

Free space optical communication utilizing mid-infrared interband cascade laser

A. Soibel^{1a}, M. Wright^a, W. Farr^a, S. Keo^a, C. Hill, R. Q. Yang^b and H. C. Liu^c

^aJet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, 91109, USA

^bSchool of Electrical and Computer Engineering, University of Oklahoma, Norman, Oklahoma, 73019, USA

^cInstitute for Microstructural Sciences, National Research Council, Ottawa, Ontario, Canada, K1A 0R6

ABSTRACT

A Free Space Optical (FSO) link utilizing mid-IR Interband Cascade lasers has been demonstrated in the 3-5 μm atmospheric transmission window with data rates up to 70 Mb/s and bit-error-rate (BER) less than 10^{-8} . The performance of the mid-IR FSO link has been compared with the performance of a near-IR link under various fog conditions using an indoor communication testbed. These experiments demonstrated the lower attenuation and scintillation advantages of a mid-IR FSO link through fog than a 1550 nm FSO link.

Keywords: semiconductor lasers, infrared sources, optical communication

1. INTRODUCTION

Interband Cascade (IC) lasers¹ are novel Sb-based semiconductor lasers that have demonstrated a high performance operation in the 3-5 μm wavelength region, including high output power,² cw room temperature operation^{3,4} and high-speed modulation.⁵ This progress enables utilization of IC lasers as optical transmitter in the free space optical (fso) communication links operating in the 3-5 μm atmospheric transmission window. Due to the favorable atmospheric properties, mid-infrared (mid-IR) atmospheric transmission windows occupying 3-5 or 8-12 μm spectral bands are of particular interest for realization of high-speed fso data links. The molecular (Rayleigh) and particulate (Mie) scattering⁶ as well as the wavefront propagation phase errors decrease with wavelength⁷ and therefore, the transmission loss of an optical link operating in the mid-IR would be significantly reduced compared to the loss of the optical link at 1.5 μm . The lower loss advantage of fso link in 8-12 μm spectral window has been recently demonstrated for operation during a bad weather condition such as fog.⁸ In addition, the spectral radiance of the main sources of background

¹ Alexander.Soibel@jpl.nasa.gov

radiation in atmosphere (Sun, Earth, Moon, city lights, etc.) has a pronounced minimum around $3.5\mu\text{m}$, and thus the background noise will have a minimum as well. Yet, the progress in the development of mid-IR fso links has been hindered by the lack of high speed lasers, optical amplifiers and detectors operating in the desirable wavelength regions. In this work we have utilized a recently developed high speed IC lasers⁵ to realize a mid-IR fso link operating at data rates up to 70 Mb/s with bit-error-rate (BER) less than 10^{-8} . These results are the first step in the development of a practical mid-IR fso communication system and are important for the future improvement of mid-IR lasers and detectors.

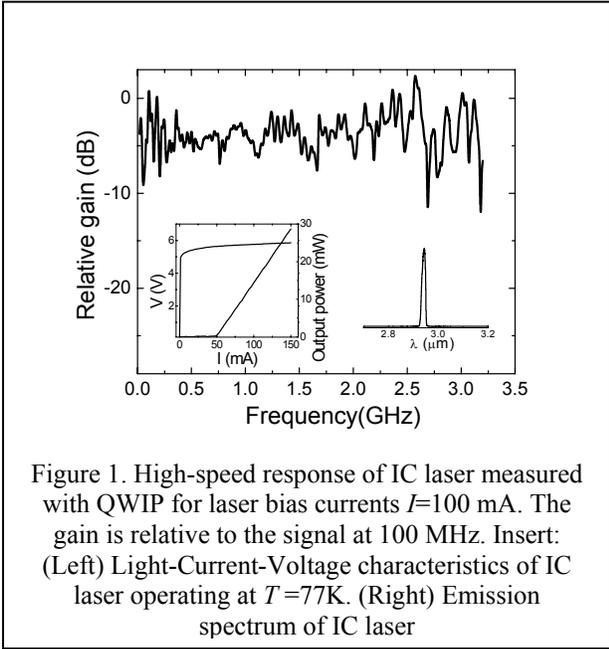


Figure 1. High-speed response of IC laser measured with QWIP for laser bias currents $I=100$ mA. The gain is relative to the signal at 100 MHz. Insert: (Left) Light-Current-Voltage characteristics of IC laser operating at $T=77\text{K}$. (Right) Emission spectrum of IC laser

We evaluated the high speed performance of our standard structures reported previously.⁵ In short, these lasers have been grown in a solid source Veeco Applied-EPI Gen-III molecular beam epitaxy (MBE) system on undoped p-type GaSb substrates. After the epitaxial growths, parts of the wafer were processed into broad-area mesa stripe (100 or 150- μm -wide) lasers by wet chemical etching and metal deposition. Two mm in length lasers were mounted onto an oxygen free copper holder and wire bonded to 50 Ω RF microstrip line. Lasers were mounted on the temperature-controlled cold finger of an optical cryostat that was modified to enable high speed measurement up to 18 GHz. Initially, Light-Current-Voltage (L-I-V), spectral and high speed characteristics of fabricated IC lasers have been evaluated (Fig. 1). In the latter, the high speed modulation was achieved by driving the laser with an RF signal from a low-phase-noise signal generator and photocurrent signal was measured with the fast Quantum Well Infrared Photodetector (QWIP).⁹ The high speed response of the IC laser (Fig. 1), which was calculated from the measured amplitude of RF signal, shows that the modulation bandwidth of IC lasers used in this work exceeds 3.2 GHz.

2. FREE SPACE OPTICAL LINK

Figure 2 shows the experimental set-up used for measurements of the optical link utilizing an IC laser. In these experiments, the IC laser was modulated with a pseudorandom bit sequence (PRBS) signal from a bit-error-rate transmitter (BERT) and a bias tee was used to combine the high speed modulation and laser dc bias current. The laser operated at $T = 77$ K under applied dc bias of about $I = 100$ mA with output power of ~ 10 mW at $3.0 \mu\text{m}^5$ and the laser emission was collimated by a ZnSe lens. After a free space transmission of about 1 m, the optical signal was collected by a second lens and focused on a high speed Mercury-Cadmium-Telluride (MCT) detector manufactured by Vigo. Compared to QWIP used in the initial high-speed laser characterization experiments, Vigo MCT detectors have much better sensitivity and higher operational temperature reachable with thermoelectric coolers that make them more practical for use in fso experiments, yet their useful bandwidth was limited to about 70 MHz. After the detection, the high frequency photocurrent signal was fed into a high speed amplifier followed by second BERT receiver or high speed oscilloscope after the bias tee.

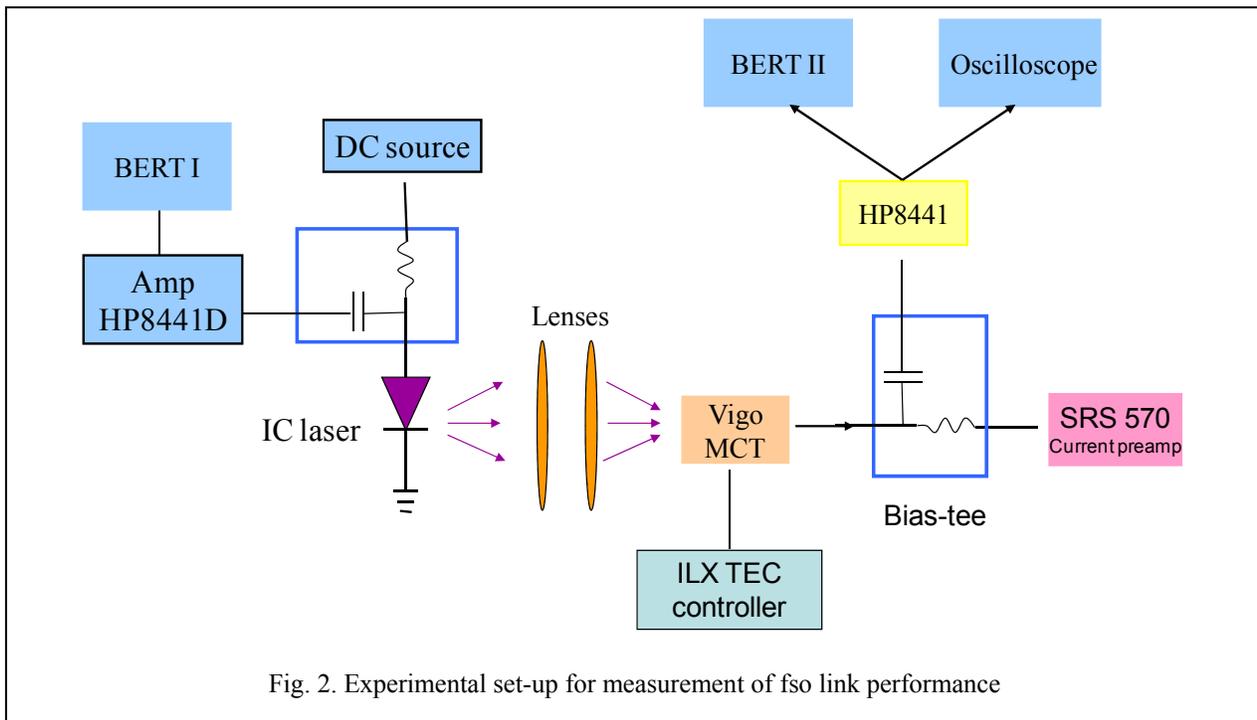
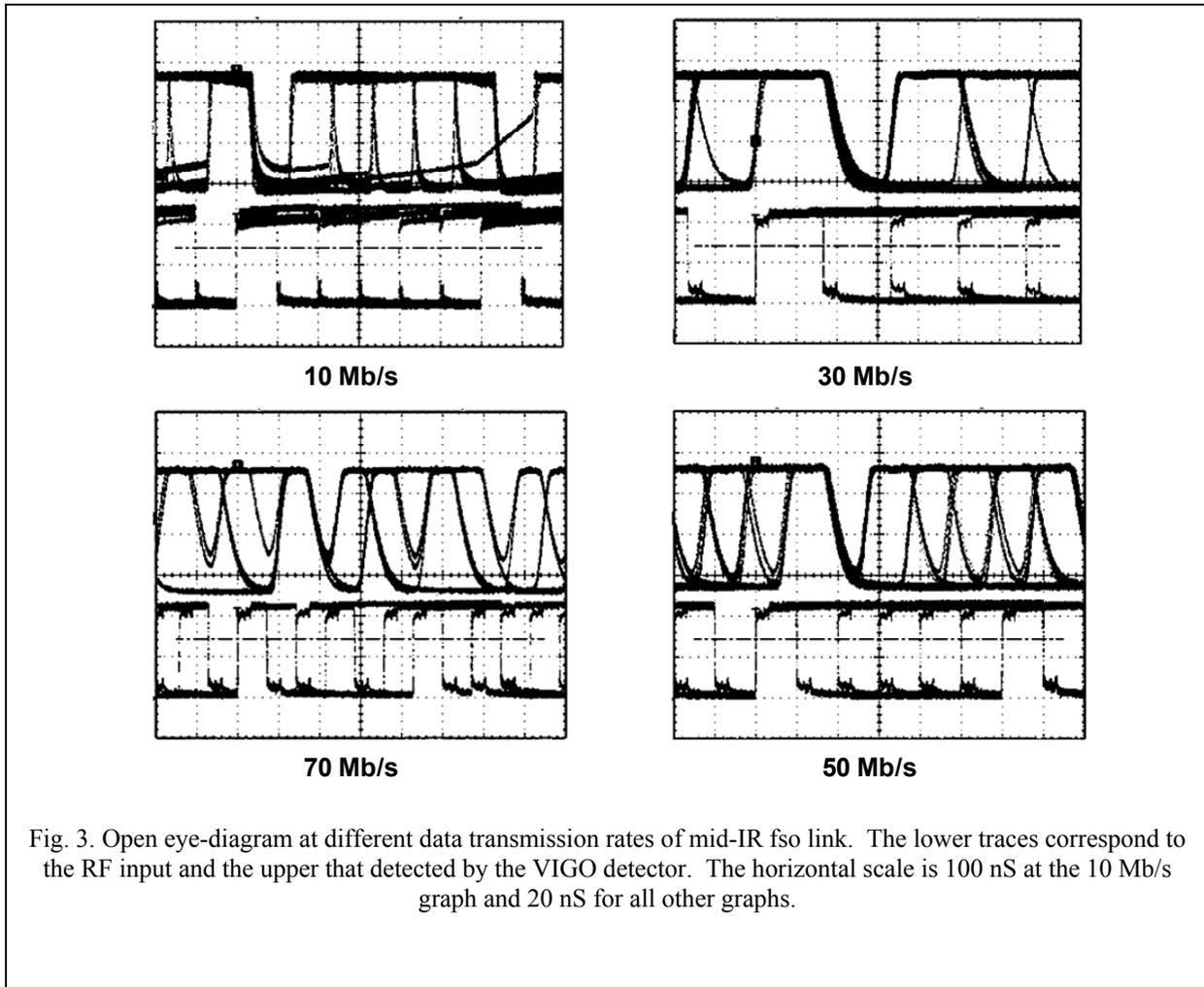


Figure 3 shows the results of an indoor fso transmission experiment for data transmission rates from 10 Mb/s to 70 Mb/s. The open-eye diagrams acquired for different data transmission rates

are clearly seen in this graph. At data rates of 30 and 50 Mb/s, the observed large size of eye opening, small distortion and time variation of zero crossing demonstrate high performance of FSO link based on the developed IC lasers. The degradation of open-eye diagram at data rates below 10 Mb/s was attributed to the laser heating/cooling during long on/off times and the upper limit of data transmission rate of about 70 Mb/s was set by the VIGO MCT detector bandwidth. These limitations to achievable data transmission rates can be overcome by using IC lasers with better thermal properties such as narrow waveguide ridge devices and by utilizing detectors with higher bandwidth.



The performance of FSO links for different attenuation of the optical signal was also studied and BERs were measured using the BERT receiver (Fig. 2). Figure 4 shows the open-eye diagrams acquired for data transmission at rate of 30 Mb/s for different attenuation of FSO link and the measured BER vs. optical attenuation, showing exponential dependence at low BER. This graph

demonstrates that FSO link utilizing developed IC lasers can operate with BER less than 10^{-8} that was the sampling time limit in this experiment, with attenuation up to 14 dB. The link BER was limited by the receiver sensitivity where, for example, 18 dB attenuation corresponded to a received power of about $50\mu\text{W}$. With the availability of more sensitive and high-bandwidth detectors, the high quality eye diagrams reveal that the transmitters could support much higher photon efficiency optical links.

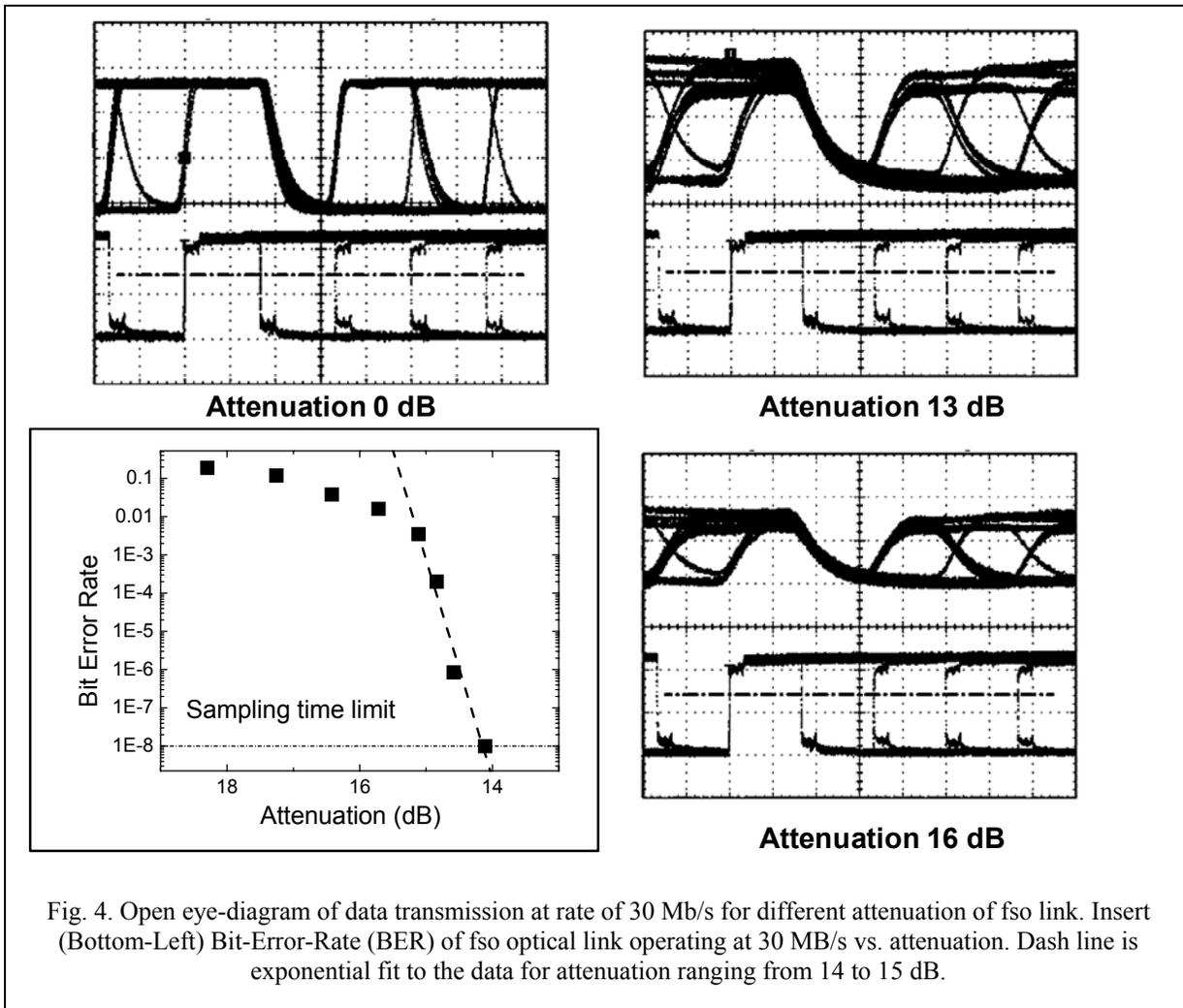
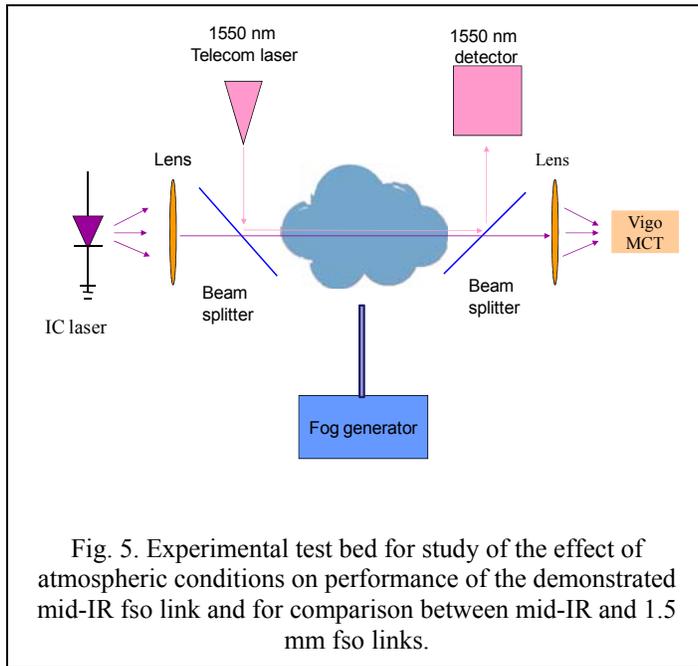


Fig. 4. Open eye-diagram of data transmission at rate of 30 Mb/s for different attenuation of fso link. Insert (Bottom-Left) Bit-Error-Rate (BER) of fso optical link operating at 30 MB/s vs. attenuation. Dash line is exponential fit to the data for attenuation ranging from 14 to 15 dB.

3. FSO LINK AT 1.5 MICRONS VS. 3.0 MICRONS:

Figure 5 shows the experimental testbed that was used to study the effects of fog on performance of the demonstrated mid-IR fso link and for comparison between mid-IR and 1.5 μm fso links. The mid-IR fso link utilized the developed IC laser, and a commercial telecom laser and detector were

used for the 1.5 μm link. In this test, the collimated optical beams from both lasers were combined

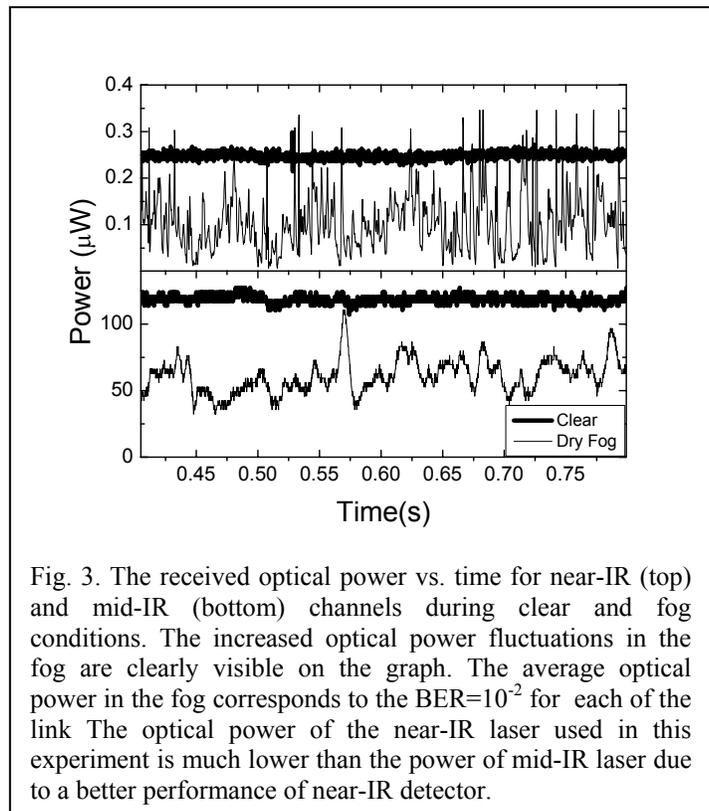


by a beam splitter, and after that both signals passed through the fog so the mid-IR and near-IR free space optical link shared the same optical path through the fog. After completing the assembly, both mid-IR and near-IR fso links were tested and BERs vs. attenuation for both links were measured (not shown).

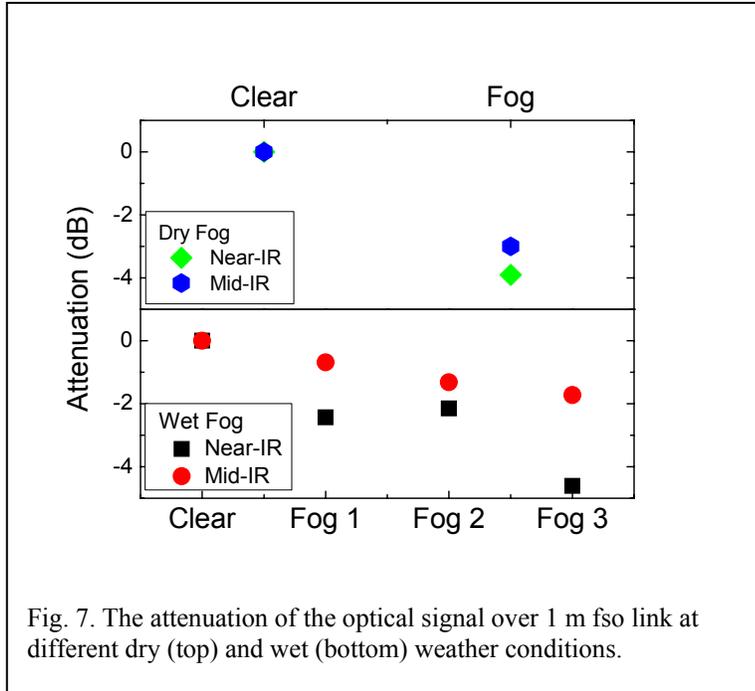
Next, properties of the fso link were evaluated in the clear and in the presence of “dry” and “wet” fogs, where the former was created by the flow of liquid nitrogen (LN_2) in the air and the latter by a

commercial fog generator. The three different “wet” fogs were generated (Fog 1, 2, 3), in which the fog density and the water particle size was minimal in the “Fog 1”, and both density and particle size were increased in the “Fog 2” and “Fog 3” conditions. Based on the fog generator specifications, the average size of the water particles was estimated to increase from 7 μm to 15 μm between Fog 1 and 3 but that was not verified experimentally.

The influences of the different fog conditions on the fso link were investigated by measuring the temporal fluctuations of the received optical power for both mid-IR and near-IR channels at different fog



conditions as shown in figure 6. Initially, the power fluctuations were measured in the absence of any air flow (denotes as “Clear” in the figures), then in the presence of the fog created by LN₂ (dry



fog) and in the wet fog (Fog 1, 2, 3). Figure 7 shows the attenuation of the average optical power (relative to the optical power measured in clear) over 1m link for both channels at different fog conditions. This graph shows that optical power of near-IR link decreased faster than the power of mid-IR signal for all fog conditions, and at the “Fog 3” conditions for example, the attenuation of 1.5 μm channel is 2 times stronger than that of the 3 μm channel for 1m long fso link.

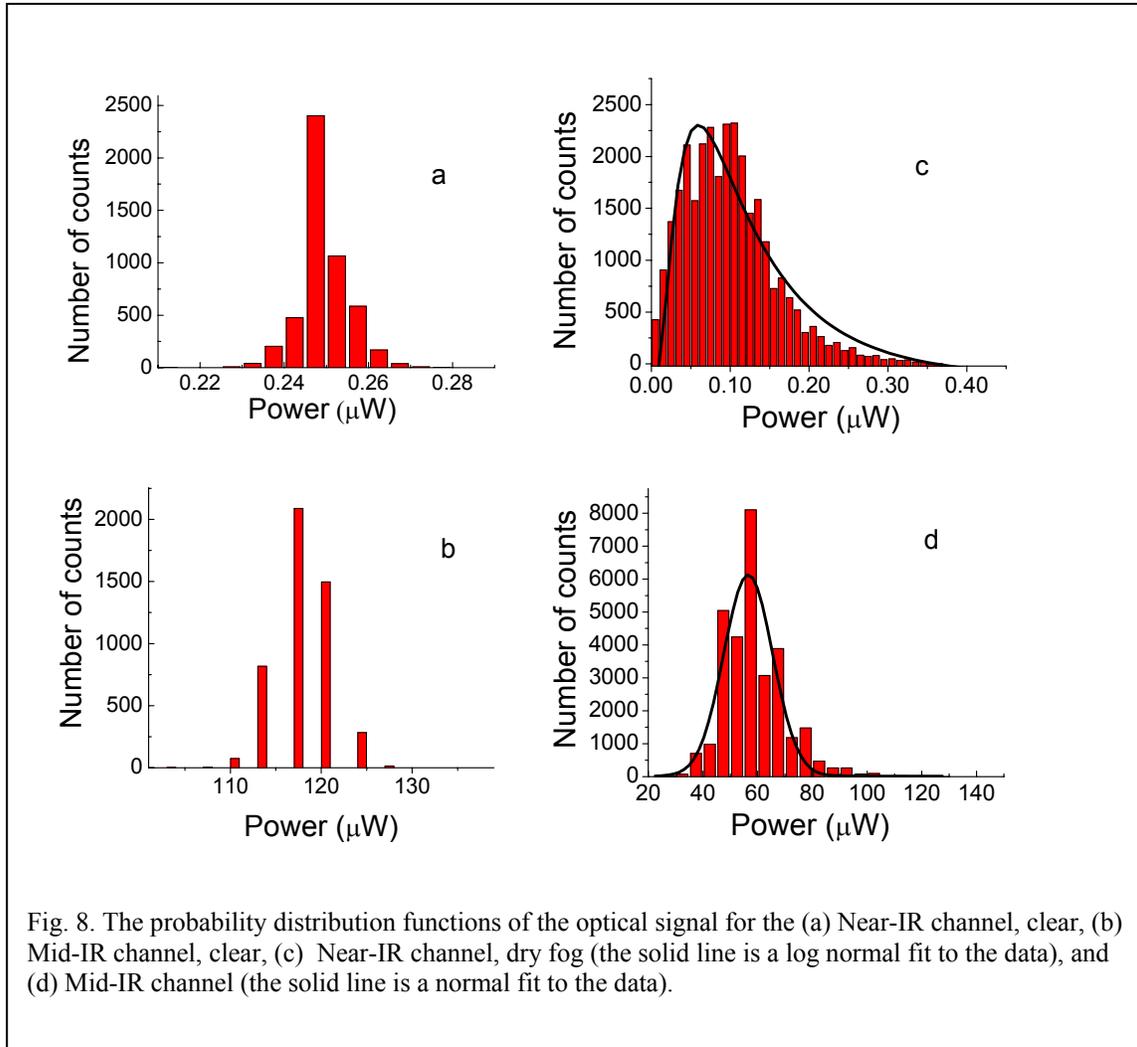
Figure 8 shows the probability distribution function of the optical signals with and without fog for 1.5 μm and 3 μm channels. The optical power of near-IR channel showed a normal distribution with no flow, but in the dry fog it exhibited a strongly log normal distribution typical of turbulent atmosphere. The scintillation index, σ^2_1 calculated from $\sigma^2_1 = \langle I^2 \rangle / \langle I \rangle^2 - 1$, where $I(t)$ is the measured signal strength, is large ($\sigma^2_1 = 0.35$) for the near-IR channel in the dry fog showing that near-IR channel is strongly affected by scintillation. In contrast, the mid-IR 3 μm data showed only normally distributed power in both scenarios (without and with fog from the LN₂ flow), demonstrating the advantage of using 3 μm for transmission under strongly scintillating effects.

In the wet fog, the scintillation indices were found to be small indicating very weak turbulence. Also, the measured ratios of the scintillation index did not follow that predicted by theory¹⁰ when comparing the two wavelengths. These results indicated that in wet fog conditions the scintillation was not dominated by the wavelength dependence but by the detection and/or transmission power variations. This was also confirmed by looking at the probability distribution

functions that show a normal behavior for both no flow and under fog conditions for both wavelengths (not shown).

In conclusion, we have utilized the high speed IC lasers to realize the fso link operating in 3-5 μm atmospheric transmission window and compared its performance with that of near-IR link at different fog conditions using an indoor communications testbed. This work has validated suitability of IC lasers as a mid-IR light source for high speed free space optical communications links and has demonstrated the advantages of mid-IR fso link in fog due to its lower attenuation and scintillation.

Acknowledgments: The authors are grateful to H. Hemmati, S. Forouhar, S. D. Gunapala, M. Hermann, E. Kolawa, J. A. North, L. G. Gref and R. T. Odle for their support and encouragement. The research described in this Letter was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (NASA).



REFERENCES

- ¹ R. Q. Yang, "Infrared laser based on intersubband transitions in quantum wells", *Superlattices and Microstructures*, vol. 17, pp. 77-83, 1995.
- ² C. L. Canedy, W. W. Bewley, J. R. Lindle, C. S. Kim, M. Kim, I. Vurgaftman, and J. R. Meyer, "High-power and high-efficiency midwave-infrared interband cascade lasers", *Appl. Phys. Lett.*, vol. 88, 161103, 2006.
- ³ K. Mansour, Y. Qiu, C. J. Hill, A. Soibel, and R. Q. Yang, "Mid-infrared interband cascade lasers at thermoelectric cooler temperatures", *Electronics Letters*, vol. 42, no. 18, pp 1034-1035, 2006.
- ⁴ M. Kim, C. L. Canedy, W. W. Bewley, C. S. Kim, J. R. Lindle, J. Abell, I. Vurgaftman, and J. R. Meyer, "Interband cascade laser emitting at $\lambda=3.75 \mu\text{m}$ in continuous wave above room temperature", *Appl. Phys. Lett.*, vol. 92, 191110, 2008.

⁵ A. Soibel, M. W. Wright, W. Farr, S. Keo, C. Hill, R. Q. Yang and H. C. Liu, “High speed operation of Interband cascade Lasers”, *Electronics Letters*, vol. 45 , no. 5, pp 264-265, Feb. 2009.

⁶ E. D. Hinkley, “Laser Monitoring of the Atmosphere”, Springer-Verlag, Berlin, 1976.

⁷ L. C. Andrews, and R. L. Phillips, “Laser Beam Propagation Through Random Media”, SPIE Press, Bellingham, 2005.

⁸ R. Martini, C. G. Bethea, F. Capasso, C. Gmachl, R. Paiella, E. A. Whittaker, H. Y. Hwang, D. L. Sivco, J. N. Baillargeon, and A. Y. Cho, “Free space optical transmission of multimedia satellite data streams using mid-infrared quantum cascade lasers,” *Electronics Letters*, vol. 38, no. 4, pp 181-183, 2002.

⁹ H. C. Liu, M. Buchanan, and Z. R. Wasilewski, “Short wavelength 1–4 μm . infrared detectors using intersubband transitions in GaAs-based quantum wells,” *J. Appl. Phys.*, vol. 83, no. 11, pp. 6178-6181, 1998.

¹⁰ M. W. Wright, J. Roberts, W. Farr and K. Wilson, “Improved optical communication performance combining adaptive optics and pulse position modulation”, *Opt. Eng.*, vol. 47, no 1, 016003, 2008.