FY23 Innovative Spontaneous Concepts Research and Technology Development (ISC)

Ultra-Low-Power Optical Encoder Enabling "Laser-less" Data Transmitter in Optical Communications

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OBJECTIVES

The objective is to leverage the developed design approach using machine learning and validate in a typical operation scenario to bring forward a quantum well modulator design that can support a 10Mbps data rate of optical communication with distances of 10-100km, at milli-watt level power consumption. The quantum-well device design and supporting simulation should be mature enough to enable the devices to be fabricated in-house at JPL, and the optical system design and analysis should be mature enough to be proposed to a follow-on proposal/funding (such as R&TD topical area) to carry out a laboratory demonstration in 2–3 years' time frame.

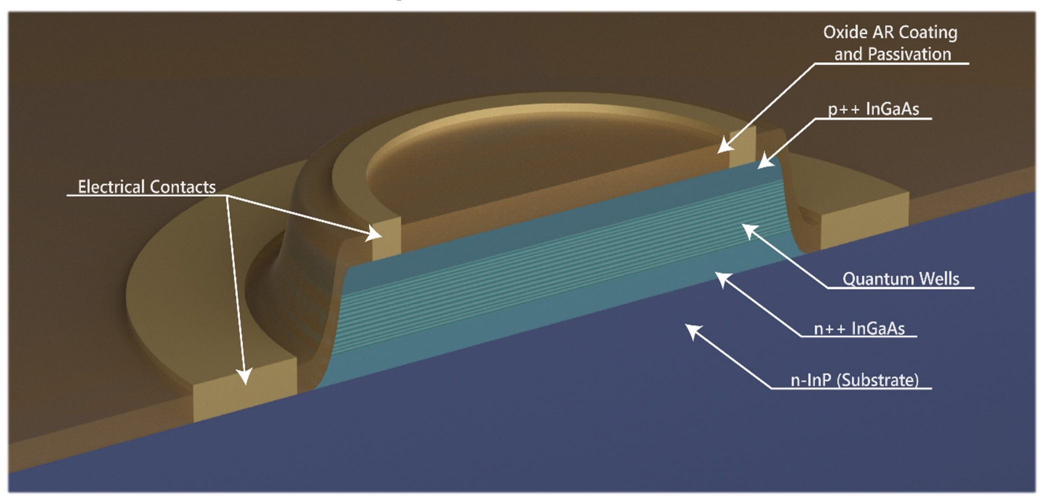

Figure 1. *A 3D illustration of the SQW modulator*

BACKGROUND

"Laserless" data transmission in optical communications is feasible with a wide-angle retroreflector and an ultra-low-power optical modulator to efficiently encode information onto the reflected optical beam [1][2]. This is particularly attractive to mission concepts requiring comprehensive data communication and sensing channels operating with extreme size, weight, and power constraints. For example, a long-lived Lunar Geophysical Network is prioritized as a New Frontiers mission in the Planetary Science and Astrobiology Decadal Survey 2023-2032 [4]. Such a "laserless" communication method can "beam" back the sensors' science data without an active optical carrier device (laser) located at the geophysical nodes, relieving the concern of lasers' power consumption and survival through the lunar nights. The laser can be instead installed on remote space assets such as a lunar orbiter, a large rover/lander, or be handheld by an astronaut. Another example is the space-based radio interferometry at 1-100MHz to study the "Dark Age" (prioritized as a "Discovery Area" in the Astro2020 decadal survey [3]), involving using optical links for the baseline ranging determination and data exchange between a mothership and a large swarm (N>1000) of small CubeSats forming a gigantic radio telescope.

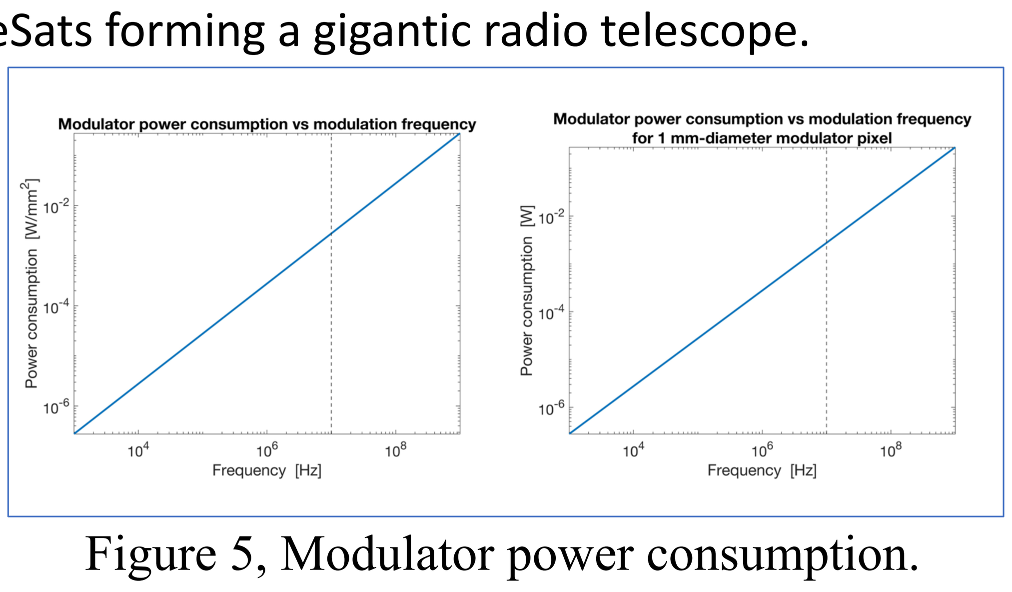

Figure 5, Modulator power consumption.

SIGNIFICANCE OF RESULTS/BENEFITS TO NASA/JPL

The research effort demonstrated the feasibility of using SQW-based modulating retroreflecting optical communication to significantly simplify the architecture and lower the cost of the Lunar Geophysical Network and low-frequency space-based radio interferometric telescope for data communications and ranging sensing. The mW level power consumption at a 10Mbps data rate at a distance of 50km would work in both mission concepts. The "laserless" optical transceiver would address the critical telecommunication challenge for distributed assets on planetary surfaces. This technology will enable alternative low-mass, low-power approaches to long-term lunar geophysical stations based on small packages, like the Farside Seismic Suite, scheduled to fly to the Moon on a commercial lander as part of the CLPS program. Additionally, this type of communication channel may be mission-saving when the lunar lander or other lunar surface asset's battery level is too low to use active RF/microwave/optical transmitters.

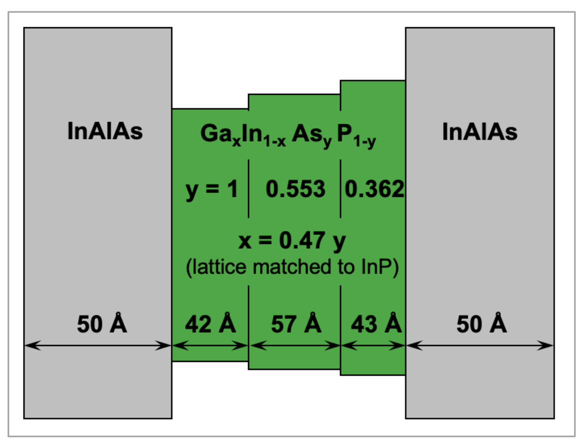

Figure 2. The *SQW design The above quantum well (middle, green) structure is repeated 200 times with a total thickness of 5.04 µm.*

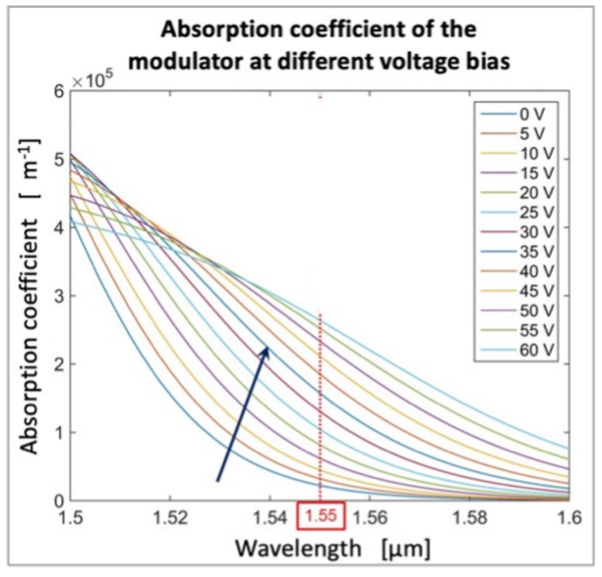

Figure 3. *The light absorption coefficient at different voltage bias (input modulating signal)*

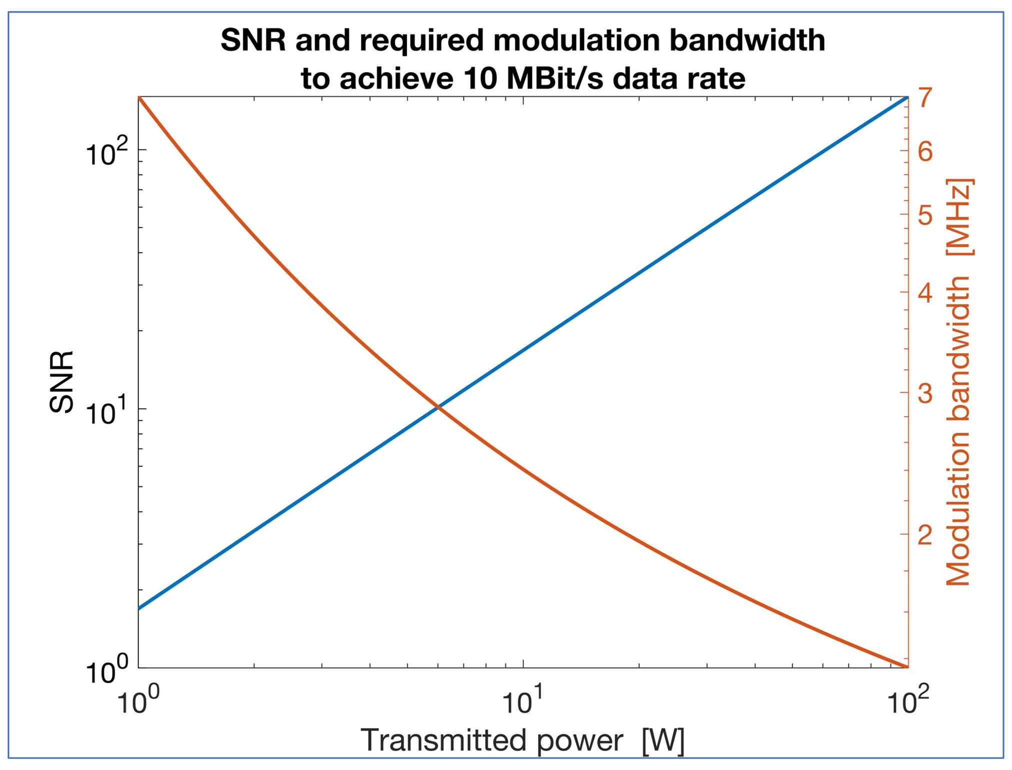

Figure 4. *Shannon limit for modulator design with -140dB link budget, detection NEP = 5 pW/sqrt(Hz)*

REFERENCES

[1] Peter, G. Goetz, et al. *2010 MILITARY COMMUNICATIONS CONFERENCE*. IEEE, 2010. ***[2]*** *Wheaton, Skylar, et al. Scientific Reports, 11, 8504 (2021).* ***[3]*** *NASEM "Pathways to Discovery in Astronomy and Astrophysics for the 2020s," (2021).* ***[4]*** *NASEM "Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032," (2022).* ***[5]*** *Bianconi, Simone, et al. IEEE Journal of Selected Topics in Quantum Electronics, 24, 6, (2018).*

APPROACH AND RESULTS

Surface-normal electro-absorptive modulators are advantageous for optical communication since they enable efficient optical collection over large areas. In particular, stepped quantum well (SQW) modulators leverage the quantum-confined Stark effect to achieve strong electro-optical coupling over reduced interaction lengths, enabling angle-insensitive retroreflectors for optimal optical interrogation. Advanced simulation tools allow tailoring the epitaxial structure of these modulators for optimal performance at the required driving voltage and modulation depth, enabling a minimized power consumption at a given data rate [5]. Using this approach, the Co-I designed SQW modulators for remote optical tagging, which demonstrated optical data rates exceeding 1 Gbps with an energy consumption below 3 pJ/bit [1,5]. The key challenge is that to achieve such performance levels, the design of these modulators needs to be tailored to the specific conditions and requirements of each given application.

We leveraged the design approach formulated in [5] and validated in [1], and brought forward a quantum well modulator design that can support a 10Mbps data rate of optical communication with distances of 10-100km, at milli-watt level power consumption. As shown in Figure 2, we have designed an optimized modulator at 1550nm at 300K operation temperature with the following expected performance: 5% modulation depth, 89%transmission, 5V voltage swing, 1mm by 1mm size, in the highest power consumption scenario with a modulation frequency of 10MHz, the expected power consumption is 2.76mW.

We also finalize the optical system design and analysis specifically for two future mission concepts: Lunar orbiter-surface communication, and radio telescope with a swarm of CubeSats. We have derived a preliminary communication link budget applicable to both mission concepts. For a distance of 50km, the total optical link budget is estimated as -140dB with the following optical design: 2mm transmission beam waist, quality factor 2, transceiver aperture 100mm, beam divergence 1mrad, reflected beam waist 100mm, receiver aperture 200mm. As a result, with a 10-watt laser in the orbit, the receiver at the orbiter (together with the laser) is 1.6 microwatts. Assuming the optical detection is limited by shot noise and dark noise to NEP~ 5 pW/sqrt(Hz), we expect the communication data rate to be 10Mbps with ~ 2MHz modulation frequency.

We have quantitatively studied the potential impact of lunar dust deposition onto the retroreflecting surface and estimated for a worst case (the landing site is 2500m away from the reflector), the optical transition is expected to be at 60% after 1 year.

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Subrahmanya V Bhide, Simone Bianconi, and Lin Yi "Passive Optical Links Supporting Spaceborne Low Radio Frequency Interferometric Telescope," submitted to *IEEE Aerospace Conference 2024, Big Sky*, MN, 2024.

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