Exploring Novel Vanadium Dioxide Tunable Optical Structures

Chico Paulics Bresler, with the supervision of **Dr Sebastian Schulz**
School of Physics and Astronomy
University of St Andrews

LAIDLAW SCHOLARS

University of St Andrews

What

This research project aimed to review the existing literature on vanadium dioxide and ENZ materials, design layered structures made of vanadium dioxide and several other materials, write a program to measure different characteristics on those structures, and then optimize their design towards some properties such as ENZ and phase shifting.

Why

Vanadium dioxide has a low temperature (around 68º C) metal insulator transition, where it also changes molecular structure. Many of its material properties change, making it an easy material to "switch on and off" for some things. The research done into vanadium dioxide applications is quite extensive however there is still space for the layered structures presented in this project. They would be very useful for optical circuits and light manipulation, ENZ materials also displaying strong non-linear behavior. In short, underexplored design space with potentially useful structures.

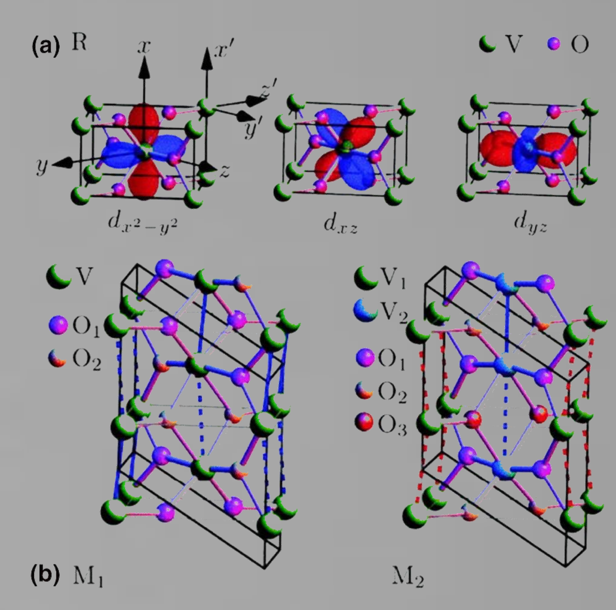


Figure 1 (above): Two different atomic structures of vanadium dioxide, taken from [1].

How

The computational modelling was done through MATLAB and making use of a Transfer Matrix Method (TMM) and a retrieval method. Instead of calculating each reflection of light, the TMM looks at how the electric wave reacts to each bilayer [2]. The structures were designed as a repetition of pairs of vanadium dioxide and another material, as well as the thickness of each layer. The code then outputted reflection, transmission and permittivity data for each of the structures. This project looked at 14 materials including metals and dielectrics, and thicknesses between 2 and 80 nanometers.

ENZ

Epsilon refers to relative permittivity, more or less how prone a dielectric is to be polarized by a magnetic field. One of the properties looked after was epsilon near zero, referring to permittivities very close to zero, which lead to a multitude of things, including minimizing losses, easier bending and trapping of light and non-linear optics [3]. ENZ has usually been achieved for a narrow wavelength range.

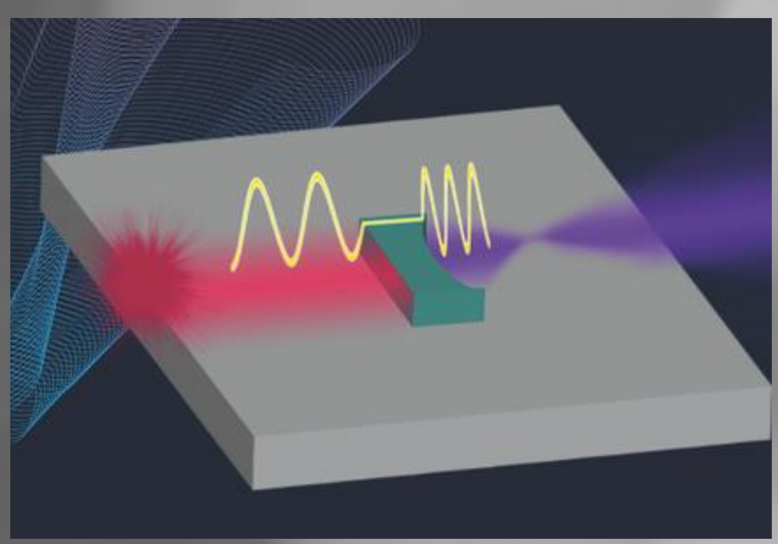


Figure 2 (to the left): Artistic representation of ENZ, taken from [4]

Phase Shifter

Materials that change the phase of light reflected, in this case by π. Light that interacts with itself phase shifted by π cancels out through destructive interference. Very useful for optical circuits as it allows for light to be used as transistors of sorts and can be used to build optical gates.

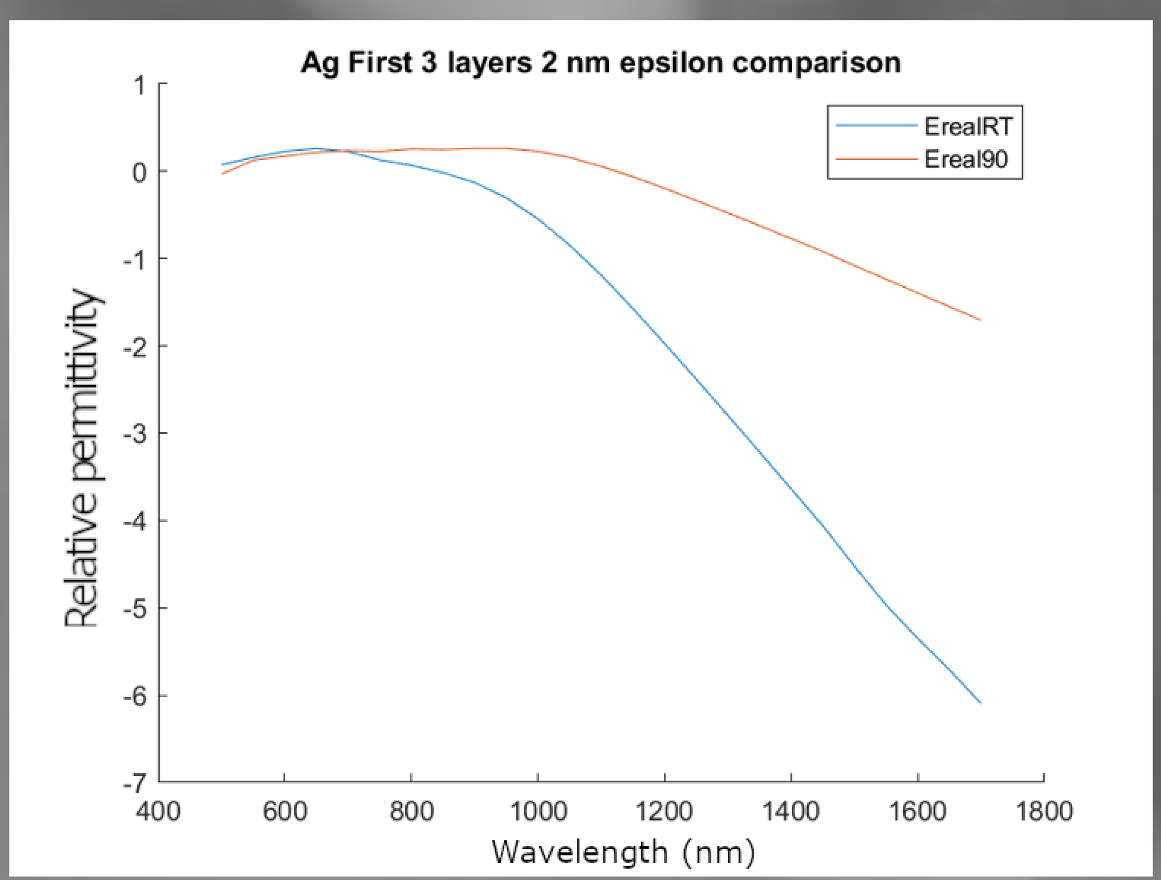
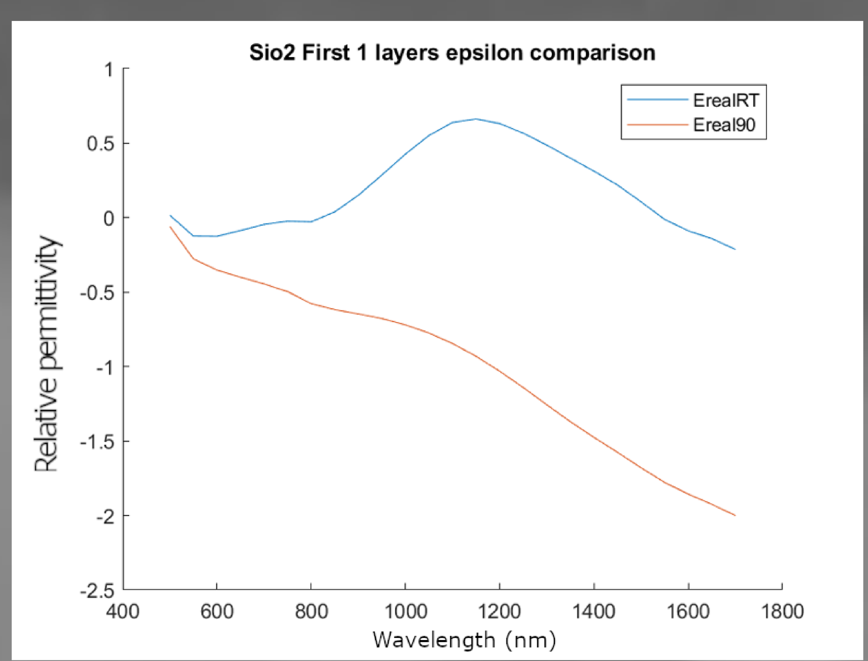


Figure 3 (above): The graph displays Silver at three repetitions of 2 nm layers, and there are about 600 nm of ENZ (orange line, 90 Celsius).
Figure 4: (to the right): Plot of Silica, at one repetition of 10 nm, and it achieves ENZ twice.
As it can be seen comparing to the blue lines (room temperature), this feature can be "turned off" by cooling the vanadium.



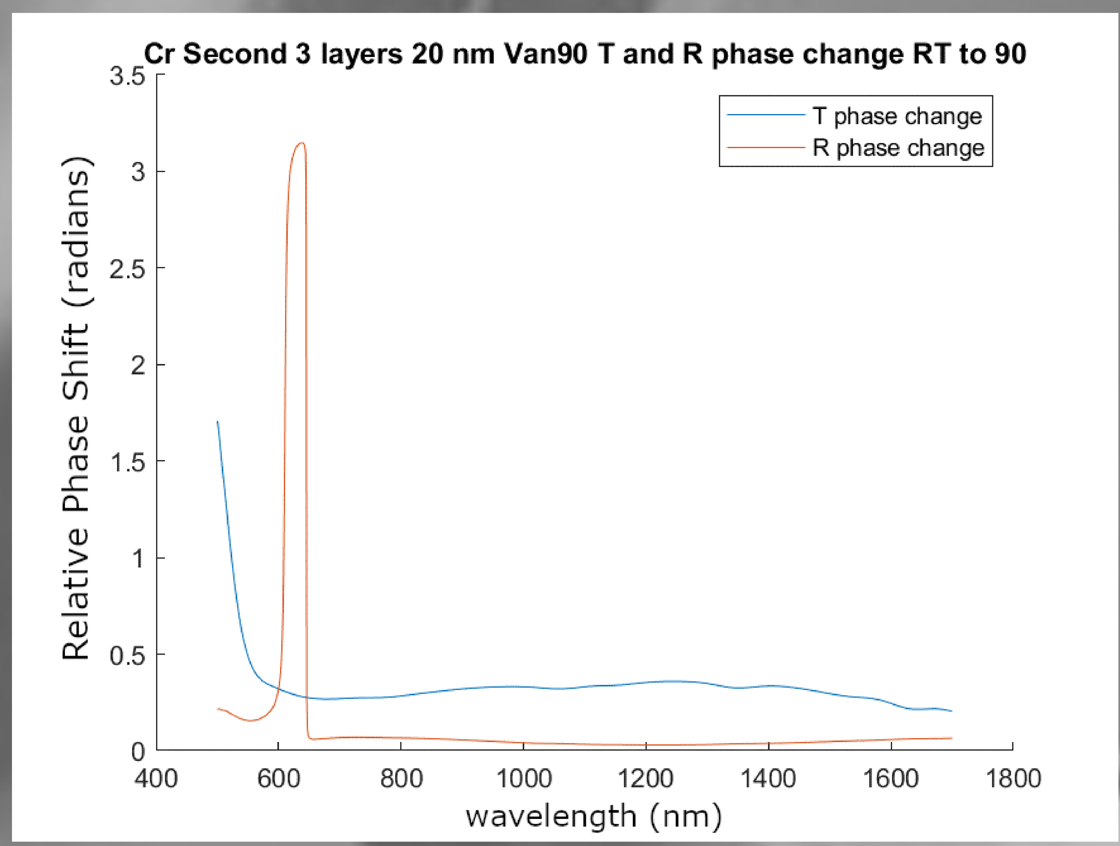


Figure 5 (above): Plot of Chrome at three repetitions. 20 nm. At around 600 the phase shift peaks to about pi, making it an adequate phase shifter. This happens here due to a resonance in the light frequency. Cannot be seen here but this feature is also dependent on the phase of the vanadium, so it can be switched off.

Summary

Vanadium Dioxide has a low temperature Metal Insulator transition, and this leads to its optical properties being tunable. This study designed and modelled many layered structures with vanadium dioxide and other compounds using MATLAB and a TMM algorithm. The initial intention was finding a tunable epsilon near zero material however the best candidates had very poor transmission. The promising results included instead a tunable phase shifter for optical circuits and a relatively simple structured wide epsilon near zero material, both of which are interesting and hard to achieve properties.

Acknowledgements

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References

[1] Liu, Kai, et al. "Recent progresses on physics and applications of vanadium dioxide."
[2] Mackay, Tom G., and Akhlesh Lakhtakia. The transfer-matrix method in electromagnetics and optics. Springer Nature, 2022.
[3] Niu, Xinxiang, et al. "Epsilon-near-zero photonics: a new platform for integrated devices." Advanced Optical Materials 6.10 (2018): 1701292.
[4] Niu, Xinxiang, et al. "Epsilon-near-zero photonics: a new platform for integrated devices." Advanced Optical Materials 6.10 (2018): 1701292.