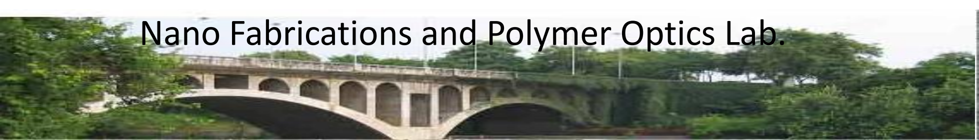


	Experiment	Simulation
Grating	Period=385 nm Depth=90 +/- 10 nm	Period=385 nm Depth=85 nm
TiO2 layer	T_TiO2=60 +/- 5nm; n_TiO2=2.19 at 634 nm	T_TiO2=55 nm; n_TiO2 is dispersion
SU8 layer	T_SU8=1000 +/- 50nm; n_SU8=1.58 at 634 nm	T_SU8=950 nm; n_SU8 is dispersion
PFO film	T_PFO=280+/- 20nm ; n_PFO=1.60 at 634 nm	T_PFO=280 nm ; n_PFO is dispersion

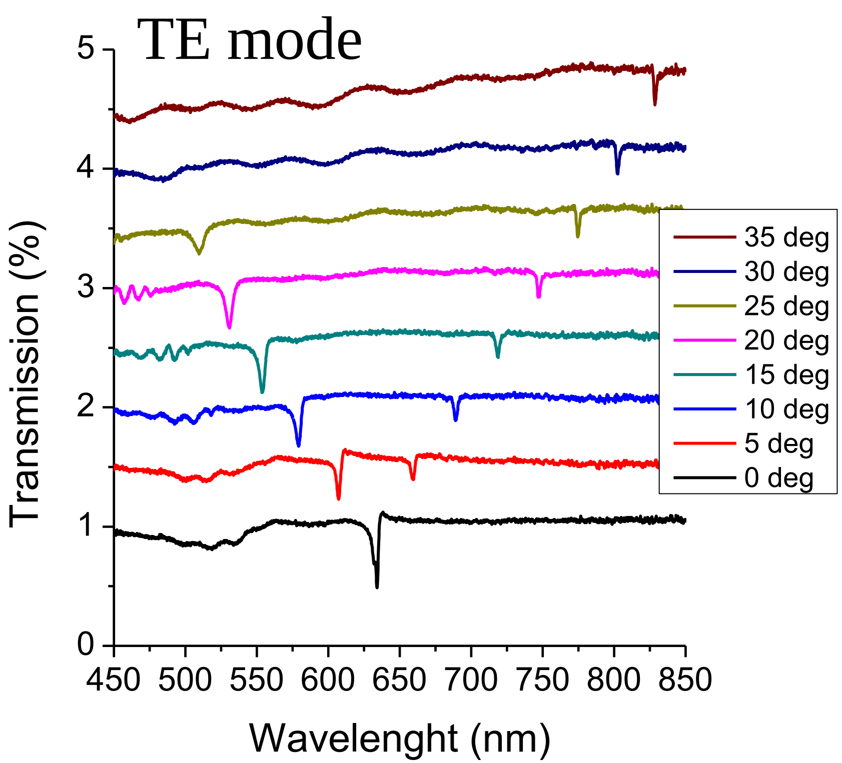
GMR in transmission spectra !

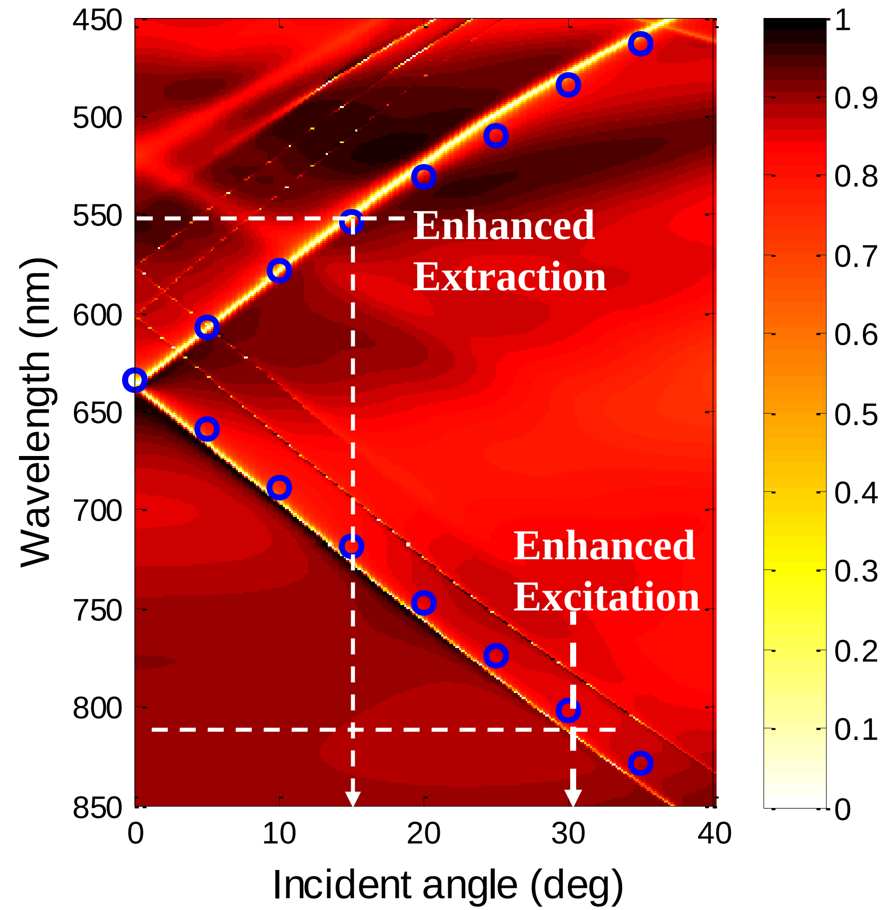


1. TE 634 nm resonant mode at norma incident, and its bandwidth is 4 nm !
2. Agrees well with the prediction of simulation !



Experimental and simulation of angular resolved GMR

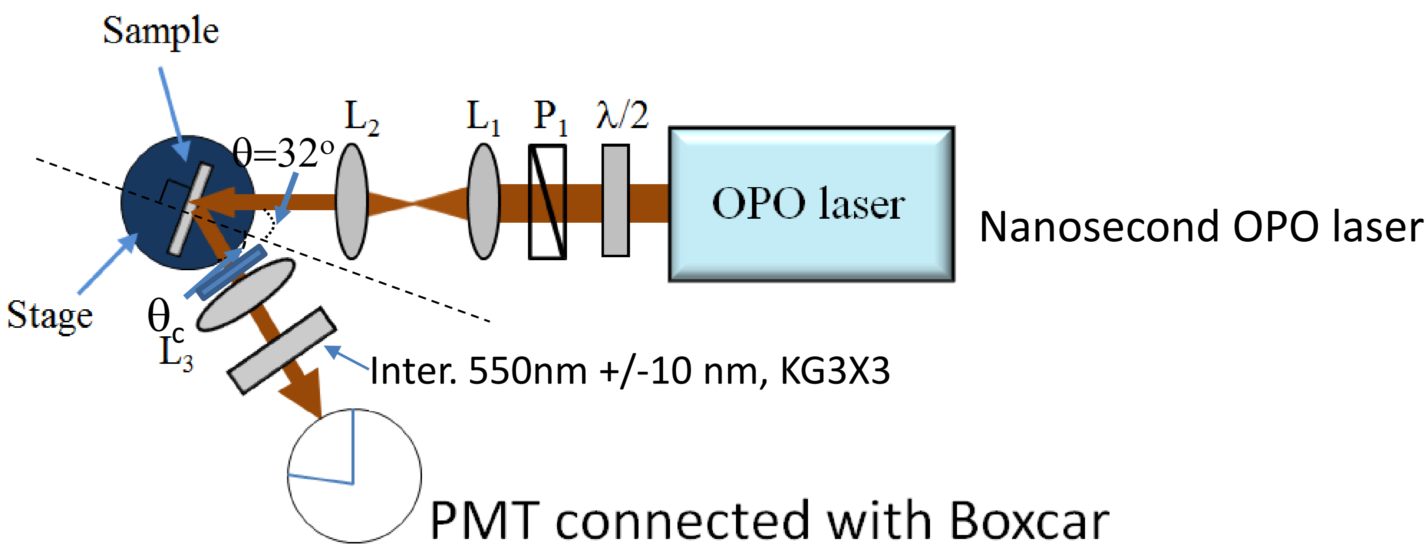




1. GMR at θ=31º ~ 32º can be matched with excitation wavelength (810 nm) !

2. Enhanced PL extraction (550 nm) using GMR at at θ=14º~15º !

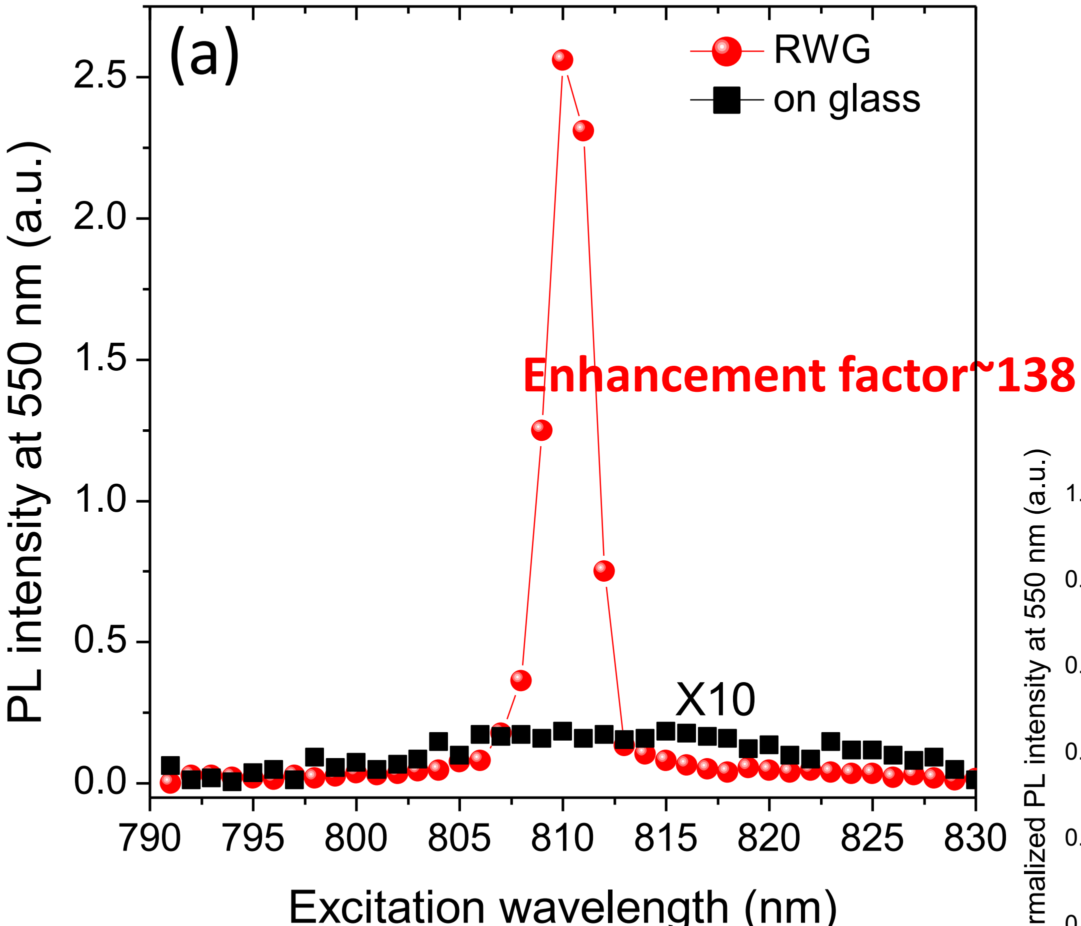
PL measurement setup

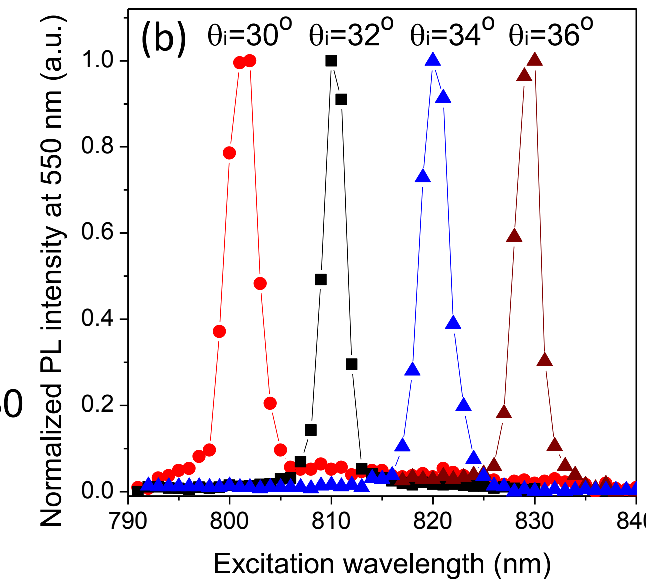


Power= 3 mW at 770-840nm
Pulse width: 5 ns
Repetition rate: 10Hz
Aperture size: 4mm

$θ_c$: emission angle (collected angle)
θ : incident angle

Enhanced PL via resonant two-photon excitation

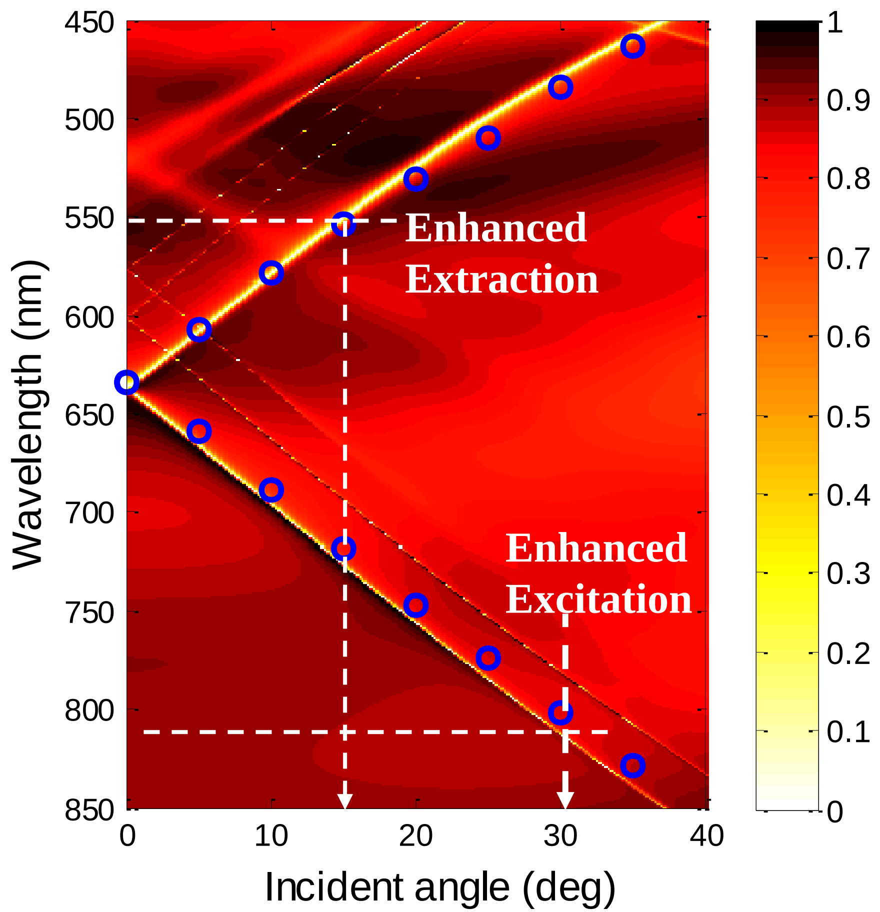




Incident angle at 32 deg

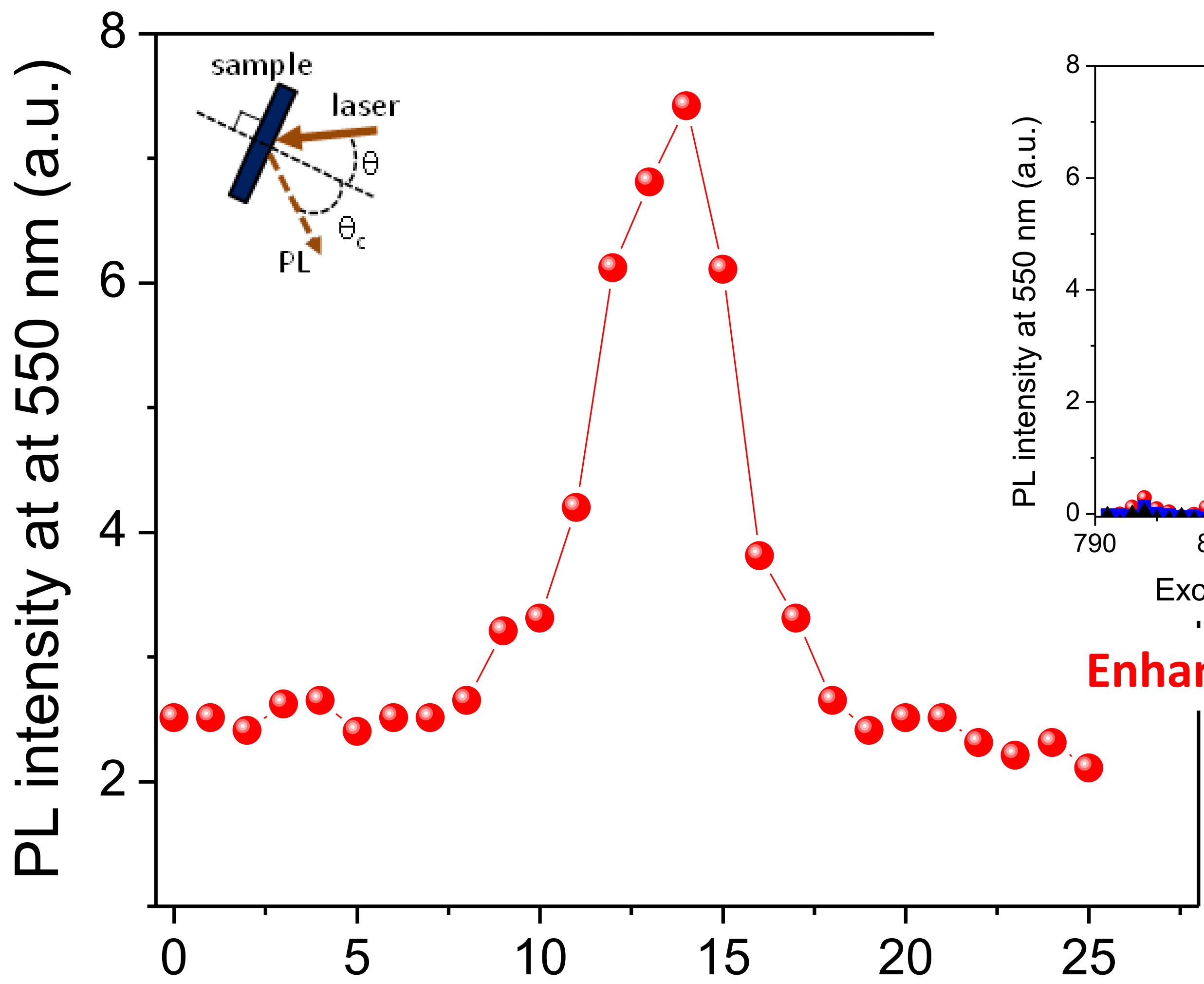
Enhanced PL via GMR enhanced PL and resonant TPE

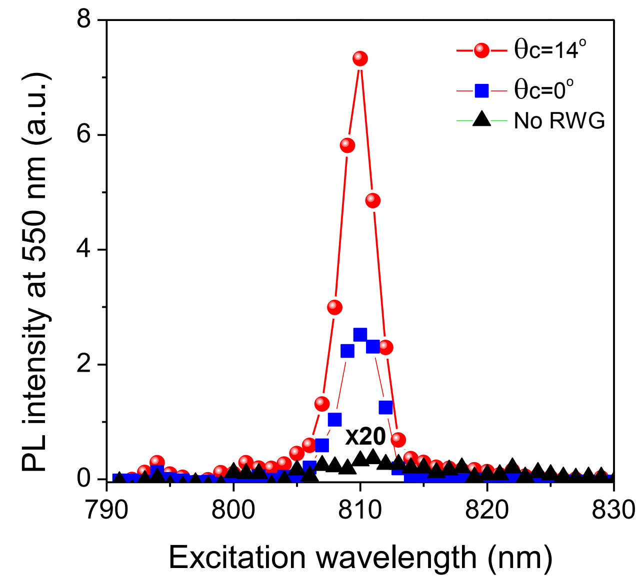
Angular resolved transmission spectra



GMR enhanced PL at collected angle ~14 deg

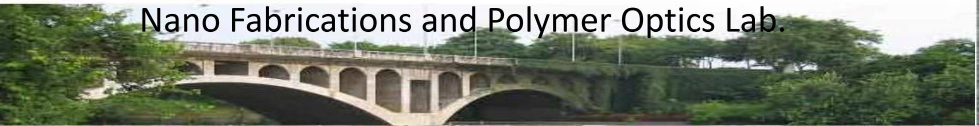
Enhanced PL via GMR enhanced PL and resonant TPE



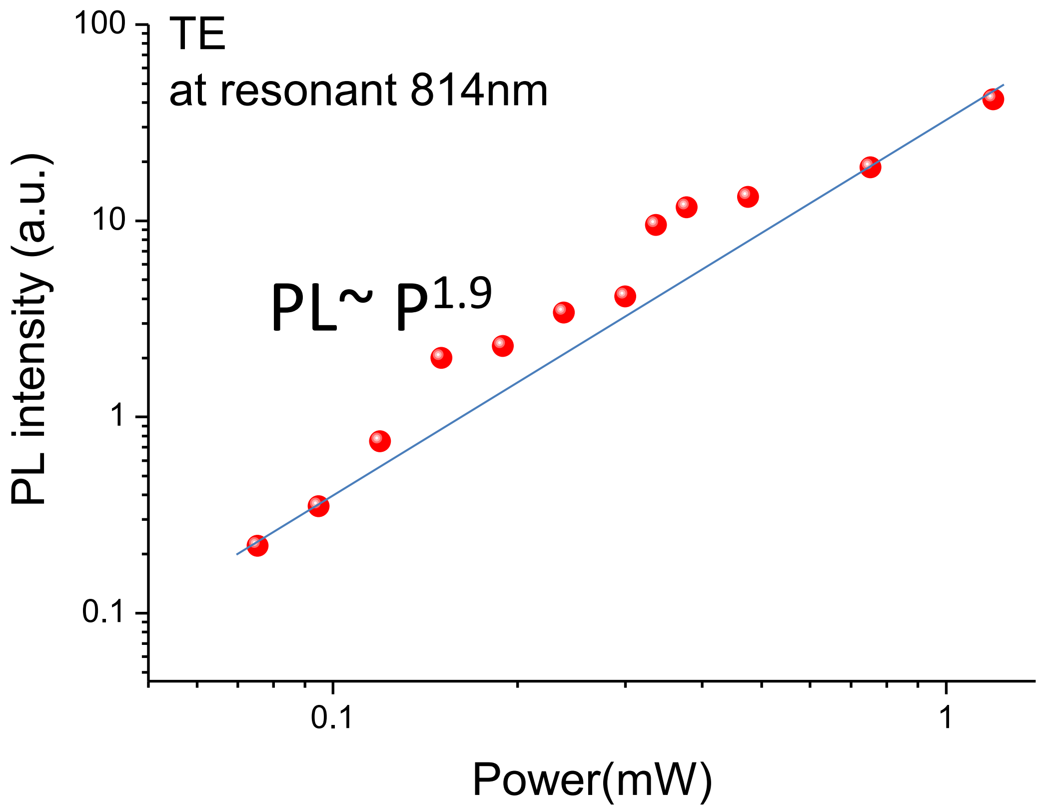


Enhancement factor~300

Incident angle of excitation laser is fixed at 32 deg.



GMR enhanced PL vs two-photon excitation power



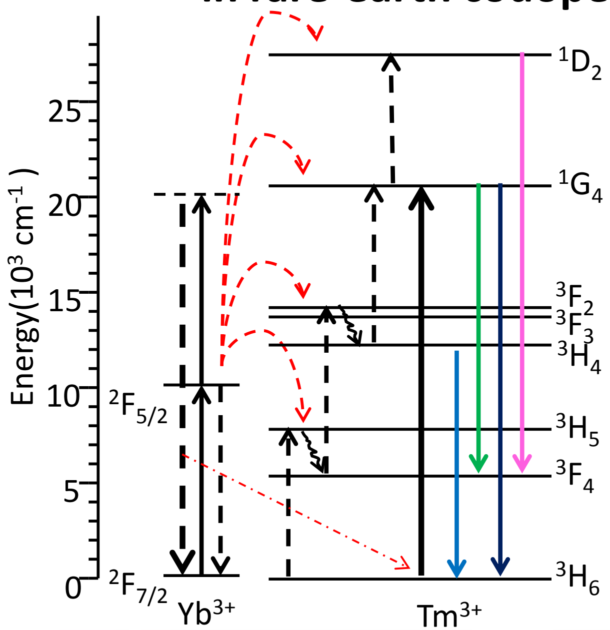
GMR enhanced PL is close to square dependence on excitation power !

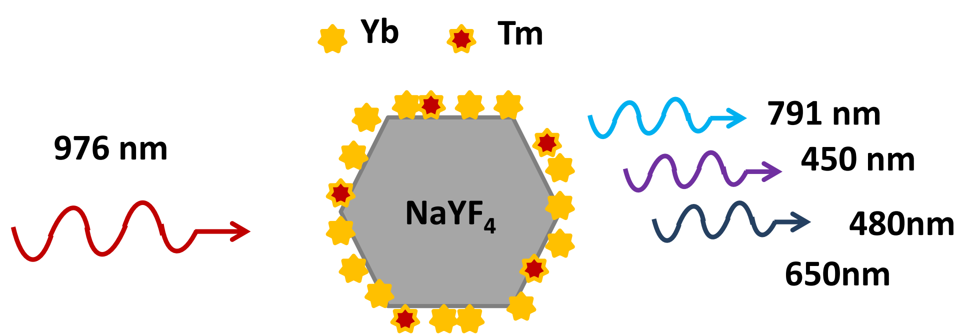
Opt. Express 21, 24318-24325 (2013)

Photonic crystal substrate

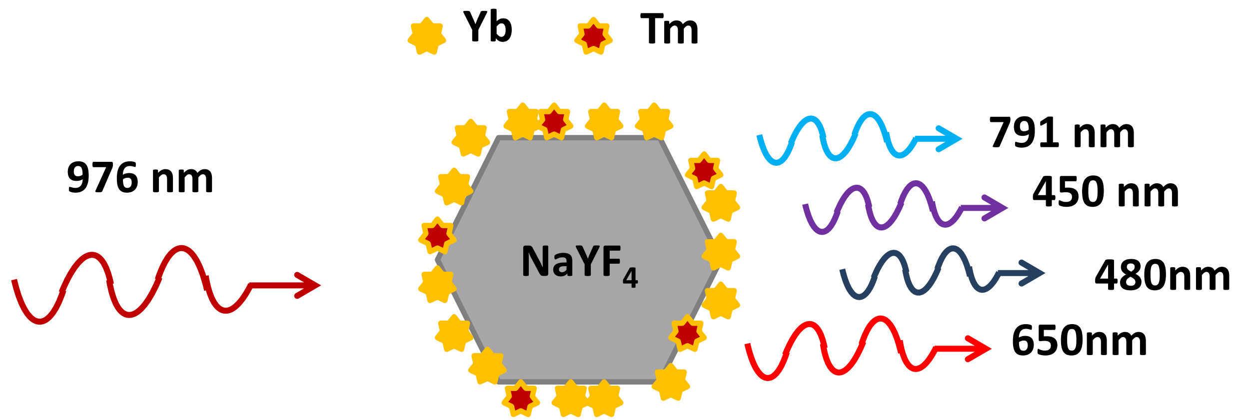
➢GMR enhanced upconversion photoluminescence !

3. Energy diagram of upconversion photoluminescence in rare-earth codoped upconversion nanocrystals

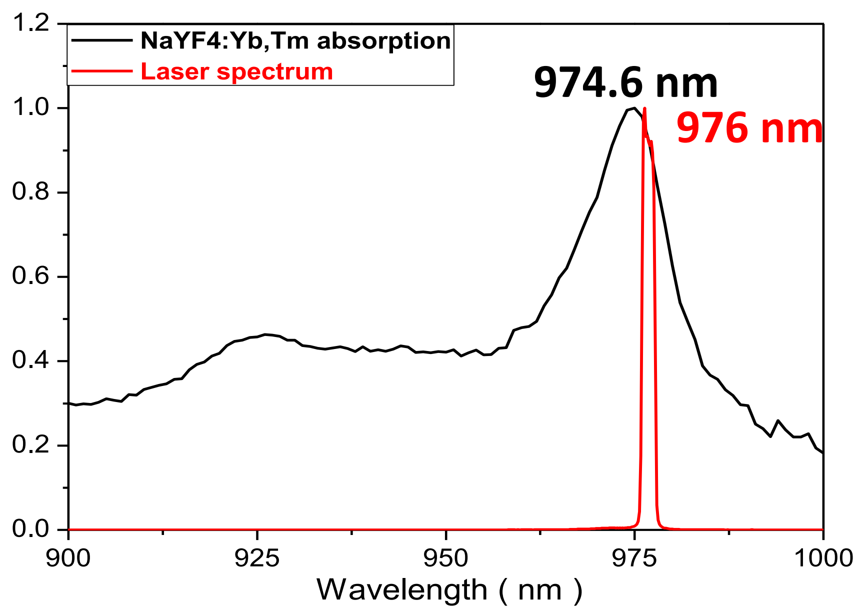




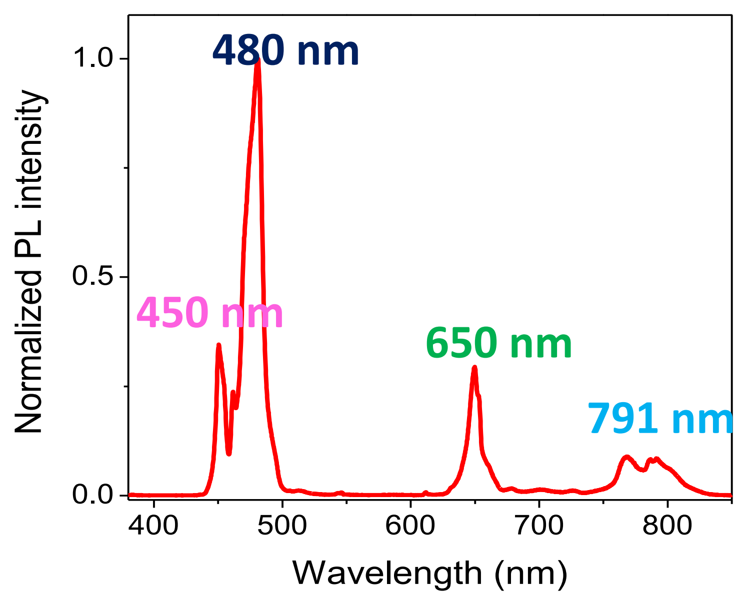
What is up-conversion fluorescence ?



Absorption spectrum



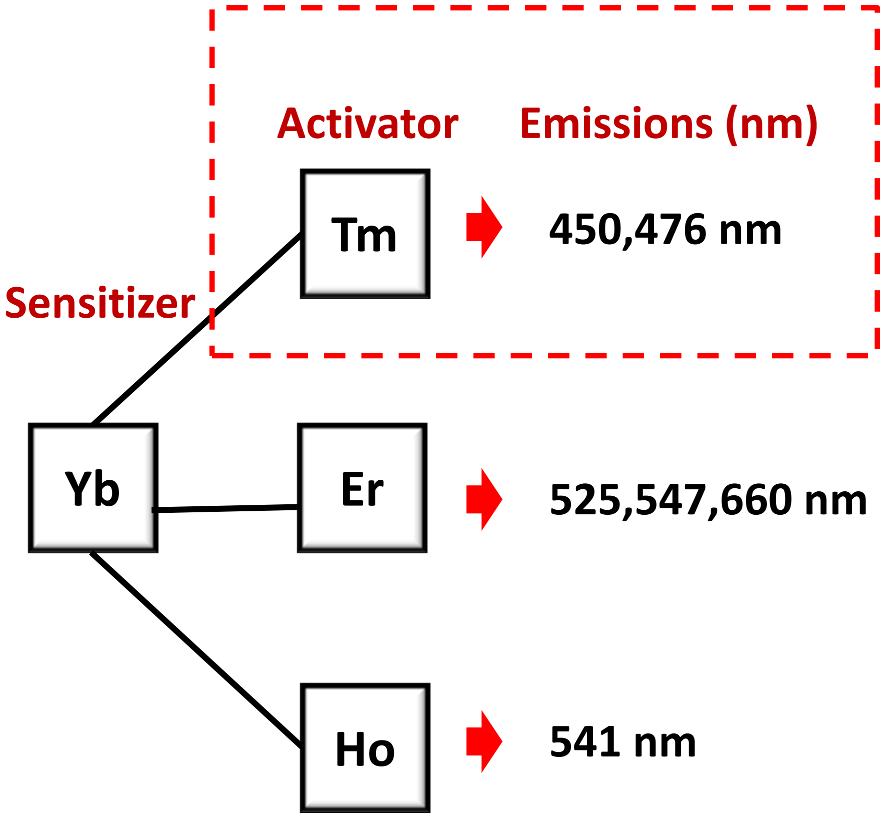
Fluorescent spectrum

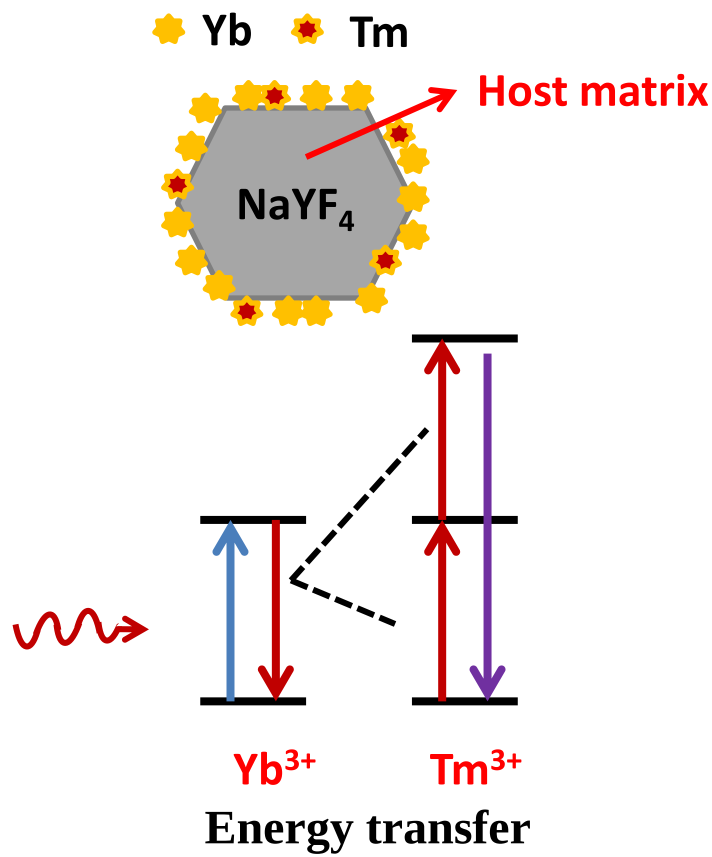


What is up-conversion ?

- Lanthanide series

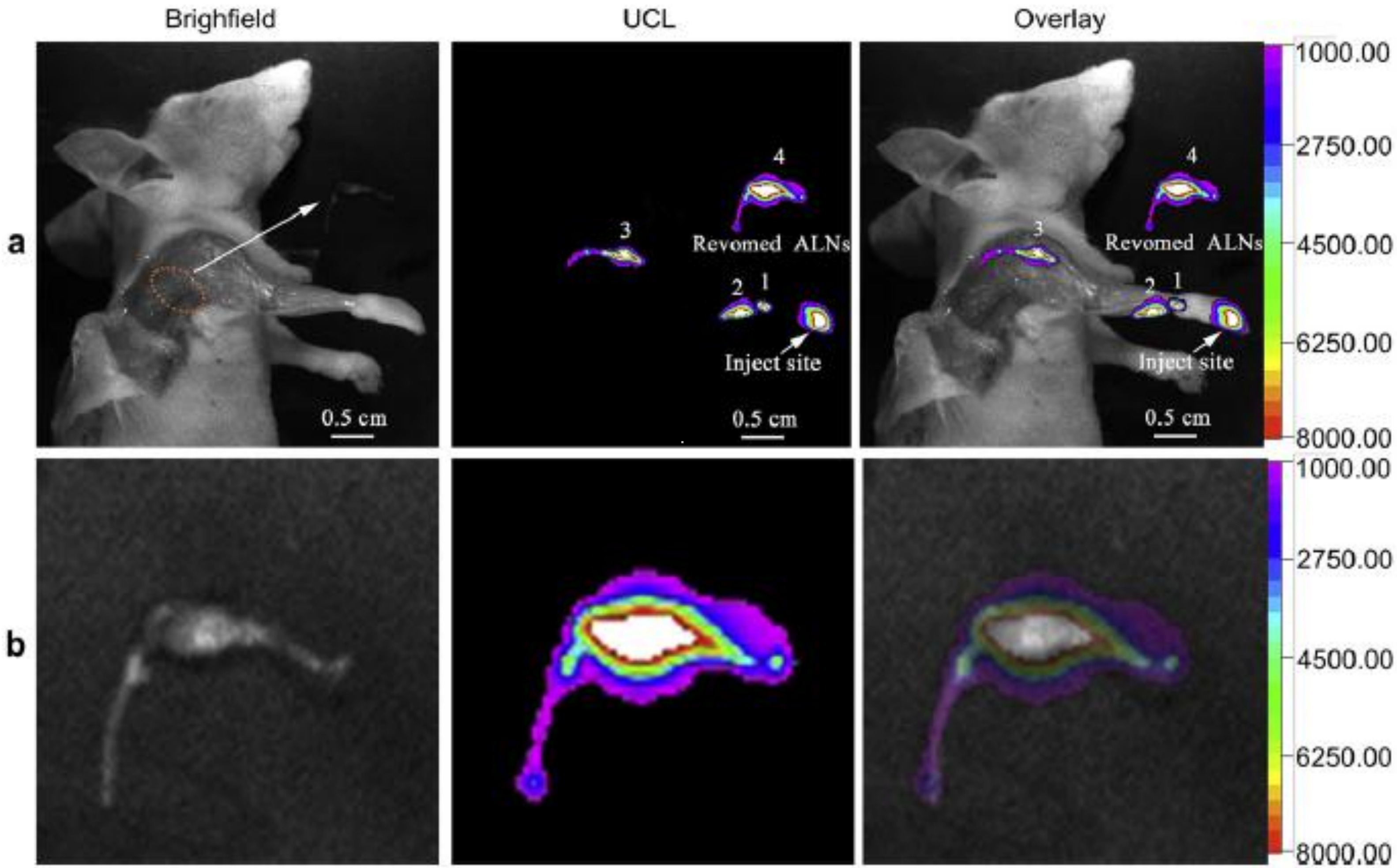
La	Ce	Pr	Nd	Pm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb





Applications of up conversion

Photoluminescence Bioimaging



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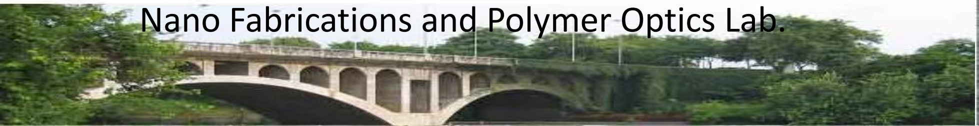
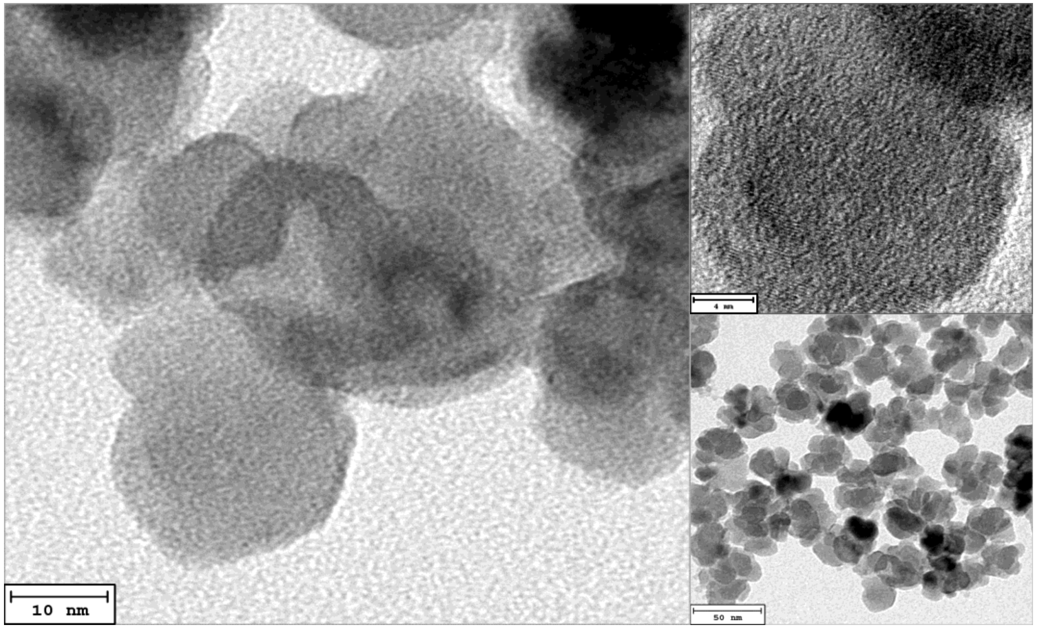
Experimental results

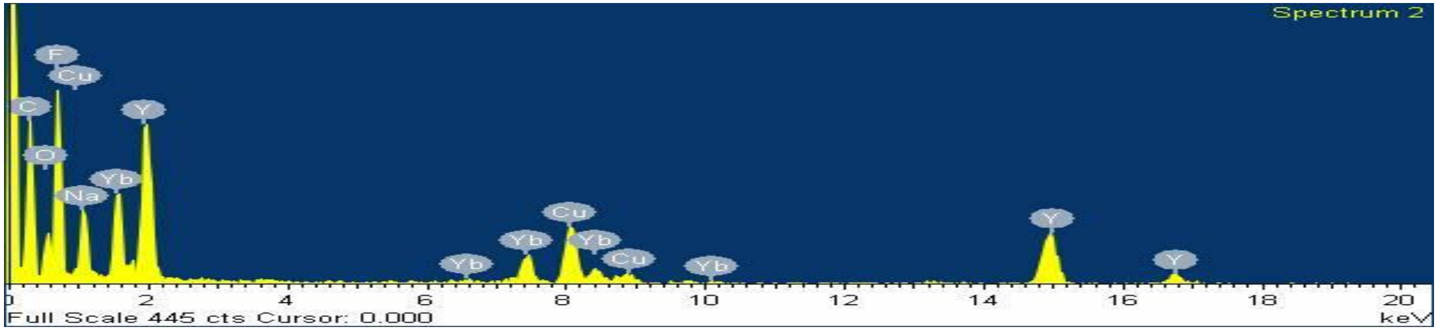


TEM of up-conversion

NaYF4 (40wt%) solution of TEM

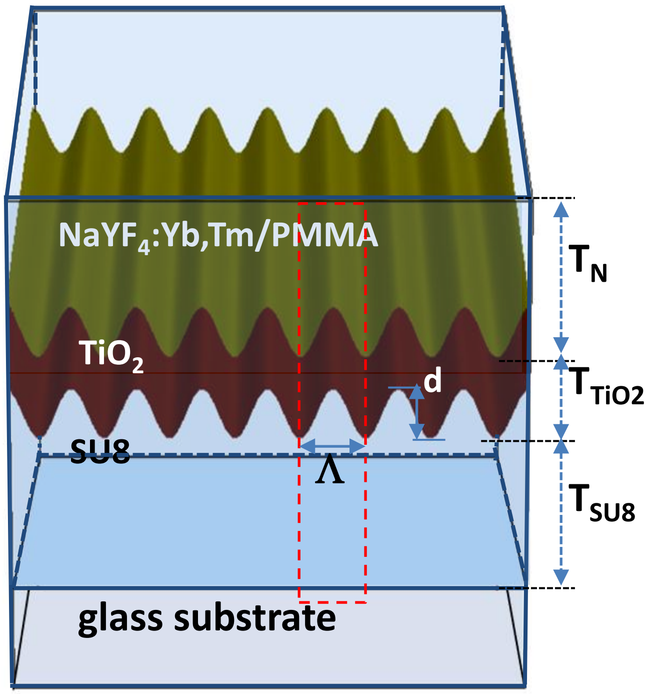


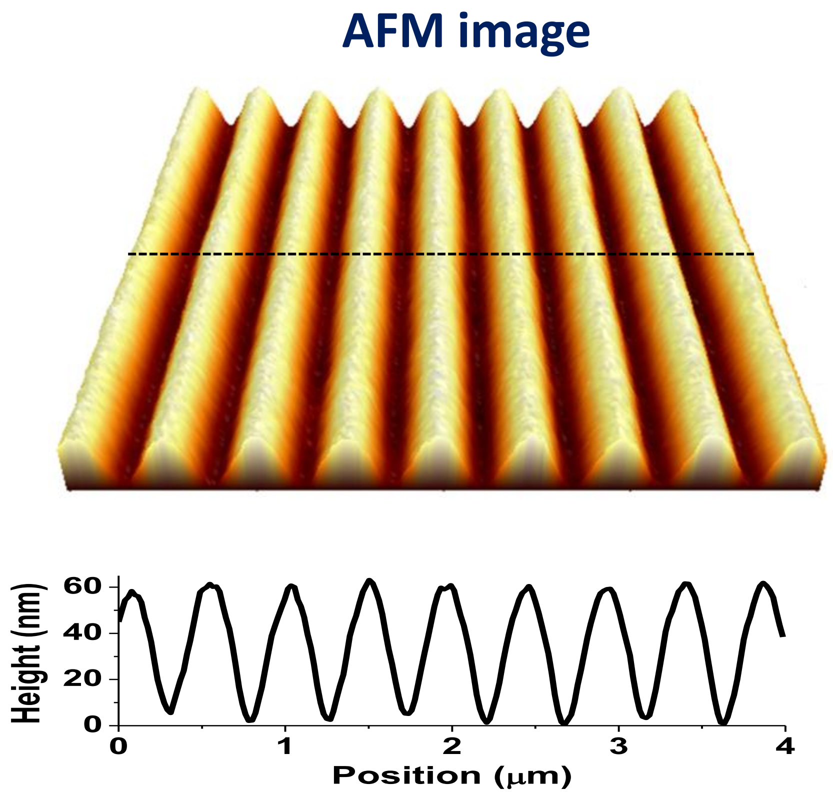
Element	Atomic%
C K	34.30
O K	7.27
F K	22.71
Na K	6.35
Cu K	12.80
Y L	10.71
Yb L	5.85
Totals	



Provided by Prof. Ding

Design and fabrication of RWG

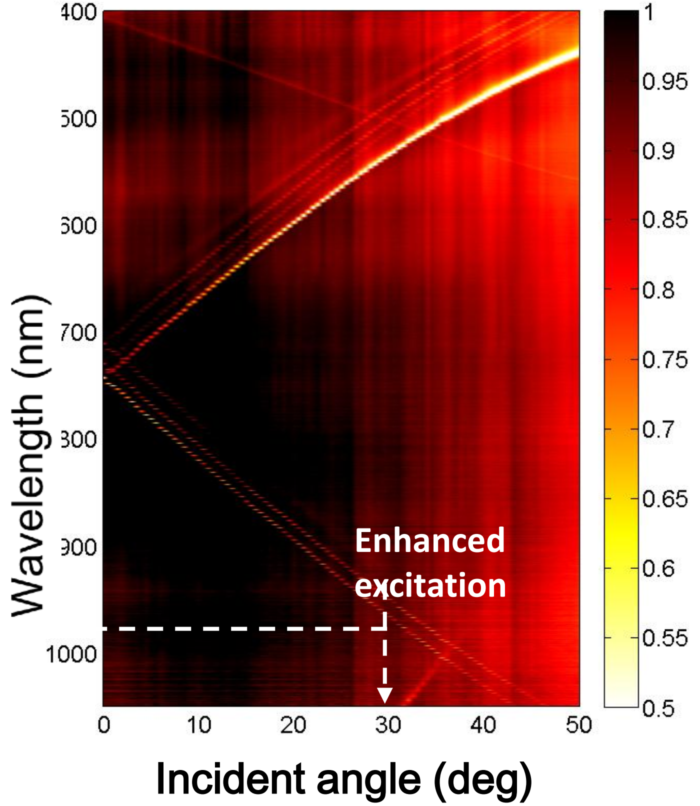


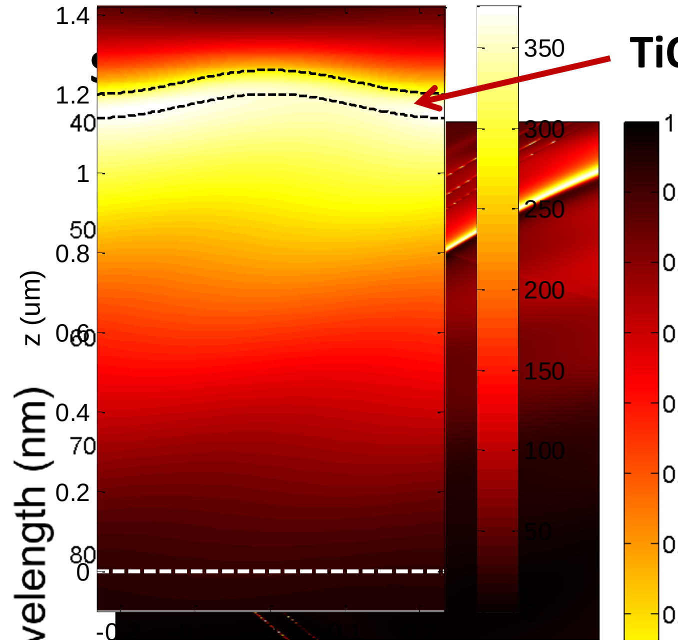


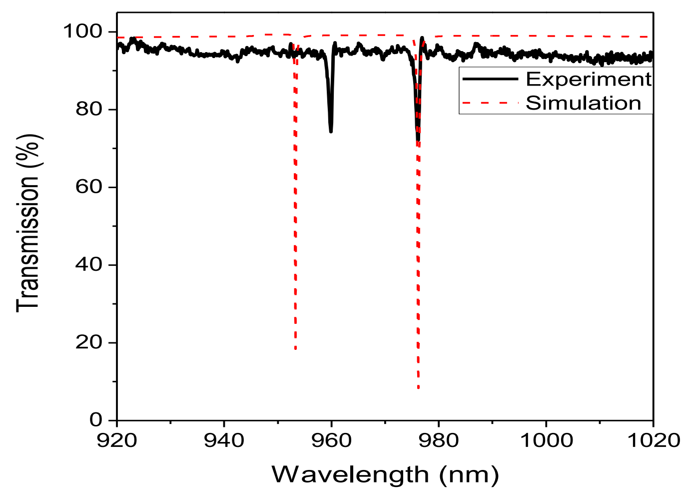
Experimental parameters	
SU8 grating period : 466 nm	PMMA thickness : 250-266 nm
SU8 grating depth : 60 +/- 5 nm	TiO_2 thickness : 60 nm
SU8 thickness : 1500 +/-100 nm	Glass substrate thickness : 2 mm

Transmition spectra of TE mode

Measurement :



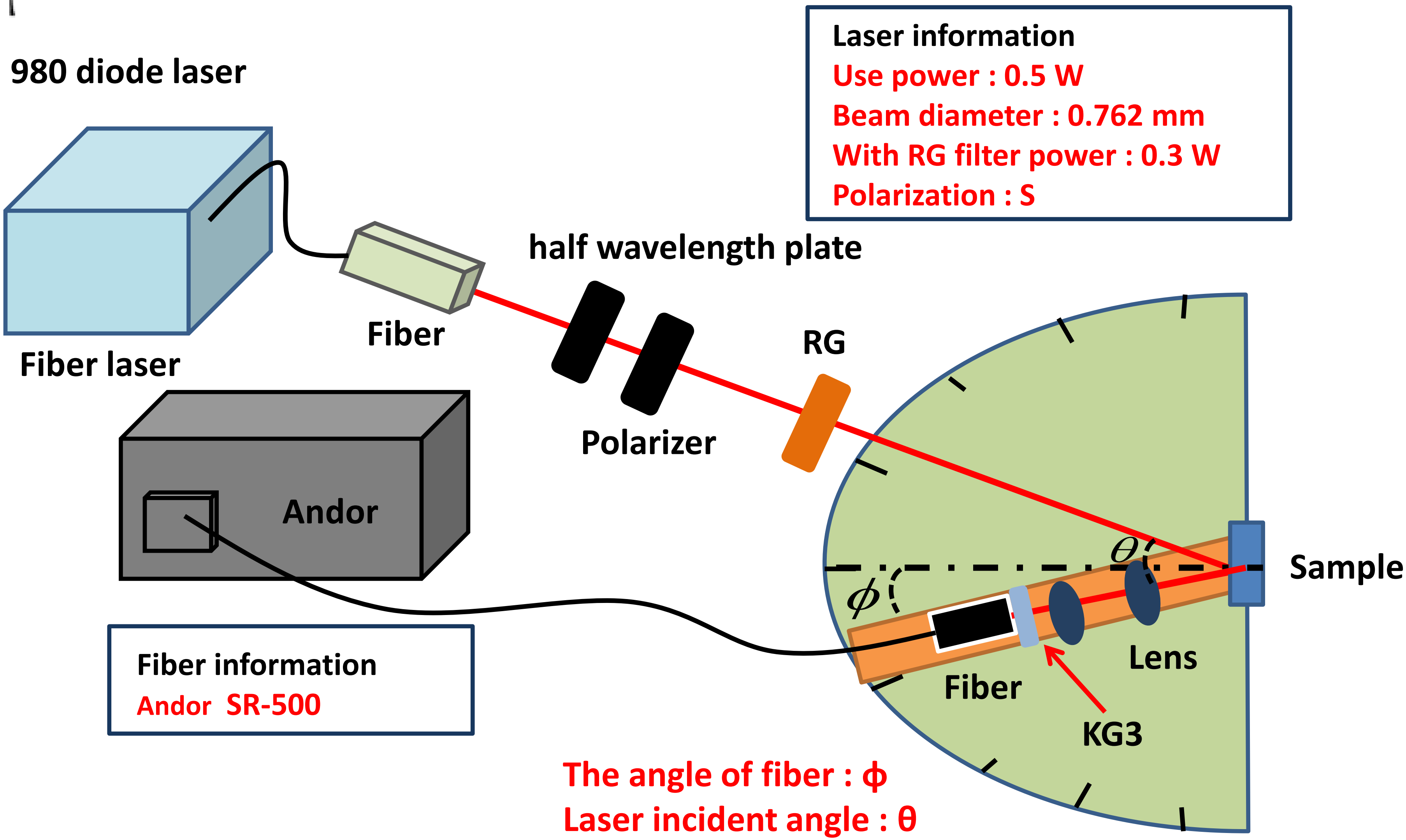




Laser wavelength : 976.2 nm

Resonance angle of TE : θi = 31.5˚.

Measurement setup



GMR enhanced up-conversion fluorescence

-- Use strong local field of GMR to enhance up conversion fluorescence with an resonant waveguide grating

✔ Experimental results

4. Up-conversion fluorescence (UCF) enhance

--- Excitation resonance

(Change the laser pumping angle θ & fixed the collect angle ϕ)

--- Excitation & Extraction resonance

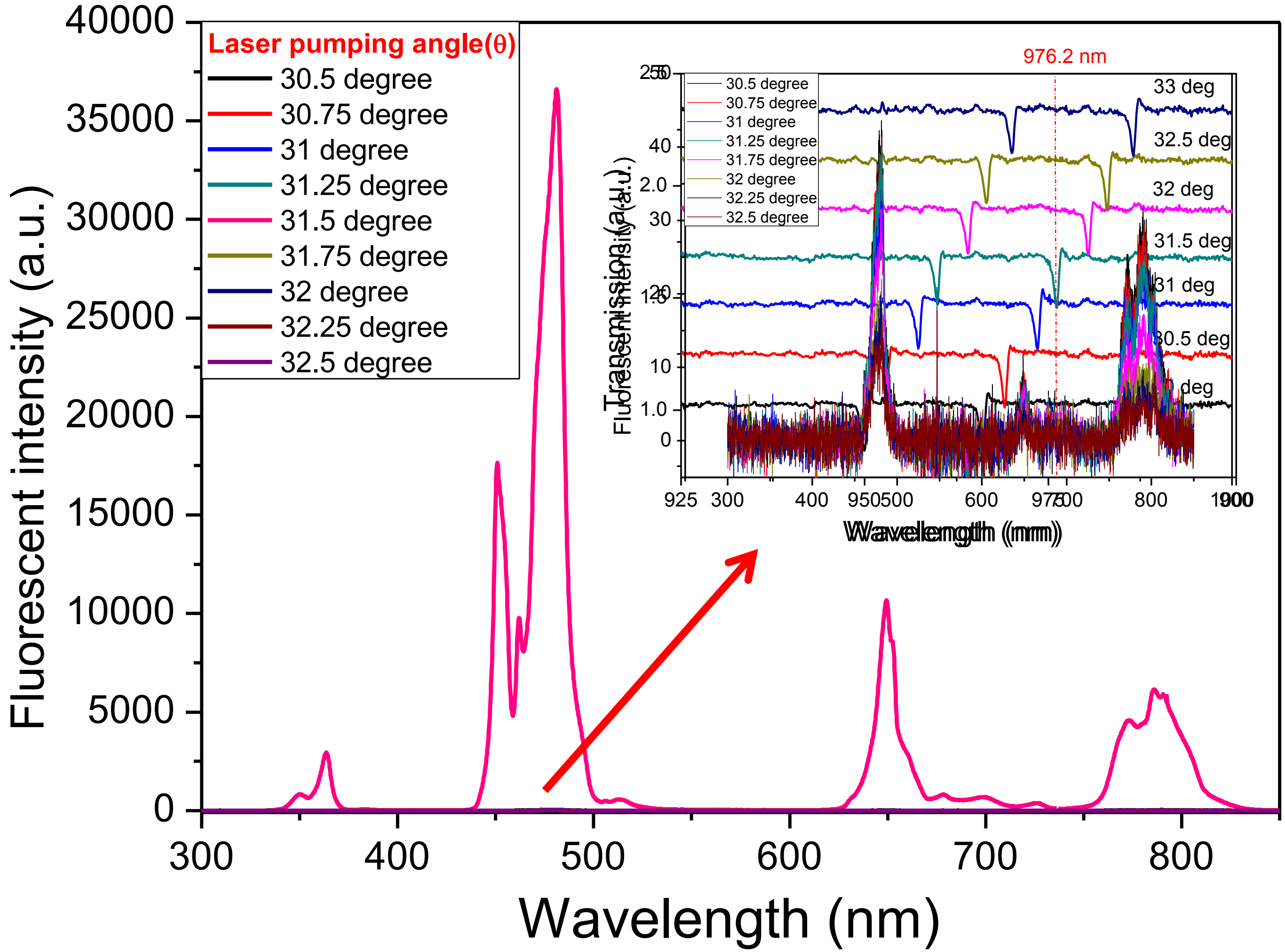
(Fixed the laser pumping angle θ & change the collect angle ϕ)

Nano Fabrications and Polymer Optics Lab.

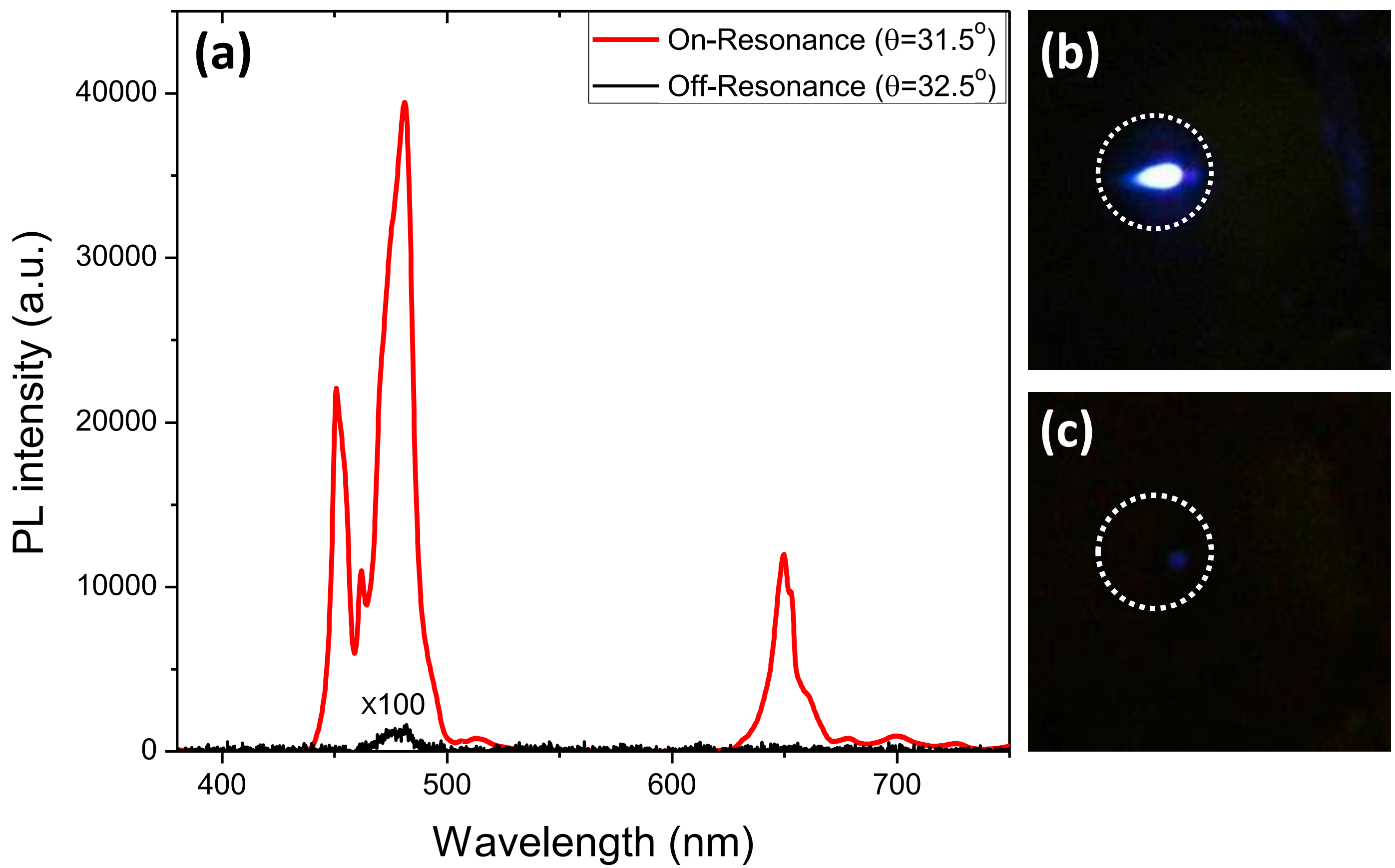
Excitation Resonance

Fiber Collection angle ϕ : 0 degree

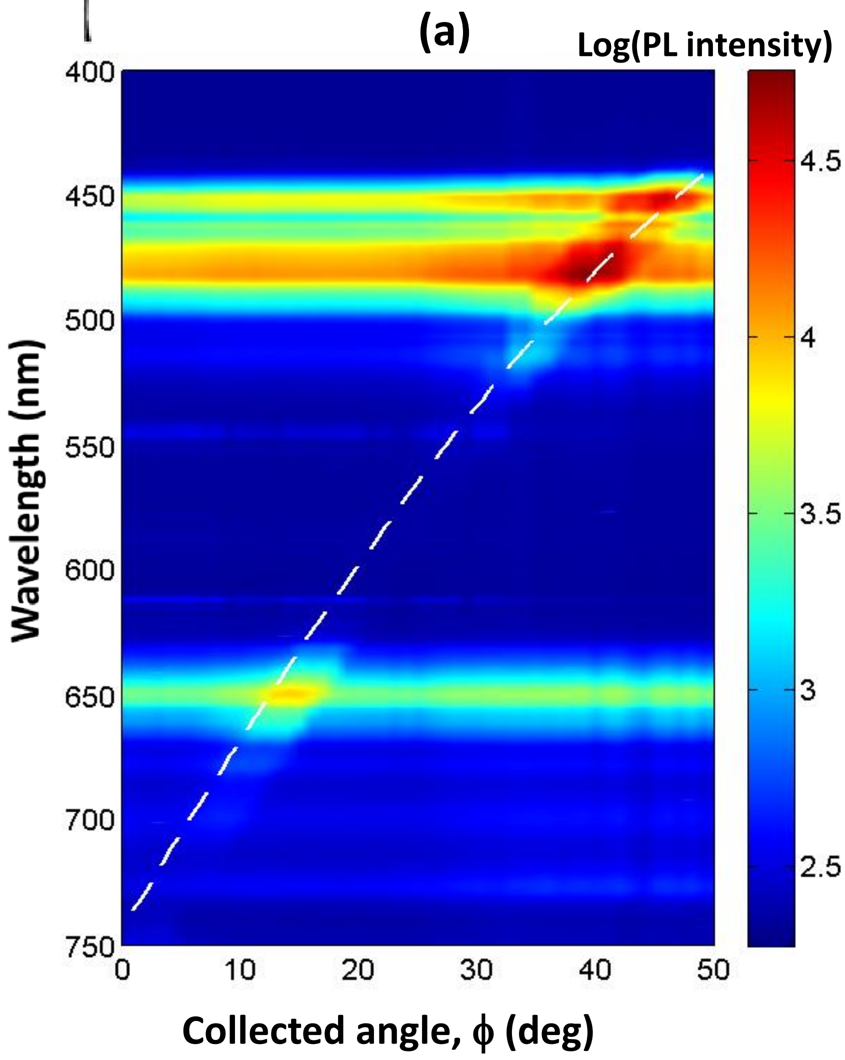
Integral time : 20 s

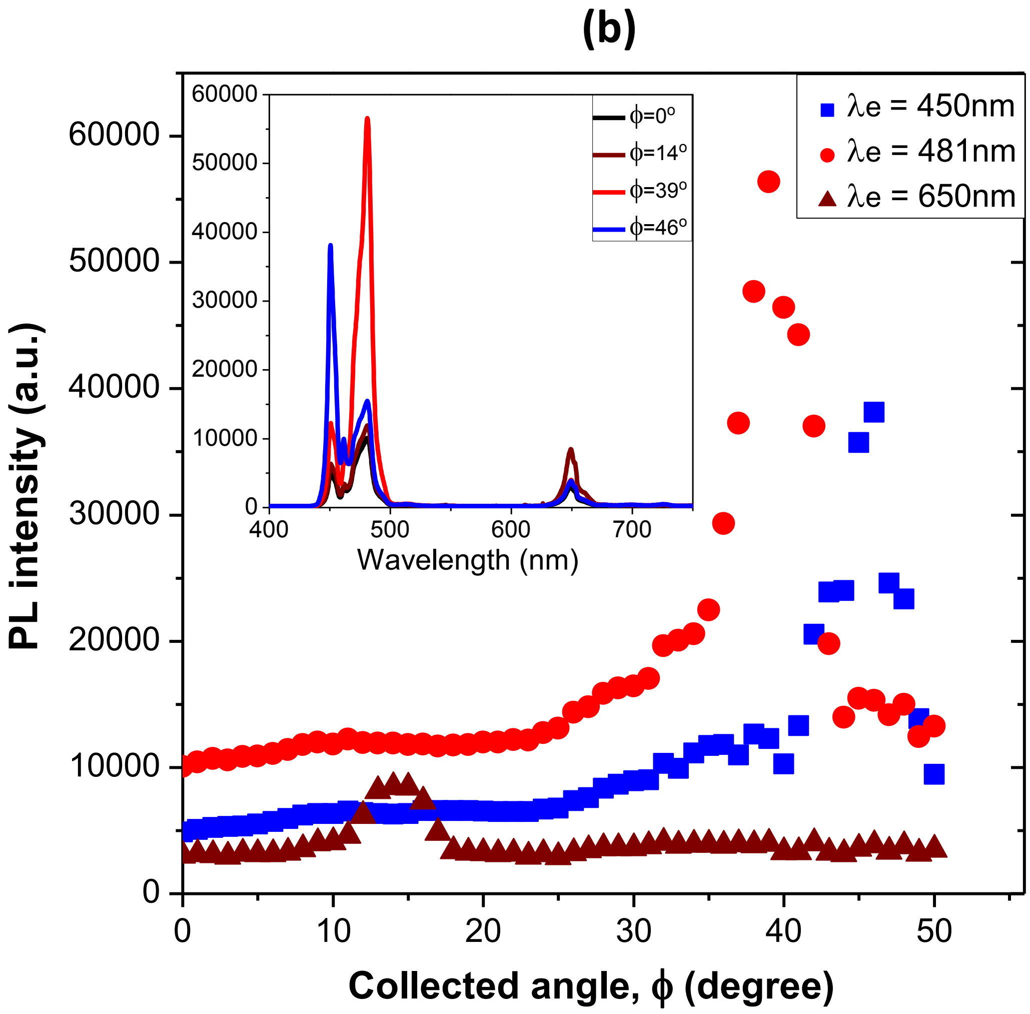


Excitation Resonance (2)

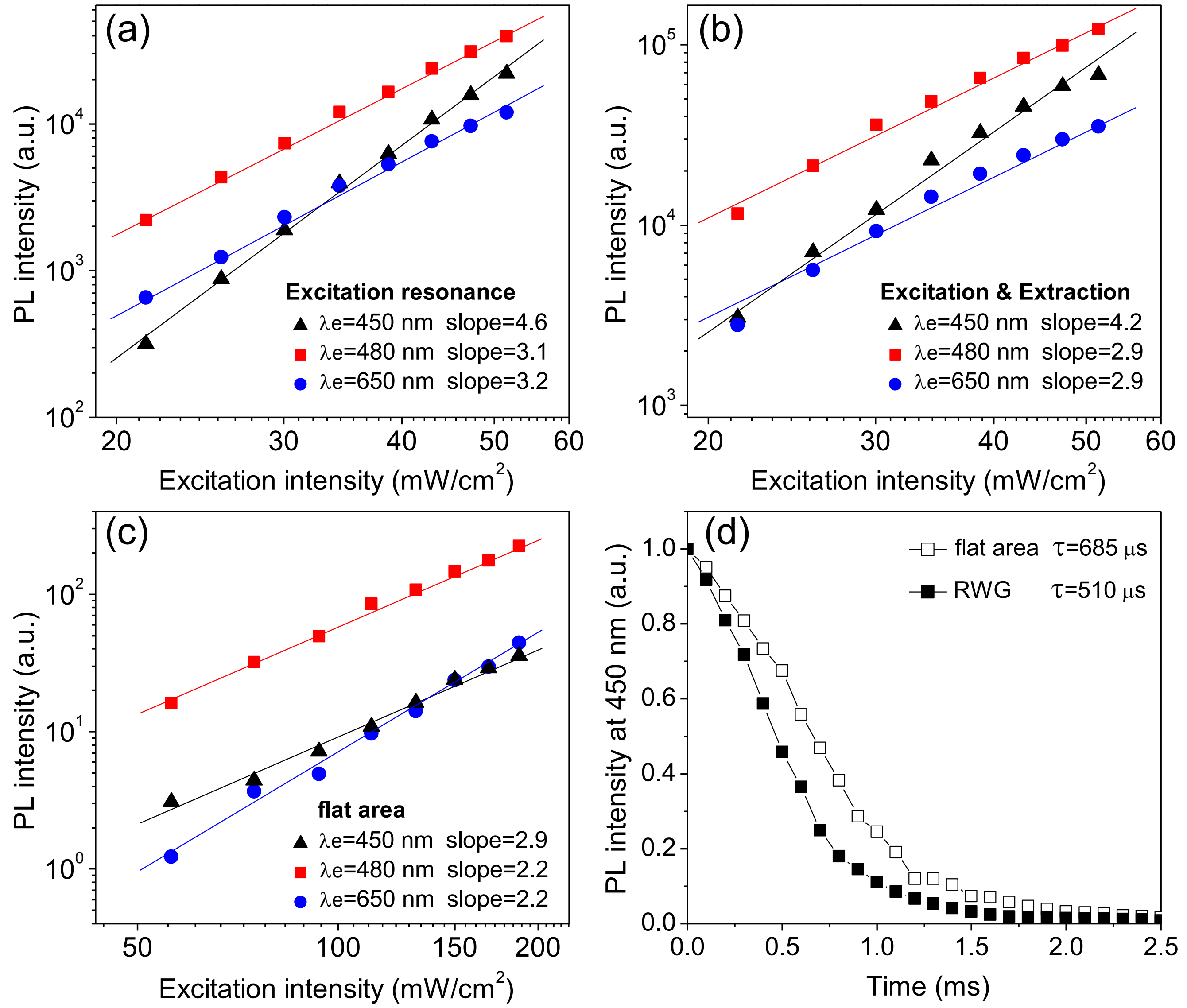


Excitation & Extraction Resonance





Excitation & Extraction Resonance (3)



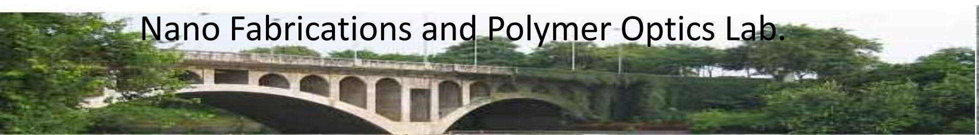
Power dependent

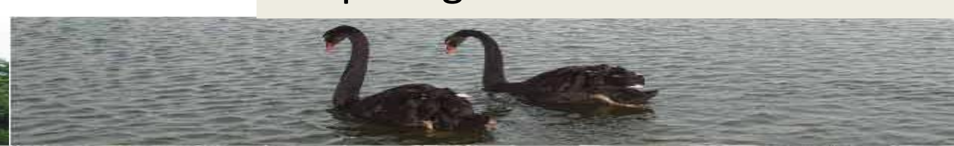
Table I. Summary of enhancement factor of three emission wavelengths (450nm, 480nm, 650nm) in the RWG under excitation resonance and both excitation and extraction resonances.

	Enhancement factor		
	λe=450nm	**λe=480 nm**	**λe=650 nm**
Excitation resonance	2.2×10^4	2.8×10^3	5.6×10^3
Excitation & Extraction	6.8×10^4	8.8×10^3	1.6×10^4

UCF intensity can be enhanced up to 10^4 times in visible range and 10^3 times in near-IR range compared with that from a flat area.

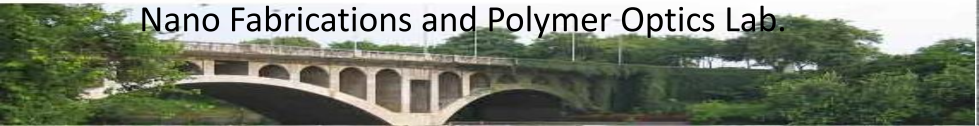
Preparing to submit to Nano Lett.





Conclusions

- We demonstrated that the nonlinear signals can be enhanced by aligning the GMR modes with the incident excitation light in the RWG structure !
- By setting the incident angle of the excitation wavelength at resonant angle, incident light resonates with the grating wave structure and produced **strongly enhanced E-field** near the TiO_2 and active layer interface, leading to enhanced excitation field !
- Furthermore, the nonlinear signal can be further enhanced by setting the collection angle of the detection system at the other resonant mode away from the normal direction of the RWG, another **2.2-fold enhancement of TPP and 6-fold enhancement of UCF** was obtained due to the high reflection of the GMR mode !



Thanks for your attention !