

Hybrid OFDM experimentation based on arrayed waveguide grating for all-optical FFT implementation in PON architecture

J. Morosi, P. Boffi[✉], P. Martelli, P. Parolari, G. Cincotti, S. Shimizu and N. Wada

A hybrid optical frequency division multiplexing (OFDM) system based on the electrical generation of the OFDM signal at the transmitter and on the all-optical demultiplexing of the OFDM subcarriers is experimentally demonstrated by exploiting a purposely designed arrayed waveguide grating (AWG) with 12.5 GHz frequency spacing. The AWG passively and all-optically processes a 3-subcarrier OFDM signal with fast Fourier transform functionalities, demultiplexing it into three 12.5 Gbit/s on-off keyed data at the corresponding output ports, which are then connected to the optical network users. Transmission over a 40 km feeder link is experimentally demonstrated. Taking into account the AWG's available 16 ports and four 3-subcarrier OFDM signal generators modulating independent wavelength carriers, a passive optical network (PON) architecture can be realised serving 12 optical network units with 150 Gbit/s total aggregate downstream capacity.

Introduction: Optical orthogonal frequency division multiplexing (O-OFDM) is a promising approach for next generation high-capacity passive optical networks (PONs) [1, 2]. Recently, all-optical OFDM (AO-OFDM) [3] has been demonstrated, thanks to the implementation of the inverse fast Fourier transform/fast Fourier transform (IFFT/FFT) operation directly in the optical domain by means of passive and energy efficient arrayed waveguide gratings (AWGs) [4, 5]. The AWG employment shows significant advantages, in terms of exploitation of a simple planar lightwave circuit layout, with low insertion losses and with the possibility to scale the number of processed OFDM subcarriers with the number of the device ports. AO-OFDM appears particularly interesting for the downstream transmission as, at the PON remote node (RN), the AWG can be exploited to optically demultiplex the OFDM subcarriers before the optical network unit (ONU) detection. However, AO-OFDM requires a complex transmission stage, based on a stable and flat comb generator, necessary to provide subcarriers' orthogonality.

In a previous paper [6] we proposed a hybrid OFDM system, based on electronic digital signal processing (DSP) at the optical line terminal (OLT) to generate the OFDM signal and on AO-FFT processing and demultiplexing at the RN. This solution guarantees drastic simplicity for the PON implementation, increased by the choice of the on-off keying (OOK) modulation format for the OFDM subcarriers, which allows one to exploit the direct detection (DD) at the ONU. In this way, the hybrid OFDM can maintain the capabilities of AO-OFDM for future PONs, exploiting the whole available transmission spectrum together with a fine granularity in the subcarriers' assignment with dynamic bandwidth access. At the same time, the proposed solution ensures reduced complexity and cost in the realisation.

In [6] a preliminary proof-of-principle experimentation was reported, but by employing a waveshaper filter with limited resolution, in order to experimentally emulate the AWG transfer function operating as a FFT block to demultiplex the OFDM subcarriers. In this Letter, we demonstrate the experimental feasibility of the proposed hybrid solution, by exploiting the proper 16-port AWG, suitably designed to passively perform the FFT processing with a frequency spacing of 12.5 GHz. In a PON the experimented solution ensures the transport of 37.5 Gbit/s aggregate downstream capacity per wavelength with 12.5 Gbit/s data to each ONU user, corresponding to a specific OFDM subcarrier. Experimental evaluation of transmission over more than 40 km standard single-mode fibre (SSMF) is also performed, exploiting the developed AWG.

PON network based on the hybrid solution: We propose to exploit the aforementioned hybrid OFDM transmitter in a wavelength division multiplexed PON, which is presented in Fig. 1. The architecture employs multi-wavelength sources emitting 50 GHz spaced carriers, each optical carrier is separately modulated at the OLT by a hybrid OFDM transmitter block, generating a 37.5 Gbit/s 3-subcarrier OFDM signal. This aggregate bit rate and subcarrier configuration are due to two constraints: the availability of state-of-the-art AWG components operating as a FFT block with a frequency spacing between the demultiplexed

neighbour OFDM subcarriers of 12.5 GHz [7]. The limitations of the available DSP and digital-to-analogue converters (DACs) are necessary at the OLT to generate in the electrical domain the OFDM signal. Both constraints forced us to assume to have the availability of a maximum of three OFDM subcarriers, each modulated at 12.5 Gbaud. In the case of OOK modulation, each OFDM transmitter block thus offers 12.5 Gbit/s data to each ONU, corresponding to a specific OFDM subcarrier, ensuring 37.5 Gbit/s aggregate downstream capacity per wavelength.

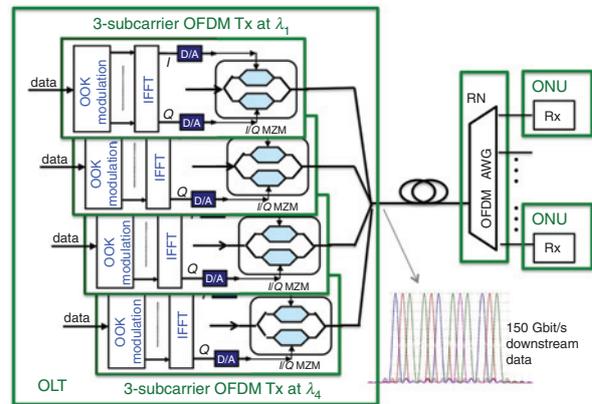


Fig. 1 PON network based on hybrid OFDM solution in case of 16-port OFDM AWG exploitation

After modulation the OFDM subcarriers coming from the multi-wavelength sources are aggregated by a simple coupler and transmitted via the feeder link. At the RN a single AWG is employed to demultiplex in an all-optical and passive way the OFDM subcarriers. Given that the experimented AWG has 16 ports and supposing to maintain a 12.5 GHz guard band between the OFDM subcarriers coming from adjacent wavelength carriers, four different 3-subcarrier OFDM signals can be FFT-processed and demultiplexed at the same time by the AWG. The proposed PON can thus accommodate 12 ONUs achieving a total 150 Gbit/s aggregate downstream capacity. The whole downstream capacity and the number of served ONUs can be easily enhanced by increasing the number of output ports of the employed AWG and consequently the number of optical carriers.

In the following, we experimentally evaluate the performance of the single-wavelength transmitter block.

Experimental setup: Fig. 2 presents the experimental setup employed to demonstrate the behaviour of a single 37.5 Gbit/s OFDM transmitter block, described in the previous Section. The OFDM signal with three 12.5 Gbit/s OOK modulated subcarriers is electronically generated through DSP and DACs by means of a pair of synchronous Tektronix arbitrary waveform generators 70001A operating with 50 GS/s sampling rate. They feed the real and imaginary components of the signal to the *I* and *Q* arms of a nested Mach-Zehnder modulator (MZM). In [6] just one arbitrary waveform generator was used to drive the MZM, hence no independent subcarriers were generated. The parallel OFDM symbols are generated through the DSP in the IFFT block. The DSP generation provides full OFDM subcarriers decorrelation, avoiding inter-carrier interference underestimation. No cyclic prefix is inserted in the OFDM signal.

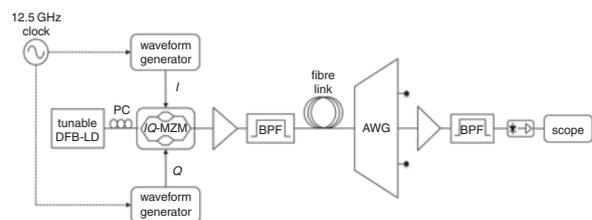


Fig. 2 Experimental setup

After the fibre propagation over SSMF, at the receiver side, a tailored 16-port AWG is used as a passive and AO-OFDM subcarrier demultiplexer with 12.5 GHz frequency spacing and 200 GHz free spectral

range [7], performing the FFT operation. Thus the demultiplexed and demodulated subcarriers are output at the corresponding AWG ports, which are then linked to the ONU user receivers. As each subcarrier is OOK-modulated, a DD scheme is applied at the receiver.

Experimental results: Fig. 3a shows the optical spectrum of the 3×12.5 Gbit/s OFDM signal per wavelength generated by the pair of arbitrary waveform generators and measured after the MZM by means of an optical spectrum analyser. Owing to the limited bandwidth of the arbitrary waveform generator, the external subcarriers are more penalised with respect to the inner subcarrier during the electro-optical generation. In Figs. 3b–d the spectra at the output ports of the AWG are reported. The effect of the demultiplexing and the filtering of the subcarriers is visible and a good extinction ratio is demonstrated.

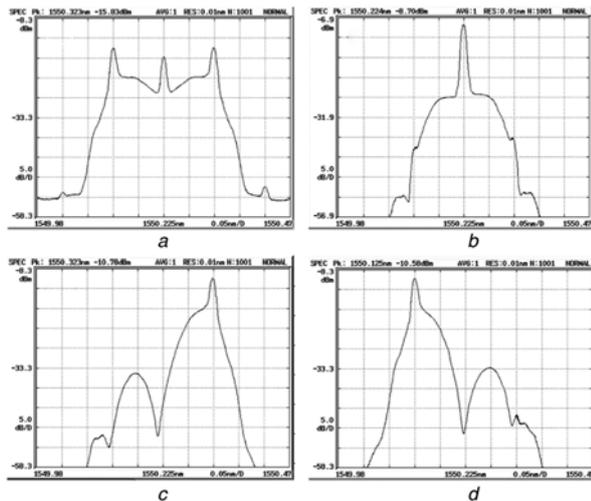


Fig. 3 Spectrum of 3×12.5 Gbit/s OFDM signal before AWG (Fig. 3a); spectra at AWG output ports corresponding to selected inner subcarrier (Fig. 3b); selected external subcarriers (Figs. 3c,d)

Fig. 4 shows the system performance in terms of bit error rate (BER) evaluated in back to back (BTB) and after propagation over 20 and 40 km SSMF, the typical reach of PONs. After 20 km SSMF, about 4 dB penalty is present at 10^{-4} BER with respect to the BTB, while after 40 km SSMF the penalty goes up to almost 8 dB, due to the increasing effect of chromatic dispersion (CD) for 12.5 Gbit/s OOK subcarrier modulation. No cyclic prefix is inserted in the OFDM signal. We have performed dispersion compensation by exploiting a reverse dispersion fibre (RDF) after 40 km propagation, obtaining a strong performance improvement and BER values comparable with the BTB case.

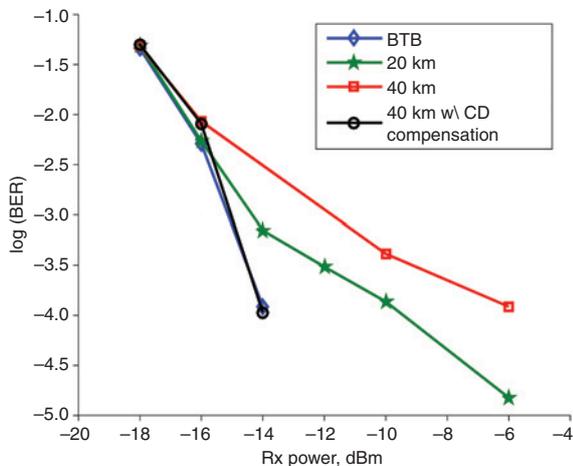


Fig. 4 Experimental measured BER against received power per subcarrier in case of 3×12.5 Gbit/s OOK hybrid OFDM system in case of BTB, 20 km SSMF propagation and 40 km SSMF propagation. Also, BER performance when RDF is employed after 40 km SSMF propagation to compensate for CD

Conclusion: The transport of a 37.5 Gbit/s aggregate OFDM signal over a more than 40 km reach has been demonstrated by exploiting a hybrid solution based on the electrical generation of the OFDM signal and on the all-optical and passive subcarrier demultiplexing implemented by the AWG. Performance evaluation in terms of BER has been performed by exploiting a suitable AWG to optically implement the FFT operation. The OFDM signal is characterised by three subcarriers, modulated at 12.5 Gbit/s rate, compliant with the specifications given by the experimental devices employed in the experimentation. Low complexity and cost at the ONU are obtained by adopting OOK modulation for each subcarrier. A downstream capacity of 150 Gbit/s can be achieved by exploiting the proposed PON solution based on the developed 16-port AWG and four DFB sources with 50 GHz channel spacing, but it can be easily increased by exploiting an RN AWG with a larger port number.

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One or more of the Figures in this Letter are available in colour online.

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