# Nanophotonic structures fot lightsails

## Admission to second year
## cicle XXXV

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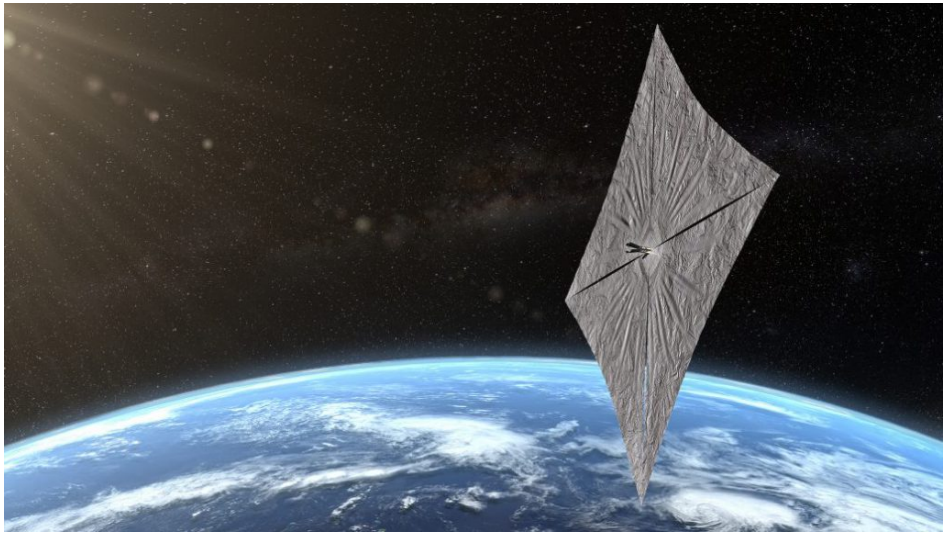
PhD Course in Space Science, Technologies and Measurements (STMS)
Sciences and Technologies for Aeronautics and Satellite Applicatons (STASA)


# What is a lightsail?



## Solar radiation propelled

- solar sailing
- made of Mylar, a reflective polyester film
- low speed

## laser propelled

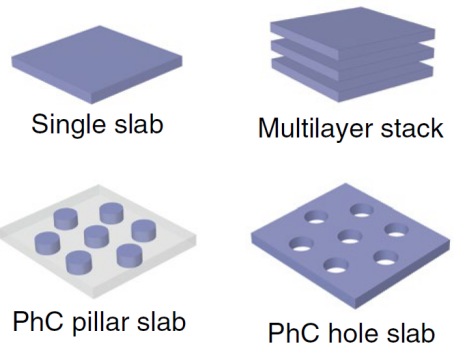
- multiband electromagnetic functionality
- relativistic speed

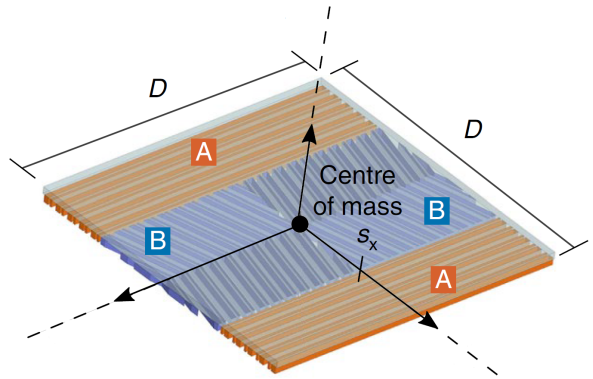
# Research Project

The final goal of this project is to design and characterize a lightsail prototype for photonic propulsion. Main objectives are:

## Main objectives

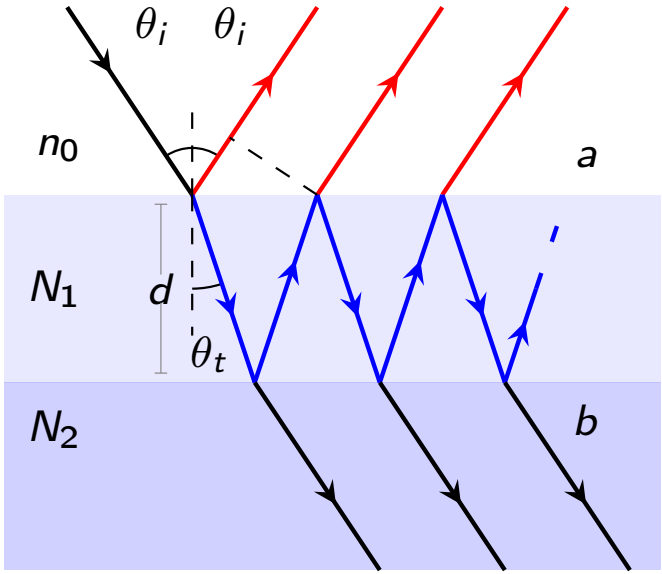
1. Material selection
2. Design and properties analysis of nanophotonic structures
3. Production and test of 1D lightsail samples
4. Publications



# 1D Multilayer

An assembly of thin films with with *quarter-wave optical thickness* (QWOT) stacked on a substrate is among the best solutions to achieve high reflectance.



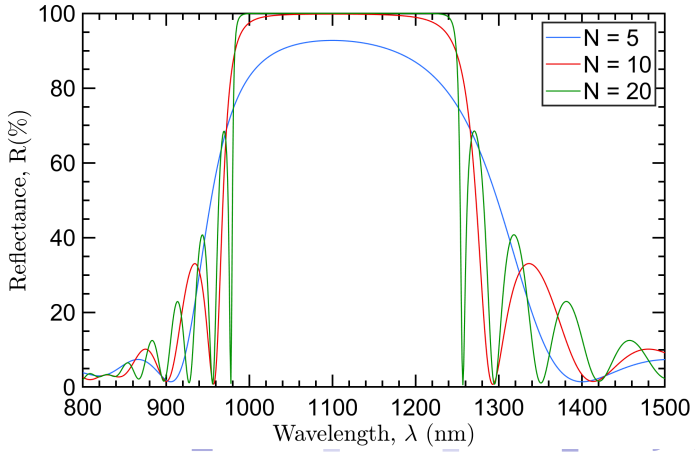

## Transfer Matrix Method

$$M = \prod_{k=1}^{N} M_k = \prod_{k=1}^{N} \begin{bmatrix} \cos\delta_k & \frac{i\sin\delta_k}{\eta_k} \\ i\eta_k \sin\delta_k & \cos\delta_k \end{bmatrix}$$

$$\begin{bmatrix} \tilde{E} \\ \tilde{H} \end{bmatrix} = M \cdot \begin{bmatrix} 1 \\ \eta_{sub} \end{bmatrix}$$

$$R = \left(\frac{\eta_0 - Y}{\eta_0 + Y}\right)\left(\frac{\eta_0 - Y}{\eta_0 + Y}\right)^*$$

In order to exploit the QWOT condition, all layers have to be distributed in a periodic repetition of alternating *high* $n_H$ and *low* $n_L$ refractive index and sized $d = \lambda/(4 \cdot n)$. The figure to the right shows an example of N unit cells $(n_H,\ n_L)$ repeated $N$ times with $n_E = 1$, $n_H = 2.1$, $n_L = 1.52$, and $n_S = 1.52$.



# Figure of Merit

Optimizing solely for reflectance, however, can result in structures with large per-area mass. A more relevant optimization is achieved through the definition of a figure of merit (FOM), for example to minimize the acceleration distance:

$$L(\beta_f) \simeq \left(\frac{c^3}{2P_0}\right) \int_0^{\beta_f} \frac{m_T}{R(\beta)} \frac{\gamma\beta}{(1-\beta)^2} d\beta$$

With few assumptions, this expression can be approximated by:

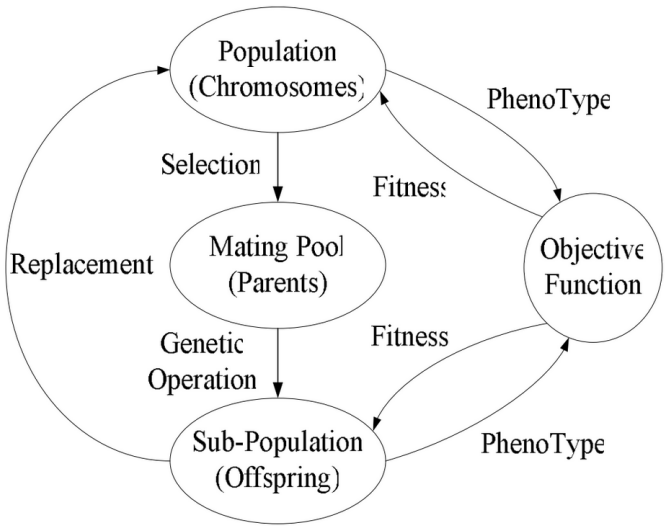
$$P_0 d_0 = 2\lambda_0 c^3 \sqrt{m_p} \int_0^{\beta_f} \frac{\rho_S}{R(\beta)} \frac{\gamma\beta}{(1-\beta)^2} d\beta = 2\lambda_0 c^3 \sqrt{m_p} \cdot W[x]$$

where $P_0$ is the laser power incident on the sail, $d_0$ is diameter of the phased array, $m_p$ is the mass of the payload and $\rho_s$ is the density of the sail.

By optimizing the layers' thicknesses we are able to minimize the function $W[x]$.

Genetic Algorithm

# Genetic Algorithm



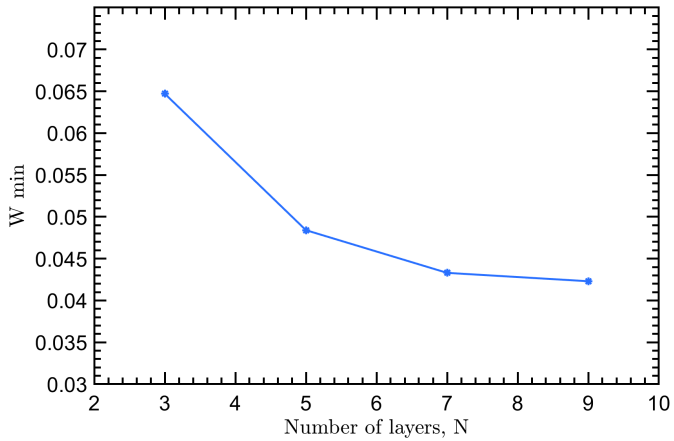

The genetic algorithm identifies the best-performing multilayer among a population of solutions that evolves while random mutations are applied to the thickness of the layers.

## Software

1. Define the initial parameters ($\lambda_0$, materials, thicknesses, repetitions number,...)
2. Create the initial population
3. Evaluate W
4. Sort the population for increasing values of W, than apply the mutation;
5. Repeat point 1 until minimum is reached

## Example

Optimization results for $N$ layers of $SiO_2$-air multilayer. In the case of $N = 3$ the layer thicknesses are 194 nm, 397 nm and 194 nm respectively to be compared with the QWOT thicknesses $d_H = 205$ nm and $d_L = 300$ nm.



# Thermal Balance

The lightsail must survive to the extreme conditions of the accelerating phase.

## Absorbed Power

- absorbed photons in the redshifted spectral range $[\lambda_0, \lambda_f]$

$\Downarrow$

- low absorption in the Near-IR

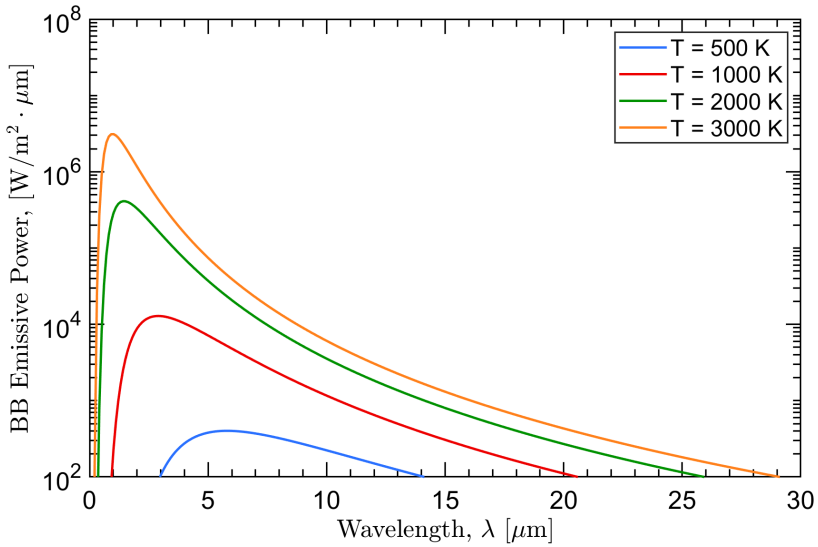
## Emitted Power

- only through radiative emission

$\Downarrow$

- high emission in the Mid-IR

$$E(T) = \int_{\lambda} \varepsilon_{\lambda}(T, \lambda) \cdot E_{b,\lambda}(T, \lambda) \mathrm{d}\lambda$$



# Future Work

- **TASK 1: Production and test**
  - Candidate 1D structures will be fabricated and tested in terms of optical performance and structural composition
- **TASK 2: Design of a 2D/3D structure**
  - Investigation of possible improvements driven by metasurfaces and 3D nanostructured materials
  - Simulation with COMSOL multiphysics
- **TASK 3: Scientific papers**
  - Publication of the knowledge acquired during the research activity