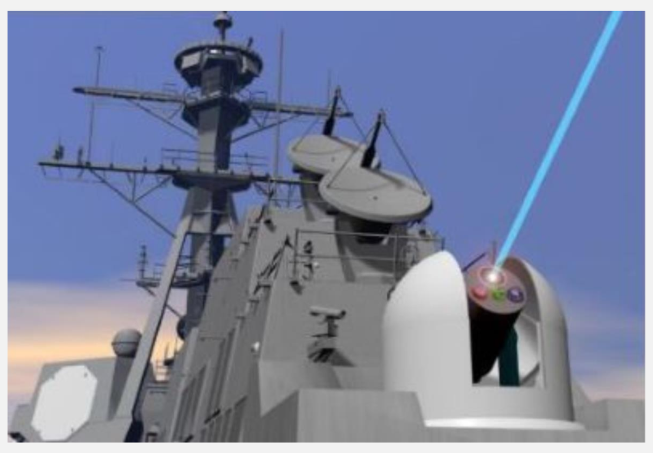
Multilayered Nanostructured Coatings for Optical Limiting of Directed Energy Beams

Penn State Applied Research Laboratory

Wolfe Research Group
The Pennsylvania State University
Sergei Stepanoff, Patrick Albert, Justin Reiss, Emily Trageser, Dr. Douglas E. Wolfe

PennState College of Earth and Mineral Sciences
Department of Materials Science and Engineering

Motivation



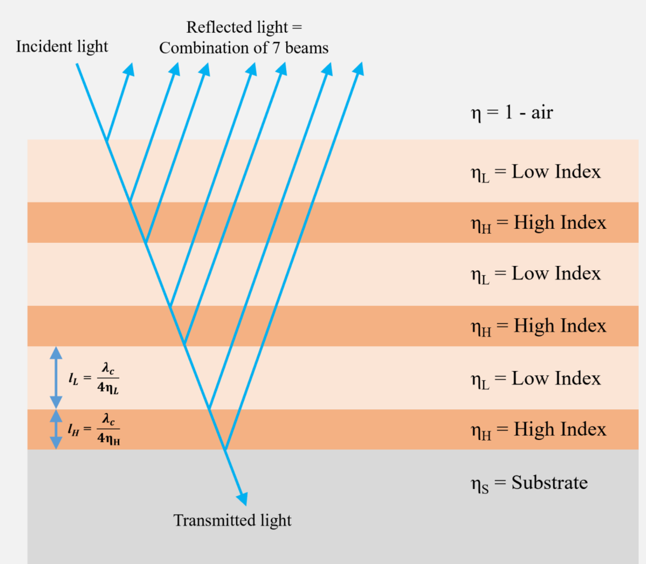
High-energy laser weapon system installation on warship
[U.S. Navy]. (2013, April 8). *Laser Weapon System (LaWS)* [Video file]. Retrieved from https://www.youtube.com/watch?v=OmoldX1wKYQ

High powered lasers are increasingly used for new warfighting capabilities. In order to maintain an asymmetric military advantage, a defensive coating needs to be developed that can reflect high intensity light while allowing for transmission at specific wavelengths.

The resulting coating provides protection while maintaining functionality of the components they coat.

Defensive laser coatings tend to require higher reflectivity than metallic coatings can offer. Instead, multilayer dielectric coatings, which take advantage of constructive interference from Fresnel reflections are used to achieve high reflectivity.

Goal - To design a process for depositing a multilayered, nanostructured dielectric coating, which allows for broadband reflection of light over a range of wavelengths.



Schematic of the fundamental geometry of a Bragg reflector that results in a stop band, a region of no transmission to the underlying component.

Deposition Methods

Electron beam physical vapor deposition (EB-PVD) and sputtering deposition techniques were used for fabricating the optical coatings. Each of these methods provide unique processing flexibility for tailoring composition, microstructure, and performance. Oxide material systems were fabricated using EB-PVD while Nitride material systems were fabricated using Sputtering techniques.

EB-PVD
Primary Advantages:
- Fast deposition rates
- Structural and morphological control of films
- Can evaporate all known materials

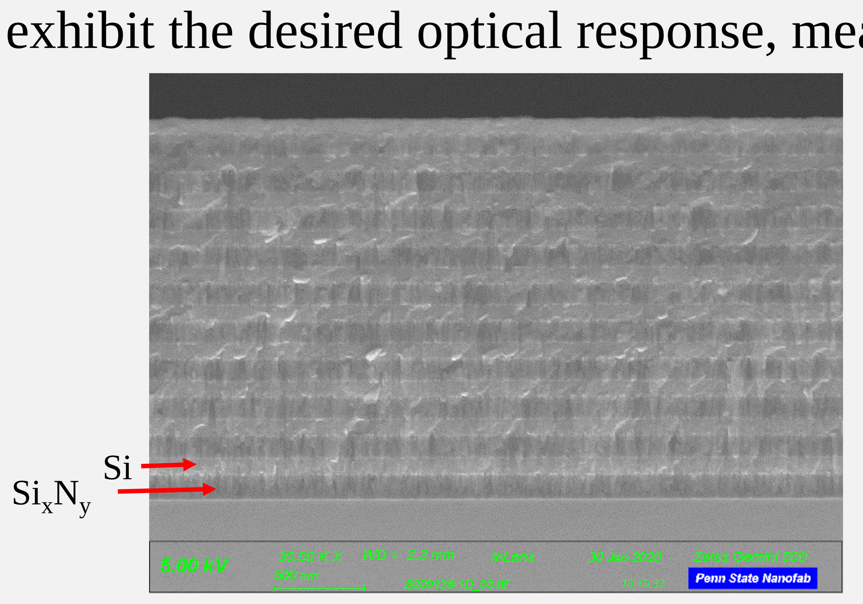
Primary Disadvantages:
- Non-conformal films
- Poor processing control

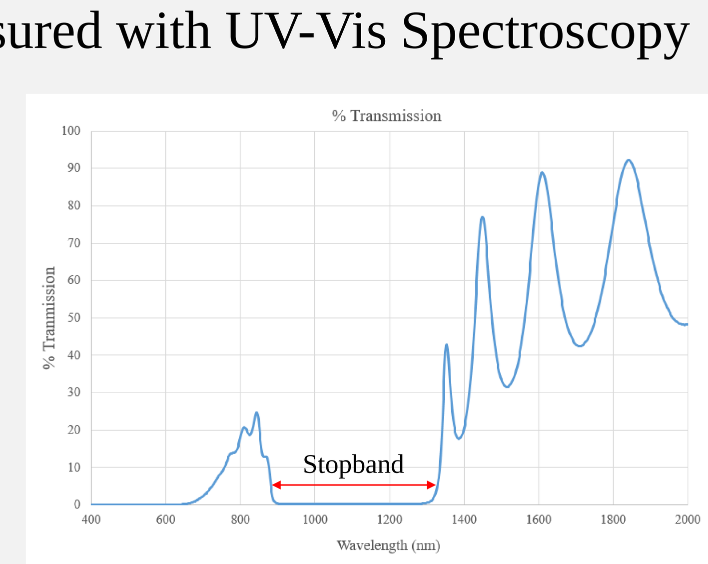
Magnetron Sputtering
Primary Advantages:
- Excellent process control
- Conformal films

Primary Disadvantages:
- Limited in types of materials able to be sputtered
- Amorphous films

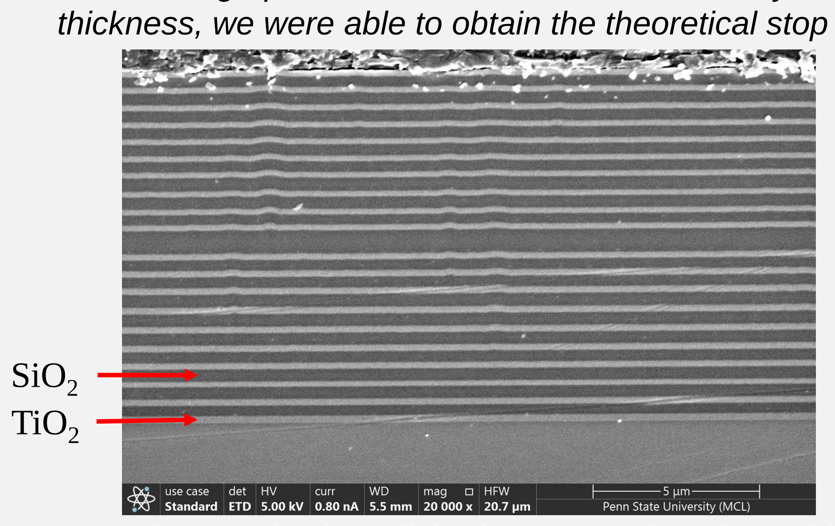
Results

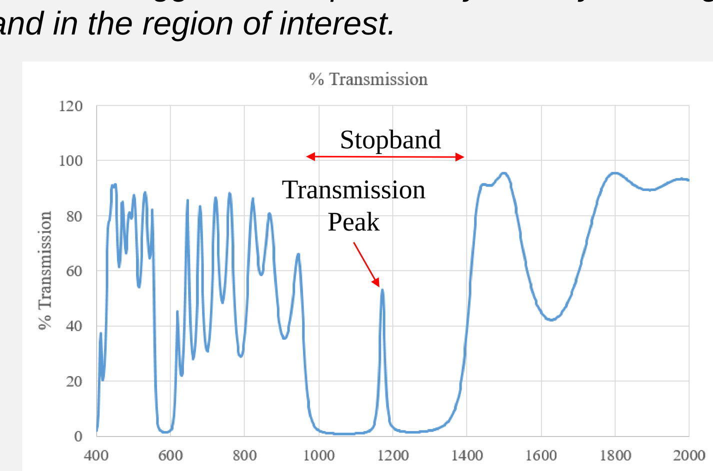
Optical Limiter coatings deposited by EB-PVD and Magnetron Sputtering exhibit the desired optical response, measured with UV-Vis Spectroscopy



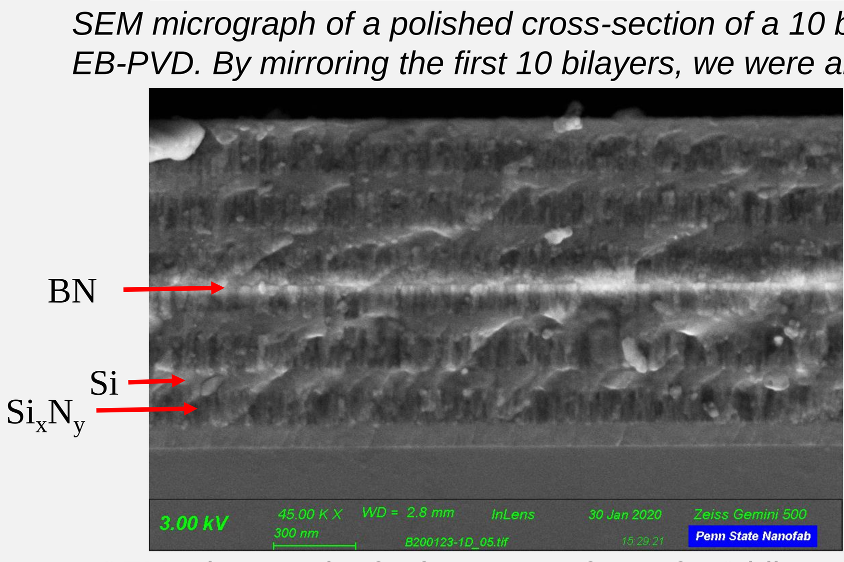


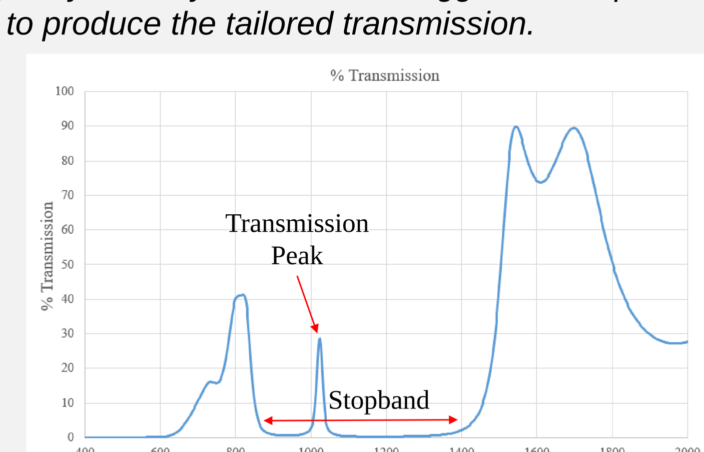
SEM micrograph of a fracture surface of a 10 bilayer reflective Bragg Mirror deposited by MS. By tailoring layer thickness, we were able to obtain the theoretical stop band in the region of interest.





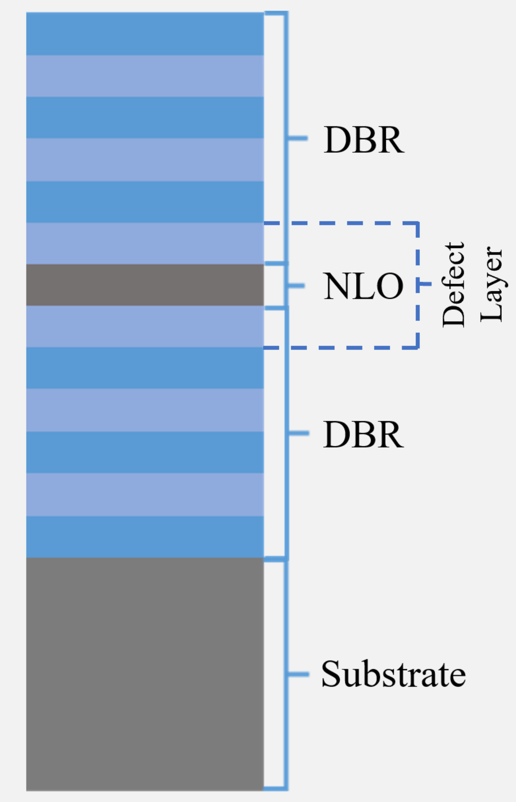
SEM micrograph of a polished cross-section of a 10 bilayer by 10 bilayer reflective Bragg Mirror deposited by EB-PVD. By mirroring the first 10 bilayers, we were able to produce the tailored transmission.





SEM micrograph of a fracture surface of a 3 bilayer by 3 bilayer reflective Bragg Mirror deposited by MS. By mirroring the first 3 bilayers with a BN defect layer in the center, we were able to produce our design of a reflective optical limiter. Further characterization will be needed to test performance properties.

Construction of the Optical Limiter Coating



Schematic of a reflective optical limiter to allow for tailored transmission in the stop band at low incident intensities and to suppress it at high intensities.

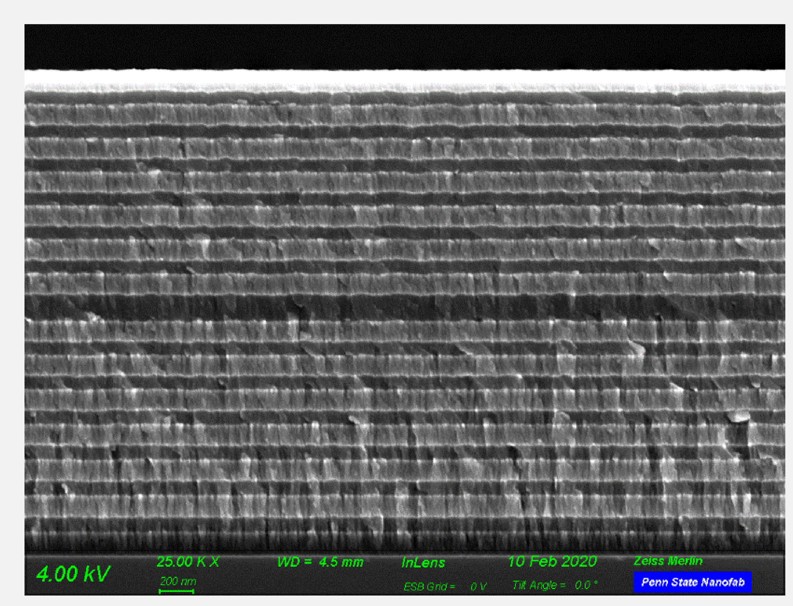
Reflective optical limiter coatings are comprised of multiple layers with alternating high (η_H) and low (η_L) refractive index materials sandwiched around a nonlinear optical material (NLO).

The constructive interference of the reflections arise from the thickness of each layer ($l_{H/L}$), which corresponds to a quarter-wavelength in the material. This $\lambda/4$ dielectric mirror, known as a distributed Bragg reflector (DBR), maximizes the reflectivity at a wavelength of interest (λ_c).

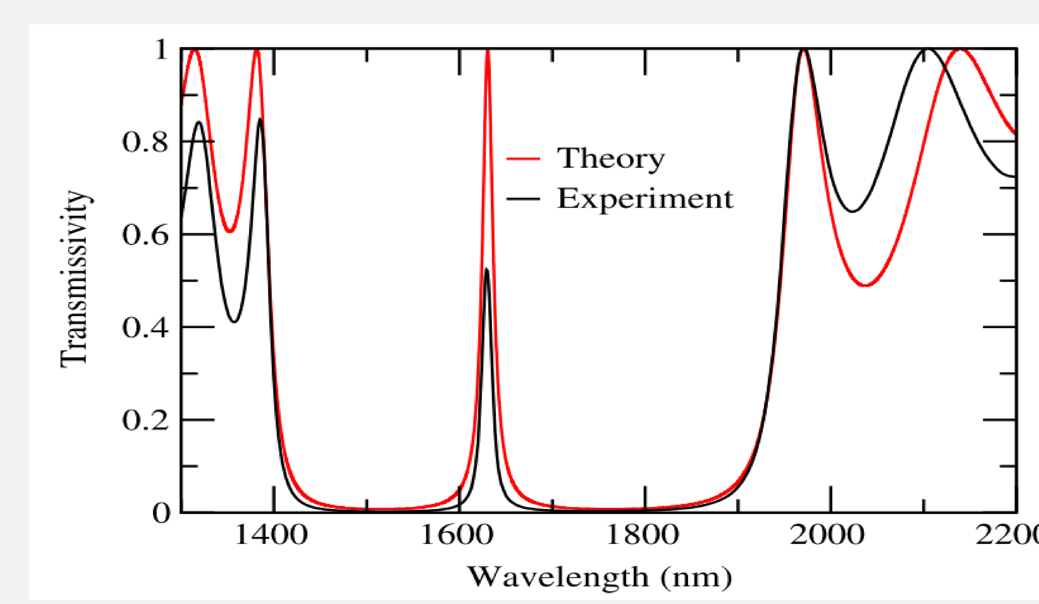
$$\lambda_c = 2(\eta_H l_H + \eta_L l_L) \qquad \Delta\lambda = \frac{4}{\pi}\sin^{-1}\left(\frac{\eta_H - \eta_L}{\eta_H + \eta_L}\right)\lambda_c$$

This structure is highly reflective over a range of wavelengths, called the stopband ($\Delta\lambda$). The center of the stopband features a small region of transmission, which arises from resonance in the defect layer and allows for communication with the coated component.

The NLO enables suppression of resonance when exposed to high intensity laser light, resulting in a stopband that is entirely reflective.



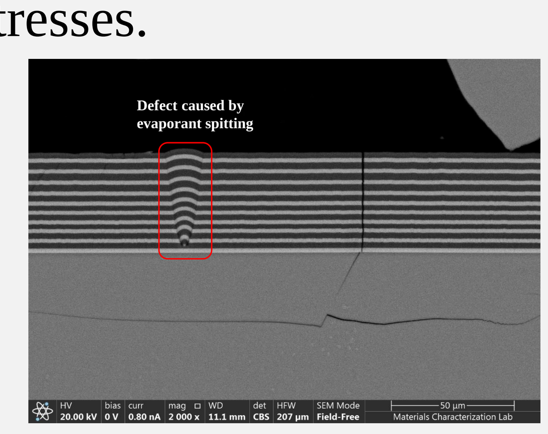
SEM micrograph of a reflective optical limiter fracture surface. The coating is alternating layers of Si and SiN with a BN layer (NLO material) in the center of the sandwich structure.



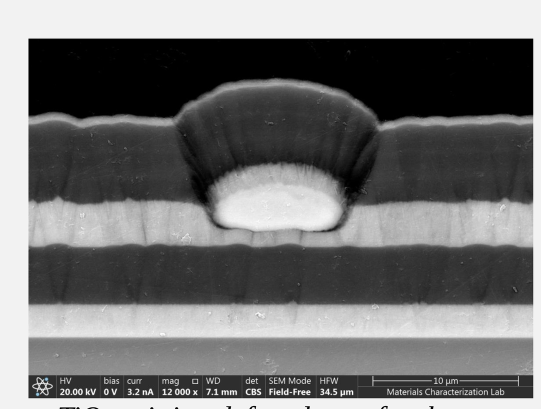
The above plot is the theoretical and experimental response of the initial trials of and Optical Limiter coating system. Vella, Jarrett H., et al. "Experimental realization of a reflective optical limiter." Physical Review Applied 5.6 (2016): 064010.

Challenges

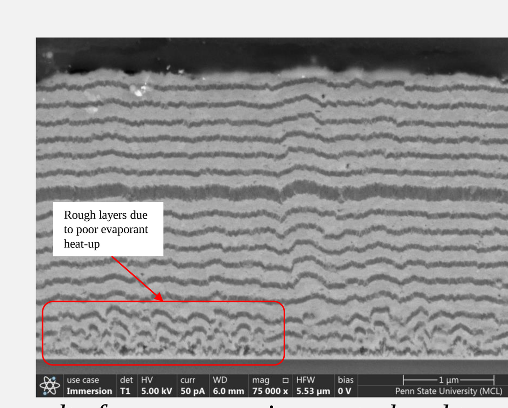
Challenges in coating fabrication are primarily process-related, including processing time to produce a full 10x10 bilayer stack, large standard deviations in layer thickness, and controlling deposition rates to minimize defects and increase coating uniformity. Additional challenges involve tailoring the number of material bilayers to maximize optical performance (near 100% reflectance) while minimizing internal stresses.



Spitting defects and cracking as a result of high residual stresses in the DBR.



Large TiO_2 spitting defect due to fast heat up of evaporant material.



A result of poor processing control and target layer thicknesses varies due to poor control of pressure.

Future Work

Fabrication – To reduce the intrinsic internal stress and increase the energy during deposition to densify and potentially crystallize each layer during deposition, an ion-beam source (IBS) for EB-PVD and high power impulse magnetron sputtering (HiPIMS) for Sputtering will be explored to improve the optical properties and durability of the coating.

Defect Layer – For the EB-PVD coatings, processing optimization will be required to incorporate the WS_2 layer in the DBR stack. For the Sputtered coating systems, the HiPIMS will allow for comparison of crystallized vs amorphous BN. Further research is required to examine the interaction of the oxide and sulphide layers.

Characterization – An I-scan/Z-scan technique would determine the non-linear absorption coefficient of the defect layer. This will quantify the coatings ability to withstand directed high energy sources.