Broadband optical sources for low-cost WDM-MB-OFDM networks

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***Abstract*—Multiband OFDM signal transmission through a 10 km optical fiber link is experimentally demonstrated by using a broadband source. We propose the use of optical broadband sources in multiband OFDM signal transmitters as a low-cost and power fading free solution. The OFDM band is dynamically selected in the receiver by means of an MZI. Therefore, MB-OFDM is demonstrated at 1.5 Gb/s per band in access networks, supporting up to 20 ONUs.**

***Index Terms*—Optical fibers, optical networks, Orthogonal Frequency Division Multiplexing (OFDM), OFDMA, broadband sources.**

I. Introduction

THE increasing demand of bandwidth per end-user required by current Internet services drives the advanced modulations to play a significant role in optical networks. Optical Orthogonal Frequency Division Multiplexing (OOFDM) has been widely employed as a solution for network communications [1], [2] due to its advantages, such as overcoming chromatic and polarization dispersion impairments [3], its adaptability to channel variations [4] and its high spectral efficiency [5].

Optical OFDM signal can be transmitted by using either direct detection (DD-OFDM) or coherent detection (CO-OFDM). The former is the preferred option for short and medium reach applications, because of its simplicity and cost-effectiveness [5], [6]. The latter option, for long-haul applications, owns a better spectral efficiency and a lower optical to noise ratio (OSNR) sensitivity [5], [7].

The generation of intensity-modulated (IM)DD-OOFDM signals using double-sideband (DSB) external modulation [8] leads to an ineffective use of the bandwidth, and suffers a power fading penalty due to chromatic dispersion [9]. Alternatively, single-sideband (SSB) modulated signals occupy lower bandwidth and overcomes power fading [10], although higher complexity is required in the modulation stage.

A potential application of OFDM is orthogonal frequency division multiplexing access (OFDMA), whereby several users are assigned to different OFDM carriers. Accordingly, optical OFDMA expects to satisfy future requirements of access networks because of its high signal transmission capacity, flexibility, granularity, optimal cost-effectiveness, adaptability to impairments, and compatibility with both conventional time division multiplexing (TDM) and wavelength division multiplexing (WDM) passive optical networks (PONs) [11]. Recent examples in the literature demonstrate 1 Tb/s symmetric WDM-OFDMA-PON over a 90 km standard fiber and 1:32 splitting factor [12], or 11.25 Gb/s over a 25 km fiber link incorporating reflective semiconductor optical amplifiers in an IM/DD OOFDMA PON [13].

Furthermore, optical multiband OFDM systems have been recently proposed for a wide set of applications, including dynamic bandwidth allocation in schemes compatible with OFDMA, that also exploit the advantages of OFDM [14]. Experimental demonstrations of multiband DD-OFDM lead to the transmission of several bands with lower data rate, providing high granularity and flexible access to a large number of users over tens of kilometers [15]. The main limitations arise from the proper selection of the band to avoid crosstalk of the adjacent ones, the power budget, and the electrical analog bandwidth of the transmitter.

Multicarrier sources based on external cavity [14], semiconductor mode-locked lasers [16], or distributed feedback lasers [12], amongst others [17], have demonstrated good performance in DD-OFDM systems. However, optical broadband sources would be an interesting solution for moderate bitrate OOFDM access networks [18]. They offer a low-cost option, high stability, low cost operation and the possibility to transmit RoF signals [19].

To the best of our knowledge, in this paper we experimentally demonstrate the first optical multiband OFDM signal transmission system based on a broadband source to be used for multiple access in future WDM access networks.

The paper is structured as follows: section II describes the proposed system and includes several design issues. The experimental setup is presented in section III and section IV reports the main experimental results in the transmission system. Finally, section V summarizes the main conclusions of the paper.

II. System description

Let $S(\omega)$ be the power spectral density of the optical signal emitted by a broadband optical source with $\delta\omega_{3dB}$ spectral bandwidth. It is amplitude-modulated by an RF signal using DSB modulation in an electro-optic modulator, and transmitted over an optical fiber link of length L and dispersion parameter β_2, as depicted in Figure 1.

The influence of chromatic dispersion prevents the RF signal transmission using optical broadband sources [19]. However, when a MZI is introduced just before the optical signal

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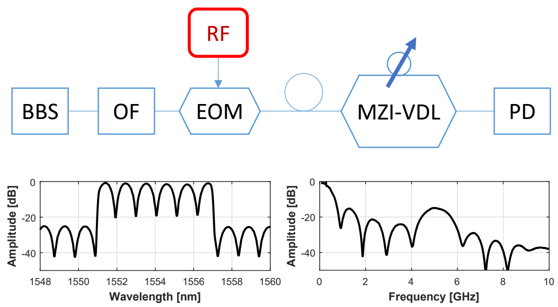

Fig. 1. Schematic of the RF signal transmission system based on an optical broadband source. BBS: BroadBand Source, OF: Optical Filter, EOM: Electro-Optical Modulator, RF: RadioFrequency, MZI: Mach-Zehnder Interferometer, VDL: Variable Delay Line, PD: PhotoDetector. Insets: (a) Optical spectrum of the MZI output signal ($\delta\omega_{3dB}$ = 6 nm, $\Delta\tau$ = 7.28 ps) , (b) RF electrical transfer function of the transmission system after a 10 km fiber link.

detection, the transfer function includes two new terms, which can be calculated as [19]:

$$H_0^{RF}(\Omega \pm \Omega_0) = \frac{\int_{-\infty}^{+\infty} S(\omega) exp\left\{-j\beta_2 L(\omega-\omega_0)(\Omega \pm \Omega_0)\right\} d\omega}{\int_{-\infty}^{+\infty} S(\omega) d\omega}. \tag{1}$$

And therefore, an RF bandpass window, free of induced chromatic dispersion power fading, appears in the electrical transfer function. The central frequency Ω_0 of the new RF operational window is:

$$\Omega_0 = \frac{\Delta\tau}{\beta_2 L}, \tag{2}$$

where $\Delta\tau = \tau_1 - \tau_2$ is the differential delay between the MZI fiber arms. As an example, insets (a) and (b) of Figure 1 show the optical spectrum of the MZI output signal for $\Delta\tau$ = 7.28 ps and the corresponding RF electrical response after photodetection, respectively, when an optical source of $\delta\omega_{3dB}$ = 6 nm is employed. Therefore, the central electrical frequency can be tuned by changing either the optical delay $\Delta\tau$, or the total fiber chromatic dispersion $\beta_2 L$. Furthermore, the inclusion of the interferometer structure in the system avoids the carrier suppression effect on the spectral region where the RF signal is transmitted [19], even when the DSB conventional scheme is employed, which also simplifies the modulation stage.

Since the interferometer scheme opens an RF transmission band, the selection of an OFDM band will be addressed just before the receiver allocated in the ONU of each user, by setting the proper delay $\Delta\tau$. Figure 2(a) shows the theoretical and experimental central frequencies for different optical delays set in the MZI when a $\delta\omega_{3dB}$=6 nm optical broadband source is used. The graph also plots the measured electrical 3dB bandwidth at different central frequencies.

However, the proper design of the transmission system requires the analysis of the electrical bandwidth dependence on the optical parameter $\delta\omega_{3dB}$. These measurements are depicted in Figure 2(b), where the optical filter was configured to modify the 3 dB optical bandwidth of the signal carrier from 3 to 18 nm. The electrical signals, ranging from 3 to 6 GHz, were transmitted through a 10 km standard single-mode fiber link (β_2=-22.71 ps^2/km). For a 5-nm optical bandwidth, the corresponding electrical bandwidth is approximately 1 GHz.

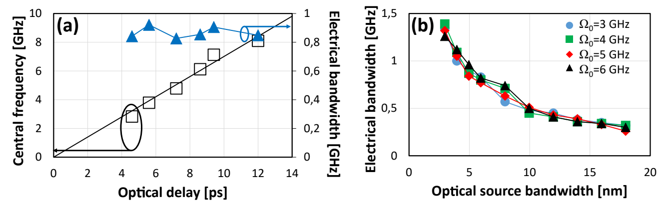

Fig. 2. (a) Bandpass characterization with respect to the optical time delay using a $\delta\omega_{3dB} = 6nm$ BBS: theoretical central frequency (black line), experimental central frequency (squares) and electrical 3dB bandwidth (triangles). (b) Electrical 3dB bandwidth as a function of the bandwidth $\delta\omega_{3dB}$ of the optical source, with the RF bandpass centered at different frequencies.

III. Experimental Setup

Figure 3 depicts the experimental setup. The electrical multiband OFDM signal is generated offline in Matlab [2] and loaded into an arbitrary waveform generator (AWG7122C, Tektronix), sampling at 24 GS/s. An IFFT size of 2048 with 256 QPSK data-bearing subcarriers is used, satisfying Hermitian symmetry. For multiband signal, the first band (band #1) is composed by subcarriers from #534 to #661, while the second band (band #2) covers subcarriers from #790 to #917. It gives rise to two OFDM bands of 750 MHz-bandwidth, centered at 3.5 and 5 GHz, respectively, with a raw data rate of 3 Gb/s. A 6.25% cyclic prefix of the symbol is applied, and equalization in detection process is performed by the inclusion of a block-type equispaced pilot pattern of 10%. A pre-emphasis filter is also applied to overcome the non-flat response of the electrical transmitter. The electrical power spectral density of the transmitted signal is presented in Figure 3(a).

The optical carrier is generated by a broadband source and an optical filter. The broadband source is an NP Photonics C&L Band ASE Source, emitting 19.5 dBm optical power in the 1525-1610 nm spectral range. The optical signal is DSB modulated by an OFDM signal in an AVANEX electro-optic modulator, and transmitted through a 10 km SSMF link. The broadband optical spectrum is optically sliced by using a multiport tunable optical filter (WaveShaper 4000S, Finisar) which provides coarse wavelength division multiplexation (CWDM). It allows the selection of the central frequency from 1527.4 to 1567.5 nm with steps of 77 pm, and a roll-off value of 0.06 dB/pm of each transmitting output port $(1-M)$. Each CWDM output port holds a number of ONUs, where each ONU selects the OOFDM operating band. Thus, if each optical channel in a WDM network transmits N OFDM bands, a total of $M \times N$ ONUs can be fed by the proposed network. Compared to fixed OFDM, the structure has the added value of changing dynamically the operating band.

In our setup, an optical CWDM port was configured to feed the set of ONUs with an optical carrier whose spectrum is centered at 1554 nm and its bandwidth is 6 nm.

The OFDM band is selected according to the configuration of the MZI at each ONU. It is composed by two 50:50 optical couplers and a variable delay line (VDL) in one of the arms. The VDL insertion loss is approximately 1 dB, and the maximum differential delay $\Delta\tau$ is 330 ps.

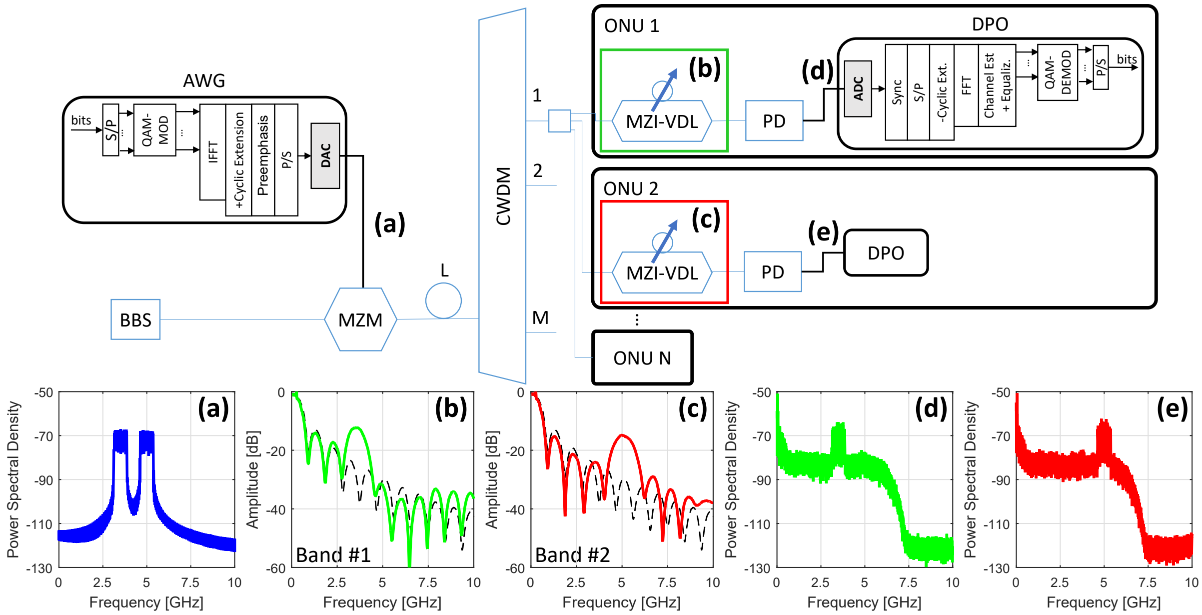

Fig. 3. Experimental setup for multiband OOFDM signal transmission using a BBS. AWG: Arbitrary Waveform Generator, MZM: Mach-Zehnder Modulator, CWDM: Coarse Wavelength Division Multiplexer, DPO: Digital Phosphor Oscilloscope. Insets: electrical power spectral density of the OFDM transmitted signal (a); measured transfer function without (dotted line) and with (solid line) the MZI-VDL: f_1=3.5 GHz (b) and f_2=5 GHz (c); electrical power spectral density of the recovered OFDM bands #1 (d) and #2 (e).

Figures 3(b) and 3(c) depict the measured electrical transfer function of the system based on an MZI, using a 6 nm broadband source when the transmission band is centered at both electrical frequencies 3.5 and 5 GHz, respectively. As explained in the previous section and according to (2), the $\Delta\tau$ parameter is properly tuned to select each central frequency band, at 5.25 and 7.28 ps, respectively. The corresponding transfer functions show passbands with electrical 3dB bandwidths of 0.84 and 0.96 GHz, respectively, according to Figures 2(a) and 2(b). For the sake of comparison, both Figures 3(b) and 3(c) also include the transmission system response when a BBS is employed but no MZI is included, showing that low-pass filtering avoids signal transmission for frequencies greater than 1 GHz.

Just after the MZI, the signal is photodetected. The resulting electrical signal is sampled in a real time digital oscilloscope (DPO72004C, Tektronix) at 50 GS/s. Figures 3(d) and 3(e) plot the power spectral density of the received OFDM bands. Digital signal processing has been implemented in Matlab. The captured samples are synchronized and parallelized for processing in the regular OFDM receiver blocks. Once the cyclic prefix is removed from every OFDM symbol, a 2048-FFT is applied. The channel is estimated via block-type pilots, specifically one of every 10 OFDM symbols contains the training sequence (PSK symbols). Both the Least Squares method [2] and time averaging to reduce noise, provide the estimated channel. Channel equalization is performed on the rest of the symbols. Finally, QPSK data symbols are detected and the transmitted bit stream is recovered after serialization.

IV. Transmission Results

In this section, QPSK modulation format is employed as a proof of concept although higher level modulation formats

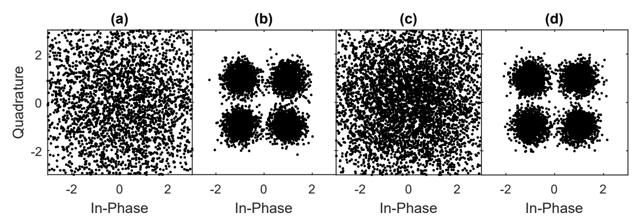

Fig. 4. Received constellations for QPSK 2-bands OFDM signal transmission using a broadband source without the MZI module (a, c) and using it just before optical detection (b, d) for both bands (#1 in a) and b) and #2 in c) and d)).

can be transmitted using further equipment with better performance. Figure 4 shows the constellations of the transmitted signals in bands #1 (a, b) and #2 (c, d) when the MZI module is not employed (a, c) and when it is inserted prior to optical detection (b, d). As shown, the signal detection is infeasible when a BBS is employed unless the properly configured MZI is inserted and their EVM values are 30.33% and 31.70%, satisfying the 7% FEC limit [20].

The OOFDM transmission system based on a BBS and a MZI has been also tested in a WDM network, as depicted in Figure 3, to evaluate its viability. In this case, three WDM channels were transmitted over the same configuration as the single one described previously, but using 6 nm bandwidth optical signals centered at 1546, 1554 and 1562 nm. Figure 5(a) presents the optical spectrum of the modulated signal before the fiber link, whereas Figure 5(b) shows the bandpass spectra at every port after demultiplexing and after the MZI, configured with $\Delta\tau$=7.28ps. The experimental transmission of 3 channels results in a raw data rate of 9 Gb/s.

Figure 6 depicts the EVM and BER measurements versus the received power of the transmitted signals for each channel

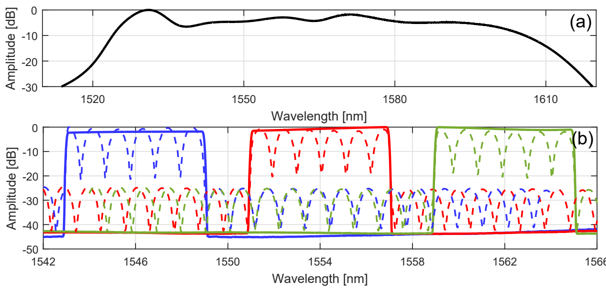

Fig. 5. Optical spectra: (a) after OFDM signal modulation at the MZM, (b) after demultiplexing at ports 1, 2 and 3 (red, green and blue solid lines, respectively) and prior to photodetection when the MZI is configured with $\Delta\tau$=7.28 ps (corresponding dashed lines).

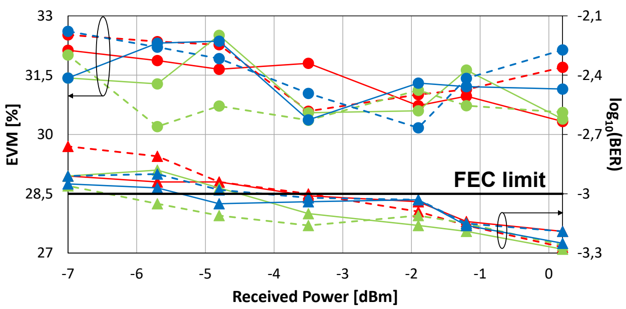

Fig. 6. EVM [%] and BER vs receiver power for three WDM channels carrying a 2-band OFDM signal. Channels 1, 2 and 3 in red, green and blue. Corresponding measurements of bands #1 and #2 are shown in continuous and dotted lines (EVM: circles, BER: triangles).

and both OFDM bands. All the transmitted channels lead to EVM values below 32.6% over the received optical power range. Assuming 7% FEC bounds, the worst case satisfying the limit BER=10^{-3} requires a received power of -3.5 dBm. Lower values of sensitivity are expected in future experiments when the equipment limitations are overcome.

Note that the use of broadband sources as a multiwavelength transmitter in WDM access networks results in a very cost-efficient solution, which also offers high levels of flexibility and tuning. Since the broadband source has an optical bandwidth of 85 nm, the system can be extended to transmit more than 10 optical channels of 6 nm each one using the proper multiport tunable optical filter. Therefore, the proposed system would be able to transmit 30 Gb/s with the added value of a flexible band selection for each user over an access network of 20 ONUs.

V. Conclusions

A novel multiband OFDM signal transmission system based on broadband sources has been experimentally demonstrated for WDM low-cost access networks. The system, based on a8Mach-Zehnder interferometer, also overcomes impairments related to power fading induced by chromatic dispersion when DSB modulation is employed. Proper tuning of the MZI structure allows the transmission of an RF band, which can be employed to allow flexible multiband OFDM transmission with tunable central frequency. Our system also allows dynamic bandwidth allocation, provided the bandwidth of the optical source is modified by an optical filter. Three WDM channels have been experimentally transmitted, each one carrying a 2-band OFDM signal over a 10 km fiber link, with a data rate of 1.5 Gb/s/band/wavelength. Higher electrical bandwidth of the transceiver and an improvement of the total power budget would lead to increase the number of transmitted bands and, accordingly, the number of ONUs (i.e. the total data rate). Further work is being carried towards the application of multiband transmission to allow dynamic optical OFDMA using low-cost WDM transceivers based on broadband sources.

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