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Universal Fiber for Short-Distance Optical Communications

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(Invited Paper)

***Abstract*—Universal fiber is an optical fiber that supports both multimode and single-mode transmission. It is a multimode fiber with a mode field diameter of the fundamental mode roughly matching that of a standard single-mode fiber. In today's short-distance communications, both multimode fiber and single-mode fiber are used. Universal fiber can accommodate the needs of single-mode and multimode transmission so that end users can take advantage of the cost and performance benefits of each transmission type. In this paper, we present the design and properties of universal fiber, as well as its transmission performance for 100G systems. We also explore several application scenarios where the fiber can be utilized. In particular, we illustrate how the fiber can be used in 5G wireless fronthaul applications to meet the current needs while providing a path for future upgrades. Testing results and discussions of practical issues are also presented.**

***Index Terms*—5G wireless application, multimode fiber, optical fiber communications, single mode fiber.**

I. INTRODUCTION

A. Use Multimode Fiber and Standard Single Mode Fiber in Short Distance Communications

IN SHORT distance optical communications, OM3/OM4 multimode fibers (MMFs) have been widely used for data transmission for distances less than 100–150 m. The distance range covers not only data centers, but also high-rise buildings and wireless fronthaul applications. MMF is widely deployed because the associated VCSEL-based optical transceiver is very cost effective and power efficient. As the industry moves to higher data rate of 100G, the multimode (MM) transmission still covers most of the distances needed [1]. On the other hand, single-mode fiber is used in data centers for both short and longer distance applications. Because single mode (SM) transmission is capable of high system bandwidth and longer reaches, mega- and hyper-scale data centers tend to adopt standard single mode fiber as a single transmission medium. For distances up to several hundred meters, MM and SM transmission are both viable options.

TABLE I
COMPARISON OF COSTS FOR MULTIMODE AND SINGLE-MODE TRANSCEIVERS. FOR THE COST COMPARISON, THE VALUES ARE SHOWN RELATIVE TO THAT OF 10G MM TRANSCEIVERS

Fiber	Relative transceiver cost		
	10G	40G	100G
MMF (OM2-OM4)	1	6	13
SMF	2	15-21	13-37

B. Pros and Cons of Using SM and MM Solutions

MM systems enjoy widespread use in short distance communications because they are more cost effective than SM systems. Despite the fact that MMF is more expensive than standard single mode fiber, MM transmission is lower in cost due to the lower transceiver costs as shown in Table I [1]. Here we use the 10 Gb/s MM transceiver cost as a reference and the relative prices are shown in comparison. As speeds approach 100G and higher, the relative difference in price shrinks and the trend will likely continue over time. However, the absolute price differences at 40G and 100G remain significant between most SM transceivers and MM transceivers.

Another factor that has attracted increased attention is the power consumption in data centers. SM transceivers typically consume more energy than MM transceivers. The relative power consumption information is shown in Table II [1].

C. Dilemma of Choices and Introduction of a Uniform Fiber Medium

Short distance communications are evolving quickly to accommodate new technologies moving toward higher data rates and higher densities. Since cable and connectivity infrastructure is typically considered as capital investment, it is expected to last one to two decades and sustain multiple generations

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TABLE II
COMPARISON OF POWER CONSUMPTIONS BY MULTIMODE AND SINGLE-MODE TRANSCEIVERS. FOR COMPARISON, THE VALUES ARE SHOWN RELATIVE TO THAT OF 10G MM TRANSCEIVERS

Fiber	Relative power consumption		
	10G	40G	100G
MMF (OM2-OM4)	1	2	4
SMF	1.5	5	5.5

of transceiver technology. Two significant factors affecting the choice are cost and future-proofing. The technical capability and the cost considerations are related and end users are faced with a difficult choice among different options. On one hand, even up to 100G transmission, the MM solutions remain cost effective with low power consumption and can address the majority of short distance needs. On the other hand, SM transmission is gaining more traction due to its future-proofing at higher than 25 Gbaud data rate and ability to work at distances longer than 100 m even though the overall cost remains much higher than MM solutions.

A unified transmission fiber can potentially serve as a bridge to accommodate the needs both for the present and the future. Such fiber can simplify fiber cable management and transceiver/connectivity logistics, and provide flexibility for future transceiver upgrades. A specially designed MMF, referred to as universal fiber (UF) was proposed in Ref. [2] for both MM and SM transmission. UF is a MMF with the LP_{01} mode approximately matching the mode field diameter (MFD) of a standard single-mode fiber. An improved UF design favoring VCSEL-MMF coupling was subsequently reported in Ref. [3], and improved performance in several system types was demonstrated. Additional efforts were made to further understand the transmission properties of UF with updated performance results and analysis reported in Ref. [4].

In this paper, we review the recent progress of UF and provide new insights on potential application scenarios in short distance communications. Specifically, we present new results and address practical issues of using UF in 5G wireless fronthaul applications. In Section II, we review fiber designs and properties of UF, and system performance results using UF with various 100G SM and MM transceivers. In Section III, we explore several general scenarios of using UF. In Section IV, we focus on the application of UF for 5G wireless fronthaul networks by presenting the detailed application scenarios, testing results and discussion of practical issues. Finally, in Section V, we present a brief conclusion.

II. UNIVERSAL FIBER PROPERTIES AND TRANSMISSION PERFORMANCE

The key consideration of the UF design is its ability to operate both for multimode transmission at 850 nm and single-mode transmission around 1300 nm and 1550 nm [3]. The core of the UF has a simple gradient refractive index profile similar to that of conventional OM3 and OM4 MMFs, as described by the following equation:

$$n(r) = n_0 \cdot \sqrt{1 - 2\Delta (r/a)^{a}} \tag{1}$$

where n_0 is the refractive index in the center of the core, a is the core radius, $\Delta = (n_0^2 - n_1^2)/(2n_0^2)$ is the relative refractive index delta, where n_1 is the refractive index of the cladding, and α is a constant with value around 2.1. To accommodate SM transmission, it is necessary for the mode field diameter of the fundamental LP_{01} mode to approximately match that of a standard single-mode fiber, which is around 9.2 μm at 1310 nm. On the other hand, for multimode operations, the core diameter and numerical aperture both need to be high enough to facilitate easy VCSEL coupling to the fiber. Analysis done in Refs. [2], [3] studied the properties of the UF that affect optical coupling with conventional MMF and standard single mode fiber.

Since the UF is an MMF with a smaller core than OM3/OM4 MMFs, the coupling of light from VCSEL to a UF is different. In Ref. [3], detailed modeling and experimental studies were conducted to show how the coupling loss varies with the fiber parameters. Considering design tradeoffs, we have fabricated a UF design that has a core delta of 1.2%, core diameter of about 30 μm, which supports 12 mode groups [3]. The LP01 MFD is slightly higher than standard single mode fiber, but it also increases significantly the coupling efficiency to VCSEL or MMF. The numerical aperture of 0.225 further improves the coupling efficiency. This choice of UF parameters provides a reasonable balance between SM and MM performance. Experimental studies of an initial UF [2] and later an improved UF [3] agree well with the theoretical analyses. The chromatic dispersion of the UF at 850 nm is around -100 ps/nm.km similar to that of OM3 and OM4 MMFs. The chromatic dispersion values of the UF at 1300 nm and 1550 nm are around -1 ps/nm.km and 19.5 ps/nm.km respectively.

In addition to insertion loss, another aspect of interest for SM transmission is multi-path interference (MPI) [4]. In conventional SM transmission, MPI may result from multiple reflections at the connector interfaces. For UF, the MPI results from the slight amount of light launched into higher-order modes at one connector interface and coupled back to the fundamental mode at the next connector interface. The small amount of higher-order mode light can cause power fluctuation due to coherent interference and therefore leads to power penalty. The difference in delay between different paths can also cause intersymbol interference (ISI) related penalty. However, since the UF has a MFD of LP_{01} mode matched closely to that of standard single mode, the MPI can be well managed to minimize the impairments.

Of ultimate interest is the transmission performance. In short distance communications, the data rate of the transceivers moves up from 1 Gb/s, 10 Gb/s, 40 Gb/s, to 100 Gb/s and even higher. The 100G transceivers are state of the art and are suitable for testing the capabilities of the UF. Several transceiver types both for MM and SM transmission are used, as listed in Table III. For MM transmission, 100G SR4 is the only standards-defined transceiver. Others are proprietary solutions supported by

TABLE III
THE TYPES OF TRANSCEIVER USED IN THE TESTING

	Connectivity Form Factor	
Transmission Type	Duplex LC	Parallel Optics
SM	100G CWDM4	100G PSM4
MM	100G SWDM, 100G BiDi	100G SR4

TABLE IV
DEMONSTRATED TRANSMISSION DISTANCES FOR THE FIVE TYPES OF 100G TRANSCEIVERS USING UF

Transceiver Type	Transmission Distance (m)
100G SR4	200
100G SWDM [5]	150
100G BiDi [6]	200
100G CWDM4 [7]	2700
100G PSM4 [8]	2000

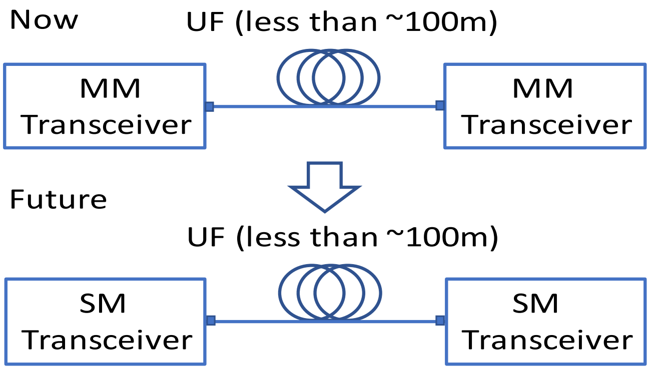


Fig. 1. Illustration that UF can be used for MM transmission now and reused for SM transmission in the future.

multi-source agreements (MSA). There are also two connectivity form factors. One is MPO connectivity based on using eight-fiber parallel optics. Another is duplex LC connectivity. It has become popular in recent years since the same data traffic can be transmitted with two fibers instead of eight fibers using wavelength division multiplexing.

Here are brief descriptions of each transceiver type we tested.

- 100G BASE SR4: The 100G SR4 VCSEL-based QSFP transceiver operates at 4 × 25 Gb/s in compliance with the IEEE 802.3 bm standard. It uses MPO connectors. The specified distances are 100 m for OM4 and 70 m for OM3.
- 100G SWDM [5]: The proprietary transceiver utilizes four wavelengths around 850 nm, 880 nm, 910 nm and 940 nm, each operating at 25 Gb/s for an aggregate 100G data rate within a single fiber. The transceiver utilizes 2 fibers with two LC connectors. The 100G SWDM transceiver has the QSFP form factor and supports up to 70/100/150 m over OM3/OM4/OM5 multimode fibers.
- 100G BiDi [6]: The proprietary transceiver utilizes 2 fibers that transmits 100G per fiber with two 50G wavelengths (850 nm/900 nm) per fiber. 25G baud rate PAM4 technology is used to double the number of bits per symbol into 2 bits/symbol, providing a 50G data rate per wavelength. The 100G BiDi transceiver has the QSFP form factor and supports up to 70/100/150 m over OM3/OM4/OM5 multimode fibers.
- 100G CWDM4 [7]: The proprietary CWDM4 QSFP transceiver is a 100G or 4 × 25G single mode transceiver targeting data center applications with an expected system reach of up to 2 km. It operates at four wavelengths around 1300 nm. The transceiver utilizes only two fibers with two LC connectors.
- 100G PSM4 [8]: The proprietary PSM4 QSFP transceiver utilizes parallel single-mode (4 × 25G/fiber) transmission to provide 100G. It is designed to support reach of up to 500 m. The transmission of 100G PSM4 can be based on either 1310 nm lasers or 1550 nm lasers.

Using a UF with modal bandwidth around 3000 MHz.km [4], we conducted system testing for all five types of 100G transceivers. We have conducted system testing using two sets of equipment. For majority of the transceiver types including 100G SR4, 100G SWDM, 100G CWDM4 and 100G PSM4, we have conducted detailed bit error rate (BER) testing using commercial transceivers with proper connector interface to access the individual fibers to gather the detailed performance data. In the case of the transceivers having MPO connectors such as 100G SR4 and 100G PSM4, a fan-out cable is used to allow the access of an individual fiber with LC connector. For other cases, LC connectors are attached to the ends of the fiber. For each individual channel, the data rate is 25.78125 Gb/s using $2^{31} - 1$ PRBS pattern. For all transceiver types, we have also used optical network tester (ONT) [9] from Viavi to conduct the full testing with traffic involved. The transmission distances that show bit error free performance are listed in Table IV. They all show equal or longer distances that are specified for the corresponding fiber types.

III. GENERAL APPLICATION SCENARIOS OF USING UF

There is a range of potential application scenarios where UF can be used. In this section, we present each of them. Since UF is an experimental fiber that is not yet commercially available, below in our discussions, we assume that the deployment is new deployment or often referred to as green field, and UF has similar modal bandwidth and therefore system reach as existing OM3 and OM4.

Scenario 1: Use UF for MM transmission now but have a path to SM transmission in the future. At 25 Gb/s per lane data rate, standard MM fiber transmission can reach up to 100 m. With extended reach solution, the distance can be boosted to 200 m for OM3 and 300 m for OM4. In the current scenario, one can take advantage of cost effective MM transceivers using UF. But in the future, if the SM transceiver prices drop to a certain point, or the MM transmission cannot support higher data rate at the same distance, one can switch to SM transceivers and still use the same transmission fiber. The situation is illustrated in Fig. 1 below.

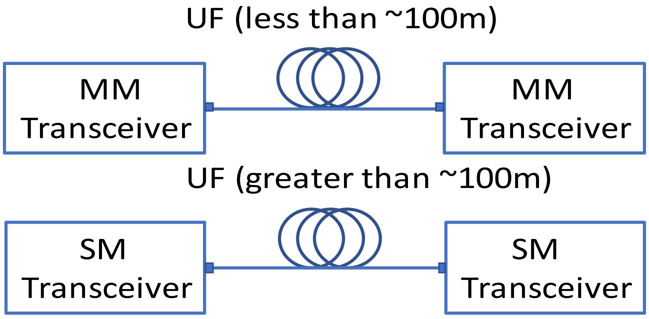


Fig. 2. Illustration of UF as a single fiber medium that can support MM transmission at short distance and SM transmission at longer distance beyond what MM transceivers can do.

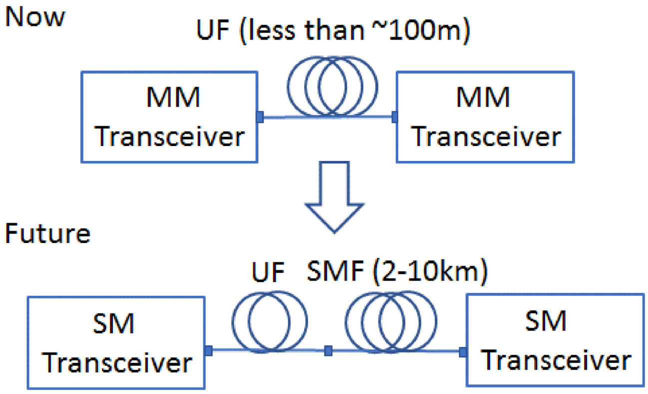


Fig. 3. Illustration of how a UF link used for MM transmission at short distance can be extended for much longer SM transmission without removing and replacing the initial MM fiber link.

Scenario 2: Use UF as a uniform medium for both SM and MM transmission. In many short-reach applications, optical transmission links are less than 100 m. However, there are cases, e.g., in high rise buildings, where certain transmission links involve distances beyond what MM transmission can handle. In those cases, one must use SM transceivers and therefore standard single mode fiber as the transmission medium. This is a situation that both standard single-mode fiber and MMF are used in a hybrid deployment environment. Managing such a hybrid use case is more complex and more expensive. One may choose to use standard single mode fiber and high cost SM transceivers across the board. With UF, one can use it as a uniform fiber medium with lower cost MM transceivers in short distances and with SM transceivers for longer distances. This situation is illustrated in Fig. 2.

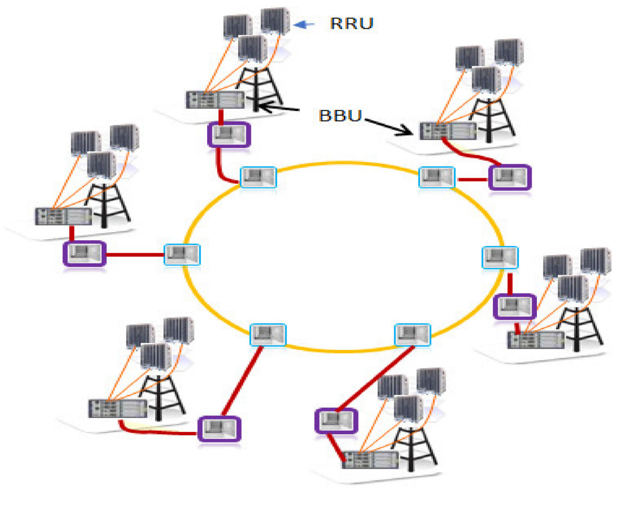
Scenario 3: Migrate MM links to SM links for longer distance transmission. In Scenario 1 we described a situation in which existing links presently used for MM transmission can be reused for SM transmission in the future. In another situation, the MM links are initially used, and then reused and extended for much longer SM transmission by concatenating with standard single mode fibers later as illustrated in Fig. 3. This is done without removing and replacing the initially deployed UF. The advantage of this configuration is that UF can be used in short distance to take advantage of the cost-effective MM transceivers and when a much longer link is needed, UF is compatible with standard single mode fiber to form the longer link. This can be particularly useful for some applications. For example, in a 5G wireless fronthaul application, one can migrate from a Distributed-RAN (D-RAN) architecture to a Centralized-RAN or Cloud-RAN (C-RAN) architecture, which will be discussed in the next section.

IV. UF FOR 5G WIRELESS FRONTHAUL APPLICATION

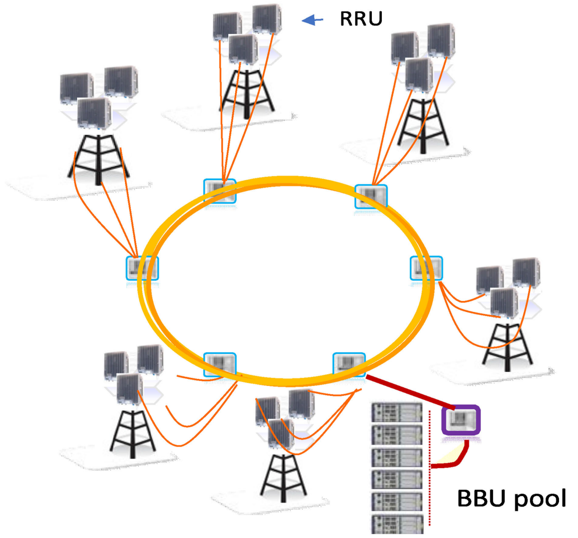
A. *Needs of MM and SM Solutions in 5G Fronthaul Application*

In this subsection we investigate the potential application of UF in 5G wireless fronthaul networks. Recently, 5G wireless and its commercial deployment in the next few years have been discussed [10]. The fronthaul application is one area of interest for using UF. In the fronthaul application, there are two types of architectures for radio access network (RAN) called D-RAN and C-RAN as illustrated in Fig. 4. For D-RAN, as illustrated in Fig. 4(a), the baseband unit (BBU) is located close to the remote radio unit (RRU) with distance less than 150 m. For C-RAN, a centralized BBU pool is used and the distance between individual RRU and BBU pools can be up to 10 km as illustrated in Fig. 4(b). In Fig. 4, in addition to BBU and RRU as labelled, grey box is the outdoor optical cross-connecting cabinet (OCC), purple box is the indoor Optical Distribution Frame (ODF), red line is drop cable, yellow line is access trunk cable, and orange line is remote cable connect to RRU. Note that BBU and RRU are terms used specifically for 4G LTE networks. In 5G wireless networks, the counterpart for RRU is called active antenna unit (AAU). The counterpart of BBU is called distributed unit (DU) or central unit (CU). Both 5G RAN architectures are being deployed. Many of the existing 4G deployments use D-RAN with optical transmission at 10 Gb/s data rate. When a base station is upgraded from 4G to 5G, the data rate of optical transceivers between BBU and RRU will also be upgraded from 10 Gb/s (CPRI protocol) to 25 Gb/s (eCPRI protocol [11]) or higher (100 Gb/s with CPRI protocol) to achieve more than 10 $\sim$ 100-time peak wireless speed. Since many of the 4G deployments have been based on D-RAN, one way to upgrade legacy 4G cells to 5G is to use the same architecture with upgraded equipment and higher speed optical transmission links. C-RAN is used for new build of 5G cells.

Many of the D-RANs are deployed with RRUs located on top of a building and BBUs located on the ground. Such deployment is expensive and complex as it involves the permission from the building's owners and is subject to local regulations. It is preferred that such deployment be done only once. At 25 Gb/s data rate, the MM transceiver price is significantly cheaper than that of SM transceivers. Therefore, MM solution is favored in the legacy upgrade. However, in the future, many D-RAN deployments will be further upgraded and converted into C-RAN architecture. The question is whether the MM cable deployed for 5G D-RAN can be reused for C-RAN deployments where SM transmission is used. The application configuration in Fig. 5 conceptually illustrates how this can be done by concatenating the UF cable with standard single mode fiber.



(a)



(b)

Fig. 4. Illustrations of two different 5G RAN architectures. (a) D-RAN; (b) C-RAN.

B. 25G Transmission Experiments, Results and Analysis

We have done experiments to test the feasibility of using UF for both SM and MM transmission for application scenarios described above. Several types of transceivers are used in the 5G fronthaul application for optical transmission between BBU and RRU. They are 25G SR transceivers, 25G LR transceivers and 100G CWDM4 transceivers. System testing was done using actual BBU with traffic at the designated data rate around 25 Gb/s. Passing or bit-error free is determined for a test period of 5 minutes. 25G SR transceivers are used for MM transmission over 70 m of OM3 or 100 m of OM4. 25G LR transceivers are used transmission over standard single mode fibers up to 10 km. The 100G CWDM4 transceiver is designed for 2 km SM applications while the enhanced 100G CWDM4 transceiver can support 10 km applications. Here the CWDM4 transceivers used are for 10 km transmission.

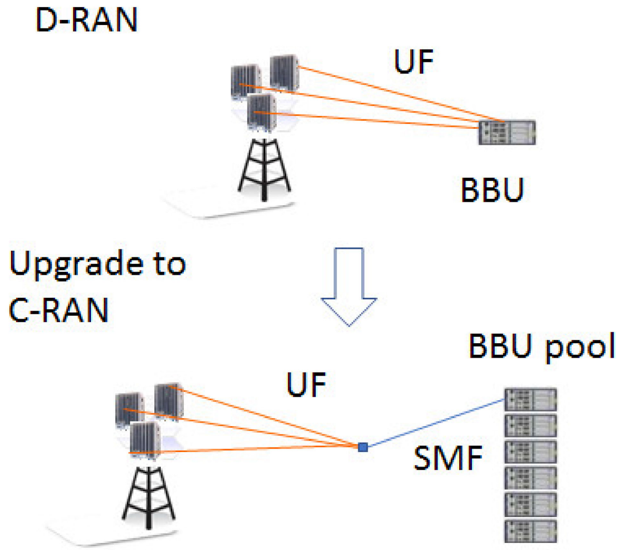


Fig. 5. Upgrade from D-RAN to C-RAN by reusing UF used in D-RAN.

TABLE V
25G SR BER Testing Results and Measured Coupling Loss

Transceiver	BER	UF coupling loss (dB)
Transceiver A1	Pass	0.55
Transceiver A2	Pass	0.23
Transceiver A3	Pass	0.02
Transceiver A4	Pass	0.08
Transceiver A5	Pass	2.66

First, we tested five 25G SR transceivers used in the 5G fronthaul application. Five transceivers, each from a different manufacturer, were tested. A 100 m UF with around 3000 MHz.km bandwidth was used in the testing. The UF was cabled and had LC connectors on both ends. All five transceivers connected with 100 m UF passed the BER testing with no bit errors over test period of 5 minutes. Since the UF is a MMF with smaller core diameter than 50 μm core MMF, there could be additional coupling loss. 2 m of UF and 2 m of 50 μm core MMF cables were plugged into each transceiver separately to measure the output powers from these fibers. The difference is the UF coupling loss shown in Table V. In 4 out of 5 cases, the coupling loss is quite low (less than 0.6 dB). The coupling loss for Transceiver A5 is 2.66 dB, higher than others due to its larger launch spot size. But this coupling loss is still within a reasonable range considering UF has smaller core than OM3 or OM4 MMFs. The testing shows that the MM transmission performance is robust for the 25G SR transceivers tested.

Next, we conducted the BER testing for two other types of transceivers, the 25G LR and 100G CWDM4 transceivers. Both are SM transceiver types rated for 10 km transmission. Four transceivers from four different manufacturers were used for each testing. The results are shown in Table VI and VII respectively. We first tested using 2 km UF, which was cabled and terminated with LC connectors similar to the 100 m UF sample. For both types of transmission, 3 out of 4 transceivers passed the BER testing over 5 minutes of testing period. We further tested the case where the 2 km UF was concatenated with 10 km

TABLE VI
25G LR Testing Results

	BER (2km UF)	BER (2km UF + 10km SMF)
Transceiver B1	Pass	Pass
Transceiver B2	Pass	Pass
Transceiver B3	Pass	Pass
Transceiver B4	Fail (Pass with SM adapter)	Pass

TABLE VII
100G CWDM4 Testing Results

	BER (2km UF)	BER (2km UF + 10km SMF)
Transceiver C1	Pass	Pass
Transceiver C2	Pass	Pass
Transceiver C3	Pass	Pass
Transceiver C4	Fail (Pass with SM adapter)	Pass

standard single mode fiber. For both types, 4 out of 4 transceivers passed the BER test.

We further analyzed failure modes in the SM transmission for transceivers B4 and C4. There could be situations where there is transmission failure. Some of the SM transceivers still use a lens system at the transmitter to launch the light into the fiber. Since the single mode fiber only supports one mode, when a single mode fiber is plugged into the transceiver housing, only the fundamental mode is launched. However, when a UF is plugged in, the light from a lensed system can launch into higher order modes of the fiber and degrade the system performance. In another situation, many SM transceivers, especially 100G transceivers, use single-mode stub fibers for mating with the fiber plugged into the transceiver. If the stub fiber is truly single-moded, the light would launch into the LP_{01} mode of UF, but if the fiber is not truly single-moded, the light from the transmitter can pass through the cladding of the stub fiber and launch into higher order modes of UF. With this understanding, we can use a simple single mode adapter external to the transceiver to act as a higher order mode filter to avoid launching unwanted light into higher order modes. To test this idea, we inserted a single mode jumper cable to concatenate with the UF. This type of system then passed the BER testing for both transceivers B4 and C4. Using 10 km standard single mode fiber to concatenate with UF, we also obtained error free results. Using an additional SMF jumper cable may not be an acceptable field practice as the extra jumper may cause confusion in the installation for operators. One can use an adapter with a segment of single mode fiber to achieve the same goal as illustrated in Fig. 6. We have experimentally verified that with proper choice of the single mode fiber, one can implement a short adapter or cable to do the modal conditioning and achieve error free system performance.

The above experiment illustrates how SM transceivers work with UF directly or combined with additional standard single mode fibers for SM transmission. For most transceivers, they work directly with UF with no transmission errors. For some SM transceivers that cannot work error free, an SM adapter can ensure that the light is launched into UF correctly.

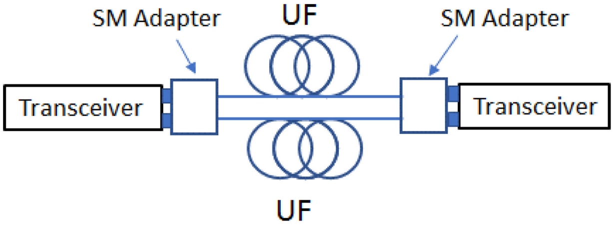


Fig. 6. Schematic of using SM adapters with SM transceivers and UF.

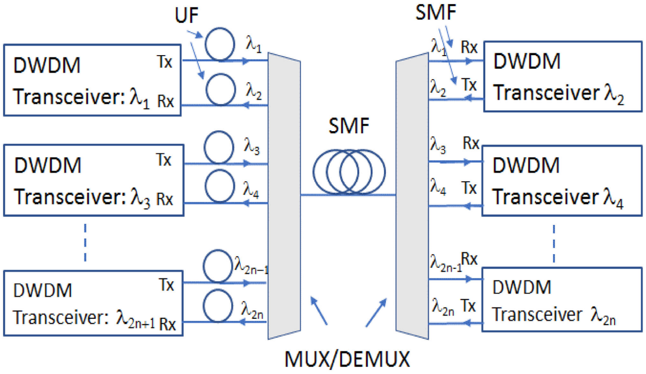


Fig. 7. Schematic of DWDM transmission over a combined link with UF and standard single fiber through Mux/Demux.

C. Aggregated SM Transmission Using CWDM and DWDM for CPRI Application

As noted above, for 5G wireless network, one configuration for the data transmission between BBU and RRU is based on 25 Gb/s data rate using eCPRI protocol. Single mode fibers are used to transmit for long distances up to 10 km, and typically with much larger amounts of data over each fiber. CWDM and DWDM technologies have been used in the CPRI applications [12]. Here we explore an application scenario that utilizes DWDM to merge several optical data streams from individual RRUs connected with UF into one standard single mode fiber as shown in Fig. 7. This scenario could potentially help the migration from D-RAN using shorter distance transmission to C-RAN using longer distance transmission without the need to change the fibers that have been used for MM transmission. To aggregate the data coming from multiple RRUs, the transmitted signals from several DWDM transceivers through UFs can be combined through a multiplexer into a standard single mode fiber. At the end of the long single mode fiber link, the signals are de-multiplexed into individual single mode fibers before reaching the receiving ends of the transceivers. The transmission is bi-directional and data can be transmitted in the opposite direction over different DWDM wavelengths and different multiplexer/de-multiplexer (Mux/Demux) channels.

To experimentally test the case, we used four DWDM transceivers with operating wavelengths of 1548.92 nm, 1549.72 nm, 1550.52 nm, and 1551.32 nm, respectively. They operate at 10 Gb/s and are rated for 40 km transmission with nominal Tx power of –1 to 2 dBm and with SFP+ transceiver form factor. We also used two 40 channel Mux/Demux boxes based on AWG with 100 GHz ITU grid spacing [13] with 50 GHz frequency shift. The insertion loss for each device is

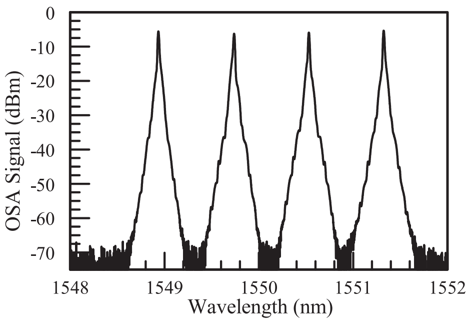


Fig. 8. The optical spectrum captured from the output of the first Mux/Demux with the light aggregated from four DWDM transmitters.

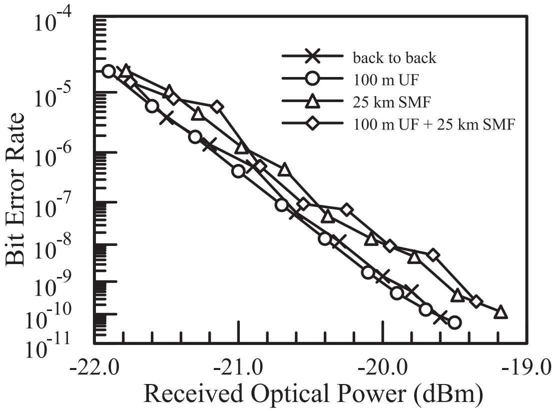


Fig. 9. The BER vs. received optical power curves for wavelength channel 1548.92 in four fiber testing configurations.

around 6 dB. The 25 km standard single mode fiber contributes a link loss of 4.8 dB due to attenuation around 1550 nm. The link loss from 100 m of UF around 1550 nm is negligible. The chromatic dispersion value of LP_{01} mode at 1550 nm is around 19.5 ps/nm.km. At the length of 100 m, the contribution from the chromatic dispersion is negligible. For convenience, we configured the experimental setup to operate in one direction using four transceivers. We expect that the performance would be essentially the same for the other direction. Four sets of BER testing equipment were used. Fig. 8 shows the aggregated optical spectrum coming from four transmitters after the first multiplexer.

Next, we conducted BER testing for each wavelength channel. 100 m UF is connected between the transceiver and the input of first MUX. The 25 km SMF is placed between MUX and the DEMUX. For case without the 100 m UF, a short singe mode jumper is connected to the transceiver and input of MUX. All four channels passed the BER testing and stayed bit error free for more than 10 minutes, the duration of the testing. For one channel with the wavelength of 1548.92 nm, we further obtained the BER vs. received optical power curves for four fiber testing conditions. It is found that the 100 m UF introduces little penalty compared to the back to back case with only very short fibers for optical connections. Similarly, the performances using 25 km vs. using 100 m UF and 25 km standard single mode fiber combined link are similar to each other. The results indicate that the UF as a part of the link behaves just like a segment of standard single mode fiber even in the DWDM transmission involving Mux/Demux. Although, we have used 10 Gb/s DWDM transceivers as available to us in our experiment, we expect the feasibility of using UF in the DWDM configuration will carry over to higher data rate if 25 Gb/s DWDM transceivers are used, judged by the observation that UF introduces little to no system performance penalty.

V. CONCLUSION

In this paper, we reviewed the recent progress on UF and presented new results in UF applications, in particular, wireless 5G fronthaul application. UF is a multimode fiber that has an LP_{01} mode field diameter approximately matched to that of the standard single-mode fiber. It can transmit both multimode and single-mode signals using transceivers designed for either MMF or single-mode fiber. By using UFs, one can bridge the needs for both single-mode and multimode transmission through a uniform and simplified cable infrastructure to accommodate the full distance range needed. It also has the upgradability from 10G to 40G to 100G and even higher data rates. We presented the fiber properties and system performance at 100G. We also explored several detailed application scenarios where the fiber can be utilized. Specifically, we showed how the fiber can be used in the 5G wireless fronthaul application. Our testing results and analyses suggest that UF can potentially provide low initial installation cost using MM transmission and simplify the upgrade path to SM transmission in the future.

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