Low size, weight and power concept for mid-wave infrared optical communication transceivers based on Quantum Cascade Lasers

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

The low complexity, low size, weight and power Mid-Wavelength Infra-Red optical communications transceiver concept presented, realized and tested in the laboratory environment. Resilience to atmospheric impairments analyzed with simulated turbulence. Performance compared to typical telecom based Short Wavelength Infra-Red transceiver.

OCIS codes: *(140.5965) Semiconductor lasers, quantum cascade; (010.1330) Atmospheric turbulence; (060.2605) Free-space optical communication*

http://dx.doi.org/10.1364/AO.99.099999

1. INTRODUCTION

Free Space Optical Communication (FSO) technology through multiple demonstrations has proved to be a viable solution for high data rate, always spectrum available and low probability of detect and intercept demanding applications.

FSO community demonstrated solutions to all technical challenges including micro-radian level pointing and atmospheric turbulence correction [1]. The remaining critical hurdle to trigger wide spread of FSO systems in commercial and military applications is system's cost effectiveness. To accomplish this FSO systems shall be simple and efficient. Elimination of complex and power "hungry" elements of the system will support an aim for low cost solutions.

Atmospheric attenuation and scintillation play significant role to the health of FSO links. Mid-wavelength infrared (MWIR) region (3 um – 5um) has a superior transmission through atmosphere compared with that of Visible, Near-Infrared (NIR), Short-wavelength infrared (SWIR) and even Long Wavelength Infrared (LWIR) [2,3]. Compared with NIR and SWIR it has better penetration through fog and therefore shall enable better links availability for tropical and marine locations [4,5]. Moreover, atmospheric turbulence has lesser impact on MWIR links. Therefore Adaptive Optics is not required for most applications [6,7]. Also, diffraction limited MWIR systems requiring less sophisticated pointing stability sub-systems due to larger beam divergence. Lastly, MWIR terminals can transmit more power and stay below Maximum Permissible Exposure (MPE) threshold to avoid damaging biological effects to the eye or skin [8].

Since 1970s there was an aim to develop longer wavelength FSO systems. Those systems were based on bulky, high power consuming and expensive gas lasers and cryogenically cooled detectors [9]. The recent accelerated advances in Quantum Cascade Lasers (QCLs) as well as progress in mercury cadmium telluride (MCT) photo-diodes enable low Size, Weight and Power (SWaP) and therefore cost efficient optical systems operating in MWIR and LWIR spectrum regions [10]. Moreover, it is feasible to operate Quantum Cascade Lasers at room temperature without cooling [6,7].

Pulse Position Modulation (PPM) is an efficient modulation format for "photon starved links". With the high order M-ary format it is possible to reach high peak power at moderate average power levels [11]. PPM enables operation of high peak power QCLs at room temperature, therefore increasing wall-plug efficiency of communication system [12]. Our MWIR system operates with 32-ary PPM signals reaching sub-tenth percent duty cycle. An uncooled photoelectromagnetic Mercury Cadmium Telluride detector was used to complete the low SWAP communication transceiver model system.

In this paper we investigate MWIR communication concept which promises to eliminate SWaP driving thermal management and wavefront correcting system components. Performance of MWIR is also compared to traditional SWIR system in the presence of simulated atmospheric turbulence. Anticipated size, weight and power of FSO system is analyzed. Sample link analysis demonstrating feasibility of this concept for real applications is presented.

2. TRANSCEIVER CONCEPT

Our communication transceiver concept is based on the premise of low complexity approach with minimum utilization of power "hungry" and "bulky" components. Elimination of the need for transceiver cooling and atmospheric correction (adaptive optics) enables efficient and low cost free space communication concept.

A. Uncooled Quantum Cascade Laser

Uncooled QCL installed in custom copper mount. Low duty cycle operation (for high order PPM) enables room temperature operation without cooling. The transmitter is a directly modulated Quantum Cascade Laser with distributed feedback (DFB) structure needed to achieve single mode operation. Because of QCL's low alpha parameter, the adiabatic chirp caused by direct modulation is negligible. Due to QCL's wide angle emission a large size hemispherical lens is used to capture the laser output.

B. Photoelectromagnetic receiver

Photoelecromagnetic effect enables the operation of Mercury Cadmium Telluride (MCT) based receiver in uncooled condition. With a D* of ~1e-9 [13] the required power to close the link is ~1 uW.

Figure 1 Photoelectromagnetic Detector from Vigo System

C. Size, Weight and Power

It is expected that transceiver will weigh about 90 grams, will be less than 60 cubic cm and draw less than 5 watts of power. The breakdown of these parameters is given in the

	Size (cm^3)	Weight (grams)	Power (Watts)
Transmitter	1	20	1.5
Receiver	8	50	0.2
Drive Electronics	50	50	3
Total Packaging	59	90	4.7

Table 1 Size, Weight and Power breakdown of MidIR Transceiver

D. Expected Link Analysis

To support low size and weight approach we've assumed 1 cm diameter transmit and receive apertures for link analysis. Having small apertures also helps to simplify pointing system to tenth of milljradian stability. We assumed simple pointing system will be able keep pointing error penalties under 1 dB. For the link we've selected a typical 10 km limit for horizontal terrestrial and marine applications where coherence length r0 parameter could be substantially low (3 cm in our case).

We have chosen 5.1 W of peak power as it was demonstrated by Razeghi group [12] in 2014. Because of use of large area MWIR receivers we can claim fairly low fading losses (0.5 dB). Scintillation losses are low as well. Somewhat large transmit and receive coupling (static) and implementation losses associated with the aim for simple inexpensive transceiver solution.

Our link analysis points to the "healthy" 3 dB margin on 10 km MidIR communication links through the "harsh" atmospheric link (Figure 2).

LINK SUMMARY	
Transmitter	
Tx laser power	7.1 dBW
Static Tx optical losses	-1.5 dB
Tx Pointing losses	-1.0 dB
Tx antenna gain	86.1 dBi
Range	
Isotropic loss	-102.0 dB/m^2
Atmospheric loss	-0.3 dB
Scintillation loss	0.5 dB
Receiver	
Rx aperture area	-41.0 dB/m^2
Static Rx optical losses	-1.5 dB
Dynamic Fading losses	-0.5 dB
RX Comm implementation loss	-2.6 dB
Received Power	**-56.7 dBW**
Receiver Sensitivity	**-60.0 dBW**
MARGIN	**3.3 dB**

Figure 2 Notional Link Analysis for Mid-IR Free Space Optical Communications link. Wavelength – 4.1 um, distance – 10 km, data rate – 100 Mbps, r0 ~ 3.0 cm

3. EXPERIMENTAL SETUP

A. Atmospheric Turbulence Simulator

In our setup we simulated optical turbulence with a simple approach described by Sandrine Thomas [14]. Optical phase plate was prepared by coating a 2-inch Si window with resin material and installed it into commercial rotary stage [15]. Resulting phase screen was characterized by measuring the value of r0 with the optical transfer function method similar to the one outlined in [16].

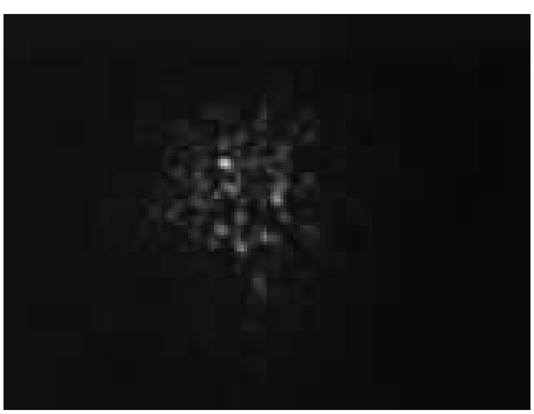

Figure 3 Snapshot of QCL beam through prepared phase plate

B. Measurement Concept

A bonded QCL die was installed into custom copper mount with no cooling. QCL emission was captured with hemispherical lens and directed to photo-detector. Turbulence simulator (rotating phase plate) was placed in the collimated space of the QCL beam in off-axis position. Perturbed by simulated turbulence the beam was focused on an uncooled photoelectromagnetic Mercury Cadmium Telluride detector from Vigo Systems (see Figure 4).

SWIR system was comprised of fiber pigtailed telecom DFB laser and LiNbO3 modulator and pin detector. Optical collimators were used to collimate transmit beam and couple received beam into fiber (Figure 4). SWIR beam was perturbed with phase plate in the same fashion as MWIR beam.

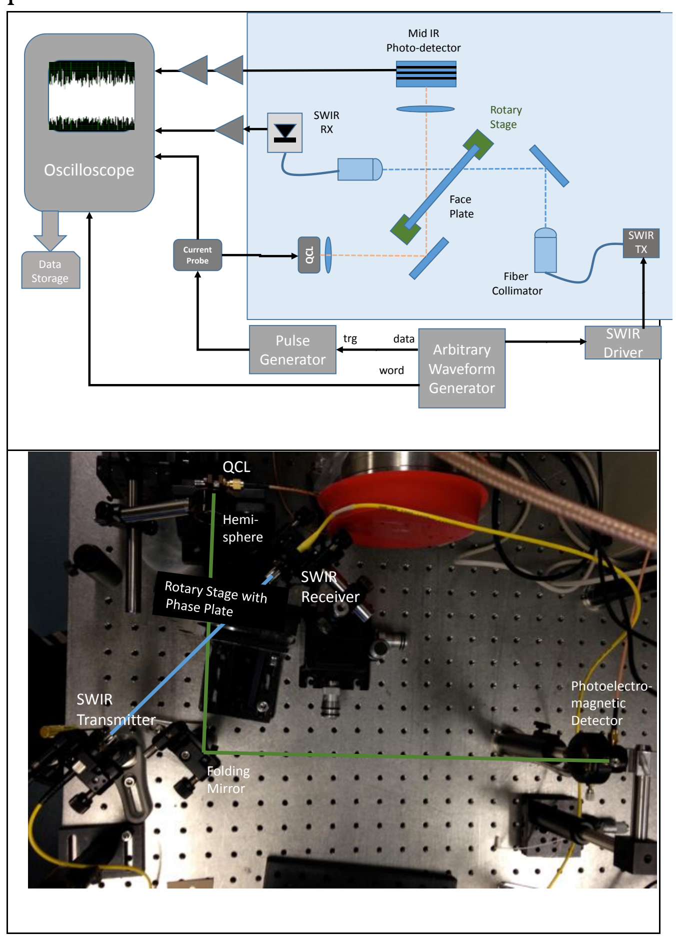

Figure 4 Measurement Setup

PPM signals were generated by Arbitrary Waveform Generator. 32-ary PPM modulation format was chosen to keep QCL duty cycle operation at few percent, therefore minimizing QCL thermal effects and enabling room temperature operation without any cooling. Due to bandwidth limitation of pulse generator slot rate was chosen at 20 MHz.

Data was captured at various SNR levels with and without rotating phase plates.

About 200 PPM words were used for each data set. Synchronized drive and PPM word boundaries signals were also recorded to support post processing analysis. All data was captured and initially processed with Labview (Figure 5).

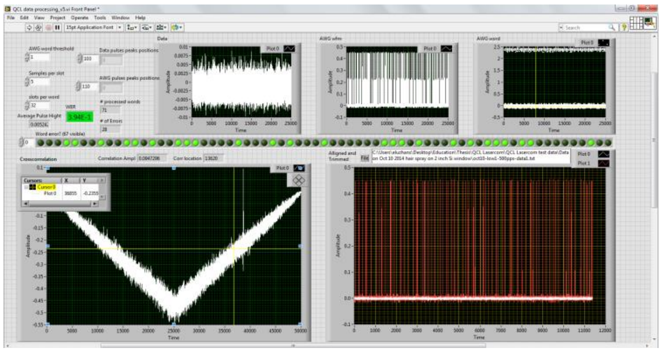

Figure 5 Labview GUI for capturing and cross-correlating 32-ary PPM data

C. Measurement Results and comparison to SWIR links

Each data sample was cross-correlated (Figure 5) and aligned with drive signal. Subsequently, words boundaries signal was aligned to data.

By aligning signal data with drive signal we were able to accurately locate slots and words positions. Next, samples within each slot were summed. The slot with largest summed value was declared a "winner" and word data was decoded. This result was compared to drive signal's data and word was defined in error or not based on whether data winning slot was matching that from the corresponding drive signal word. Word Error Rate (WER) was calculated from a complete set of co-aligned words (between 90 and 150 depending on cross-correlation off-set). Most of WER values were above 5e-3 due to the limited sample data range.

4. MEASUREMENTS RESULTS

Figure 6 demonstrates measurement results for both MWIR (dash) and SWIR (dot) links [16]. The relative WER is plotted against phase plate's rotation speed. As can be seen, MWIR links demonstrate significantly smaller dependence on presence of turbulence. SWIR test results show clear deterioration of WER with increased turbulence speed, simulating increased Greenwood frequency.

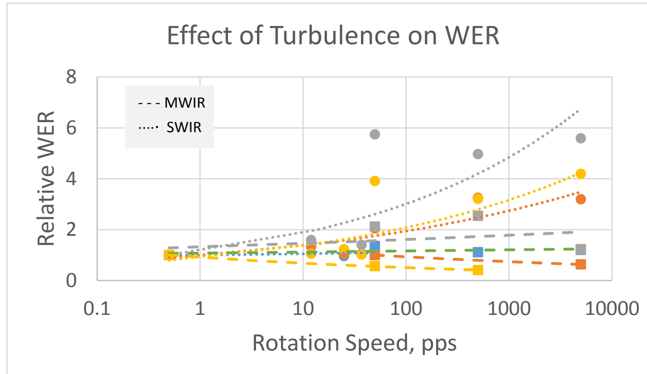

Figure 6 Effect of phase plate rotation speeds on WER of MWIR and SWIR links

With hard decoding Bit Error Rate will be equal to Word Error Rate. But, BER can be improved with soft decoding. We used Gagliardi's [17] concept

$$BER_{soft} = \frac{M}{2} Q\sqrt{SNR} = \frac{\mathbf{M}}{2(\mathbf{M}-1)} WER$$

, where **M** is the PPM order.

Jitter is one of the key "culprits" impacting health of PPM communication links. And, due to the nature of our concept (low cost concept) it is expected that jitter would be substantial. It was previously shown [18] that utilization of Gray coding minimizing susceptibility of PPM links to poor jitter. Gray codding is a reflected binary code allowing only one bit change between consecutive values. As such it is allowing to spread errors for the effective error correction. However, investigation of the test data with Gray coding demonstrated no change in system performance (Figure 7) comparing to binary coding. As such, we conclude that jitter impact was negligible in our experiments.

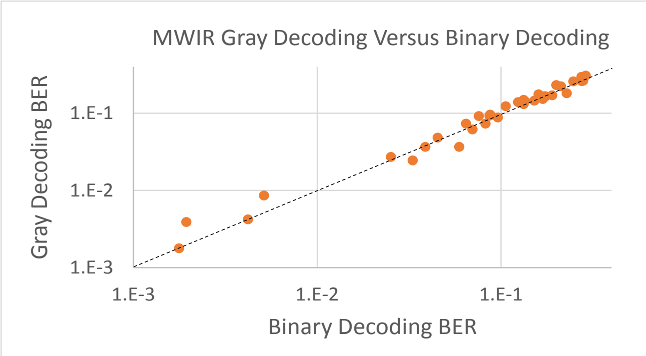

Figure 7 Gray decoding of MWIR BER results versus Soft Decoding

5. CONCLUSIONS

Low cost MWIR transceiver concept was developed, tested and analyzed against comparable SWIR system. As predicted, MWIR system demonstrated superior tolerance to simulated atmospheric turbulence. Anticipated MWIR system performance on notional 10km free space link with sub-optimal atmospheric conditions was analyzed. Expected MWIR transceiver size, weight and power were presented as well.

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