

Polycrystalline Anatase Micro-Ring Resonators at Telecommunication Wavelengths

Orad Reshef¹, Katia Shtyrkova², Michael Moebius¹,
Christopher Evans^{1,3}, Sarah Griesse-Nascimento¹,
Erich Ippen², Eric Mazur¹

¹Harvard School of Engineering and Applied Sciences, Cambridge, MA

²Massachusetts Institute of Technology, Cambridge, MA

³Kavli Institute at Cornell University, Ithaca, NY

CLEO: Advanced Fabrication Methods

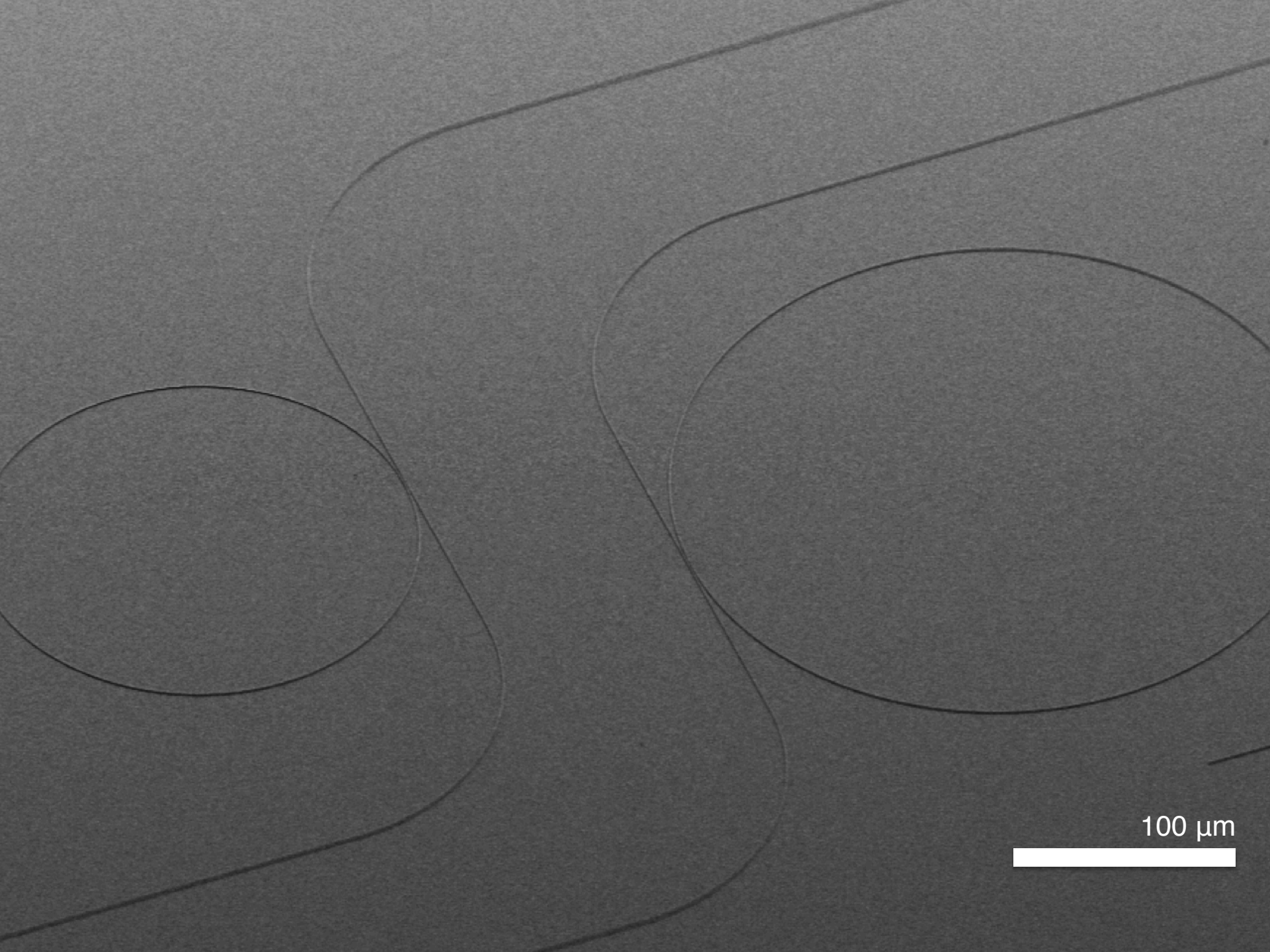
San Jose, California

June 09, 2014



HARVARD
School of Engineering
and Applied Sciences





100 μm

Why anatase?

It is easy to deposit low-loss anatase TiO_2 thin films.

We have demonstrated integrated nonlinear optics using anatase.

Why micro-rings?

They help evaluate the quality of our fabrication.

They can be used to enhance nonlinear interactions.

Outline

Introduction to TiO_2 and anatase as a photonic platform

Fabrication process

Design parameters

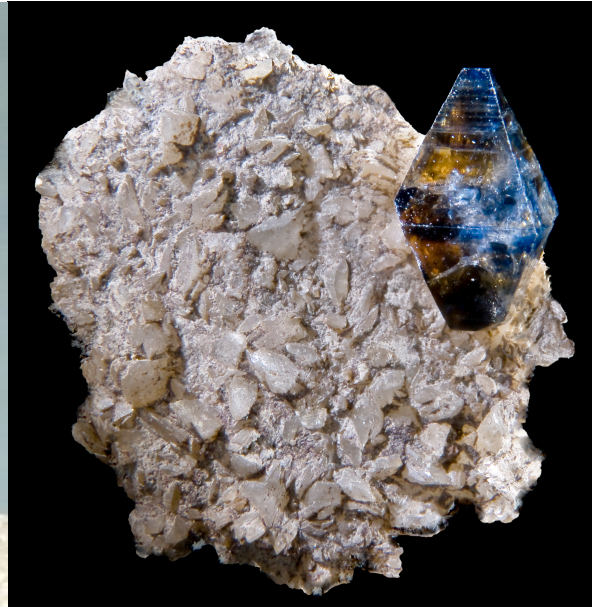
Characterization of fabricated devices

Titanium dioxide

Titanium dioxide (TiO_2) is found in 3 naturally occurring phases:



Rutile



Anatase



Brookite

TiO₂ is inexpensive, abundant and non-toxic.

NEW

**Crest**

PRO-HEALTH

CAVITIES
GINGIVITIS
PLAQUE
SENSITIVITY
TARTAR
WHITENING
FRESHENS
BREATH



**CLINICAL
GUM
PROTECTION**

Helps Prevent Gingivitis &
Helps Reverse Gingivitis
in 4 weeks

NET WT 4.0 OZ (113 g) FLUORIDE TOOTHPASTE FOR ANTICAVITY, ANTINGIVITIS AND SENSITIVE TEETH

**INVIGORATING
CLEAN MINT**

Drug Facts Active Ingredient Stannous fluoride 0.454% Anticavity, antigingivitis, (0.16% w/v fluoride ion) antisensitivity toothpaste Purposes Uses <ul style="list-style-type: none">• aids in the prevention of cavities• helps prevent gingivitis• helps interfere with the harmful effects of plaque associated with gingivitis• helps control plaque bacteria that contribute to the development of gingivitis• builds increasing protection against painful sensitivity of the teeth to cold, heat, acids, sweets or contact Warnings When using this product do not use for sensitivity longer than four weeks unless recommended by a dentist	Drug Facts (continued) Stop use and ask a dentist if the sensitivity problem persists or worsens. Sensitive teeth may indicate a serious problem that may need prompt care. Keep out of reach of children. If more than used for brushing is accidentally swallowed, get medical help or contact a Poison Control Center right away. Directions <ul style="list-style-type: none">• adults and children 12 yrs. & older: apply at least a 1-inch strip of the product onto a soft bristled toothbrush. Brush teeth thoroughly for at least 1 minute twice a day (morning and evening) or as recommended by a dentist. Make sure to brush all sensitive areas of the teeth.• do not swallow• children under 12 yrs.: ask a dentist	Drug Facts (continued) Other Information <ul style="list-style-type: none">• products containing stannous fluoride may produce surface staining of the teeth• adequate toothbrushing may prevent these stains which are not harmful or permanent and may be removed by your dentist• this Crest is specially formulated to help prevent staining• see your dentist regularly Inactive Ingredients glycerin, hydrated silica, sodium hexametaphosphate, propylene glycol, PEG-6, water, zinc lactate, flavor, trisodium phosphate, sodium gluconate, sodium lauryl sulfate, carrageenan, sodium saccharin, stannous chloride, xanthan gum, polyethylene, titanium dioxide, blue 1 lake Questions? 1-800-594-4158
--	---	--

Anatase TiO_2 has desirable properties for integrated nonlinear optics in the visible regime.

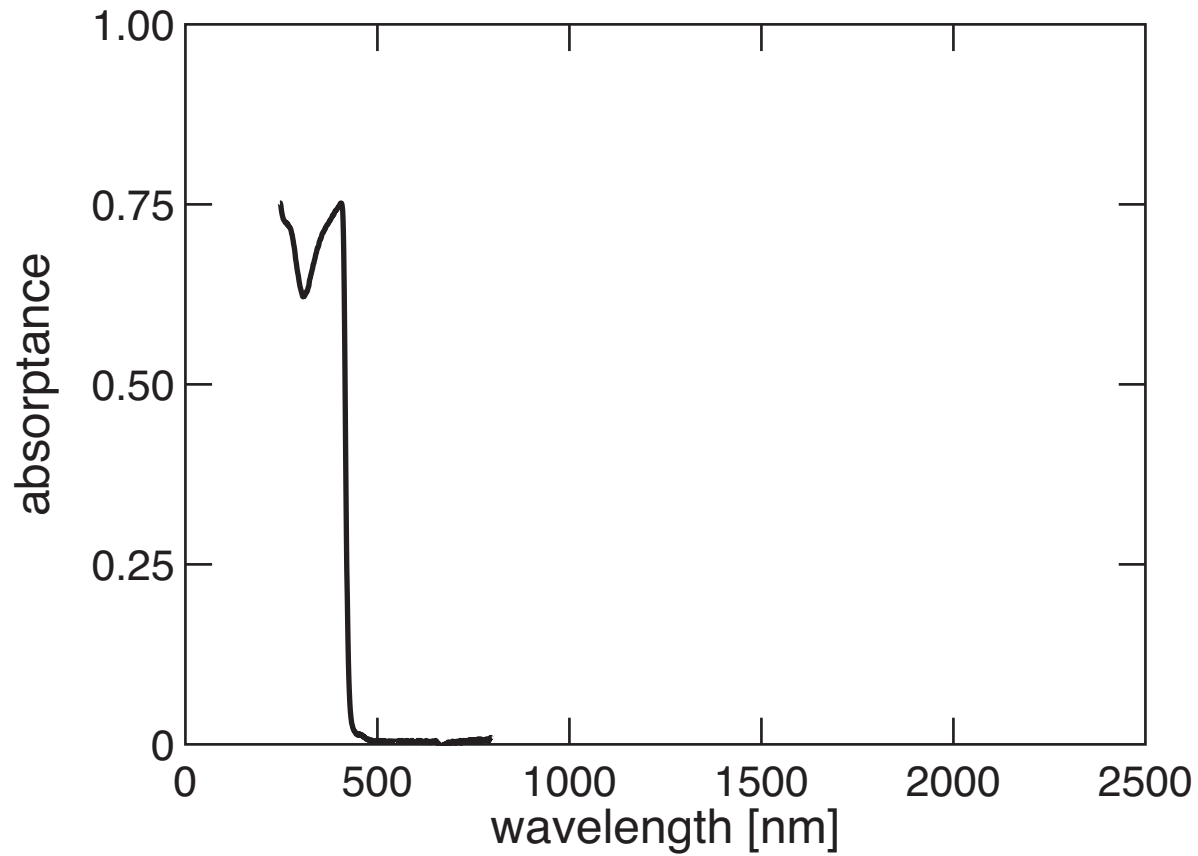
Large refractive index: $2.4 @ \lambda = 1550 \text{ nm}$

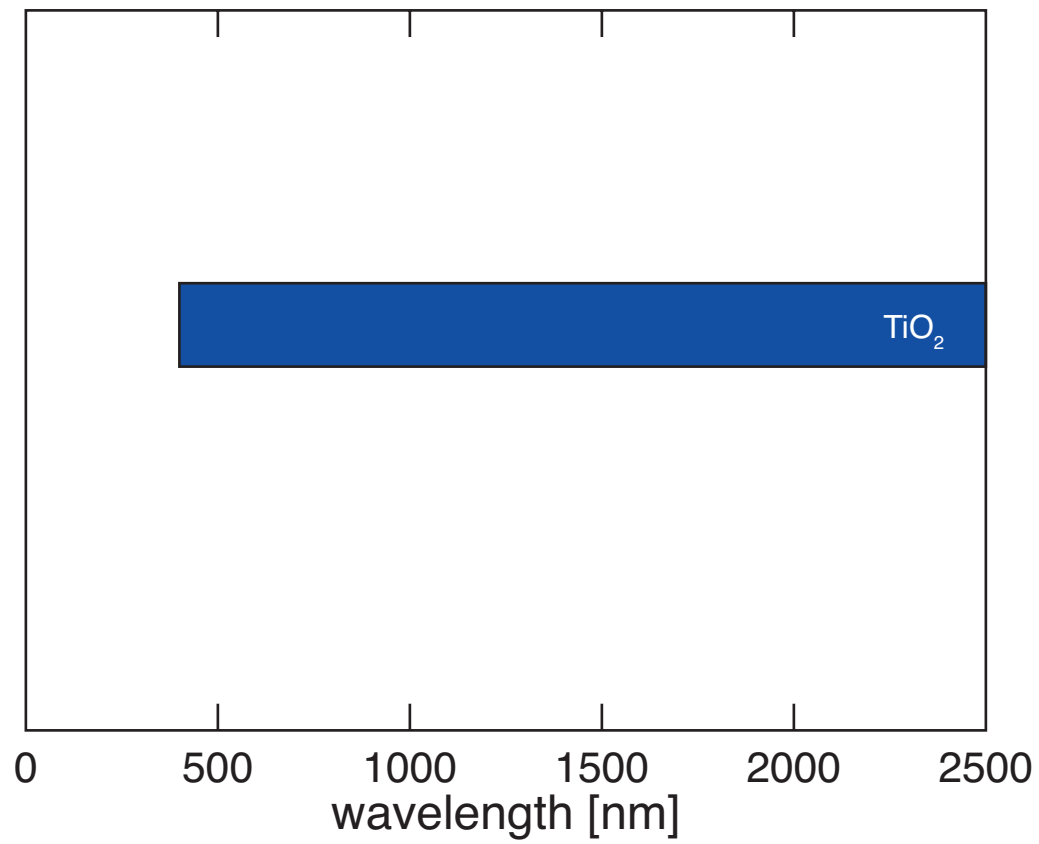
Large nonlinear index: $1.8 \times 10^{-15} \text{ cm}^2/\text{W} @ \lambda = 1550 \text{ nm}$
 $2.5 \times 10^{-15} \text{ cm}^2/\text{W}$ for SiN

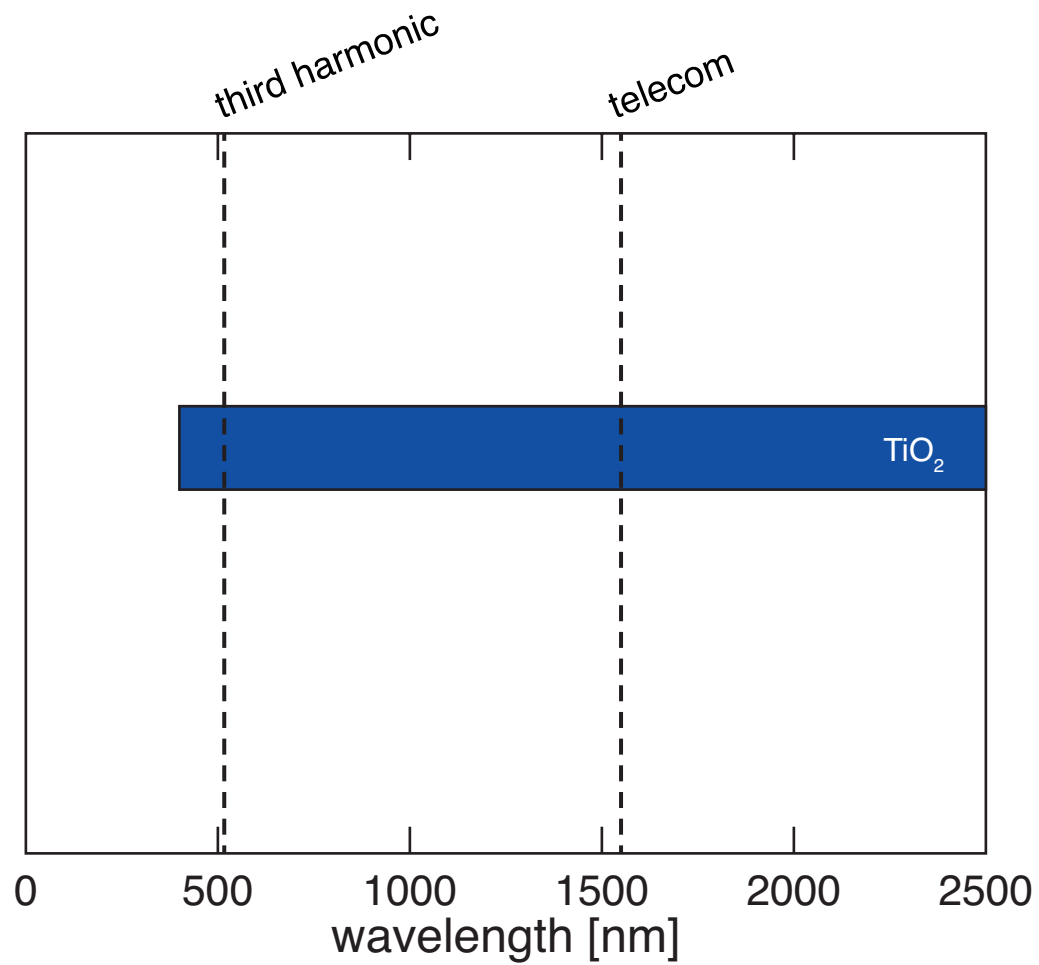
Large transparency: $> 400 \text{ nm}$
 $> 800 \text{ nm}$ - no 2PA
 $> 1200 \text{ nm}$ - no 3PA

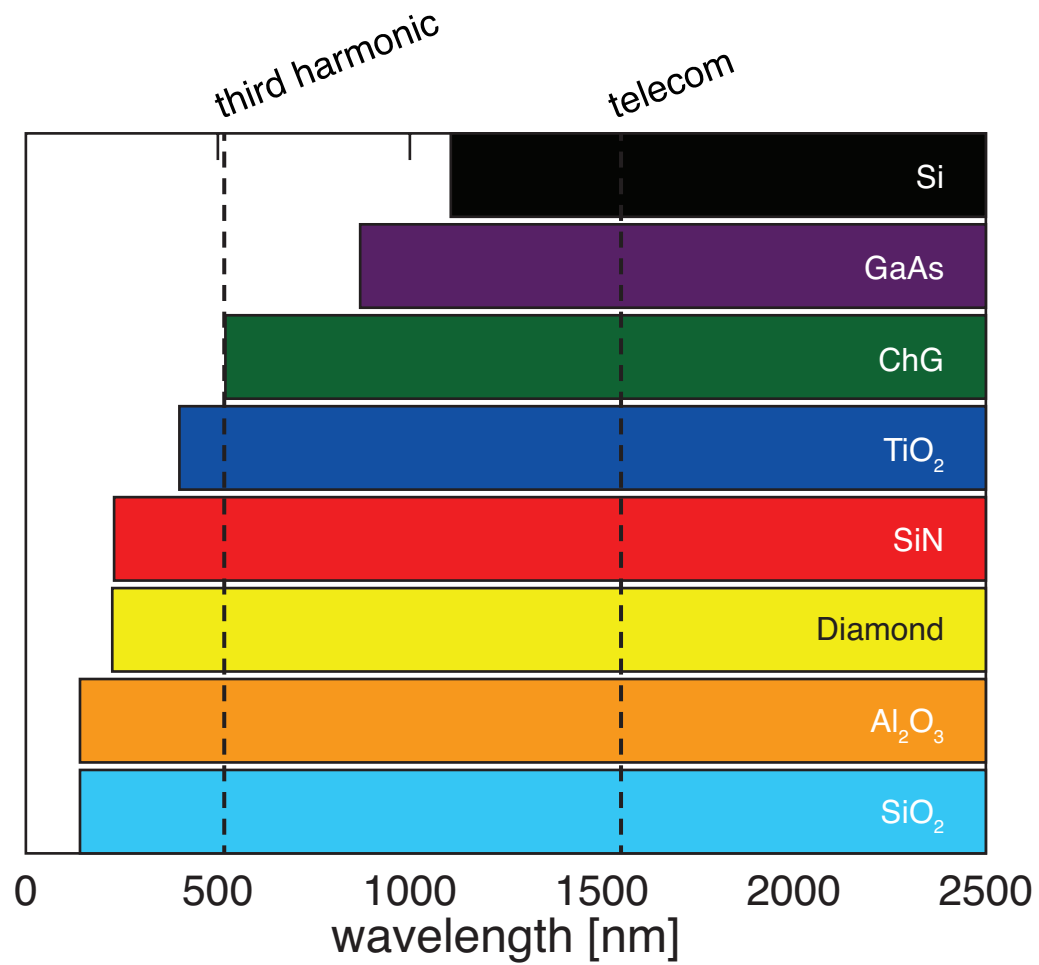
How does this compare to other materials?

First, let's compare transparency:

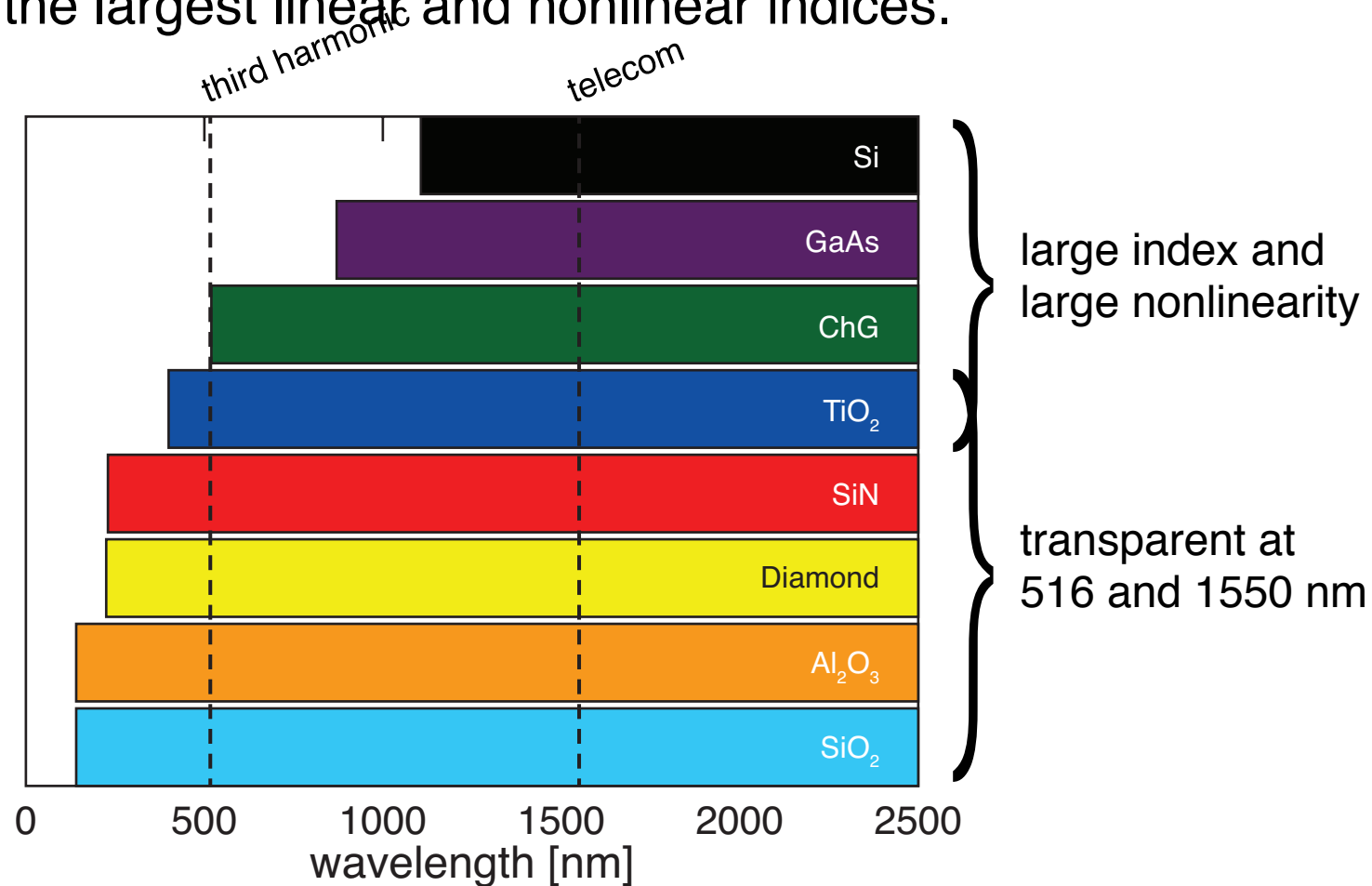




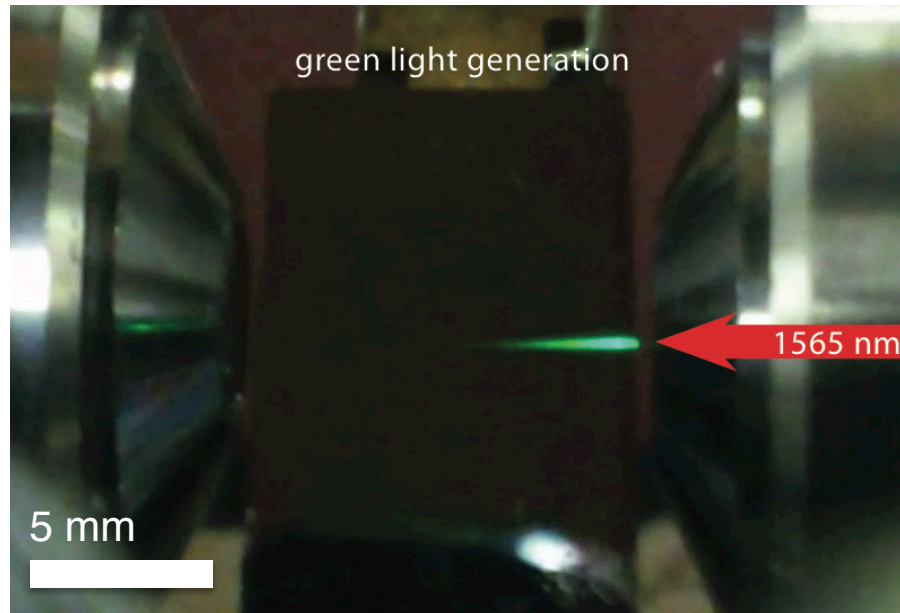




Of the photonic materials that are transparent in the visible, TiO_2 has the largest linear and nonlinear indices.



Presentation of third harmonic generation in TiO_2 this week:

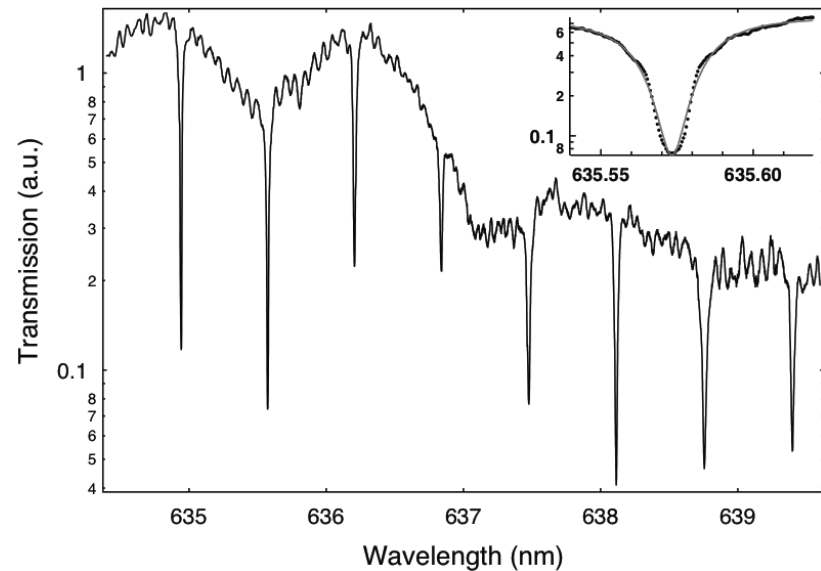
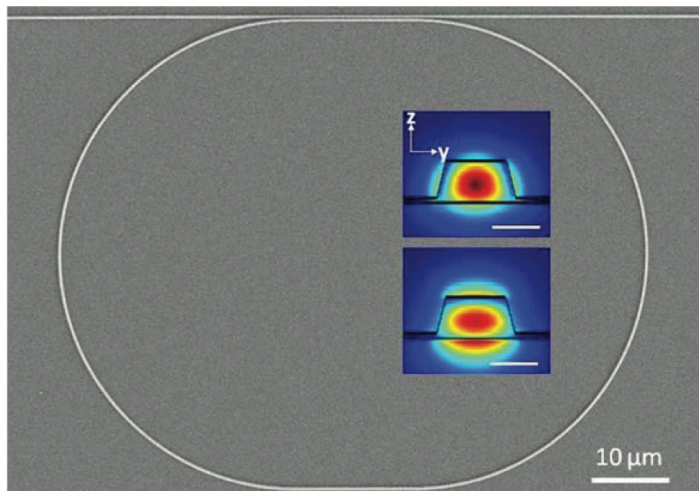


Katia Shtyrkova et al., "Third Harmonic Generation in Polycrystalline Anatase Titanium Dioxide Nanowaveguides"

Wednesday June 11 5:45 PM
Meeting Room 211 B/D

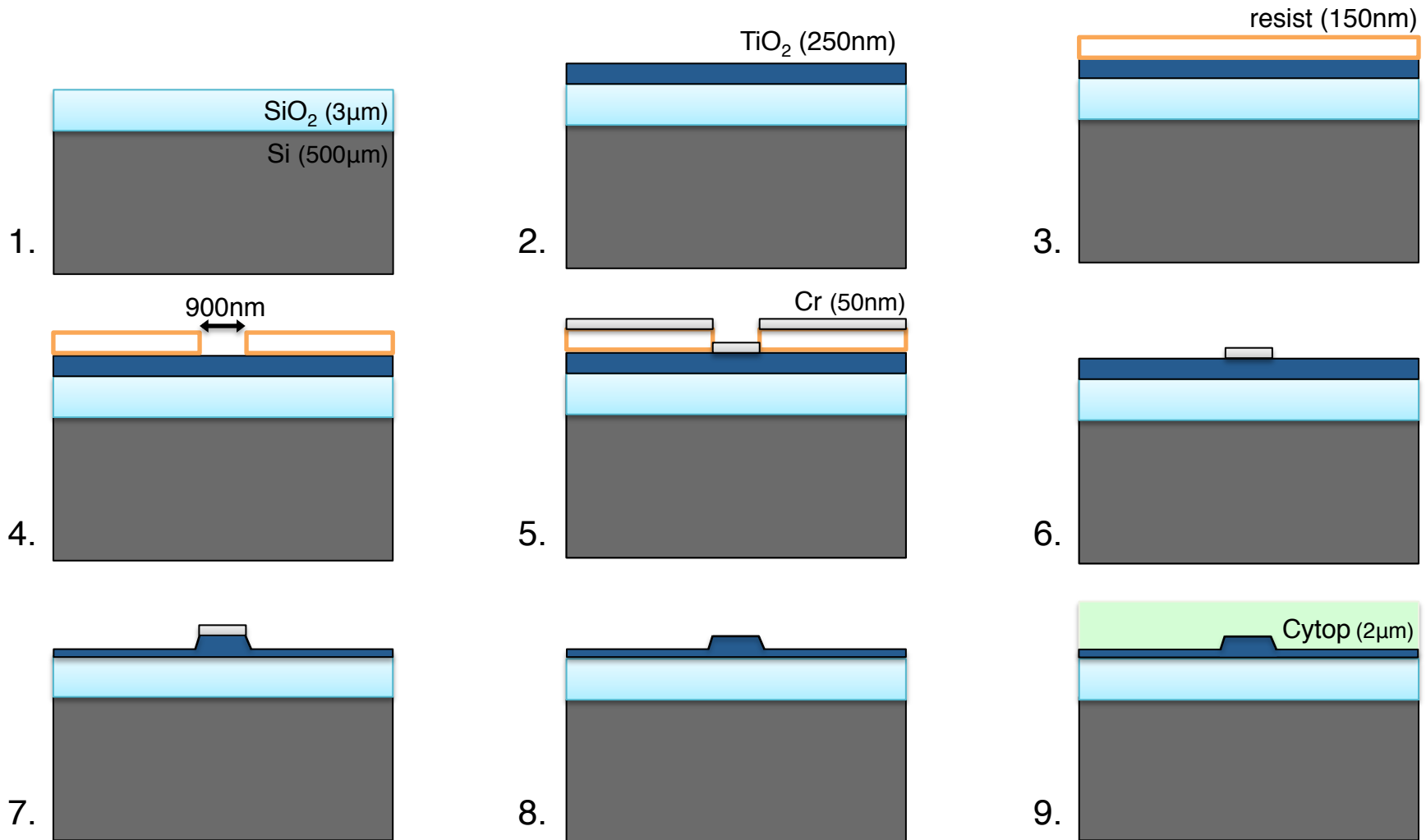
Micro-ring resonators have been previously studied in amorphous TiO_2 .

$$Q = 2.2 \times 10^4 \text{ at } \lambda = 633 \text{ nm}$$

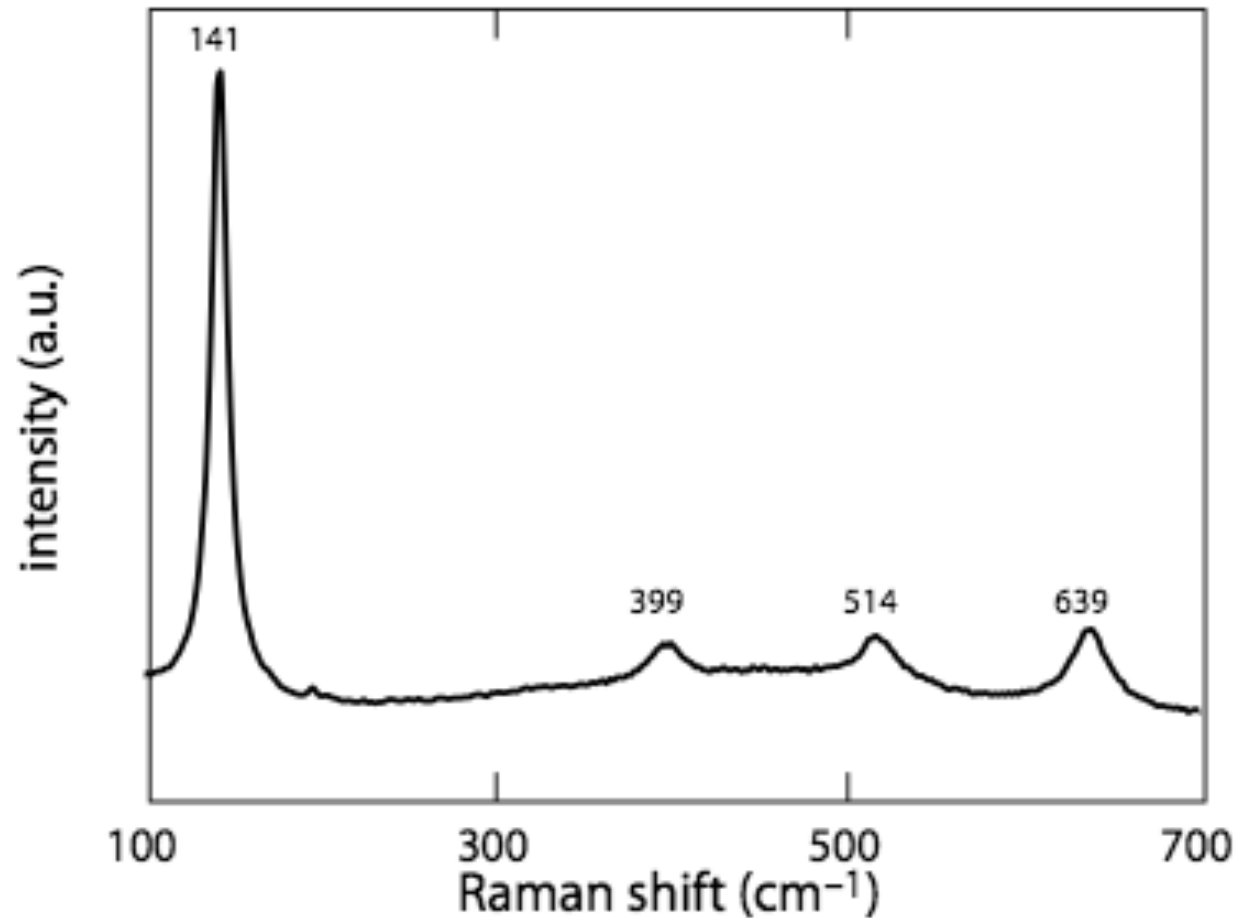


Fabrication

We use standard lithographic techniques to structure thin films into nanowaveguides.

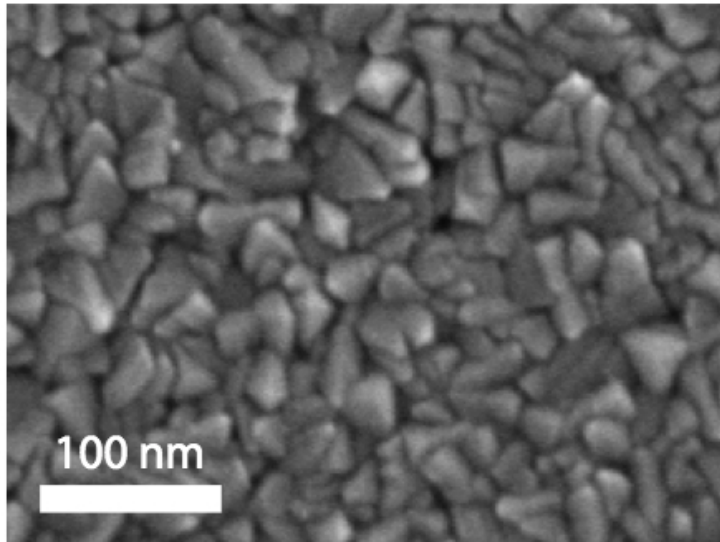


Raman spectroscopy confirms the deposition of anatase.

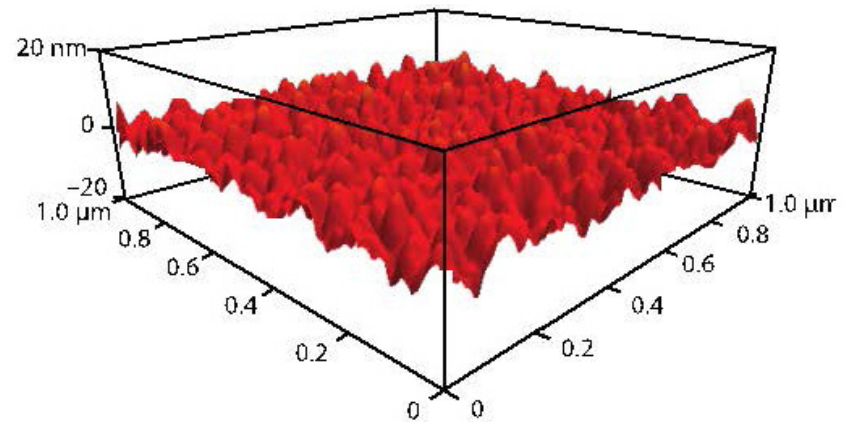


The rough surface contributes to propagation losses.

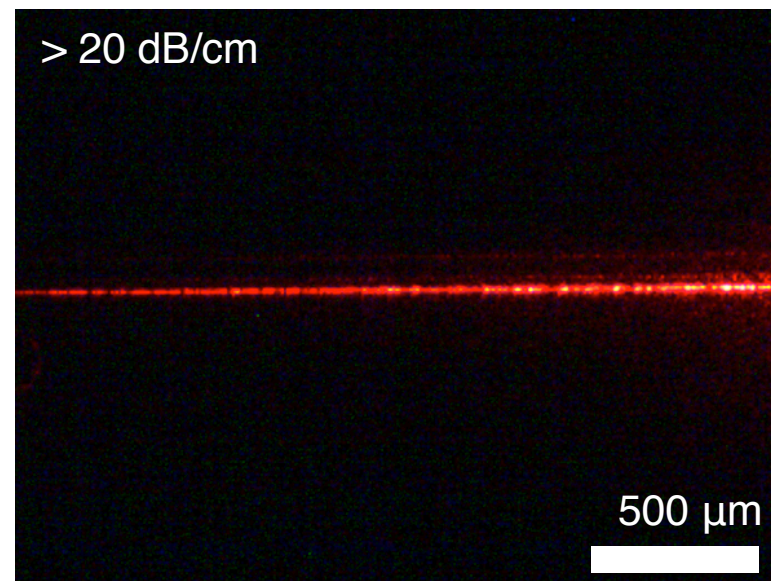
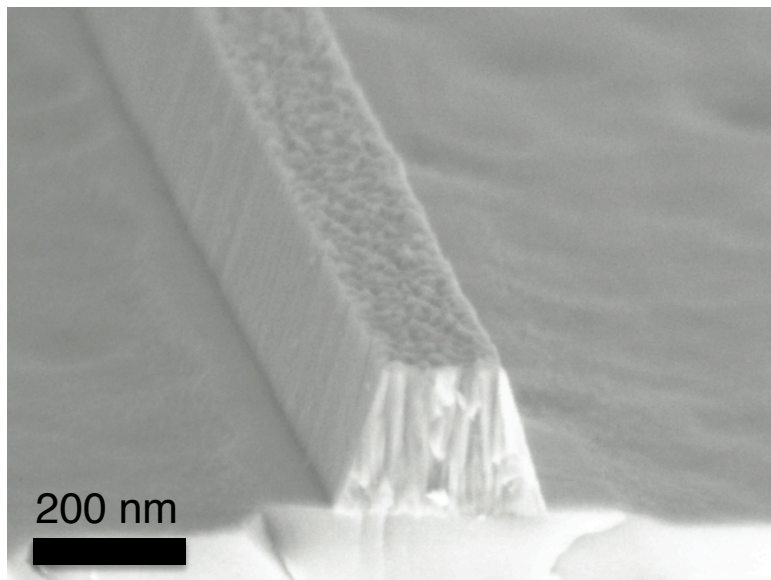
SEM



AFM

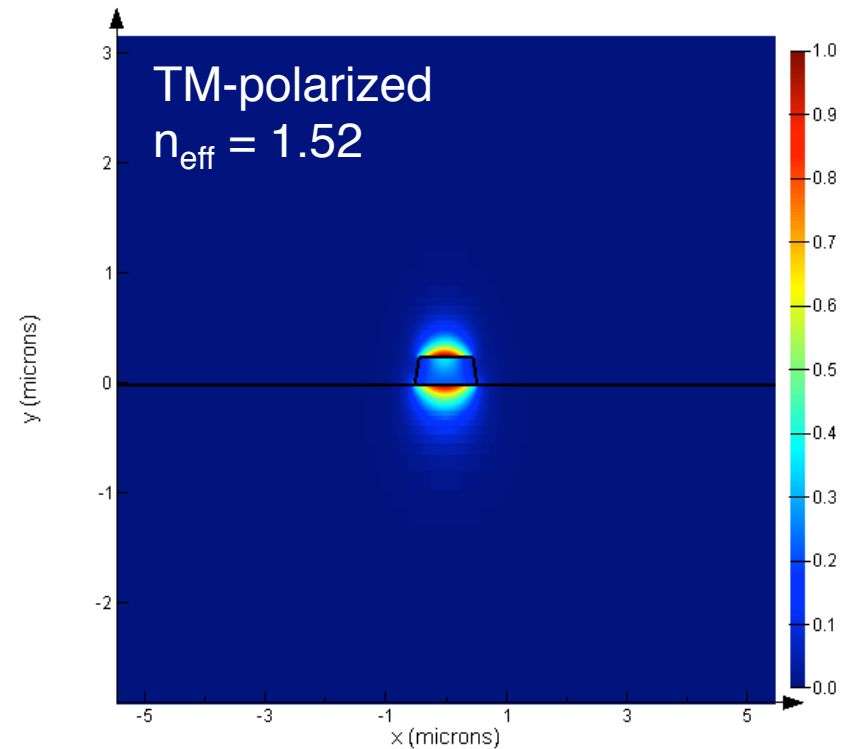
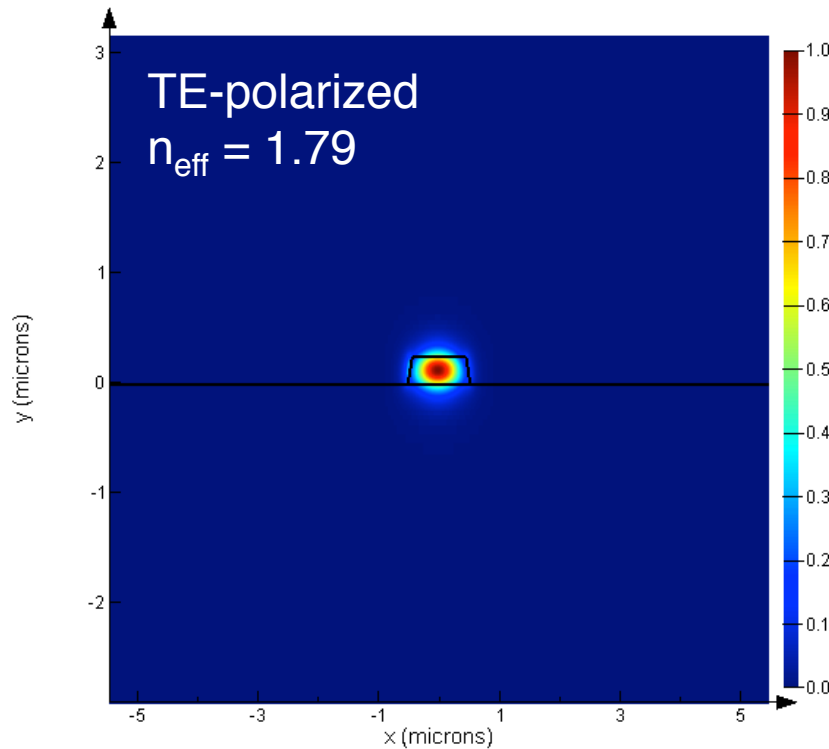


RMS Roughness: 2.7 nm



Design parameters

Waveguide cross-sectional dimensions: 250 nm x 900 nm



Design parameters were chosen to ensure single mode operation at $\lambda = 1500$ nm.

Ring radius:

100 and 150 μm

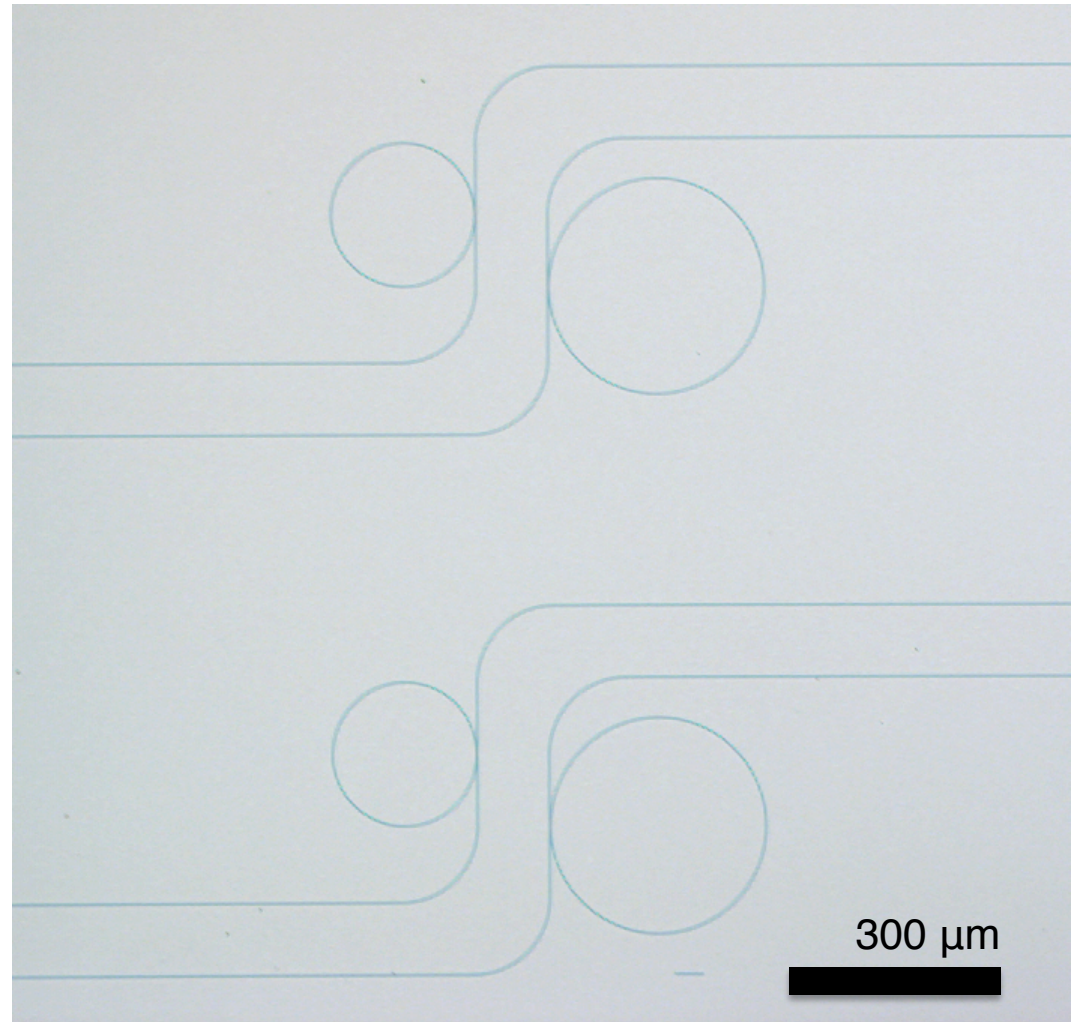
$$\Delta\lambda = \lambda^2 / 2\pi r \cdot n_{\text{eff}}$$

Predicted FSR:

2.16 and 1.43 nm

Gap size:

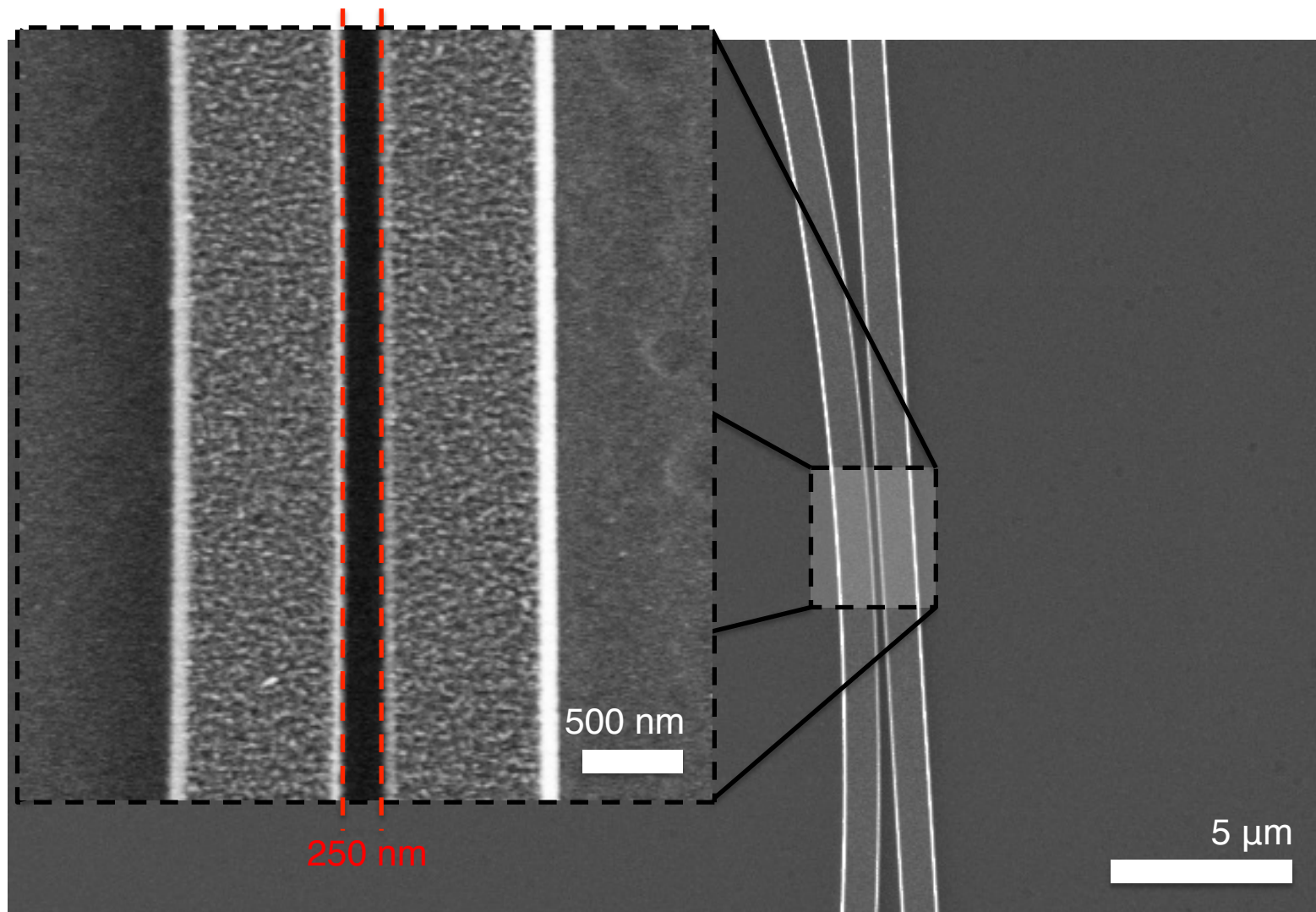
250, 300, and 350 nm



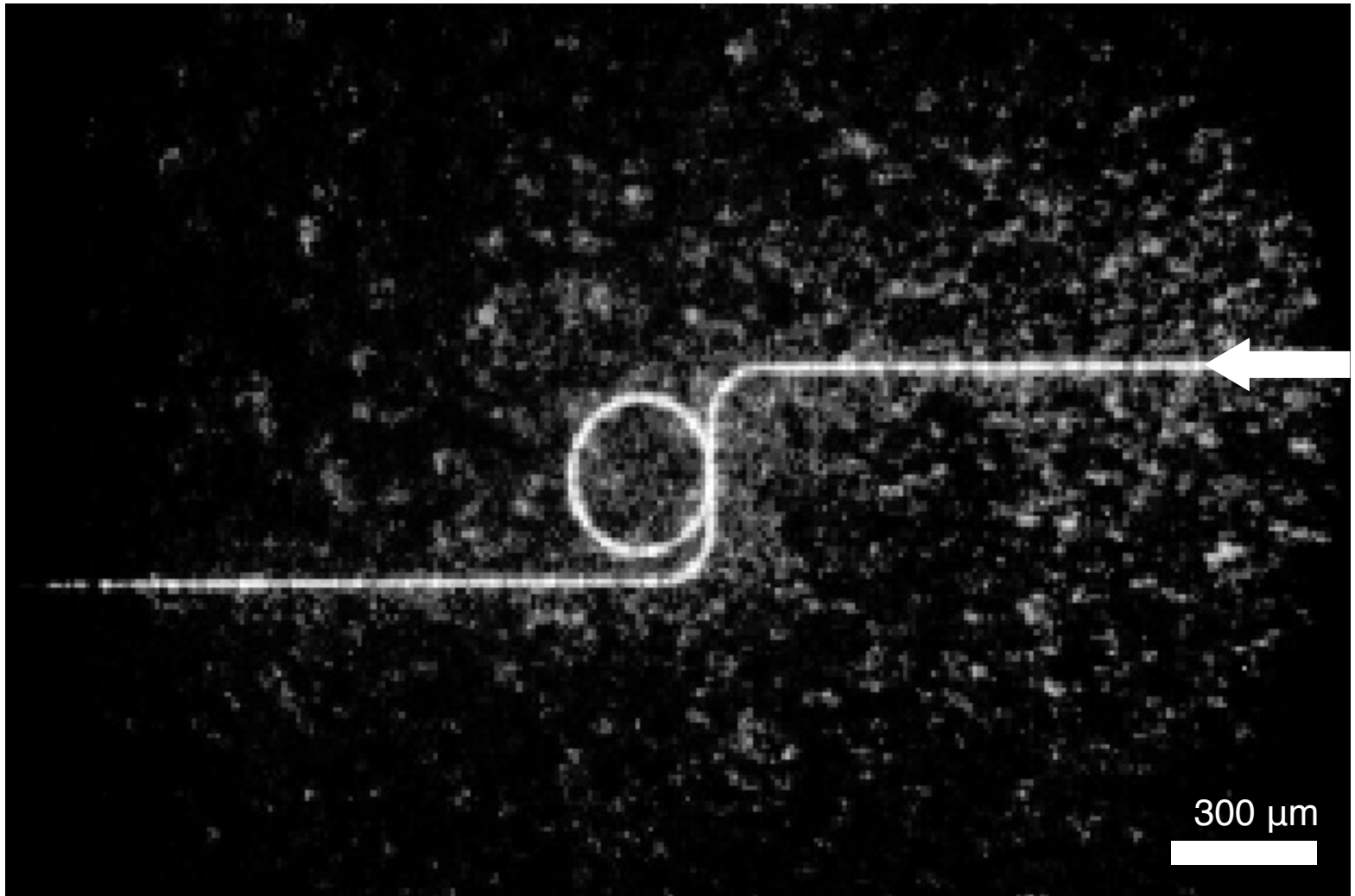
SEM
45° tilt

100 μm

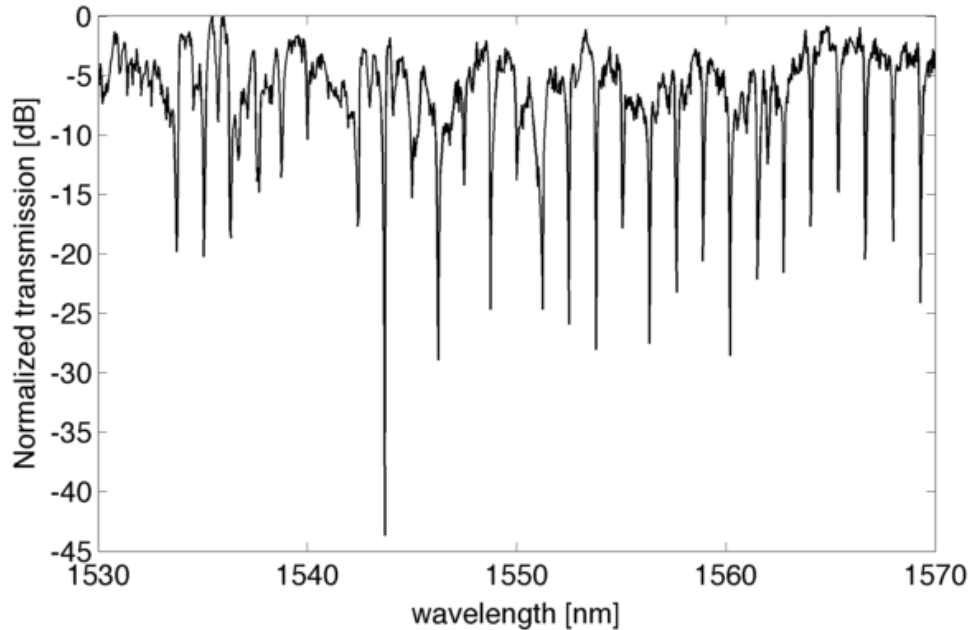




Device characterization



Sweeping from 1530 to 1570 nm yields sharp resonances.



Q-factor: 1.5×10^4

Comparable to poly-Si¹: 2.0×10^4

Free-spectral range @ 1550 nm:

1.32 nm for 150 μm rings

Theoretical: 1.43 nm

2.02 nm for 100 μm rings

Theoretical: 2.16 nm

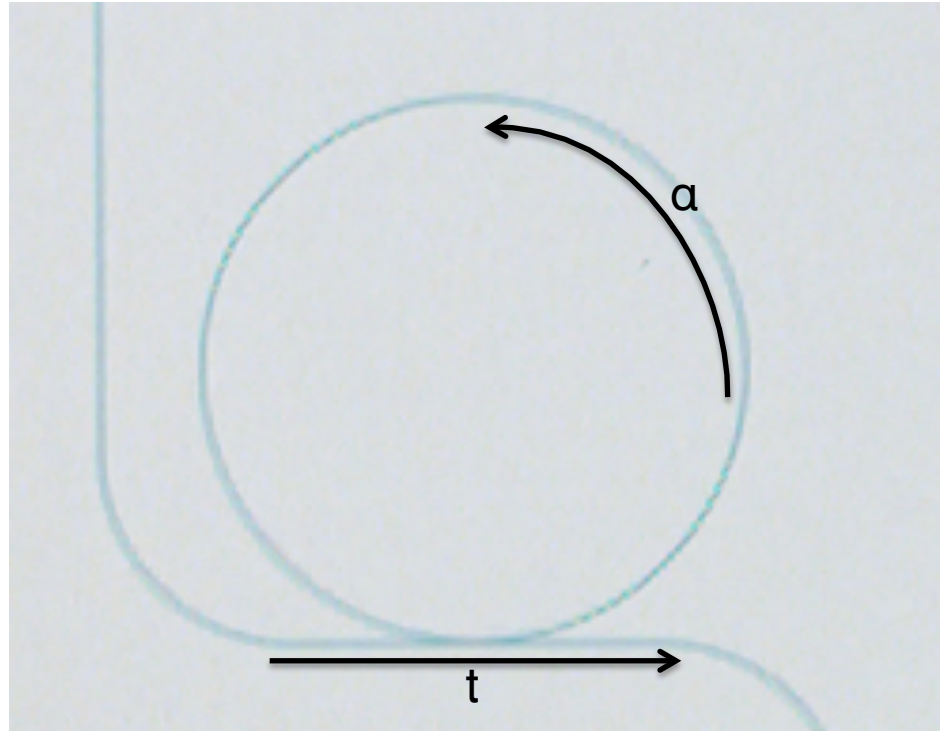
¹K. Preston et al., *Optics Express* 15, 17283 (2007)

We can model the behavior of these resonances using a scattering matrix:

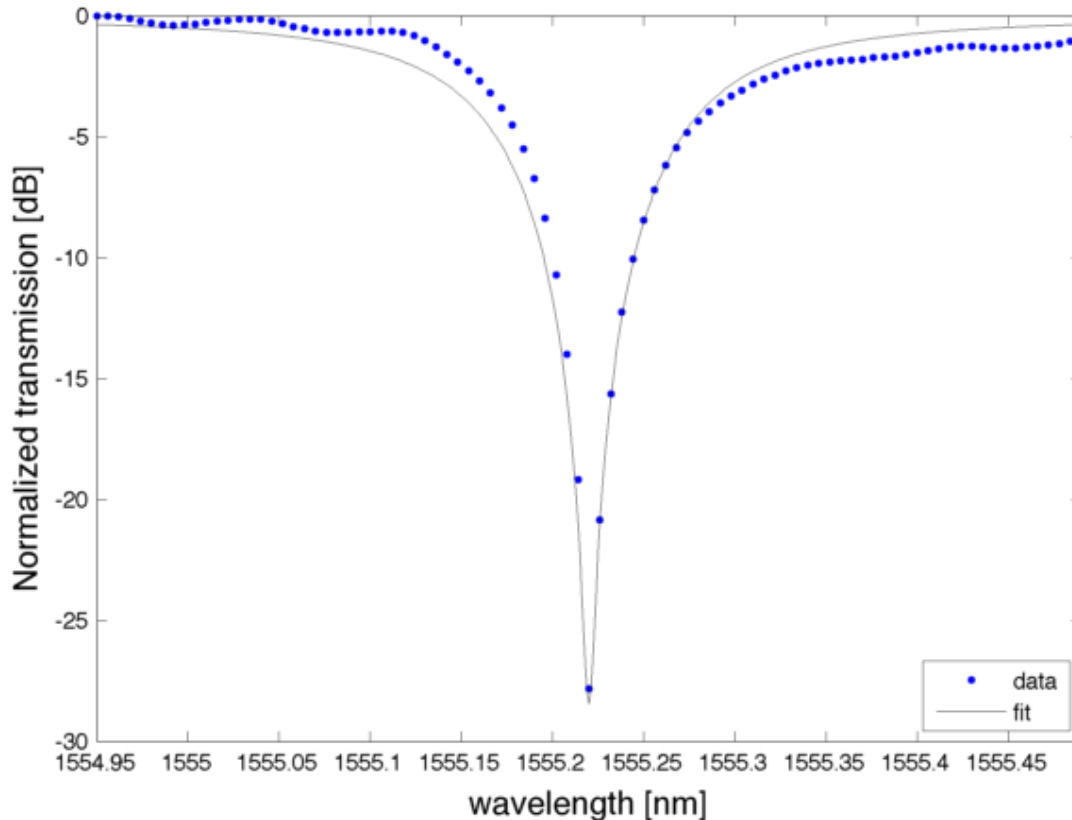
$$T = \frac{t^2 + \alpha^2 - 2\alpha t \cos(\phi)}{t^2 + \alpha^2 + 2\alpha t \cos(\phi)}$$

t = transmission coefficient
of the coupler

α = total loss coefficient
 $= e^{-\alpha L}$



By fitting the resonances to this equation, we can extract a propagation loss.



Extracted parameters:
 $t = 0.83$
 $\alpha = 0.84$

Corresponding loss:
8.0 dB/cm!

Summary

We fabricated and characterized anatase TiO_2 micro-ring resonators

Q-factor of 1.5×10^4

Propagation loss of 8.0 dB/cm

Polycrystalline anatase is a promising material for nonlinear optics

Future work

Lower the losses of the waveguides (increase the Q-factor)

- Optimize deposition parameters

- Optimize etching parameters

Enhance nonlinear effects with the help of these resonant cavities



Harvard University
Center for
Nanoscale
Systems

HQOC

HARVARD
Quantum Optics Center



Katia Shtyrkova, "Third Harmonic Generation in
Polycrystalline Anatase Titanium Dioxide Nanowaveguides"

Wednesday June 11 5:45 PM
Meeting Room 211 B/D



HARVARD
School of Engineering
and Applied Sciences



Thank you

Katia Shtyrkova, “Third Harmonic Generation in
Polycrystalline Anatase Titanium Dioxide Nanowaveguides”

Wednesday June 11 5:45 PM
Meeting Room 211 B/D

For a copy of this presentation:
<http://mazur.harvard.edu>

