Study of Ultrafast Laser-Induced Acoustics with Plasmonic Gratings

MSc Physics and Astronomy
Master thesis

By Jeffrey SUEN
Supervisors: Prof. dr. Paul Planken, ir. Thomas van den Hooven
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Introduction

- Nanolithography machine
- Alignment gratings - buried
- Laser-induced acoustic waves
- Reflect grating shape
- Detect with probe laser

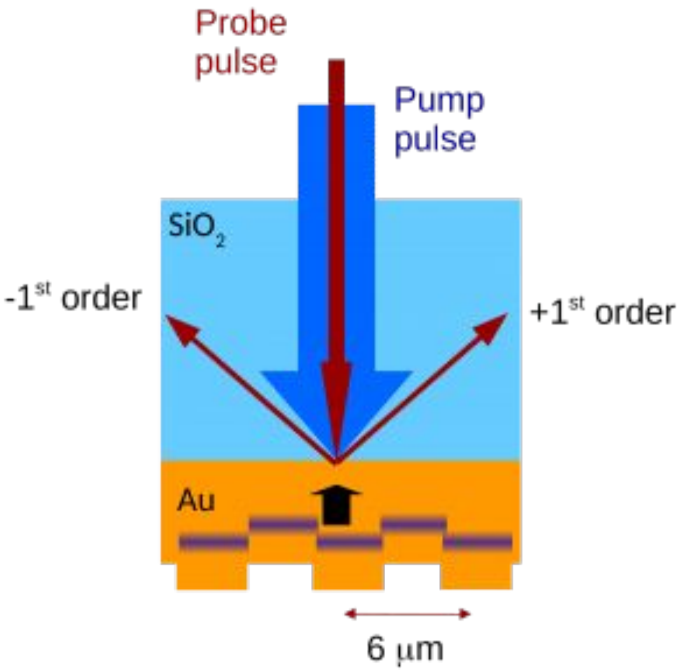


Fig: arcnl.nl/research-groups/light-matter-interaction

Introduction

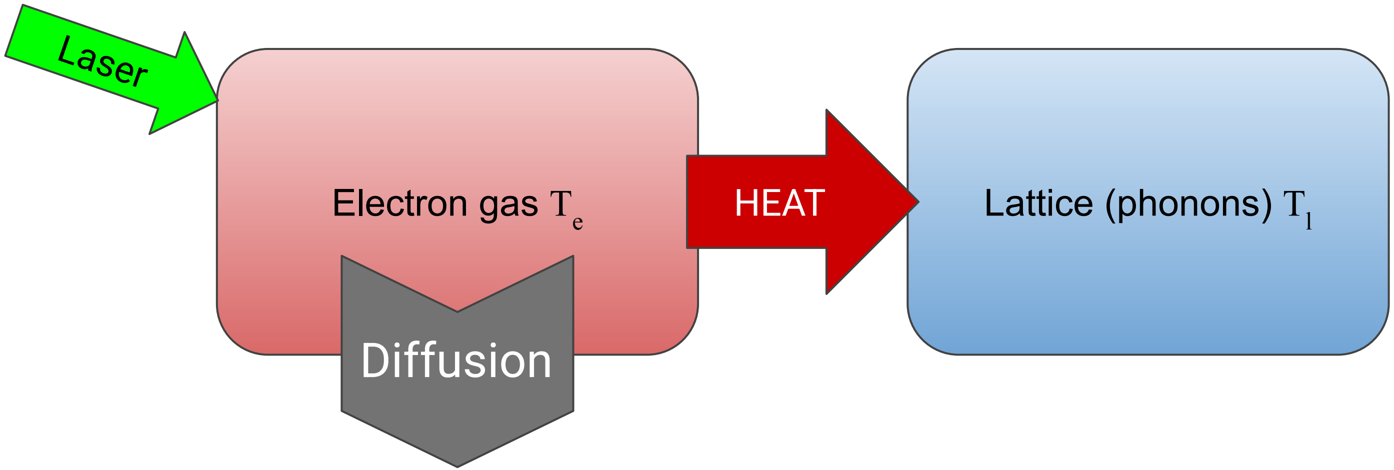
- Challenge: Signal too weak for industrial use
- Enhance with plasmonic resonance

Research:

How does plasmonic resonance enhance signal?

Two-Temperature Model

- Electrons absorbs laser
- Heat transfer to the lattice
- Diffuse through electrons
- Determines the time-dependent temperature distribution



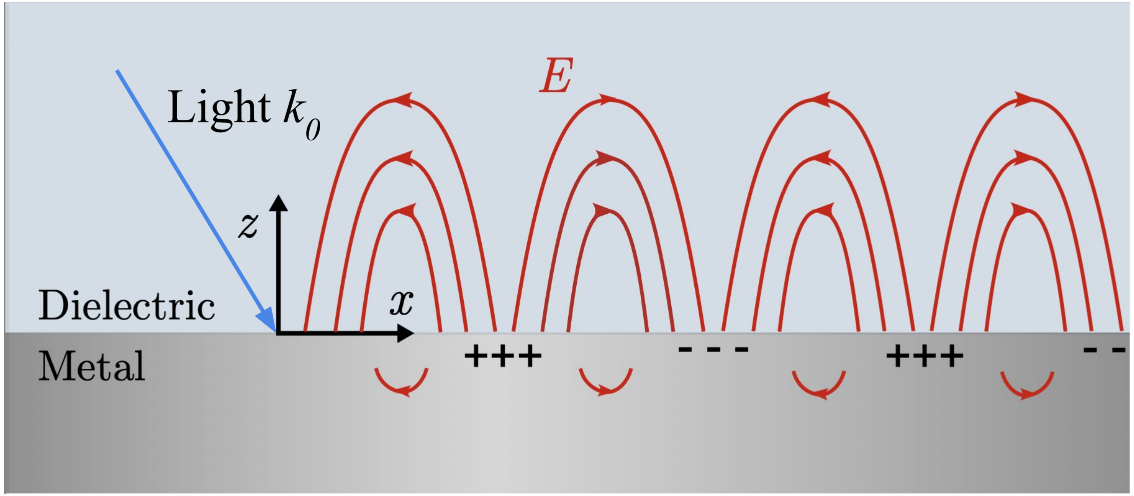
Photoacoustics

What happens after absorption?

- Lattice wants to expand
- Thermal stress
- Propagate into the layer
- Longitudinal wave
- Changes reflectance or diffraction efficiency

Surface Plasmon Polariton (SPP)

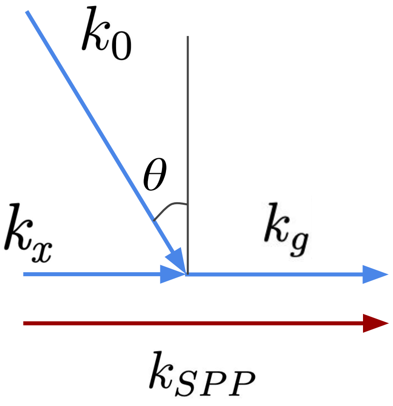
Electromagnetic wave bound to surface of a metal



$$k_{SPP} = \frac{\omega}{c}\sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}} > k_0 = \omega/c$$

Impossible in air!

Surface Plasmon Polariton (SPP)



$$|k_x \pm N k_g| = k_{SPP}$$

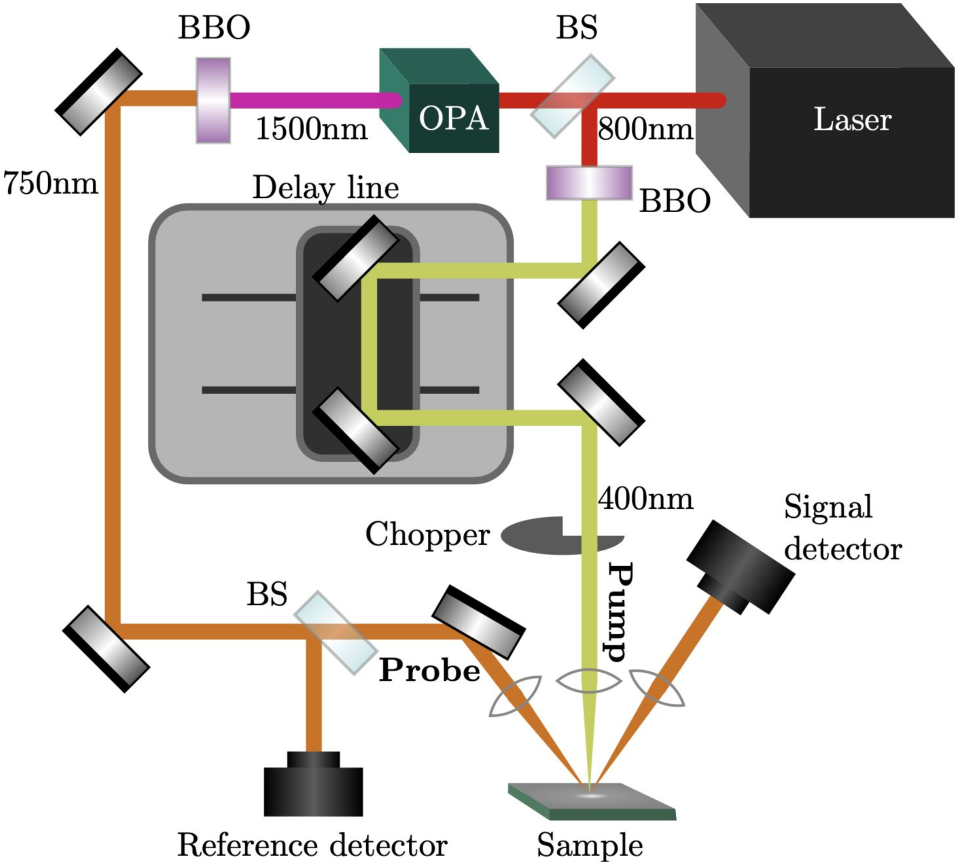
$$\left| \frac{\omega}{c} \sin\theta \pm N \frac{2\pi}{\Lambda} \right| = \frac{\omega}{c} \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}}$$

- Grating adds extra k-component
- Absorbs more light when coupled -> minimum reflectance
- Longitudinal wave density oscillation -> change resonance wavelength
- LW induced reflectance change is enhanced near SPP resonance

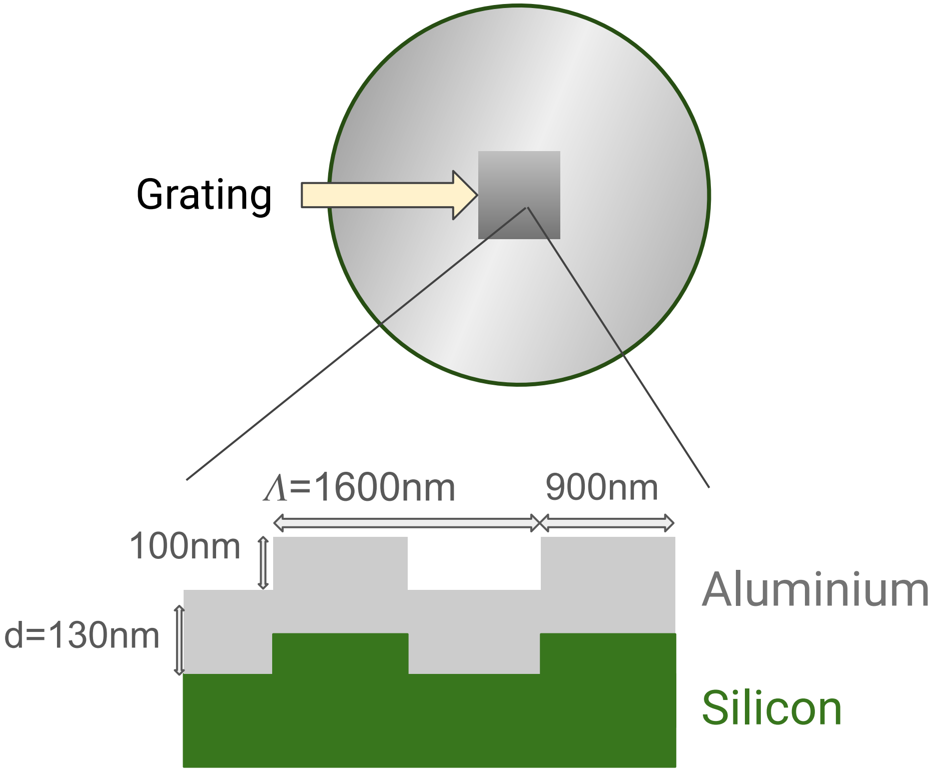
Experiments: Setup

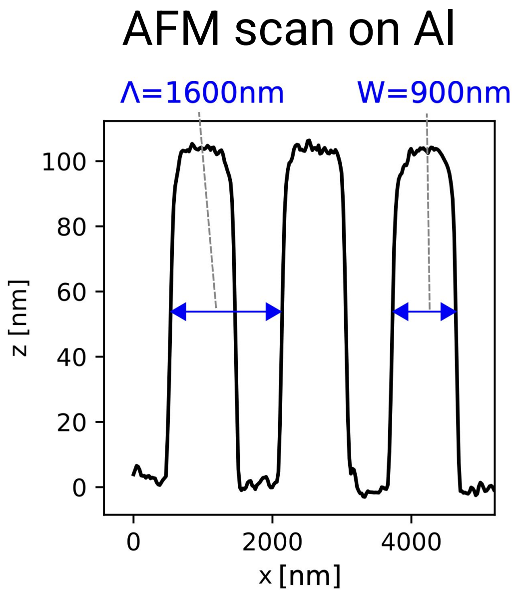
Pump-probe experiments

- 800 nm ultrafast Laser source
  - 35 fs, 1 kHz
- Variable pump-probe delay
- Pump 500 Hz
- Compare with and without pump



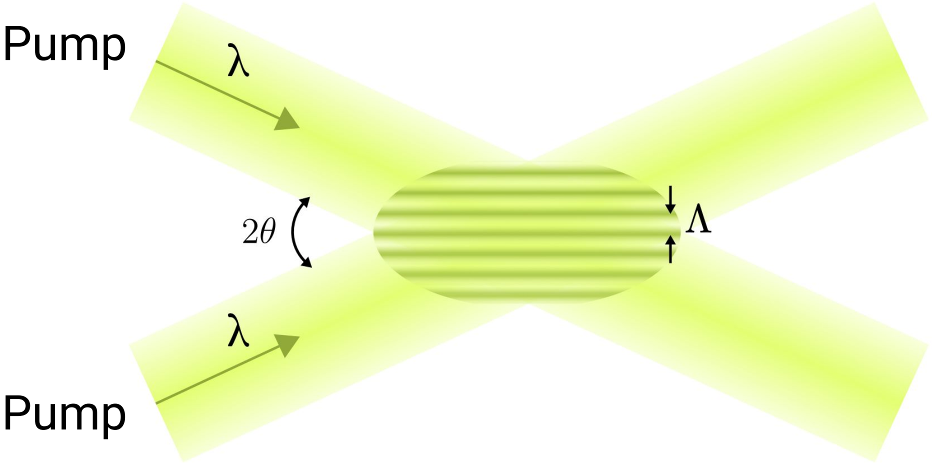
Sample


Grating
Λ=1600nm
900nm
100nm
d=130nm
Aluminium
Silicon


AFM scan on Al
Λ=1600nm
W=900nm
z [nm]
x [nm]
0
20
40
60
80
100
0
2000
4000

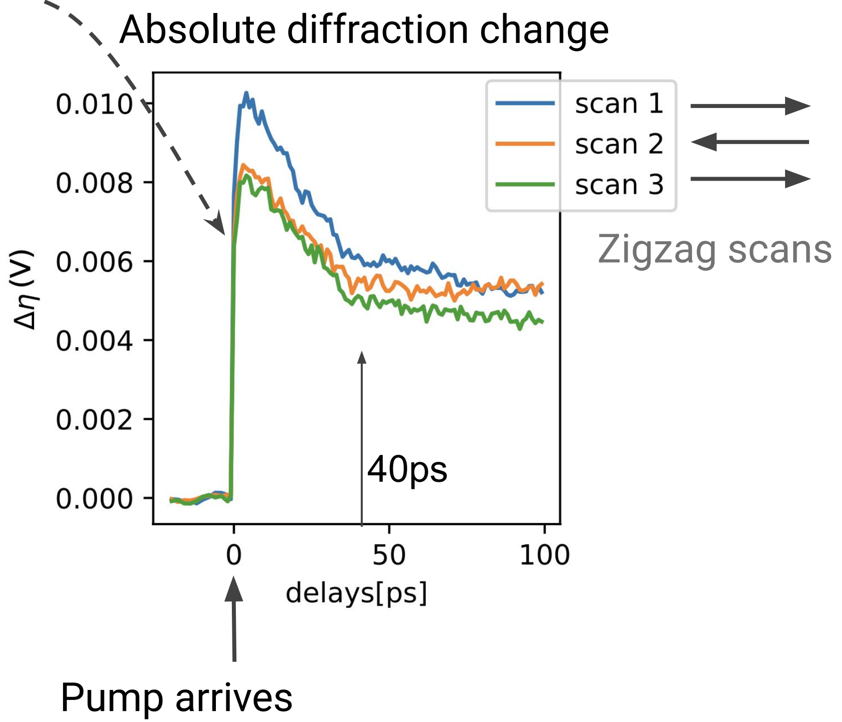
Experiment 1: Transient grating diffraction change

- Split into two 400 nm pump beams
- Cross on flat part of sample
- Interference pattern -> grating
- 750 nm probe pulses
- Diffraction only with pump
- High signal-to-noise



Experiment 1: Transient grating diffraction change

- Rapid absorption by electrons
- Longitudinal wave reflection round trip time: $2d/v_\ell = 40.5$ ps
- Increased diffraction for blocked
- Potential damage

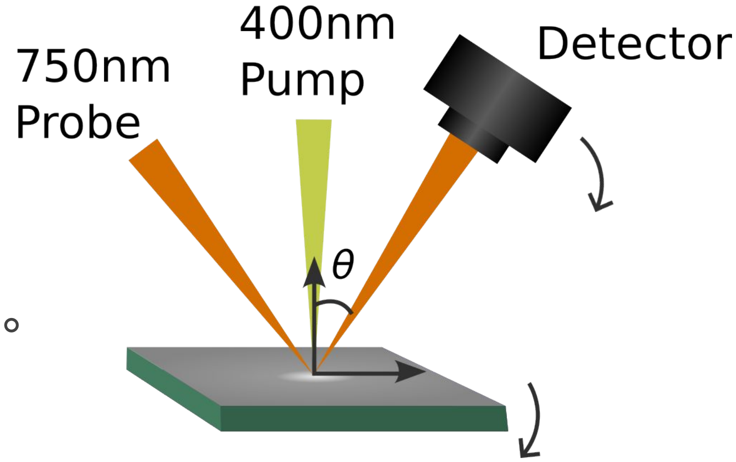


- **No clear LW reflection**
- **Control pump fluence**

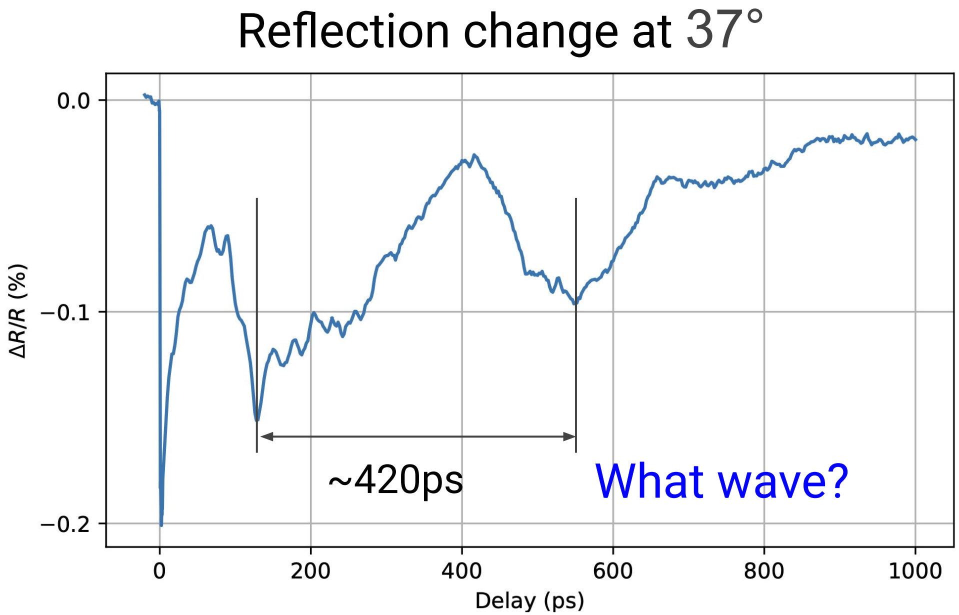
Experiment 2: Etched grating reflection change 750 nm probe, multiple angles

- ONE 400 nm pump beam
- 750 nm probe
- On etched grating
- At and around SPP resonance angle 37°

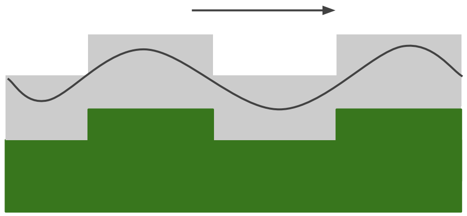
- Compare SPP resonance with off-resonance



Experiment 2: Etched grating reflection change 750 nm probe, multiple angles



Surface Acoustic Waves



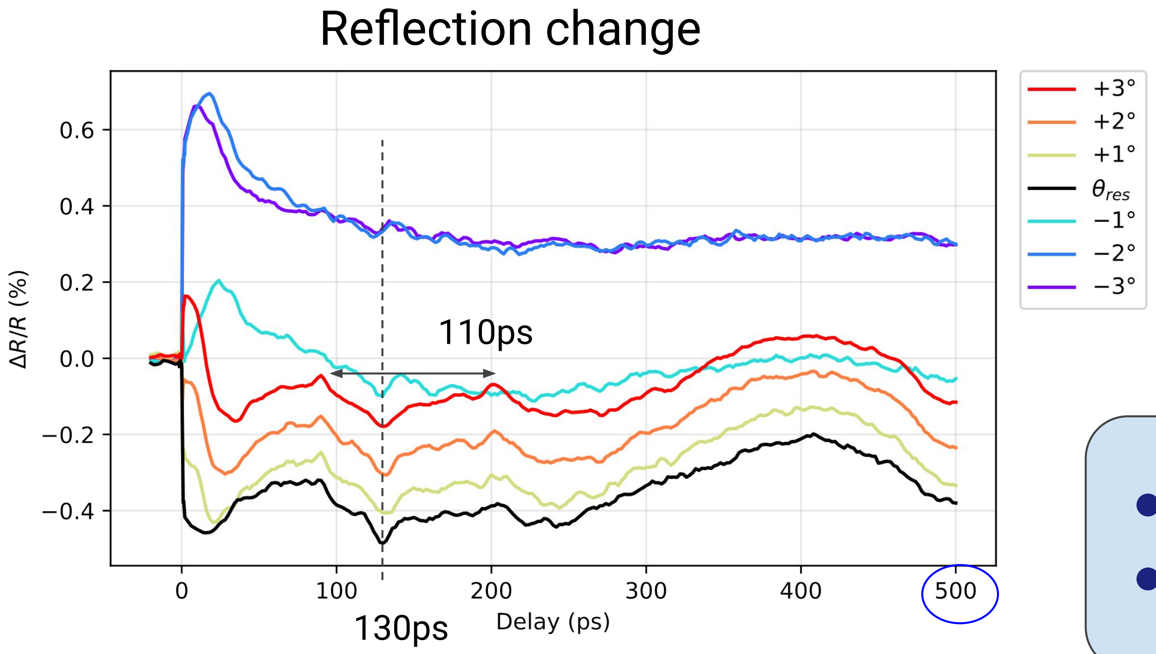
$$T = \frac{\text{grating period}}{\text{transverse speed of sound}}$$

= 526ps

Maybe SAW?

No LW (40.5ps)

Experiment 2: Etched grating reflection change 750 nm probe, multiple angles



Larger oscillations at +angles

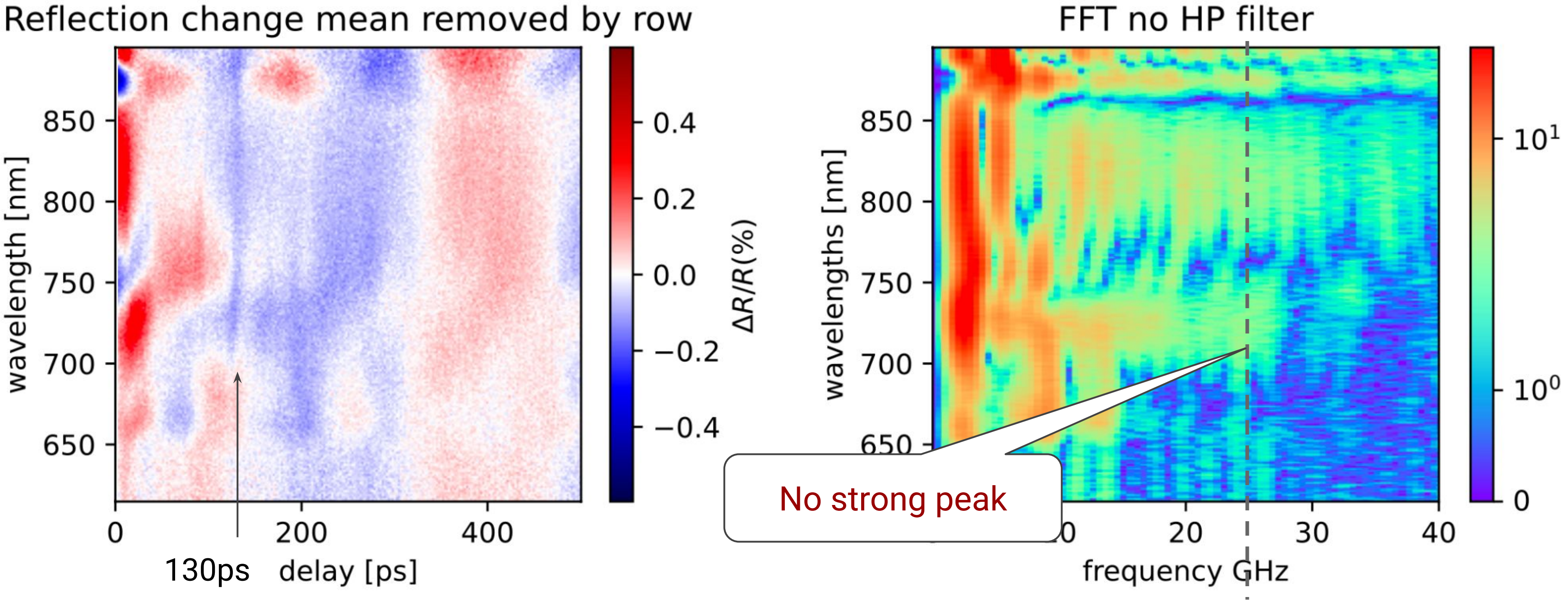
Changes sign at –angles

- **Unknown oscillations**
- **No longitudinal waves**

Experiment 3: Etched grating reflection change White light probe, fixed angle

- Probe → white light continuum 600~900nm
- Detector → spectrometer
- Incidence at resonance angle for 750 nm ~37°

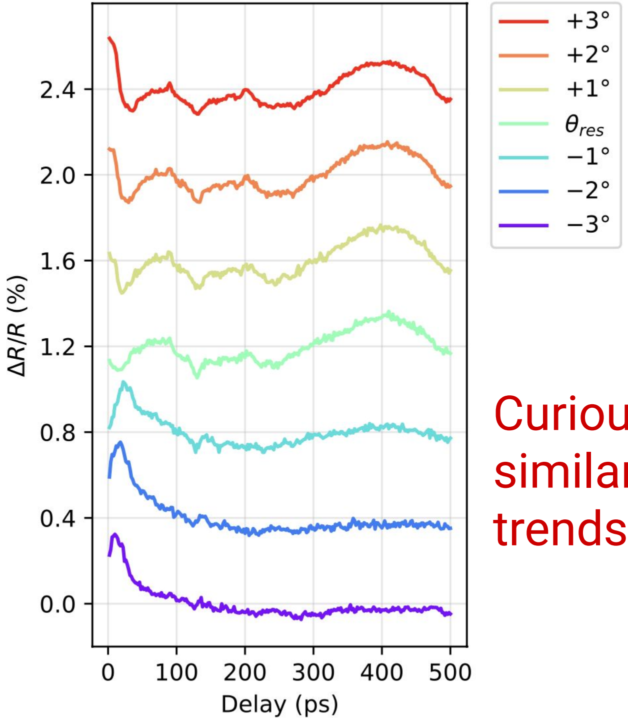
Experiment 3: Etched grating reflection change White light probe, fixed angle



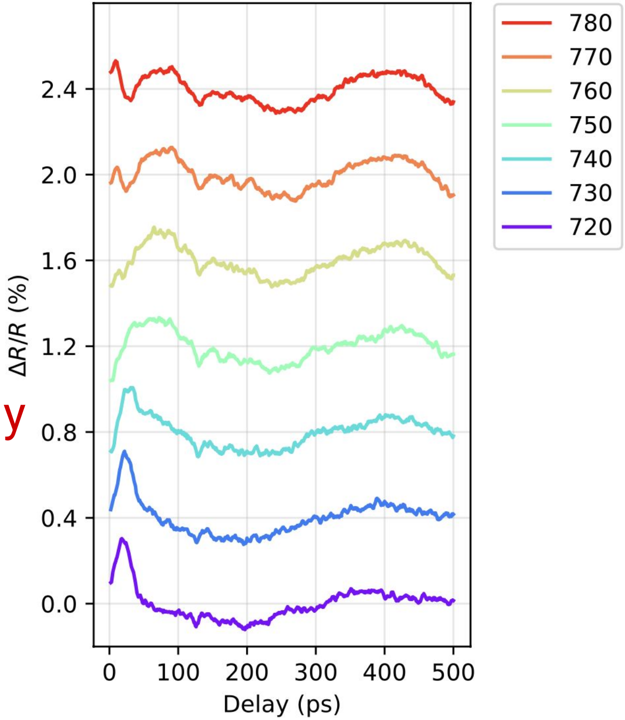
LW: 24.7 GHz

Vary angle of incidence vs Vary probe wavelength

750 nm probe, vary angle



White light probe, 37°



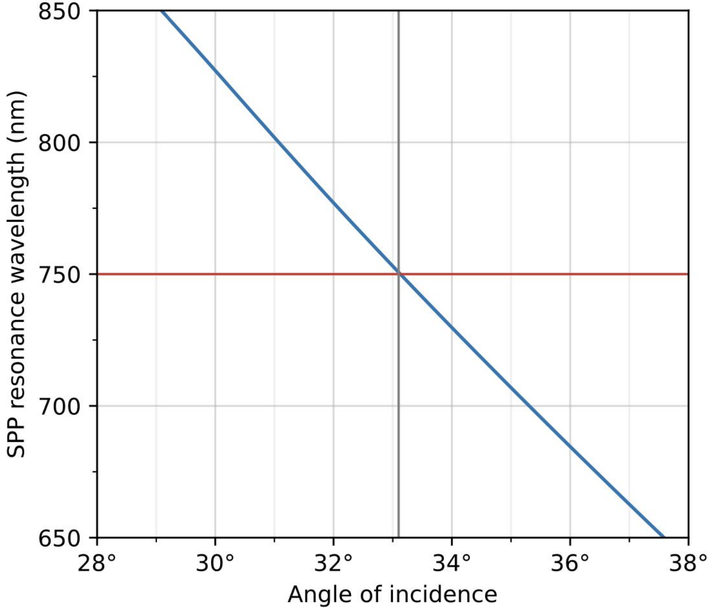
Curiously similar trends!

How are angle of incidence and probe wavelength related?

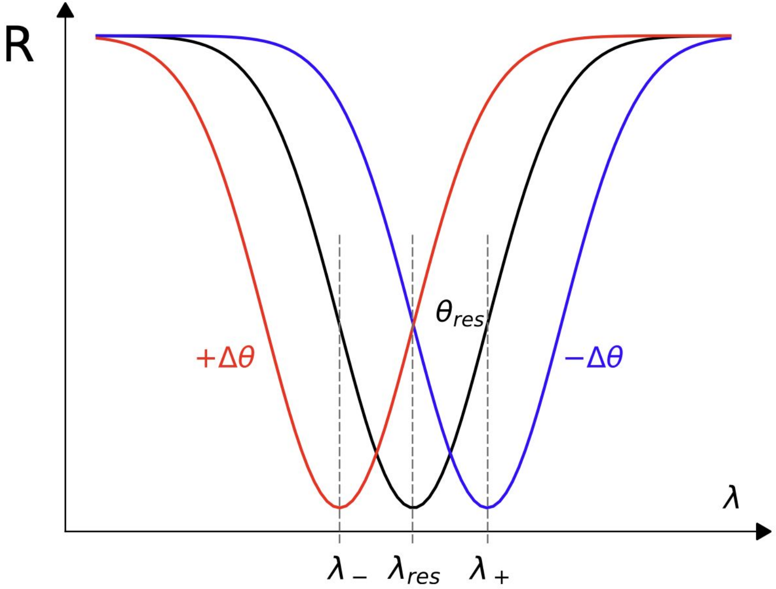
Vary angle of incidence vs Vary probe wavelength

SPP resonance condition

$$\left|\frac{\omega}{c}\sin\theta \pm N\frac{2\pi}{\Lambda}\right| = \frac{\omega}{c}\sqrt{\frac{\epsilon_m\epsilon_d}{\epsilon_m+\epsilon_d}}$$



Angle⇧ ⇌ wavelength⇧



No LW: Acoustic Impedance Mismatch

Acoustic impedance: resistance to acoustic waves

$$Z = \rho v$$

Material	Al	Si
Acoustic impedance Z ($10^6\ \mathrm{kg\,s^{-1}\,m^{-2}}$)	17.4	19.6

Acoustic impedance mismatch small !

Reflection coefficient: fraction of amplitude reflected

$$r = \left|\frac{Z_1 - Z_2}{Z_1 + Z_2}\right| = \boxed{6\%}$$

Very low LW reflection from substrate !!!

Conclusion

- Complex oscillations
- Unexplained origins
- Angle⇧ ⇌ wavelength⇧

Expected enhanced LW signal

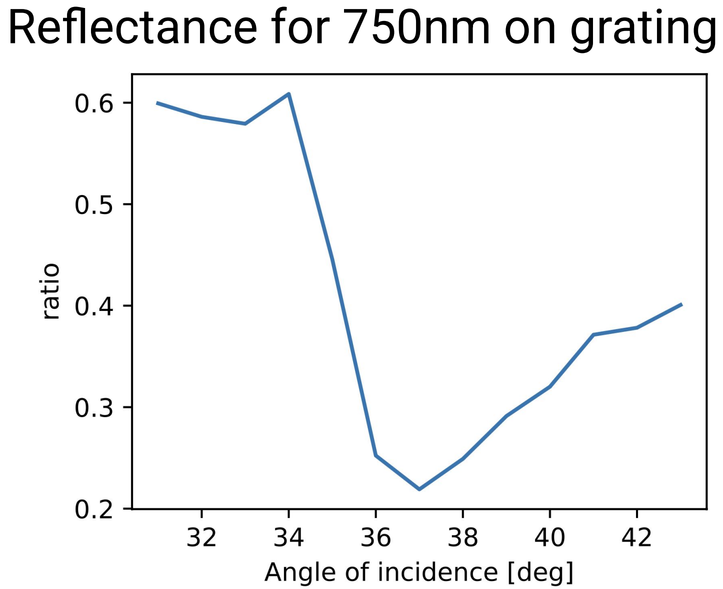
No longitudinal waves reflections!

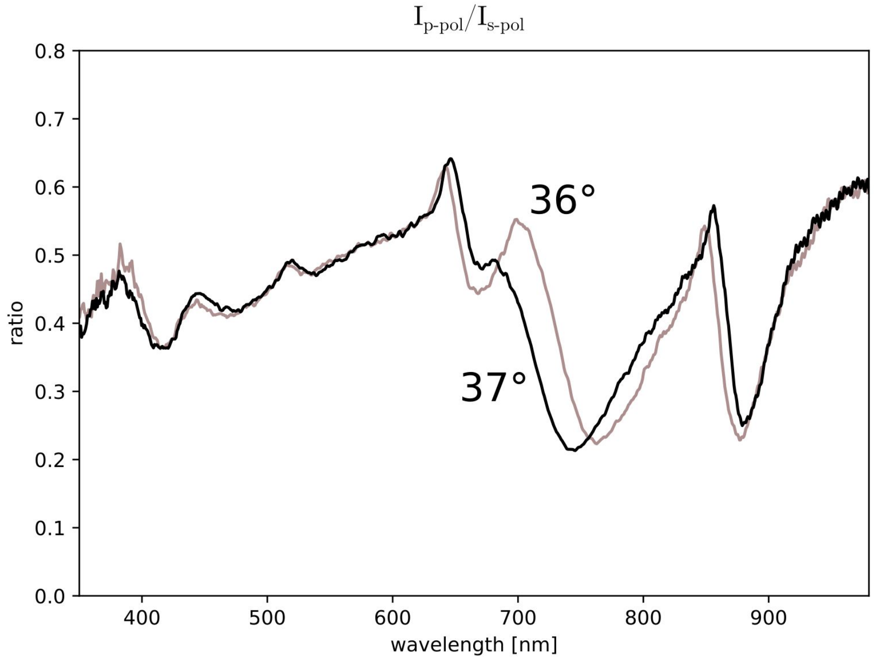
Main reason:

Acoustic impedance mismatch

too small for Al/Si

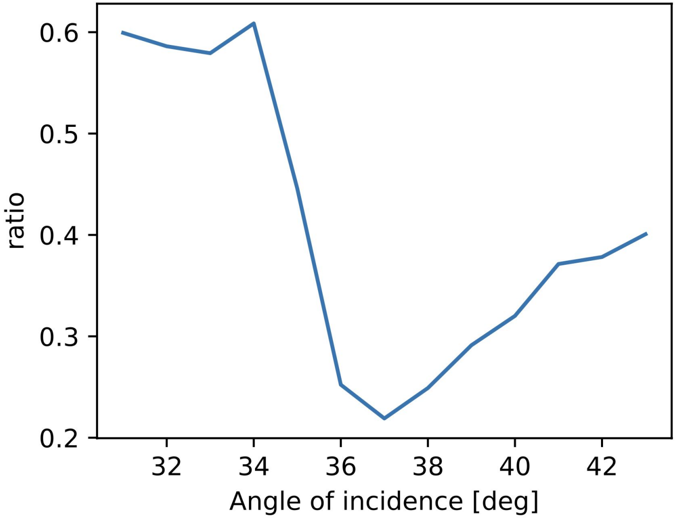
Supplementary

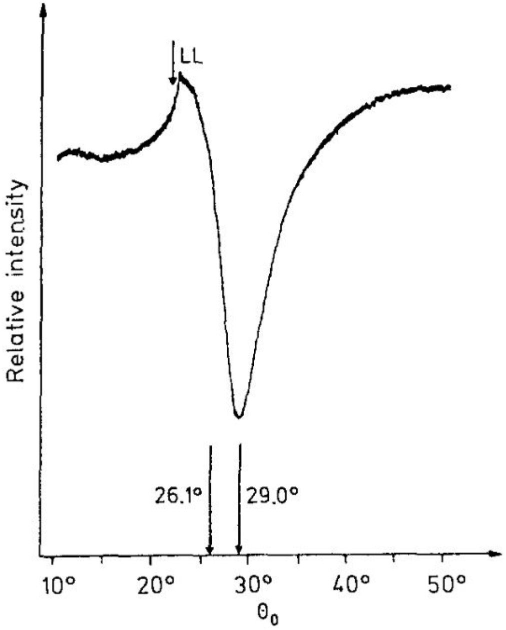




Supplementary

Reflectance for 750nm on grating





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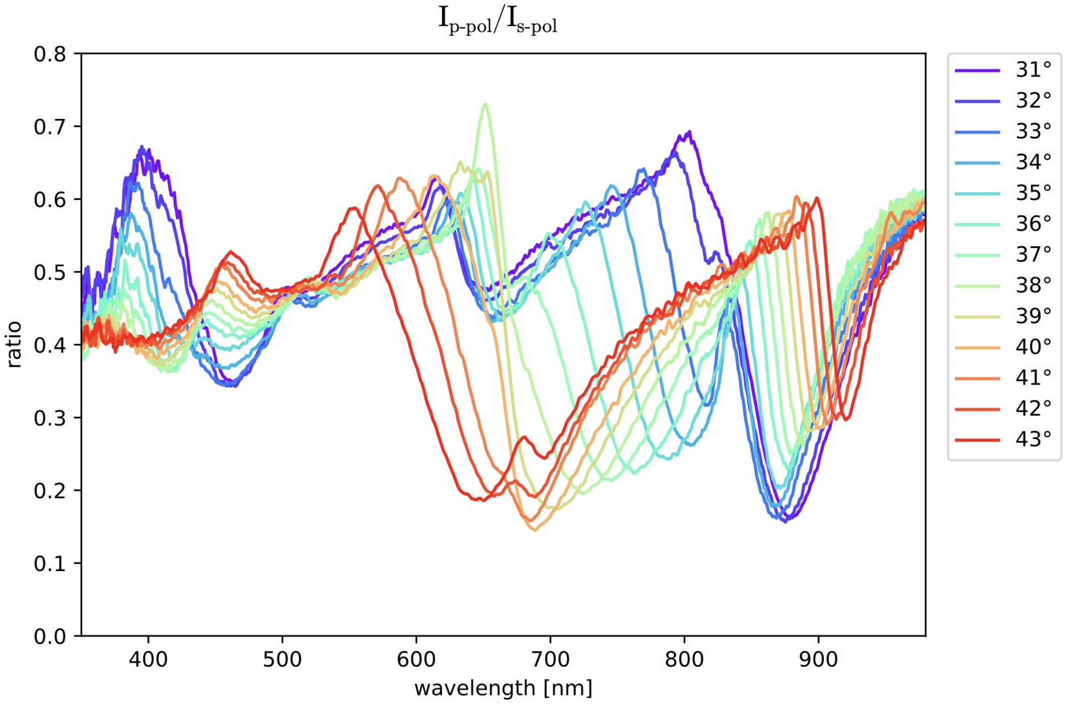

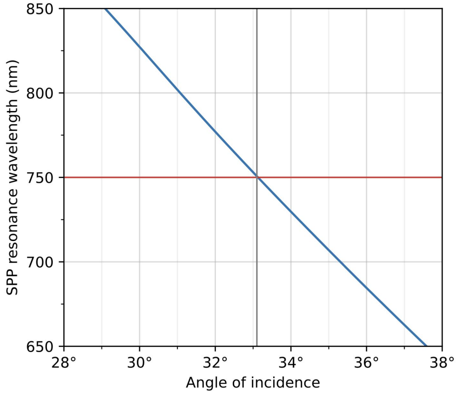

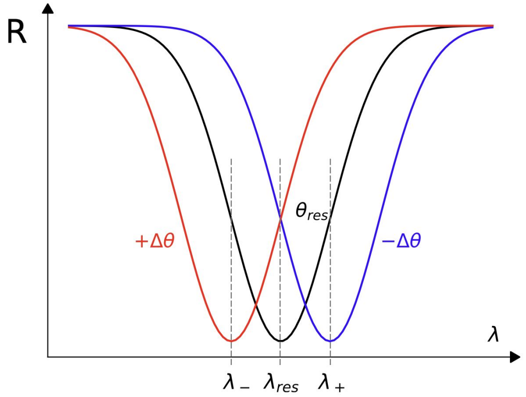

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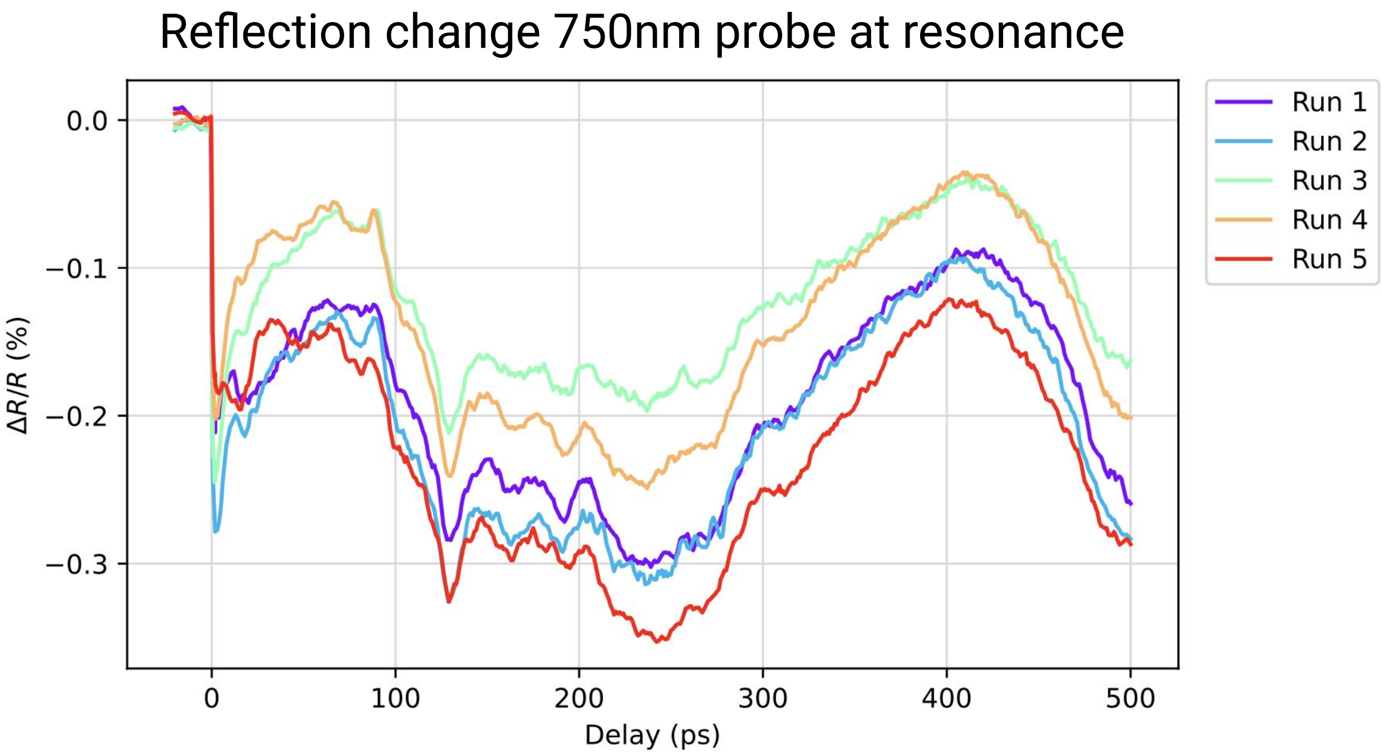
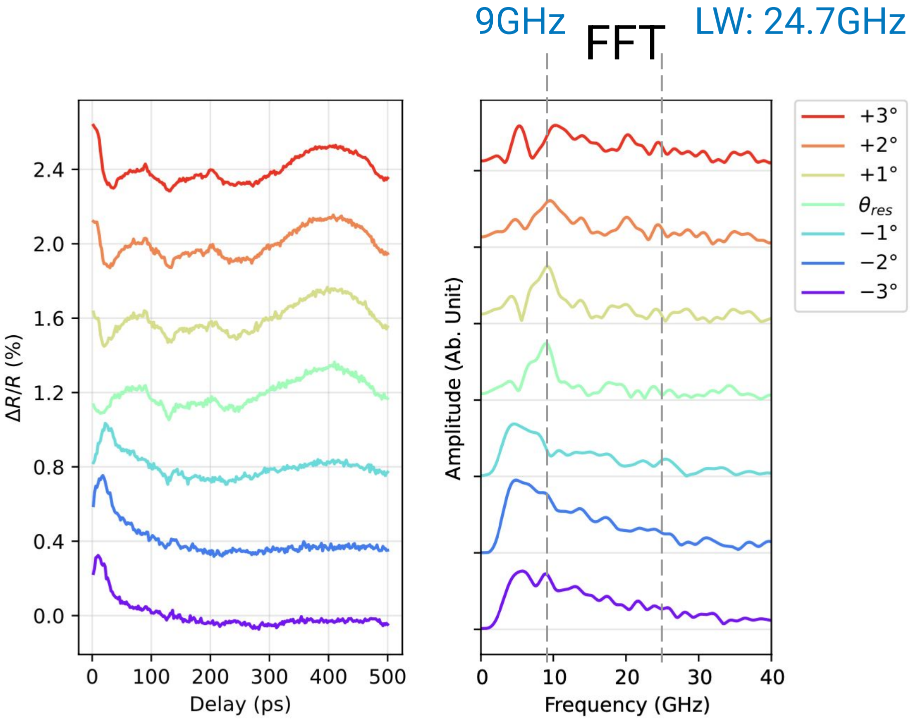
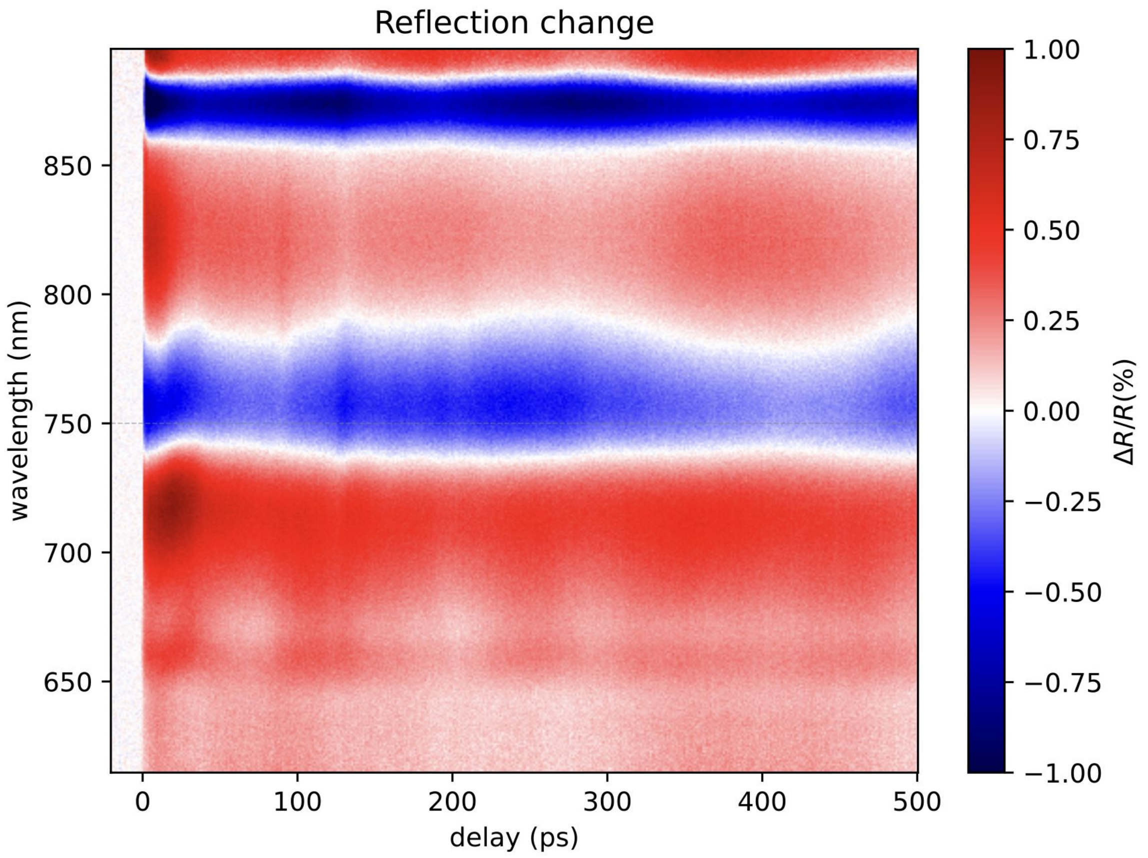


Experiment 2: Etched grating reflection change 750 nm probe, multiple angles



LW: f = 1/40.5 ps = 24.7 GHz

Supplementary



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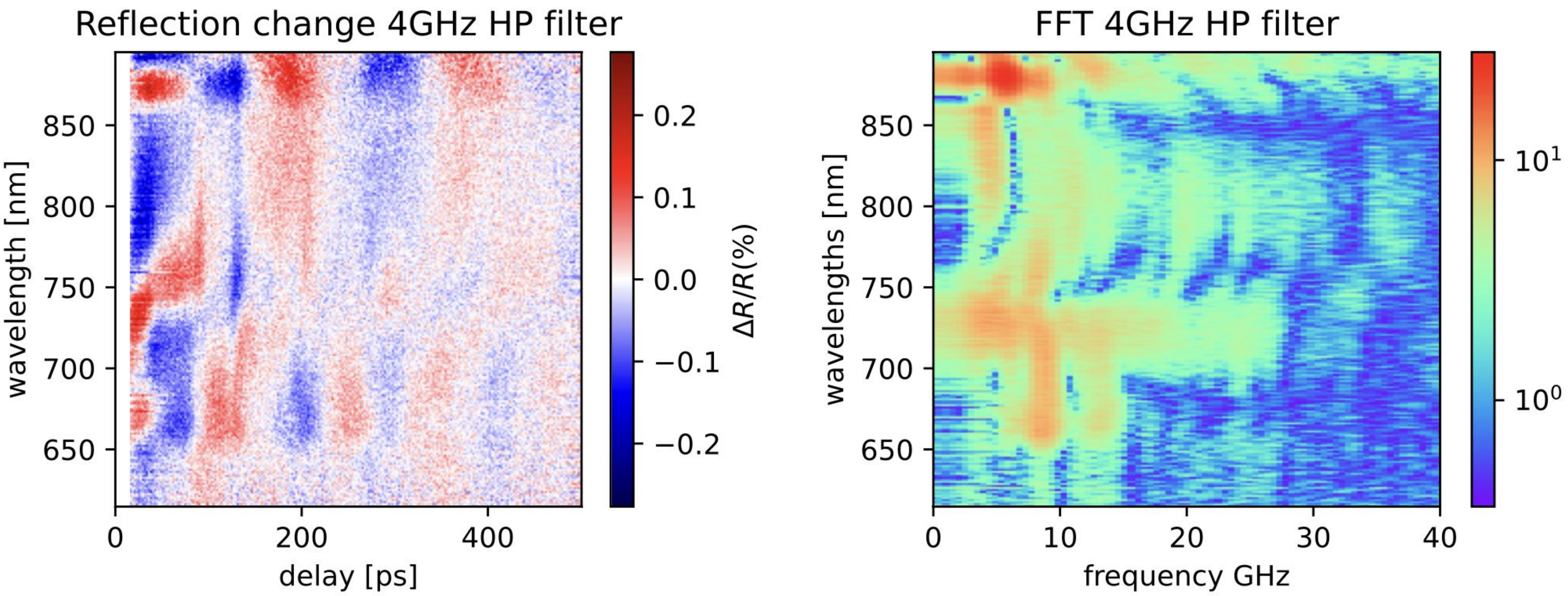
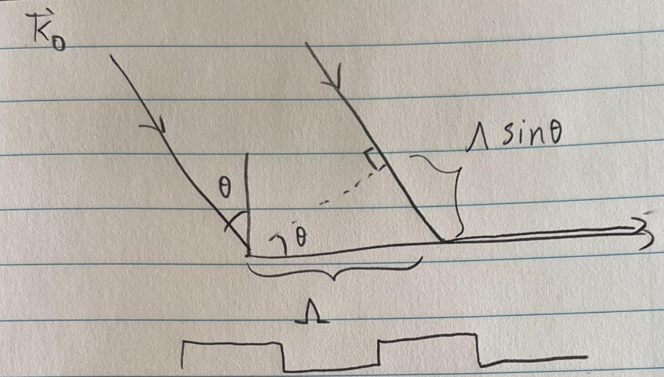


Supplementary

Material	Al	Si	SiO_2
Density ρ ($\mathrm{kg\,m^{-3}}$)	2710	2330	2650
Speed of sound v ($\mathrm{m\,s^{-1}}$)	6420	8430	5780
Acoustic impedance Z (10^6 $\mathrm{kg\,s^{-1}\,m^{-2}}$)	17.4	19.6	15.4
Reflection coefficient r with Al	0%	5.95%	6.10%

Supplementary



Phase difference:

$$\frac{\Lambda}{\lambda_{spp}} - \frac{\Lambda \sin\theta}{\lambda_0} = N \quad \text{— Constructive}$$

$$k_{spp} - k_0 \sin\theta = N \frac{2\pi}{\Lambda}$$

$$k_{spp} = k_0 \sin\theta + N k_g$$