Ultrafast Optical Beamsteering for Space Applications (UFOS)

Final Presentation | 10/31/2023

MDA

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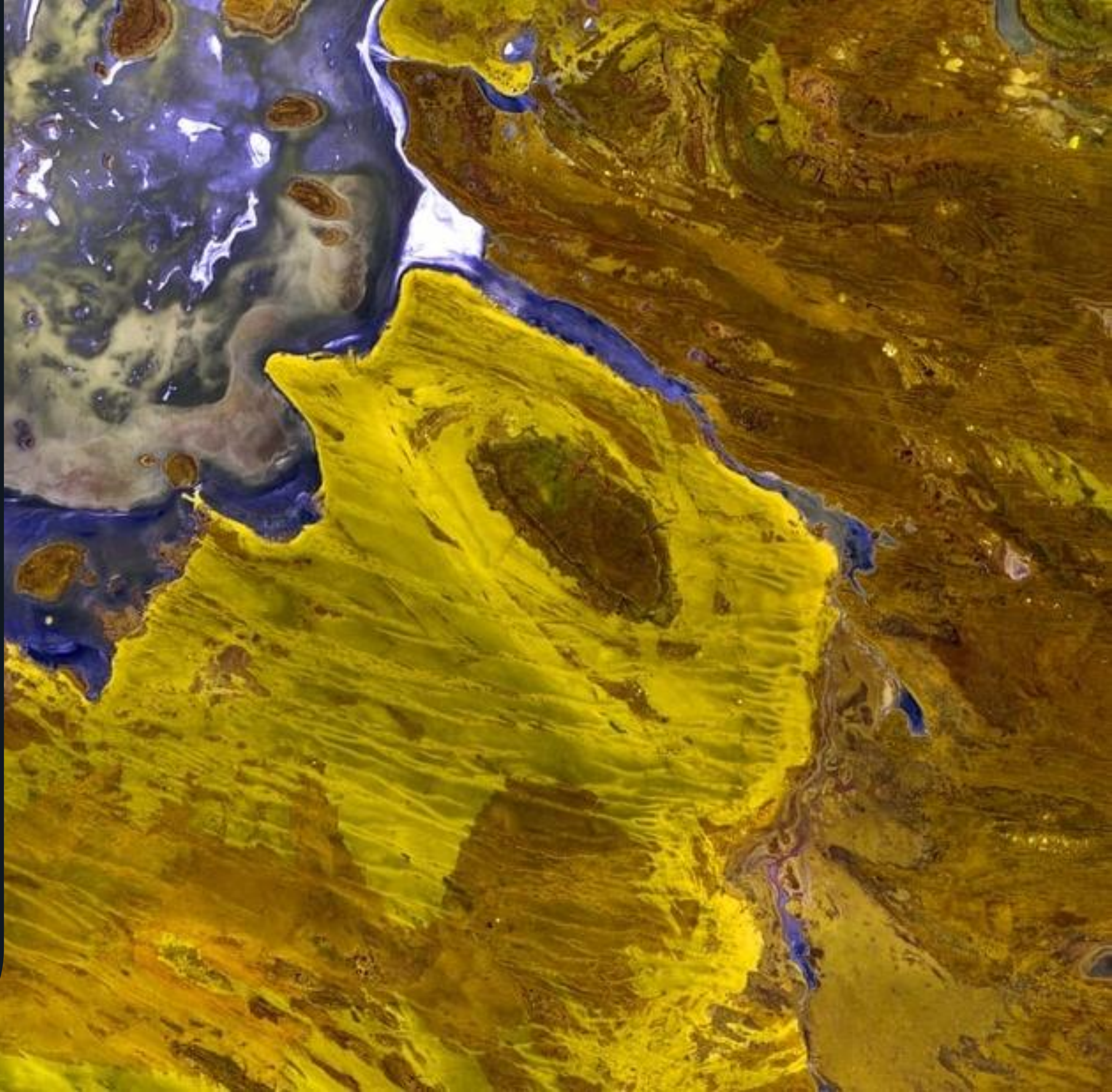
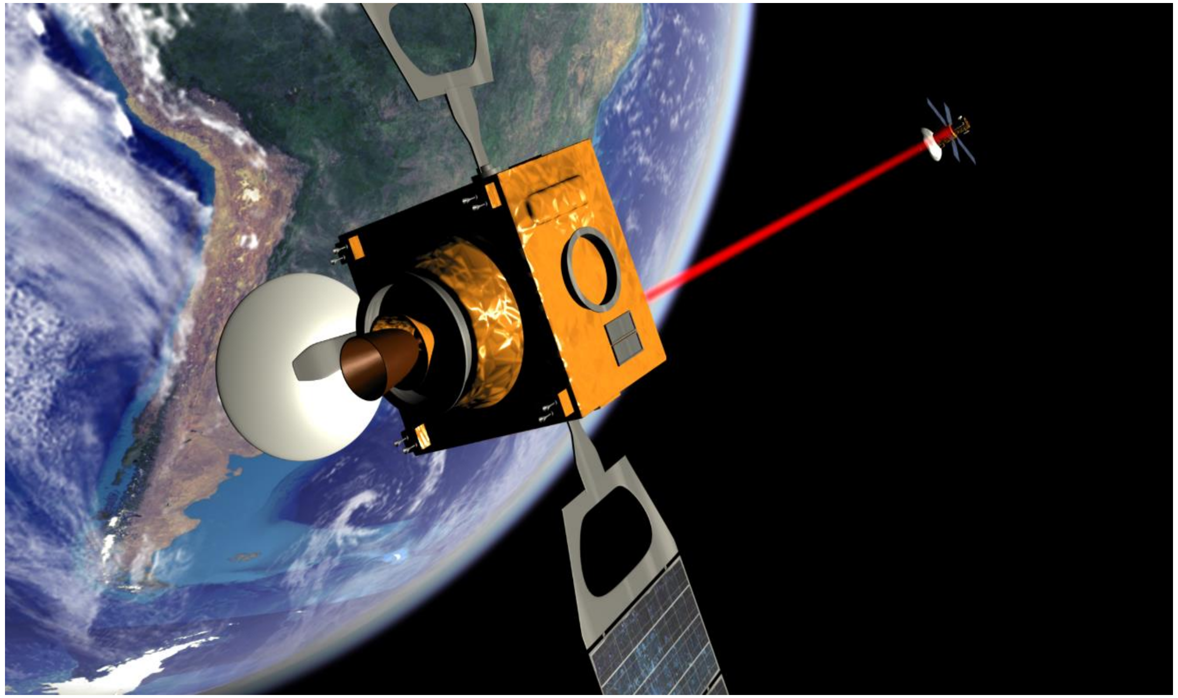
SECTION 1

UFOS Overview



UFOS Programme Abstract

Optical phase beam steering enables motionless pointing of light. The lack of mechanical moving parts not only reduces overall Mass, Volume, and Power (MVP) to a fraction of conventional solutions, but also reduces the associated risk due to friction fatigue. Moreover, actuator vibrations are completely eliminated, enabling Space interferometric experiments that were previously not possible. The applications of this technology both on Earth and in Space are only beginning to be fully understood and realised. In the context of telecommunications, the need for steerable beams has become the latest commercial frontier for market advantage allowing for communications channels to be differentiated spatially as well as time/frequency. In the context of LiDAR, leading public, military, and private organizations have shown interest in reduced MVP LiDAR for Space, automotive and airborne applications.

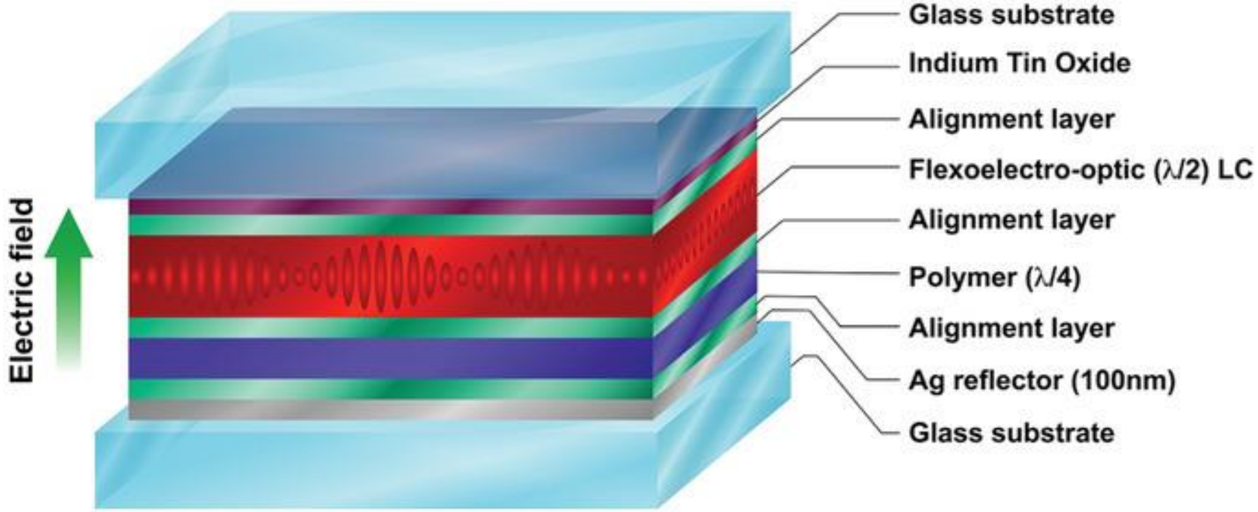


SLM Background: What is a Spatial Light Modulator

- An SLM is a photonic multipixel device of the width of a laser beam. The medium within it is a liquid crystal (LC), and applying an electric field to the LC causes a desired effect to be applied to a light beam passing through the medium. In short, an SLM is a device that can manipulate light (phase or amplitude) by applying an electric field.

- The current performance of commercial LC-SLMs is typically constrained by the switching speeds and/or phase modulation capabilities.

- Prior to the UFOS program, The University of Oxford had developed a proof of concept for a LC that can combine high switching speeds (~1kHz) with full phase modulation capabilities, enabling fast ultrafast beam-steering (UFOS).



The case for UFOS Lidar: MVP Budget

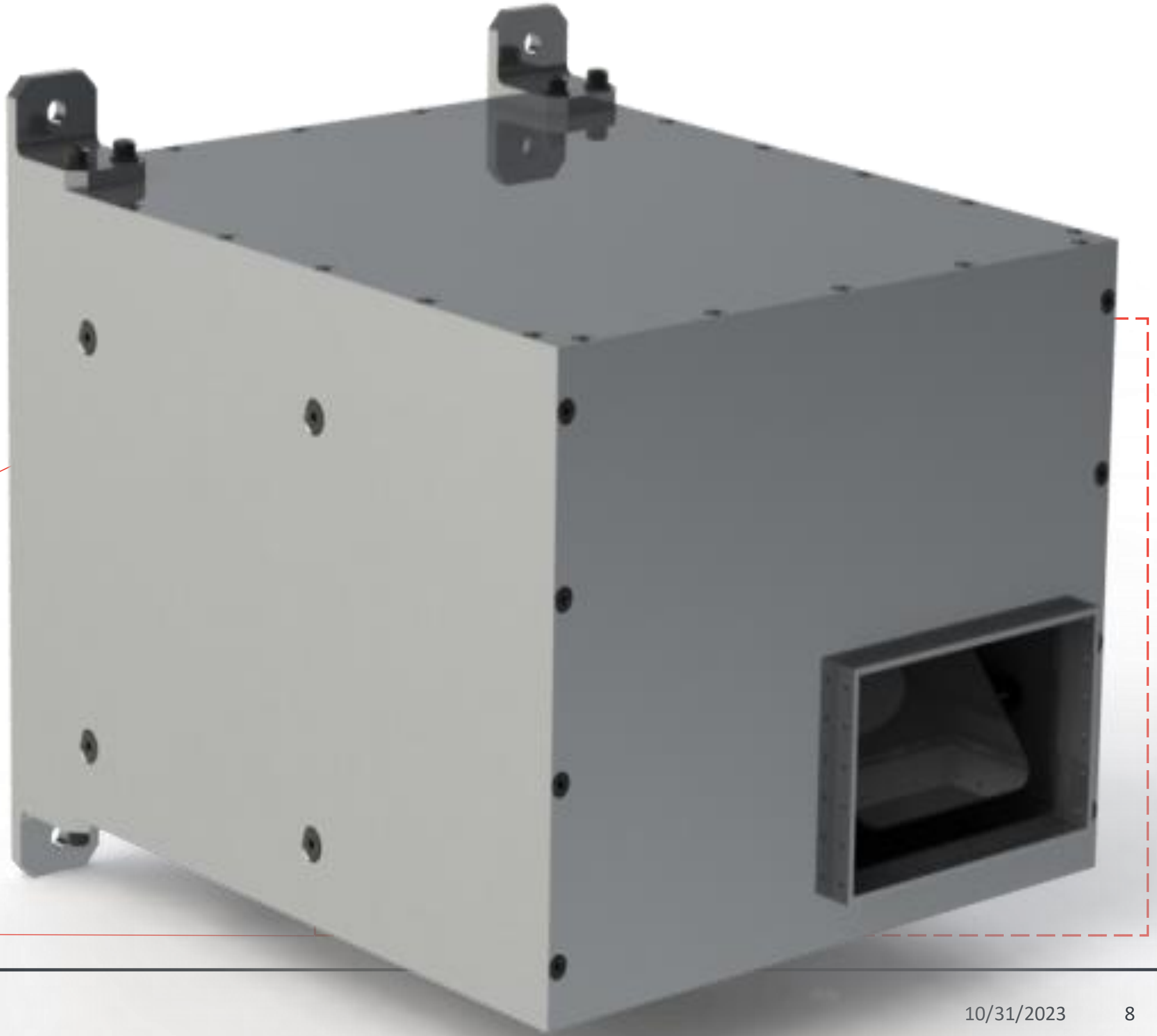
- High resolution and the ability to work without background illumination favor the use of Light Detection and Ranging (LiDAR) in a vast range of space applications.

- Government and commercial mission parameters are converging, requiring a step change from payload providers to minimize size and cost.

- Space LiDAR Mass, Volume, and Power is higher than complementary technology such as cameras and bolometers.

SLM-Based LIDAR: a Low MVP Solution

- The technology uses light interference to point, replacing the need for mechanical scanning.
- This allows an estimated 70% reduction in MVP, with applications in smaller platforms such as cubesats and small rovers



The Case for UFOS FSOC: Remote Connectivity

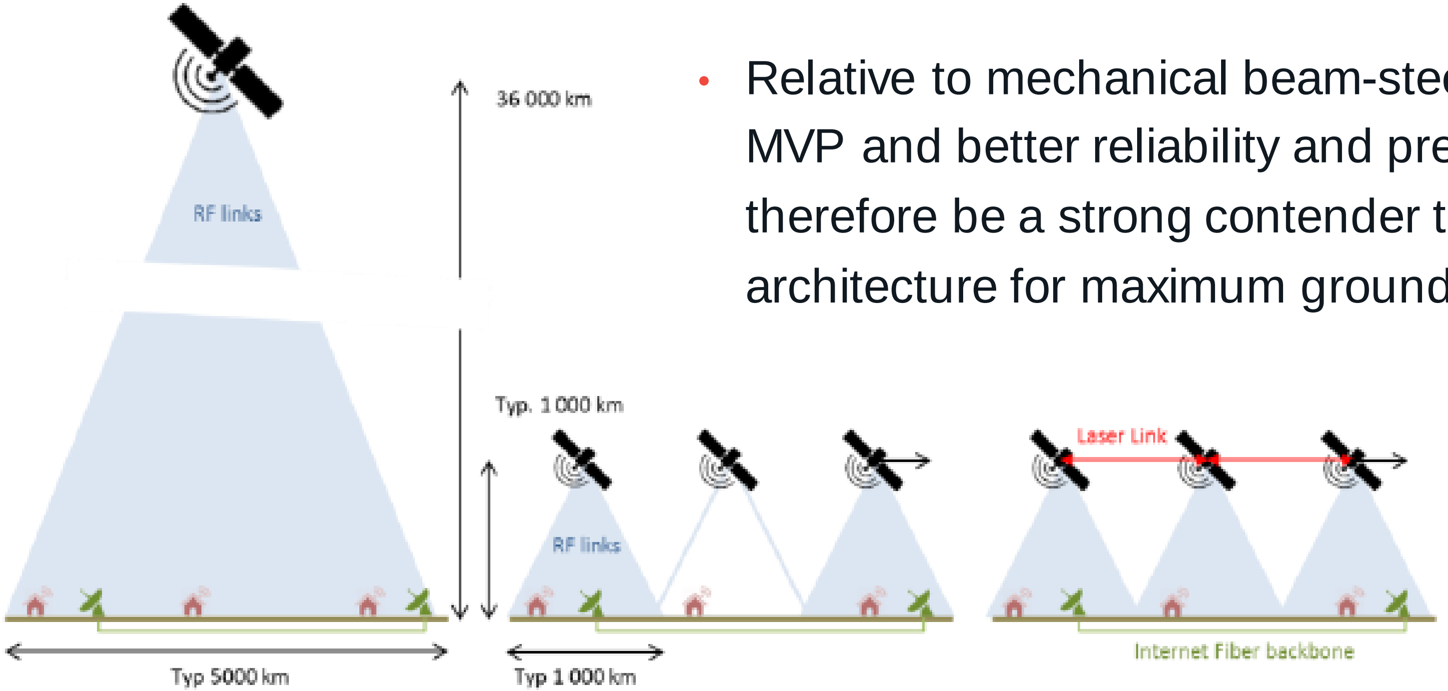
- Until now the growth of the internet traffic has been supported by fiber connectivity (trans-oceanic cables as well as Fiber to the Home “FTTH” services) combined with mobile 4G networks.

- In the last decade, several new generation of satellites, named HTS for High Throughput Satellites, have been launched to geo stationary orbit in order to provide internet access in rural areas but also for mobile connectivity (boat, aircraft, etc …). Due to the long distance (36 000 Km) they only provide connectivity with a quite long latency (0.5 s round trip). Thay also have limited capacity and therefore limited societal impact.

- More recently, new satellite architectures are starting to be launched based on large constellations (100-1000s of units) in LEO/MEO orbits (~1000 Km) of low cost (< 1 M€/unit), small (< 500 kg), High Throughput (typ. >10 Gbps) Satellites (HTS) using advanced and up to date terrestrial technologies.

The Case for UFOS FSOC: Remote Connectivity

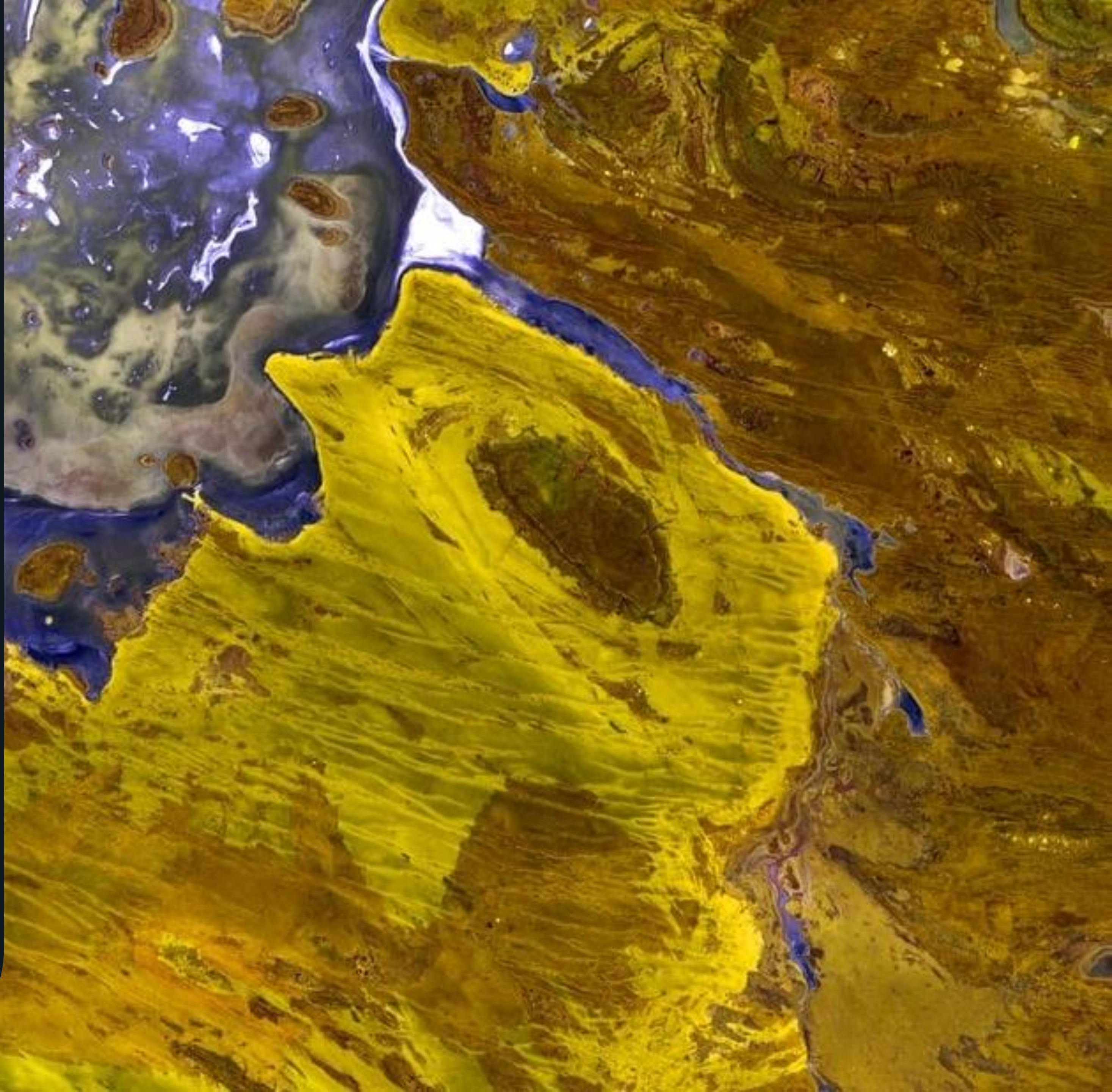
- The most significant obstacle to implementing OISL is in the aiming of the laser beam from one satellite to another, and then tracking the satellite as they move relative to each other. The target subtends an angle of approximately 20 microradians for an intersatellite distance of 100km.



- Relative to mechanical beam-steering, optical phased array enables lower MVP and better reliability and precision. UFOS-FSOC terminals would therefore be a strong contender to enable OISL and the preferred LEO architecture for maximum ground connectivity.

SECTION 2

UFOS Programme Objectives



TRL Level of LC mixture prior to UFOS Programme

- Prior to the UFOS programme, The University of Oxford had been able to demonstrate the concept of and ultrafast switching in novel liquid crystal technology.
- During previous experiments, UoO was able to demonstrate a liquid crystal switching at 1kHz using a distributed optical breadboard setup.
- In partnership with MDA UK, several performance issues were identified with this first liquid crystal mixture that would degrade its capabilities within potential Space markets.
- UoO had achieved an experimental proof of concept of the LC technology (TRL3)

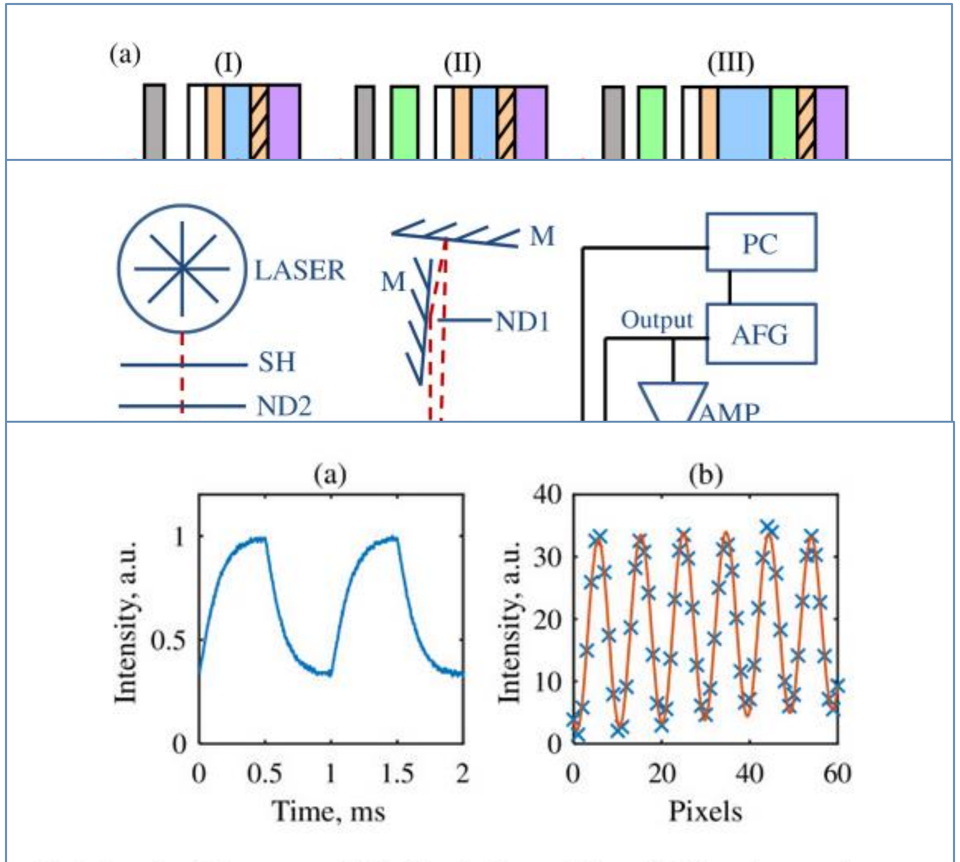


Fig. 5. Experimentally measured data: (a) optical transmission of LC through crossed polarizers (with no other components) under an applied 1 kHz square-wave drive of ± 11 V. The device optic axis at zero electric field was at an orientation of $\pi/8$ from the transmission axis of one of the polarizers. (b) (× blue) fringe data recorded from the camera, (— red) fit to fringe data.

Performance Issues Identified Prior to UFOS Programme

(i) the high temperature of the current LC formulation that would lead to a high operational temperature (>100°C);

(ii) a relatively high drive voltage of ~50V to switch the LC layer;

(iii) the potentially high loss due to a low-quality LC lying helix alignment (likely >6dB);

(iv) mechanical stability and recovery of the alignment of the LC layer.

UFOS Programme Objective: Raise LC TRL Level for Space

- **Optimising operating temperature and drive voltage (UoO):** develop a mixture with a wide operating temperature range that balances speed with large electro-optic switching at voltage amplitudes accessible with conventional CMOS backplane technology

- **Developing new stra** … **crystal technology (UoO):** investigate methods o … nt to be easily achieved in a commercial manufact …

- **Enhancing mechani** … use of polymer stabilisation to make the devices more mechanically rugged and durable

- **Space applications requirements analysis and application planning (MDA UK):** MDSRL will provide requirements analysis on Space-related applications related to mid to long-term ESA needs with particular focus on Free Space Optical Communications (FSOC) and LIDAR for situational awareness. MDA was to engage SLM manufacturing partners for follow-on activities to develop Space LIDAR and FSOC terminals.

Overall Objective: Component and/or breadboard validation in laboratory environment (TRL 4)

Work Package WP1-WP3

MDA UK (Prime): WP1-WP3

- Project management
- Requirements analysis
- Manufacturing partner investigation

WP1: monthly reporting to ESA, delivery of all contractual deliverables.

WP2: State of the art investigation of lidar and telecoms terminals. Requirements flow-down from mission/market to component (SLM) level. Guiding UoO analysis to identified target requirements

WP3: Use MDA and UoO contacts worldwide to build consortium for next phase.

Work Package in Practice: WP4-WP7

The University of Oxford (Subco):

- LC compound selection
- LC mixture design
- Device ruggedization
- Manufacturability

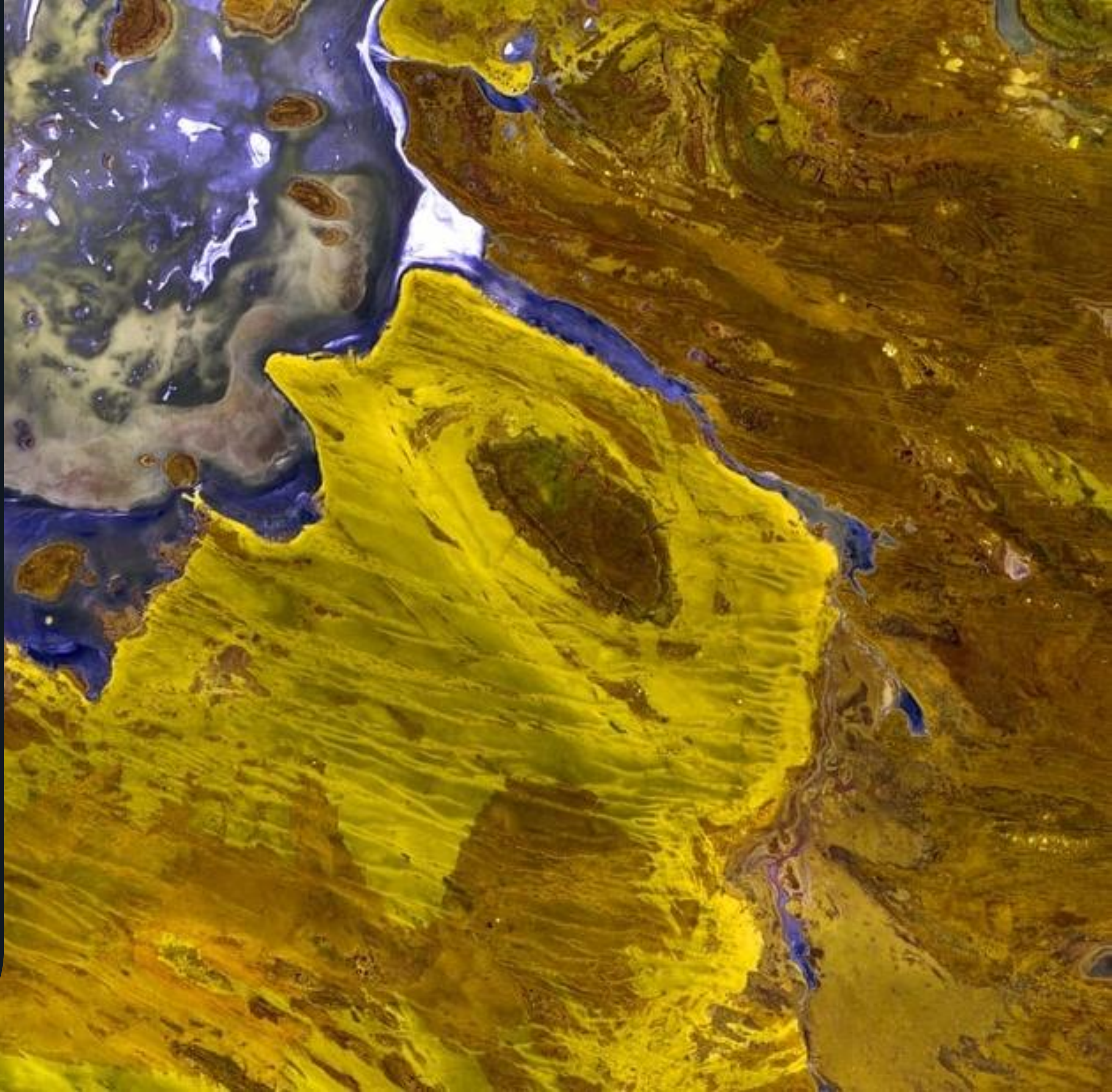
WP4 and 5: Procure materials, test in laboratory environment. Find wide temperature range, high-speed, high phase swing with low voltage. Develop a robust method for mixture selection. Use time-resolved characterization techniques.

WP6: aim is to improve UFOS resilience to external stimuli. Polymer stabilization techniques applied and tested in lab. Applied using UV light and laser writing, tested using microscopy inspection. Good alignment should result in low dispersion loss.

WP7: aim is to improve UFOS manufacturability to achieve desired performance. Laser writing techniques explored for ruggedization and alignment to allow for industrial process.

SECTION 2

UFOS Programme Results



WP4&5 Results: Optimising LC Mixture

- LC Dimers: High flexoelectro-optic effect. These components are added into the LC mixture to maximize electric field coupling to light phase rotation.
- Chiral additives: high twisting power required for chiral-nematic phase. Short pitch for fast switching speed
- Reactive mesogens: can be used to ruggedize the mixture using a photoinitiator to form polymer networks. This stabilizes the LC structure
- Liquid Crystal host: chosen for wide operating temperature range and compatibility with other compounds

Material parameters to be considered

(i) Birefringence

(ii) Dielectric anisotropy

(iii) Flexoelastic ratio

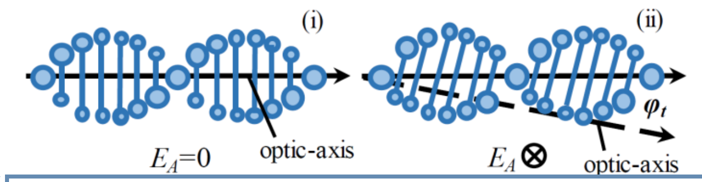
(iv) Viscoelastic ratio

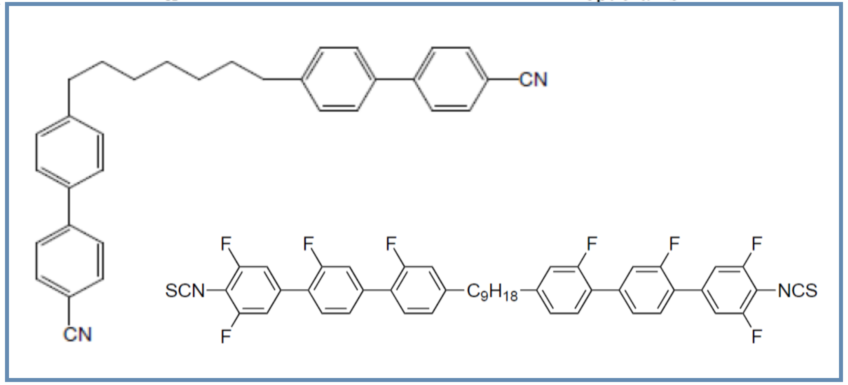
Device parameters

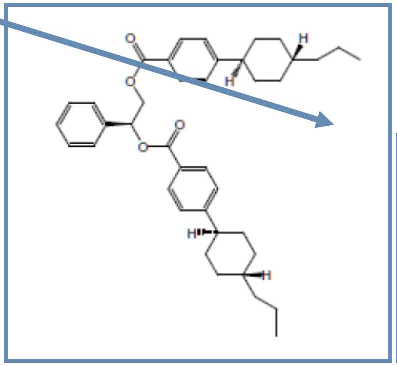
(i) Flexoelectro-optic tilt angles and switching speeds

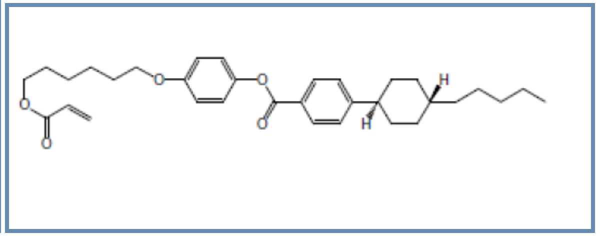
(ii) Phase modulation.

(iii) Temperature range



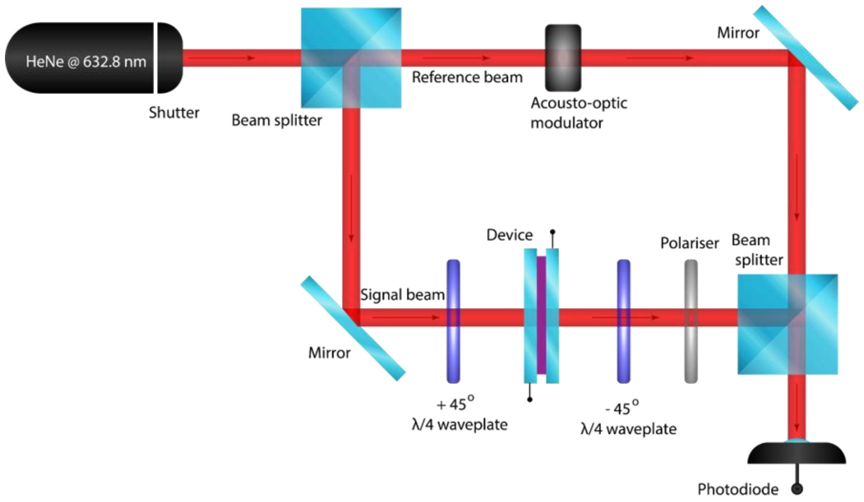


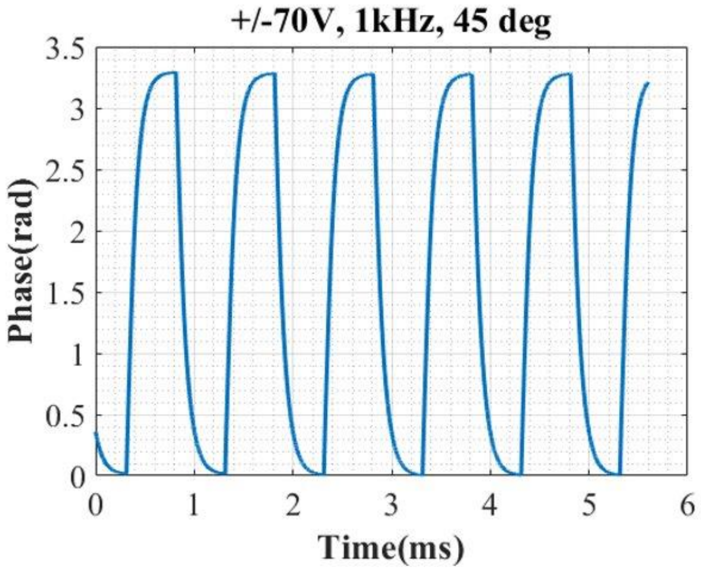




WP4&5 Results: FE-14 Mixture

- Switching above 1kHz
- Temperature range ~35 to 50 degC
- 45deg angle switching with +-70V. 45deg angle switching results in full 2pi phase modulation in SLM configuration





WP6 Results: Ruggedization

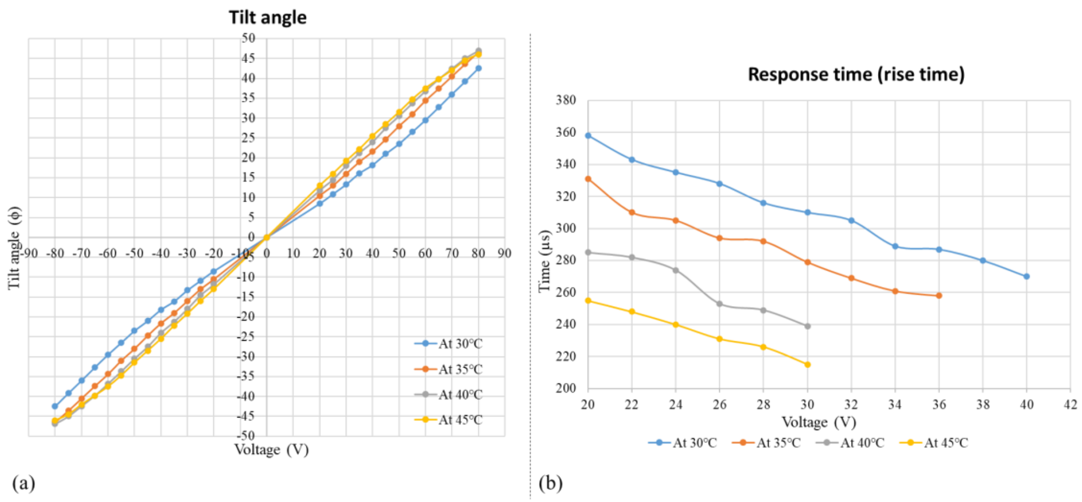
Aim: Form polymer networks to make the devices more mechanically rugged and durable. Explore whether this will also enable the LC alignment to be made permanent, avoiding the need to develop a complex driving scheme for aligning the LC each time the modulator is powered up.

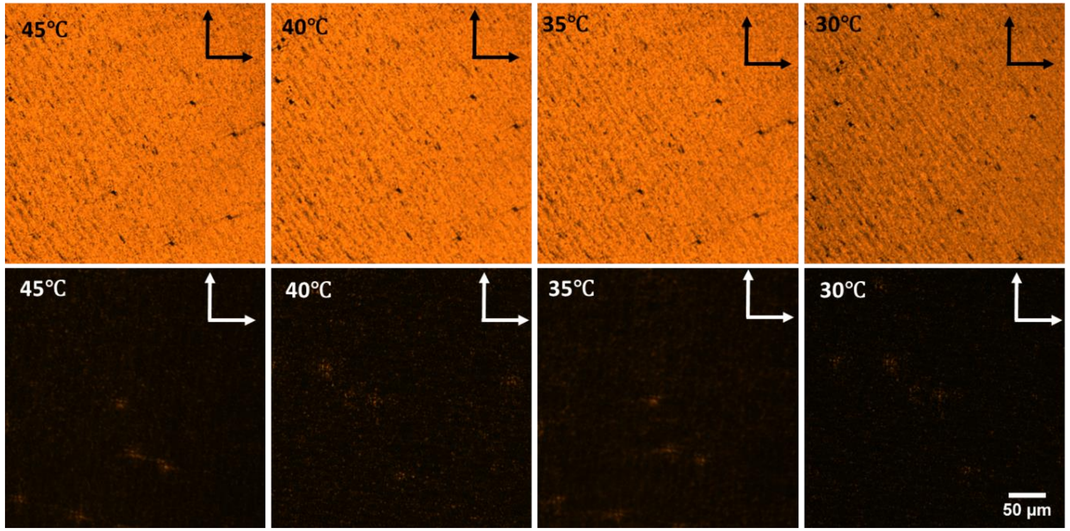
The addition of polymer stabilisation will make the device more robust for Space applications and may also provide extra benefits such as a reduced temperature dependence of the operating parameters.

WP6 Results: FE-16 Mixture

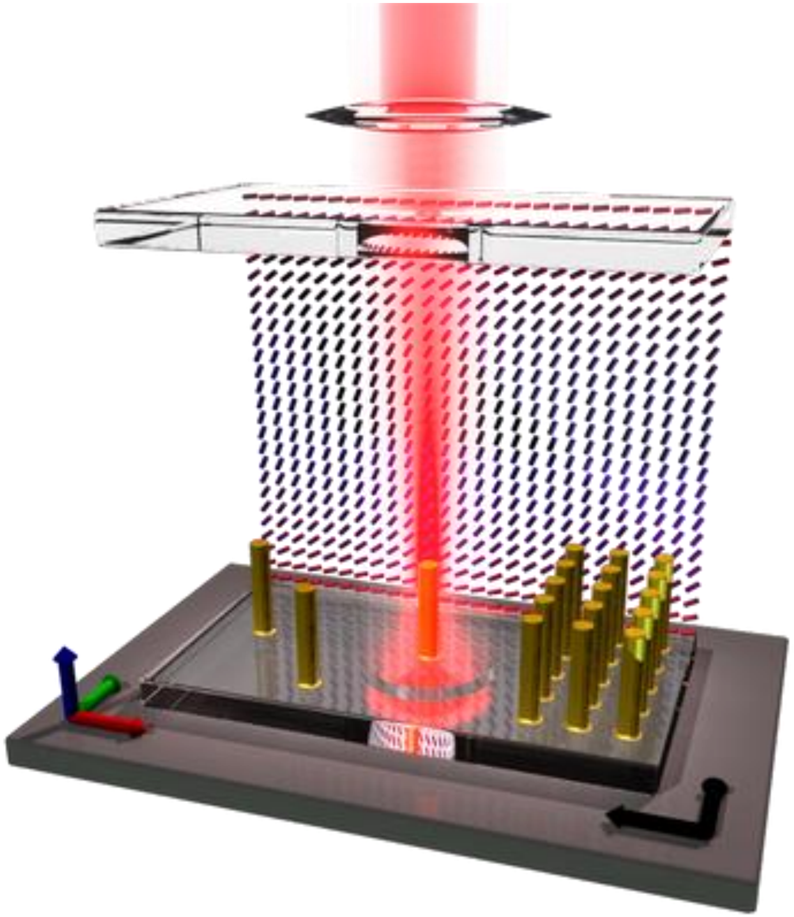
- Polymerizable mixture FE-016 based upon FE-014 from the previous WP

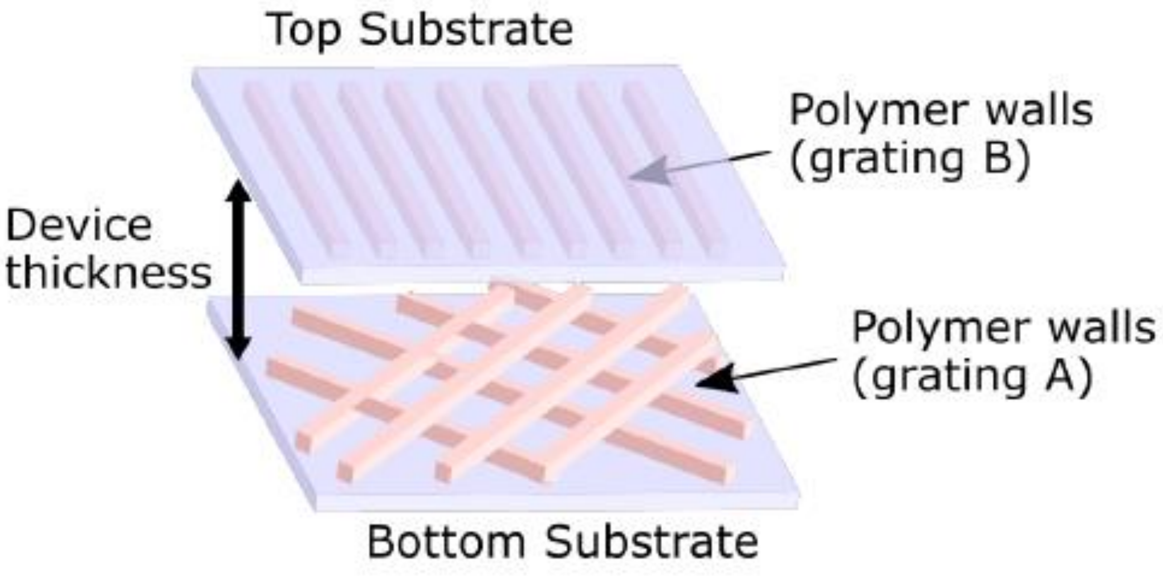
- Tilt-angle, response time, and alignment recovered after thermal cycling 8 times between 30degC and 80degC





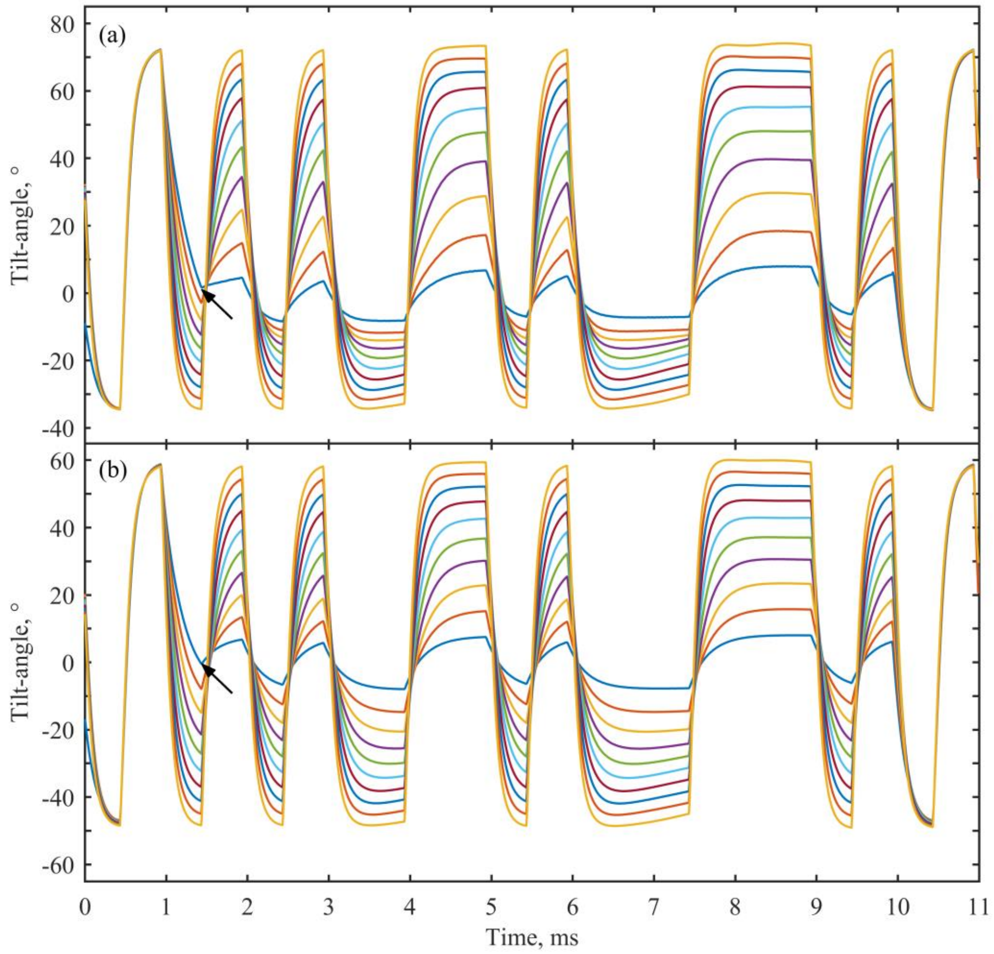
WP7 Results: Manufacturability and Alignment





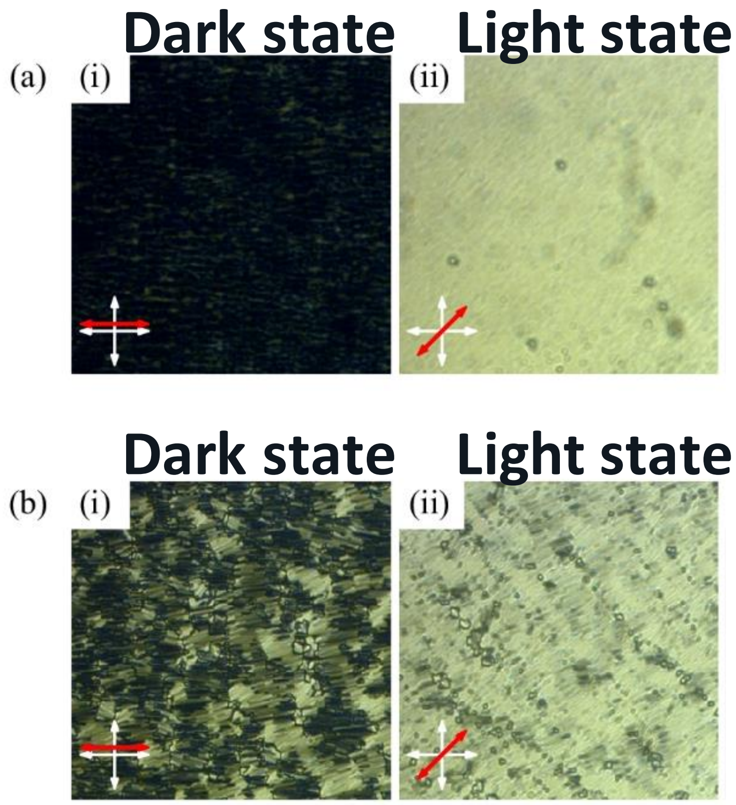
The Oxford Team have developed a laser writing technique to structure the polymer network in the liquid crystal. This will be explored as a strategy to make the devices more mechanically rugged under (WP6) and to improve the alignment layer quality and reduce losses (WP7).

WP7 Results: Manufacturability and Alignment



Developed a measurement technique that was agnostic to the alignment quality.

Polarisation Optical Microscope Images



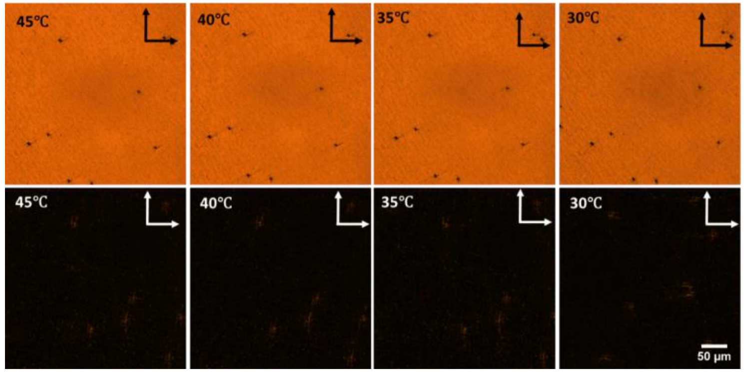
Example of a good alignment (low loss)

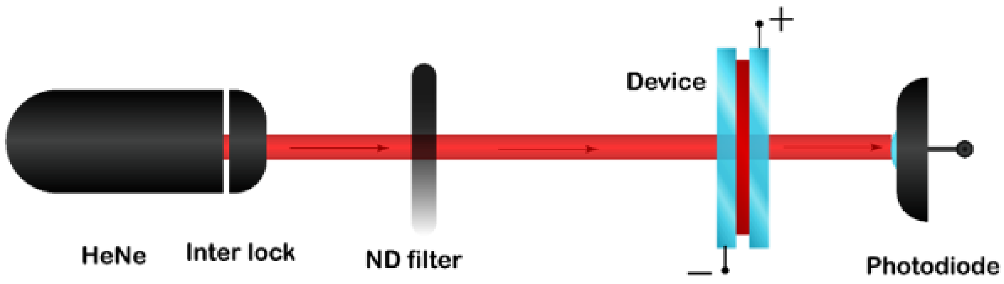
Example of a poor alignment (low loss)

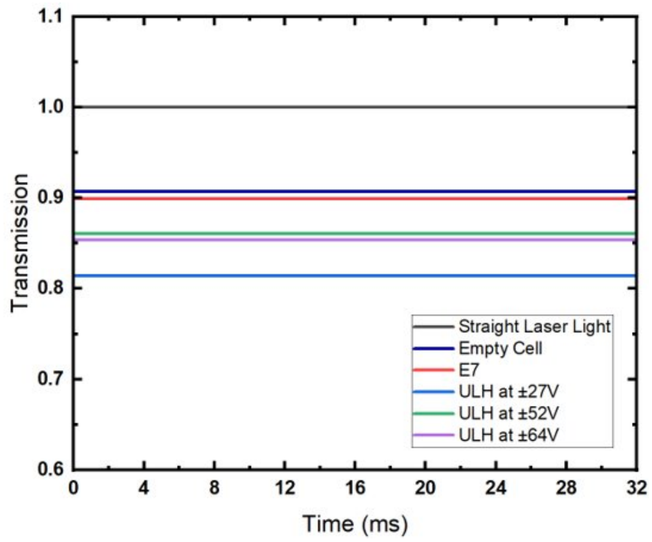
Optics Express **27**(11), 15184-15193 (2019)

WP7 Results: further testing of FE-016

- FE-016 mixture was found to be stable when exposed to UV light for a period of 1.5 hours.
- FE-014 showed that it was stable when exposed to a 2W laser for a prolonged period.
- Transmission loss <15-20%, 8% due to Fresnel reflections.







WP1-3 Results: LIDAR Requirements Summary

Navigation science and exploration: planned lunar activities include NASA CLPS and ARTEMIS, as well as ESA activities. Together, they have committed large sums that must be spent. The lunar market is not included above but it could be assumed Altimetry and Landing markets will be important, as well as rdv and docking and rover operations.

Rendezvous and Docking / Clean-Space: this can become a very interesting commercial market well beyond the estimates in the previous slide. This application includes satellite servicing and de-orbiting for debris removal. Planned LEO constellations number in the 1000s of satellites and some have started operating in the last few years. Depending on legal and insurance requirements, de-orbiting will be a much larger market

For LIDAR, based on the above and other factors known to MDA, the main target applications should be:

- Landing: to access lunar landing market
- Rendezvous and docking: for normal lunar operations, as well as servicing and de-orbiting

High speed
High FOV
Medium range
Medium MVP

Another application of interest less well known is:

- Rover applications: although less clear, some of the lunar committed funding would be for lunar surface operations

Low speed
High FOV
Low range
Low MVP

WP 1-3 Results: High Priority Requirements

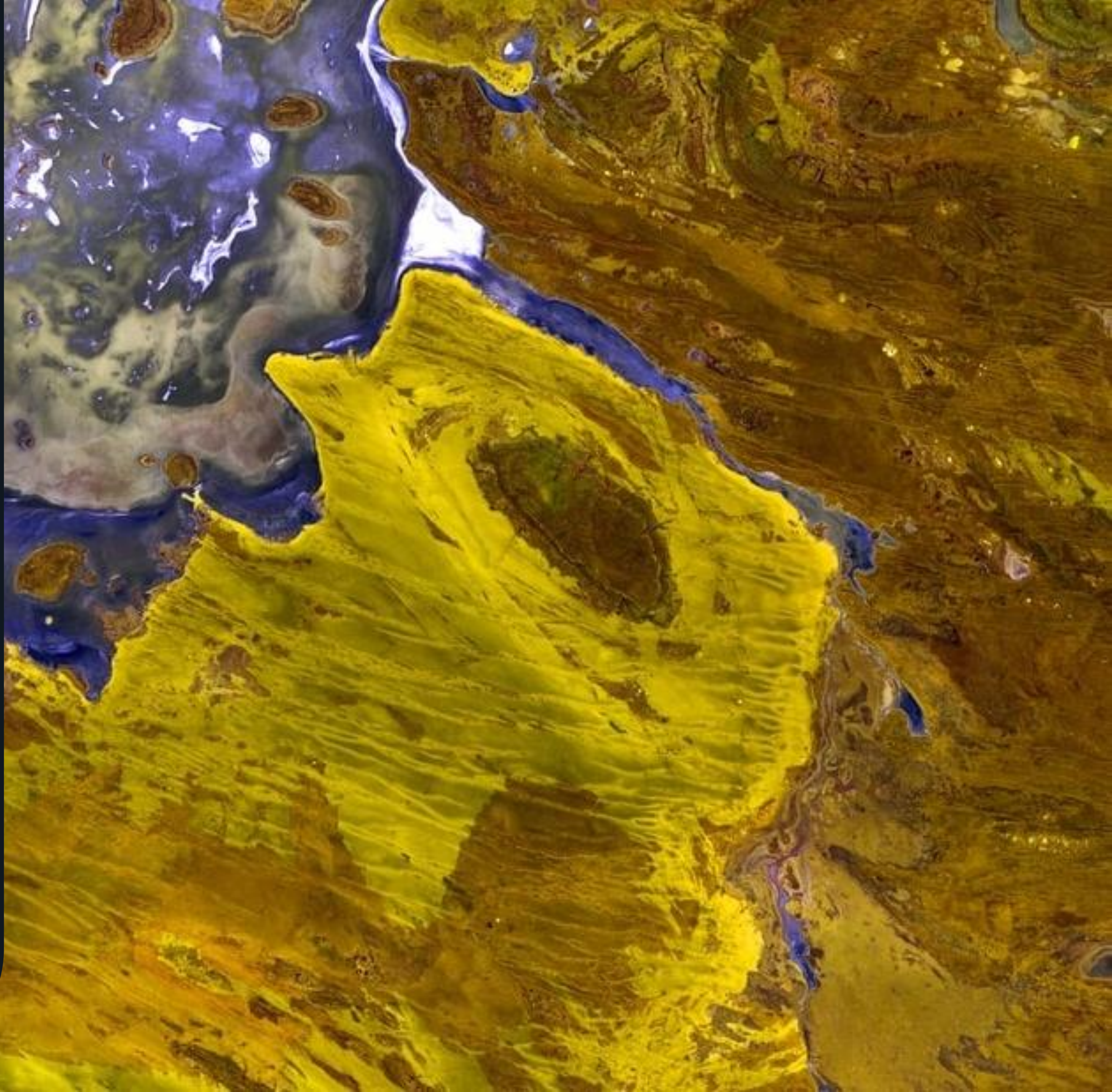
Text	Rationale	V
SLM shall steer an incident light beam into at least 1 output beam with 2 DOF	This replaces 2 scanning mirrors	**2DOF** Experimental evidence that mixture FE-016 exhibits full 2π phase modulation required for hologram generation
SLM shall operate in reflection mode	MDA UK LIDAR and communication terminal designs operate on reflection	**Reflection** Experimental evidence that mixture exhibits full 2π phase modulation in reflection.
SLM shall generate a new output for all pixels at a rate of >1kHz **Target**: > 10kHz – 100kHz	This is the minimum possible speed that would maintain relevance in the LIDAR market (currently limited only by laser PRF)	**≈ 1kHz** Experimental evidence that mixture FE-016 exhibits a response to a 1 kHz generation rate.

WP 1-3 Results: High Priority Requirements

Text	Rationale	V
SLM shall be compatible with a minimum range of 1km. **Target intersatellite:** > 100km **Target earth to LEO:** > 600km **Target earth to MEO: >** 8000 km **Target interorbital:** > 36000km	This is sufficient for most LIDAR applications. Higher target required for intersatellite communications intersatellite and interorbital communications	**>1 km** Experimental evidence that existing SLMs have been characterized with propagation distances of at least 1 km in optical communications. FE-016 stable after lasing with 2W 560nm continuous power.
SLM shall have a scattering loss <25% **Target: <**5%	This would be comparable to the scattering loss using steering mirrors. Important to achieve target range - Related to range, target 5% to be comparable with mirrors, which would then mean we do not need more powerful laser. High scattering loss would mean only low range applications are possible (rover navigation)	**<25%** Experimental evidence that mixture exhibits a scattering loss that is less than 20%

SECTION 2

UFOS Programme Conclusions and Further Plans



UFOS Programme Results: Overall Status

- Developed LC formulation FE-016 that addresses the following requirements

  - Lower operating temperature (<45°C) (Req. ID - SLM – 0190);
  - Larger temperature range (30°C to 45°C) (Req. ID - SLM – 0190);
  - Large tilt angles (±45°) (Req. ID - SLM-0100).
  - High speed (1 kHz switching frequencies) (Req. ID - SLM-0120)
  - Low transmission losses (<15%) (Req. ID - SLM-0140)
  - >1 W Optical handling capability (Req. ID - SLM-0210)

- The mixture … uous
  Laser powe…

- The operati…

- The next ph… ased
  Lidar and F…

LC TRL: 4

SLM TRL : 3 - 4

UFOS LIDAR TRL: 3

UFOS FSOC Terminal TRL: 3

UFOS: Verification Status of High Priority Requirements

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