Bit error rate performance of a free space optical link using double clad fibers

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ABSTRACT

Mobile and embedded applications are emerging in the growing field of free space optical links (FSOL). Some mobile applications for FSOL include spacecraft, aircraft, and automotive. These applications by nature require low size weight and power (SWaP) solutions. The main challenge with any FSOL system is the strict pointing requirements. Common solutions to pointing and alignment of FSOL include gimbals, fast steering mirrors, and adaptive optics. All of which provide viable solutions at the cost of increased SWaP. Previously, we presented the use of both large core fibers and double clad fibers (DCF) to interface FSOL transmit and receive optics with small form factor pluggable optical transceivers (SFP). Double clad fibers have been shown to enable a common optical path by transmitting through a single mode core and receiving through a large inner cladding. This enables a single set of symmetric transmit and receive optics, which decreases the SWaP. In addition, using DCF increases the received power stability of the link relative to a multi-mode fiber (MMF) transmitting. To determine the viability of the system, bit error rate performance needs to be investigated. The results of this paper show that at a bit rate of 10 Gbps, double clad fibers offer similar bit error rate performance to single mode fibers when transmitting and multi-mode fibers when receiving enabling a symmetric duplex FSOL reducing SWaP.

Keywords: Free Space Optical Communications, Optical Bit Error Rate Testing, Double Clad Fiber, Small Form-Factor Pluggable Optical Transceiver

1. INTRODUCTION

Free space optical links (FSOL) can enable up to 10 Gbps (gigabits per second) wireless communication systems. A challenge for any FSOL is maintaining alignment in the system. This is usually solved using active control measures, however this increases the complexity and cost of the system. To reduce size, weight, and power (SWaP) passive systems were investigated, favoring designs that incorporated small form-factor pluggable optical transceivers (SFP+) and used a common optical path for transmitting and receiving.

In FSOL systems, fibers can be used to guide the light between the transceiver and optics. In a previous paper [1], a system was investigated using varying fiber core sizes to carry light between a transceiver and associated transmit and receive optics. It was shown that using large core receiving fibers increased the misalignment tolerance however the study revealed power instabilities when transmitting from large core multi-mode fibers (MMF). Another previous paper [2] investigated the bit error rate (BER) performance of a 10 Gbps FSOL using the large core fibers and showed that modal dispersion must be taken into consideration when using MMF. Reference [3] demonstrated that the performance of Double clad fibers (DCF) match the power stability of using SMF transmitting to MMF. This is because the light from the transmitter is sent through the single mode core. As a receiving fiber, the DCF has the same misalignment tolerance as an MMF [3] where the light is received in the larger multi-mode inner cladding. Therefore, the DCF enables a symmetric bidirectional optical setup by transmitting through the single mode core and receiving in the large inner cladding. Using a symmetric setup allows for further decreases of the SWaP of the system by reducing the number of fibers and optics needed.

The previous study on double clad fibers investigated lateral misalignment but used received power as the only figure of merit. In this paper, the effect of lateral misalignment on BER performance of the free space optical link utilizing double clad fibers will be presented.

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2. EXPERIMENTAL SETUP

This section describes the experimental setups used to collect the data presented. The BER measurements are taken under two conditions: a fiber only setup used for comparative purposes as a best-case scenario, and a free space system where the effect of misalignment on the BER of the system was investigated. The system parameters that are varied are the type of fiber used to transmit the signal, the type of fiber used to receive the signal, the divergence angle of the beam in free space, the vertical misalignment of the system, and the horizontal misalignment of the system. The fibers tested are given in Table 1. All fibers tested are two meters in length.

In both systems a Spectronix Eye-BERT gen-2 is used with an extended range (ZR) SFP+ plugged into the SFP+ port. The Eye-BERT generates a 2^{31} pseudo random bit sequence (PRBS) at 10 Gbps and sends it to the SFP+ on board. The SFP+ modulates 1550 nm light using on-off keying and sends it into the transmit fiber. The signal is sent through either the fiber only system or the free space optical link system and is routed back into the receive port in the SFP+ plugged into the Eye-BERT. The Eye-BERT compares the received signal with the transmitted signal and determines how many bits were evaluated in error to calculate the corresponding bit error rate (BER).

Table 1. Test Fibers

Fiber	Core Size (μm)	Graded or Step Index	Numerical Aperture
Single Mode Fiber (SMF)	9[a]	Graded	0.12[b]
Multimode Fiber (MMF)	105	Step	0.22
Double Clad Fiber (DCF)	9, 105	Step	0.12, 0.22

[a]Mode Field Diameter. [b]Not Given, Typical Reported

2.1 Fiber Only System

The fiber only setup baselines the fiber performance to isolate the effects of the free space system. The tests are controlled and automated using a PC running Python. A block diagram of the setup is presented below in Fig. 1. In the fiber only system, the light is launched into a single mode fiber (SMF). The light is then attenuated using the digital variable attenuator and sent through a 50/50 splitter. Half the signal is sent to a power meter and half the signal is launched into the test fiber and back to the receive port of the SFP+ in the Eye-BERT.

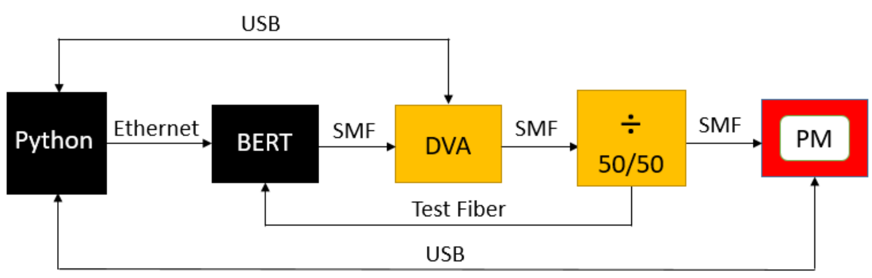

Figure 1. Fiber only test block diagram.

2.2 Free Space System

The BER tests are run at divergence full angles of -0.5 mrad, 0.0 mrad, 0.5 mrad, 1.0 mrad, and 1.5 mrad. The divergence angle was calculated by measuring the beam diameter at two locations in between the optics. The divergence angle was calculated using Eq. (1) below,

$$\theta = \operatorname{atan}\left(\frac{d_2 - d_1}{L}\right) \tag{1}$$

where θ is the full divergence angle in radians, d_2 is the measured beam diameter in mm furthest from the transmitting optics, d_1 is the measured beam diameter in millimeters closest to the transmitting optics, and L is the separation distance in millimeters of the two locations where d_1 and d_2 were measured.

The free space optical link is setup on a table with the transmitter and receiver two meters apart. The transmitting optics are mounted onto a horizontal motorized stage and the receiving optics are mounted onto a vertical motorized stage, as seen in Fig. 2. Each set of optics is also equipped with a linear motor to control the distance from the fiber end to the lens. This distance determines the divergence angle of the setup.

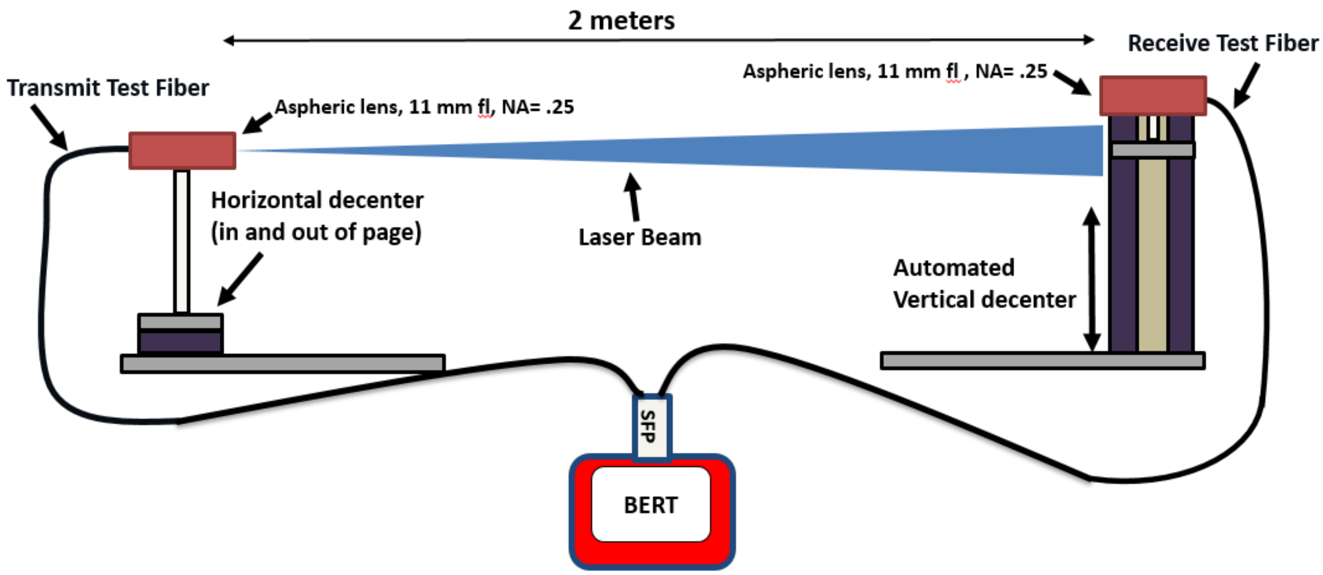

Figure 2. Free space optical link testbed diagram.

In addition to the BER tests, a beam profiler is used to investigate the effect of misalignment on launch condition of the receive fiber. The measurements are taken at a centered location, a slightly misaligned location, and a location where the power is just barely enough to see with the profiler (minimum power approximately -15dBm).

2.3 System Automation

A single control system was used to automate the collection of the BER, received power levels and control the misalignment. This allowed for easily repeatable tests. Each BER measurement for both the fiber only and free space systems was run until a pre-defined confidence level (C_L) was reached. To determine the C_L, a Poisson distribution was used. When no errors are detected, Equation (2) is used to calculate the C_L [4]

$$C_L = 1 - e^{-N_{bits} * BER} \tag{2}$$

where C_L is the confidence level, N_{bits} is the total number of bits analyzed by the Eye-BERT, and BER is the measured bit error rate. If errors are detected, a new distribution must be used to calculate the C_L.

Equation (3) is used to calculate the confidence level with errors detected (C_{LE}) [4]

$$C_{LE} = 1 - \left(e^{-N_{bits} * BER} * \frac{1}{N_{error}!} * \left(BER * N_{bits} \right)^{N_{error}} \right) \tag{3}$$

where N_{error} is the number of errors detected. After the C_L or C_{LE} is reached the control system then increases the attenuation or moves to the next misalignment depending on whether the test configuration is the fiber only setup or the FSOL. The C_L and C_{LE} were set to 95% or higher for all the measurements taken in this paper.

3. RESULTS AND DISCUSSION

3.1 BER v Power Received

Various data sets were taken to show trends in BER performance between transmit fiber type, receiving fiber type, and divergence angle. Figure 3 shows the BER verses received power when a SMF is used to transmit to a receiver using the various receive fiber types. The BER verses received power in the fiber only tests resulted in similarly shaped profiles with DCF having slightly higher BER than both the MMF and SMF for common power levels. When compared with the results from the fiber only tests, the free space tests using DCF and MMF at the receiver have higher BER while the SMF at the receiver maintains about the same performance. This is expected because the increased modal dispersion in the large core of the receive fibers.

The only significant physical difference between the DCF and MMF is the presence of the single mode inner core. The cause for the increase of BER in the systems using DCF may be explained by the interface between the inner core and inner cladding. The single mode inner core may increase BER in the system through differential mode delay. The single mode inner core allows the most direct to propagation down the fiber which is faster than the higher order modes propagating in the inner cladding. If the larger inner cladding is not filled the signal pulses in can spread so far as to cause pulse splitting at the detector.

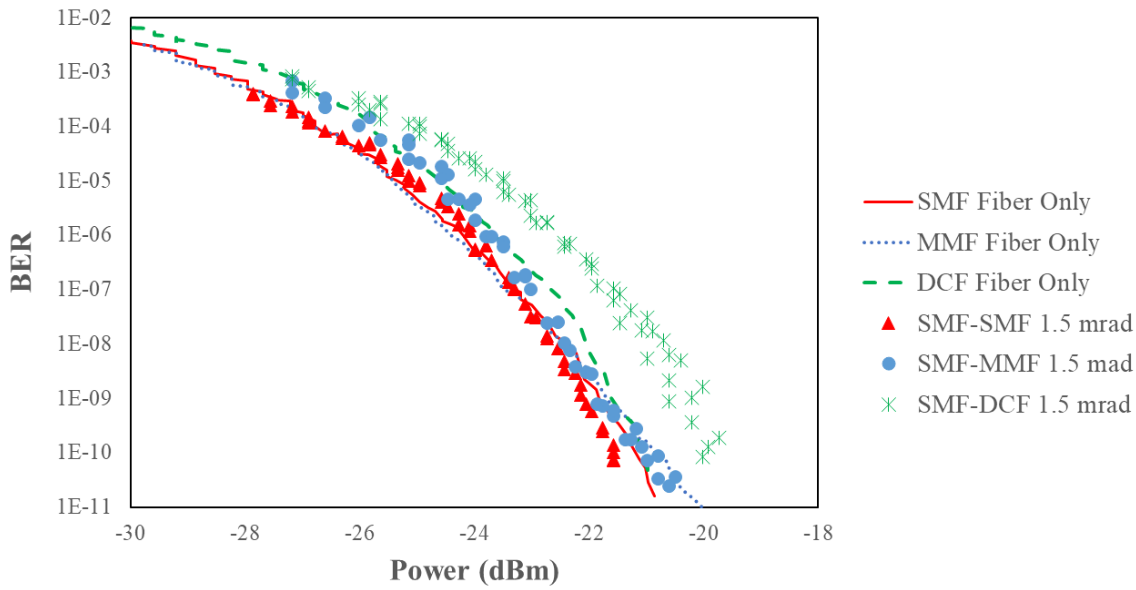

Figure 3. BER vs Power curve for fiber only and single mode fiber transmitting. BER are higher for DCF for same receive power. Two-meter length fibers were used.

Figure 4 shows the BER vs received power when a large core fiber is used at the transmitter. The BER of the system had a greater variance when both the large core MMF and DCF fibers were used for transmitting and receiving. This effect can be attributed to modal dispersion. The BER increases as the sum of the number of modes allowed by the system increases. As investigated in [3], the DCF as a transmit fiber allows fewer modes in the beam than the MMF as transmit fiber. This results in a power profile with less spatial variance than the MMF when transmitting. Higher spatial variance in the beam results in areas of low power. As misalignment increases the probability of the high-power areas of the beam missing the receive fiber increases, decreasing the received power at the SFP+. The MMF and DCF can both receive a high number of modes. Overall, the MMF-MMF system has the highest BER, followed by the DCF-DCF, with the DCF-SMF having the best performance. As the length of the large core fiber increases, the modal dispersion increases [10], leading to higher BER for the same receive power. In the MMF-MMF case high order modes are propagated in both transmit and receive fibers. In case of DCF-DCF only the receive fiber propagates the higher order modes which effectively shortens the length of modal dispersion as compared to the MMF-MMF case. In the case of DCF-MMF the total amount of higher order modes per length is equal to the DCF-DCF however due to differential mode delay as discussed above the DCF-DCF system has higher BER then the DCF-MMF.

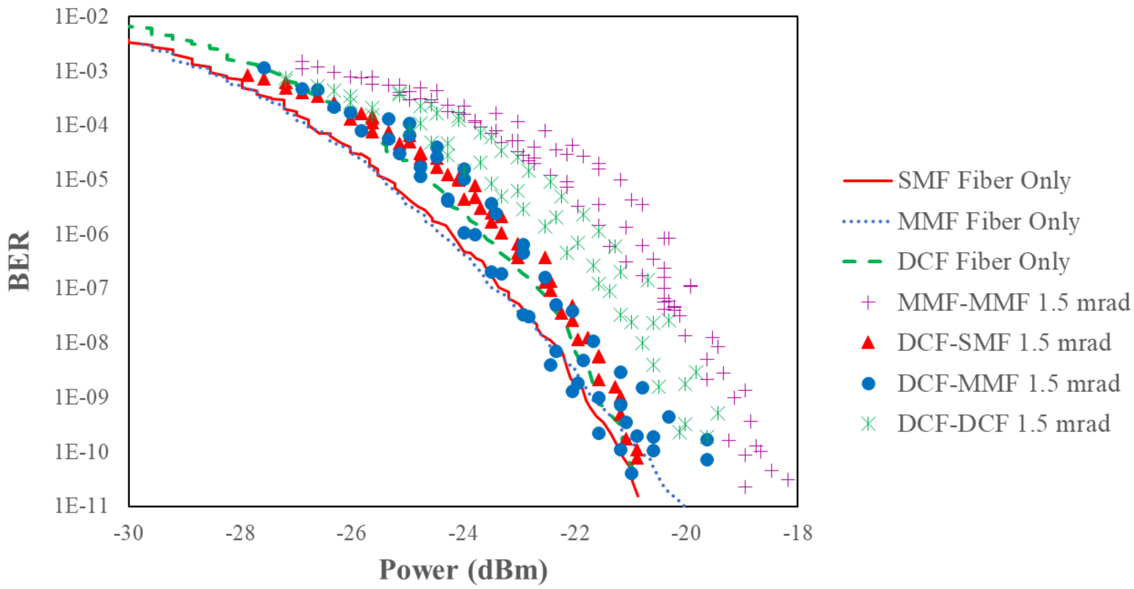

Figure 4. BER vs Power curve for fiber only and large core fiber transmitting. BER are highest for MMF-MMF for same receive power. Two-meter length fibers were used.

3.2 BER Decenter Span

For the free space tests, the major figure of merit is the misalignment tolerance of the system. By processing the data to find the distance between points where the BER was less than 10^{-8}, a decenter span can be defined. This BER limit was arbitrarily chosen, as each application will have different BER requirements. The decenter spans were taken for each fiber combination and divergence angle in both the vertical and horizontal direction. The vertical and horizontal decenter spans were averaged to find the decenter span reported below. First the DCF and MMF are compared as receiving fibers. Figure 5 displays the decenter span verses the divergence angle of the transmitted beam in free space using the SMF as the transmitting fiber. The figure shows that the DCF and MMF have roughly equal misalignment tolerance as receiving fibers. The SMF as a receive fiber has the least tolerance as expected.

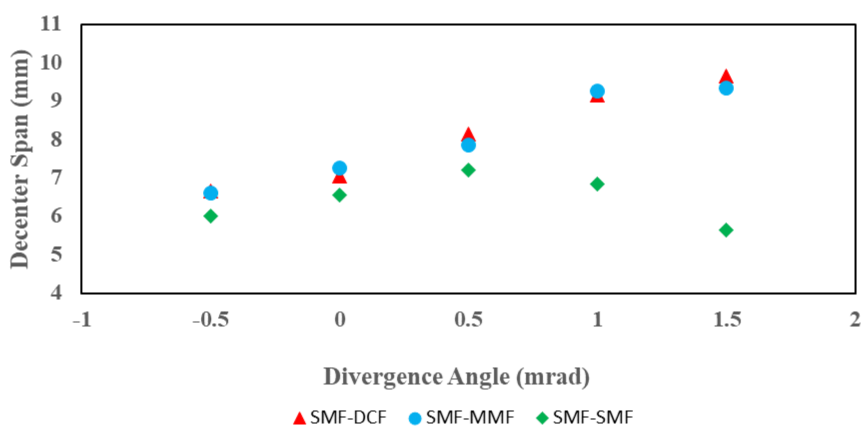

Figure 5. Decenter Span vs Divergence Angle Receive Fiber Comparison. The decenter span is defined as the distance over which the BER is less than 10^{-8}.

Next, the SMF and DCF are compared as transmitting fibers. Figure 6 shows the BER defined decenter span verses divergence angle for the SMF to SMF, SMF to DCF, DCF to SMF, and DCF to DCF combinations. The DCF and SMF have roughly equal BER defined decenter spans over the various divergence angles. The misalignment tolerances of the systems using DCF as a receive fiber increase with divergence angle. As the divergence angle increases the peak power decreases as it is spread into a larger spot size. The larger spot size increases the misalignment tolerance of the system up to a point where the decreased power density is too low for error-free communication. At an optimal divergence angle these factors will be balanced and misalignment tolerance maximized. A peak was not observed for the DCF and MMF receiving fibers, as the optimal divergence angle was higher than those that were tested. The SMF as a receive fiber reaches a maximum at 0.5 mrad divergence angle. Figure 6 demonstrates that DCF can act as a transmitting fiber with equal performance to a SMF, independent of receiving fiber.

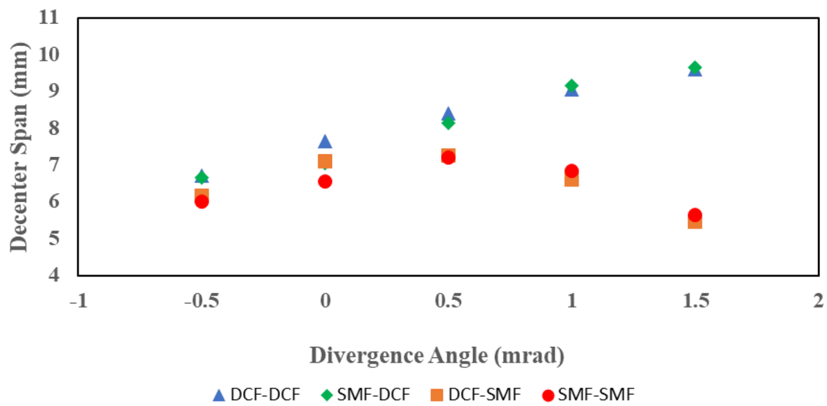

Figure 6. Decenter Span vs Divergence Angle Transmit Fiber Comparison The decenter span is defined as the distance over which the BER is less than 10^{-8}.

Next, we compare the SMF-MMF and DCF-DCF cases. From figures 3 and 4, the BER was higher in DCF-DCF for the same power levels as the SMF-MMF. However, the decenter span of the system was similar or higher for the DCF-DCF case. Comparing power levels at the misalignment limit, the DCF-DCF system experienced -20.5 dBm at 1.5 mrad and 4.8 mm offset from center. The SMF-MMF system receive power was -22.05 dBm at 1.5 mrad and 4.6 mm offset from center. This shows that while the BER for the SMF-MMF is lower for common power levels, the DCF-DCF system makes up for this with higher power for the same misalignment.

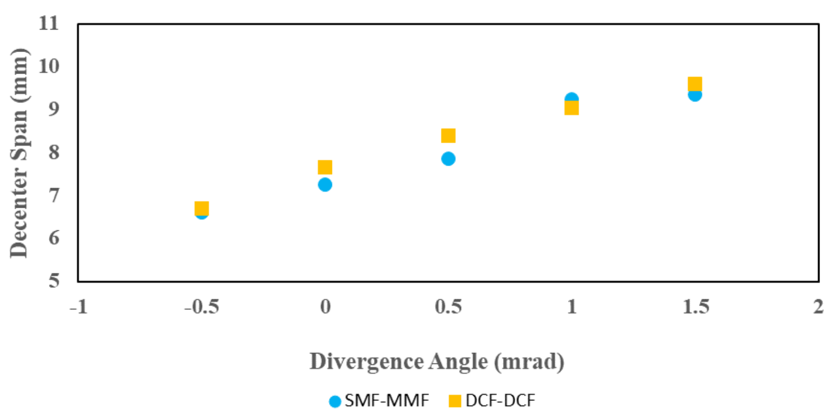

Figure 7. Decenter Span vs Divergence Angle SMF-MMF and DCF-DCF. The decenter span is defined as the distance over which the BER is less than 10^{-8}.

3.3 Receive Fiber Launch Condition

Initial investigations into the effects of launch conditions in the receive fiber on the BER of the FSO used a beam profiler to measure the power profile of the receive fiber. Investigation into the launch condition of the receive fiber indicate there are power inefficiencies in the MMF as a receiving fiber. This may be due to skew rays, which are observed in the MMF receive fiber at higher misalignments. The exposure and gain settings on the beam profiler were adjusted for every reading to prevent saturation. At higher misalignments the exposure and gain settings were maximized to see as much of the low power signal as possible with this setup. The profiles, below in figures 7 and 8, showed that skew rays were present at significant misalignment in the MMF but not present in the DCF. This leads to less power in near the center of the fiber, resulting in less power being received by the SFP+. At 5 mm misalignment and 1.5 mrad beam divergence, the DCF-DCF system had a receive power of -26.75 dBm. At the same misalignment and divergence angle, the DCF-MMF system had a receive power of -28.73 dBm, demonstrating the reduced power coupled into the SFP+ because of the presence of skew rays.

a) b) c)

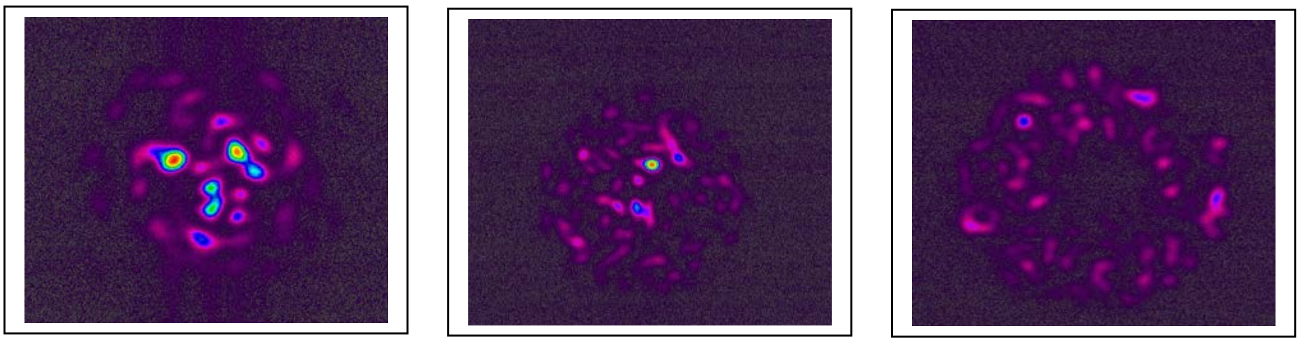

Figure 8. Receive Fiber Power Profiles for DCF-MMF link with a beam divergence angle of 1.5 mrad. a) The fiber profile with the beam centered. b) The fiber profile with the beam misaligned by 3 mm. c) The fiber profile with the beam misaligned by 5 mm.

a) b) c)

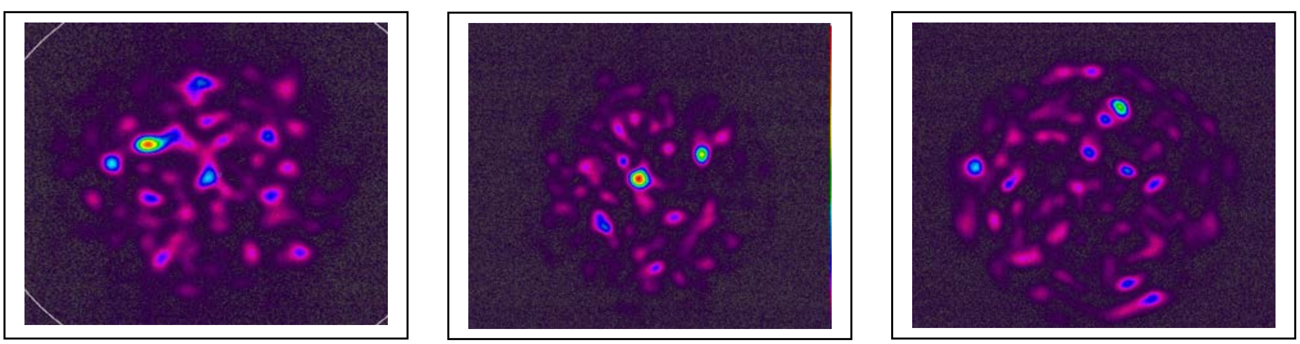

Figure 9. Receive Fiber Power Profiles for DCF-DCF link with a beam divergence angle of 1.5 mrad. a) The fiber profile with beam centered. b) The fiber profile with the beam misaligned by 3 mm. c) The fiber profile with the beam misaligned by 5 mm.

4. CONCLUSIONS

This paper has presented data for a 10 Gbps FSOL using combinations of SMF, MMF, and DCF as transmitting and receive fibers. Setups utilizing a symmetric DCF setup showed elevated BER for common receive powers when compared to the SMF-MMF setup. However, the DCF-DCF system showed higher receive powers for the same misalignment, resulting in an increased misalignment tolerance. The results show that DCF have similar misalignment tolerance to a SMF when transmitting and has similar misalignment tolerance when compared to the MMF for receiving. These results demonstrate the viability of a bi-directional free space optical link utilizing small form-factor pluggable optical transceivers and double clad fibers to transmit and receive through a single symmetric optical path, enabling a decrease in system SWaP. Future work will focus on quantifying the effects of skew rays on BER performance and using higher transmit powers to determine if skew rays appear in DCF at higher misalignments.

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