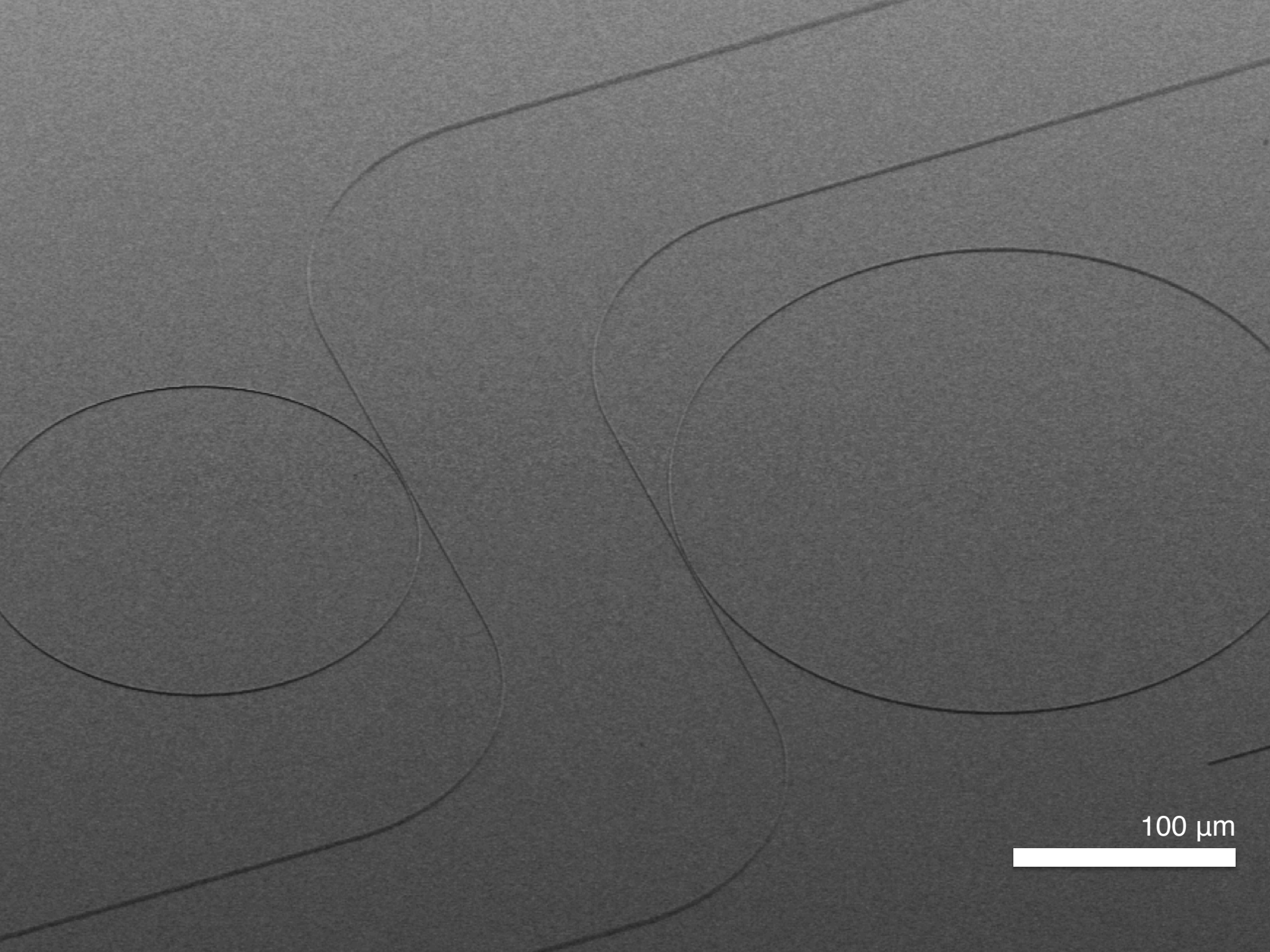
Polycrystalline Anatase Micro-Ring Resonators at Telecommunication Wavelengths

Orad Reshef[1], Katia Shtyrkova[2], Michael Moebius[1], Christopher Evans[1,3], Sarah Griesse-Nascimento[1], Erich Ippen[2], Eric Mazur[1]

[1]Harvard School of Engineering and Applied Sciences, Cambridge, MA
[2]Massachusetts Institute of Technology, Cambridge, MA
[3]Kavli 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

C. Evans et al., *Optics Express* 21, 18582 (2013)

Titanium dioxide

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

Rutile

Anatase

Brookite

TiO_2 is inexpensive, abundant and non-toxic.

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

Large refractive index: 2.4 @ λ = 1550 nm

Large nonlinear index: 1.8×10^{-15} cm^2/W @ λ = 1550 nm

2.5×10^{-15} cm^2/W for SiN

Large transparency: > 400 nm

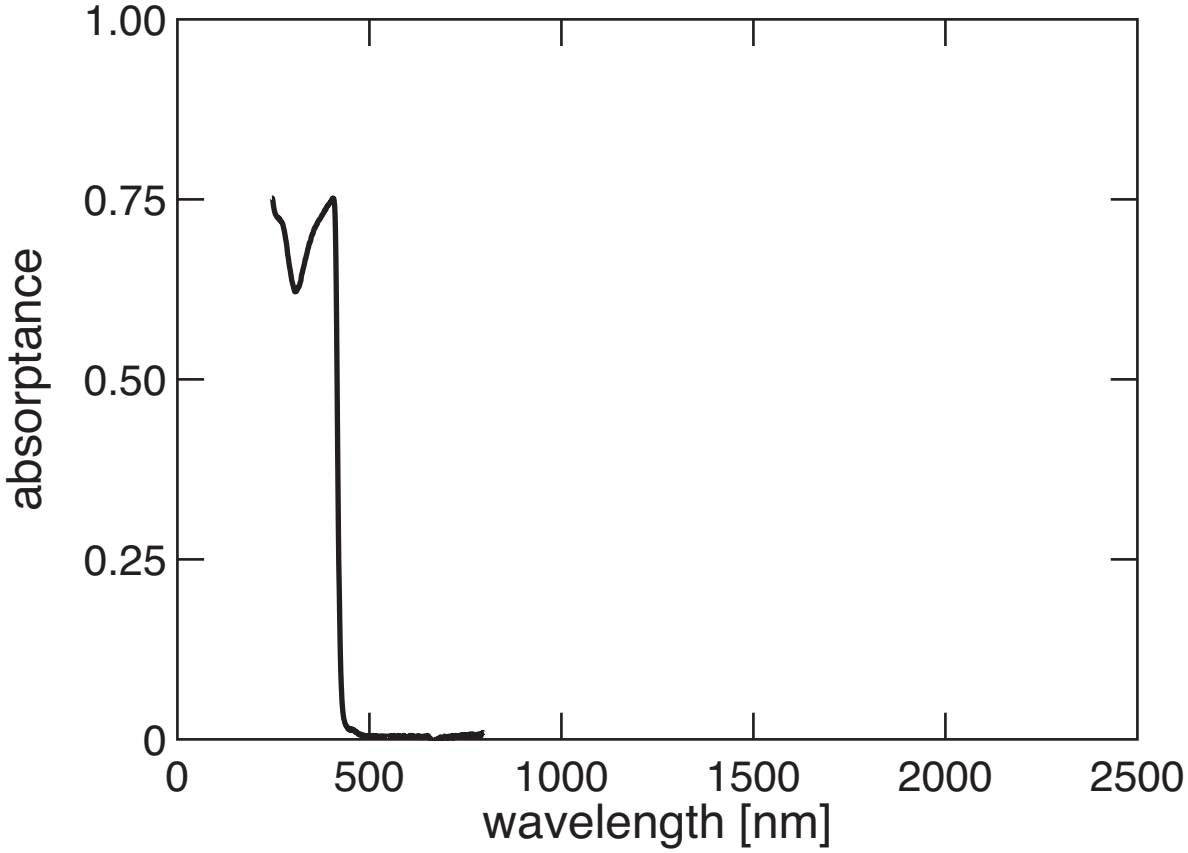
> 800 nm - no 2PA

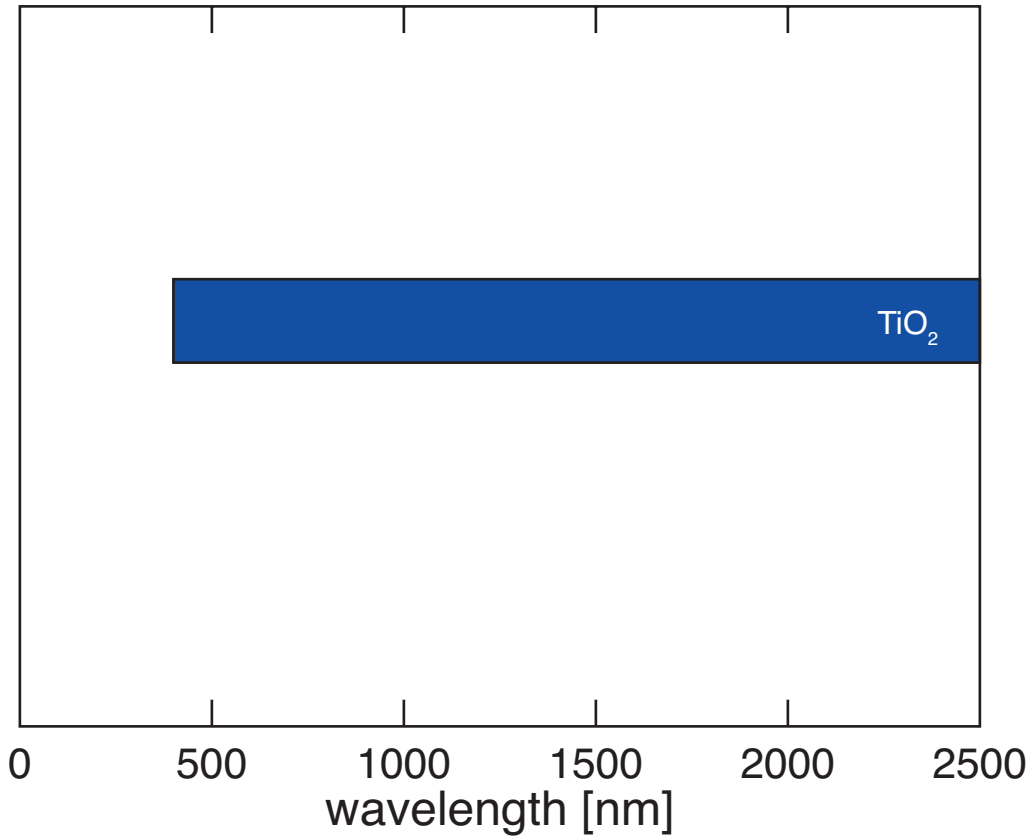
> 1200 nm - no 3PA

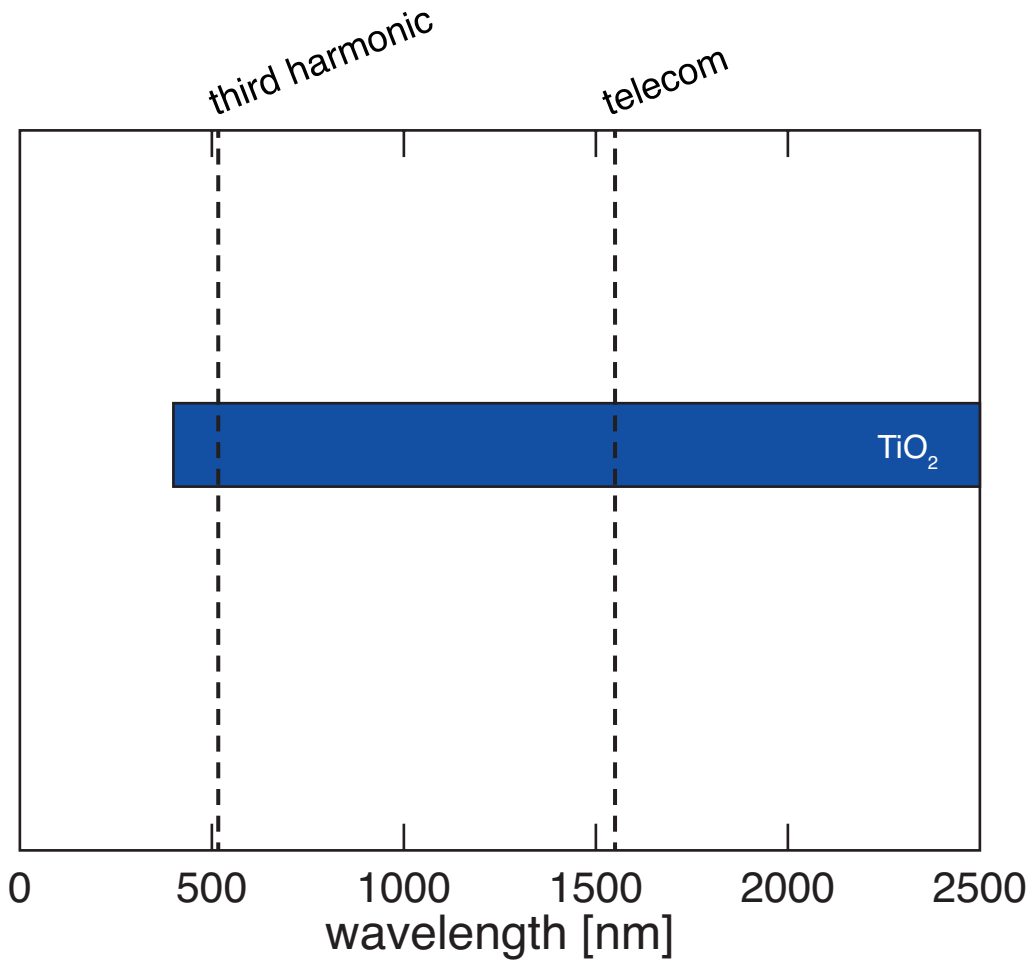
How does this compare to other materials?

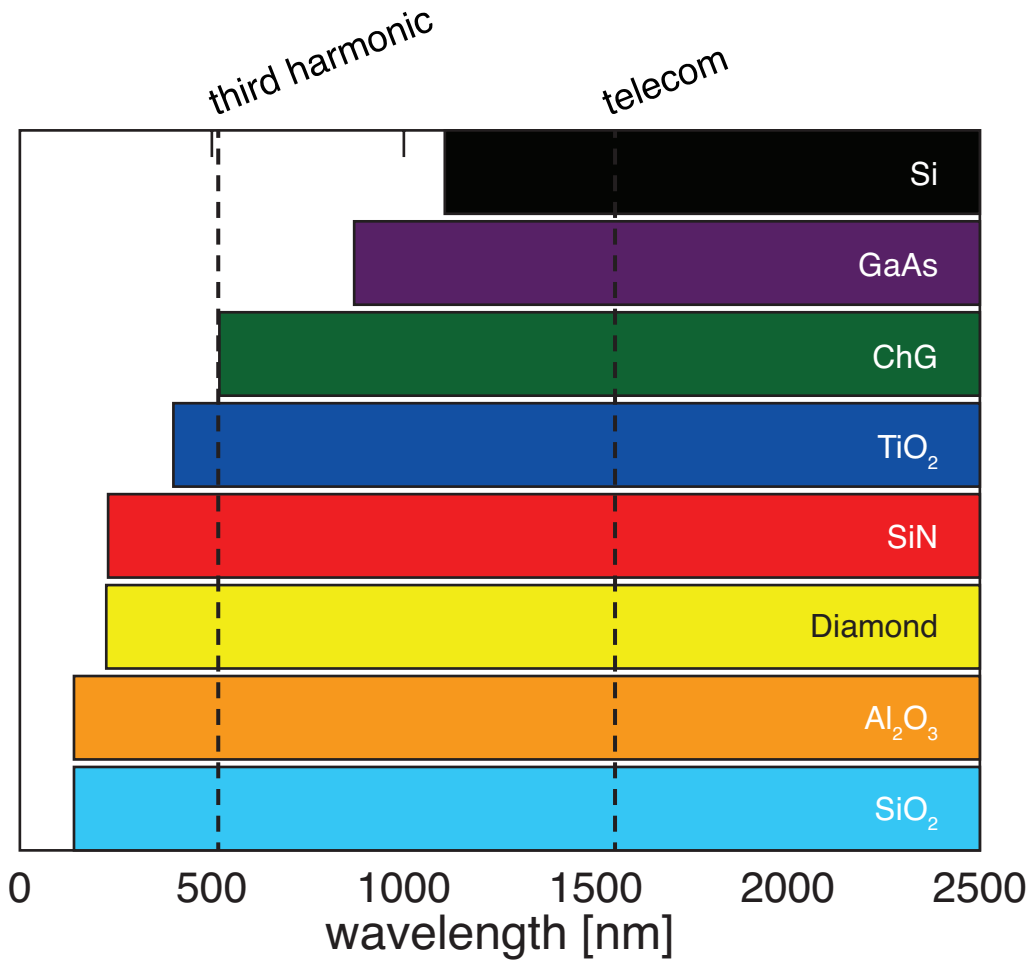
C. Evans et al., *Optics Express* 21, 18582 (2013)

First, let's compare transparency:

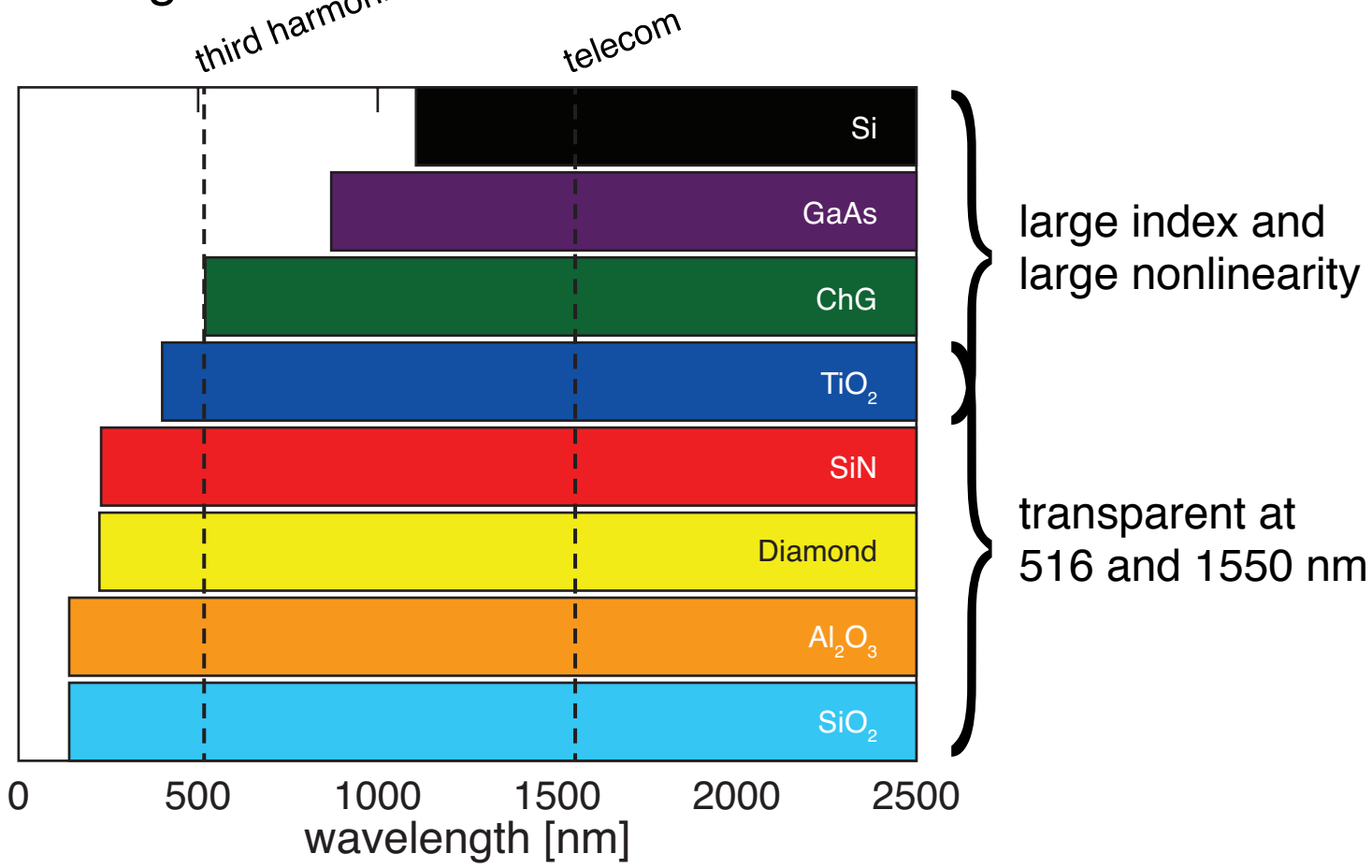



TiO2
0
500
1000
1500
2000
2500
wavelength [nm]

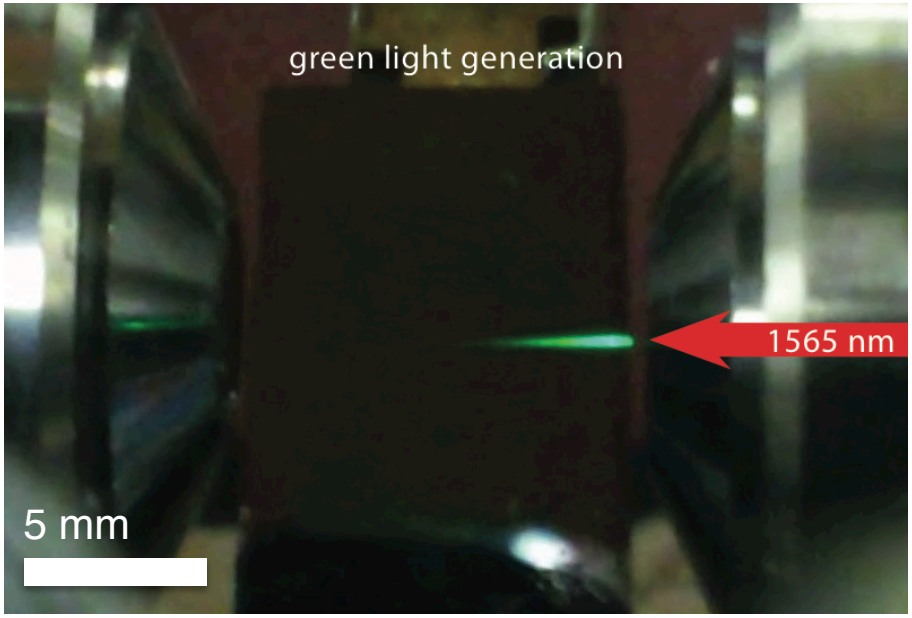

third harmonic
telecom
TiO2
0
500
1000
1500
2000
2500
wavelength [nm]


third harmonic
telecom
Si
GaAs
ChG
TiO2
SiN
Diamond
Al2O3
SiO2
0
500
1000
1500
2000
2500
wavelength [nm]

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:

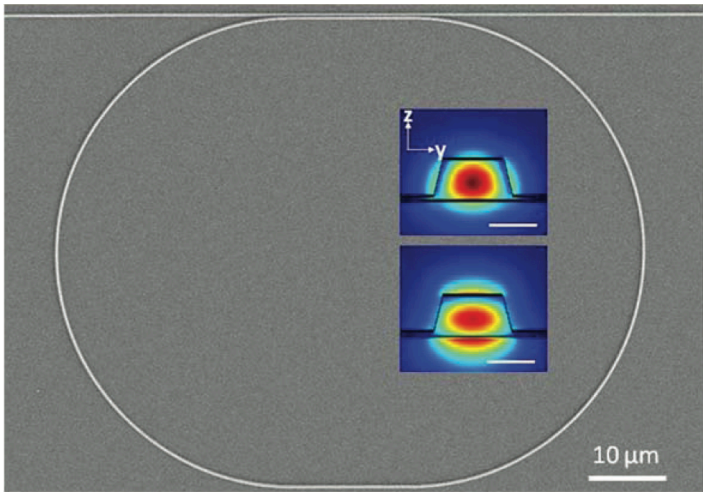


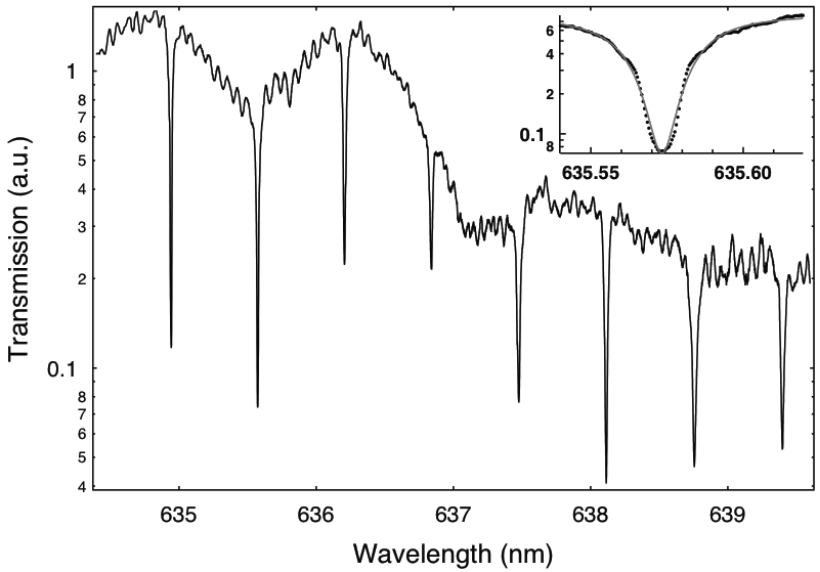
Katia Shtyrkova et al., “Third Harmonic Generation in Polycrystalline Anatase Titanium Dioxide Nanowaveguides”

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

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

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

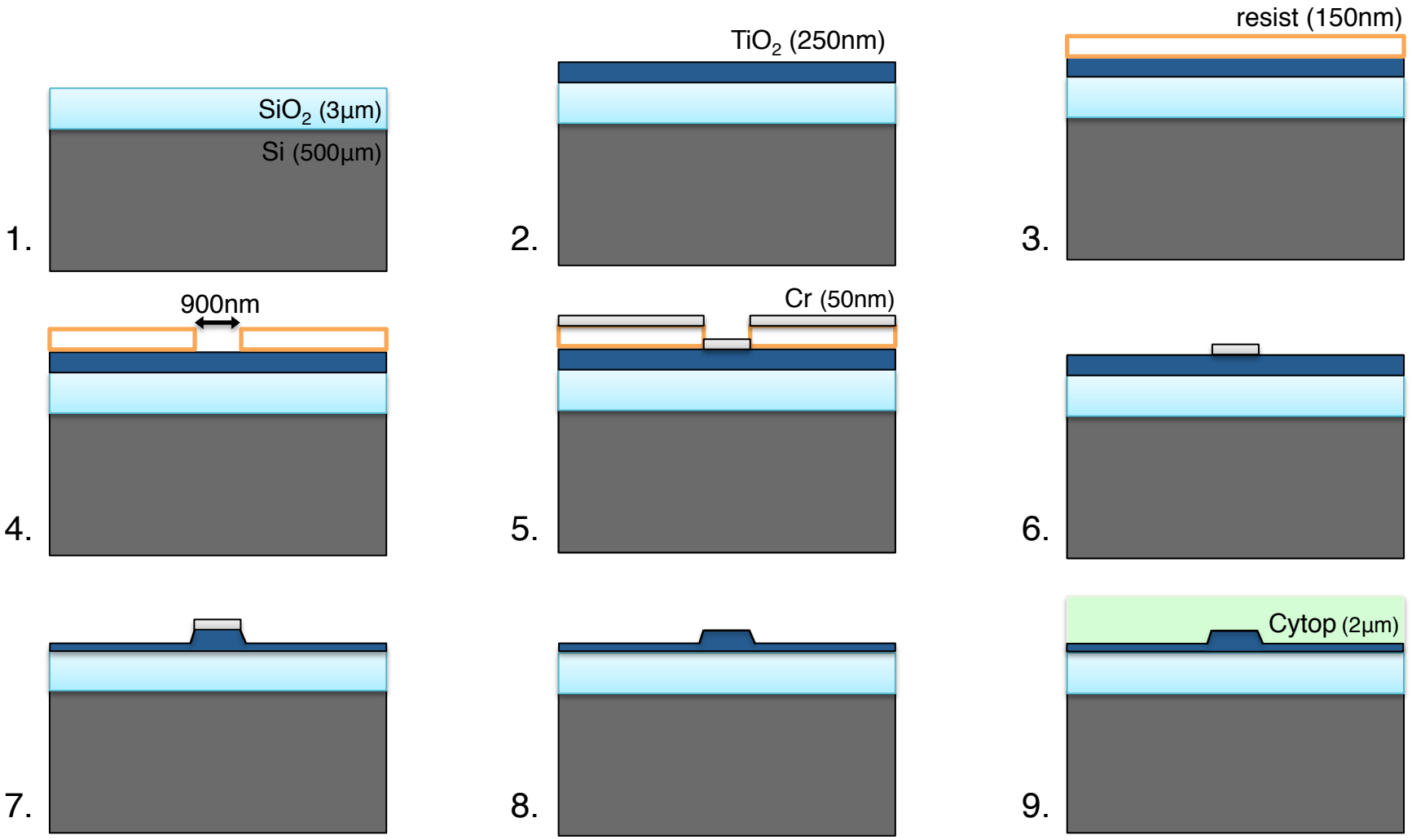




J. T. Choy et al., *Optics Letters* 37, 539 (2012)

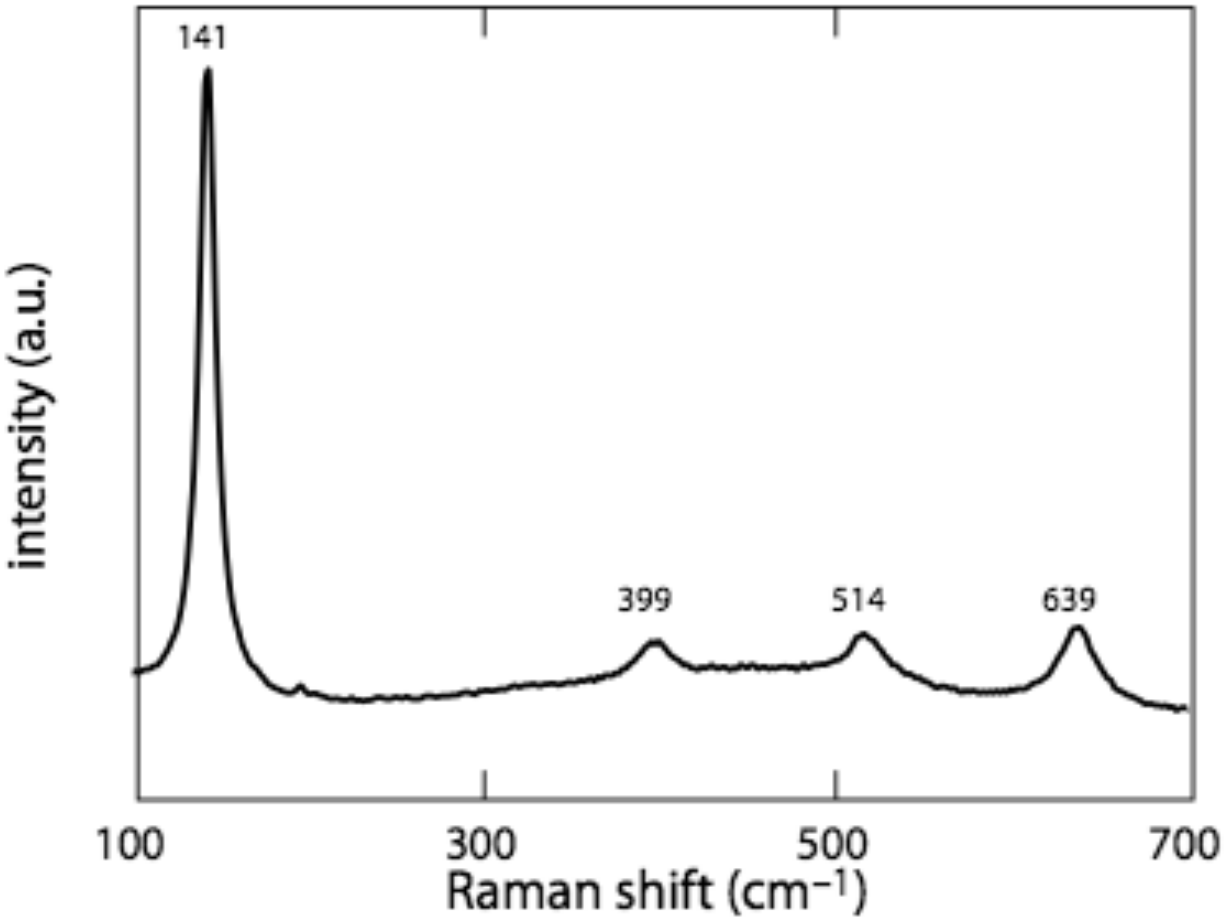
Fabrication

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



J. D. B. Bradley et al., *Optics Express* 20, 23821 (2012)

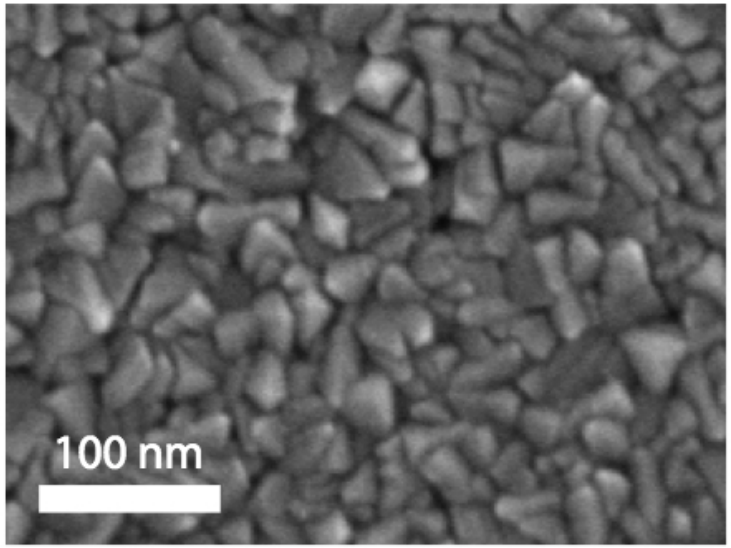
Raman spectroscopy confirms the deposition of anatase.



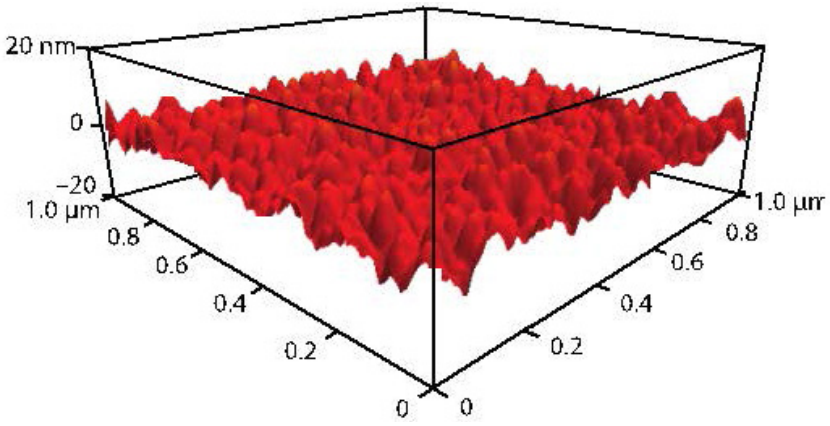
J. D. B. Bradley et al., *Optics Express* 20, 23821 (2012)

The rough surface contributes to propagation losses.

SEM

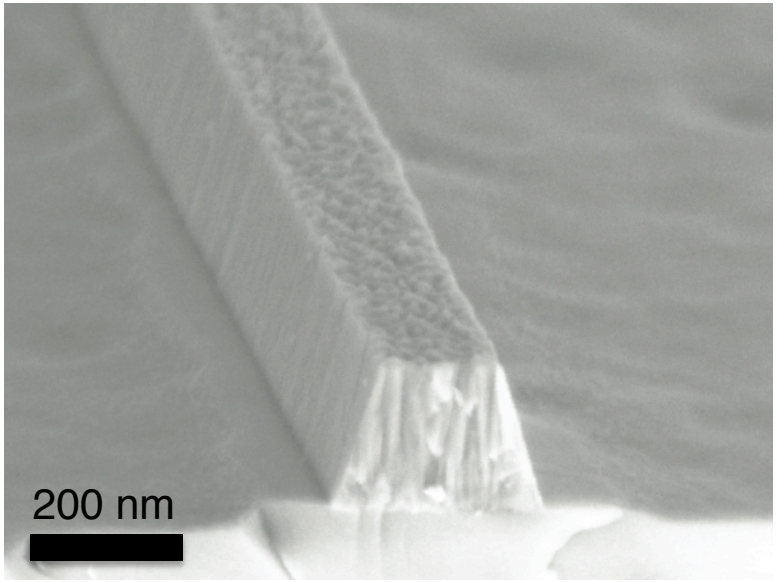


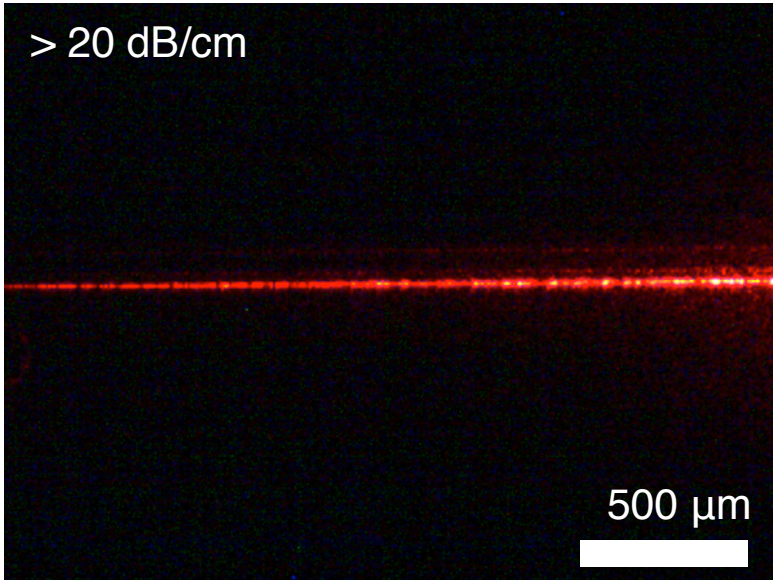
AFM



RMS Roughness: 2.7 nm

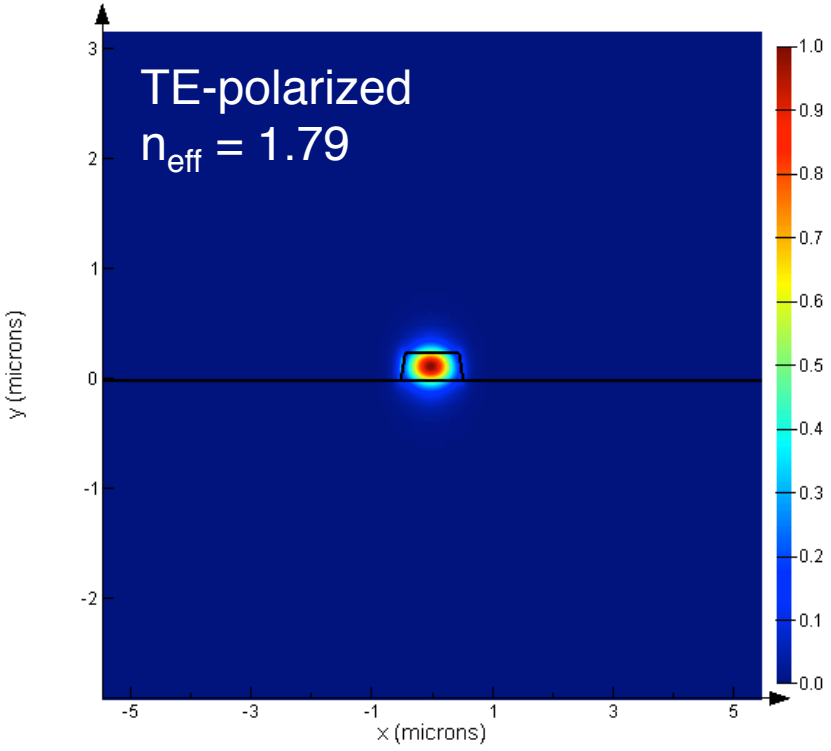
J. D. B. Bradley et al., *Optics Express* 20, 23821 (2012)

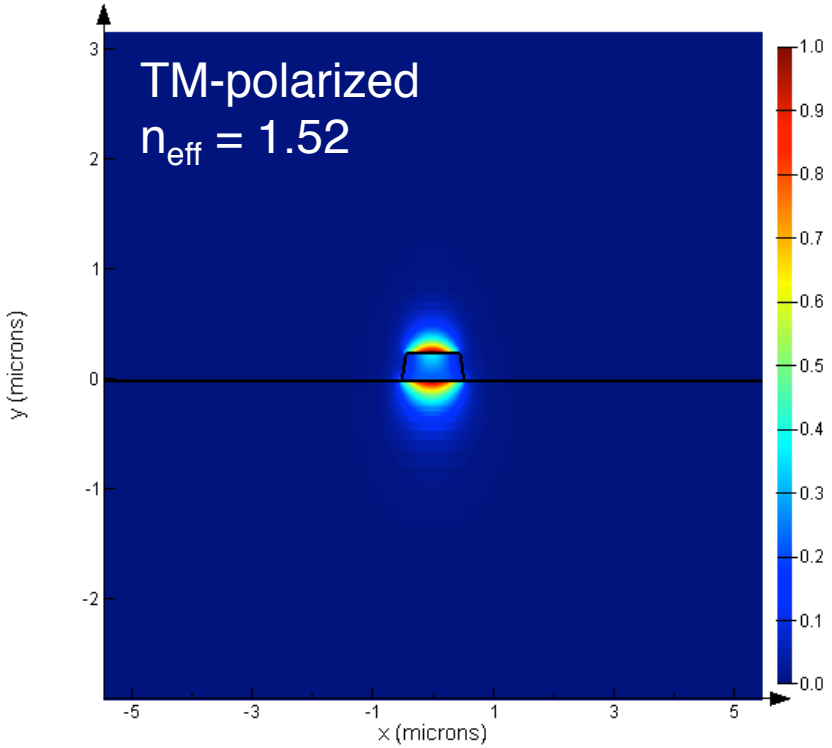

200 nm


> 20 dB/cm
500 µm

Design parameters

Waveguide cross-sectional dimensions: 250 nm x 900 nm





Design parameters were chosen to ensure single mode operation at λ = 1500 nm.

Ring radius:

100 and 150 μm

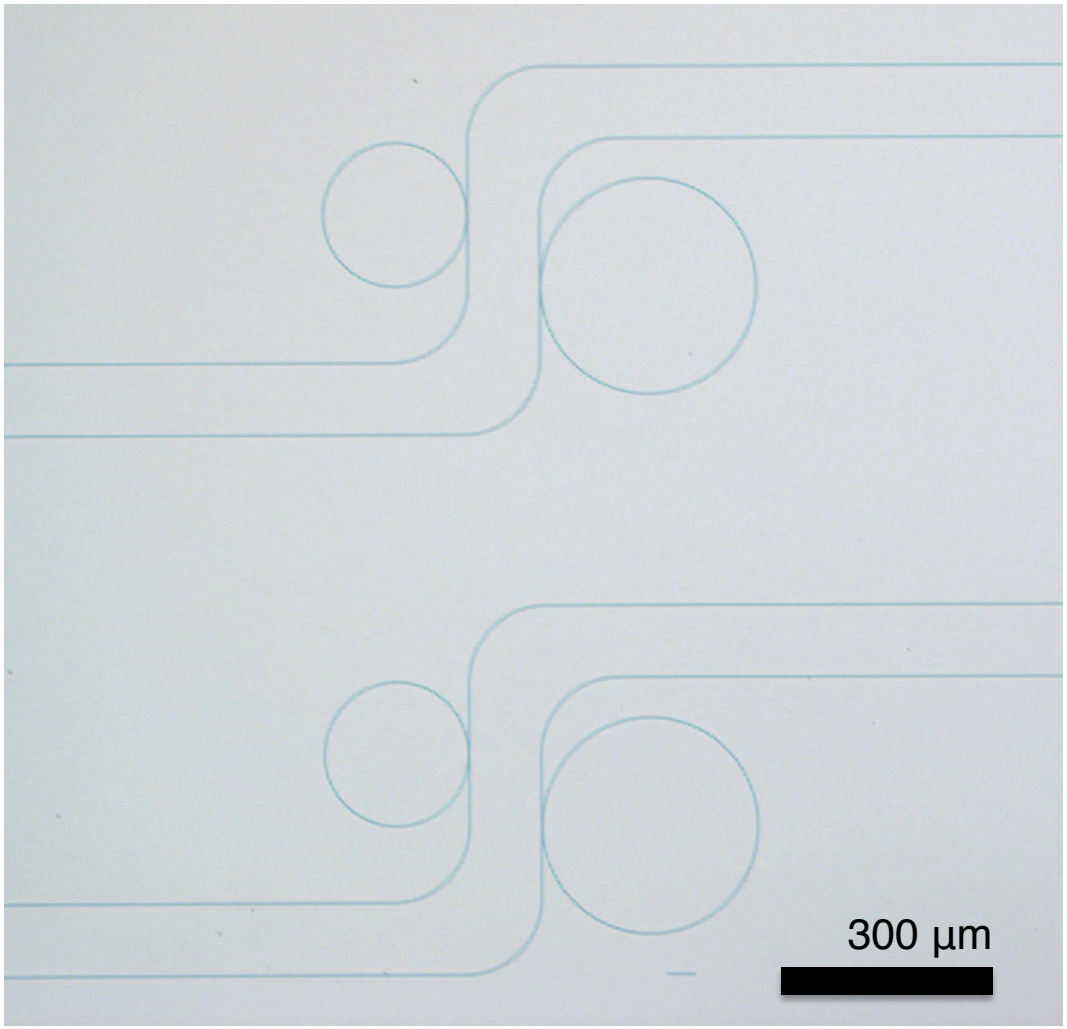
$$\Delta\lambda = \lambda^2 / 2\pi r \cdot n_{eff}$$

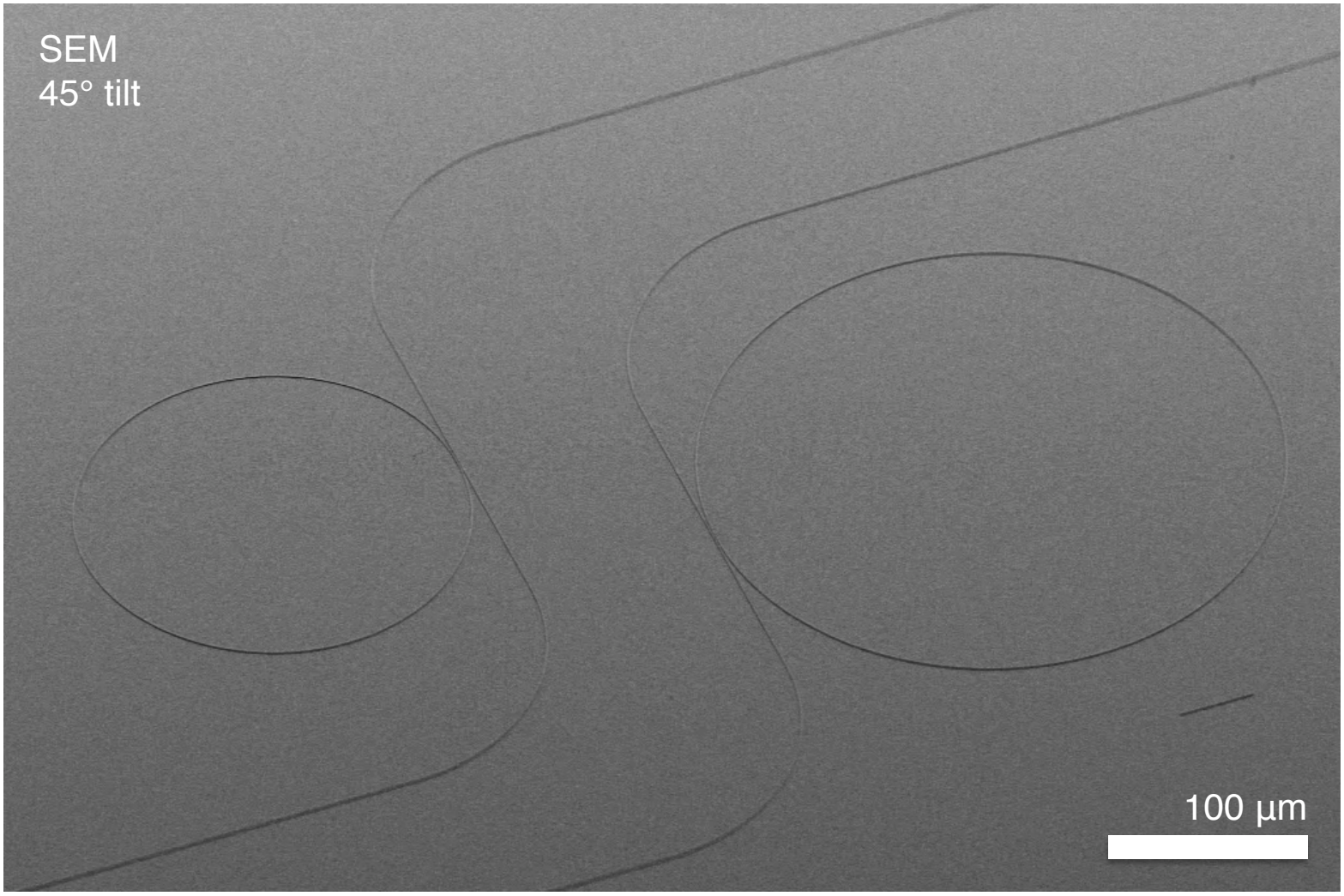
Predicted FSR:

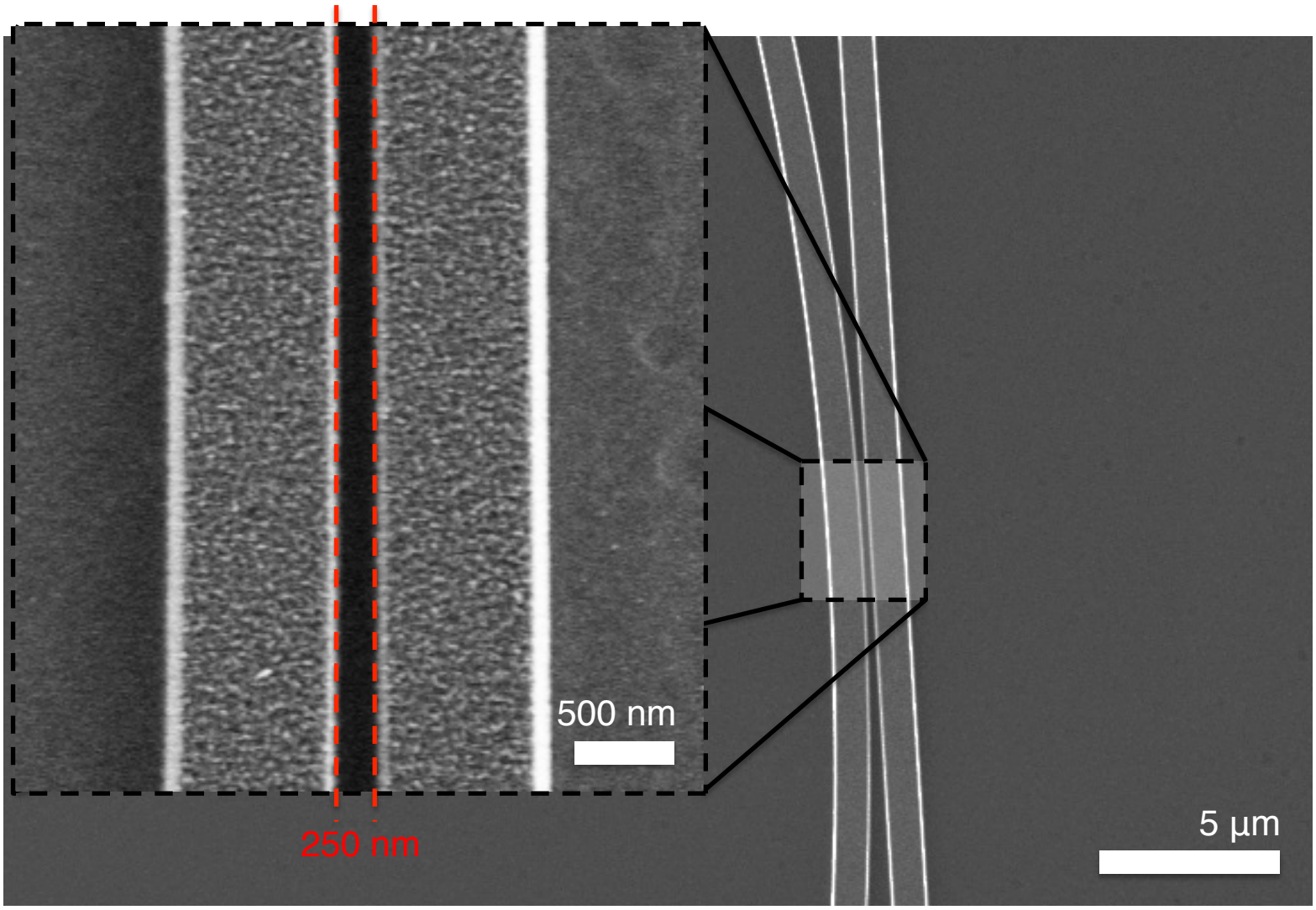
2.16 and 1.43 nm

Gap size:

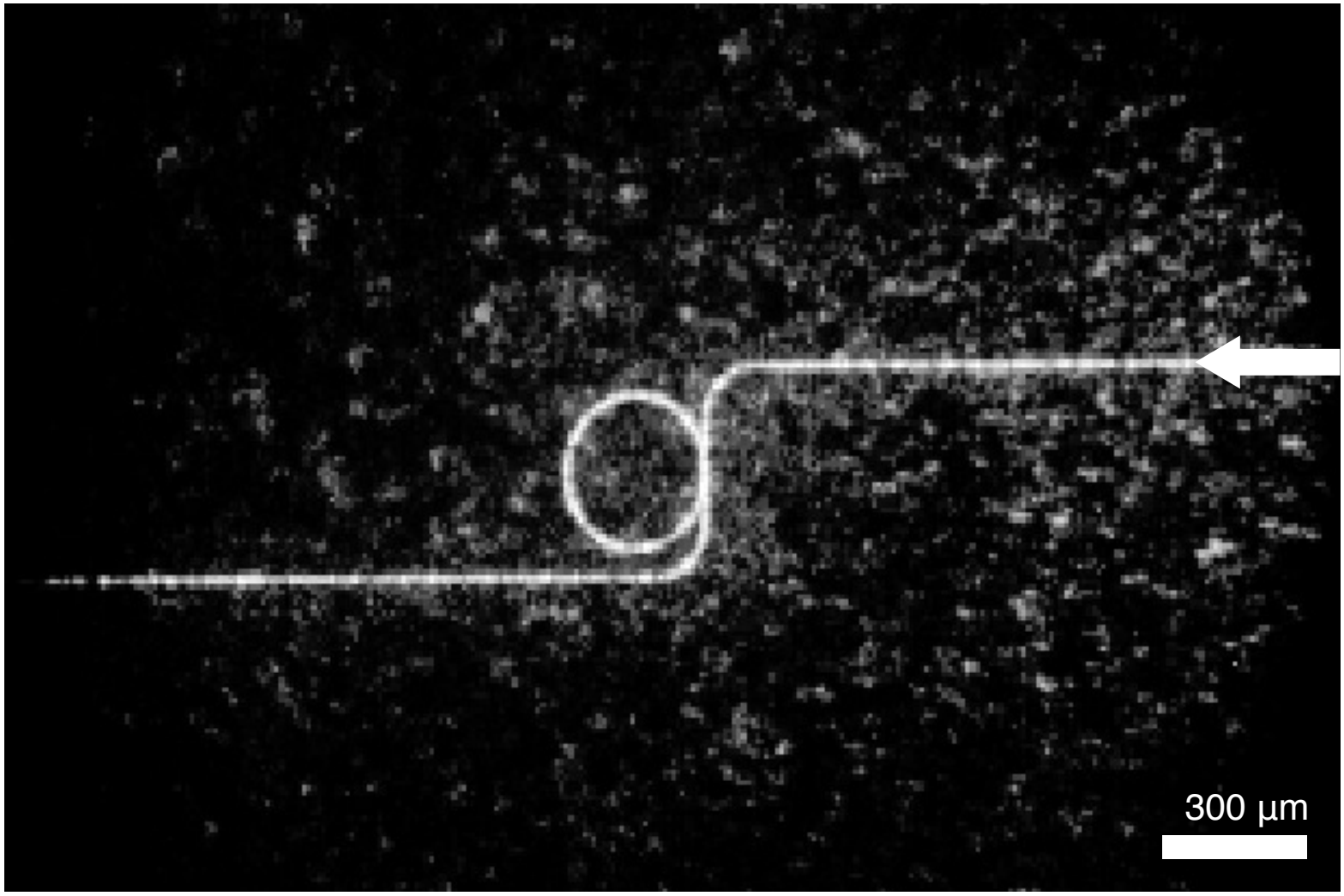
250, 300, and 350 nm



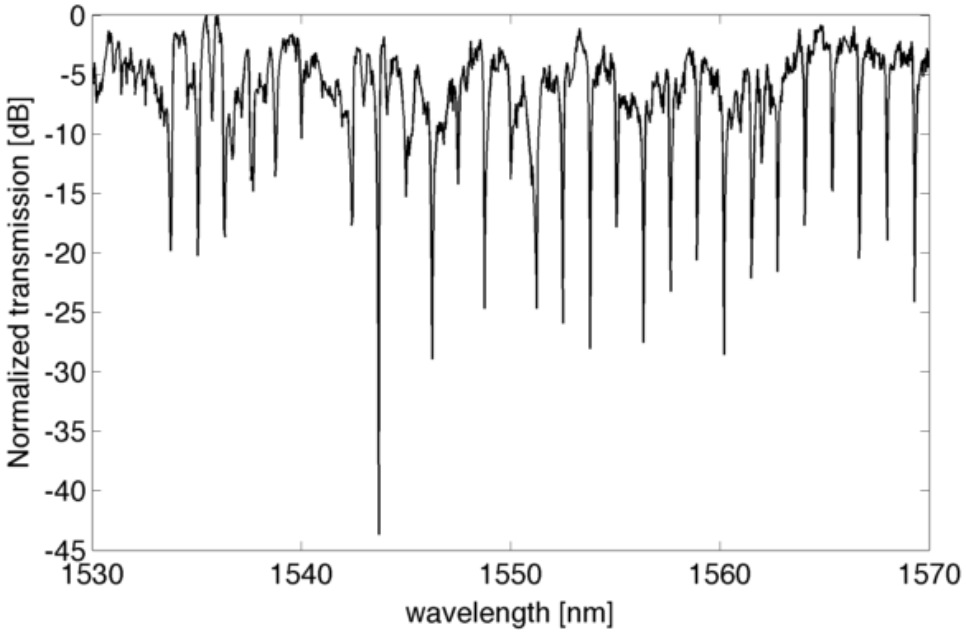

SEM
45° tilt
100 µm


500 nm
250 nm
5 µm

Device characterization


300 µm

Sweeping from 1530 to 1570 nm yields sharp resonances.



Q-factor: 1.5×10^4

Comparable to poly-Si[1]: 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

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

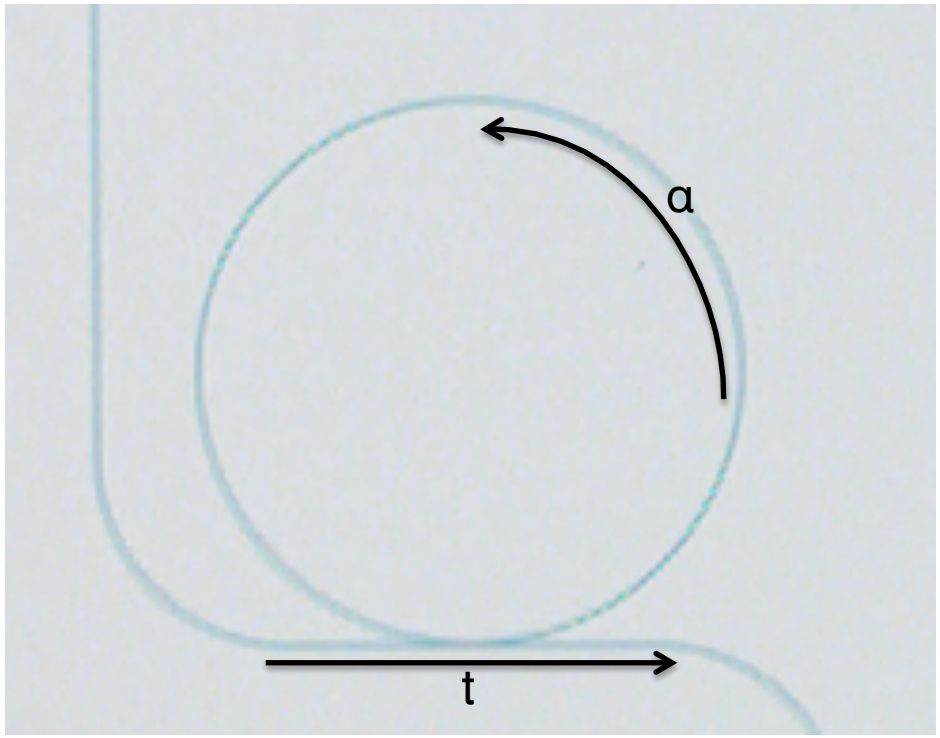
We can model the behavior of these resonances using a scattering matrix:

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

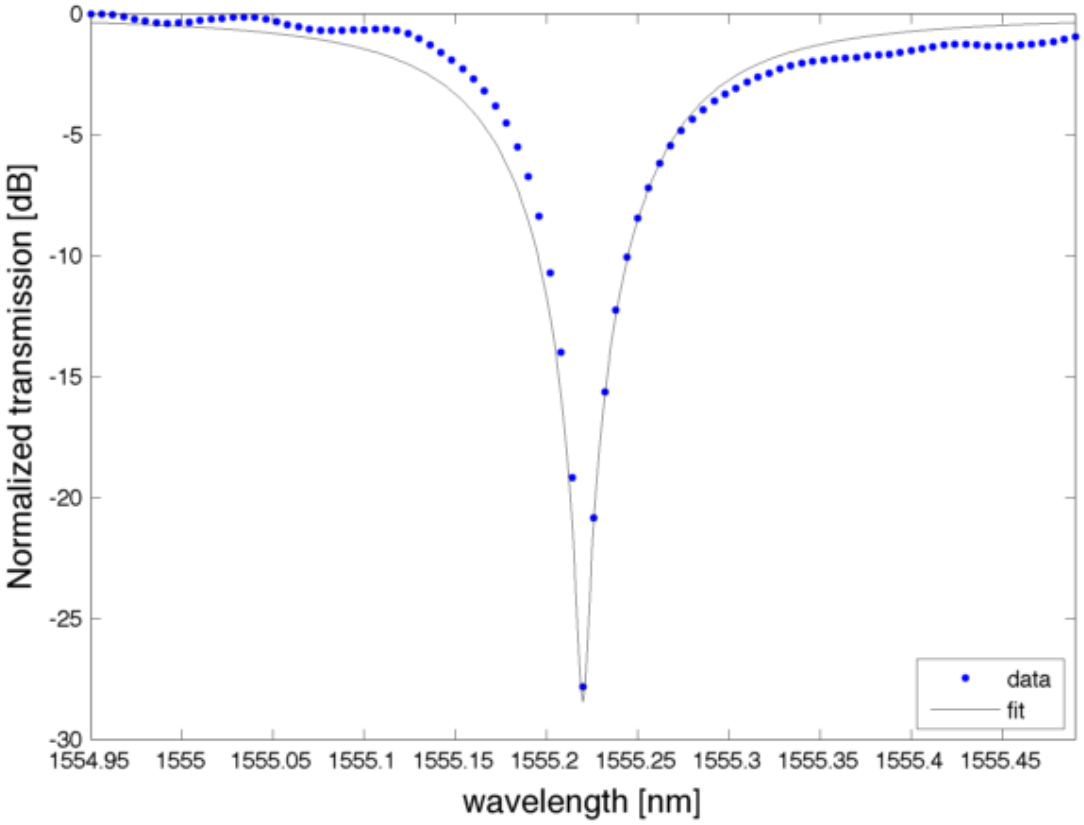
t = transmission coefficient of the coupler

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
α = 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

NSERC CRSNG

THE KAVLI FOUNDATION

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

MZOR GROUP

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