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***Abstract*— We experimentally investigate the feasibility of transmission of radio frequency (RF) signals over a 900 m polarization-maintaining, elliptical ring core fiber. No multiple-input multiple output (MIMO) processing is used to recover the RF signals carried by different modes; we recover the 16QAM, orthogonal frequency division multiplexing (OFDM) RF signals with the same techniques used for single mode fibers. For the first time, we report transmission of four RF streams over four channels in a few mode fiber. Also, for the first time, we transmit RF signals over two polarizations of a mode in few mode fibers and successfully recover data in both polarizations without polarization tracking or digital signal processing to separate polarizations. Furthermore, we examine the impact of fiber bending on crosstalk among channels. We show that even under severe bending, the polarization states remain separated and the RF streams transmitted on polarization states of a mode could be recovered with low power penalty.**

***Index Terms*—Elliptical ring core fiber (ERCF), few mode fiber (FMF), polarization maintaining, radio over fiber (RoF).**

I. Introduction

Extensive research is underway for novel radio over fiber (RoF) technologies [1]. The number of wireless network users is increasing annually; popular mobile applications exploit high bandwidth connections, leading to intensified demand [2]. The use of 64 antennas per sector is planned, so called massive multiple input, multiple output (MIMO), but will put a great burden on optical front haul. 5G is heading for a tremendous capacity shortfall in RoF front haul.

Different multiplexing techniques in optical systems used in RoF architectures have been proposed to cope with future traffic demands on wireless networks. Polarization division multiplexing (PDM) offers a two-fold increase in capacity of single mode systems, but requires optical polarization tracking or relies on additional MIMO processing for joint optical/wireless channel [3], [4]. Wavelength division multiplexing (WDM) [5-7] can increase capacity, but cost is high if wavelengths must be densely packed.

In space division multiplexing (SDM), based on multimode fibers (MMF) [8], few mode fibers (FMF) [9], [10] or multicore fibers (MCF)[11], [12], capacity is scaled by the number of modes/cores exploited. As a rule of thumb, MMF sees the greatest interaction (i.e., modal mixing causing crosstalk) among channels, while MCF sees the lowest. FMF interactions depend widely on the fiber used. MIMO algorithms in digital signal processing (DSP) at reception can mitigate interactions, at the cost of greater DSP complexity. We review the use of RoF with all fiber types.

The feasibility of RoF over MMF was investigated via characterization techniques in [13]. Two and three modes in conventional MMF were used for RoF data transmission in [14] and [15], respectively, but required MIMO processing. At the other end of the spectrum, MCFs have low inter-core crosstalk, whose impact on RoF was studied in [16], [17]. RoF systems using 2, 4 or 6 cores of MCF with low modal mixing were demonstrated [18-21].

As SDM capacity can be pushed by having multiple cores supporting a few modes per core, the study of FMF for this application is of interest. Beside the increase in total system capacity, FMF also offers advantages in the suppression of nonlinearities such as four wave mixing and stimulated Brillouin scattering. These characteristics would also be beneficial when using these fibers for RoF transmission. The impact of FMF larger effective area and modal orthogonality when transmitting analog signals was studied in [22], [23], showing a reduction in nonlinear effects in the presence of high power. In [24], the impact of nonlinearities, as well mode dependent loss for different mode orders in two modal basis of LP and OAM modes, was studied experimentally.

Only limited RoF demonstrations on FMF have been reported. In [25] two RoF signals were transmitted over an elliptical core few mode fiber with MIMO processing [26]. MIMO processing is being exploited in digital optical systems in FMF to separate modes and in wireless transmissions to separate antennas paths. The optical and wireless channels are by their nature very different, with interactions parameterized by different time constants and memory length. One-tap frequency domain

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equalization over narrow frequency bins are sufficient to establish MIMO-OFDM link in wireless channel [27]. Wideband optical systems have relied on time domain MIMO equalization with hundres of taps [28]. These systems also target vastly different sampling and bit rates. It remains to be established if the optical/wireless channel will suffer the capacity reduction identified for concatenated wireless channels in [29]. Rank deficiency was identified for these product channels, attributable to spatial correlation and lack of scattering richness. Here, we would take another approach. Instead of relying on MIMO for FMF transmissions, we focus on FMF with low modal mixing [30-34]. By using a fiber with low modal mixing, we can avoid full MIMO for optical channel. A mode multiplexing system that does not require MIMO processing allows fiber capacity to grow in the spatial dimension without imposing extra requirement on DSP or impinging on the capacity of the wireless channel.

In this paper, we will investigate the feasibility of RoF transmission over a polarization-maintaining elliptical ring core fiber (PM-ERCF) [35]. We transmit, for the first time, RoF signals over four linearly polarized vector (LPV) modes of PM-ERCF. We demonstrate transmission of 4×1.152 Gbps 16QAM orthogonal frequency division multiplexing (OFDM) signals with direct detection and without MIMO processing over a 900 m fiber link. For the first time, we also exploit two polarizations of a mode for transmission of RoF signals over FMF. The data transmission experiment validates RoF signals mode division multiplexed (MDM) in FMF are recovered without intermingling of RoF data streams.

In [36], we showed the viability of RoF data transmission over PM-ERCF. We evaluated the bit error rate (BER) performance of the four RoF channels when centered at RF carriers of 2.4 GHz (WiFi) and at 3.3 GHz (a candidate carrier [37] for 5G) and also the BER performance under bending. Here the setup and the results of [36] are discussed in more detail. Furthermore, we characterize the RoF system in terms of crosstalk over spatial channels for signals with RF carriers ranging from 800 MHz to 6 GHz. We also study the performance penalty due to varying levels of fiber modal crosstalk. Finally, we investigate the loss and crosstalk changes as a function of bending over the range of RF carriers of 800MHz to 6GHz, discussing the polarization maintaining property of PM-ERCF.

The remaining sections of this paper are organized as follows. In section II, we discuss the fiber under test and our strategy for probing the isolation it provides between channels. In section III, we describe the RoF transmission setup including transmitter, receiver and SDM link. In section IV, we evaluate the RoF transmission performance. In section V, we investigate the bending property of the fiber and in section VI, we conclude the paper.

II. Multiplexing on Vector Modes

We exploit a few mode fiber (PM-ERCF) whose characteristics are detailed in [35]. This fiber is designed to support the propagation of vector modes (fiber Eigen modes) that are linearly polarized, and whose effective indices are sufficiently separated to suppress modal interactions. While very wideband digital signals have been shown to have interactions that can be mitigated with standard DSP in coherent detection [34], it remains to be seen if this also is true of much narrower band signals in a RoF system employing non-coherent detection.

Most FMFs to date have polarizations that mix within the modes. PM-ERCF is designed to achieve the polarization maintaining property for higher order Eigen modes, while the fundamental mode polarizations mix as in standard FMF. The PM-ERCF supports eight channels: two linearly polarized modes in each of the four spatial modes in the fabricated fiber. These linearly polarized vector modes, labeled LPV, are LPV_{01x}, LPV_{01y}, LPV_{11ax}, LPV_{11ay}, LPV_{11bx}, LPV_{11by}, LPV_{21ax} and LPV_{21ay}. Simulated and measured mode profiles can be found in [34], [35]. We focus on the six higher order modes in which polarization is maintained.

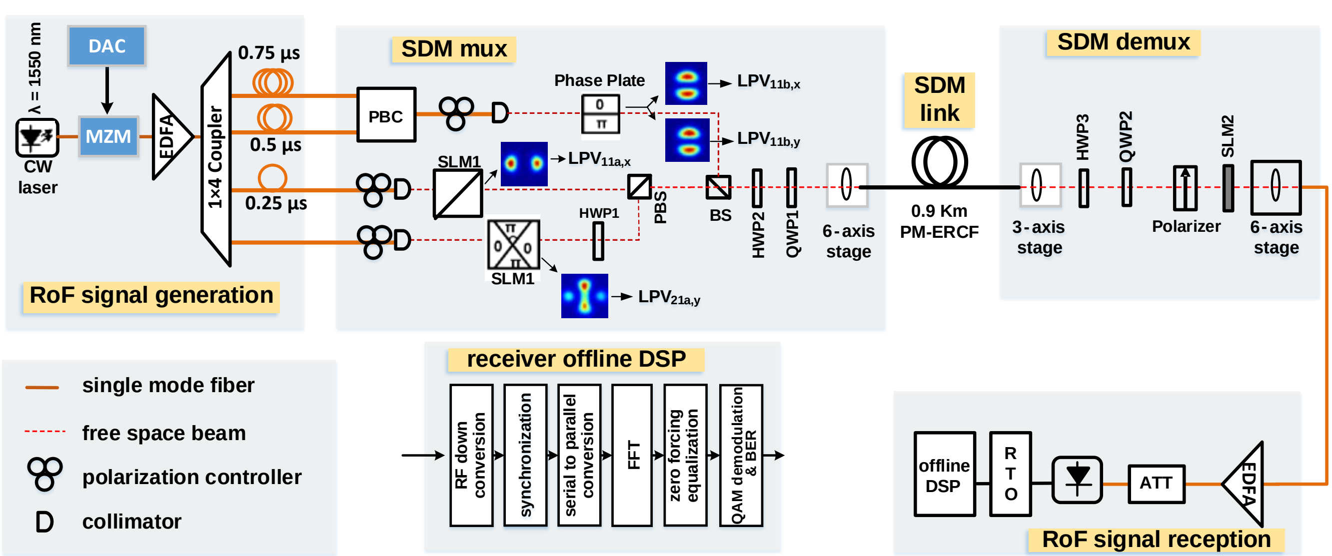


Fig. 1. RoF over PM-ERCF data transmission setup

Table I
Measured effective index separation between data-carrying vector modes

$LPV_{11a,x} \leftrightarrow LPV_{11b,x}$	$LPV_{11b,x} \leftrightarrow LPV_{11b,y}$	$LPV_{11b,y} \leftrightarrow LPV_{21a,y}$
4.33×10^{-3}	3.07×10^{-4}	2.9×10^{-3}

One potential source of modal interaction is when RoF signals are carried by two polarizations of the same mode. The other is when we use different modes, either on the same or opposite polarizations. We wish to examine the isolation of RoF signals in each of these cases, so we make a strategic choice of vector modes to be tested. We eschew the fundamental mode as it clearly would require MIMO processing for optical interactions, potentially leading to less capacity or greater complexity in the combined optical/wireless MIMO link.

To investigate the polarization multiplexing property, two polarizations of LPV_{11b} mode are employed. To probe modal isolation, we add one polarization on the higher order LPV_{21a} mode, and another polarization on a mode of the same order, but spatially orthogonal, i.e., the LPV_{11a} mode. In total therefore, we use $LPV_{11a,x}$, $LPV_{11b,x,y}$ and $LPV_{21a,y}$ modes as our four data carrying channels. The measured effective index separation between the closest pairs of these four channels reported in [34] are reproduced in Table I. These modes were selected as they had the best separation among the available supported modes. Choosing other mode combinations and to a greater extent including more channels would result in higher levels of crosstalk and therefore a performance degradation.

III. RoF over PM-ERCF Experiment

In this section, we describe the setup, depicted in Fig. 1, used for validation of RoF data transmission over PM-ERCF. We spatially multiplex four RF signals simultaneously over PM-ERCF. Each channel is detected separately. No MIMO processing is performed on modes or polarizations. This is achievable due to the minimal crosstalk in fiber propagation. In section A, we describe the signal generation; in section B, we briefly describe the SDM link including fiber, mode multiplexer and demultiplexer. In section C, we describe the signal reception and overview the DSP blocks at the single-mode receiver.

A. RoF signal generation

We adopt RF carriers of 2.4 and 3.3GHz and a modulation format (OFDM) consistent with standards such as WiFi and (emerging) 5G. For experimental expediency, we use an arbitrary wave generator (AWG) to generate the OFDM signal. Standard building blocks of DSP are used in transmitter and receiver. The DSP is applied offline.

The baseband OFDM signal is generated offline and loaded into a digital to analog converter (DAC). The OFDM signal was generated with a size 64 fast Fourier transform (FFT). There are 40 data-carrying subcarriers; the sampling rate is 640 MSa/s. The baseband OFDM signal has bandwidth of 640 MHz, with subcarrier spacing of 10 MHz. The cyclic prefix ratio of an OFDM symbol is ¼; a frame of 20 symbols has a two symbol

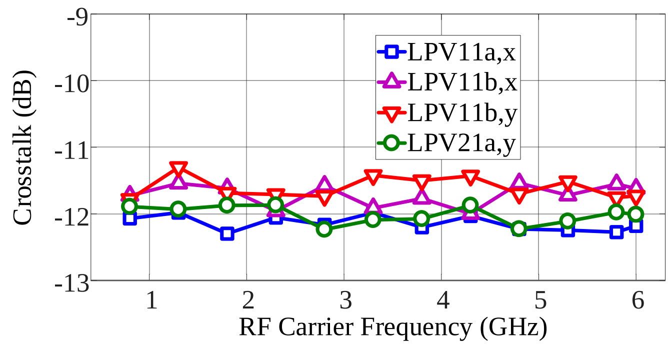


Fig. 2. Crosstalk versus RF carrier frequency for each mode channel

training sequence for channel estimation. Subcarriers are modulated with 16QAM, yielding 1.152 Gbps per spatial channel.

The baseband OFDM signal is up-converted to an RF carrier in DSP. The OFDM signal on the RF carrier is generated by a DAC operating at 64 GSa/s. The RF electrical signal is fed to a Mach-Zehnder modulator (MZM) modulating a continuous wave (CW) laser diode working at λ = 1550 nm with 100 kHz linewidth. After amplification with an erbium-doped fiber amplifier (EDFA), the optical signal carrying RoF transmissions is sent to the fiber link where four decorrelated replicas of the RoF signals are generated using an optical splitter and delay lines.

B. SDM link

The SDM link consists of a mode multiplexer, PM-ERCF, and a mode demultiplexer. To generate the two polarizations of LPV_{11b}, two decorrelated signals are combined on orthogonal polarizations states of a single mode fiber (SMF) using a polarization beam combiner (PBC). A fiber polarization controller is present to ensure that orthogonal linear polarization states will be present at the SMF output. The conversion to the LPV_{11b} is achieved in free space with a phase plate.

We generate $LPV_{11a,x}$ and $LPV_{21a,y}$ modes with two phase masks on separately programmed sections of a spatial light modulator (SLM). The mode profile for all the generated LPV modes are shown as insets in Fig. 1. All free-space signals are carefully aligned in the multiplexing stage. The beam splitter/combiner and wave plates are used to reject any spurious signal features resulting from non-ideal components. The six axis translation stage is used to align the beams on the proper axis of the elliptically shaped ring core of the fiber.

After propagation over 900 m of the PM-ERCF, light is sent to the demultiplexer. The demultiplexer consists of a half wave plate (HWP), a polarizer and a SLM. Proper HWP orientation and SLM programming allows us to select which channel will be demultiplexed. By rotating the HWP to ±45 degree, either *x* or *y* polarization is selected. By programming the SLM with the appropriate phase mask for the desired mode, that mode is converted to fundamental mode, while all other channels are shunted to higher order modes. The final demultiplexer stage is the SMF that acts as a mode stripper, allowing only the newly created fundamental mode to be detected. More detailed on the demultiplexer and its alignment can be found in [34]. Undesired channels are rejected by the combined effects of the HWP, SLM and SMF. We test separate detection of each of the channels in a round-robin fashion.

C. Signal Reception

After fiber transmission and mode demultiplexing, the optical signal is amplified by an EDFA and converted to the electrical domain by a 10 GHz bandwidth Agilent photodetector. The RF signal at the output of the photodetector is captured by a 40 GSa/s Keysight real-time oscilloscope. The DSP is applied offline. The blocks used in DSP of the receiver include RF down conversion, data-aided synchronization, serial to parallel conversion, FFT, one-tap zero-forcing equalization with 10 MHz spacing between taps, QAM demodulation and finally bit error rate (BER) measurement.

IV. Performance Evaluation

The main limiting impairment of the fiber transmission is the crosstalk on each channel due to the other propagating channels. In this section, we will first characterize the crosstalk between the channels as a function of RF carrier frequencies for a range from 800 MHz to 6 GHz. Then, we will investigate the performance of each channel by evaluating the BER versus received power for two RF carriers of 2.4 GHz and 3.3 GHz.

A. Crosstalk measurement

We begin with RoF signals generated for data transmission in the setup described in Section II. We use a power meter to measure the received power at the demultiplexer output port. To calculate the crosstalk on channel *i*, *i* = 1,..,4, we set the HWP and SLM in the demultiplexer to receive channel *i* at the output port, i.e., creating output port *i*. We send, in turn, an RoF signal on each of the four channels, measuring the received power. Let $P_{i,j}$ be the power at receiver port *i* when transmitting on mode *j*. The crosstalk for channel *i* is calculated as

$$10\log_{10}\left(\frac{P_{i,i}}{\sum_{j=1, i\neq j}^{4} P_{i,j}}\right) \qquad (1)$$

We observed some power fluctuations at the demultiplexer output port, (around 2 dB), similar to observations discussed in [38]. We attribute the main source of power fluctuations to the coupling among different channels as they propagate along the PM-ERCF. The relative phases of propagating modes relate directly to the modal coupling. The phase of the modes are highly sensitive to the environment and perturbations on fiber, and these phases are therefore constantly fluctuating. In this manuscript, and in our crosstalk calculations throughout the paper, the averaged value for the received power fluctuations is considered instead of their time varying values.

We sweep RF carrier frequencies from 800 MHz to 6 GHz, but the RoF signal has a constant bandwidth of 400 MHz. Results are reported in Fig. 2 for case of sending all the channels simultaneously. The crosstalk is approximately -12 dB, and varies by less than one dB across channels. Our measurements show that the crosstalk on a channel changes a little over this

Table II
Modal received power matrix at 3.3 GHz RF carrier;
columns are transmitted modes and rows are received modes

	$LPV_{11a,x}$	$LPV_{11b,x}$	$LPV_{11b,y}$	$LPV_{21a,y}$
$LPV_{11a,x}$	0	-14.3	-20.5	-18
$LPV_{11b,x}$	-18	-0.6	-16.1	-18.6
$LPV_{11b,y}$	-22	-16.3	-1.3	-17
$LPV_{21a,y}$	-20.3	-18.2	-17.1	-1.4

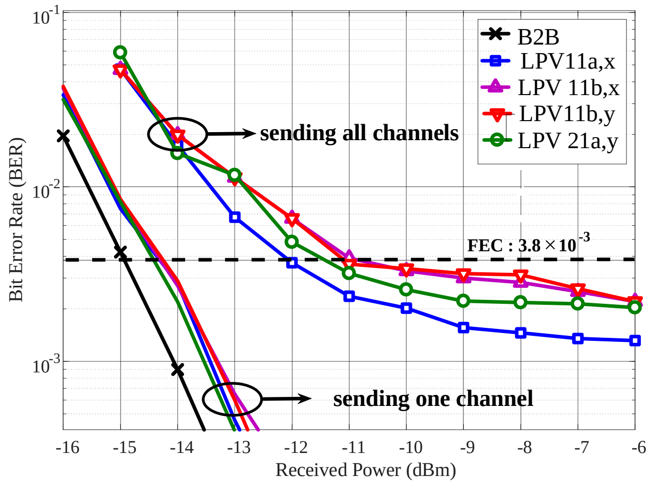
RF carrier range, with variations of a fraction of a dB. Therefore, we restrict BER performance evaluation to only two carriers in this range – two carriers likely to be adopted, i.e., 2.4 GHz and 3.3 GHz. For a better insight to the dynamics of modal interactions, we also report the crosstalk on each channel due to each of the other channels at RF carrier of 3.3 GHz in Table II. The measured powers are all normalized to the power when sending and receiving $LPV_{11a,x}$ channel . For each channel, we observe the highest crosstalk from the channel that has the closest effective index to the main channel. We attribute the difference between the power transfer matrix in results reported here and the corresponding values in Table 3 in [32] to various factors. In [32], we normalized all the powers in the matrix with respect to LPV_{11ay}, a mode that is not used in our current experiment; in our experiment, we normalized all the powers with respect to LPV_{11ax}. Given that data channels could follow different physical paths through the free space setup for this and previous work, some variations are to be expected. Despite the differences between individual elements in the channel power transfer matrix in different experiments, the total crosstalk on each channel is similar.

B. BER Evaluation

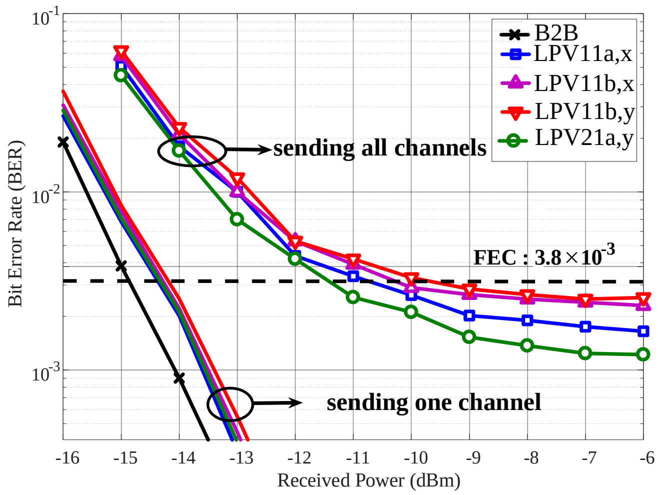
To calculate the final BERs reported in this manuscript, We averaged results from thirty sets of captured data, each of length 10^6 samples, to estimate of average BER, despite the power fluctuations in the fiber. We did not study the statistics of power fluctuations, but this would be an interesting subject for future investigation.

In Fig. 3(a) and 3(b), we report BER versus received power for RF carrier frequencies of 2.4 GHz and 3.3 GHz, respectively. As can be observed, we could reach BER below the forward error correction (FEC) threshold of 3.8×10^{-3} for all the channels. For the purpose of comparison, BER performance of back to back (B2B) and single channel data transmission are also plotted. When sending one channel, the performance of each channel was, more or less, equal. Hence, we did not include markers on these curves, but colors are keyed to the figure legend.

By comparing the cases where a single channel was launched as opposed to all channels being transmitted, we observe power penalties near to 4 dB at the FEC threshold in case of using four channels. This penalty is mainly due to the crosstalk between



(a)



(b)

Fig. 3. BER versus received power at RF carrier of (a) 2.4 GHz, (b) 3.3 GHz

channels and we will investigate it with more details in next figure. The same trend can be observed in RF carrier of 3.3 GHz in Fig 3. b. Referring to Fig. 2, we observed almost the same level of crosstalk on channels for carriers of 2.4 and 3.3 GHz and then in Fig. 3, the same BER performance.

In Fig. 4, we show the BER versus received power for different number of channels where the crosstalk level is different in each case. This helps us to identify the impact of crosstalk in PM-ERCF on RoF system performance and how increasing the crosstalk will impose power penalty to reach the BER of 3.8×10^{-3}. The demux is opted for reception of $LPV_{11b,y}$. BER curves are plotted for cases of sending, one, two or three channels along with the main channel of $LPV_{11b,y}$ resulting in different levels of crosstalk. The crosstalk due to each of the 3 other channels could be read from Table II. For case of two channels, we transmitted the opposite polarization of the same mode, i.e. $LPV_{11b,x}$ which has the highest level of crosstalk with its effective index be the closest to $LPV_{11b,y}$. For the case of sending three channels, we examined the two cases of transmission of either $LPV_{11a,x}$ or $LPV_{21a,y}$ along with $LPV_{11b,x,y}$. Between the

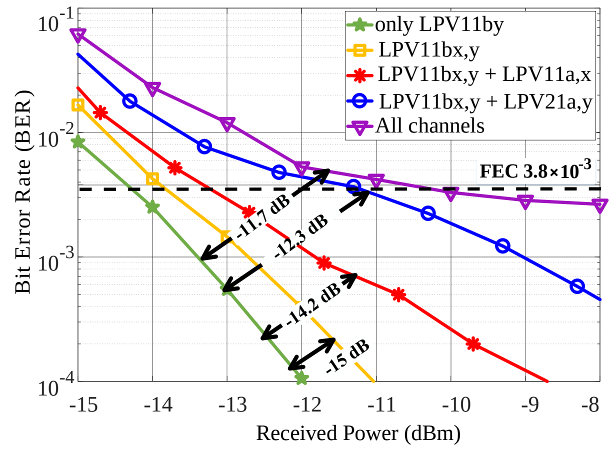


Fig. 4. BER versus received power at RF carrier of 3.3 GHz for $LPV_{11b,y}$ channel when transmitting various combinations of channels; insets are measured crosstalk on $LPV_{11b,y}$

two other channels, the crosstalk from $LPV_{21a,y}$ which is at the same polarization of y is larger than $LPV_{11a,x}$ from the opposite polarization. The total crosstalk on $LPV_{11b,y}$ is shown for each case in Fig. 4 on the curves. By using the results in Fig. 4, we can clearly confirm that the power penalty observed in Fig. 3 is due to the crosstalk where higher levels of crosstalk result in higher power penalty at FEC threshold. Increase of crosstalk also increases the minimum achievable BER by system.

C. *Comparison with coherent detection results*

In [32], the same fiber was used to transport wideband digital data on 6 channels: $LPV_{11,a}$, $LPV_{11,b}$ and $LPV_{21,a}$ modes in two polarizations were used. Coherent detection of QPSK data at baud rates up to 32 Gbaud achieved BERs below the FEC threshold for all channels. As in this experiment, no polarization control or digital signal processing was used to separate polarizations.

Although the use of six channels led to higher crosstalk (-9 to -10.5 dB) in that experiment compared to those reported in this paper, better BER was achieved. This could be attributed to the greater sensitivity of coherent detection; however, other factors can also come into play. For instance, performance could be influenced by non-ideal optical to electrical conversion in the RoF receiver, nonlinearities that degrade the performance of RoF systems and different time scales in equalizers in DSP, i.e., time resolution of milliseconds compared to nanoseconds resolution for coherent detection at 32 Gbaud.

Another difference between RoF vs. digital data transmission is the significant spread in BER floors across channels. In Fig. 3, the RoF BER floors span only 1×10^{-3} to 3×10^{-3}. The QPSK signals at 32 Gbaud have BER floors from 1×10^{-3} to 5×10^{-5}. The variation in BER floor across channels can be attributed to: i) higher overall crosstalk means greater disparity among channel crosstalk experience, and ii) the lower BER floors, leaves the system more sensitive to other impairments becoming dominant.

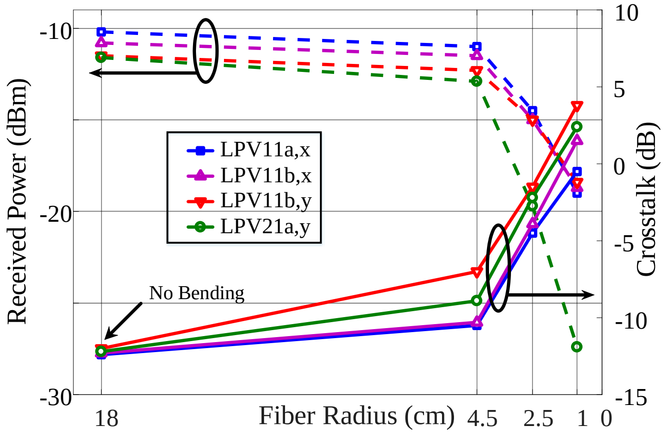


Fig. 5. Loss and crosstalk measurement versus fiber spool bending at RF carrier of 2.4 GHz

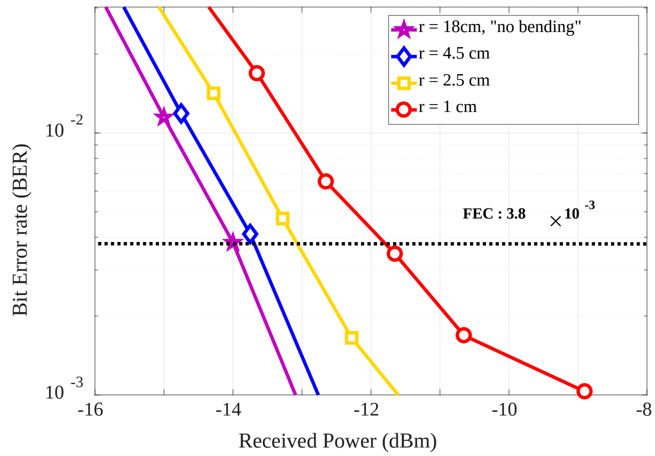


Fig. 7. BER vs received power for sending two polarizations of LPV_{11b} with bending applied to the fiber at RF carrier of 2.4 GHz

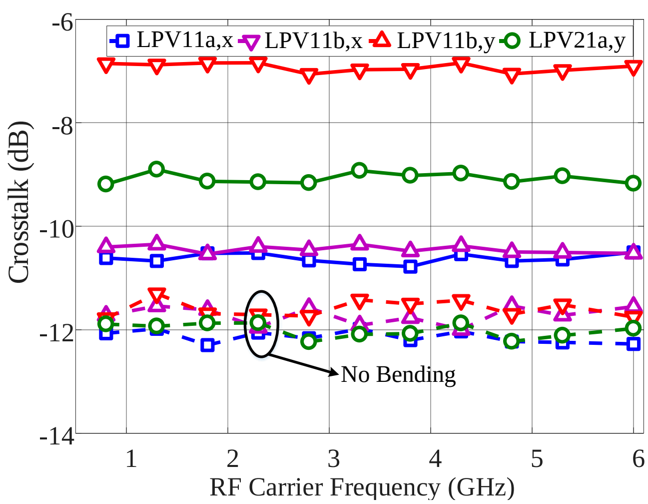


Fig. 6. Crosstalk on channels versus RF carrier frequency when bending fiber with a radius of 4.5 cm over a length of 15m

Table. III
Received modal power matrix at RF carrier of 3.3 GHz for bending radius of 4.5 cm; columns are transmitted modes and rows are received modes

	$LPV_{11a,x}$	$LPV_{11b,x}$	$LPV_{11b,y}$	$LPV_{21a,y}$
$LPV_{11a,x}$	0	-13.3	-19.2	-15.9
$LPV_{11b,x}$	-16.5	-0.5	-15.4	-15
$LPV_{11b,y}$	-23.8	-16.3	-1.3	-9.1
$LPV_{21a,y}$	-19.4	-19.2	-12.3	-1.9

V. Fiber Bending

In this section, we study the bending property of the polarization maintaining elliptical core fiber. While bending is always important, this is never more true for short links, such as fronthaul, with many constraints. For example, in-building fiber installations are more likely to be torturous and impose some performance penalty.

In [32], power stability and polarization maintaining property of the fiber was examined by inducing pressure and twist using a polarization controller. Stable modes with low power fluctuations were observed. Here, we would like to observe the changes in those parameters by introducing bending.

To study the bending effect on the fiber, we begin with a main spool with radius of 18 cm on which we roll 885 meters of fiber. To this default configuration, we take a final 15 meters of fiber and roll it on progressively tighter windings. All measurements are for a total of 900 m. The "no bending" configuration has all 900 m on the main spool. The three tighter windings we examine have spools of radiuses of 4.5, 2.5 and 1 cm for the final 15 m of fiber.

In Fig 5, we use dual y-axes to show the changes in demultiplexer output power and crosstalk. The x-axis is scaled for fiber radius, with "no bending" on the left, and more severe bending on the right. A curve is presented for each of the four channels examined. Comparing the channel power loss, $LPV_{21a,y}$ mode is clearly more sensitive to bending and has more loss than the other three channels. As a higher order mode, $LPV_{21a,y}$ has more tendency for power leakage to the cladding (or for that matter to lower order modes) and therefore more loss due to bending. Losses for the three other modes (the LPV_{11} mode group) reach with bending to the values around – 19 dB level. The higher order mode has 8 dB more loss at the same bending radius.

The crosstalk level increases with decreasing the bending radius for all modes. We see an almost linear progression of crosstalk in dB for tight windings. These crosstalk levels are enough to push the system into a region where MIMO processing is required, indicating that bending is a serious concern.

The measurements in Fig. 5 are done at RF carrier of 2.4 GHz. To study the impact of RF carrier frequency on crosstalk values when bending occurs, we swept the RF carrier frequency from 800 MHz to 6 GHz. The results for bending radius of 4.5 cm are depicted in Fig. 6. For the purpose of comparison, the crosstalk levels for no bending case is also shown. As can be observed, the bending induced crosstalk levels, similar to the case of no bending, are almost independent of RF carrier frequency;

however, due to dynamics of modal interactions due to bending, the difference among crosstalk on the four channels is larger than the case of no bending.

For a better insight to dynamics of modal mixing, we also report, in table III., the received modal powers at RF carrier of 3.3 GHz at bending radius of 4.5 cm. Again, the powers are all normalized to the received power when sending and receiving $LPV_{11a,x}$. By comparing the received powers in tables II and III, we observe the highest crosstalk increase on channels is contributed by $LPV_{21,a,y}$ mode. This is caused due to higher tendency of higher order modes for power leakage to lower order modes. It has the highest interaction with $LPV_{11,b,y}$ whose effective index is closest to $LPV_{21,a,y}$ and they are both on polarization *y*.

Although the bending results in increase of crosstalk between channels, the two polarizations of LPV_{11b} mode remain still well separated. This confirms the coupling between orthogonal polarizations is resistant against bending. The crosstalk levels of –15.5, –14.9, -14 and -13.1 dB from $LPV_{11,b,y}$ on $LPV_{11,b,x}$ channel is observed in cases of no bending and bending spools with radiuses of 4.5, 2.5 and 1 cm, respectively. In Fig. 7, the BER performance for case of sending $LPV_{11bx,y}$ and receiving LPV_{11bx} at RF carrier of 2.4GHz is plotted. The RF signal could be recovered; at the FEC threshold, a maximum power penalty of around 2 dB is observed. This signifies that, even under severe bending conditions, PM-ERCF fiber can provide at least two channels without considerable power penalty and without recourse to MIMO processing to compensate for impairments in optical channel.

VI. Conclusion

We showed for the first time, transmission of four RF signals over four LPV modes in a PM-ERCF via spatial division multiplexing with a total bit rate of 4.608 Gbps. Successful transmission on RF carriers of 2.4 GHz and 3.3 GHz was demonstrated without using MIMO processing. The fiber crosstalk could impose 3-4 dB of power penalty at the 3.8×10^{-3} FEC threshold. In investigating crosstalk changes due to the bending, we showed two polarizations of a mode remain separated under bending, where data on polarization states could be recovered without recourse to MIMO processing.

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