

Engineering a multiple-quantum-well modulating retroreflector for space optical communications: prototype development, system architecture, and validation strategy

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ABSTRACT

Modulating retroreflectors (MRRs) offer a low-size, low-mass, and low-power alternative to conventional optical terminals by transferring the laser source, receiver aperture, and tracking functions to an interrogator. This paper summarises findings gathered during the development of a multiple-quantum-well (MQW) MRR for resource-constrained platforms, with emphasis on CubeSats and very-low-Earth-orbit spacecraft, while also considering UAVs and planetary surface nodes. The system discussion identifies mass, spacecraft surface allocation, power, optical aperture, modulator area, retroreflector quality, data rate, and link performance as coupled design drivers. Corner-cube, cat's-eye, and metasurface architectures are compared, highlighting trade-offs between optical return, MQW capacitance, modulation bandwidth, driver power, thermal loading, field of view, and integration complexity. Representative 1550 nm link budgets indicate that demonstrated MRR parameters can support kilometre-scale UAV links, whereas a 250 km ground-to-VLEO link requires a larger, higher-transmission retroreflector and a high-performance ground terminal. Project progress is demonstrated through the fabrication and characterisation of an initial 980 nm *n-i-n* MQW device. The prototype shows a voltage-dependent spectral shift above approximately 985 nm and a peak-to-peak relative transmission variation of approximately 3.7% at 5 V, although the uncalibrated setup does not provide absolute insertion loss or modulation depth. A staged validation strategy is proposed, progressing from calibrated component and integrated-terminal testing to environmental qualification, balloon-based link demonstration, and eventual operational validation.

Keywords: modulating retroreflector, multiple quantum well, free-space optical communication, electroabsorption modulator, CubeSat, very low Earth orbit, optical link budget, technology validation

1. INTRODUCTION

Small satellites, unmanned aerial vehicles, robotic platforms, and distributed sensors require high-data-rate communication systems under strict size, weight, and power constraints. Free-space optical (FSO) communication offers high bandwidth, immunity to radio-frequency interference, freedom from conventional spectrum-allocation requirements, and a low probability of interception or jamming.¹ Conventional optical terminals, however, generally require a laser transmitter, receiver optics, and acquisition, pointing, and tracking equipment at both ends of the link. These requirements can be prohibitive for small or power-constrained platforms.

Modulating retroreflector (MRR) communication transfers most of this complexity to a larger terminal, referred to as the interrogator. The interrogator illuminates a remote MRR with a continuous-wave laser beam. The retroreflector returns part of the incident beam, while an optical modulator encodes the remote-terminal data onto the reflected power. The remote terminal therefore requires no onboard laser transmitter or precision pointing assembly and can be reduced to a retroreflector, modulator, driver electronics, and, where necessary, a receiver for the incoming channel.^{2,3}

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Early multiple-quantum-well (MQW) MRR systems demonstrated megabit-per-second communication and compressed video transmission from airborne platforms.^{2,4} Later systems established optical links to mobile robots and unmanned aerial vehicles, confirming that the high-power laser, telescope, and tracking system can remain at the interrogator while the remote payload remains compact and energy efficient.^{5,6}

This simplification comes at the cost of a demanding link budget. The optical signal propagates to the remote terminal and back, causing received power to decrease with the fourth power of range. Atmospheric losses also affect both propagation directions. Conversely, the returned signal increases strongly with retroreflector aperture, with its fourth power.^{7,8} Link performance is therefore highly sensitive to aperture, beam divergence, pointing error, atmospheric transmission, modulator contrast, receiver diameter, and detector sensitivity.

A central trade-off exists between optical aperture and modulation bandwidth. In corner-cube architectures, a larger aperture generally requires a larger modulator, increasing capacitance, reducing switching speed, and raising dynamic power consumption. Cat's-eye architectures reduce this limitation by focusing the incident beam onto a smaller modulator in the focal plane, thereby separating the optical aperture from the active modulator area.⁹ Pixelated arrays further reduce element capacitance and increase modulation bandwidth.¹⁰

These developments enabled demonstrations ranging from 45 Mbit/s over 7 km to 500 Mbit/s over 560 m to a flying unmanned aerial vehicle.^{6,7} More recent telecentric systems have demonstrated bidirectional 10 Gbit/s transmission over a field of view of up to 110° under laboratory conditions.¹¹ Power consumption can be reduced further through active-pixel selection, illumination sensing, and photovoltaic or zero-bias detection concepts.^{3,12}

This paper develops a system-level evaluation of a 1550 nm electro-absorption-modulator-based retroreflective optical link for a size-, weight-, and power-constrained remote terminal. The analysis relates the interrogator, propagation channel, retroreflector, modulator, and receiver parameters to the received optical levels for on-off keying. Additionally, results from an initial 980 nm MQW modulator prototype are presented.

2. SYSTEM SCENARIOS AND DESIGN DRIVERS

2.1 Application Scenarios

Modulating retroreflectors are primarily suited to asymmetric links in which the remote platform is strongly constrained in mass, power, surface area, or pointing capability, while a larger interrogator provides the laser source, receiver aperture, and tracking functions. This addresses a recurring problem in small-spacecraft design: payloads may generate more data than can be transmitted using the remaining resources, whereas higher-capacity communication systems reduce the mass and power available for the payload itself. An MRR can partially resolve this conflict by transferring the most demanding optical functions away from the spacecraft. Its narrow optical return may additionally support communication-security and low-probability-of-intercept requirements.^{1,13}

A principal scenario is a CubeSat below 8U in low Earth orbit. Such spacecraft may require higher data rates than basic UHF or VHF modules can provide, but may be unable to accommodate a conventional laser terminal or continuously point a high-gain antenna. MRRs could support higher-rate downlinks, satellite laser ranging, precision localisation, and communication during different spacecraft attitudes. Similar advantages apply in very low Earth orbit, where limited power, short contact windows, and strict aerodynamic constraints further restrict terminal size and placement.

Terrestrial UAVs represent another relevant application. A lightweight MRR can provide long-range transmission of video or sensor data without carrying a stabilised laser transmitter. Depending on the interrogator design, the same optical link may also support secure communication or precision position determination. High-rate retroreflective links have already been demonstrated with moving UAV platforms.^{4,6}

A further scenario is a small rover or sensor node on another celestial body. An orbiting spacecraft could interrogate the MRR, receive data, and provide ranging or position information. The surface terminal would therefore avoid a large, power-intensive transmitter, leaving more resources for sensing, mobility, and thermal control. Photovoltaically powered MRR concepts have previously been investigated for autonomous planetary sensors.¹⁴

Attitude-control performance is decisive in all scenarios. If the platform can maintain its orientation within a few degrees, the field of view of a conventional retroreflector or compact cat's-eye system may be sufficient, avoiding continuous precision pointing. Larger attitude excursions require multiple MRR units on different faces, increasing coverage but also mass, power demand, and occupied spacecraft surface.

2.2 System Design Drivers

The remote-terminal concept is governed by eight interacting drivers: mass, external surface-area allocation, power consumption, MRR aperture, MQW diameter, retroreflector quality, data rate, and link-budget performance.

Mass includes the retroreflector optics, MQW modulator, driver electronics, mounting structure, cabling, shielding, and thermal provisions. Individual MRR units can be lightweight, but arrays installed to increase the field of view may create a relevant cumulative penalty. Internal volume should also remain low, although it must be considered separately from mass. A dense component may occupy little internal volume while still producing a significant structural or launch-load impact.

External surface-area allocation is particularly critical for CubeSats. The MRR aperture requires an unobstructed view and competes directly with solar cells, antennas, radiators, payload sensors, and access panels. Installing several devices on different faces can substantially reduce solar-cell area and therefore limit onboard energy generation. This effect is distinct from the MRR's own power consumption.^{12,15}

The MRR aperture is one of the strongest optical parameters because the ideal returned power scales with the fourth power of the retroreflector diameter. Increasing the aperture can therefore significantly improve link margin or range. This benefit must be balanced against mass, surface occupation, optical alignment sensitivity, and manufacturing complexity.⁷

The MQW diameter controls the electrical capacitance and therefore the achievable modulation bandwidth and switching energy. In a corner-cube MRR, the MQW usually covers the complete optical aperture, directly coupling optical gain to electrical bandwidth. Larger apertures then require larger and slower modulators. A cat's-eye architecture separates these quantities by focusing the incident beam onto a smaller MQW element or pixel array. This permits a large entrance aperture together with high modulation speed, but introduces additional constraints relating to focal-plane alignment, field of view, optical aberrations, as well as component volume and mass.^{7,9}

Retroreflector quality includes reflectivity, alignment, and the precision of the returned beam direction. High nominal reflectivity alone is insufficient if optical aberrations or assembly errors increase beam divergence. The effective benefit of a larger aperture is therefore only obtained when the complete optical system retains near-diffraction-limited performance.⁷

The required data rate determines the modulator bandwidth, driver current, receiver bandwidth, encoding scheme, and onboard processing load. Increasing the data rate may raise both electrical consumption and the required received optical power. It can therefore conflict with aperture, MQW size, thermal limits, and available energy. These interactions must ultimately be evaluated through the link budget.

2.3 Link-Budget Analysis

Two representative link budgets are considered: a short-range ground-to-UAV link and a ground-to-VLEO link (Table 1). Both cases are evaluated at a wavelength of 1550 nm. Following established treatments of MRR communication links, the total link budget is expressed as

$$LB = G_{TX} + L_{TX} + 2L_{FS} + 2L_{Atm} + G_{MRR} + L_{MRR} + L_{RX} + G_{RX}. \quad (1)$$

This decomposition follows the MRR link-budget formulations presented in.^{6-8,16,17} Here, G_{TX} and G_{RX} describe the transmit and receive gains of the laser communication terminal (LCT), while L_{TX} and L_{RX} represent internal optical losses. The LCT configurations are simplified terminal classes selected from the range of optical terminal and ground-station parameters discussed by Giggenbach et al.¹⁸ LCT1 represents a mobile terminal comparable to what Gbit/s satellite systems offer, while LCT2 represents a stationary high-aperture station. A transmission and reception efficiency of 50 %, corresponding to $L_{TX} = L_{RX} = -3$ dB, is assumed.

The one-way free-space loss L_{FS} is calculated from range and wavelength using the conventional free-space propagation relation employed in previous MRR link-budget analyses.^{16,17} The atmospheric term L_{Atm} is treated as an effective one-way propagation penalty. The selected values are representative of experimentally observed atmospheric losses and additional propagation penalties in MRR links.^{7,8,19}

The MRR gain G_{MRR} is calculated from the effective retroreflector aperture and Strehl factor following the procedure from Rabinovich et al.⁷ The MRR-specific loss L_{MRR} is obtained from the retroreflector reflectivity

Table 1. Link-budget results for the investigated ground-to-UAV and ground-to-VLEO use cases.

Parameter	Use case 1	Use case 2
	Ground-UAV	Ground-VLEO
LCT / MRR	LCT1 / MRR1	LCT2 / MRR2
Range	5 km	250 km
P_{TX}	5.0 W	5.0 W
G_{TX}	+103.0 dB	+121.7 dB
L_{TX}	-3.0 dB	-3.0 dB
$L_{FS,up}$	-212.1 dB	-246.1 dB
$L_{Atm,up}$	-5.0 dB	-10.0 dB
G_{MRR}	+176.5 dB	+196.3 dB
L_{MRR}	-7.7 dB	-3.4 dB
$L_{Atm,down}$	-5.0 dB	-10.0 dB
$L_{FS,down}$	-212.2 dB	-246.1 dB
L_{RX}	-3.0 dB	-3.0 dB
G_{RX}	+103.0 dB	+121.7 dB
Total LB	-65.5 dB	-81.9 dB
P_{RX}	-28.5 dBm	-45.1 dBm
P_{RX}	1410.7 nW	32.3 nW

and the single-pass MQW transmission in the two modulation states, following the optical parameters reported for MQW-based MRRs in Goetz et al. and Rabinovich et al.^{7,17}

Use case 1 represents a 5 km ground-to-UAV link. The LCT1 ground terminal is assigned a transmit power of 5 W and transmit and receive gains of 103.0 dB. The MRR1 terminal represents previously demonstrated MRR technology and uses a 16 mm effective aperture, a Strehl factor of 0.4, approximately 85 % retroreflector reflectivity, and MQW single-pass transmission values of 60 % and 40 %.^{7,17} These parameters result in $G_{MRR} = 176.5$ dB and $L_{MRR} = -7.7$ dB. A one-way atmospheric penalty of 5 dB is assumed.

Use case 2 represents a 250 km ground-to-VLEO link. The higher-performance LCT2 ground terminal is assigned a transmit power of 5 W and transmit and receive gains of 121.7 dB. In contrast to Use case 1, an improved MRR2 terminal is assumed, with a 50 mm effective aperture, a Strehl factor of 0.4, 95 % retroreflector reflectivity, and MQW transmission values of 80 % and 40 %. MRR2 represents a design target rather than demonstrated hardware. These parameters result in $G_{MRR} = 196.3$ dB and $L_{MRR} = -3.4$ dB. A one-way atmospheric penalty of 10 dB is assumed.

Use case 1 provides a comparatively strong optical return using parameters representative of already demonstrated MRR hardware. The calculation therefore supports ground-to-UAV communication over several kilometres without requiring substantial improvements to the retroreflective terminal. The VLEO case is considerably more demanding and requires both a high-performance ground-based LCT and an improved MRR. Extending the concept towards higher LEO altitudes will consequently require MRR terminals with higher optical transmission, larger effective apertures, and higher retroreflector reflectivity, together with strong ground-based terminals. However, further analysis is necessary in order to calculate Bit Error Rate (BER) and Signal-to-Noise-Ratio (SNR) for specific ground stations with different environmental conditions in mind.

3. MODULATING RETROREFLECTOR SYSTEM ARCHITECTURE AND DESIGN TRADE-OFFS

The remote MRR terminal consists primarily of the retroreflector optics, the electroabsorption modulator, the driver circuit, and the mechanical framework required for integration into the spacecraft. These elements form a tightly coupled opto-electro-mechanical assembly.^{6,20}

The retroreflector optics collect the interrogation beam and return it towards the source. Their main design parameters are aperture, field of view, optical efficiency, wavefront quality, and alignment tolerance. The modulator imposes the data signal on the returned beam. At system level, its relevant properties are active area, capacitance, contrast ratio, insertion loss, operating voltage, and wavelength.^{7,9,15,21} The driver circuit converts the spacecraft data stream into the required voltage waveform and must charge the capacitive modulator sufficiently fast at the target data rate. The mechanical framework maintains the relative alignment of the optical

elements, transfers launch loads, and provides the structural and thermal interface to the spacecraft.^{6,10,20} Additional subsystems may include thermal-control elements and receiver electronics. Receiver electronics are required when the terminal must detect an uplink, determine illumination, or identify the illuminated modulator pixel.^{3,12} Thermal-control provisions may range from a conductive mounting interface and temperature sensor to active temperature stabilisation, depending on the sensitivity of the modulator and optical assembly.^{15,22}

3.1 Electroabsorption Modulator Options

The electroabsorption modulator (EAM) can use several III–V material systems and quantum-well architectures. The choice is governed primarily by the operating wavelength and required drive voltage. GaAs/AlGaAs and InGaAs/AlGaAs MQW devices have been demonstrated around 850–980 nm, while InGaAs/InAlAs structures on InP are commonly used near 1550 nm.^{4,15} Surface-normal devices are particularly attractive for MRR applications because they permit comparatively large apertures and two-dimensional pixel arrays. Electrically, the structures are typically implemented as *p-i-n* diodes, with the quantum wells located in the intrinsic region. Square quantum wells provide a comparatively simple baseline, whereas coupled-quantum-well designs can achieve similar modulation contrast at lower reverse-bias voltage.^{15,21} Optically, EAMs may operate in transmissive or reflective configurations; reflective implementations can additionally employ an asymmetric Fabry–Pérot cavity to increase the effective modulation depth, at the cost of tighter spectral and fabrication tolerances.^{20,21} Device geometry ranges from large circular mesas to pixelated arrays, with smaller pixels reducing capacitance and increasing modulation bandwidth.^{9,10}

3.2 Retroreflector Architecture Options

The principal architecture options are corner-cube, cat’s-eye, and metasurface-based retroreflectors.

A corner-cube MRR provides a comparatively simple and robust optical arrangement with a broad intrinsic field of view. Its main limitations are that the modulator generally needs to cover most of the optical aperture, and they are heavy and bulky. Increasing the aperture also increases the modulator area, capacitance, and driver load. Arrays of corner cubes can increase angular coverage and reduce the required volume.^{2,4,5}

A cat’s-eye MRR focuses the interrogation beam onto a smaller modulator or focal-plane array. This separates the effective optical aperture from the electrically active modulator area and is therefore attractive for higher data rates. The disadvantages are increased optical complexity, tighter focal-plane tolerances, and field-dependent aberrations. Cat’s-eye architectures have demonstrated substantially higher data rates than large-area corner-cube implementations, but due to their optical layout require substantial volume.^{6,7,9,20,23}

Metasurface or metalens retroreflectors offer a potential low-profile alternative in which focusing and retroreflection functions are implemented in a thin planar structure. Their possible advantages include low volume and high functional integration. However, their optical efficiency, angular bandwidth, polarisation sensitivity, environmental stability, and compatibility with an active MQW modulator require further assessment. They therefore represent a less mature option.^{24,25}

3.3 Architecture-Specific Design Trade-Offs

In a corner-cube architecture, optical aperture and modulator area are directly coupled. Since modulator capacitance C_{MQW} increases approximately with active area A_{MQW} ,

$$C_{\text{MQW}} \propto A_{\text{MQW}}, \quad (2)$$

and the corresponding RC-limited bandwidth can be approximated by using the modulator capacitance and the equal resistance R_{eq} of the system

$$f_{\text{RC}} \approx \frac{1}{2\pi R_{\text{eq}} C_{\text{MQW}}}, \quad (3)$$

a larger aperture generally reduces the achievable electrical bandwidth and increases driver demand. Cat’s-eye systems reduce this coupling by focusing the collected beam onto smaller modulator pixels.^{7,9}

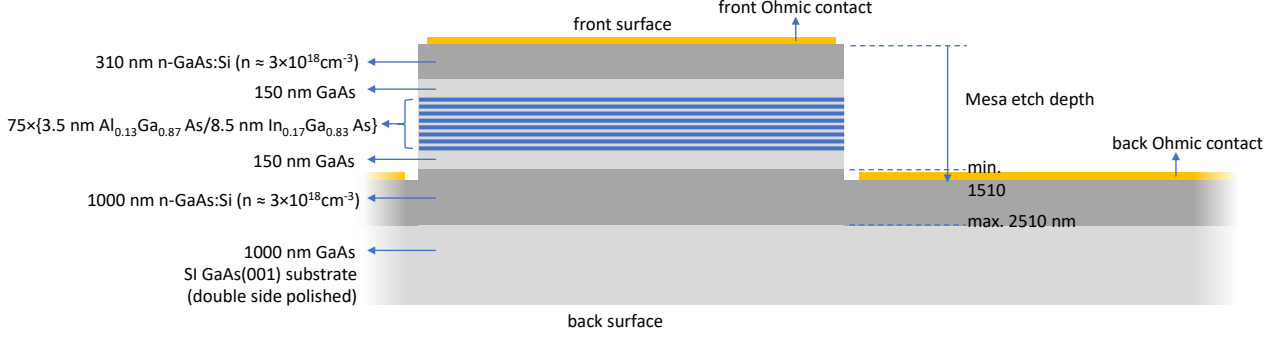


Figure 1. Schematic layer sequence, mesa geometry, and front-side contacts of the fabricated *n-i-n* MQW modulator.

Pixelation further reduces the capacitance per driven channel, but introduces inactive gaps, electrical routing, and additional driver complexity. Driving all pixels simultaneously increases bandwidth but provides little reduction in total switching energy. Selective activation of the illuminated pixel can reduce power, but requires illumination detection and control logic.^{3, 10, 12, 20}

The achievable modulation speed is closely coupled to the electrical and thermal design of the MRR terminal. For a predominantly capacitive modulator, the dynamic driver demand scales approximately as

$$P_{\text{dyn}} \propto C_{\text{MQW}} V_{\text{pp}}^2 f_{\text{sw}}, \quad (4)$$

such that increasing the switching frequency f_{sw} , modulator capacitance C_{MQW} , or peak-to-peak drive voltage V_{pp} directly increases the electrical power requirement and associated heat dissipation. This creates a fundamental trade-off between modulation bandwidth and thermal loading. Reducing the active area through pixelation and using lower-voltage quantum-well structures can alleviate this constraint, whereas larger devices or higher voltage swings increase the demand on both the driver and thermal-control system.^{9, 15, 21} The resulting temperature increase is not only a spacecraft-level thermal concern, but can also affect the optical performance of the modulator. Heating of quantum-well structures shifts the absorption spectrum and can therefore change insertion loss and modulation contrast at a fixed interrogation wavelength; this effect becomes increasingly relevant at higher modulation frequencies and drive voltages.^{15, 22} Temperature variations may additionally affect the optical assembly through thermal expansion, changing lens spacing, focal-plane position, and the alignment between the retroreflector and modulator. The mechanical framework must therefore provide both sufficient structural stability and a defined conductive heat path towards the spacecraft. Potential measures include thermally stable structural materials, conductive mounting, duty-cycle limitations, and adjustment of the modulator bias. Active heating or cooling could be an option, too.^{6, 20}

4. MQW MANUFACTURING

The multiple-quantum-well (MQW) structure was adapted from the modulator demonstrated at 980 nm by Rabinovich et al.⁹ The design was selected because it had already been experimentally demonstrated at the intended wavelength. Its additional photodetection capability was not required and could not be transferred directly to the fabricated *n-i-n* structure.

The epitaxial layers were grown by molecular beam epitaxy on a double-side-polished, semi-insulating GaAs(001) substrate. As illustrated in Figure 1, the nominal layer sequence consists of a 1000 nm undoped GaAs buffer layer, a 1000 nm Si-doped n-GaAs contact layer, a 150 nm undoped GaAs spacer, the MQW region, a second 150 nm GaAs spacer, and a 310 nm Si-doped n-GaAs contact layer. Both contact layers have a nominal doping concentration of approximately $3 \times 10^{18} \text{ cm}^{-3}$. The active region contains 75 periods of 8.5 nm $\text{In}_{0.17}\text{Ga}_{0.83}\text{As}$ quantum wells and 3.5 nm $\text{Al}_{0.13}\text{Ga}_{0.87}\text{As}$ barriers.

A *p-i-n* structure using Be-doped p-GaAs was initially intended. However, due to calibration issues for this

fabrication run, both contact layers had to be Si-doped, resulting in an *n-i-n* structure. A *p-i-n* implementation is planned for a later fabrication iteration.

Circular mesas with diameters of 0.9 mm and 1.0 mm were formed by wet-chemical etching. The etchant consisted of deionised water, 25 ml H₂O₂, and 15 ml H₃PO₄. The etch exposed the lower n-GaAs contact layer on a ledge surrounding each mesa, allowing both electrical contacts to be accessed from the front side.

Ring-shaped ohmic contacts were deposited by metal evaporation using a 5 nm Ni/100 nm AuGe/35 nm Ni/200 nm Au stack and subsequently annealed at 380 °C. The processed mesas were electrically screened, and devices exhibiting promising current–voltage characteristics were selected for packaging and optical characterisation.

The selected devices were mounted on standard 1.6 mm FR4 carrier PCBs with ENIG-finished contact pads. The upper ring electrode and the exposed lower contact were each connected to the PCB using one 17 µm gold bond wire. No series resistors, protection components, or impedance-matching elements were included on the carrier PCB.

5. TEST SETUP AND RESULTS

A laboratory test setup was assembled to characterise the voltage-dependent optical transmission of the fabricated MQW modulator. The primary objective was to verify an electrically induced change in the transmission spectrum and to identify the spectral region in which the modulation response is strongest.

The optical path consists of a Thorlabs QTH10-M quartz-tungsten-halogen light source followed by a Thorlabs SCFW6 filter wheel and a Thorlabs ID15/M iris. Although the filter wheel allows neutral-density filters to be introduced into the optical path, no neutral-density filter was used for the measurements presented here. The broadband light is subsequently transmitted through the MQW sample, which is mounted in a custom 3D-printed holder on an XYZ translation stage. The translation stage allows the selected mesa to be aligned with the optical path. No additional focusing or collimating optics are used on the illumination side (see Figure 2).

After passing through the MQW structure, the transmitted light is coupled into a Thorlabs M28L1 optical fibre using an F110SMA-980 fibre collimator and guided to an Ocean Optics HR2 spectrometer. Each measurement consists of an average over 100 spectra with an integration time of 0.1 s per individual spectrum, corresponding to a total optical integration time of 10 s per measurement point.

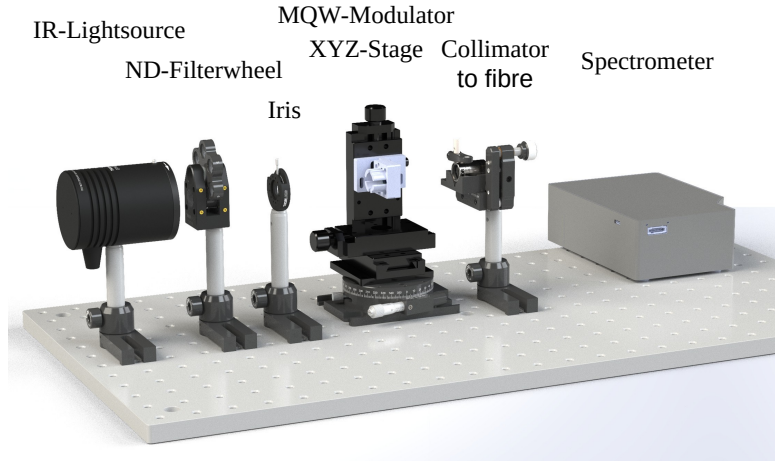


Figure 2. Experimental setup used for the voltage-dependent spectral characterisation of the MQW modulator.

The setup is not calibrated with respect to spectral irradiance. Consequently, the measurements cannot be used to determine the absolute transmission, absorption coefficient, or insertion loss of the MQW device. Instead, the biased measurements are evaluated relative to a reference spectrum acquired at 0 V. The relative transmission is defined as

$$T_{\text{rel}}(\lambda, V) = \frac{S(\lambda, V)}{S(\lambda, 0)}, \quad (5)$$

where $S(\lambda, V)$ represents the measured spectrometer signal at wavelength λ and applied voltage V . A relative transmission above unity therefore represents an increase compared with the unbiased state, while values below unity indicate reduced transmission.

A single 0 V reference spectrum was recorded before the voltage sweep. Without changing the optical alignment, the device was subsequently biased at 5, 4, 3, 2, and 1 V, respectively. The relative measurements therefore characterise the spectral change of an unchanged optical path as a function of applied voltage.

The electrical bias was supplied using a Keithley 2230-30-1 power supply. Since the fabricated device consists of an n - i - n structure rather than a conventional p - i - n diode, no conventional reverse-bias configuration exists. The current through the device was recorded using a Keithley DMM7510 while the sample remained illuminated by the QTH light source. Additional current-voltage measurements were conducted without illumination to distinguish the electrically and optically induced components of the device response.

5.1 Spectral Response

The broadband spectrum transmitted through the MQW sample is shown in Figure 3. Since the optical system is not irradiance calibrated, this spectrum represents the measured spectrometer signal rather than an absolute optical transmission.

At wavelengths below approximately 887 nm, the detected signal remains close to the measurement background.

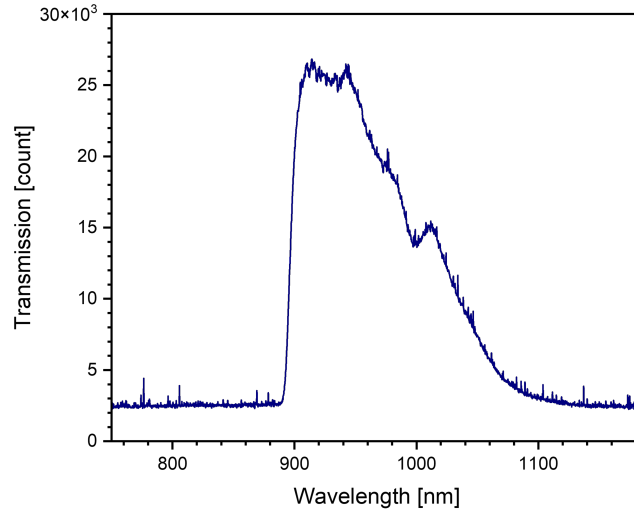


Figure 3. Unnormalised spectrum measured after transmission through the MQW sample. The sharp increase between approximately 887 and 910 nm marks the absorption edge of the GaAs-based structure.

Between approximately 887 and 910 nm, a steep increase in detected intensity is observed, which is attributed to the absorption edge of the GaAs-based structure. Above approximately 910 nm, substantial optical transmission through the sample is observed. The broadband measurement therefore defines the useful spectral range for the subsequent relative measurements.

The voltage-dependent response was evaluated by normalising each biased spectrum to the 0 V reference according to Eq. (5). Figure 4 shows the resulting relative transmission for applied voltages between 1 and 5 V.

A clear voltage-dependent modification of the optical spectrum is observed. The magnitude of the relative transmission change increases with applied voltage. The feature associated with the intended MQW operating region occurs above approximately 985 nm and develops into a pronounced maximum followed by a minimum at longer wavelengths. With increasing voltage, both extrema move towards longer wavelengths. Such bias-dependent spectral shifts are characteristic of the electroabsorption response of quantum-well structures and have previously been observed in surface-normal MQW and coupled-quantum-well modulators.^{15,21}

The magnitude of the measured modulation increases over the same voltage range. At 2 V, the maximum relative

transmission increase is approximately 0.3 %, while the minimum corresponds to a reduction of approximately 0.4 %. At 5 V, these values increase to approximately +2.0 % and -1.7 %, respectively, resulting in a peak-to-peak relative transmission variation of approximately 3.7 %.

In addition to the intended spectral feature above 985 nm, further voltage-dependent structures occur at shorter wavelengths, particularly around the 900–950 nm region. These features were not anticipated from the MQW design, but could be due to specific interband transitions. Their systematic dependence on applied voltage nevertheless indicates that they are associated with the electrically active semiconductor structure rather than exclusively with the broadband spectral shape of the illumination source.

The positive-negative shape observed around the intended MQW transition is consistent with a spectral displacement rather than a uniform change in transmission. A wavelength shift of an absorption feature produces increased relative transmission on one side of its initial position and reduced transmission on the other when normalised against the unbiased spectrum. The increasing amplitude and wavelength displacement of the measured extrema therefore provide experimental evidence for a voltage-dependent modification of the optical response.

The measurements do not provide an absolute modulation depth or insertion loss because neither the incident spectral irradiance nor the wavelength-dependent response of the complete optical system was calibrated. The results therefore quantify the relative electro-optical response of the fabricated device rather than its absolute electro-absorption characteristics.

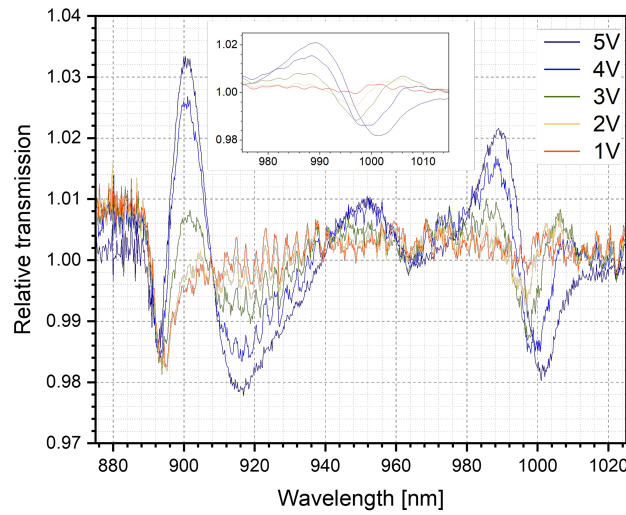


Figure 4. Change of transmission at different applied bias voltages, with moving average filtered view of target modulated wavelengths.

5.2 Electrical Response

The current through the MQW structure was recorded simultaneously with the spectral measurements. The illuminated current-voltage characteristic is summarized in Table 2.

Table 2. Measured current through the MQW structure under illumination with the QTH source.

Applied voltage (V)	Current (μA)
0	0.5
1	12
2	16
3	18
4	22
5	48

The current initially rises to approximately $12\ \mu\text{A}$ at $1\ \text{V}$. Between approximately 1 and $4\ \text{V}$, the increase is comparatively moderate, reaching $22\ \mu\text{A}$ at $4\ \text{V}$. A substantially stronger increase occurs between 4 and $5\ \text{V}$, where the measured current more than doubles to approximately $48\ \mu\text{A}$. The electrical characteristic therefore exhibits a comparatively weakly varying intermediate region followed by a pronounced increase at the upper end of the investigated voltage range.

Another current-voltage characterisation was conducted in a different setup with and without optical illumination. As shown in Figure 5, the dark characteristic exhibits a substantially weaker dependence on applied voltage than the illuminated response.

The difference between the dark and illuminated measurements demonstrates that illumination contributes significantly to the observed current. This is particularly relevant for the present n - i - n structure, for which the measured current cannot be interpreted as the conventional reverse leakage current of a p - i - n electro-absorption modulator.

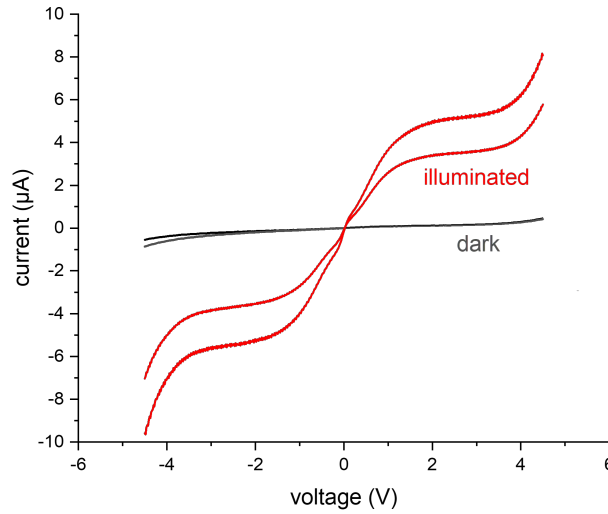


Figure 5. Comparison of the MQW current-voltage characteristic with and without optical illumination, for multiple mesas of the grown wafer.

6. VALIDATION STRATEGY AND DEVELOPMENT ROADMAP

A link-budget model should first connect the measured terminal properties with the achievable communication range.

Optical characterisation should determine the MQW transmission spectra at different bias voltages and temperatures, the absolute transmission and insertion loss in both modulation states, and the resulting contrast and modulation efficiency. The influence of wavelength, polarisation, and incidence angle should also be assessed. For the integrated terminal, the tests should quantify refraction, scattering, unwanted reflections, changes in beam shape and divergence, retroreflection efficiency, return-beam quality, field of view, boresight error, and sensitivity to assembly tolerances. Absolute transmission and contrast must be considered together, since a high contrast ratio can be offset by a low optical return.²³

Electrical testing should cover the MQW impedance and capacitance over frequency, the electrical-to-optical bandwidth, the required drive voltage, power consumption, and self-heating under representative modulation patterns. This is particularly important because MQW self-heating can shift the operating spectrum and degrade the optical performance.²³ Testing should later be extended to thermal-vacuum conditions and representative hot and cold orbital cases.

Environmental and mechanical verification should include operational and survival temperatures, reduced pressure and vacuum, material outgassing, humidity during storage and ground operation, vibration, and shock.

Radiation, charged-particle and plasma effects, ultraviolet exposure, and atomic oxygen should be assessed for later orbital hardware according to the selected orbit and mounting position. Mechanical, electrical, and software interfaces should likewise be verified through mounting and alignment checks, connector and power-supply tests, and command and telemetry tests.

For later flight-model development, these activities should be expanded into a mission-tailored ECSS verification programme. Depending on the final mission, this should include functional regression testing, physical-property measurements, sinusoidal and random vibration, shock, thermal balance and thermal vacuum, electromagnetic compatibility and electrostatic-discharge testing, endurance, contamination control, and the applicable electrical and software tests.

A high-altitude balloon campaign is proposed as the main integrated validation step. A stratospheric balloon can provide slant ranges of several tens of kilometres and a flight duration of several hours. The optical path passes through most of the dense lower atmosphere and is therefore more representative of a ground-to-space link than a horizontal ground test. The BEXUS programme is one example of a platform that could support such a campaign; its balloons typically reach 25–30 km and fly for approximately two to five hours.²⁶ The campaign should verify acquisition and tracking of the moving terminal, maintenance of the complete optical data link, agreement between measured performance and the link-budget model, and the effects of temperature and reduced pressure on the MQW and driver. Unmodulated reference intervals or a passive reference retroreflector could be used to distinguish atmospheric fluctuations from changes in modulator performance. The measured data could be used to calibrate the link-budget model and estimate performance with a larger laser ground station.

7. SUMMARY AND CONCLUSION

This paper has summarised the findings gathered during the development of a multiple-quantum-well modulating retroreflector for optical communication with resource-constrained platforms. Potential applications include CubeSats and spacecraft in very low Earth orbit, as well as UAVs and planetary surface nodes. In these scenarios, the principal advantage of an MRR is that the laser source, receiver aperture, and tracking functions can be transferred to a more capable interrogator. This can reduce the mass, volume, power consumption, and pointing requirements of the remote terminal.

The system assessment demonstrates that the design of an MRR terminal is governed by several strongly coupled parameters. Optical aperture, MQW area, capacitance, modulation bandwidth, driver power, thermal loading, field of view, retroreflector quality, and platform integration cannot be considered independently. Corner-cube architectures provide a comparatively simple and robust solution but directly couple optical aperture to modulator area. Cat's-eye systems separate these parameters and can support smaller, faster modulators, although at the cost of greater volume, optical complexity, and alignment sensitivity. Metasurface-based concepts may offer a low-profile alternative, but their efficiency, angular response, environmental stability, and compatibility with active modulators require further investigation. No single architecture is therefore universally preferable; its suitability depends on the platform and application requirements.

The representative link-budget cases illustrate the strong influence of propagation range, terminal aperture, atmospheric transmission, and retroreflector performance. Parameters associated with previously demonstrated MRR technology appear suitable for kilometre-scale UAV links. Extending the concept to a ground-to-VLEO link requires a more capable ground terminal and improvements to the effective aperture, transmission, reflectivity, and optical quality of the remote terminal.

Project progress was demonstrated through the fabrication and laboratory characterisation of an initial MQW device. The measurements show a repeatable voltage-dependent modification of the optical spectrum. The response becomes more pronounced with increasing voltage, while its extrema shift towards longer wavelengths. This behaviour provides a component-level proof of concept for electrically controlled modulation of the transmitted optical signal. The electrical measurements additionally show a clear influence of illumination on the device response. Because the optical setup was not irradiance-calibrated, the measurements describe relative spectral changes rather than absolute transmission, insertion loss, or modulation depth.

The transition from the demonstrated 980 nm *n-i-n* device to a 1550 nm *p-i-n* modulator involves more than a shift in operating wavelength, as the epitaxial structure must be redesigned using a suitable material system, such as strain-balanced InGaAs/InAlAs quantum wells on InP. In contrast to the present *n-i-n* structure, the

$p-i-n$ configuration places the MQWs within a depleted intrinsic region, allowing a well-defined electric field to control their absorption under reverse bias with comparatively low current. The underlying quantum-confined Stark effect and the general fabrication approach remain unchanged, as do the fundamental trade-offs between active area, capacitance, modulation bandwidth, drive voltage, power consumption, and thermal loading.^{15,21} Further component testing should determine the absolute optical response, capacitance, impedance, electro-optical bandwidth, drive requirements, power consumption, temperature dependence, and self-heating behaviour. The modulator should subsequently be integrated with the retroreflector optics, driver electronics, mechanical framework, and thermal interface. Integrated testing should assess return-beam quality, retroreflection efficiency, field of view, alignment sensitivity, and complete link performance. Environmental testing should then address the mechanical, thermal, vacuum, and radiation conditions relevant to the intended application. Following these steps, an airborne or balloon-based campaign could provide a later opportunity to evaluate the complete link over representative ranges and atmospheric conditions.

Overall, the work establishes a system-level foundation and an initial experimental proof of concept for further MQW-MRR development. It also identifies the optical, electrical, thermal, and mechanical interactions that must be addressed before an integrated terminal can be validated for operational communication.

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REFERENCES

- [1] Rabinovich, W. S., Moore, C. I., Mahon, R., Goetz, P. G., Burris, H. R., Ferraro, M. S., Murphy, J. L., Thomas, L. M., Gilbreath, G. C., Vilcheck, M., and Suite, M. R., “Free-space optical communications research and demonstrations at the US naval research laboratory,” *Applied Optics* **54**(31), F189–F200 (2015).
- [2] Gilbreath, G. C., Rabinovich, W. S., Meehan, T. J., Vilcheck, M. J., Mahon, R., Burris, R., Ferraro, M., Sokolsky, I., Vasquez, J. A., Bovais, C. S., Cochrell, K., Goins, K. C., Barbehenn, R., Katzer, D. S., Ikossi-Anastasiou, K., and Montes, M. J., “Large-aperture multiple quantum well modulating retroreflector for free-space optical data transfer on unmanned aerial vehicles,” *Optical Engineering* **40**(7), 1348–1356 (2001).
- [3] Klotzkin, D., Goetz, P. G., Rabinovich, W. S., Ferraro, M. S., Mahon, R., and Binari, S. C., “Integrated angle-of-arrival sensing and simultaneous bidirectional communication using a cat’s eye modulating retroreflector,” in [*Conference on Lasers and Electro-Optics/International Quantum Electronics Conference*], CMO2, Optica Publishing Group, Baltimore, Maryland (2009).
- [4] Gilbreath, G. C., Rabinovich, W. S., Meehan, T. J., Vilcheck, M. J., Stell, M., Mahon, R., Goetz, P. G., Oh, E., Vasquez, J. A., Cochrell, K., Lucke, R. L., and Mozersky, S., “Progress in development of multiple-quantum-well retromodulators for free-space data links,” *Optical Engineering* **42**(6), 1611–1617 (2003).
- [5] Rabinovich, W. S., Murphy, J. L., Suite, M., Ferraro, M., Mahon, R., Goetz, P., Hacker, K., Freeman, W., Saint Georges, E., Uecke, S., and Sender, J., “Free-space optical data link to a small robot using modulating retroreflectors,” in [*Free-Space Laser Communications IX*], *Proceedings of SPIE* **7464**, 74640B, SPIE, San Diego, California (2009).
- [6] Quintana, C., Wang, Q., Jakonis, D., Oberg, O., Erry, G., Platt, D., Thueux, Y., Faulkner, G., Chun, H., Gomez, A., Salter, M., and O’Brien, D. C., “A high speed retro-reflective free space optics links with UAV,” *Journal of Lightwave Technology* **39**(18), 5699–5705 (2021).
- [7] Rabinovich, W. S., Goetz, P. G., Mahon, R., Swingen, L., Murphy, J., Ferraro, M., Burris, H. R., J., Moore, C. I., Suite, M., Gilbreath, G. C., Binari, S., and Klotzkin, D., “45-mbit/s cat’s-eye modulating retroreflectors,” *Optical Engineering* **46**(10), 104001 (2007).
- [8] Plett, M., Rabinovich, W. S., Mahon, R., Ferraro, M. S., Goetz, P. G., Moore, C. I., and Freeman, W., “Free-space optical communication link across 16 kilometers over the chesapeake bay to a modulated retroreflector array,” *Optical Engineering* **47**(4), 045001 (2008).

- [9] Rabinovich, W. S., Mahon, R., Goetz, P. G., Waluschka, E., Katzer, D. S., Binari, S. C., and Gilbreath, G. C., "A cat's eye multiple quantum-well modulating retro-reflector," *IEEE Photonics Technology Letters* **15**(3), 461–463 (2003).
- [10] Sayyah, K., Narayanan, A., Persechini, D., and Brewer, P., "Conformal pixellated MQW modulator structure for modulating retroreflector applications," *IEEE Photonics Technology Letters* **17**(9), 1854–1856 (2005).
- [11] Tian, J., Guo, T., He, N., Du, J., Huang, Q., Hong, X., Fei, C., Wang, Y., Zhang, T., Zhang, J., and He, S., "Wide-field-of-view modulating retro-reflector system based on a telecentric lens for high-speed free-space optical communication," *IEEE Photonics Journal* **15**(5), 1–8 (2023).
- [12] Maglio, B. C., Quintana, C., Thueux, Y., and Smowton, P. M., "Photovoltaic modulating retroreflectors for low power consumption free space optical communication systems," *IEEE Journal of Quantum Electronics* **60**(5), 4000409 (2024).
- [13] Gilbreath, G. C., Rabinovich, W. S., Meehan, T. J., Vilcheck, M. J., Mahon, R., Burris, R., Ferraro, M., Sokolsky, I., Vasquez, J. A., Bovais, C. S., Cochrell, K., Goins, K. C., Barbehenn, R., Katzer, D. S., Ikossi-Anastasiou, K., and Montes, M. J., "Compact, lightweight payload for covert data link using a multiple quantum well modulating retro-reflector on a small rotary-wing unmanned airborne vehicle," in [*Airborne Reconnaissance XXIV*], *Proceedings of SPIE* **4127**, 57–67, SPIE, San Diego, California (2000).
- [14] Walters, R. J., Murphy, J. L., Rabinovich, W. S., Gilbreath, G. C., Wilt, D. M., Smith, M. A., Krasowski, M. J., Jenkins, P. P., Scheiman, D., Warner, J. H., Messenger, S. R., Lorentzen, J. R., and Summers, G. P., "Photovoltaically powered modulating retroreflectors," *Optical Engineering* **45**(3), 034003 (2006).
- [15] Stievater, T. H., Rabinovich, W. S., Goetz, P. G., Mahon, R., and Binari, S. C., "A surface-normal coupled-quantum-well modulator at 1.55 μm ," *IEEE Photonics Technology Letters* **16**(9), 2036–2038 (2004).
- [16] Salas, A. G., Stupl, J., and Mason, J., "Modulating retro-reflectors: technology, link budgets and applications," in [*Proceedings of the 63rd International Astronautical Congress*], International Astronautical Federation (2012).
- [17] Goetz, P. G., Rabinovich, W. S., Gilbreath, G. C., Mahon, R., Ferraro, M. S., Swingen, L., Walters, R. J., Messenger, S. R., Wasiczko, L. M., Murphy, J., Creamer, N. G., Burris, H. R., Stell, M. F., Moore, C. I., Binari, S. C., and Katzer, D. S., "Multiple quantum well-based modulating retroreflectors for inter- and intra-spacecraft communication," in [*Photonics for Space Environments XI*], *Proceedings of SPIE* **6308**, 63080A, SPIE, San Diego, California (2006).
- [18] Giggenbach, D., Knopp, M. T., and Fuchs, C., "Link budget calculation in optical LEO satellite downlinks with on/off-keying and large signal divergence: a simplified methodology," *International Journal of Satellite Communications and Networking* **41**(5), 460–476 (2023).
- [19] Rabinovich, W. S., Mahon, R., Burris, H. R., Gilbreath, G. C., Goetz, P. G., Moore, C. I., Stell, M. F., Vilcheck, M. J., Witkowski, J. L., Swingen, L., Suite, M. R., Oh, E., and Koplow, J., "Free-space optical communications link at 1550 nm using multiple-quantum-well modulating retroreflectors in a marine environment," *Optical Engineering* **44**(5), 056001 (2005).
- [20] Quintana, C., Wang, Q., Jakonis, D., Piao, X., Erry, G., Platt, D., Thueux, Y., Gomez, A., Faulkner, G., Chun, H., Salter, M., and O'Brien, D., "High speed electro-absorption modulator for long range retroreflective free space optics," *IEEE Photonics Technology Letters* **29**(9), 707–710 (2017).
- [21] Wang, Q., Noharet, B., Junique, S., Almqvist, S., Ågren, D., and Andersson, J. Y., "1550 nm transmissive/reflective surface-normal electroabsorption modulator arrays," *Electronics Letters* **42**(1), 47–49 (2006).
- [22] Maglio, B. C., *Electroabsorption modulators and laser diodes for free space optics and on-chip applications*, PhD thesis, Cardiff University, Cardiff, United Kingdom (2022). Available at <https://orca.cardiff.ac.uk/id/eprint/154270/>.
- [23] Rabinovich, W. S., Goetz, P. G., Mahon, R., Swingen, L., Murphy, J., Gilbreath, G. C., Binari, S. C., and Waluschka, E., "Performance of cat's eye modulating retro-reflectors for free-space optical communications," in [*Free-Space Laser Communications IV*], *Proceedings of SPIE* **5550**, 104–114, SPIE, Denver, Colorado (2004).
- [24] Arbabi, A., Arbabi, E., Horie, Y., Kamali, S. M., and Faraon, A., "Planar metasurface retroreflector," *Nature Photonics* **11**(7), 415–420 (2017).

- [25] Li, H., Lee, W.-B., Zhou, C., Choi, D.-Y., and Lee, S.-S., “Flat retroreflector based on a metasurface doublet enabling reliable and angle-tolerant free-space optical link,” *Advanced Optical Materials* **9**(21), 2100796 (2021).
- [26] Menting, E., “BEXUS user manual.” Version 8.2, Swedish Space Corporation (2024). Document BX_REF_BEXUS_User Manual_v8-2_26Dec24, 26 December 2024. Available at <https://rexusbexus.net/bexus/bexus-user-manual/>.