Solar and Laser Driven Light Sails for In-Space Propulsion

Grover Swartzlander
Center for Imaging Science
Rochester Institute of Technology, Rochester, NY

7 June 2023, ISSS, 3:30-4:00 am, Brooklyn, NY

RIT:
Prateek Srivastava
Ryan Crum
Qing Wang
Aaron Becker

NASA MSFC:
Les Johnson
Andy Heaton

JHU-APL:
Amber Dubill
Joseph Miragliatta
David Shreckenhamer
Christine Zgrabik

Beam Co:
David Roberts
Anna Tabirian

NASA NIAC Phases I, II, III

Contents

- History
- Our NIAC Space Mission
- Fundamentals
- Introduction to Gratings
- Geometric Phase Gratings
- Metasurface Gratings
- Hybrid Gratings
- Validation Experiments
- Notional Sailcraft Architecture
- Raising the TRL

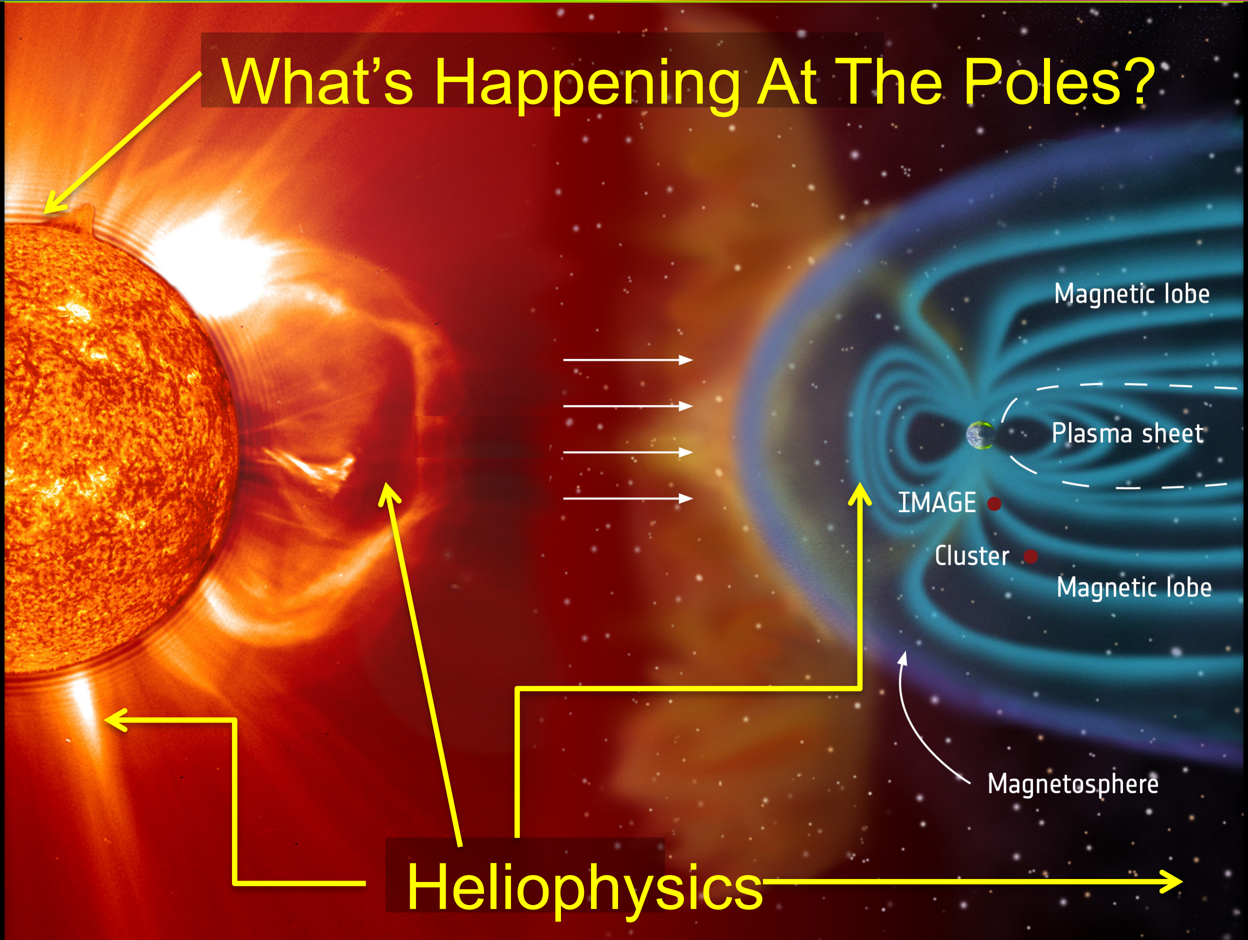
Carl Sagan & Johnny Carson (Tonight Show, 1976)

Early Radiation Pressure History

- Kepler (1619); Newton (1704) – corpuscular theory (momentum)
- Kelvin (1845) – ponderomotive (gradient) force
- Maxwell (1873) – radiation pressure, ponderomotive force
- Nichols/Hulls; Lebedev; Poynting (early 1900's)
- Tsander; Tsiolkovsky (early 1900's) – solar sailing
- NASA/CCCP (1960's); Mariner 4 stabilization; Mariner 10 rescue (1974)
- Wright; Friedman/Sagan/Murray; Forward (1970's)
- Many contributors since then (Matloff, Johnson, Vulpetti, McInnes, Landis, …

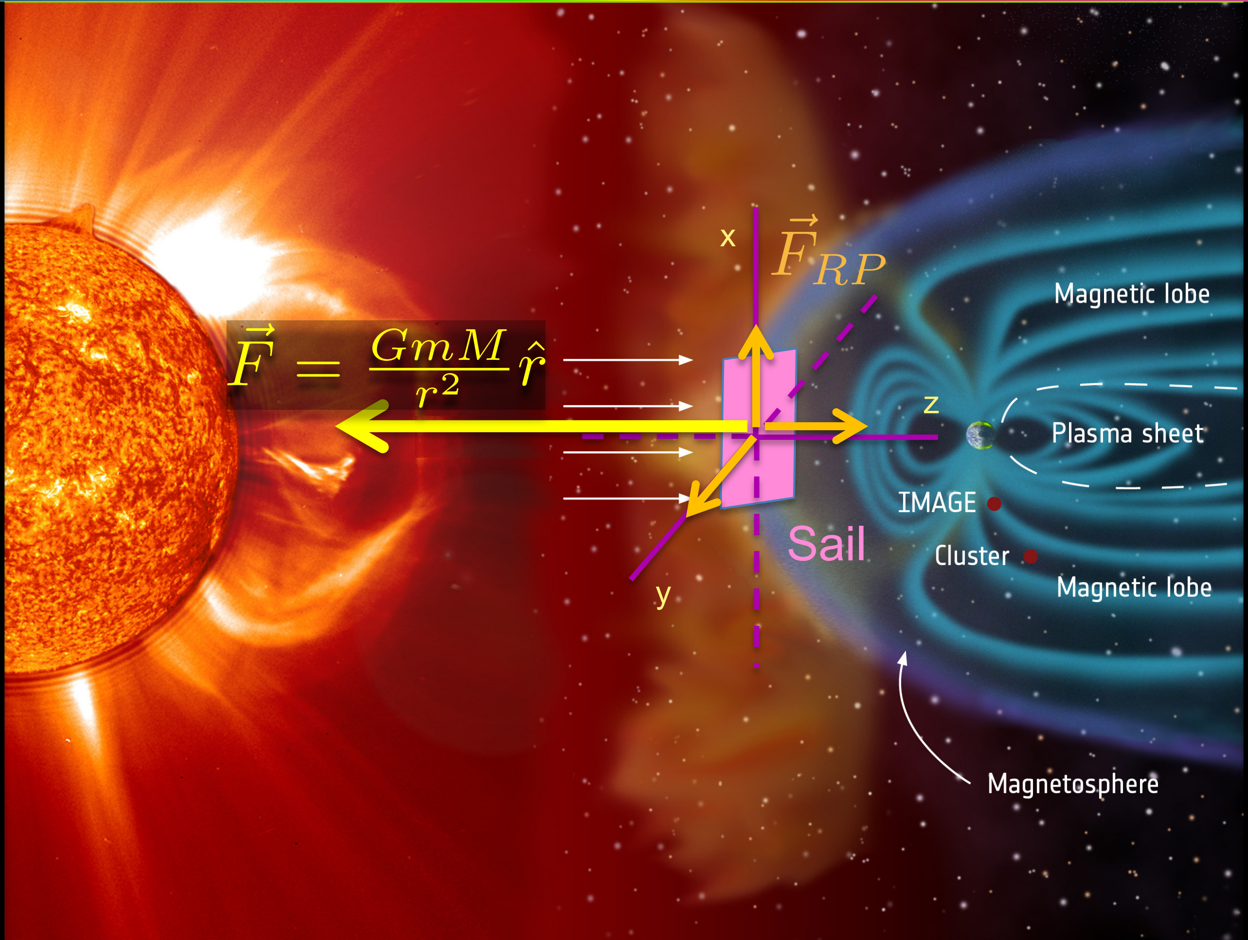
1. Schagrin, *Early observations and calculations on light pressure*, Am. J. Physics 42, 927–940 (1974)
2. www.planetary.org/explore/projects/lightsail-solar-sailing/story-of-lightsail-part-1.html
3. www.centauri-dreams.org/2014/07/07/sailing-to-halleys-comet/

Mission: Full 4π Solar Observations



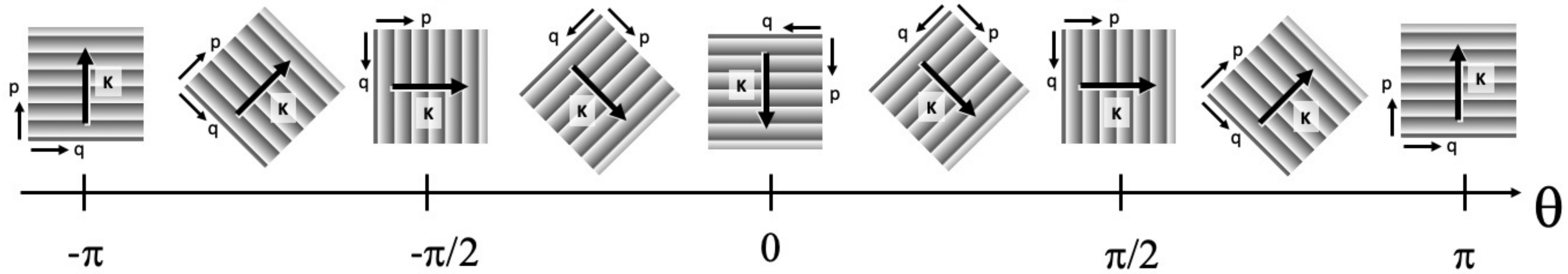
Forces: Solar Gravity + Radiation Pressure

Grover Swartzlander



Sun-Facing Diffractive "Dubill Roll Maneuver"

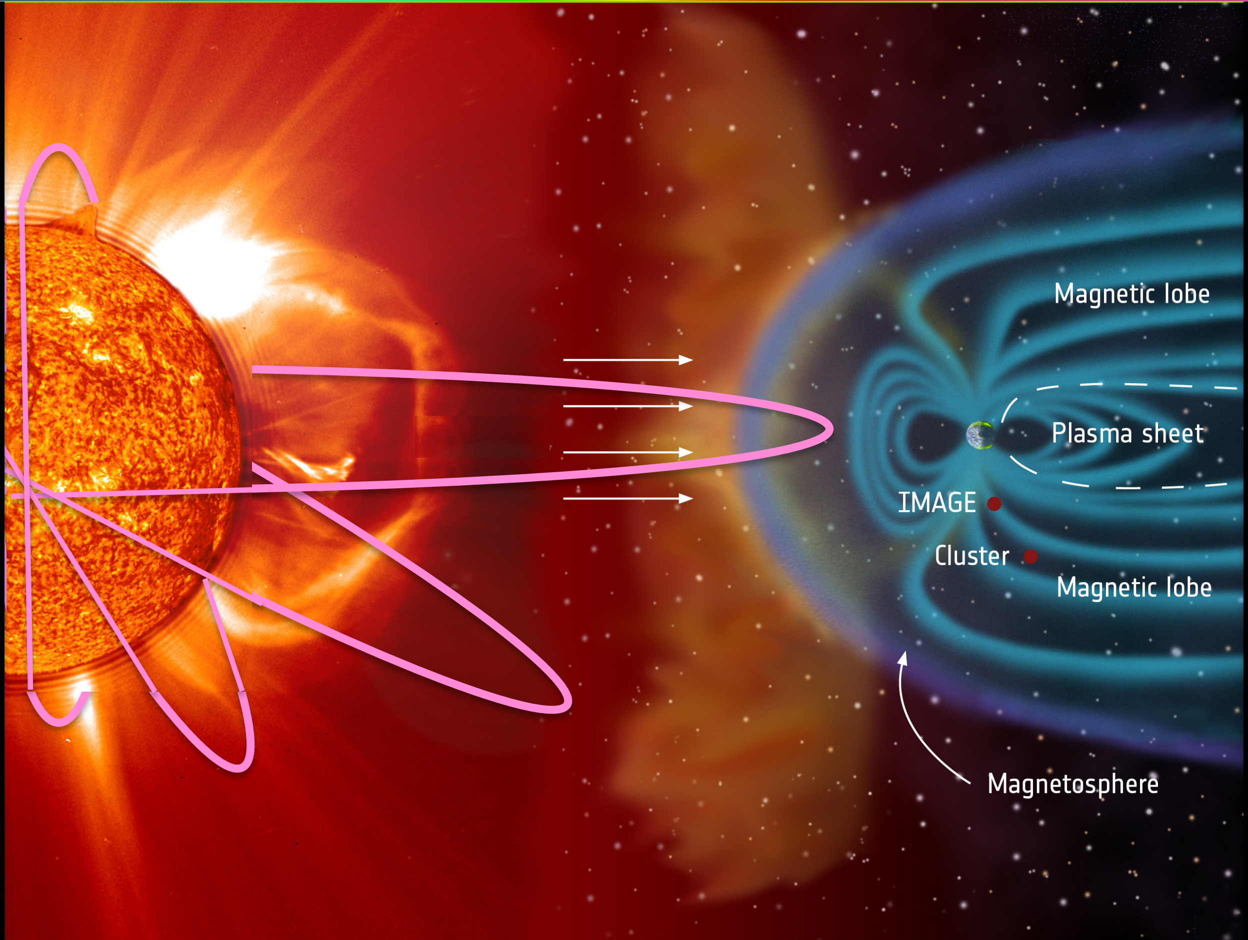
Grover Swartzlander



$$\vec{K} = (2\pi/\Lambda)\hat{p}$$

Λ : Grating Period

Trajectory: Inward Spiral + Raise Inclination Angle



Two-Body Equation of Motion (Sun + Sail)

Key Parameters :

Efficiency $\vec{\eta}$ (Control Parameter)

Sailcraft Areal Density $\sigma = m_s/A$

$$F_r = -GMm_s/r^2 + (I_E R_E^2 A_s/cr^2)\,\eta_r = -(\mu m_s/r^2)(1-\alpha_r)$$
$$= m_s\left(\ddot{r} - r(\dot{\theta}\cos\phi)^2 - r(\dot{\phi})^2\right)$$

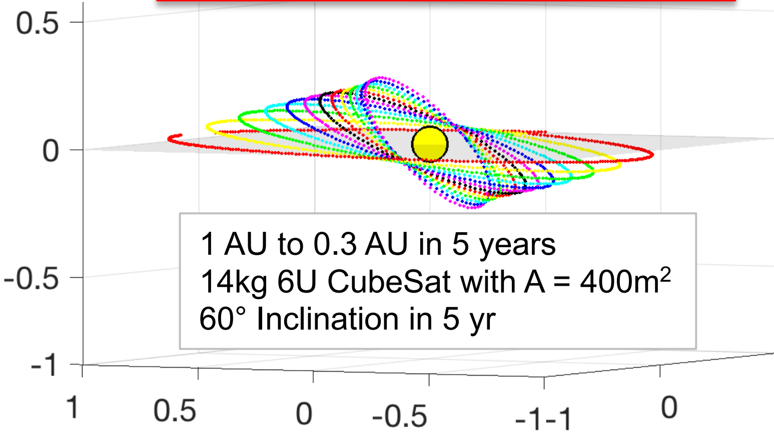
Negligible

$$F_\theta = (I_E R_E^2 A_s/cr^2)\,\eta_\theta = (\mu m_s/r^2)\alpha_\theta$$
$$= m_s\left(r\ddot{\theta}\cos\phi + 2\dot{r}\dot{\theta}\cos\phi - 2r\dot{\theta}\dot{\phi}\sin\phi\right)$$

Orbit Raising/Lowering

$$F_\phi = (I_E R_E^2 A_s/cr^2)\,\eta_\phi = (\mu m_s/r^2)\alpha_\phi$$
$$= m_s\left(r\ddot{\phi} + 2\dot{r}\dot{\phi} + r(\dot{\theta})^2\cos\phi\sin\phi\right)$$

Inclination Cranking



Initial State Vector at t=0: $(r, \theta, \phi, \dot{r}, \dot{\theta}, \dot{\phi})$

Final State Vector at t=T: $(r, \theta, \phi, \dot{r}, \dot{\theta}, \dot{\phi})$

Control Parameters: α_j depends on the momentum transfer efficiency $\vec{\eta}$ and sail areal density σ

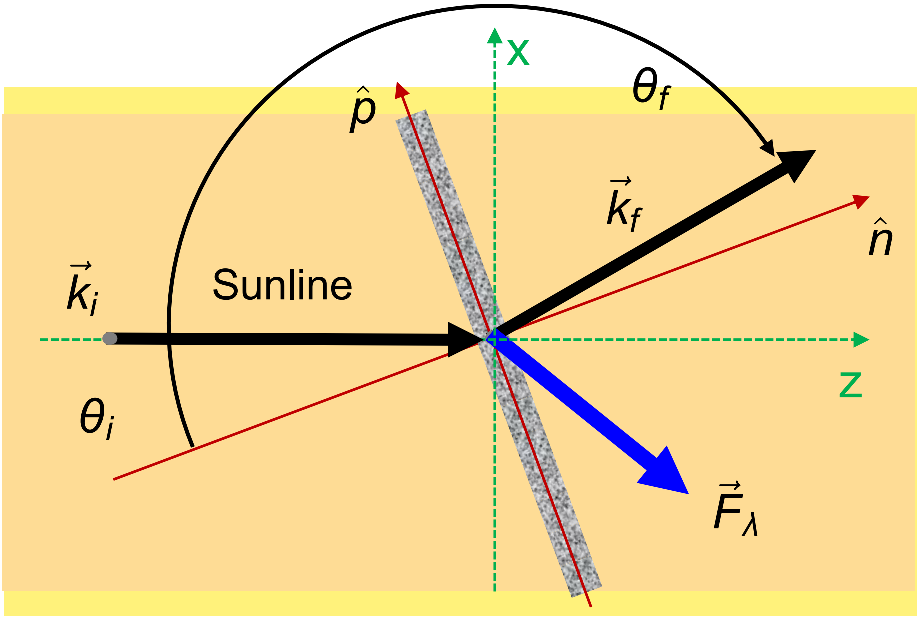
$\alpha_r = (1/2)(\sigma_{cr}/\sigma)\eta_r$; $\alpha_\theta = (1/2)(\sigma_{cr}/\sigma)\eta_\theta$; $\alpha_\phi = (1/2)(\sigma_{cr}/\sigma)\eta_\phi$;

$\sigma = m_s/A$; $\sigma_{cr} = 1.54$ [g/m^2] ; $\mu = GM$

Currently We Are Exploring Means Of Optimizing the Transverse Momentum Transfer Efficiency

Photon Momentum Transfer

Photon Momentum: $\hbar\vec{k}$ $\quad |\vec{k}| = 2\pi/\lambda = 2\pi\nu/c$



Scattering Surface Area, A
Oblique Incidence Angle, θ_i
Illuminated Projected Area, A $\cos\theta_i$

Illumination Projection Angle: A' = A $\cos\theta_\iota$

Spectral Irradiance: I_ν or I_λ

Spectral Radiation Pressure Force:

$$d\vec{F}_\lambda \equiv \frac{AI_\lambda}{c}\,\vec{\eta}_\lambda\, d\lambda$$

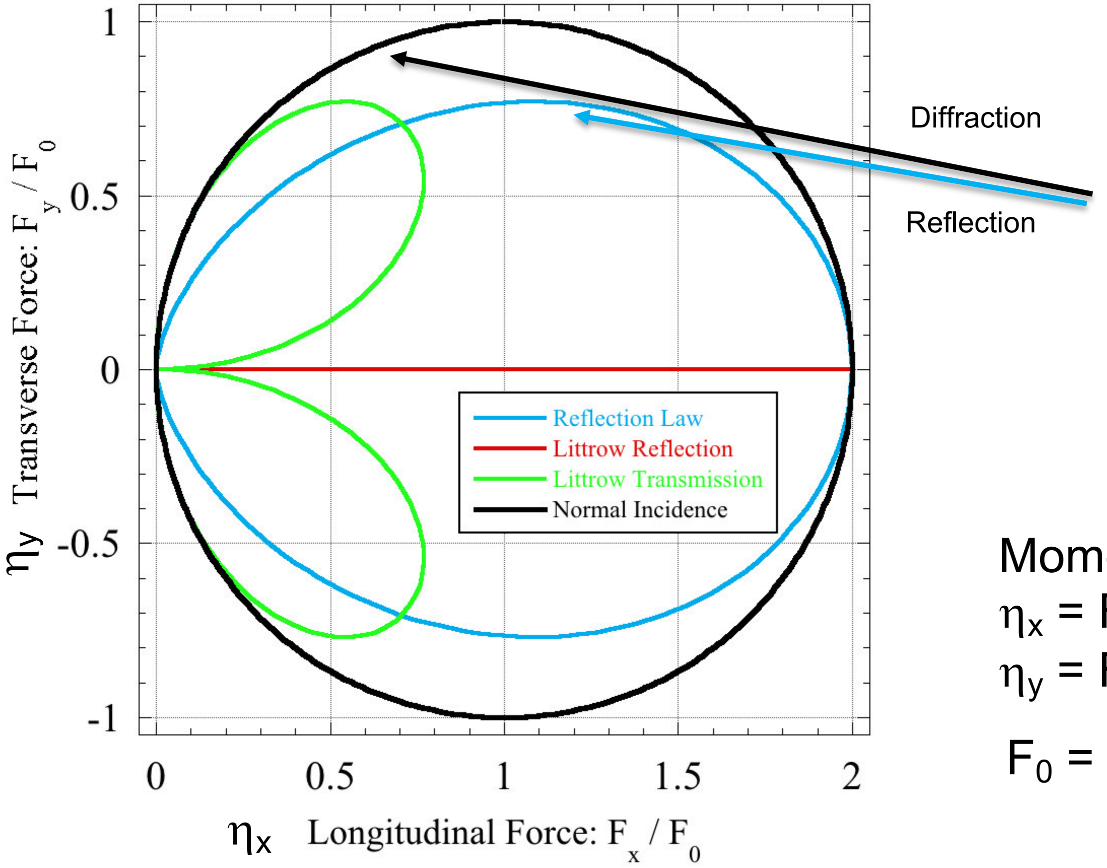
where $\boxed{\vec{\eta}_\lambda = \frac{\vec{k}_i - \vec{k}_f}{k}\cos\theta_i}$

is the momentum transfer efficiency

$$k = 2\pi/\lambda, \quad \vec{k}_i = k\,\hat{z},$$

$$\vec{k}_f = -k\cos(\theta_f - \theta_i)\,\hat{z} + k\sin(\theta_f - \theta_i)\,\hat{x}$$

Force Bubble: Diffraction vs Reflection



Spiral Orbit Missions:

High Transverse Force & Small Radial Force Desirable

Momentum Transfer Efficiencies:

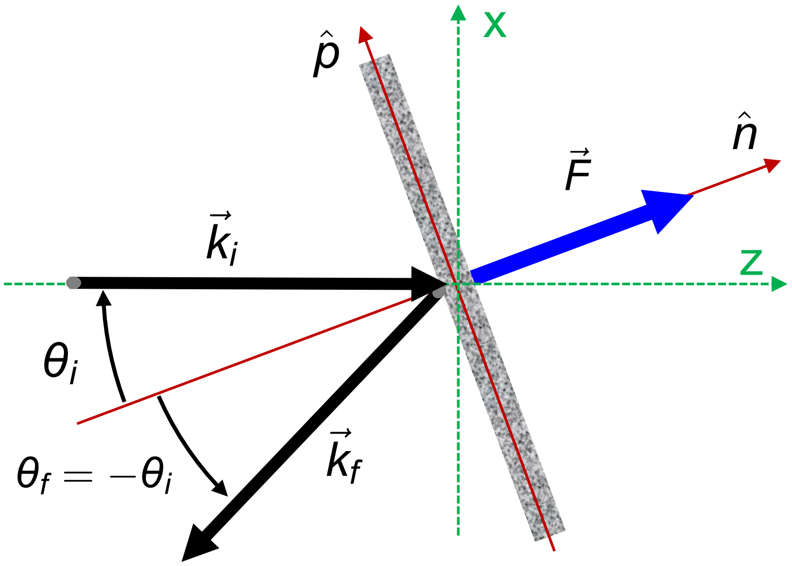
$\eta_x = F_x/F_0$ (or η_r) – along sunline

$\eta_y = F_y/F_0$ (or η_ϕ) – perpendicular to sunline

$F_0 = P/c$

Radiation Pressure on a Reflecting Surface

Reflecting Solar Sail



Mirror Surface Area, A

Law of Reflection: $\theta_f = -\theta_i \rightarrow \theta_f - \theta_i = -2\theta_i$

$\vec{k}_i = k\,\hat{z}$

$\vec{k}_f = -k\cos 2\theta_i\,\hat{z} - k\sin 2\theta_i\,\hat{x}$

$\vec{k}_i - \vec{k}_f = k(1+\cos 2\theta_i)\,\hat{z} + k\sin 2\theta_i\,\hat{x}$

$\sin 2\theta_i = 2\sin\theta_i\cos\theta_i$ and $1+\cos 2\theta_i = 2\cos^2\theta_i$

$\vec{\eta} = 2\cos^2\theta_i\,(\cos\theta_i\,\hat{z} + \sin\theta_i\,\hat{x}) = 2\cos^2\theta_i\,\hat{n}$

$\vec{F} = (IA/c)\,\vec{\eta}$ Normal to the Surface

A sun-facing reflective sail provides no transverse force ($\theta_i = 0$)

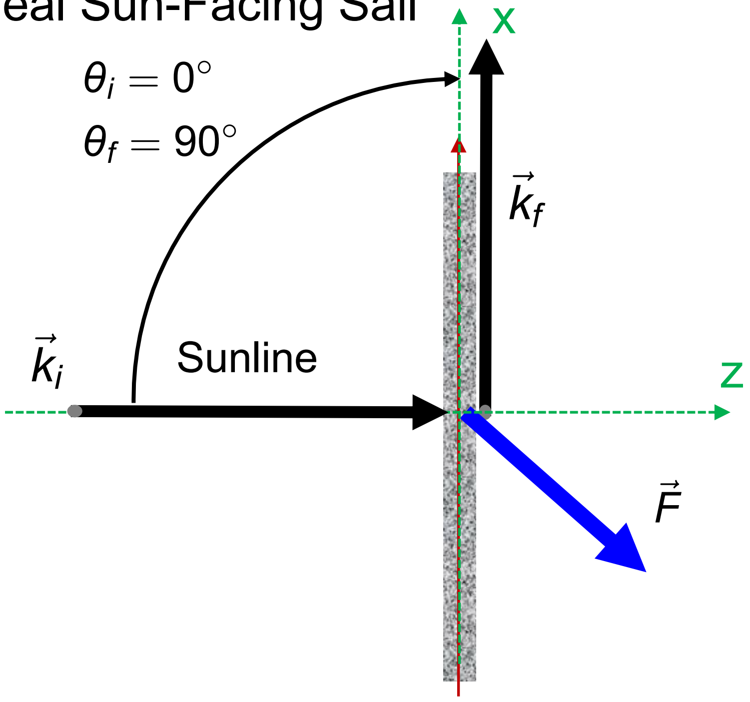
$\eta_x|_{max} = 0.77$ at $\theta_i = 35.26°$

Effective Scattering Angle: $\sin\theta_{eff} = 0.77 \rightarrow \theta_{eff} = 50.35°$

Ideal Sun-Facing Sail

$\theta_i = 0^\circ$

$\theta_f = 90^\circ$



$$\theta_i = 0^\circ \text{ and } \theta_f = 90^\circ$$

$$\vec{k}_i = k\,\hat{z} \quad \text{and} \quad \vec{k}_f = k\,\hat{x}$$

$$(\vec{k}_i - \vec{k}_f)/k = \hat{z} - \hat{x}$$

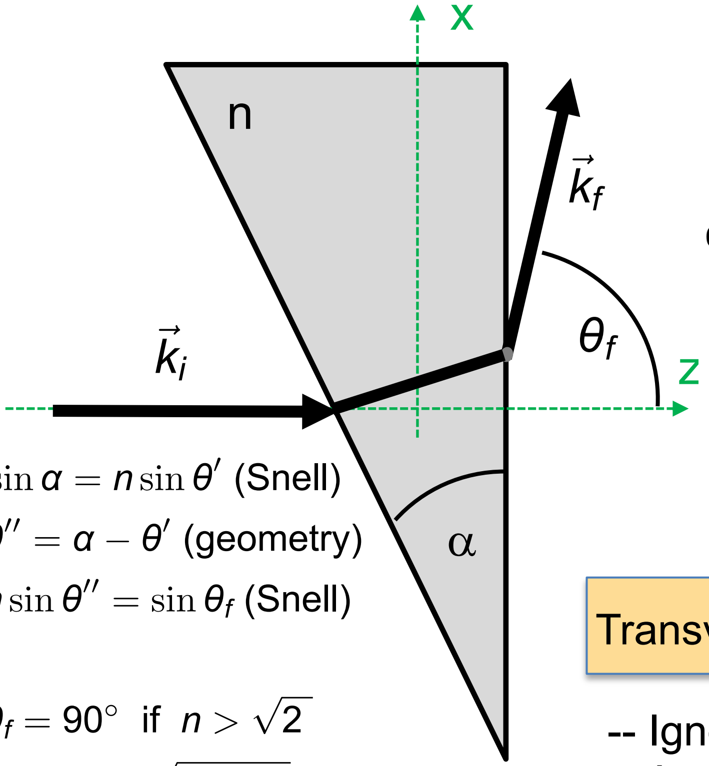
$$\vec{\eta} = \hat{z} - \hat{x}$$

$$\vec{F} = (IA/c)\,\vec{\eta}$$

Maximum Transverse Efficiency:100%

$$|\eta_x| = \sin\theta_{eff} = 1.0 \rightarrow \boxed{\theta_{eff} = 90^\circ}$$

Refracting Prism



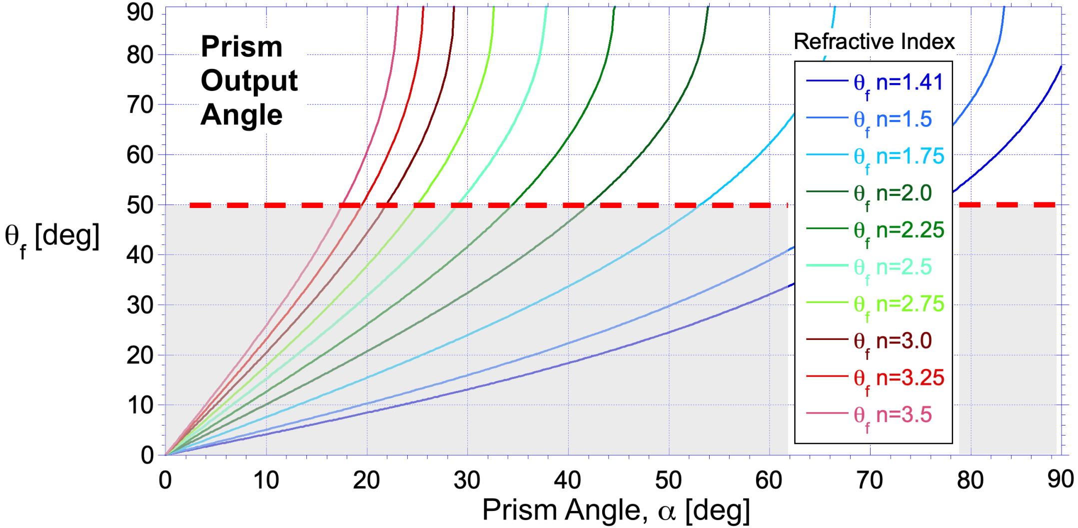
$\sin\alpha = n\sin\theta'$ (Snell)

$\theta'' = \alpha - \theta'$ (geometry)

$n\sin\theta'' = \sin\theta_f$ (Snell)

$\theta_f = 90^\circ$ if $n > \sqrt{2}$

$\cot\alpha_{cr} = \sqrt{n^2 - 1} - 1$

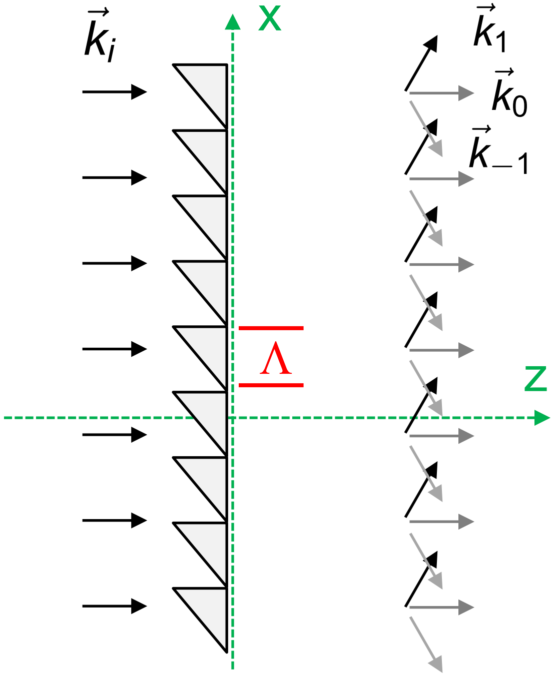


Transverse momentum transfer efficiency η_x can reach 100%

-- Ignores internal and external reflection
-- Acceleration = 0 owing to large mass

Idealized Prismatic Transmission Grating

Grover Swartzlander



Sun-Facing Idealized Transmission Grating

Far Field

(Fraunhofer Regime)

Grating Equation with Period Λ : $\sin\theta_m = m\lambda/\Lambda$

$$\vec{k}_m/k = m\lambda/\Lambda\,\hat{x} + \sqrt{1-(m\lambda/\Lambda)^2}\;\hat{z}$$

Diffraction Strength $I_{m,\lambda} = |E_{m,\lambda}|^2$

$$E_{m,\lambda} = \frac{\sqrt{I_\lambda}}{\Lambda}\int_{-\Lambda/2}^{\Lambda/2} \exp(ikx\sin\theta_f)\exp(-imKx)dx$$

where $K = 2\pi/\Lambda$ and I_λ is the incident spectral irradiance

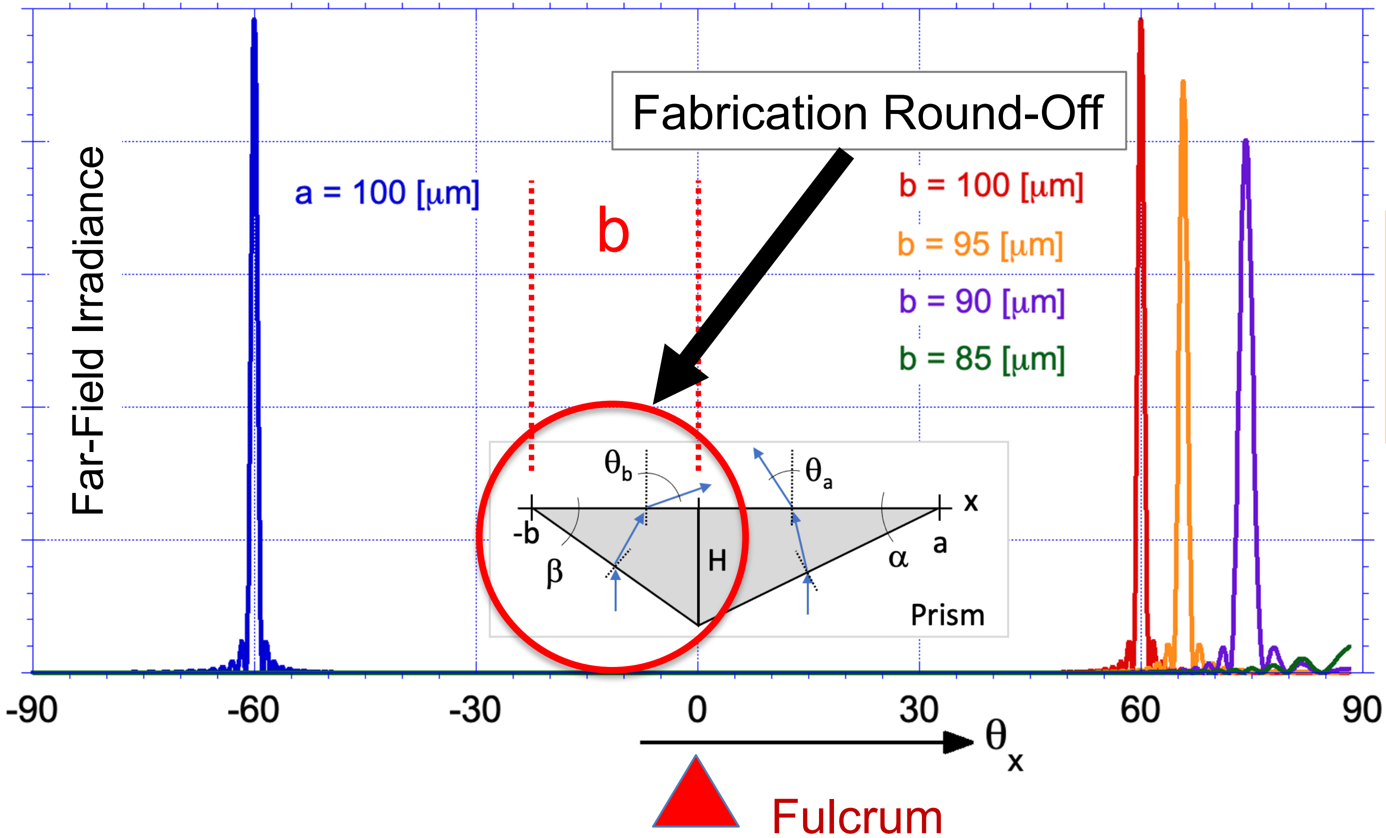
Net Momentum Transfer Efficiency:

$$\vec{\eta} = \frac{\int_0^\infty \left(I_\lambda\,\hat{z} - \sum_m I_{m,\lambda}(\vec{k}_m/k)\right)d\lambda}{\int_0^\infty I_\lambda d\lambda} \quad \text{for } |m| < \text{INT}[\Lambda/\lambda]$$

Cut-Off

Alternative Approach: Maxwell Stress Tensor

An Archimedes Dilemma

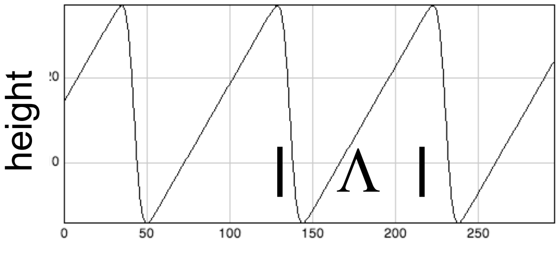


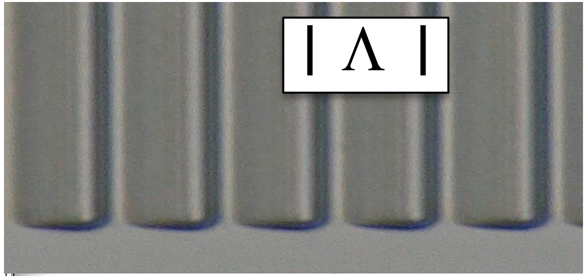
Transverse Momentum Transfer Requires A Cut-Off Condition:

$b < \lambda$

Types of Gratings (transmissive or reflective)

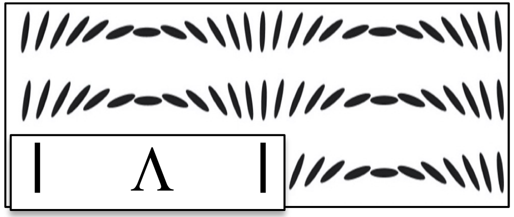
Blazed Grating (series of prisms)





Thick & Heavy

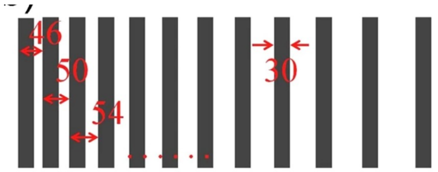
Cycloidal Polarization (Geometric Phase) Grating (BeamCo)

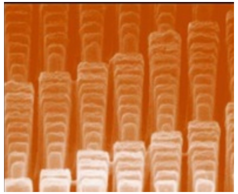


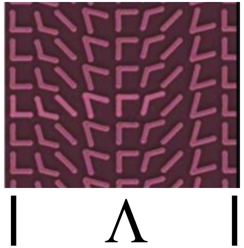
Director of Nematic Liquid Crystals

Polarization Dependent

Subwavelength Effective Media, Meta_Surface



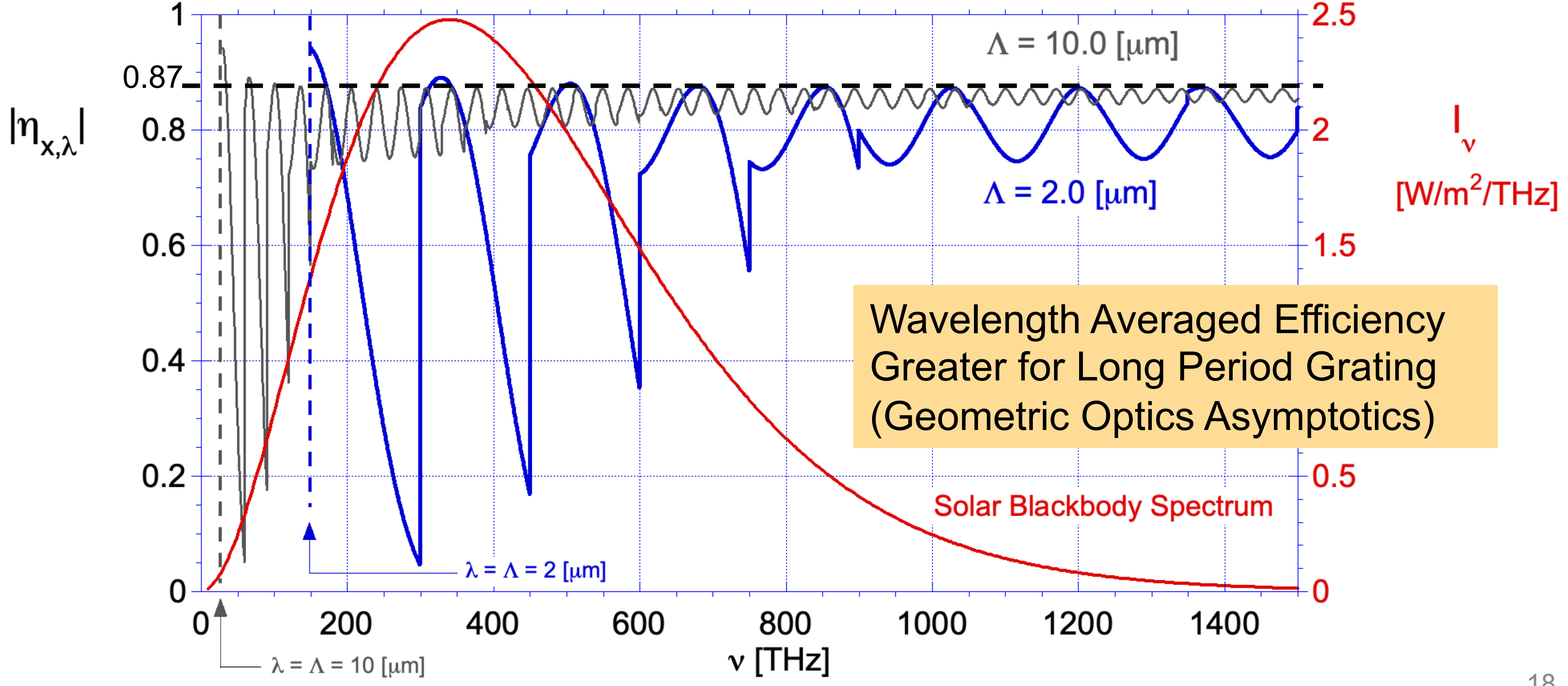




Fabrication Scale-Up Limits

Idealized Prismatic Grating (ignore shadowing)

Refraction Angle: $\theta_f = 60.5°$ ($\sin\theta_f = 0.87$)



Wavelength Averaged Efficiency Greater for Long Period Grating (Geometric Optics Asymptotics)

Geometric Phase Gratings

Pancharatum / Geometric Phase Elements

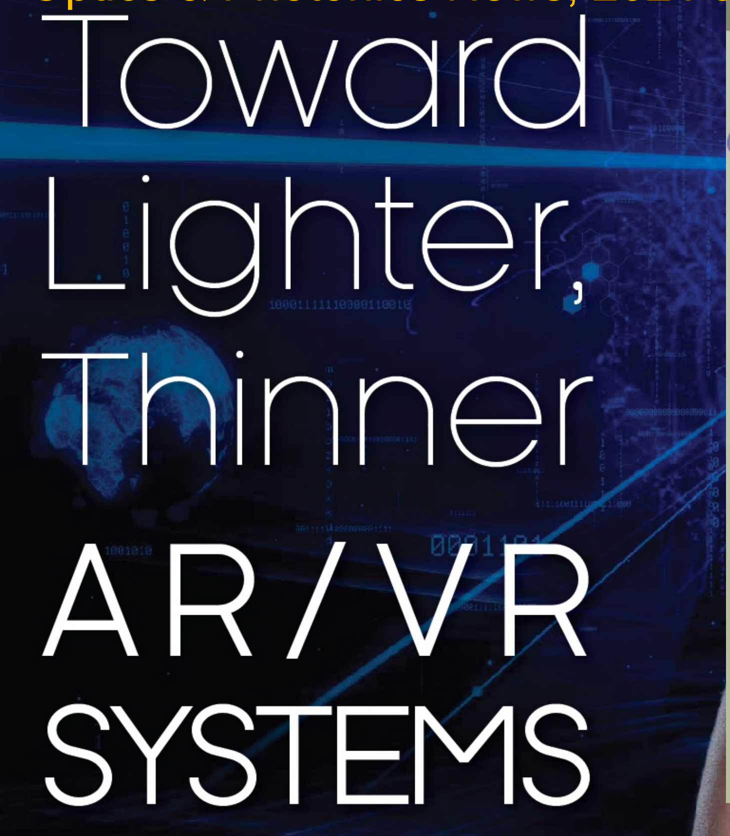
Nelson V. Tabiryan, Sarik R. Nersisyan, Diane M. Steeves and Brian R. Kimball

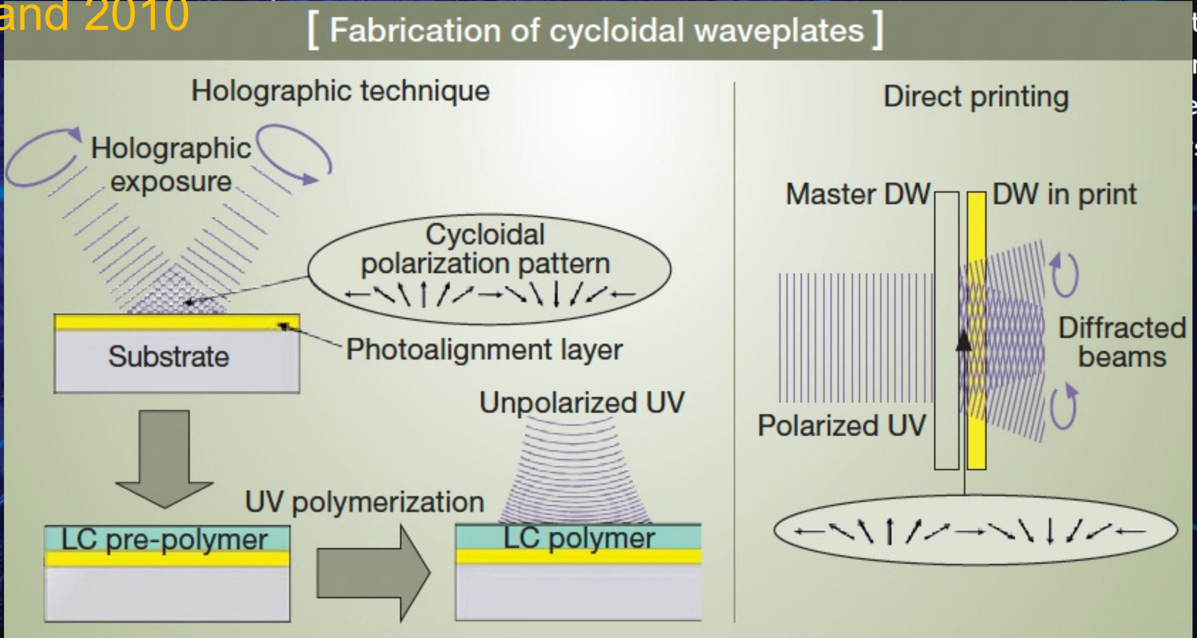
Optics & Photonics News, 2021 and 2010

Pancharatum / Geometric Phase Elements

Nelson V. Tabiryan, Sarik R. Nersisyan, Diane M. Steeves and Brian R. Kimball

Optics & Photonics News, 2021 and 2010





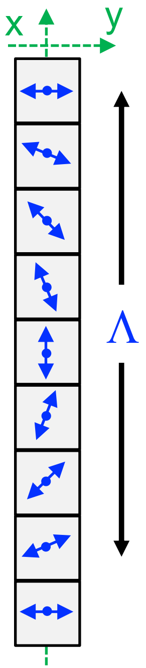
Key fabrication steps of LC polymer DW include depositing a 10- to 50-nm-thick photo-alignment layer on a substrate, exposing it to overlapping orthogonal circularly polarized beams to impart cycloidal orienting boundary conditions, and subsequently coating it with an LC pre-polymer layer to obtain cycloidal orientation pattern in a thicker material layer meeting the half-waveplate condition.

Geometric Phase Gratings

Also called "q plates", polarization diffraction gratings, etc.

Phase Retarder Rotation*: $\vec{E}_{out} = R^T \, J \, R \, \vec{E}_{in}$:

$$\begin{bmatrix} E_{x,out} \\ E_{y,out} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \exp(i\varphi_x) & 0 \\ 0 & \exp(i\varphi_y) \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} E_{x,in} \\ E_{y,in} \end{bmatrix}$$



Half-Wave Condition: $\Delta\varphi = \varphi_y - \varphi_x = 2\pi(n_y - n_x)d_{HW}/\lambda_0 \equiv \pi$

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix}_{out} = \exp(i\varphi_x) \begin{bmatrix} \cos 2\theta & -\sin 2\theta \\ -\sin 2\theta & -\cos 2\theta \end{bmatrix} \begin{bmatrix} E_x \\ E_y \end{bmatrix}_{in}$$

Left-Hand Circularly Polarized Input: $\begin{bmatrix} 1 \\ i \end{bmatrix} \rightarrow \boxed{\exp(-i\,2\theta)} \begin{bmatrix} 1 \\ -i \end{bmatrix} \exp(i\varphi_x)$

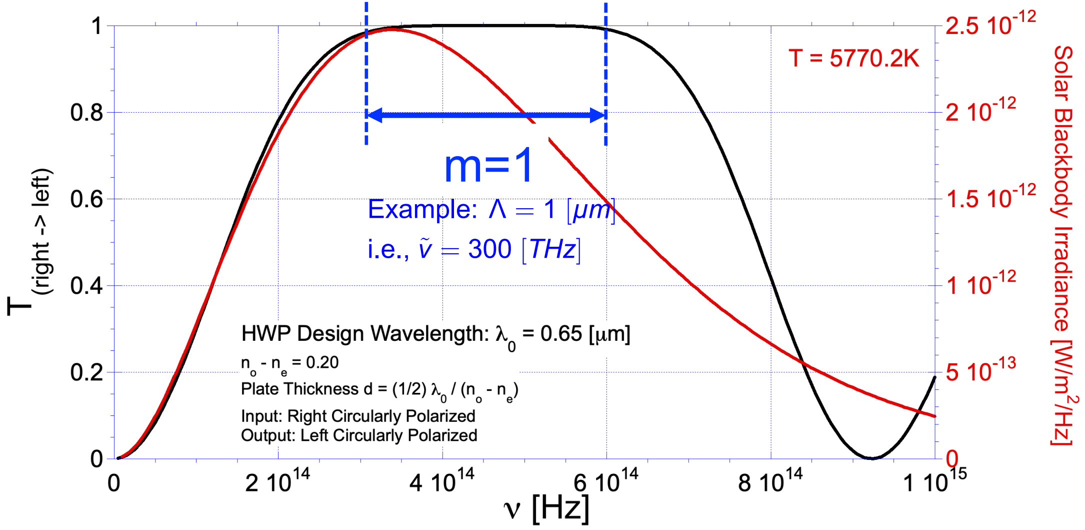
Right-Hand Circularly Polarized Input: $\begin{bmatrix} 1 \\ -i \end{bmatrix} \rightarrow \boxed{\exp(+i\,2\theta)} \begin{bmatrix} 1 \\ i \end{bmatrix} \exp(i\varphi_x)$

Linear Phase Grating: Spatially Variant Rotation Angle $\boxed{2\theta = 2\pi x/\Lambda}$

* S. Pancharatnam, "On the phenomenological theory of light propagation in optically active crystals," Proc. Indian Acad. Sci. A 44, 247–262 (1956).

Unlike a Prismatic Grating

a Geometric Phase Grating may be achromatized* to provide nearly 100% diffraction into the first order mode (for one polarization).



$$\eta_x \approx -\int_{\tilde{\nu}}^{2\tilde{\nu}} I_\nu\,(\tilde{\nu}/\nu)\,d\nu \Big/ \int_0^\infty I_\nu\,d\nu$$

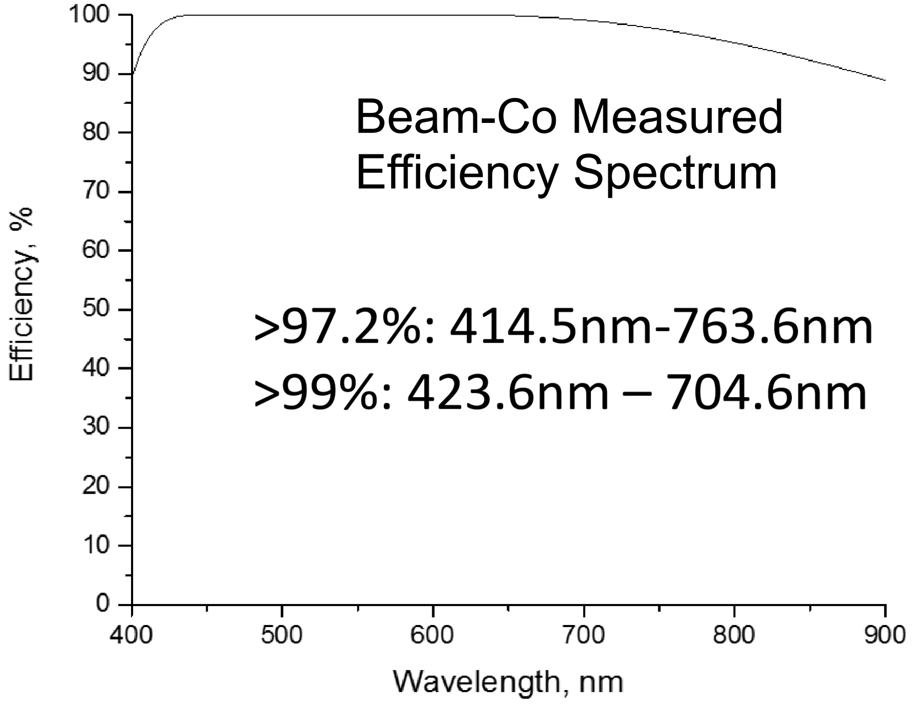
$$\eta_z \approx \int_{\tilde{\nu}}^{2\tilde{\nu}} I_\nu\left(1-\sqrt{1-(\tilde{\nu}/\nu)^2}\,\right)d\nu \Big/ \int_0^\infty I_\nu\,d\nu$$

If $I_\nu \sim 2\times 10^{-12}\ [W/m^2/Hz]$

$$\eta_x = -\frac{(2\times 10^{-12})(3\times 10^{14})}{1360W/m^2}(\ln 2) = -0.31$$

* S. Pancharatnam, “Achromatic combinations of birefringent plates," In Proceedings of the Indian Academy of Sciences-Section A 41, 137-144, Springer (1955)

Achromatic Geometric Phase Grating

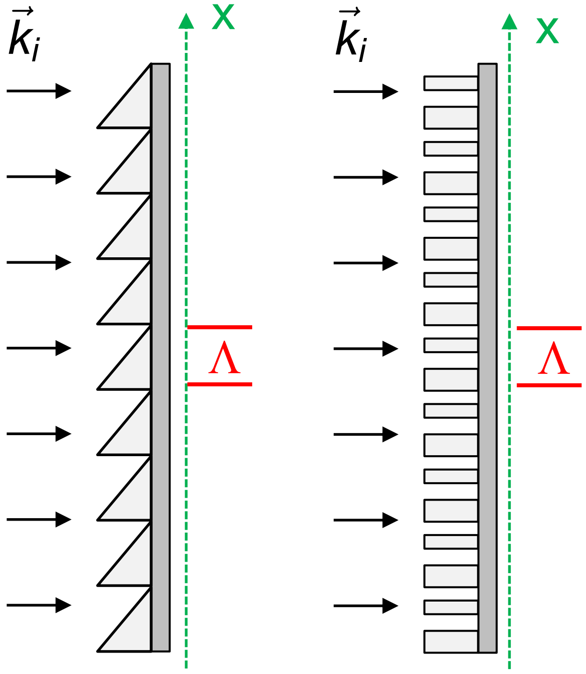


D. Roberts, H. Xianyu, S. Nersisyan,
N. V. Tabiryan and E. Serabyn,
Overcoming the tradeoff between efficiency
and bandwidth for vector vortex waveplates,
2019 IEEE Aerospace Conference, Big Sky, MT

* S. Pancharatnam, "Achromatic combinations of birefringent plates," In Proceedings of the Indian Academy of Sciences-Section A 41, 137-144, Springer (1955)

Meta-Surface Gratings

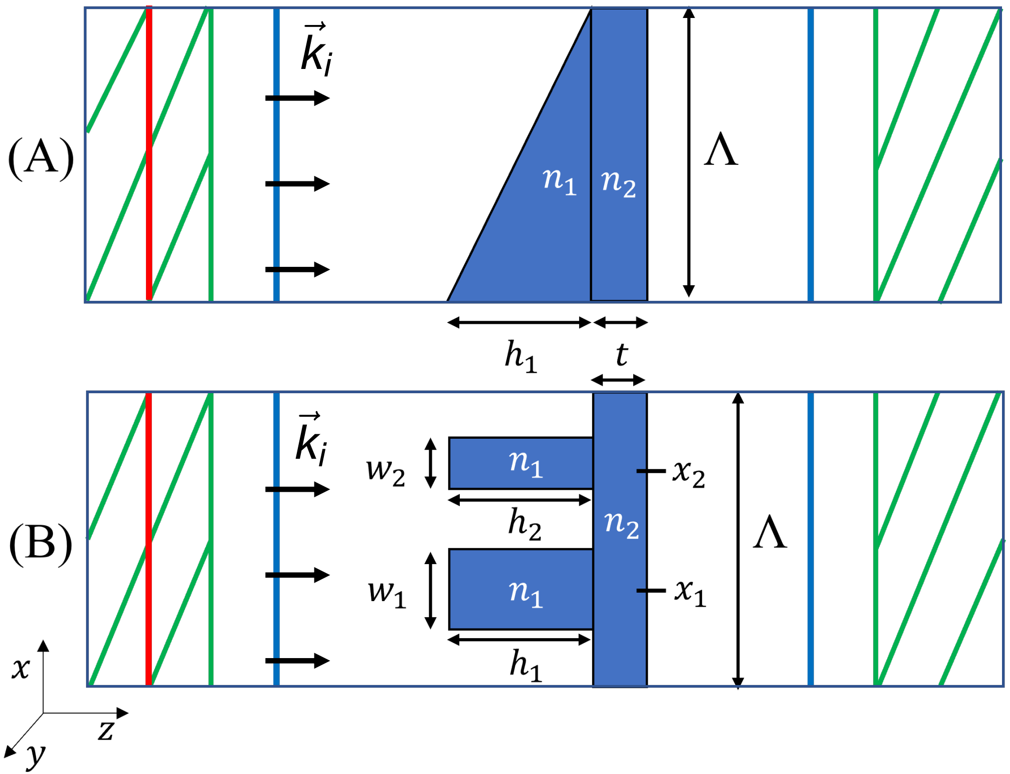
Full FDTD Simulation Comparison



Sun-Facing Prism Transmission Grating

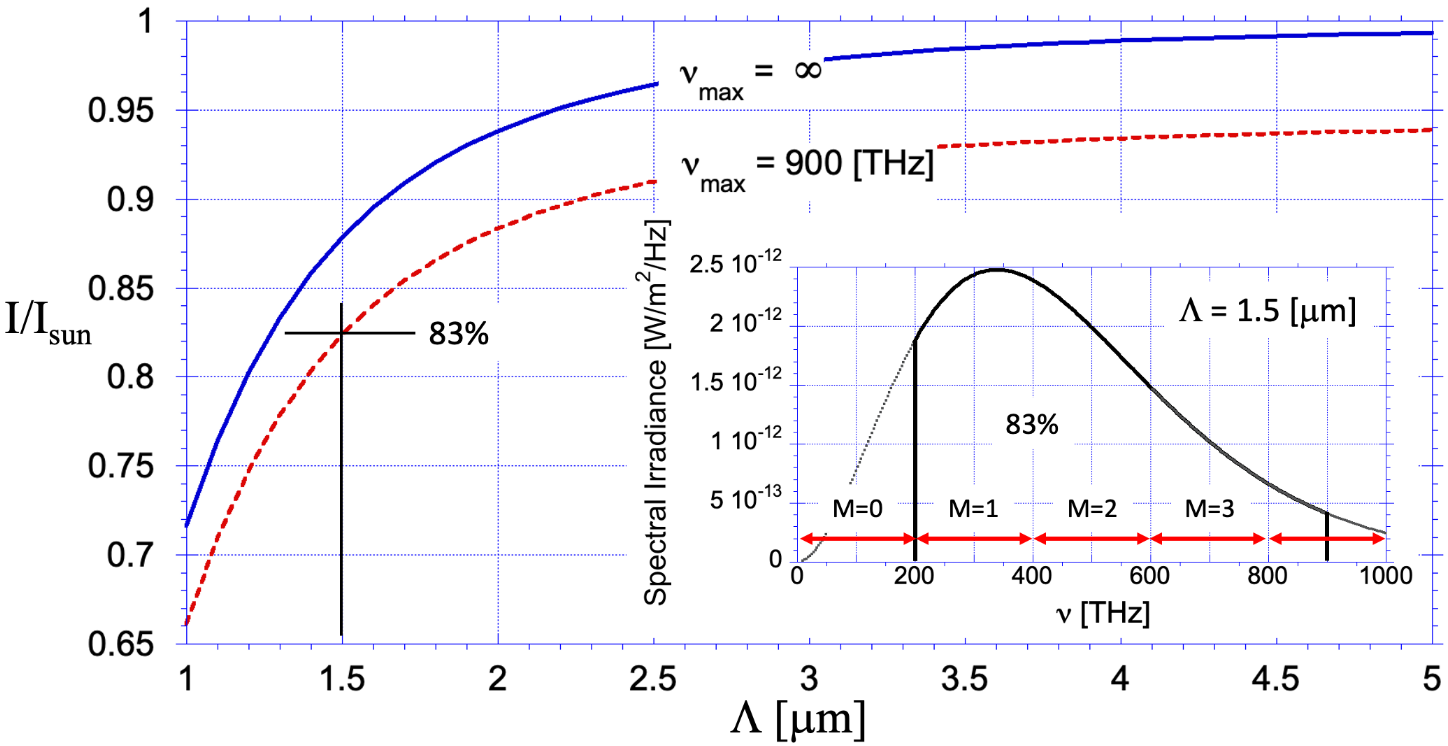
Sun-Facing Meta-Surface Transmission Grating

FDTD Unit Cell Scattering Elements

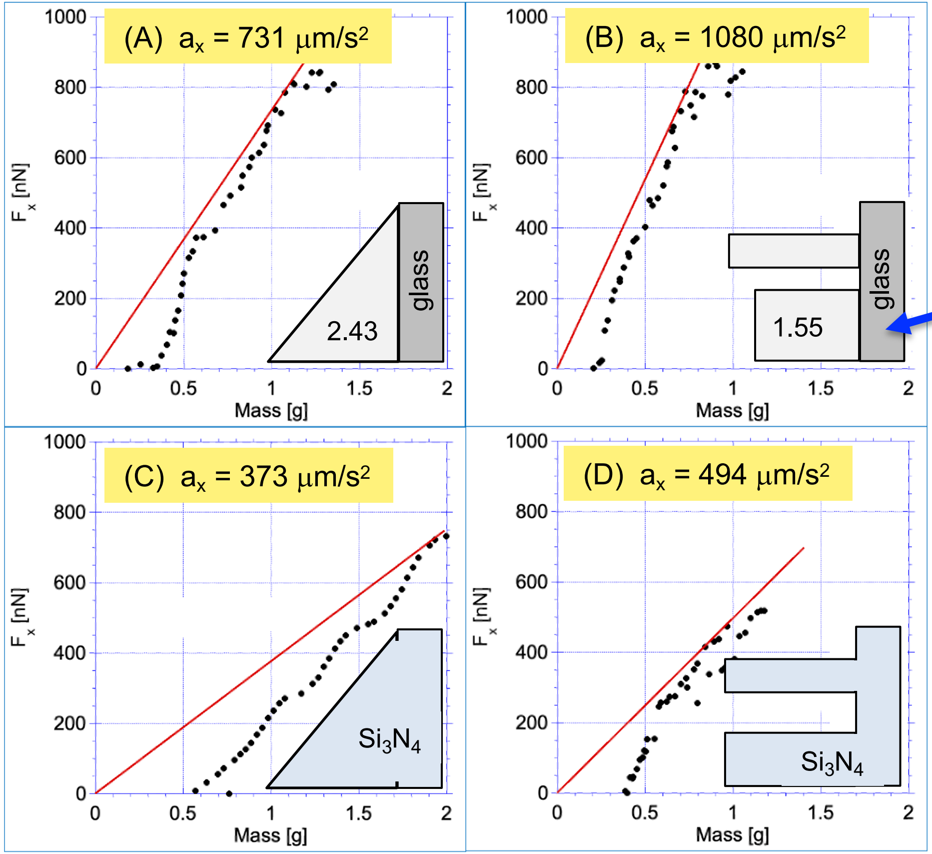


Full FDTD Simulation Comparison

Optimize for 83% of the solar spectrum: 200 – 900 THz (λ = 0.33 – 1.5 μm)



Full FDTD Simulation Comparison



Transverse Acceleration on an Optimized 1m² Area Sail Predicted to Reach > 1 mm/s²

Pillar Height ~ 1.2 μm
Substrate ~ 0.1 μm

Comparison:

Reflective Sail on 3 $\mu m \times 1\ m^2$ Polyimide Film

$F_x = (1360)(0.77)(0.83)/(3 \times 10^8) = 2.9\ \mu N$

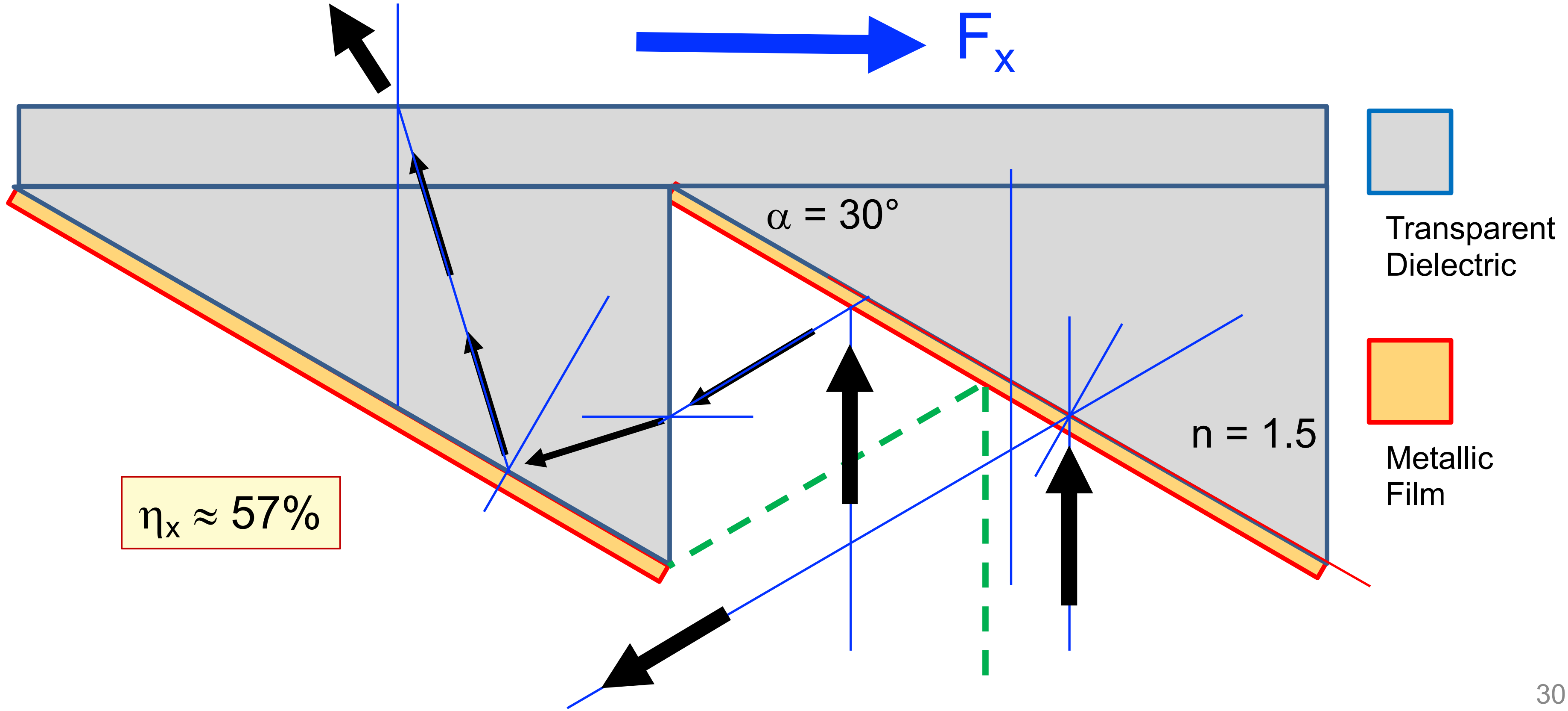
$M = (1540)(3 \times 10^{-6}) = 4.6 \times 10^{-3}\ kg$

$a_x = F_x/M = 0.63\ mm/s^2$

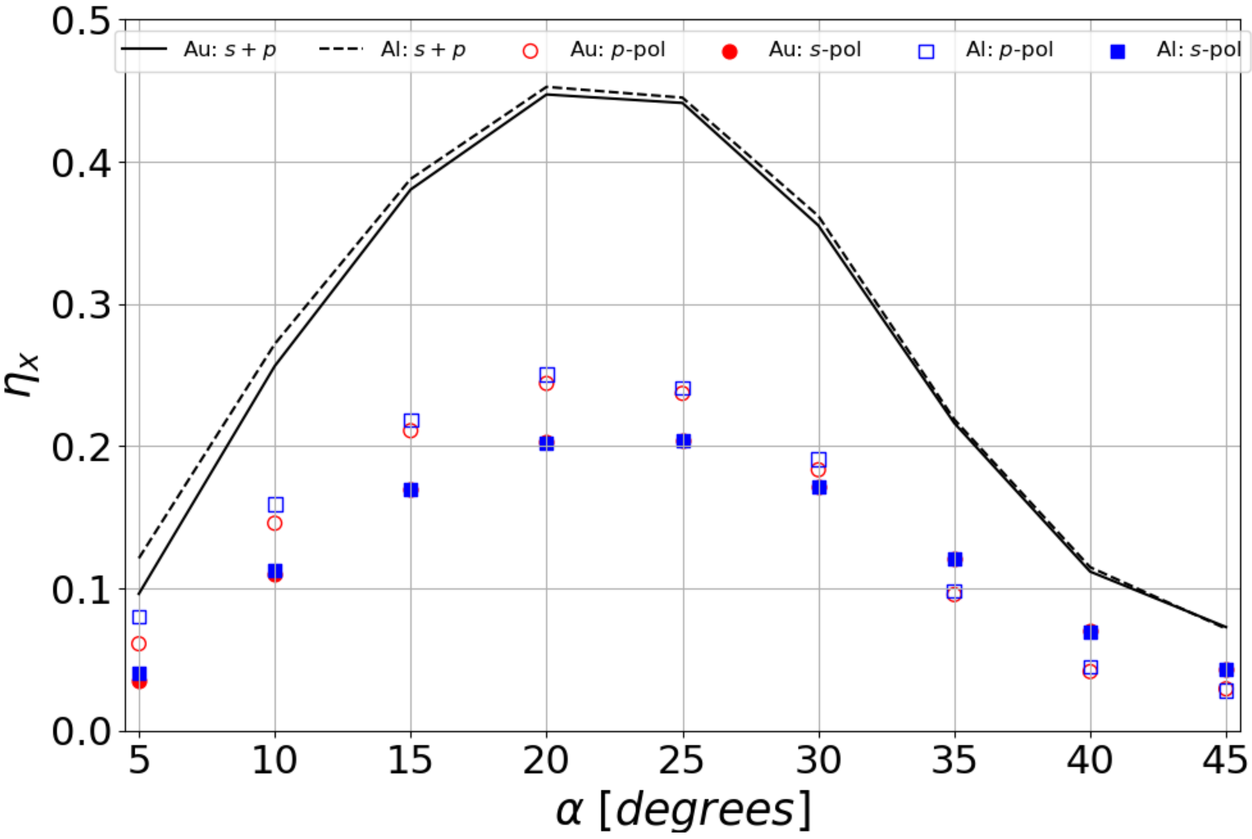
Future designs must overcome scattering in wrong transverse direction

Hybrid Gratings

Hybrid: Reflection/Transmission Grating



Hybrid: Reflection/Transmission Grating



FDTD Calculations:

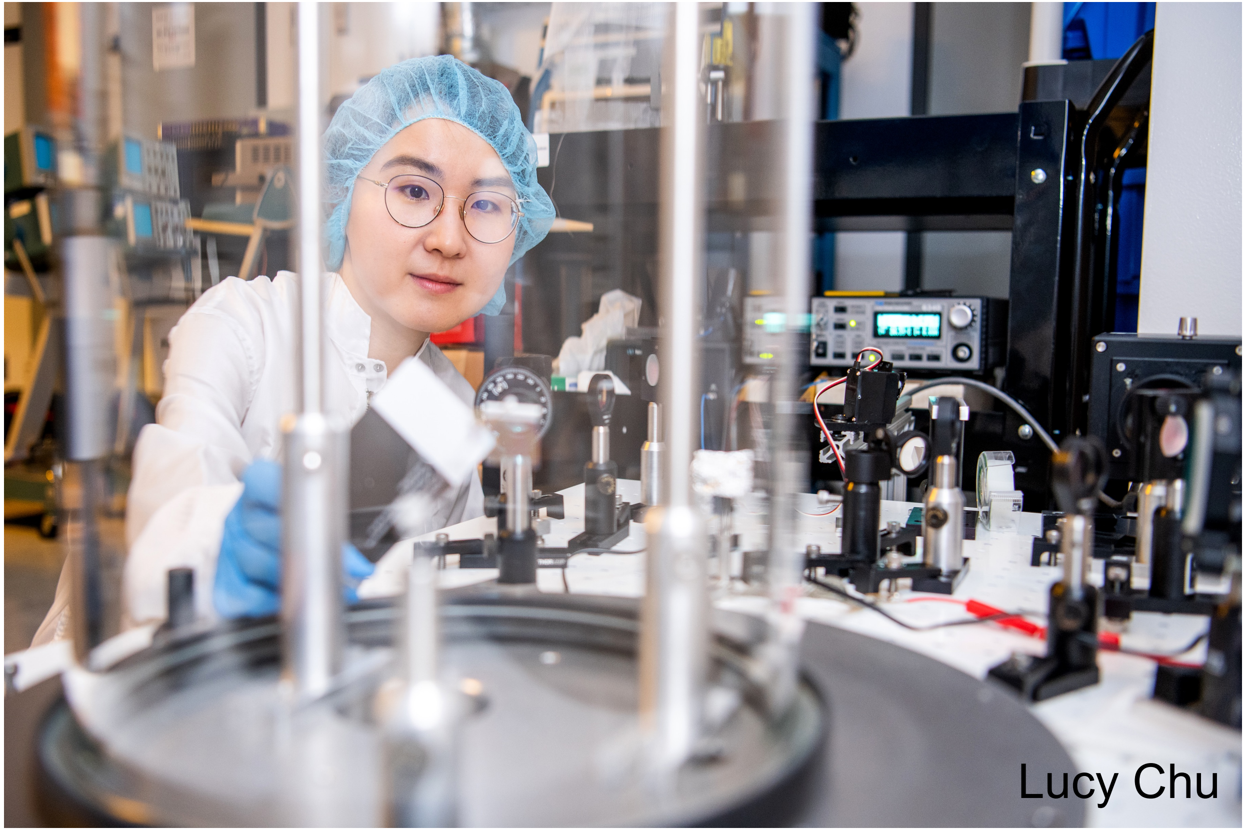
Prism Angle α = 20° provides η_x ~ 45%

F_x ~ 2 μN

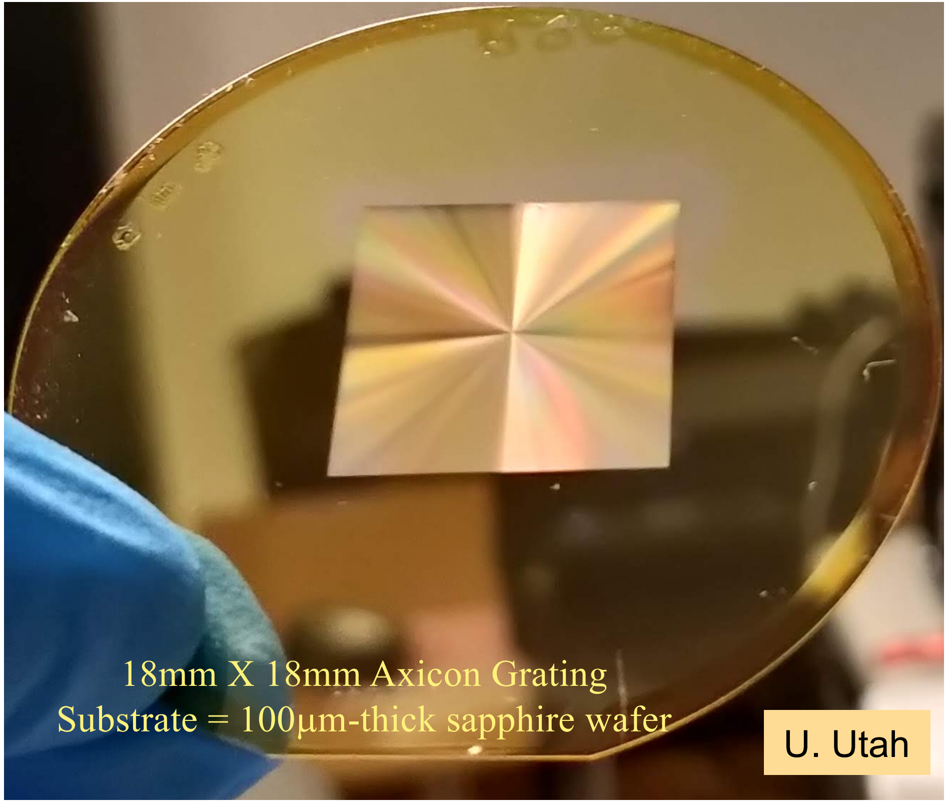
Λ = 3μm

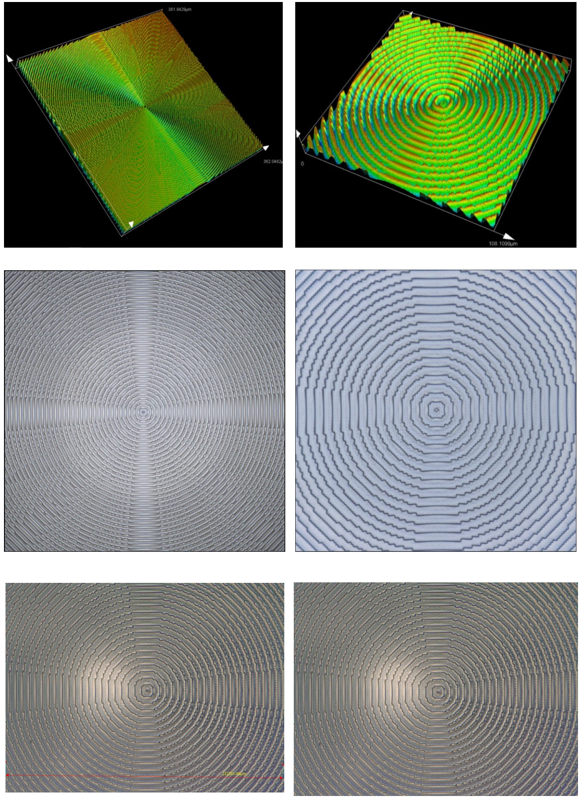
Aerogel substrate → high acceleration.

Validation Experiments

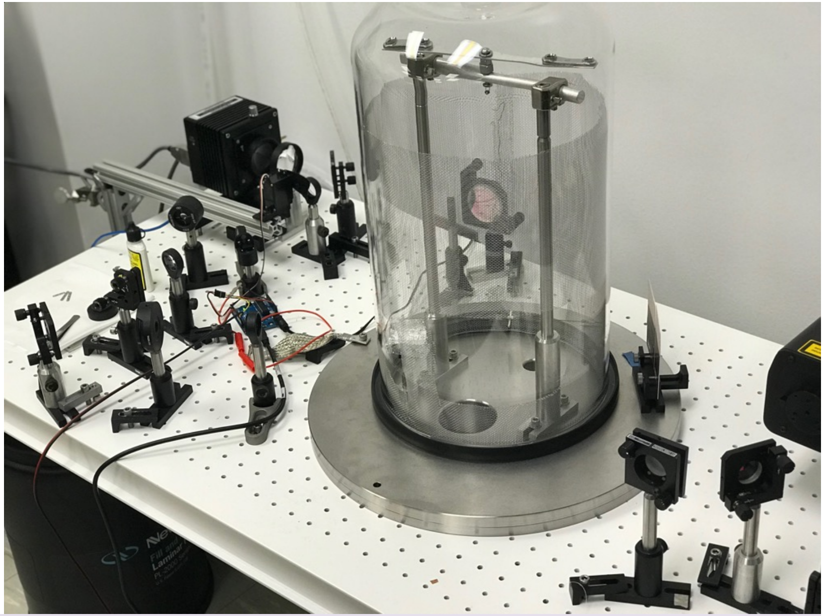


12 μm Axicon Grating: PR on Sapphire

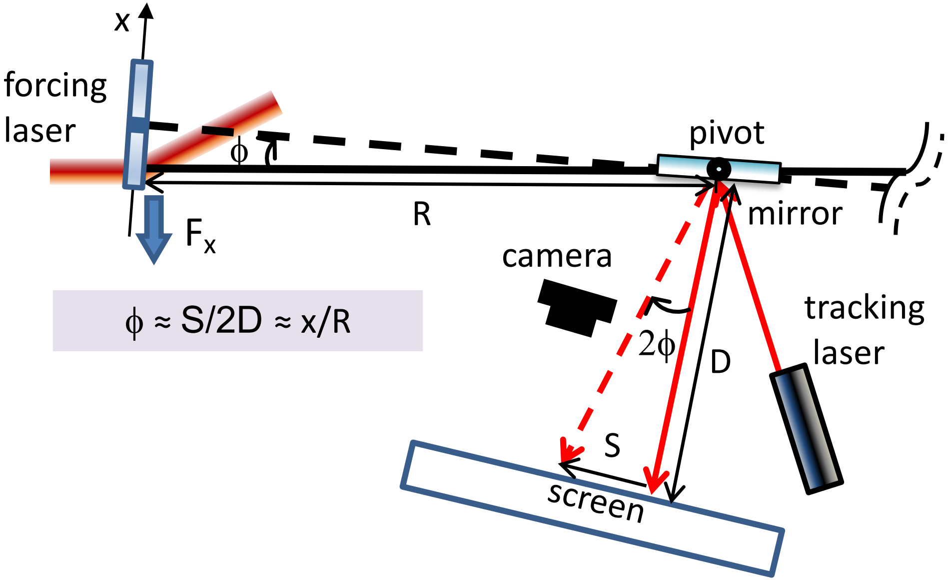




Vacuum Torsion Oscillator



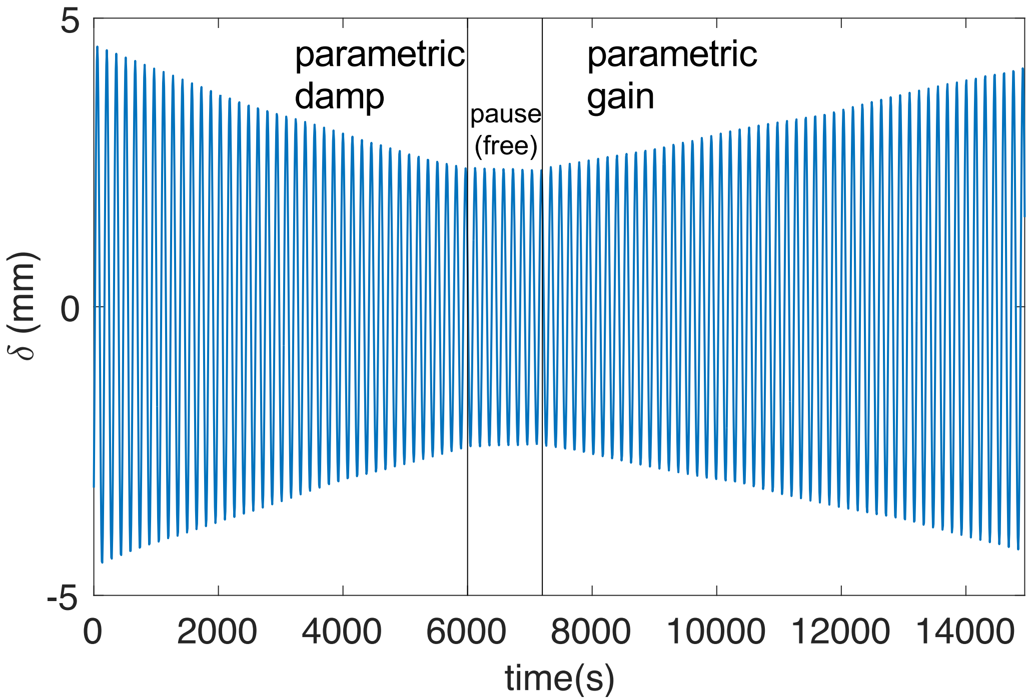
Vacuum: 1.8x10^{-5} atm
Filament restoring stiffness $K_f \approx$ 2x10^{-6} [N/m]



$\phi \approx S/2D \approx x/R$

Phys. Rev. Lett. **123**, 244302 (2019)
Phys. Rev. Lett. **121**, 063903 (2018)

Parametric Loss & Gain Demonstration



Parametric damping decay time:
τ_{damp} = 0.92E+4 [s]

Free oscillation decay time:
τ_{free} = 1.0E+5 [s]

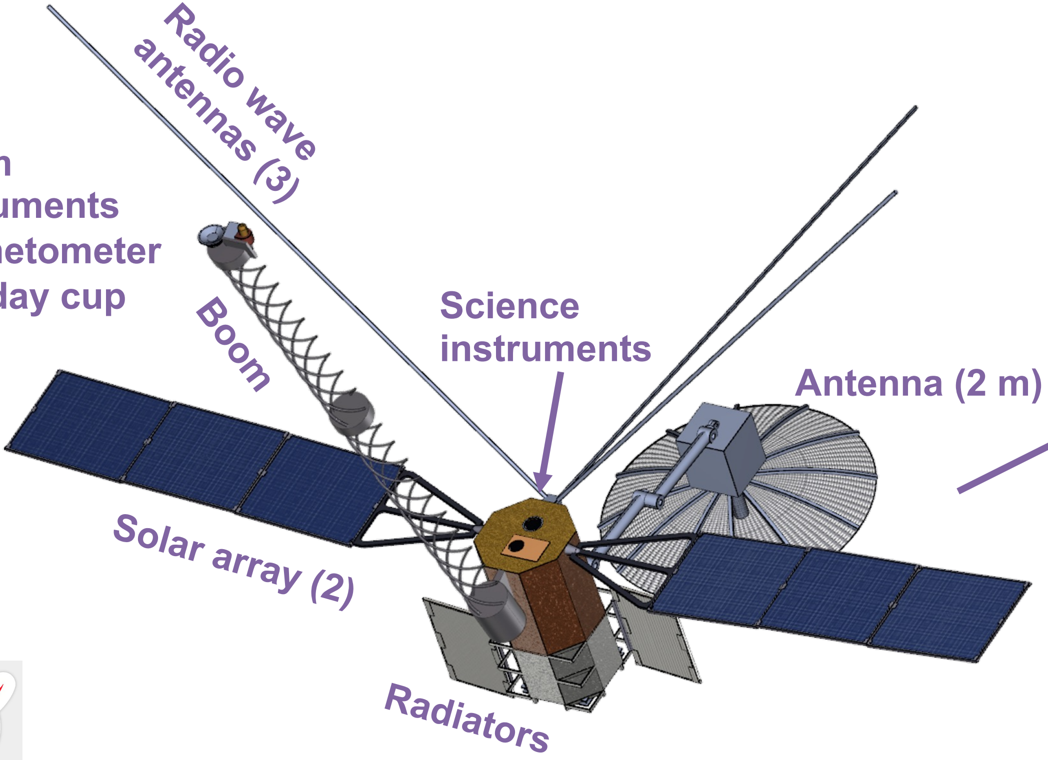
Parametric gain time:
$\tau_{gain} \approx (1/\tau_{free} - 1/\tau_{damp})^{-1}$
$\approx$ 1.1E+4 [s]

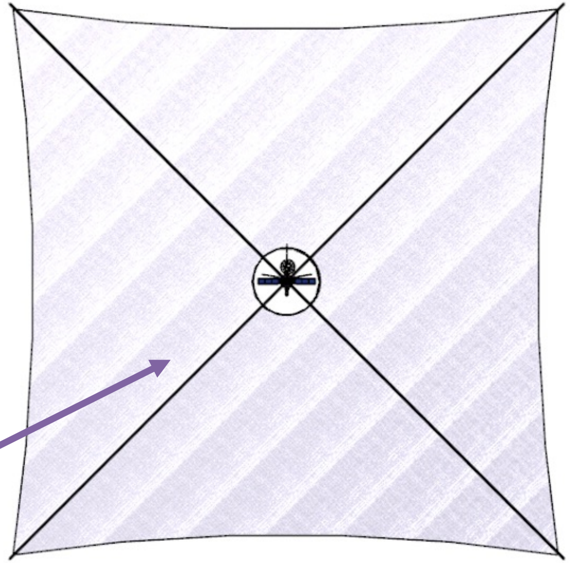
Opt. Lett 2021

Sailcraft Architecture (NASA MSFC ACO Study)

Deployed Spacecraft Bus

Boom instruments
Magnetometer
Faraday cup

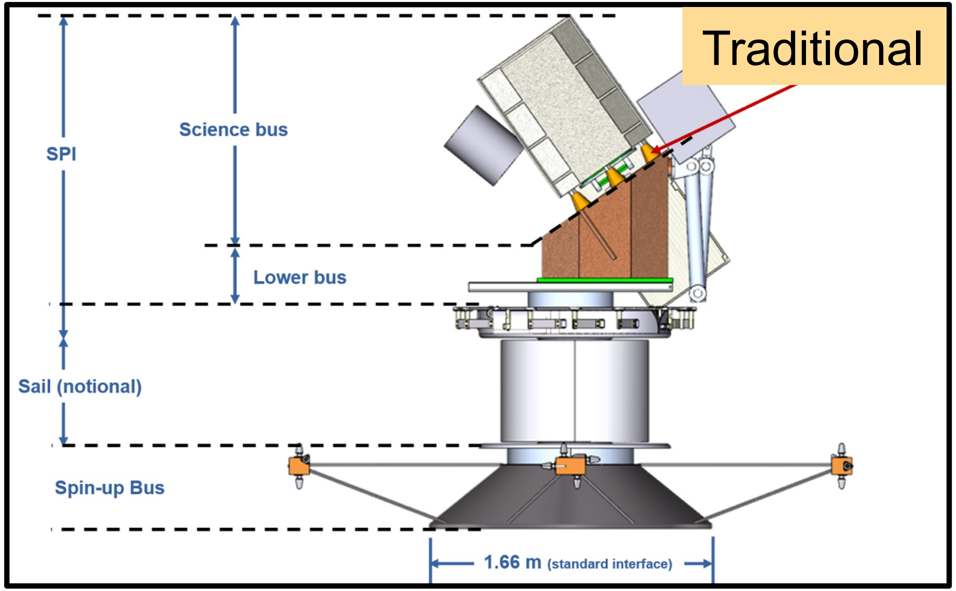


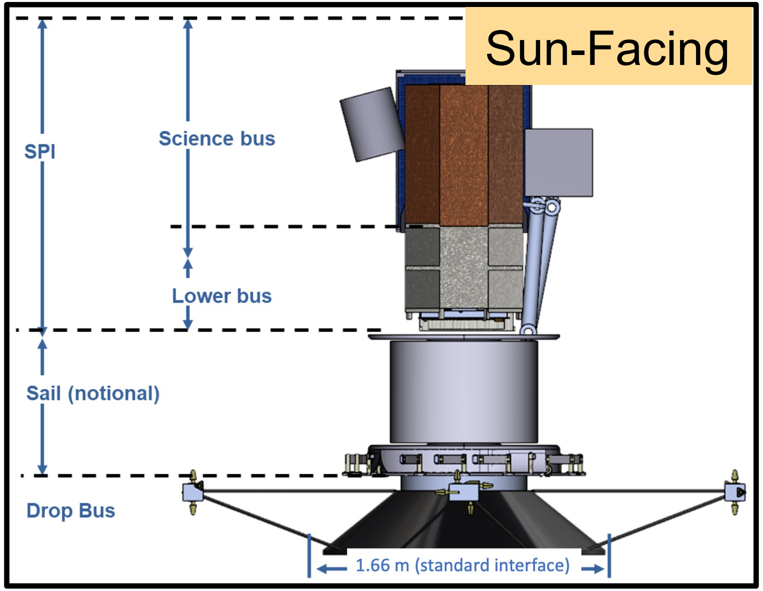


6050 m² Sail

Total Cost Est. $144M

Advantages of a Sun-Facing Sail

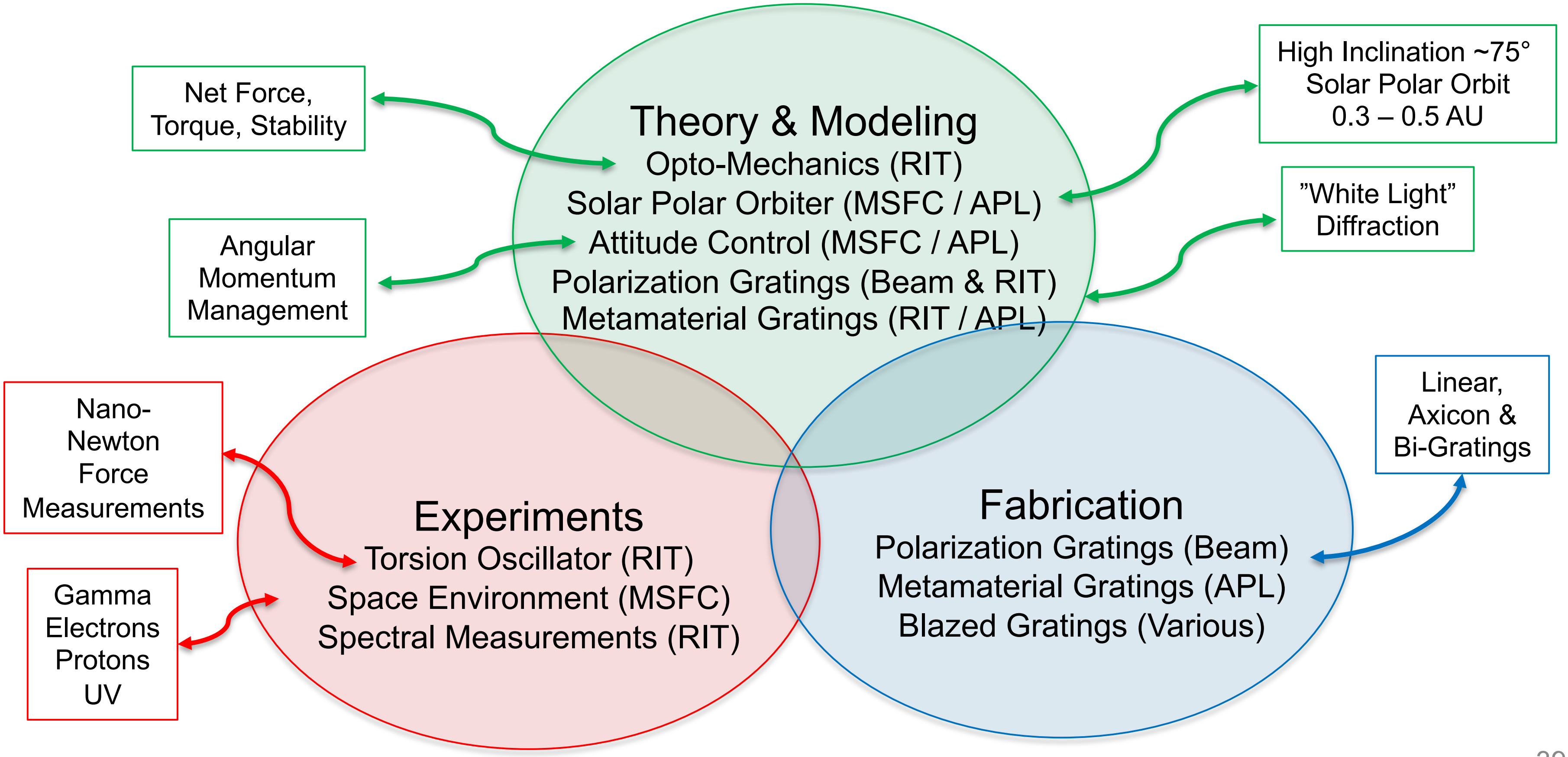




Sun-Facing Configuration Advantages:

Non-Gimbaled, Thermal Management, Moments of Inertial, Attitude Control, Non-Spinning Bus, Reduced Complexity

Raising TRL


Net Force,
Torque, Stability
Angular
Momentum
Management
Theory & Modeling
Opto-Mechanics (RIT)
Solar Polar Orbiter (MSFC / APL)
Attitude Control (MSFC / APL)
Polarization Gratings (Beam & RIT)
Metamaterial Gratings (RIT / APL)
High Inclination ~75°
Solar Polar Orbit
0.3 – 0.5 AU
"White Light"
Diffraction
Nano-
Newton
Force
Measurements
Gamma
Electrons
Protons
UV
Experiments
Torsion Oscillator (RIT)
Space Environment (MSFC)
Spectral Measurements (RIT)
Fabrication
Polarization Gratings (Beam)
Metamaterial Gratings (APL)
Blazed Gratings (Various)
Linear,
Axicon &
Bi-Gratings

Acknowledgements

Rochester Institute of Technology
  Lucy Chu

NASA-MSFC
  Ken Kobayashi
  Dan Thomas
  Paul Craven

Beam Co (Orlando)
  Nelson Tabiryan

U Utah
  Rajesh Menon
  Apratim Majumder

U Alabama
  Margaret Kim
  Anirban Swakshar

Industry
  Sydor Optics (Rochester)
  Viavi Solutions (Rochester)

Sponsors
  NASA (NIAC Phase I, II, and III)
  Breakthrough Foundation (Phase I Funding)
  National Science Foundation
  G&B Moore Foundation

Questions Please

Thank You for Attending

gaspci@rit.edu


DIFFRACTIVE SOLAR SAILING
NASA INNOVATIVE ADVANCED CONCEPTS
NASA MSFC • RIT
JHU APL

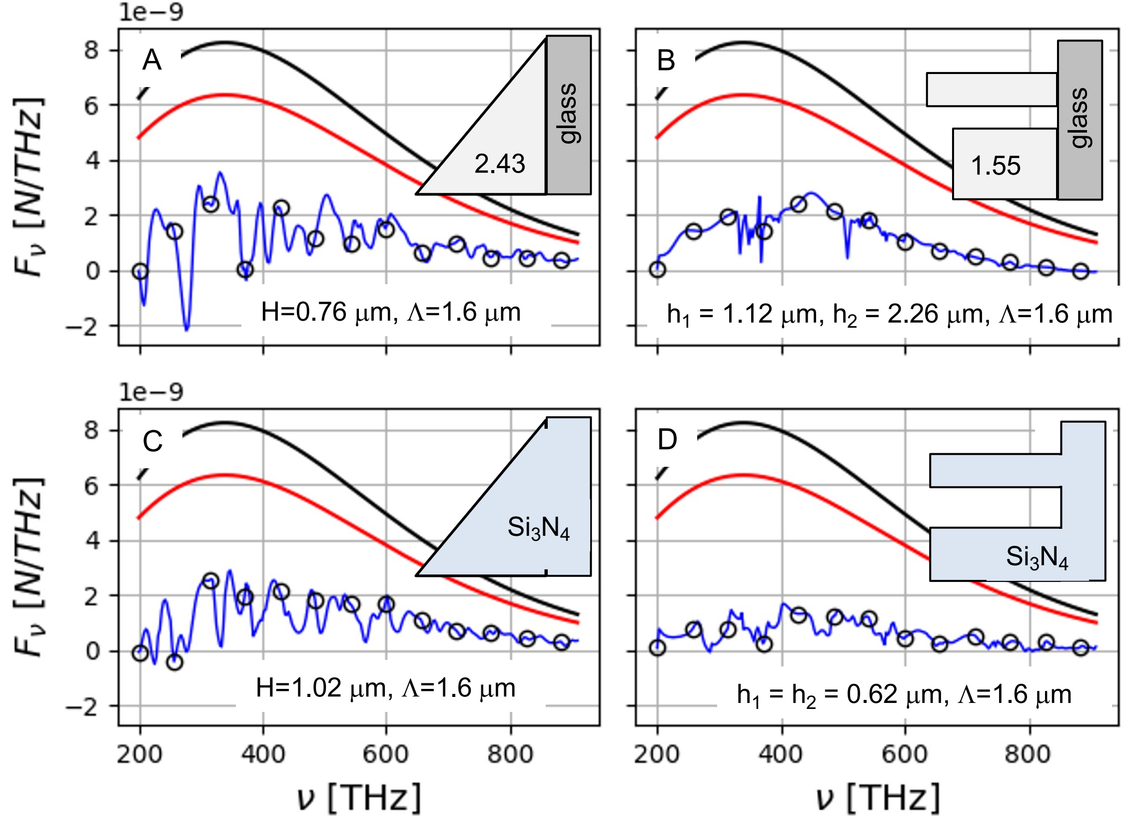
Title

Grover Swartzlander

Full FDTD Simulation Comparison

Grover Swartzlander

Transverse Force Spectra



Parameters	A	B	C	D
$h_1\,[\mu m]$	0.76	1.12	1.02	0.62
$h_2\,[\mu m]$	-	1.26	-	h_1
$w_1\,[\mu m]$	-	0.32	-	0.16
$w_2\,[\mu m]$	-	0.16	-	0.24
$x_1\,[\mu m]$	-	0.06	-	0.38
$x_2\,[\mu m]$	-	0.44	-	0.1
Prism Angle	26.87°	-	34.23°	-
n_1	2.43	1.55	Si_3N_4	Si_3N_4
n_2	1.5	1.5	Si_3N_4	Si_3N_4
$t\,[\mu m]$	0.1	0.1	0.1	0.11
Force [nN]	785	787	722	416
mass [$\times 10^{-3}$ kg]	1.07	0.73	1.93	0.84
a_x [$\mu m/s^2$]	731	1080	373	494