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Novel Centralized Lightwave Rof-system with10 GB sec^{-1} 16 QAM-OFDM Full-duplex SSb Link

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Abstract: A novel full-duplex SSB-RoF system with 16 QAM-OFDM bidirectional links was proposed. Because the configurations of the used transmitters and receivers at the central office and base station are same, the BER curves were similar for back-to-back case. The results demonstrated, after transmission over 41 km SSMF-28, the OSNR value of the received downlink signal was 10.5 dB at BER = 10^{-3} which was slightly lower than the OSNR value of the upstream signal. Hence, 16 QAM-OFDM signals could be transmitted successfully over 41 km SSMF-28 for downlink and uplink application. It would be a competitive scheme for bidirectional 16 QAM-OFDM signals application in future RoF systems.

Key words: Radio-over-fiber, centralized lightwave, 16 QAM-OFDM, SSB, full-duplex

INTRODUCTION

With the rapid development of society, the communication industry is advancing rapidly and all kinds of high-speed broadband-access services, such as video phones and high-definition television, are increasing throughout the world (Ma *et al*., 2012; Shao *et al*., 2012). To meet subscriber's demanding expectations, the traditional wireless communication system must further evolve to provide higher data rates because the current Radio-frequency (RF) spectrum is limited (Urzedowska and Yashchyshyn, 2011; Abdolee *et al*., 2007). Radio-over-fiber (RoF) technology has many advantages for the convergence of optical and wireless access systems and has attracted much interest for increasing the capacity and mobility of high-speed wireless data transmission (Ma *et al*., 2007; Hsueh *et al*., 2011; Nakajima, 2005; Chen *et al*., 2007). However, to reduce the cost of practical applications and overcome several technical obstacles, optical millimeter-wave (mm-wave) generation is getting more and more attention as key techniques in RoF system (Shih *et al*., 2009). The external modulation scheme generating the mm-wave signals includes double-sideband (DSB), single-sideband (SSB) and Optical Carrier Suppression (OCS) (Ma *et al*., 2007). The SSB modulation has more advantages than others (Sonu *et al*., 2012; Sima *et al*., 2011). Firstly, the power of SSB modulation signal is focused on one sideband which can improve the signal-to-noise ratio of transmitted signal therefore, the receiver sensitivity is higher than other cases. Secondly, the SSB optical mm-wave signal is robust to the effects of nonlinear phase noise. Thirdly, the occupied bandwidth of SSB modulation is half of DSB and the spectrum efficiency is higher which is a good method in wavelength-division-multiplexing (WDM) system application. Finally, to overcome fiber dispersion, SSB modulation is also a good option (Wen *et al*., 2011).

Recently, some researchers are focusing on the study on uplink transmission using on-off keying (OOK) or differential phase-shift keying (DPSK) modulation. Meanwhile, M-QAM as a high spectral efficiency modulation format has been proposed for full-duplex RoF links application (Ma *et al*., 2012). However, there are few report involved in OFDM signals upstream in RoF systems (Shao *et al*., 2012; Yu *et al*., 2008a). As we know, OFDM modulation has its intrinsic advantages, such as high spectral efficiency, robust to chromatic dispersion and more flexible bandwidth allocation (Armstrong, 2009; Chen *et al*., 2009; Yu *et al*., 2008a; Sano *et al*., 2009). Hence, the introduction of OFDM modulation is considered for bidirectional links application in future full-duplex RoF systems.

In this study, a novel architecture of full-duplex SSB RoF link with 10 Gb sec^{-1} 16 QAM-OFDM mm-wave signals was demonstrated. In the scheme, a 16 QAM-OFDM signal is firstly up-converted to 40 GHz by orthogonally mixing and then it is SSB modulated through a Mach-Zehnder modulator (MZM) for downstream. For further reducing the cost budget, the centralize lightwave without downlink data modulation is reused for uplink transmission. Compared with Ref. (Ma *et al*., 2012), the proposed scheme using 16 QAM-OFDM modulation for full-duplex bidirectional links

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application can achieve high spectral efficiency, robust to chromatic dispersion and more flexible bandwidth allocation. Theoretical analysis and simulation results demonstrate that it is a competitive scheme for bidirectional 16 QAM-OFDM signals application in future RoF systems.

PRINCIPLE

Figure 1 shows the block diagram of the proposed RoF-system with full-duplex SSB link. The RoF system is comprised of CO, fiber link, BS and UT. The designed CO mainly consists of OFDM transmitter and OFDM receiver. At the CO, the continuous wave optical signal from a laser diode can be expressed as:

$$E_1(t) = \sqrt{P_0}\exp(j\omega_0 t) \quad (1)$$

where, P_0 is output power of laser and ω_0 is the central frequency. The downlink data is sent to OFDM transmitter and the generated OFDM signal $x_m(t)$ can be given by:

$$x_m(t) = I(t)+j.Q(t) \quad (2)$$

For quadrature modulator, the input electrical signals are the I(t) and Q(t) and the electrical RF carriers are $V_I(t) = V_{RF}(t)\cos\omega_{RF}t$, $V_Q(t) = V_{RF}(t)\sin\omega_{RF}t$ where, ω_{RF} and V_{RF} is the frequency and amplitude of the electrical RF carrier, respectively. Assuming G is the parameter gain, the output signal of quadrature modulator can be expressed as:

$$V_I(t) = G(I)(t)-V_{RF}\cos(\omega_{RF}t)-Q(t)-V_{RF}\sin(\omega_{RF}t)) \quad (3)$$

As far as a dual-arm Lithium-Niobate-MZM (LN-MZM) is concerned, the bias voltage V_{dc} and the relative phase θ of the signals between the two arms are determinant factors which decide the components of the optical spectra and one can adjust them to generate the optical mm-waves with SSB spectra. The lightwave $E_1(t)$ is injected to the dual arm LN-MZM and a 90 degree difference is introduced between the RF modulating electrical voltage $V_1(t)$ and $E_1(t)$. The MZM is biased at $V_\pi/2$, where, V_π is the maximum transmission point and the output lightwave can be expressed as:

$$E_2(t) \approx \alpha\sqrt{P_0}[\sqrt{2}J_0(m)e^{j(\omega_0 t+\pi/4)} + 2J_1(m)x_m(t)e^{j[(\omega_0+\omega_{RF})t+\pi/2]})] \quad (4)$$

where, α is the insertion loss of LN-MZM, $m = \pi V_1(t)/V\pi$ is the RF modulation index and $J_n(m)$ is the nth-order Bessel function of the first kind. From Eq. 4, it's obvious that the output of the LN-MZM mainly consists of the optical carrier at ω_0 and the 1st-order upper-sidebands at $\omega_0+\omega_{RF}$. The frequency space is ω_{RF} and the optical SSB mm-wave is generated for the downlink.

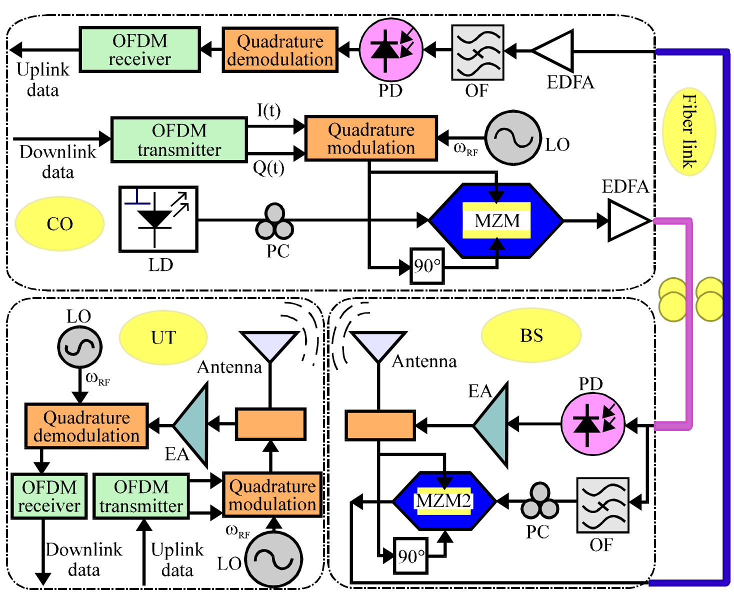

Fig. 1: Proposed RoF-system with full-duplex SSB link, LD: Laser diode, MZM: Mach-zehnder modulator, LO: Local oscillator, OF: Optical filter, PD: Photo detector, EDFA: Erbium-doped fiber amplifier, EA: Electrical amplifier, PC: Polarization controller

Since, $x_m(t)$ is only modulated onto $\omega_0+\omega_{RF}$ sideband, the generated SSB optical mm-wave signal is immune to the fiber chromatic dispersion when they are transmitted along the dispersive fiber and the bit walk-off effect of the optical mm-wave signal can be overcome (Yu *et al.*, 2008b). To compensate the loss of the component and fiber, the optical mm-wave signal must be pre-amplified with EDFA at the CO. After an Optical Filter (OF), the generated SSB optical mm-wave signal is sent to the downlink fiber.

After a z-km length of standard single mode fiber (SSMF-28), the received optical electrical field at the BS can be written as:

$$\begin{aligned} E_3(z,t) &= \alpha\sqrt{P_0}e^{-\kappa z/2}\{\lambda_1 J_0(m)e^{j[\omega_0 t-\beta(\omega_0)z]} \\ &+ 2\lambda_2 J_1(m)V_1\left(t-\frac{\beta(\omega_0+\omega_{RF})}{\omega_0+\omega_{RF}}z\right)e^{j[(\omega_0+\omega_{RF})t-\beta(\omega_0+\omega_{RF})z+\delta]}\} \end{aligned} \tag{5}$$

where, κ is the optical power attenuation along the fiber, δ is the introduced random phase noise that will broaden the beating RF spectrum and $\beta(\omega)$ is the propagation constant of the lightwave at an angular frequency of ω (Ma, 2011). The fiber dispersion can cause the bit walk-off effect in a conventional fiber link between the different tones of the optical mm-wave. In this RoF system, since a Cyclic prefix (CP), whose length is 1/16 symbol period, is used, any distortion caused by a linear dispersive channel can be corrected by simply using a 'single-tap' equalizer and the effect caused by fiber dispersion within each tone can be neglected as long as data rate is much smaller than the mm-wave frequency(Armstrong, 2009).

At the BS, the optical mm-wave is divided into two parts by a 3-dB optical coupler. One part is delivered to a PIN photodiode to convert to electrical signal. Assuming that only the optical field amplitude is affected in effective bandwidth and fiber dispersion and nonlinear response have little effect, the photocurrent can be expressed as:

$$\begin{aligned} I_1(t) &= R_{PIN}\,|E_3(z,t)|^2 \\ &= R_{PIN}\,|\alpha\sqrt{P_0}e^{-\kappa z/2}\{\lambda_1 J_0(m)e^{j[\omega_0 t-\beta(\omega_0)z]} \\ &+ 2\lambda_2 J_1(m)V_1\left(t-\frac{\beta(\omega_0+\omega_{RF})}{\omega_0+\omega_{RF}}z\right)e^{j[(\omega_0+\omega_{RF})t-\beta(\omega_0+\omega_{RF})z+\delta]}\}|^2 \\ &= R_{PIN}\alpha^2 P_0 e^{-\kappa z}\{\lambda_1^2 J_0^2(m)+4\lambda_2^2 J_1^2(m)\,|V_1\left(t-\frac{\beta(\omega_0+\omega_{RF})}{\omega_0+\omega_{RF}}z\right)|^2 \\ &+2\lambda_1\lambda_2 J_1(m)J_0(m)V_1\left(t-\frac{\beta(\omega_0+\omega_{RF})}{\omega_0+\omega_{RF}}z\right)\cos[\omega_{RF}t-\omega_{RF}\beta'(\omega_0')z+\delta]\} \end{aligned} \tag{6}$$

where, R_{PIN} is the responsivity of PIN $\omega_0' = \omega_0+\omega_{RF}/2$, $\beta'(\omega_0') \approx [\beta(\omega_0)-\beta(\omega_0+\omega_{RF})]/\omega_{RF}$. After an electrical amplifier with ω_{RF} bandwidth, the mm-wave signal is expressed as:

$$I_{\omega_{RF}}(t) \propto V_1\left(t-\frac{\beta(\omega_0+\omega_{RF})}{\omega_0+\omega_{RF}}z\right)\cos[\omega_{RF}t-\omega_{RF}\beta'(\omega_0')z+\delta] \tag{7}$$

An antenna is used to convert the electric power into radio waves. After it receives the feeble wireless signal, an amplifier with low noise figure is used to amplify the signal and the electrical Local Oscillator (LO) signal and an electrical mixer are used to down-convert the electrical signal to the OFDM baseband signal and the downlink data can be recovered thought an OFDM receiver.

The other part is prepared for uplink, an OF is used to get the central lightwave at an angular frequency of ω_0 for wavelength-reusing at the BS and the reusing optical carrier is given as:

$$E_4(z,t) = \lambda' e^{j[\omega_0 t-\beta(\omega_0)z]} \tag{8}$$

The uplink 16 QAM-OFDM signal carried by mm-wave is remodulated by MZM2 and the operating principle of uplink is similar to the downlink's.

RESULTS

The architecture of the proposed full-duplex RoF system is shown in Fig. 2. 10 Gb sec^{-1} data are sent to 16 QAM-OFDM transmitter. The generation of 16 QAM-OFDM signal includes symbol mapping, inserting pilot, Inverse Fast Fourier Transform (IFFT), adding Cyclic Prefix (CP) and digital-analog-conversion (DAC). The generated I and Q signals are mixed with a 40-GHz sinusoidal wave by an electrical analog I/Q-mixer. The electrical frequency spectrum of the transmitted signal for downlink is shown in Fig. 3a. The generated RF OFDM signal is used to drive the dual arm LN-MZM and the power of RF OFDM signal has to be carefully adjusted to maintain a certain power ratio between LO and 1st-order sidebands while suppressing the 2nd-order modes resulted from the nonlinearity of the modulation from the modulator to increase dispersion tolerance and good receiver sensitivity (Shao *et al.*, 2010). When the MZM is biased at $V_\pi/2$ = 2V and there is a 90 degree difference between the modulating electrical voltages, the optical spectrum of the output of the MZM is shown in Fig. 3b. It is clear to see, the output of the MZM consists of the optical carrier at ω_0 and the 1st-order upper-sideband at $\omega_0+\omega_{RF}$ which is corresponding to Eq. 4. To reduce cost budget, a low-noise EDFA is placed at the CO for compensating the losses of fiber transmission and passive components.

After transmission over 41 km SSMF-28, the optical spectrum of the received optical SSB signal is shown in Fig. 3c. It is divided into two output signals by a 3-dB

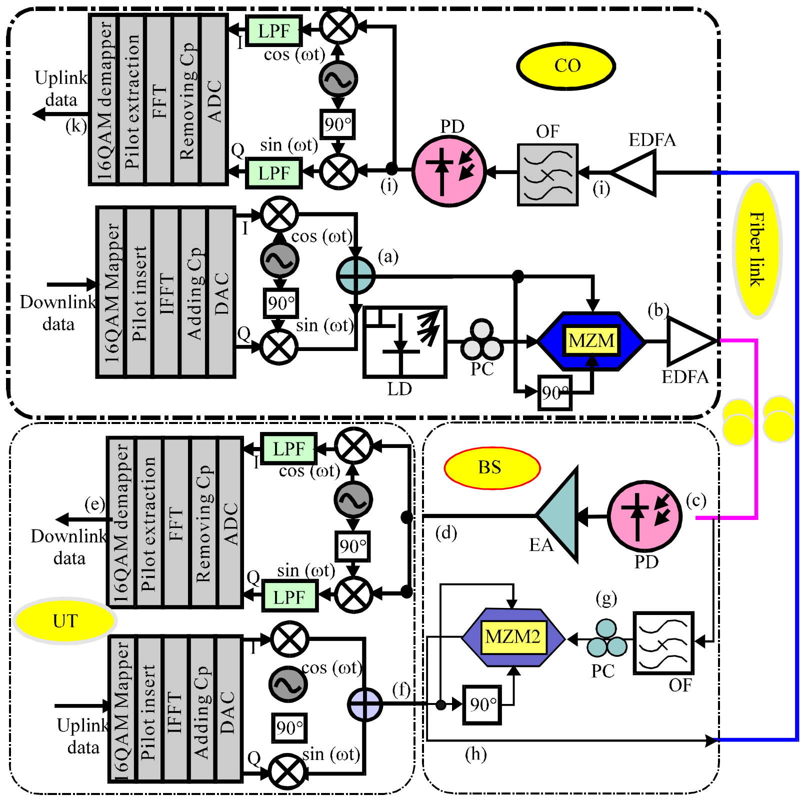

Fig. 2: Simulated architecture of the proposed full-duplex RoF system

optical coupler. One is received by a PIN receiver with a 3-dB bandwidth of 40 Ghz and beat to generate 40 GHz electrical mm-wave signal, whose electrical spectrum is shown in Fig. 3d which is in accord with Eq. 7. One electrical LO signal and an electrical mixer are introduced to down-convert the 40GHz electrical mm-wave signal to the 16 QAM-OFDM baseband signal and the downlink data can be recovered thought a 16QAM-OFDM receiver (the signal process includes analog-digital-conversion, removing CP, Fast Fourier Transform (FFT), pilot-extract and demapper). To achieve the target of a laser-less BS, the CO transmitted centralized lightwave is reused. The other firstly passes an Optical Filter (OF) with the center wavelength at 1552.52 nm and with 0.1 nm bandwidth and then passes a Polarization Controller (PC) and the optical spectrum is shown in Fig. 3f. The uplink 16 QAM-OFDM signal, whose electrical spectrum is shown in Fig. 3e, is remodulated via one dual arm MZM, the optical mm-wave spectrum of uplink from MZM2 is shown in Fig. 3g. Because there is no additional light source and no EDFA and no wavelength management function at the BS, cost is significantly reduced and system stability is improved. After transmission over 41 km SSMF-28, the optical mm-wave uplink signal is transmitted back to CO. At the CO, a low-noise EDFA with 30 dB gain is used to amplify the received optical signal and the optical spectrum is shown in Fig. 3h. The amplified optical signal is sent to PIN for generating electrical domain signal, whose electrical spectrum is shown in Fig. 3i. After the electrical mm-wave signal is demodulated, the OFDM baseband signal is obtained by one 16QAM-OFDM receiver.

Figure 4 shows the Bit Error Rate (BER) curves vs. Optical Signal to Noise Ratio (OSNR) for bidirectional transmission. For back-to-back case, the OSNR values of the received signal after downlink and uplink transmission over 41 km SSMF-28 is 9.2 dB and 9.3 dB at BER = 10^{-3}, respectively. Moreover, the BER curves are similar as the signal before downstream and upstream transmission. The results demonstrate the performance of the used transmitters at the CO and BS is almost same, since the configurations at these transmitters is same. For downlink, the OSNR value of the received signal is 10.5 at BER = 10^{-3} which is slightly lower than that of the upstream signal. The reason is the centralized lightwave

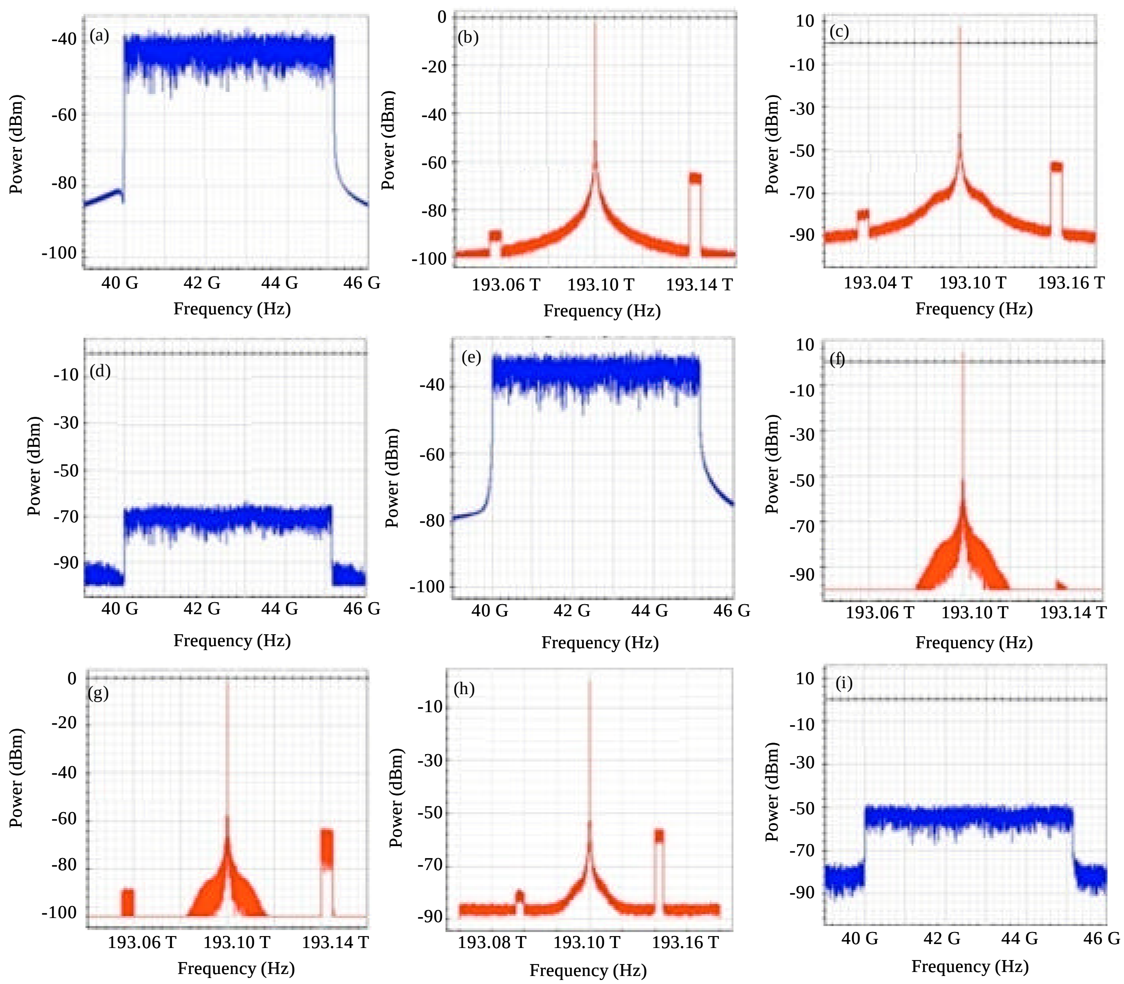

Fig. 3(a-i): Simulated spectrum (a) Spectrum of the transmitted 16QAM-OFDM signal for downlink (b) Optical spectrum of the output of MZM (c) Optical spectrum of the received optical signal (d) Spectrum after beating for downlink (e) Spectrum of the transmitted 16 QAM-OFDM signal for uplink (f) Optical spectrum for reusing (g) Optical spectrum of the transmitted signal for uplink, (h) Optical spectrum of the received optical signal and (i) Spectrum after beating for uplink

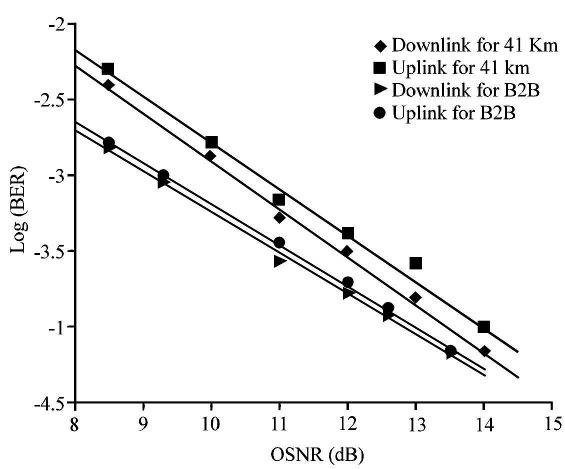

Fig. 4: BER curves of downlink and uplink signals

is firstly transmitted over 41 km SSMF-28 without data modulation and then it is modulated by 16 QAM-OFDM signals for uplink transmission.

CONCLUSION

A novel full-duplex 40 Ghz RoF system with 10 Gb sec^{-1} 16QAM-OFDM bidirectional links signals was proposed. 16QAM-OFDM signals are transmitted successfully over 41 km SSMF-28 for bidirectional links application. The results demonstrate, the performance of the used transmitters at the CO and BS is almost same, since the configurations at these transmitters is same. For downlink, the OSNR value of the received signal is slightly lower than that of the upstream signal, since the centralized lightwave is firstly transmitted over 41 km

SSMF-28 without data modulation and then it is reused for uplink transmission. Hence, it is a competitive scheme for bidirectional 16QAM-OFDM signals application in future RoF systems.

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