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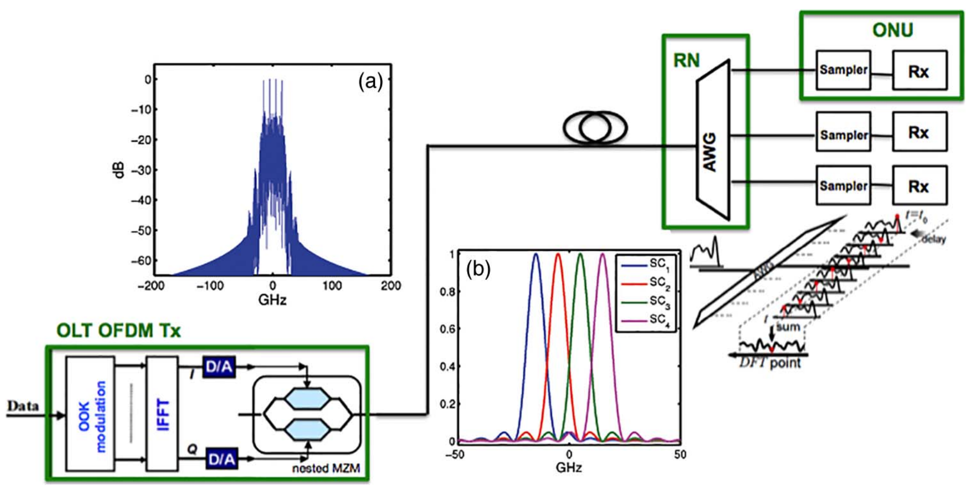

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Demonstration and Performance Investigation of Hybrid OFDM Systems for Optical Access Network Applications

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Abstract: We propose a hybrid solution to exploit the capabilities of the optical orthogonal frequency-division multiplexing (OFDM) for passive optical network applications implemented by the electronic generation of the OFDM signal at the transmitter and by the all-optical demultiplexing of the OFDM subcarriers at the remote node by means of a passive element, such as suitable arrayed waveguide grating, performing the fast Fourier transform (FFT) in the optical domain. Drastic simplicity at the optical network unit is achieved with neither coherent detection nor any high-speed electronics, allowing an effective exploitation of all the available transmission spectra. By means of simulations and preliminary experimentation, we demonstrate 4 $\times$ 10-Gb/s transmission over more than 40-km standard single-mode fiber, the main limitation to the number of subcarriers being the employed device's actual electronic bandwidth.

Index Terms: Fiber optics communications, orthogonal frequency-division multiplexing (OFDM), array waveguide devices.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is an attractive transmission format useful to increase the transported capacity. In order to guarantee the orthogonality, individual subcarriers are spaced in multiples of the reciprocal symbol duration, allowing their partial overlapping, but not interfering with one another at the sampling instants. Hence, a high spectral efficiency is achieved. OFDM was originally proposed as a modulation method in media showing bandwidth limitations and non-uniform channel performance (i.e., radio channel). In recent years, also in fiber-optic communications, optical OFDM has emerged as a smart solution [1]. Some modulation/detection combinations for optical OFDM have been proposed, showing different implementation aspects related in particular to the realization of inverse fast Fourier transform (IFFT) and FFT algorithms, which actually determine next-generation optical network applications of optical OFDM.

Optical OFDM can be implemented in a simple way by exploiting intensity modulation and direct detection (IM/DD) [2]. In the IM case, the optical intensity modulation containing the OFDM signal is a real quantity. Hence, the OFDM signal must be both real and positive, exploiting Hermitian symmetry at the IFFT output and so halving the total transmitting data rate. Furthermore, it is necessary to add a dc bias to the OFDM signal. After DD, owing to the incoherent mixing, the signal output contains not only the right beating term related to the OFDM modulation, but also undesired mixing terms. A frequency guard band to separate the mixing products at the DD receiver output is required [3], imposing a further reduction in spectral efficiency.

In coherent-OFDM (CO-OFDM) a local oscillator is used at the receiver-side in order to detect the field (and not the intensity) of the OFDM signal. With respect to the IM/DD O-OFDM, the CO-OFDM solution exploits the real capabilities of OFDM modulation in terms of spectral efficiency, increasing also the receiver sensitivity [4]. The IFFT and FFT processing is accomplished exclusively by DSP (digital signal processing) based implementation. The CO-OFDM presents several attractive benefits, but its realization requires increased complexity, cost and power consumption. The CO-OFDM has demonstrated excellent performance in case of long-reach and high-capacity applications [5], but it remains a strong challenge in case of future access systems, owing to the hardware and software complexity at the receiver.

A very innovative approach is constituted by the all-optical OFDM (AO-OFDM), where the IFFT and FFT operations are realized in the optical domain. At the transmitter side, a comb of unmodulated, phase-locked orthogonal subcarriers is produced. Then, these tones are separated, individually modulated with complex symbols, and finally recombined and transmitted in the fiber. At the receiver, the modulated subcarriers are demultiplexed once again, and processed in parallel each one by its proper receiver. Different technologies have been investigated to realize the all-optical IFFT/FFT blocks, for example cascaded Mach-Zehnder delay interferometers in planar lightwave circuits [6], multisection Sagnac interferometers [7], and arrayed waveguide gratings (AWGs) [8]. In particular, the latter solution shows many advantages, such as simple waveguide layout and design flexibility of the port number. With respect to CO-OFDM based on expensive high-speed DSP both at the transmitter and the receiver side, AO-OFDM allows to reduce the energy consumption and the system cost, using passive components and low bandwidth electronics. The AO-OFDM transmitter usually comprises a frequency comb generator, a narrow demultiplexer, a modulator array, and a power combiner. In particular, the comb generator needs key requirements, such as a good spectral flatness, accurate channel spacing and a narrow linewidth of the unmodulated subcarriers. Different approaches have been proposed for comb generation, for example based on mode-locked laser [9], on overdriven phase modulators [10], or on interferometers inside an amplified ring [11]. All these implementations result very critical, with the request of very high drive voltages.

As far as optical access networks are concerned, current standardized passive optical networks (PONs) based on time-division multiplexing (TDM) guarantee low complexity and costs. On the other hand the demand for transporting increased traffic volumes (up to several tens of Gb/s of aggregate capacity) is extremely challenging for TDM-based systems. To increase the aggregate transport capacity, wavelength-division multiplexing (WDM) based architecture has been widely studied both standalone and in combination with time-division multiple access (TDMA) [12]. However, in addition, WDM PONs demonstrate limitations in terms of scalability and efficiency in the bandwidth exploitation.

Optical OFDM can show unique advantages for future high capacity PONs, enabling the effective use of all the available fiber transmission spectra and exploiting the subcarriers as finely granular resources for dynamic, multiuser bandwidth access. While entirely compliant to operation with both WDM and TDM layers, optical OFDM approach would be really attractive for future PON applications only if it guarantees high performance with low-complexity actual implementation. High transported aggregate capacity, medium propagation reach (up to 40 km), open multioperator access, should be supported with low-cost user-side optical network units (ONUs). As we have already explained, the CO-OFDM solution shows a very complex coherent ONU, including local oscillator, ultra-fast electronics and real-time DSP operating at very high sampling rate. On the contrary, the AO-OFDM solution is based onto an optical transmitter with very critical implementation.

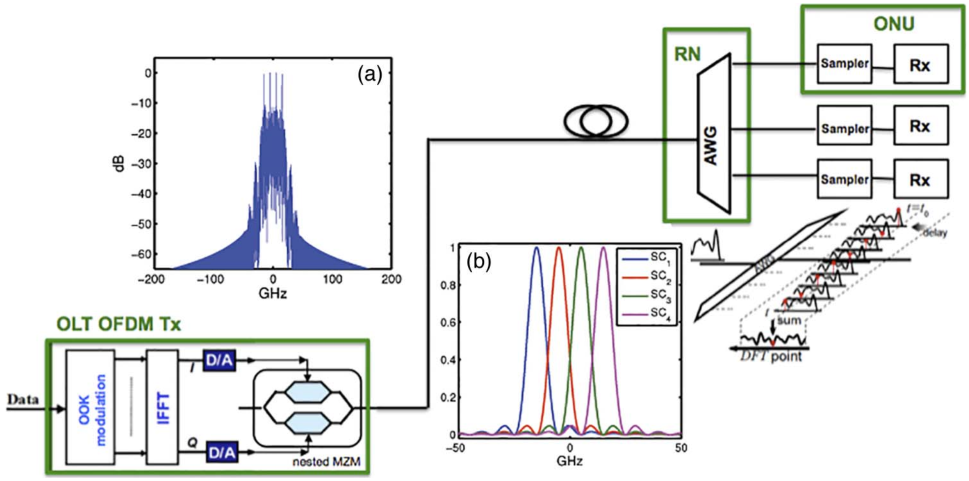

Fig. 1. Hybrid OFDM system scheme for PON applications. (a) Down-converted optical spectrum corresponding to the OFDM signal with 4 x 10-Gb/s OOK-modulated subcarriers at the TX output. (b) AWG transfer function used as FFT block in case of four output ports. The sketch showing the operation of the AWG at the RN is taken by [8].

In this paper, we propose a hybrid solution for downstream (DS) transmission able to exploit both the capabilities of the CO-OFDM in terms of optical line terminal (OLT) transmitter implementation and of the AO-OFDM in terms of ONU receiver implementation. In this hypothesis, the distinguished feature of the transmitter of the proposed hybrid OFDM is the reliance on electronic DSP to the generation of the OFDM-modulated subcarriers at the centralized OLT. Allowing computational processes tailored to the PON environment, this feature guarantees high flexibility and is compliant with the trend of the so-called software-defined networks (SDN) for the next-generation access. Moreover, the FFT operation is realized at the remote node (RN) by means of an all-optical and passive element (e.g., a suitable AWG) in order to demultiplex the OFDM subcarriers without high-speed electronics. By using on-off keying (OOK) modulation for each subcarrier, DD receivers are employed, guaranteeing drastic simplicity at the ONUs.

This paper focuses on the optical implementation of the hybrid OFDM solution by starting from devices and components commercially available or experimentally described in literature. By means of simulations we demonstrate the performance achievable by exploiting this novel proposal taking into account the constraints of the electrical bandwidth at the transmitter and of the optical bandwidth of the AWG. Finally, experimentation of 4×10 Gb/s hybrid OFDM over more than 40-km SSMF propagation is demonstrated as a proof of principle of the operation of the proposed solution.

2. Hybrid OFDM System Scheme for PON Networks

In the proposed hybrid OFDM scheme, the transmitter is based on OFDM signal generation by DSP. As shown in Fig. 1, at the transmitter side, the input high speed binary data stream is first serial-to-parallel converted and then modulated with the chosen modulation format. The multicarrier modulation is implemented by means of the IFFT block. Furthermore a cyclic prefix can be inserted to prevent inter-symbol interference (ISI) due to the fiber channel dispersion. Finally, a digital-to-analog converter (DAC) is used to convert the digital data sequence into an analog signal waveform, ready to drive the optical modulator. In particular, the subcarriers are modulated onto the optical carrier by using an I/Q optical modulator, which allows any optical amplitude and phase to be transmitted by modulating both the in-phase and the quadrature part of the field.

At the receiver side, we propose to exploit the capabilities of the AO-OFDM, using for example an AWG to implement in an all-optical way the FFT block. The considered AWG has the same configuration as a conventional AWG used in WDM applications, but its parameters have to be suitably designed to perform FFT operation. More details about the operation of the AWG as all-optical subcarrier demultiplexer are shown in [13]. By employing the AWG as an FFT block, if we detect the output signal at an AWG port, the acquired samples after optoelectronic conversion correspond to the subcarrier frequency [8]. If we exploit OOK modulation format for each OFDM subcarrier, at each AWG output port, DD-based receivers can be used.

For PON applications the proposed hybrid OFDM solution shows significant advantages. All the high-speed processing useful for the OFDM signal generation is located just at the OLT side. At the RN we put the OFDM AWG in order to achieve the passive and all-optical demultiplexing of the OFDM subcarriers. Considering OOK modulation, each ONU is very simple, requiring neither coherent detection nor high-speed electronics for receiving and processing the data. The proposed scheme guarantees the inherent capabilities of coherent OFDM modulation in terms of effective exploitation of the spectrum with respect for example of WDM, assigning partially overlapped subcarriers to the ONUs. Further, the proposed scheme responds to the request of simple and low-cost implementation of the ONU, mandatory in all the future development of the PON network.

As far as upstream transmission concerns, a solution based on ultra-dense WDM multiplexing can be adopted by exploiting the same system architecture described in Fig. 1. The same optical AWG, designed for OFDM demultiplexing, is employed to multiplex in a passive way the upstream WDM carriers generated by the ONUs, while no OFDM modulation is used. The bit rate of the upstream data transmitted by each ONU is chosen so that no spectral overlapping between the carriers occurs after WDM multiplexing. Obviously, in this case, the total capacity transported in upstream by means of ultra-dense WDM is half with respect to the OFDM-based downstream.

The proposed hybrid OFDM in PON architectures guarantees also flexibility in the resource allocation and service provisioning. In particular, the proposed solution allows to open the infrastructure to all the other licensed operators, who are then able to provide services to each users in an unbundled way, as described in [14].

3. Performance Analysis of 4 $\times$ 10-Gb/s Hybrid OOK OFDM System

The proposed hybrid OFDM solution has to meet specific constraints in the choice of the subcarrier modulation bit-rate and the number of employed subcarriers. The actually already realized integrated AWGs, operating as FFT blocks, do not allow to set the frequency spacing between the neighbor subcarriers to less than about 10 GHz. Narrower frequency spacing will present a criticism in the stability and size of the realized AWGs. In the same way, the electrical bandwidths of the commercial electronic devices useful for the DSP and the DAC implementation at the transmitter side are today limited at some tens of GHz. The number of subcarriers generated in a digital way by the transmitter is bounded by this limitation. Hence, the employment of the hybrid OFDM solution inevitably involves a trade-off between the number of subcarriers and their modulation bit-rate. Considering the specifications of the present components and devices, we choose to study the performance of the hybrid OFDM system with four subcarriers, each one OOK-modulated at 10 Gb/s.

We have numerically simulated the system setup shown in Fig. 1 At the TX the laser has a linewidth of 1 MHz and a RIN of -150 dB/Hz, in order to simulate the specifications of typical commercial telecom sources. The OFDM optical modulation is obtained by an I/Q Mach-Zehnder modulator (MZM). Each MZM electrode driving signal is suitably generated by DACs with quantization and holding functionalities. Before DACs, the parallel OFDM symbols are generated by means of digital processing in the IFFT block. OOK modulation at 10 Gb/s is applied at each OFDM subcarrier. At the output, the OFDM signal is demultiplexed by means of a suitable AWG operating as FFT block with 10-GHz frequency spacing and whose transfer function is described in [13]. The signal at the output port of the AWG, corresponding to each subcarrier, is then directly detected by a PIN photodiode with NEP 80×10^{-12} W/Hz$^{1/2}$ and bandwidth 10 GHz and then sampled.

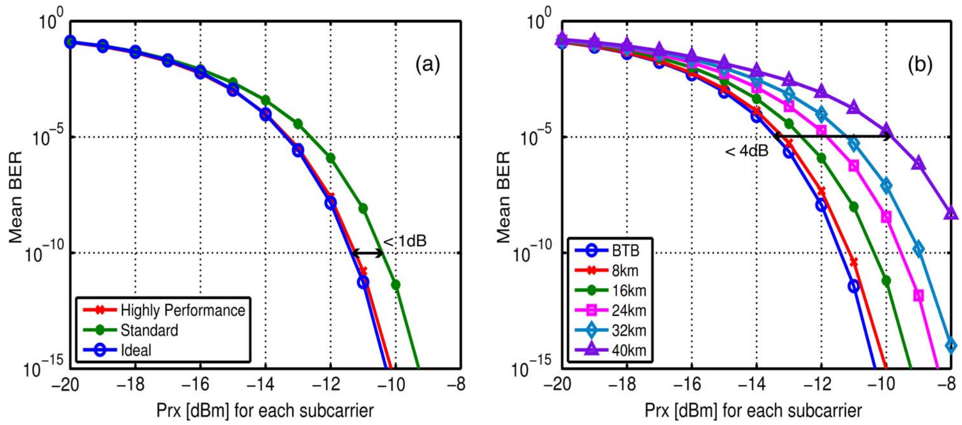

Fig. 2. 4 × 10-Gb/s OOK hybrid OFDM system performance. (a) BER versus received power per subcarrier in BTB for different cases of optical and electrical bandwidths of the employed devices at the transmitter. (b) BER versus received power per subcarrier in ideal bandwidth conditions at the transmitter for different propagation distances.

Performance of the hybrid OFDM solution in case of direct detection is evaluated through BER analysis achieved by means of a semi-analytical method. In particular, the receiver noise, described by Gaussian statistics, is added at the receiver, taking into account just shot noise and electrical noise, as in the case of direct detection without optical amplification. Signal and noise are thus separated during the propagation and combined at the receiver in order to evaluate their statistical distribution, achieving the probability density function of the symbol '1' and of the symbol such as '0' necessary for the BER calculation for each OOK OFDM subcarrier. With respect to Monte-Carlo method, this method does not have to take into account a very large number of noise realizations, taking advantage of the complete knowledge of the statistics.

Fig. 2(a) reports the BER performance in back-to-back (BTB) in case of the so-called ideal conditions, i.e., infinite optical bandwidth of the MZM and infinite electrical bandwidth of the DACs and of the driver before the MZM (blue curve in the figure). At 10 Gb/s, error-free operation (BER of 10^{-12}) is achieved with a receiver power per subcarrier of about -11 dBm. Considering actual bandwidth limitations of the employed devices the penalties remain low. In particular in case of 25-GHz DAC bandwidth, 40-GHz driver bandwidth and 35-GHz MZM bandwidth (case 1, red curve in the figure), the penalty with respect to the ideal case is negligible. In case of more stringent limitations, corresponding to already available components, i.e., 20-GHz DAC bandwidth, 25-GHz driver bandwidth and 20-GHz MZM bandwidth (case 2, green curve in the figure), the penalty is less than 1 dB at BER $= 10^{-10}$, demonstrating the experimental feasibility of the 4 × 10-Gb/s hybrid OFDM proposal. The BER shown in the figure is the mean BER calculated over the 4 subcarriers.

The performance of the 4 × 10-Gb/s OOK hybrid OFDM system is simulated also considering propagation in SSMF without optical amplification and chromatic dispersion compensation. The impact of the propagation is analyzed in case of ideal conditions for the optical and electrical bandwidth of the transmitter. In this preliminary study no cyclic prefix has been introduced, to analyze the worst case for the chromatic-dispersion robustness. As shown in Fig. 2(b), less than 4-dB penalties are obtained at 10^{-5}-BER after 40-km uncompensated propagation, confirming the robustness against chromatic dispersion of the OFDM format. This reach can include not only the feeder fiber, but also the distribution fiber, that in the PON systems is usually a few-kilometer long.

The performance previously shown is obtained when considering perfect matching of the AWG center frequency with the generated OFDM signal. A frequency mismatch, due to fabrication flaws or to operation stability, is more critical than in WDM systems, as the AWG demodulates orthogonal subcarriers. For not negligible frequency mismatches, the performed AWG

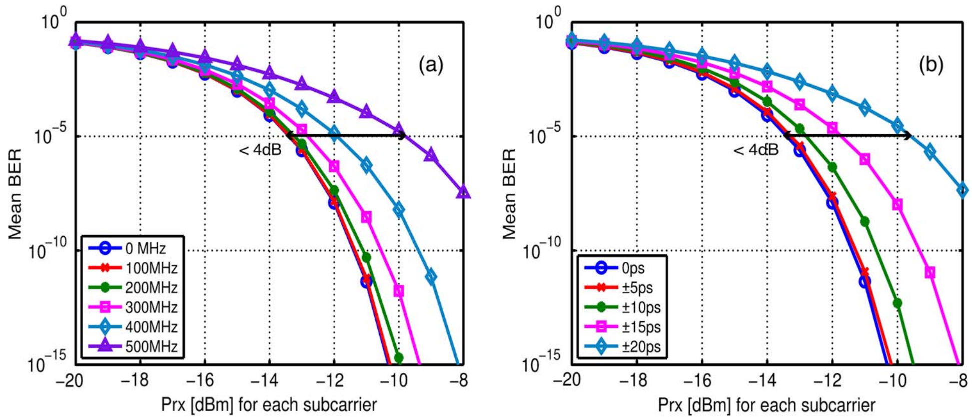

Fig. 3. 4 × 10-Gb/s OOK hybrid OFDM system performance. BER versus received power per subcarrier n BTB for different frequency mismatches between the OFDM signal and the AWG (a) and for different time mismatches in the Gb/s OOK receiver sampling time (b).

demultiplexing is thus subject to some penalties [15]. Fig. 3(a) shows the BTB performance in terms of BER vs. received power per subcarrier as a function of a fixed frequency mismatch: The frequency mismatch of 500 MHz (5% of the channel spacing) can be tolerated to keep the BER performance under 10^{-5}.

Moreover, to evaluate the system sensitivity to the sampling instant simulations have been performed for each subcarrier, while inserting a mismatch with respect to the ideal sampling. Fig. 3(b) shows the BTB performance for different values of this time mismatch: an error in the sampling time of $+/-$20ps (20% of the symbol period) is tolerated to keep the BER performance under 10^{-5}.

The proposed 4 × 10-Gb/s OOK hybrid OFDM solution guarantees to transport 40-Gb/s aggregate capacity per wavelength over more than 40-km SSMF, providing 10-Gb/s data to each end user. Even considering the implementation limitations due to the present available technology, this proposed hybrid OFDM solution can be extended to obtain larger capacity PON architectures supporting a higher number of users (for example 64 or 128). In order to pursue this target several 4 × 10-Gb/s OFDM TX blocks can be employed, each one combined with a different wavelength source. The optical carriers belonging to the different wavelength sources are separately modulated at the OLT by different OFDM transmitters with AO-OFDM signals in order to generate a large number of optical subcarriers. All the OFDM subcarriers are then aggregated by a simple coupler and then after propagation, at the RN the same AWG is able to optically and passively demodulate them [14]. While the transmitter DAC bandwidth limits the number of OFDM subcarriers that can be modulated for each optical carrier, the AWG is not limited in the maximum number of subcarriers, which can be FFT-processed and demultiplexed at the same time and so, increasing the number of 4 × 10-Gb/s AO-OFDM blocks at the transmitter, a very significant number of users can be served at very high bit rate, exploiting all the available transmission spectrum. As an example, 64 10-Gb/s users can be supported by employing 16 AO-OFDM TX blocks with 16 50-GHz spaced DWDM sources.

4. Experimental Proof of Principle Demonstration

We have experimentally demonstrated the feasibility of the proposed hybrid OFDM solution. Fig. 4 shows the employed set up: the 4×10-Gb/s OOK OFDM signal is electrically generated by exploiting the TEKTRONIX arbitrary waveform generator 70001A operating with 50-GSample/s sampling rate. In Fig. 4(a), the optical spectrum of the OFDM signal generated by the arbitrary waveform generator after the nested modulator, measured by means of an optical spectrum analyzer, is shown. All the four generated OFDM subcarriers are visible, together with the residual optical carrier. Owing to the limited bandwidth of the arbitrary waveform generator,

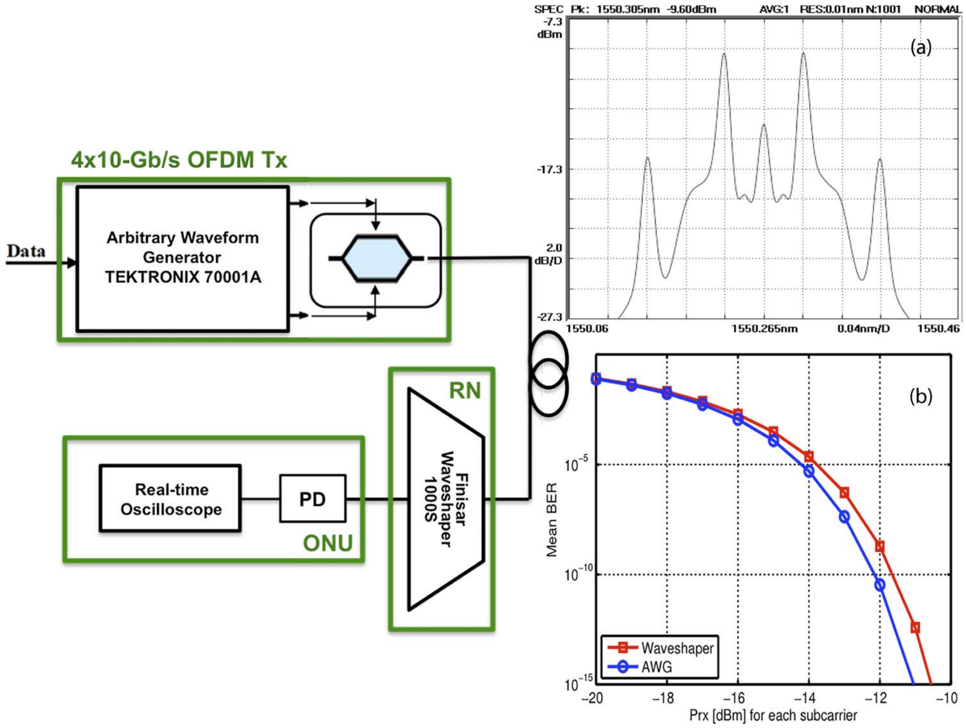

Fig. 4. Experimental setup used for the proof of principle demonstration of the proposed hybrid OFDM solution. (a) Optical spectrum of the OFDM signal generated by the arbitrary waveform generator and measured after the nested modulator by means of an optical spectrum analyzer. (b) Simulative comparison of BTB BER between the AWG and the waveshaper employment.

the more external subcarriers are penalized, but to show the capabilities of the proposed hybrid OFDM solution, the preliminary experimental proof-of-concept has been focused on the analysis of the inner subcarriers that are not penalized during the e/o generation. In order to emulate the AWG transmission spectrum able to operate as FFT block, we use a FINISAR waveshaper 1000 S with 1-GHz resolution. Fig. 4(b) presents simulations evidencing that with respect to the behavior of the ideal AWG the finite resolution of the waveshaper introduces a negligible penalty (less than 1 dB) in the demultiplexing performance of the 10-GHz spaced subcarriers. Obviously, the employment of a really-implemented AWG could introduce additional penalties induced by the non-ideal behavior of the AWG, such as for example the penalties due to the frequency mismatch with the OFDM signal shown in Fig. 3(a). After demodulation the signal is detected and acquired by means of a real-time oscilloscope with the resource to set the right sampling instant. Sets of 10^6 bits are acquired and analyzed. Propagation over uncompensated SSMF spans is also studied.

Fig. 5 shows the measured BER for one of the two inner subcarriers (the other one shows very similar performance). Some penalties with respect to the theoretical analysis are visible owing to the non-ideal conditions of the experimentation. In any case, the experimented performance confirms the results of the propagation simulations, showing about 4-dB penalty after 43.6 km of SSMF propagation (green curve) with respect to BTB (blue curve), without any cyclic prefix insertion. The experimental results shown in Fig. 5 are taken for the proper receiver sampling time, where the measured BER is lower than 10^{-6} for -5-dBm received power per subcarrier in BTB. At the same received power, the measured BER is $6.3 \cdot 10^{-2}$ and $1.45 \cdot 10^{-1}$ in case of 25-ps and 50-ps time mismatch, respectively.

5. Discussion and Conclusion

We have proposed a hybrid solution to implement the optical OFDM, based on the electronic generation of the OFDM signal at the transmitter and on the passive and all-optical

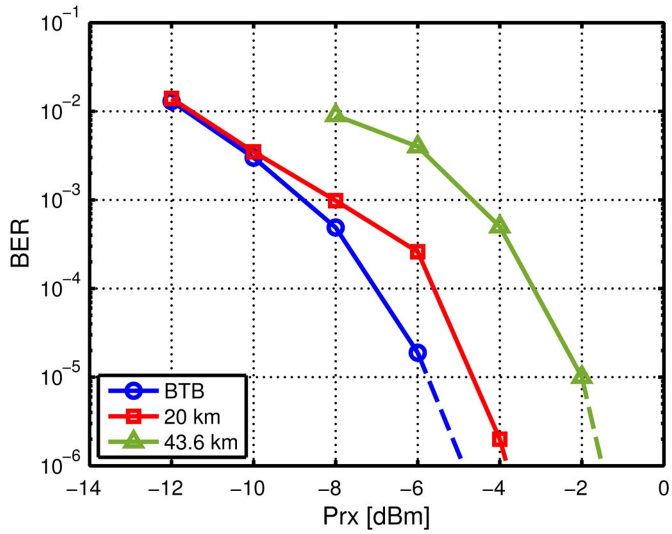

Fig. 5. Experimentally measured BER versus received power per subcarrier in case of 4 × 10-Gb/s OOK hybrid OFDM system.

demultiplexing of the OFDM subcarriers by means of a suitable AWG operating as FFT block. The solution maintains all the capabilities of the coherent OFDM, exploiting the available fiber transmission spectrum in an effective way. Considering OOK modulation, the simplicity of the receiver makes this solution very attractive for PON applications.

Owing to the bandwidth limitations of the devices and components necessary to realize the transmitter and to the issues in the AWG implementation, just a limited number of subcarriers can be generated at high bit rate. This feature is peculiar of the proposed OFDM architecture, with respect for example to the usual CO-OFDM. In particular, a 4 × 10-Gb/s OOK hybrid OFDM system has been investigated. By means of simulations and preliminary experimentation based on a suitable waveshaper able to operate as the all-optical FFT block, we have demonstrated the feasibility of the solution and shown the BER performance. The influence of the frequency mismatch between the OFDM signal and the AWG and of the sampling time have been also analyzed.

The proposed solution proved to support the transport of 40-Gb/s aggregate capacity over more than 40-km SSMF being suitable for PON access applications. Moreover, by exploiting multiple 4 × 10-Gb/s OFDM TX blocks, the proposed hybrid solution can be extended to a large capacity system with a large number of users. 10-Gb/s data are offered to each user, corresponding to a specific subcarrier demultiplexed in a passive and all-optical way at the RN by means of the same RN-AWG. Compared to TWDM-PON solutions present in literature, the proposed hybrid solution does not employ the power splitter at the RN, if TDM is not employed to further increase the total number of users. Furthermore, the ONU does not require a specific tunable filter in order to detect the proper WDM signal, the demultiplexing being performed by the RN-AWG. The use of OFDM transmission allows achieving an effective allocation of the subcarriers, resulting in a better transmission spectrum exploitation with respect to TWDM increasing the whole transported capacity. Regarding the impact of chromatic dispersion, the proposed hybrid OFDM solution takes advantage of the robustness guaranteed by the OFDM exploitation. As already shown by the 40-Gb/s aggregate-capacity experimentation, the chromatic dispersion penalty is determined by the subcarrier rate, as each user is served by 10-Gb/s data. On the other hand, for 40-Gb/s aggregate-capacity TDM transmission, the chromatic dispersion impact is influenced by the 40 Gb/s transmission rate, significantly limiting the propagation reach.

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