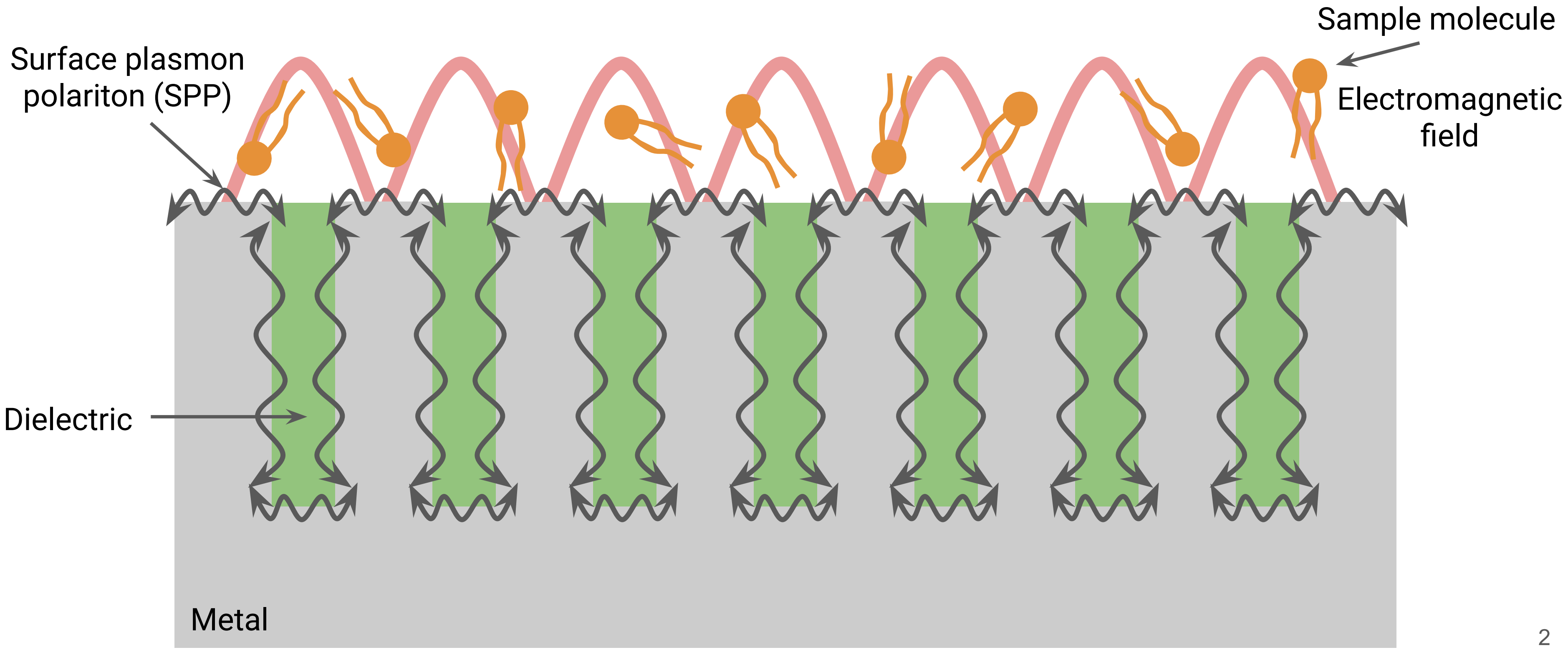
Multi-wavelength light trapping using width-graded plasmonic nanogratings

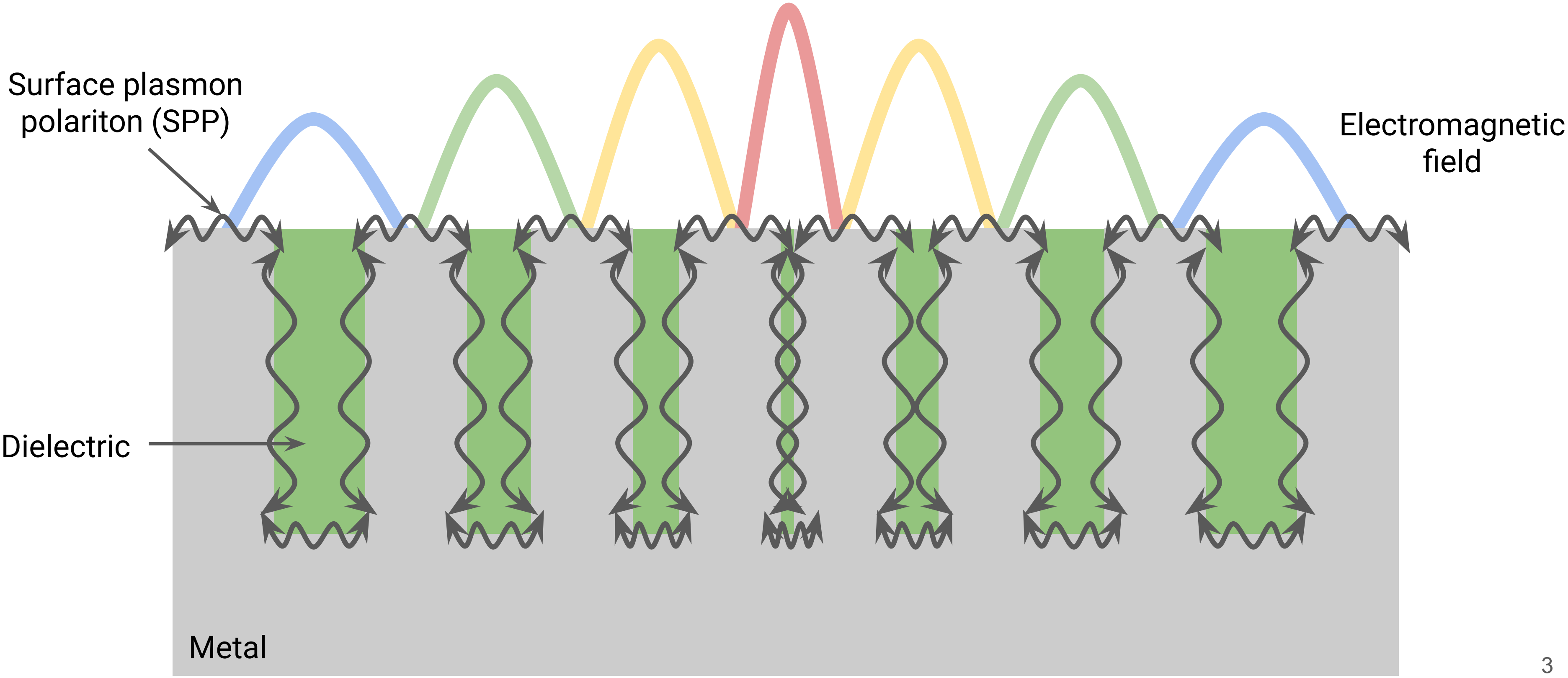
Katelyn Dixon, Ali Zeineddine, Moein Shayegannia, Nastaran Kazemi-Zanjani, Arthur O. Montazeri, Naomi Matsuura, Nazir P. Kherani

June 12, 2018

SPP resonance in uniform structures



SPP resonance in graded gratings



SPP resonance in graded gratings $n_{eff} \propto \frac{1}{w}$

Asymmetric Fabry-Perot resonator

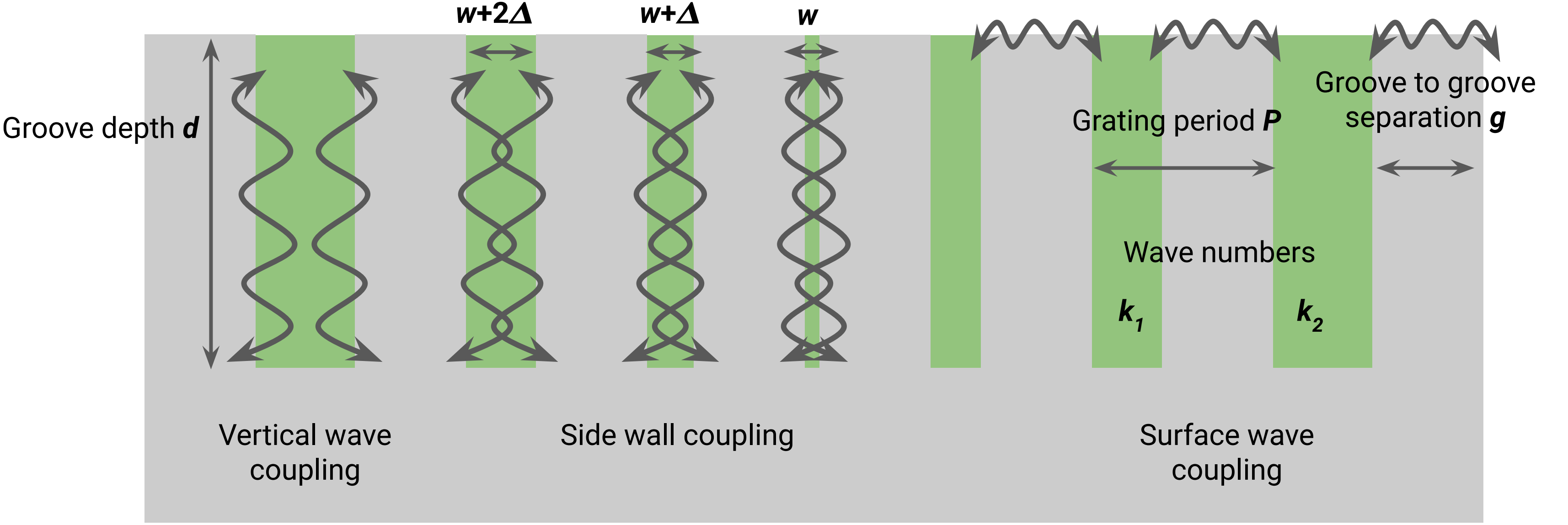
$$\left(\frac{1}{4}+\frac{m}{2}\right)\lambda_o = n_{eff}d$$

Dispersion relation

$$\tanh\left(\frac{wk_o}{2}\sqrt{n_{eff}^2-\epsilon_1}\right) = -\frac{\epsilon_1\sqrt{n_{eff}^2-\epsilon_2}}{\epsilon_2\sqrt{n_{eff}^2-\epsilon_1}}$$

Adiabaticity parameter

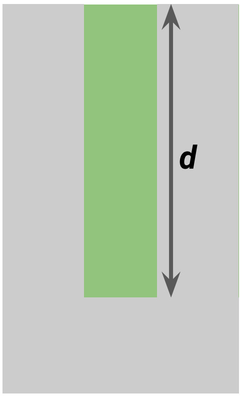
$$\delta \approx \frac{\frac{1}{k_1}-\frac{1}{k_2}}{P} \ll 1$$

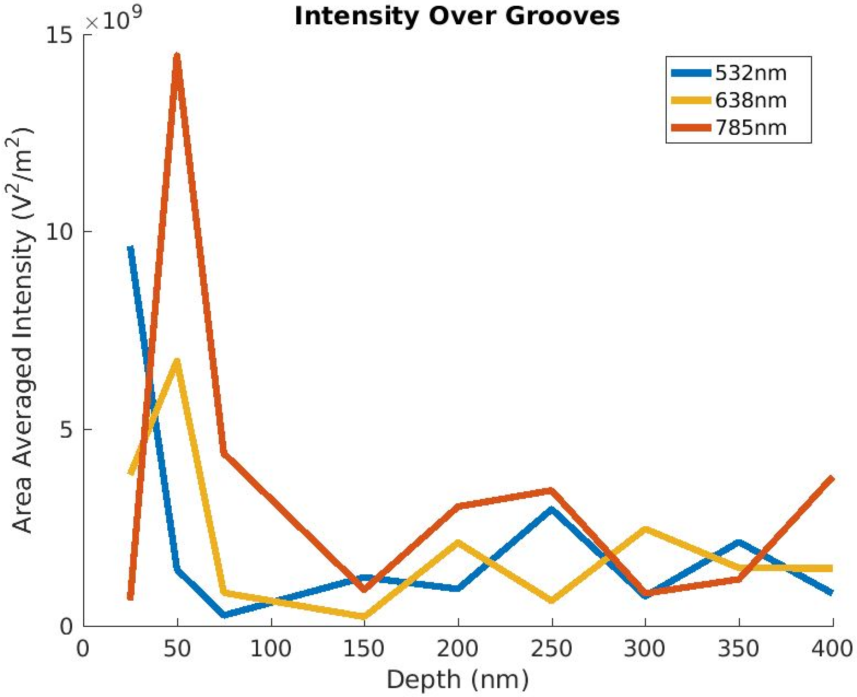


Variation in groove depth controls vertical wave coupling

Asymmetric Fabry-Perot resonator

$$\left(\frac{1}{4} + \frac{m}{2}\right)\lambda_o = n_{eff}d$$





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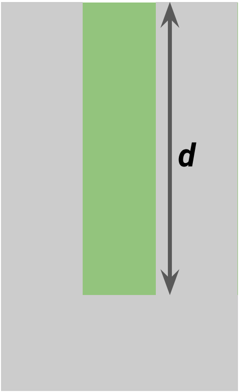
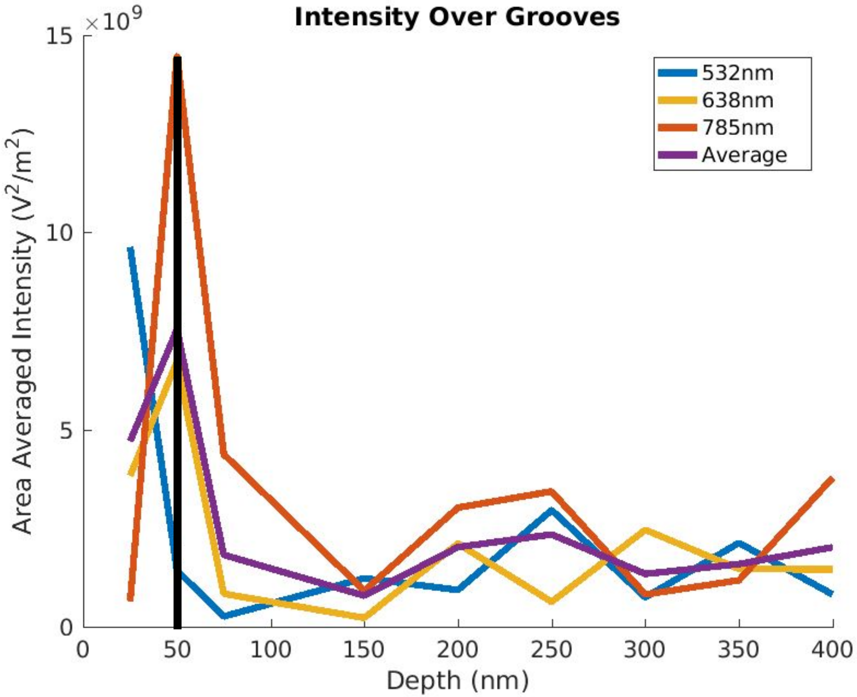
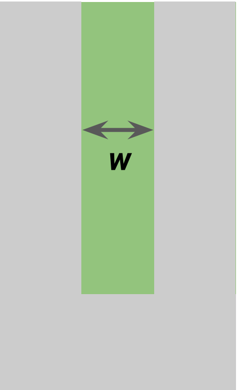


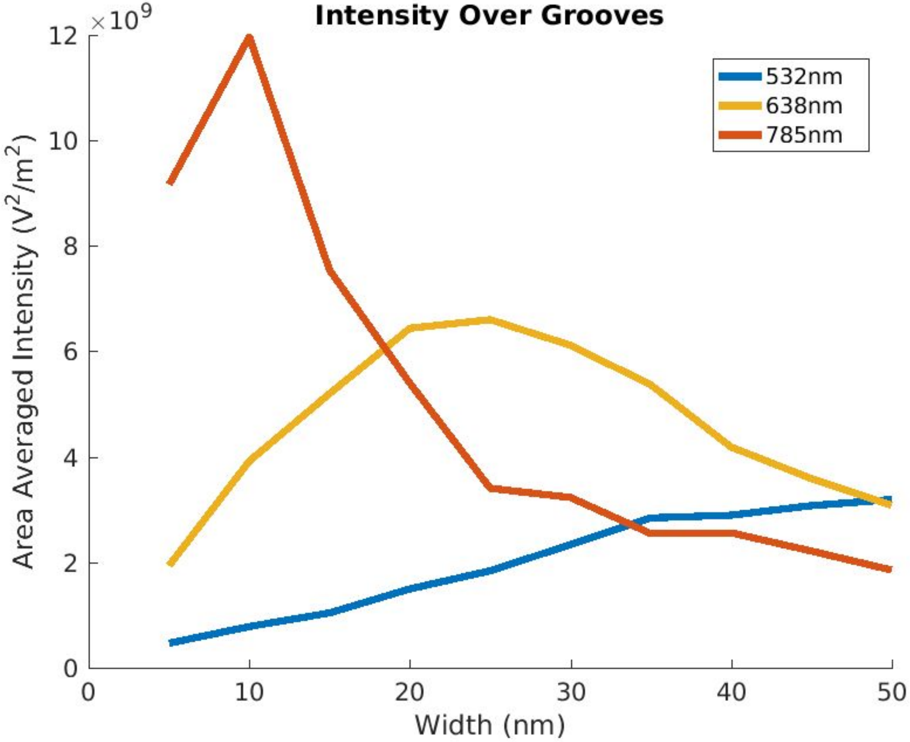


Variation in groove width controls sidewall coupling

Dispersion relation

$$\left(\frac{1}{4} + \frac{m}{2}\right) \lambda_o \propto \frac{d}{w}$$





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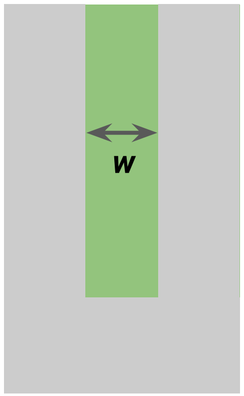

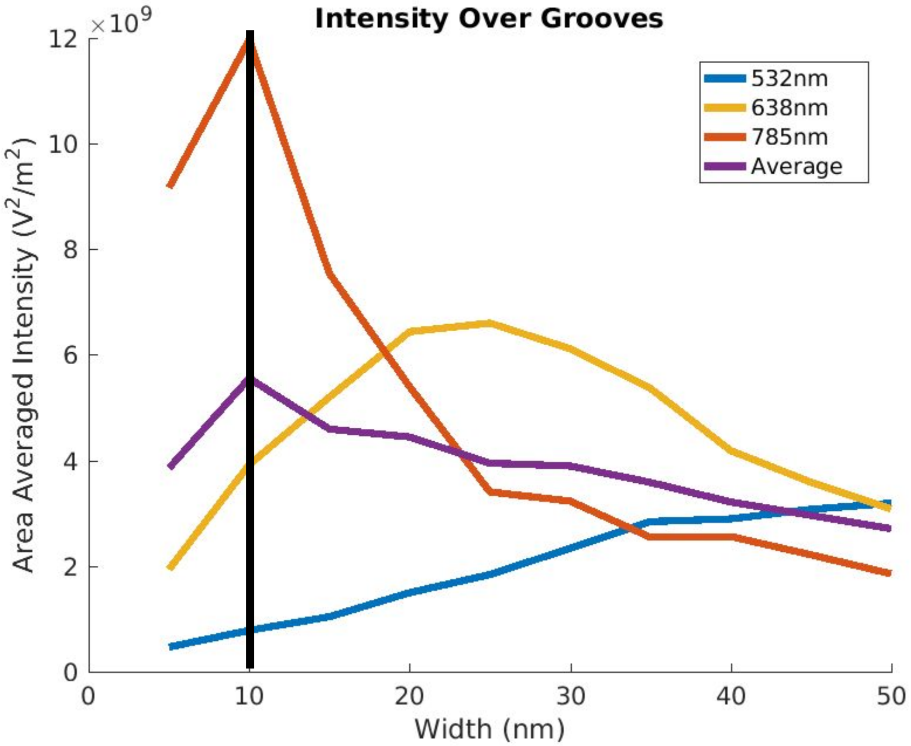

Variation in step size controls sidewall coupling

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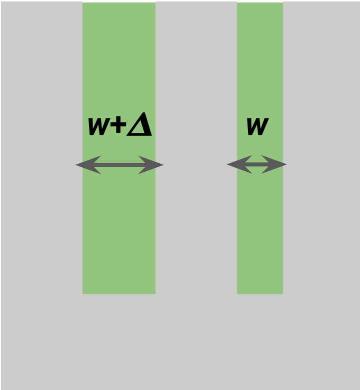

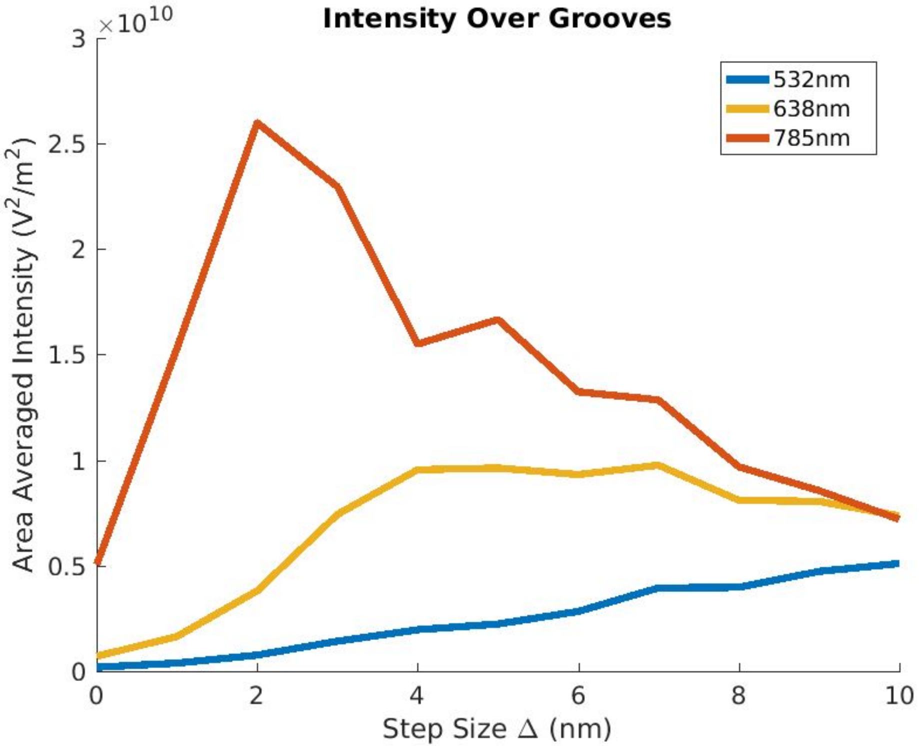

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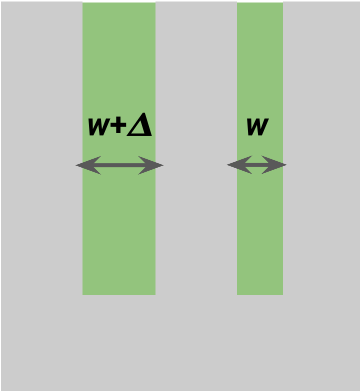
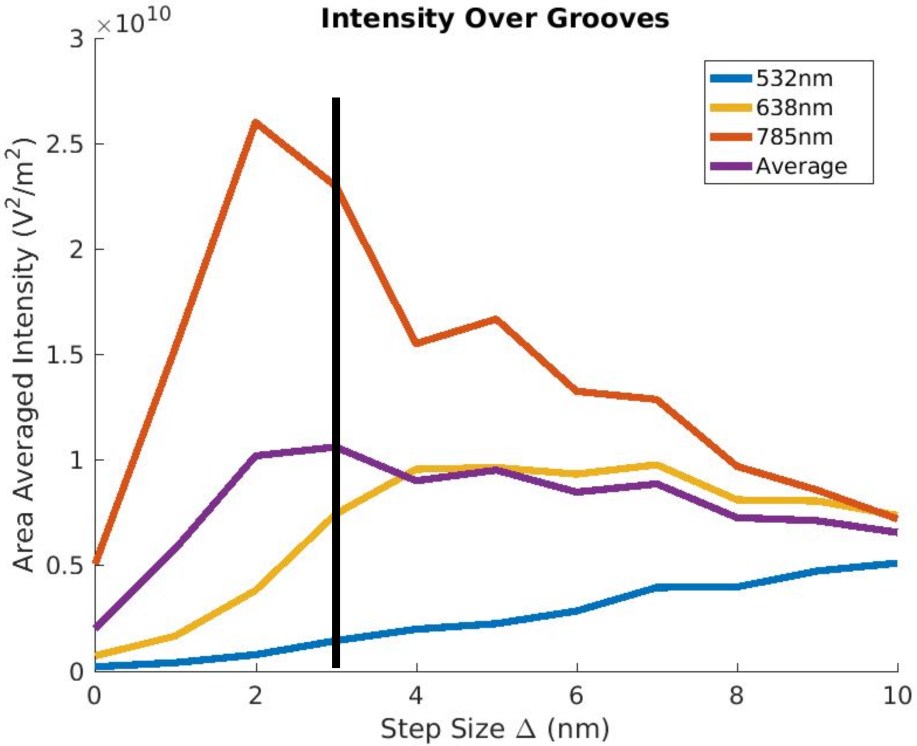
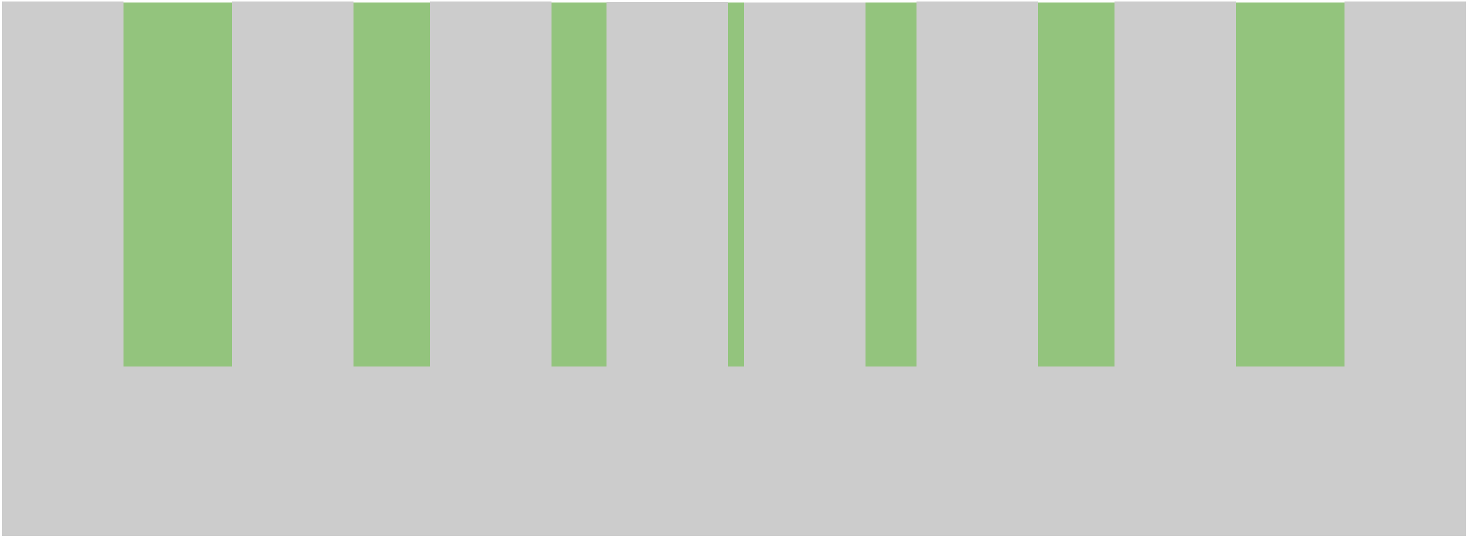




A gradient in effective refractive index leads to light guiding within the grating

$$n_{eff} \propto \frac{1}{w}$$



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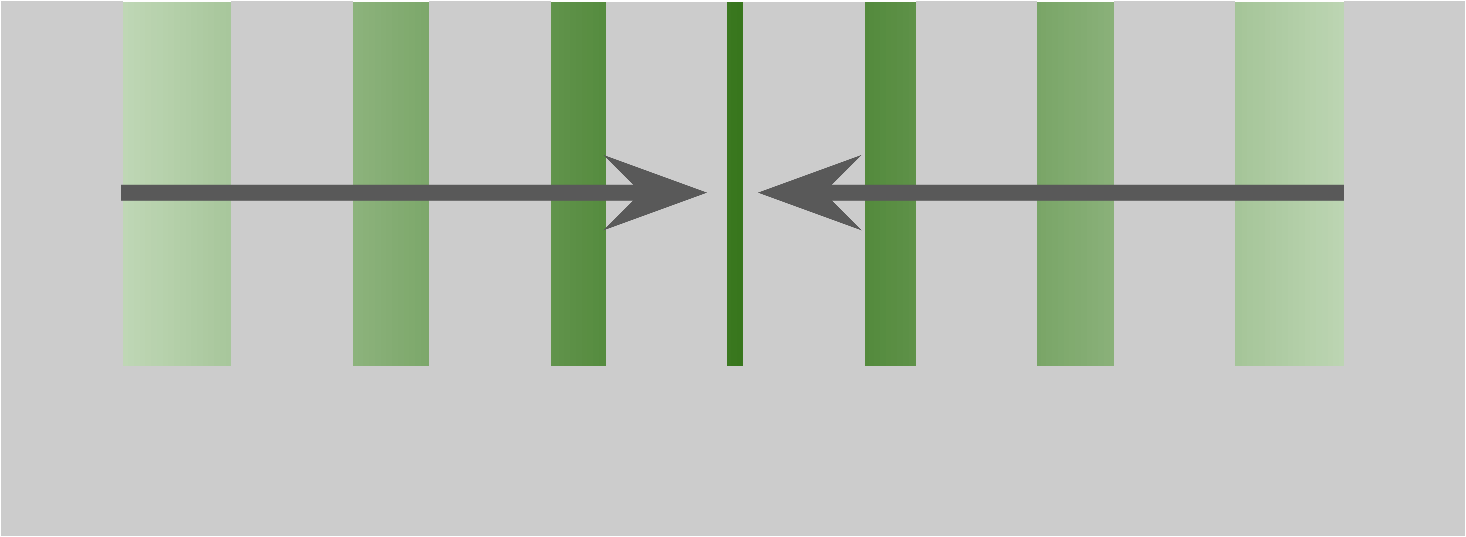

Varying groove widths allow for multiwavelength trapping

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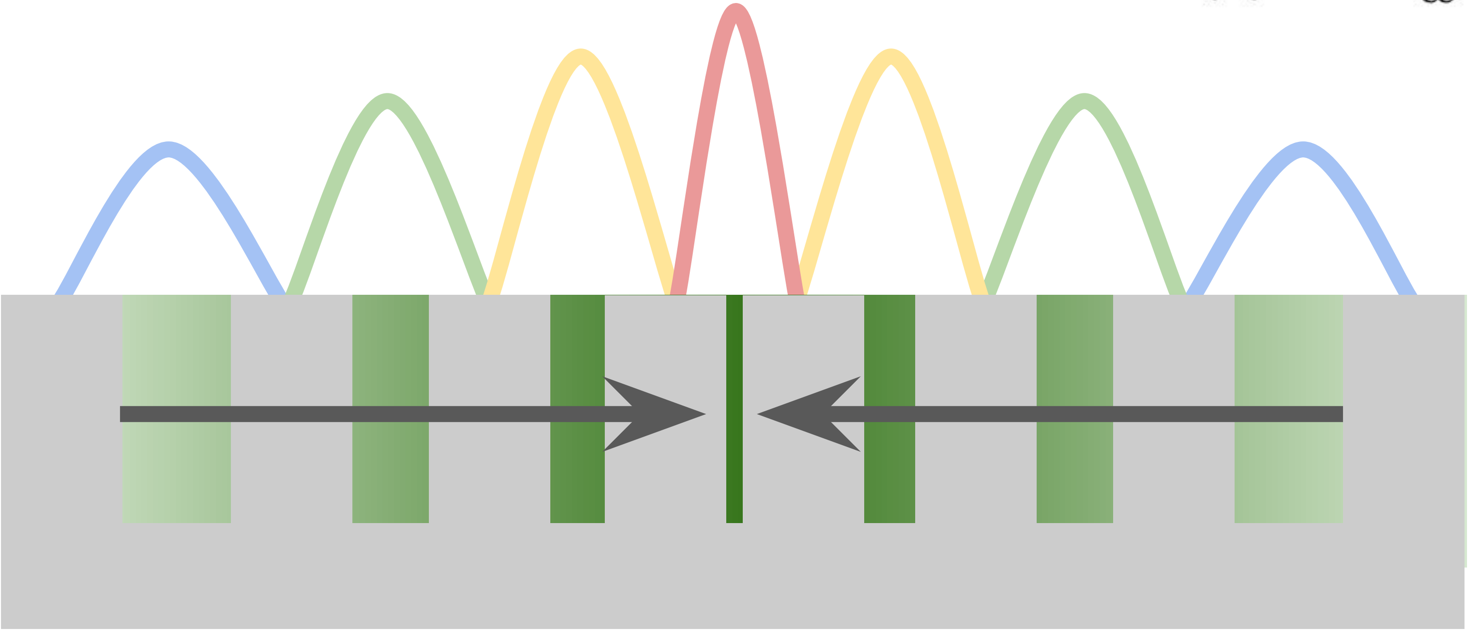

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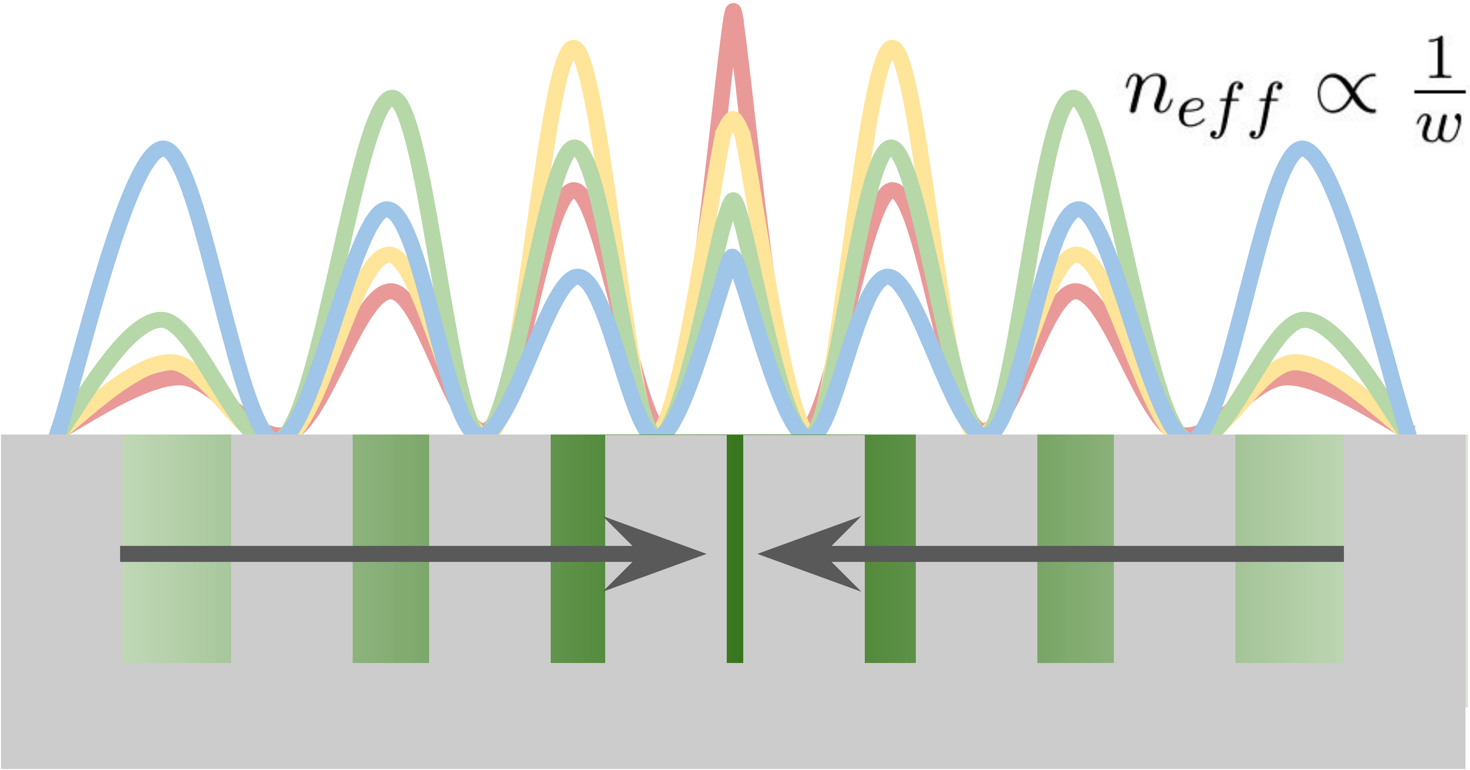
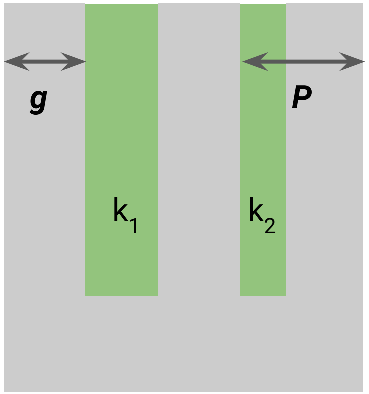


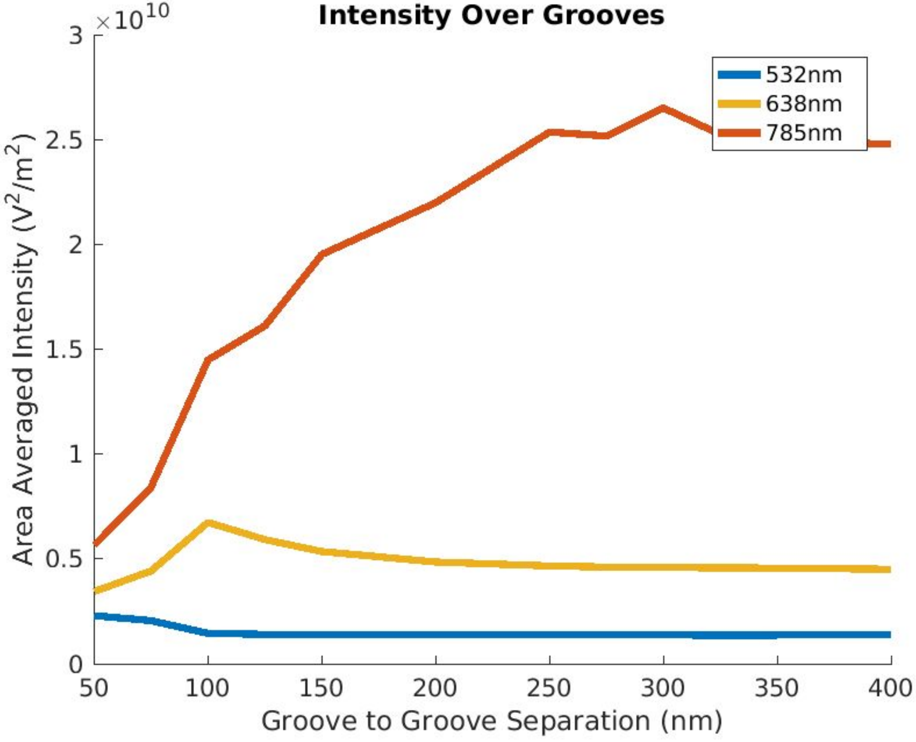
$$n_{eff} \propto \frac{1}{w}$$

Variation in groove to groove separation controls adiabicity of light guiding

Adiabaticity parameter

$$\delta \approx \frac{\frac{1}{k_1} - \frac{1}{k_2}}{P} \ll 1$$





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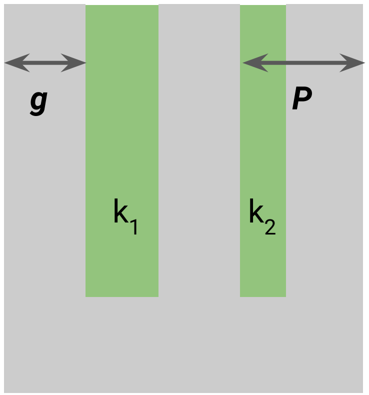
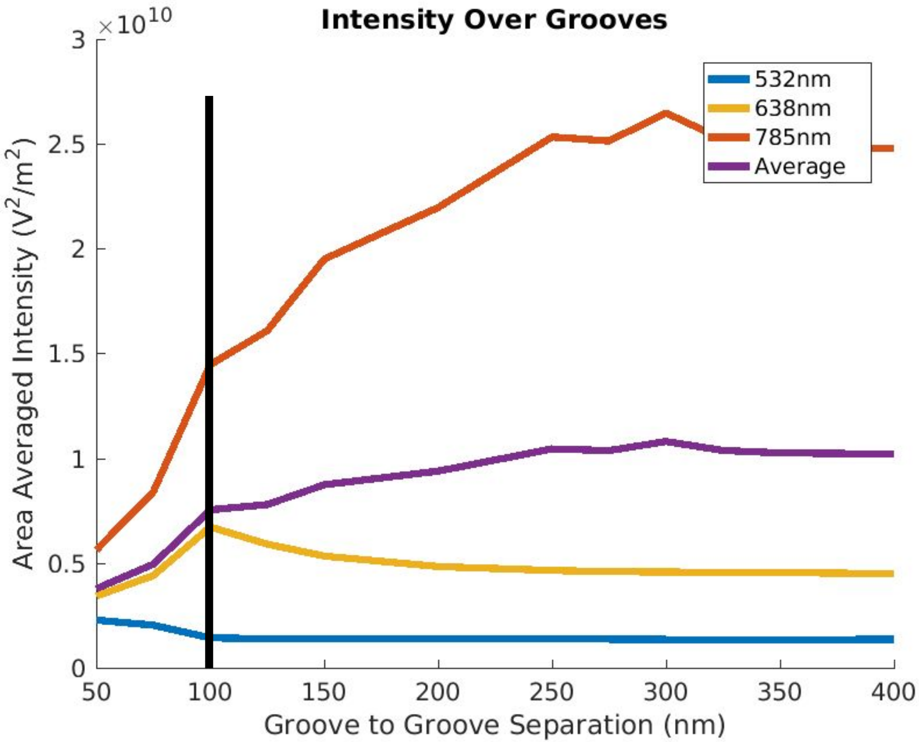
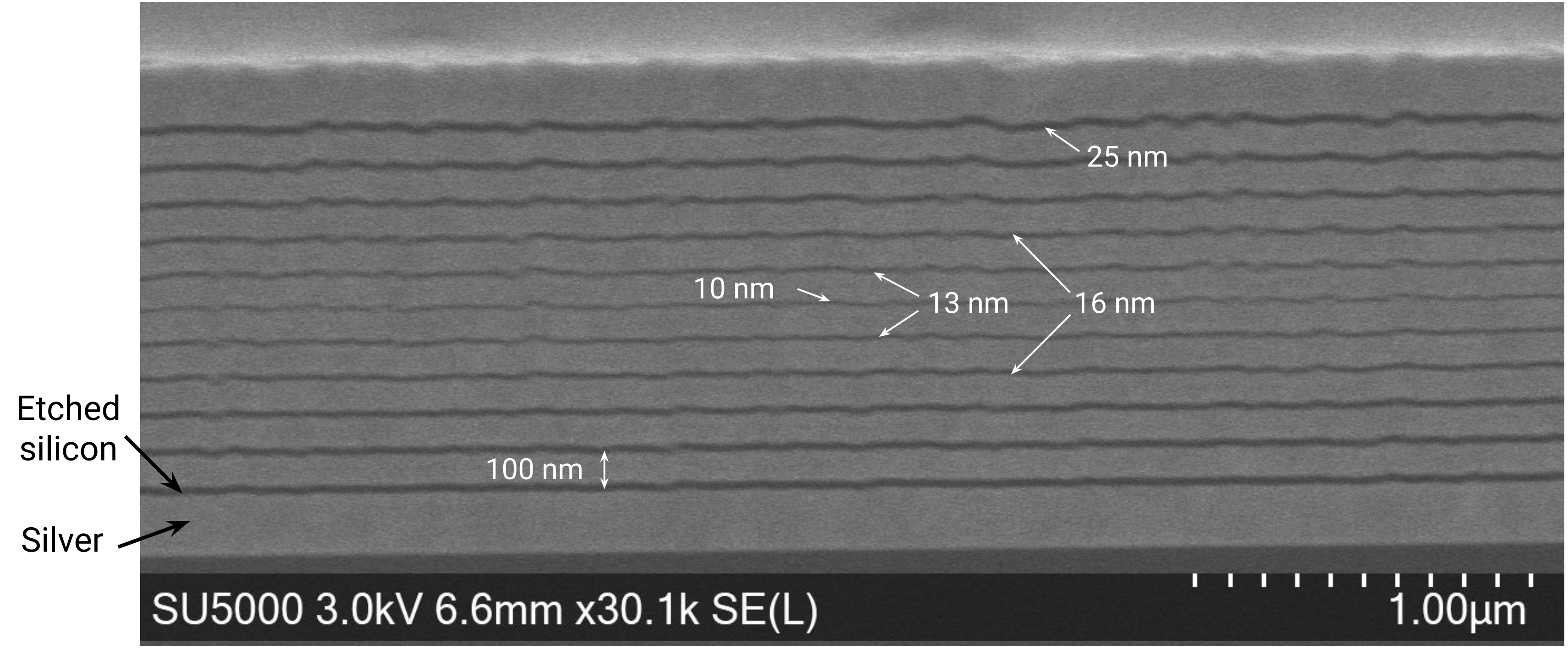


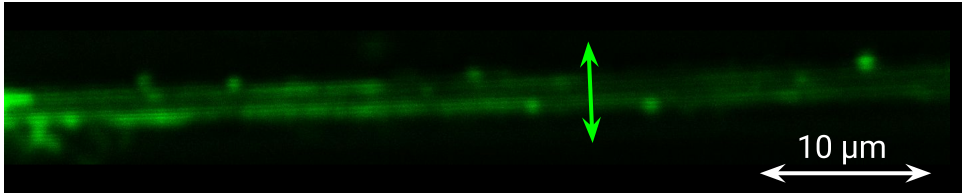


Fabrication through sputter deposition

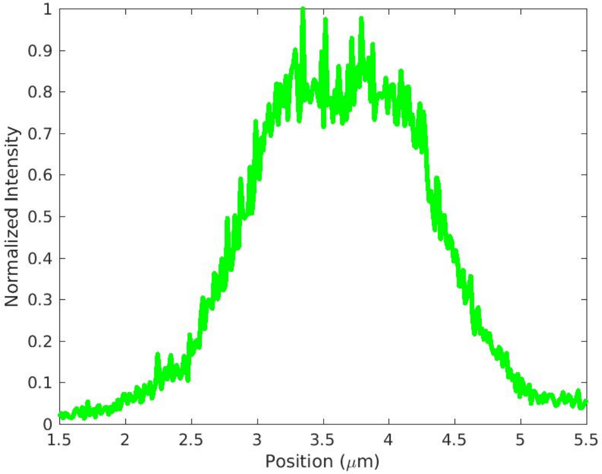


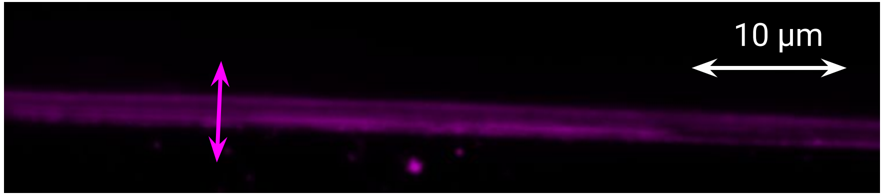
SEM image of fabricated grating cross section with 50nm groove depth

Fluorescence microscopy

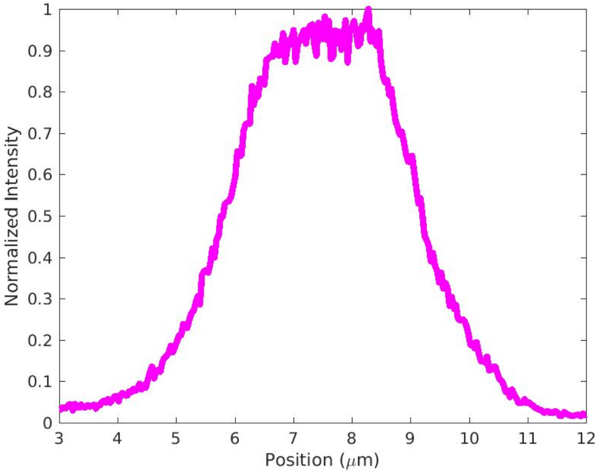


Fluorescence microscopy image of grating coated in Calcein excited at 488 nm

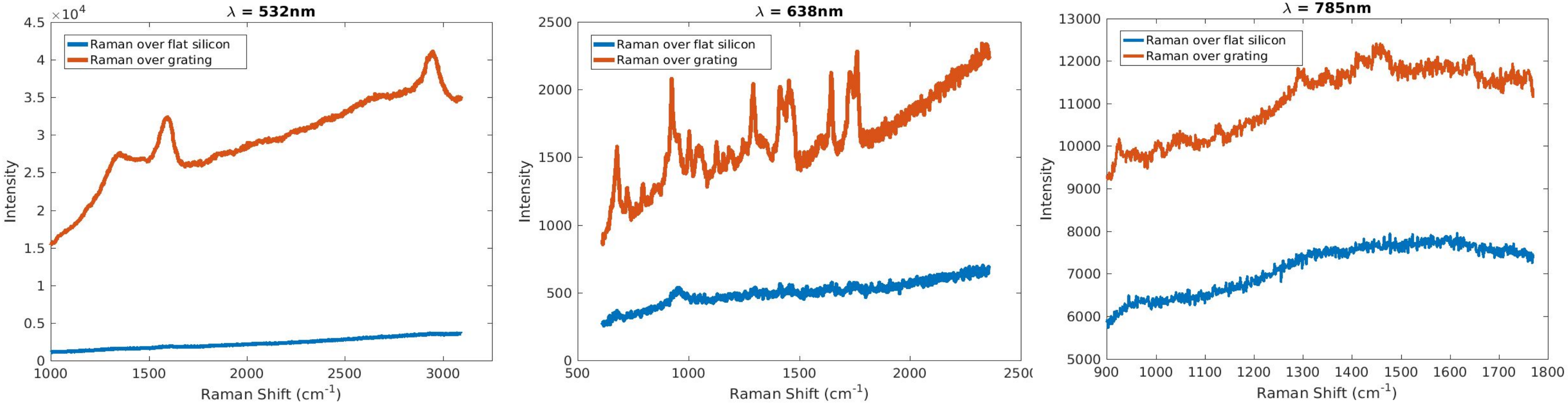




Fluorescence microscopy image of grating coated in Rhodamine B excited at 514 nm



Raman spectroscopy



Raman spectroscopy data of the phospholipid DSPG at 532nm, 638nm and 785nm both on and off the grating

Conclusion

- SPP resonance in graded gratings allows for multispectral light enhancement with applications in high sensitivity detection
- Simulations have identified the geometric parameters which allow for maximum field enhancement
- Fluorescence microscopy and Raman spectroscopy have confirmed light enhancement

Effective refractive index

For a three layer structure the SPP dispersion relation is

$$\tanh\left(\tfrac{1}{2}k_1 w\right) = -\frac{k_2\epsilon_1}{k_1\epsilon_2}$$

The effective refractive index is defined by

$$k_1 = \sqrt{n_{eff}^2 k_o^2 - \epsilon_1 k_o^2}$$

$$k_2 = \sqrt{n_{eff}^2 k_o^2 - \epsilon_2 k_o^2}$$

Through substitution we can obtain

$$\tanh\left(\frac{wk_o}{2}\sqrt{n_{eff}^2 - \epsilon_1}\right) = -\frac{\epsilon_1\sqrt{n_{eff}^2 - \epsilon_2}}{\epsilon_2\sqrt{n_{eff}^2 - \epsilon_1}}$$

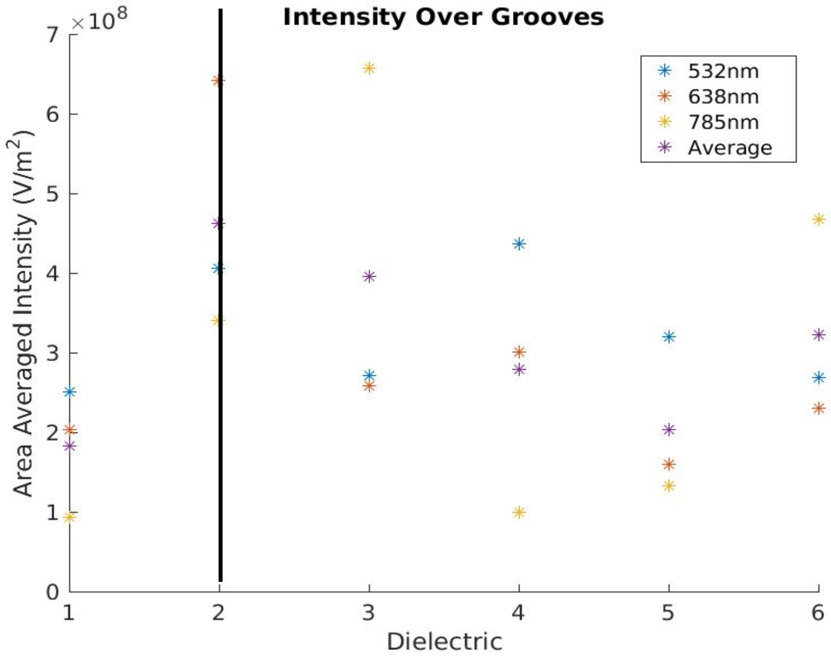
From the tanh term we can observe

$$n_{eff} \propto \frac{1}{w}$$

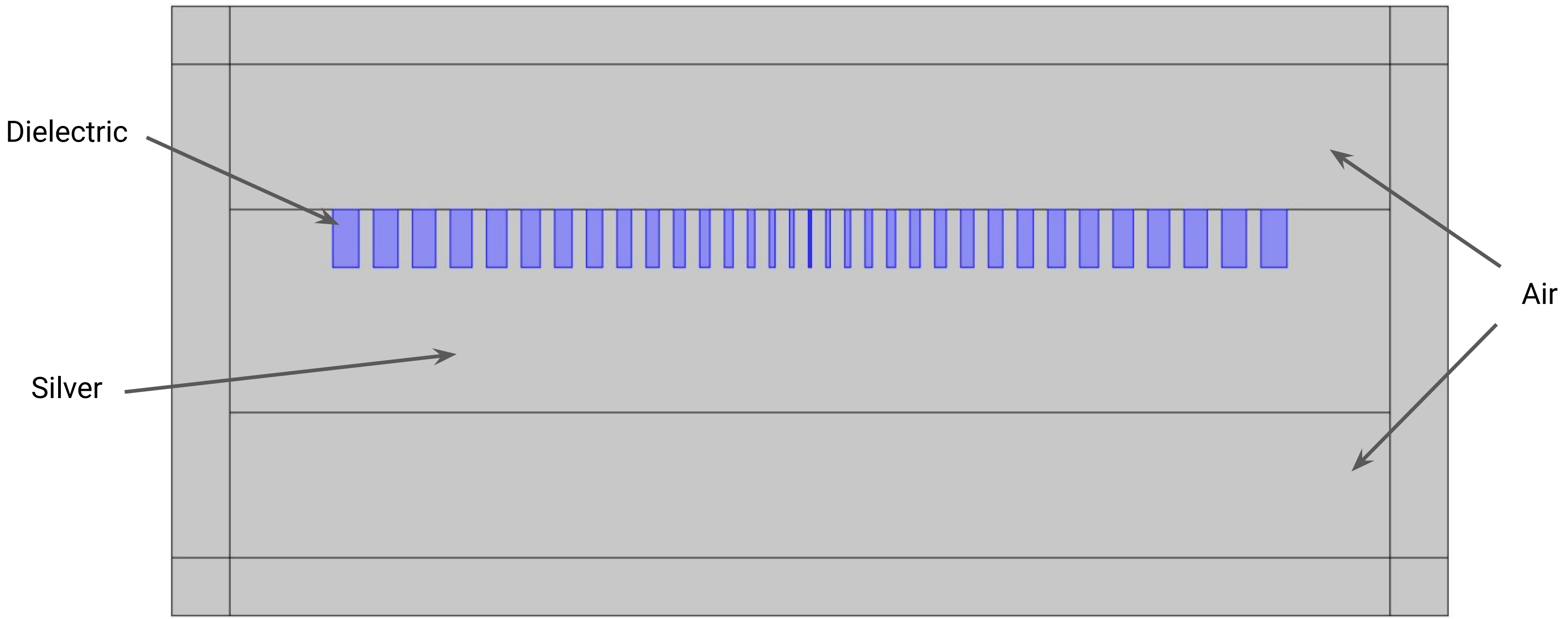
Han et al. (2007). *IEEE Photonics Technology Letters*. 19:2

Variation in dielectric material alters reflection coefficient

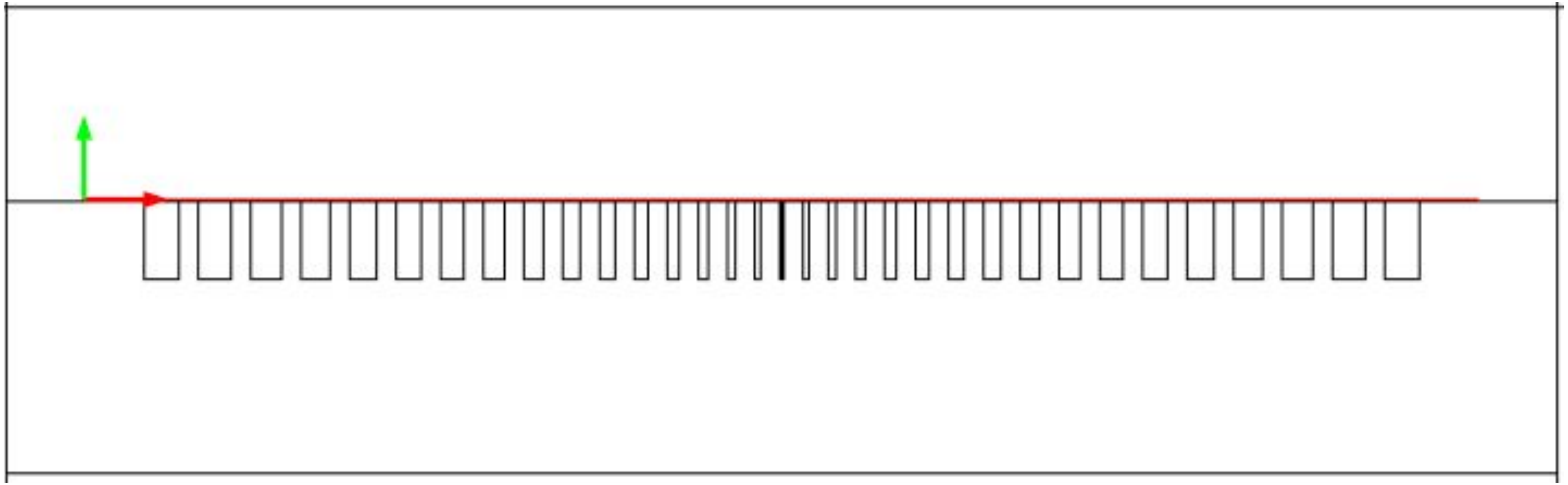
Number	Material	Refractive Index at 700nm
1	AlN	2.1883
2	MgF2	1.3878
3	Si3N4	2.0035
4	SiO2	1.4745
5	TiO2	2.5512
6	ZnO	1.9736



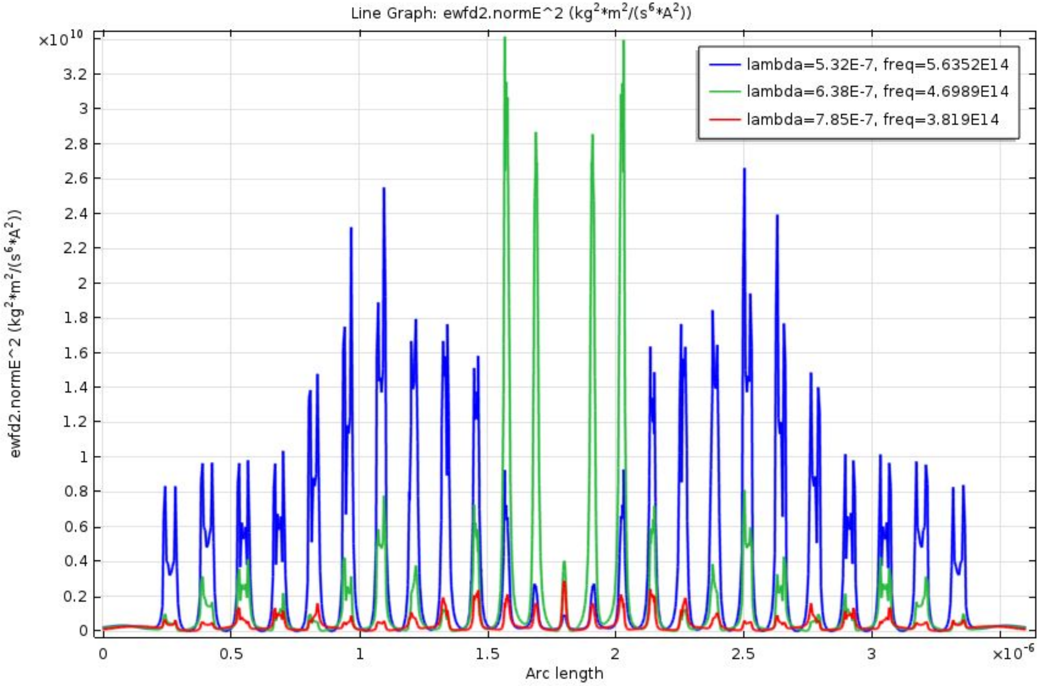
Simulation



Simulation

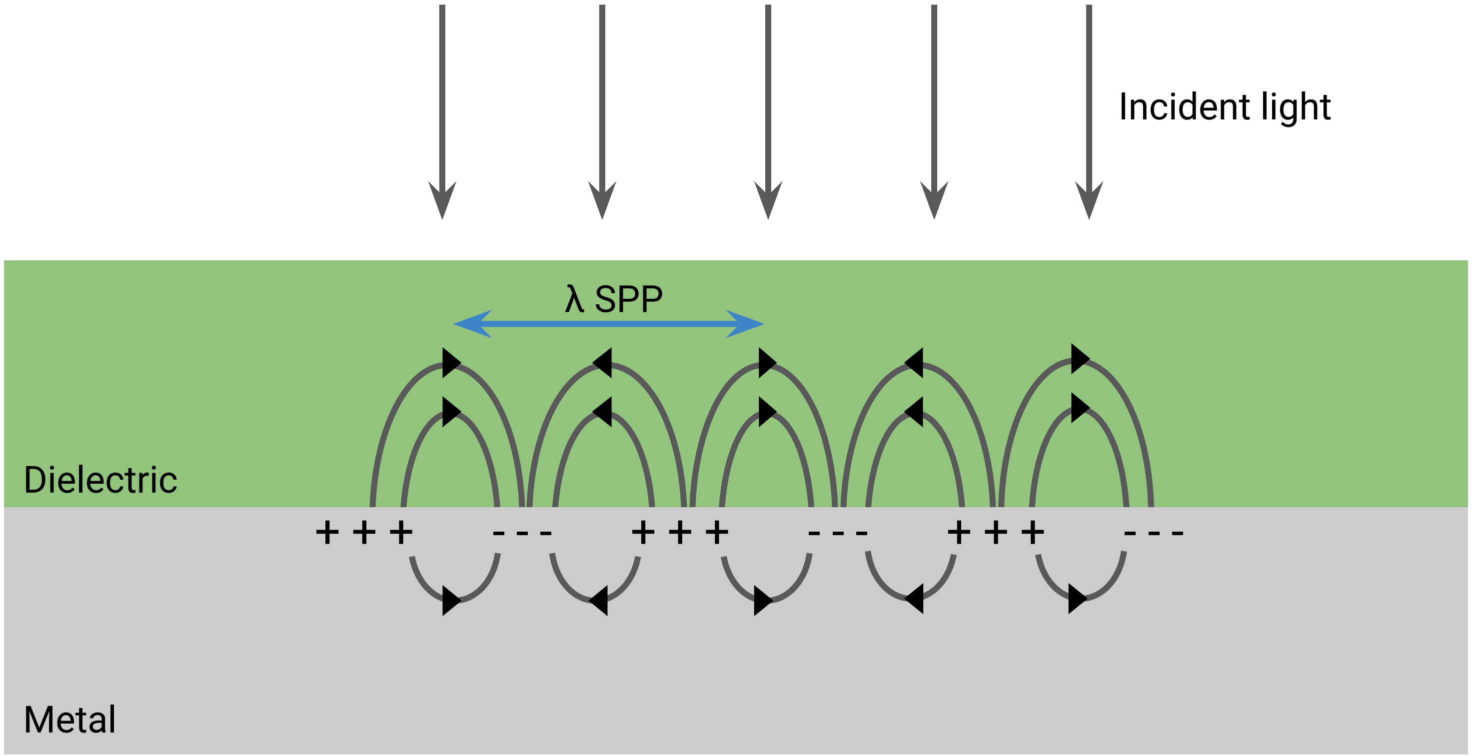


Simulation



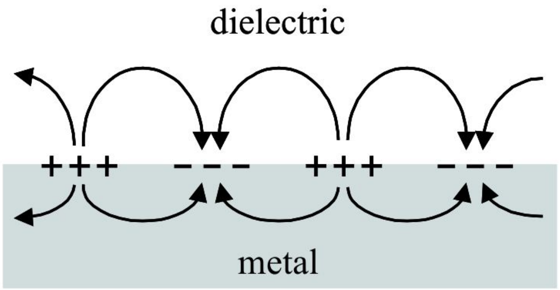
Line Graph: ewfd2.normE^2 (kg^2*m^2/(s^6*A^2))
×10^10
3.2
3
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
ewfd2.normE^2 (kg^2*m^2/(s^6*A^2))
lambda=5.32E-7, freq=5.6352E14
lambda=6.38E-7, freq=4.6989E14
lambda=7.85E-7, freq=3.819E14
0
0.5
1
1.5
2
2.5
3
×10^-6
Arc length

Surface plasmon polaritons (SPPs) are generated at metal-dielectric interfaces

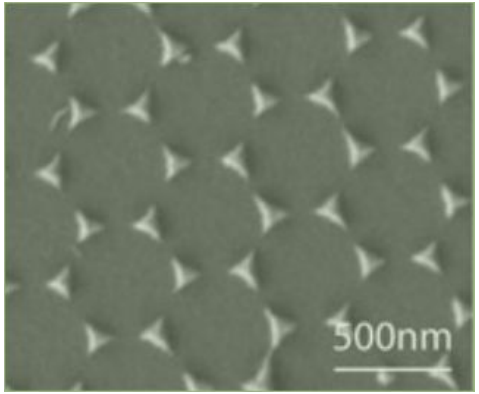


Introduction to light trapping

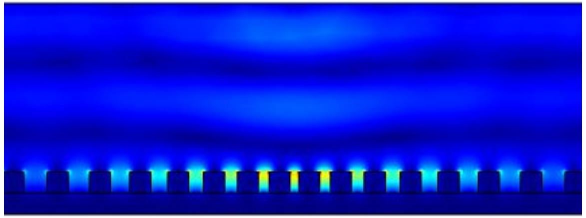
Nanostructured materials utilize surface plasmon polariton (SPP) resonances to confine and intensify incident light for highly sensitive spectroscopic measurements



Most nanostructures enhance a small number of discrete wavelengths, limiting their detection capabilities



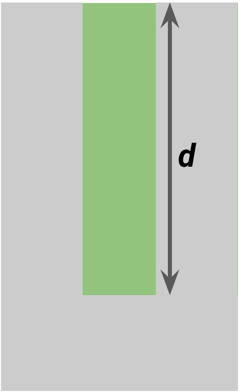
We present nanoscale plasmonic gratings capable of multi-wavelength light enhancement

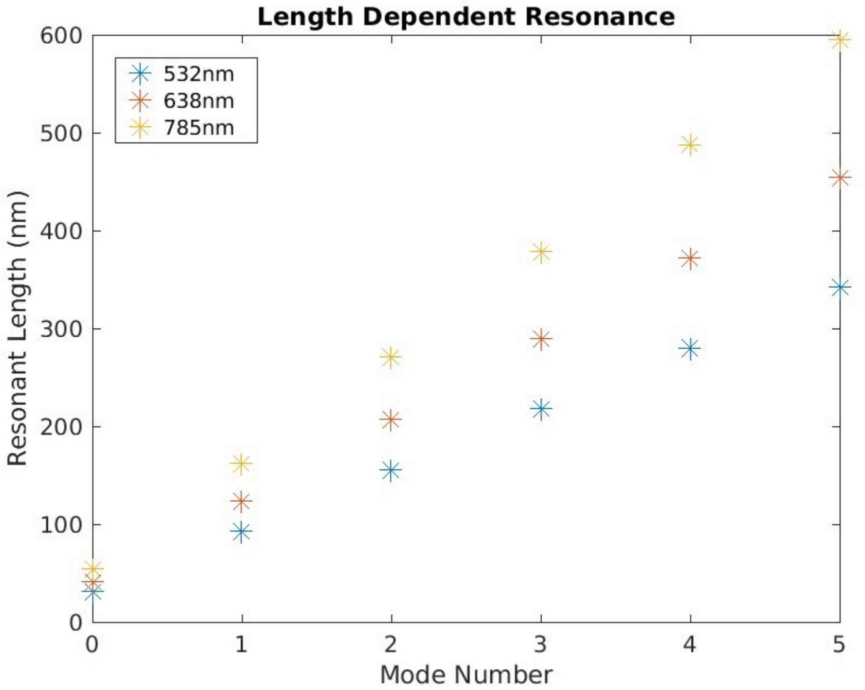


Groove Depth

For an asymmetric
Fabry-Perot resonator

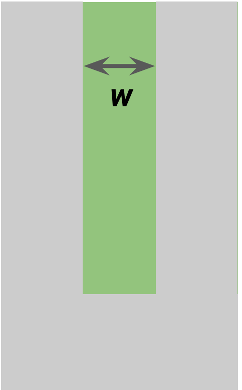
$$\left(\frac{1}{4}+\frac{m}{2}\right)\lambda_o = n_{eff}d$$

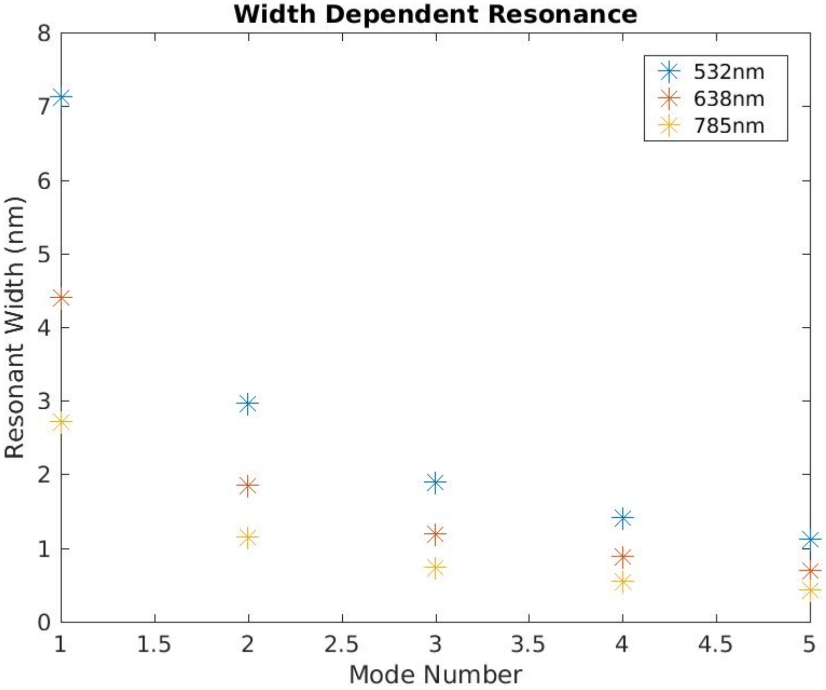




Groove Width

$$\left(\frac{1}{4}+\frac{m}{2}\right)\lambda_o \propto \frac{d}{w}$$





Groove to Groove Separation

WKB adiabaticity parameter

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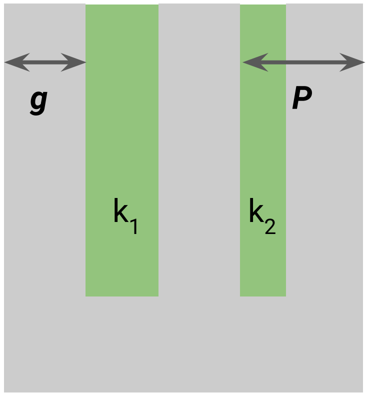
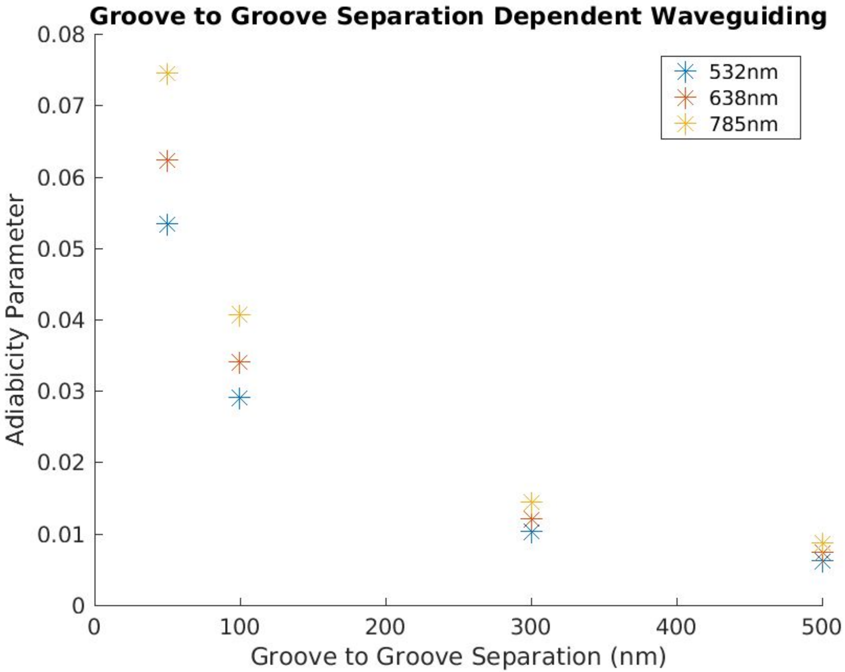
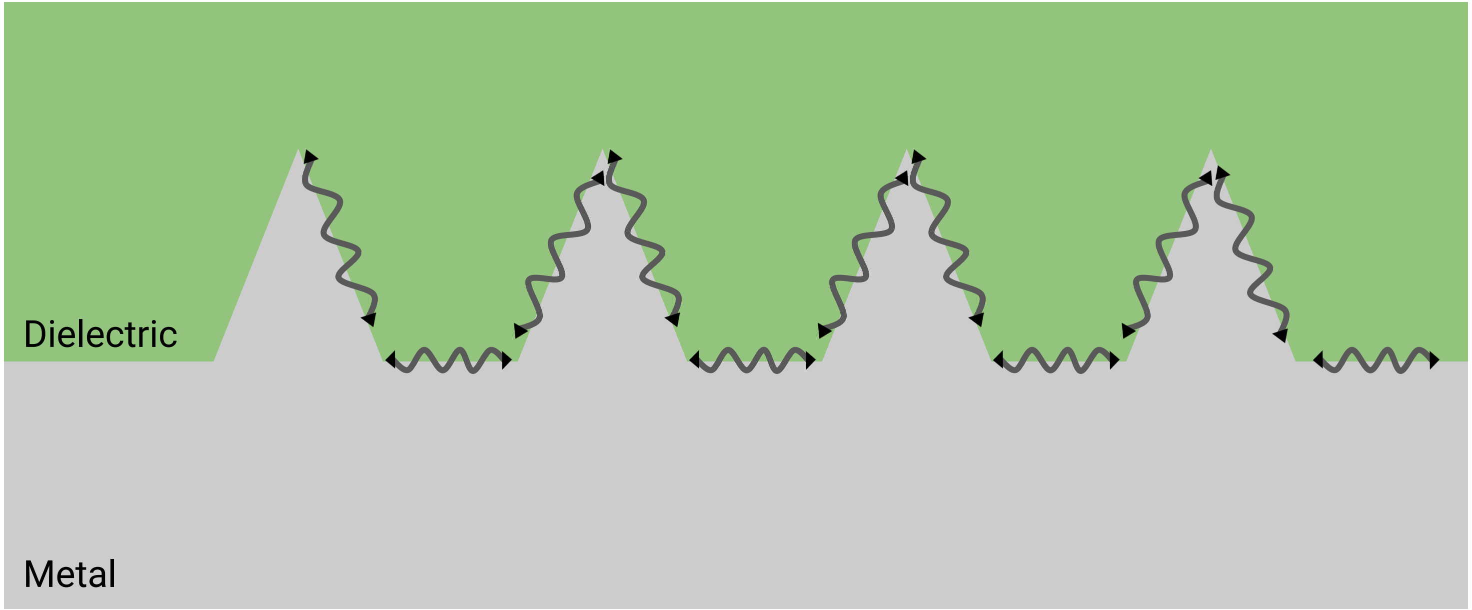




SPP Resonance



SPP Resonance