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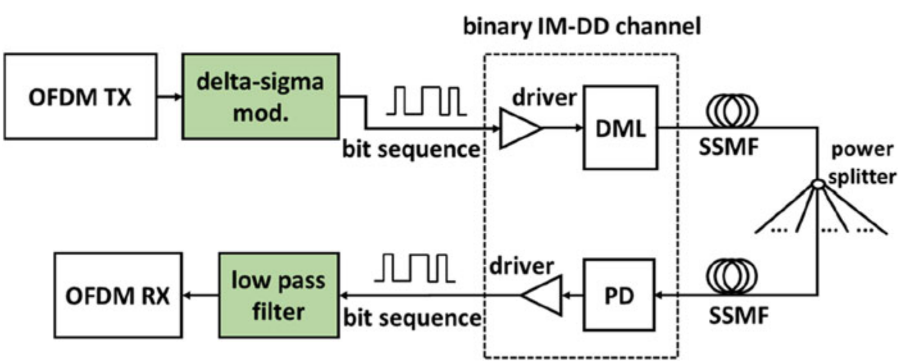

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Digital OFDM-PON Based on Delta–Sigma Modulation Employing Binary IM-DD Channels

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Abstract: In this paper, a delta–sigma modulation is proposed for the orthogonal frequency division multiplexed-passive optical network (OFDM-PON) to enable transmission of OFDM signals via binary intensity modulation and direct detection (IM-DD) channels. The delta–sigma modulation is an independent digital signal processing block that converts the analog OFDM signal into binary bit sequence. The OFDM signal can be simply retrieved from the bit sequence, using a low-pass filter at the receiver. Neither the analog-to-digital converter (ADC)/digital-to-analog converter (DAC) nor the linear modulator/detector are required, which means the proposed system can be fulfilled by employing cost-effective 10- or 40-Gb/s binary optics and electronics. Besides, the delta–sigma-modulated OFDM-PON is able to offer excellent robustness against noises and nonlinear distortions. In the experimental demonstration, the performance of proposed delta–sigma-modulated OFDM-PON system has been investigated. It is found that around a 4-dB improvement in receiver sensitivity is achieved, compared to a traditional analog OFDM-PON scheme.

Index Terms: Passive optical network (PON), delta-sigma modulation, orthogonal frequency division multiplexing (OFDM).

1. Introduction

Driven by various emerging bandwidth-hungry services such as cloud service, HDTV, video chatting, and on-line gaming, the end-users' demand for transmission bandwidth is increasing exponentially. To satisfy the requirements of optical access systems, several multiple-access candidate technologies have been proposed based on passive optical network (PON), including time division multiple access (TDMA)-PON [1]–[3], wavelength division multiplexed (WDM)-PON [4]–[6], orthogonal frequency division multiplexed (OFDM)-PON [7]–[9], as well as various hybrid options [10], [11]. As one of the candidates, OFDM-PON has been extensively investigated, due to its attractive features that satisfy the needs of next generation access networks. In OFDM-PON, multiple low bit rate orthogonal subcarriers carrying different quadrature amplitude modulation (QAM) symbols, are simultaneously transmitted in parallel. Different subcarriers can be assigned to different users, thereby making this technology particularly suitable as a multiple access scheme. The bandwidth of subcarriers can be dynamically provisioned to different services in both frequency and time domains. Practical implementation of the orthogonal subcarriers is achieved at the transmitter via

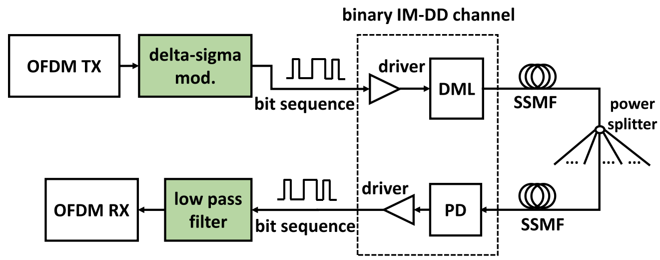

Fig. 1. Schematic architecture of OFDM-PON system based on delta-sigma modulation, employing the binary IM-DD channel.

the inverse fast Fourier transform (IFFT) algorithm and at the receiver via the FFT algorithm. The advantages of OFDM-PON include a) potential for cost-effective implementation by exploiting the advances in high-speed digital signal processing (DSP) technology; b) resistance to various linear system impairments; c) system flexibility and performance robustness due to its adaptive subcarrier manipulation capability, and d) dynamic provision of hybrid bandwidth allocation in both the frequency and time domains.

Investigations have been made by end-to-end transmission of both real-time and offline OFDM-PON to explore the feasibility of the technique for practical implementation, in which the high peak to average power ratio (PAPR), high bit resolution for the analog-to-digital converter (ADC)/digital-to-analog converter (DAC), linear RF, driver and linear modulator/detector have been proven to be the major challenges for OFDM-PON systems [12]–[14]. In this paper, a delta-sigma modulation is proposed to enable the transmission of OFDM signal via cost-effective binary intensity modulation and direct detection (IM-DD) channels. Thus, neither ADC/DAC nor linear RF driver and modulator/detector are required in the proposed OFDM-PON system. The delta-sigma modulation is an independent DSP block, which converts the OFDM signal into binary bit sequence. At the receiver end, the OFDM signal can be simply retrieved by applying a low pass filter (LPF) to the received bit sequence. Since the linear modulation is no longer required for delta-sigma modulated OFDM signals (only two levels), the proposed delta-sigma modulated OFDM-PON can offer excellent robustness against modulator/driver nonlinearity. Besides, the driving amplitude of signals can be increased accordingly, to include both the linear and nonlinear modulation region, to achieve higher OSNR. Finally, investigations are made by experimental demonstrations of end-to-end transmission of OFDM-PON system with and without delta-sigma modulation. It is found that around 4-dB improvement in receiver sensitivity can be achieved using proposed digital transmission scheme of OFDM-PON.

2. Principal

Fig. 1 shows the schematic architecture of OFDM-PON system based on delta-sigma modulation, employing the binary IM-DD channels. In the optical line terminal (OLT), downstream OFDM signal is generated in the same way as a traditional OFDM-PON [12]. Then, the generated OFDM signal is delta-sigma modulated, which outputs a binary bit sequence. The bit sequence is directly modulated by a DML and then fed into the optical distribution network. In the optical network unit (ONU), the received optical signal is first detected by the photo detector (PD), and a low-pass filter is applied to retrieve the OFDM signal from bit sequence.

The first step in delta-sigma modulation is oversampling. Then, the change in the oversampled signal (its delta) is encoded. The accuracy of the 'delta' modulation is improved by adding (sigma) the resulting signal. Lastly, a 1-bit quantization is applied to output the binary bit sequence [15]–[17]. Fig. 2 shows the block diagram of delta-sigma modulation, in which the number of cascaded feedback loops indicates the order of delta-sigma modulation. Tradeoff exists between the performance and the complexity, when the order of delta-sigma modulation increases.

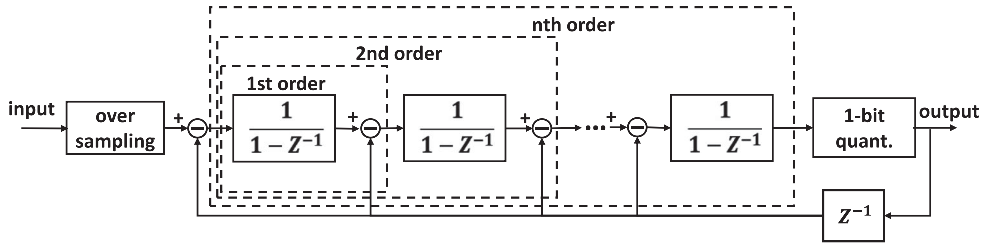

Fig. 2. Block diagram of the delta-sigma modulation.

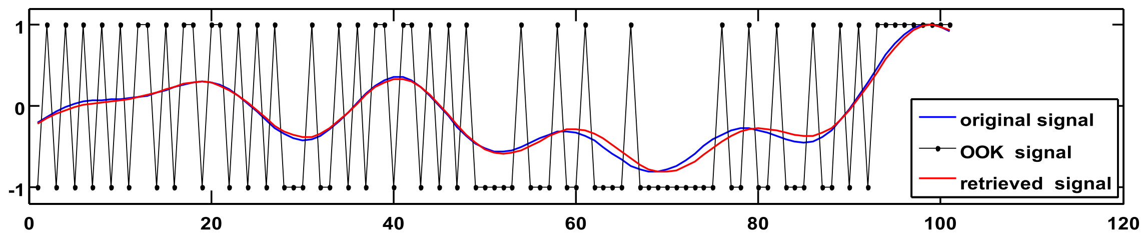

Fig. 3. Time domain waveforms before and after delta-sigma modulation.

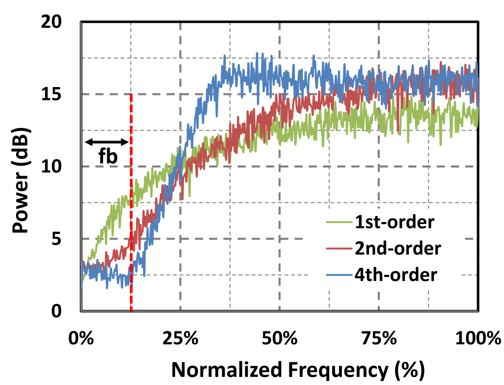

Fig. 4. Responses of noise shaping in delta-sigma modulation with first-, second-, and fourth-order structures, respectively.

Fig. 3 shows the time domain waveforms before and after delta-sigma modulation. The ‘blue curve’ represents the original OFDM signal, and the “black dot“ represents delta-signal modulated OOK sequence. The retrieved OFDM signal after LPF is also represented as the “red curve” in Fig. 3.

The delta-sigma modulator can be viewed as a noise shaper that acts like high pass filter (HPF). Fig. 4 shows the responses of noise shaping in delta-sigma modulation with first-, second-, and fourth-order structures, respectively. The responses are measured at 8-times oversampling ratio (OSR $=$ 8). In Fig. 4, “fb” denotes the bandwidth of signal and the horizontal axis represents the normalized frequency. It can be observed that the “stop-band” response gets much improved in the range of [0, fb] using the fourth-order delta-sigma modulation. Further increasing the modulation order brings little improvement.

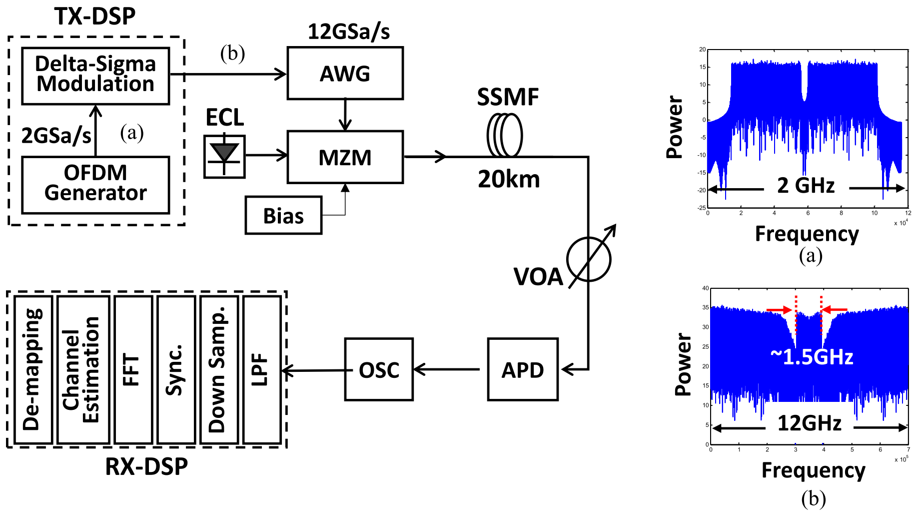

Fig. 5. Experimental setup for the proposed OFDM-PON based on delta-sigma modulation. (a) Spectrum of generated real-value OFDM signal. (b) Spectrum of delta-sigma modulated OFDM signal.

3. Experimental Setup

Fig. 5 shows the experimental setup for the proposed OFDM-PON system based on delta-sigma modulation. The OFDM signal is generated offline with an IFFT size of 1024, in which 365 subcarriers are loaded with data. The sampling rate of OFDM signal is 2-GSa/s, resulting in 1.953-MHz subcarrier spacing. Hermitian symmetry is then used to obtain the real-value output sequence, whose spectrum is shown in Fig. 5(a). A fourth-order delta-sigma modulator is applied with OSR $= 6$ and 1-bit quantization. The output sampling rate of delta-sigma modulator is 12-GSa/s, where the effective bandwidth for OFDM signal is around 1.5 GHz, as shown in Fig. 5(b). The delta-sigma modulated bit sequence is output by an arbitrary waveform generator (AWG, Tektronix 7122) working at 12-GSa/s. The intensity modulation is fulfilled by a 1550-nm external cavity laser (ECL) and a Mach-Zehnder modulator (MZM), which is biased at the linear modulation region. The optical distribution network is composed of 20-km standard single mode fiber (SSMF) and a variable optical attenuator (VOA) emulating the passive power splitter. In the receiver, the received signal is detected by a 10-GHz APD, and acquired by an oscilloscope at 50-GSa/s sample rate. The offline processes include a LPF to retrieve the OFDM signal, down sampling to 2-GSa/s, synchronization, fast Fourier transform (FFT), channel estimation, constellation de-mapping, and EVM calculation.

4. Results and Discussions

First, investigations are made through optical back to back transmission of OFDM-PON systems with or without the delta-sigma modulation, where same parameters are used in the generation of OFDM signals. For traditional OFDM-PON (without delta-sigma modulation), the AWG works at 2-GSa/s of 10-bit resolution, and the MZM is biased at the quadrature point to guarantee optimum performance. The receiver sensitivity is measured for both schemes. As shown in Fig. 6, the delta-sigma modulated OFDM-PON (DSM-OFDM) shows slightly lower EVM than the counterpart, when the received optical power (ROP) is high. When the ROP becomes lower, the EVM of OFDM signal increases rapidly above the DSM-OFDM signal, since the OFDM signal suffers more from the noise due to its high PAPR and low modulation index. Around 4-dB improvement in the receiver sensitivity can be found for DSM-OFDM-PON, considering the 20% average EVM (corresponding to $\sim$2-Gb/s data rate).

Fig. 7 shows the EVM distribution of OFDM subcarriers for both schemes, in which two ROPs of -16 dBm and -28 dBm are selected. The average EVMs are 9.9% and 18.5% for OFDM-PON, at

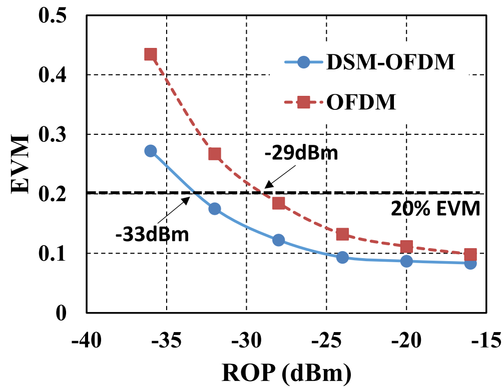

Fig. 6. Receiver sensitivity measured at optical back-to-back for both OFDM- and DSM-OFDM-PON systems.

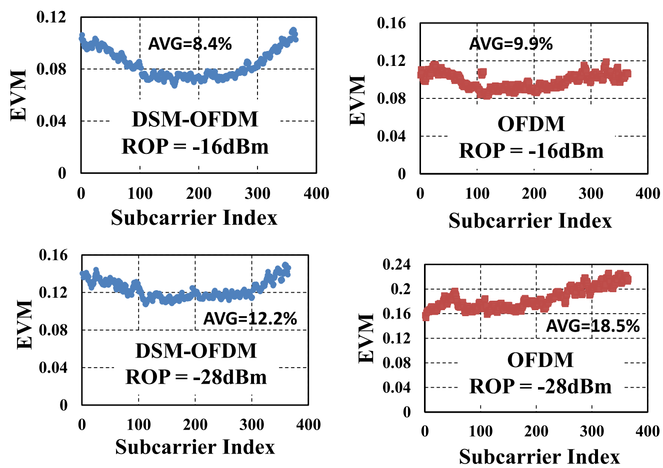

Fig. 7. EVM distribution of OFDM subcarriers for both schemes at ROP $= -16$ dBm and -28 dBm.

-16 dBm and -28 dBm received optical power. While, the corresponding average EVMs are 8.4% and 12.2% for delta-sigma modulated OFDM-PON.

For each EVM distribution, subcarrier bit loading is applied using the 7% overhead HD-FEC, with a BER threshold of 3.8×10^{-3}. The maximum achievable capacity is measured at different ROPs, as shown in Fig. 8. The bit loading profiles are also shown in Fig. 9, corresponding to the EVMs at ROP $= -16$ dBm and -28 dBm. The maximum achievable capacities are 3.48-Gb/s and 2.24-Gb/s, respectively, for OFDM-PON at -16 dBm and -28 dBm ROP. While, the corresponding capacities are 3.97-Gb/s and 3.07-Gb/s for delta-sigma modulated OFDM-PON at -16 dBm and -28 dBm ROP, respectively.

The receiver sensitivity is also measured for delta-sigma modulated OFDM-PON after the transmission over 20-km SSMF, as shown in Fig. 10. The launch power is set to around 8 dBm for the tradeoff between power budget and nonlinear distortions. Slight performance degradation is found, compared to the optical back to back measurement. In the same figure, we show the maximum achievable capacities for the delta-sigma modulated OFDM-PON at different ROPs. The maximum achievable capacities are 2.28-Gb/s, 2.98-Gb/s, and 3.48-Gb/s for power budgets of $(32 + 8 = 40)$ dB, $(28 + 8 = 36)$ dB, and $(24 + 8 = 32)$ dB, respectively.

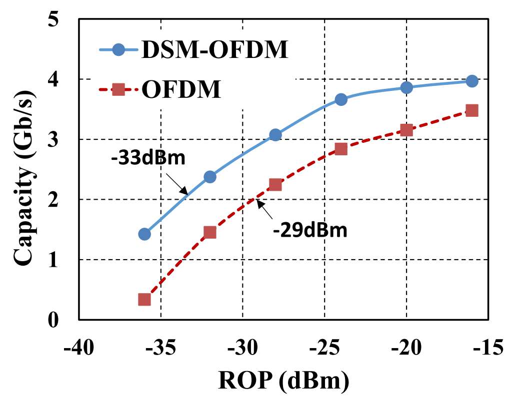

Fig. 8. Maximum achievable capacity at different ROPs for both schemes using the BER threshold of 3.8×10^{-3}.

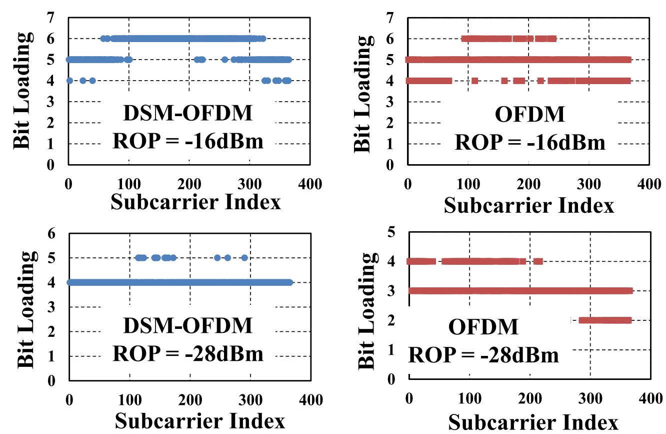

Fig. 9. Bit loading profiles for both schemes at ROP $= -16$ dBm and -28 dBm.

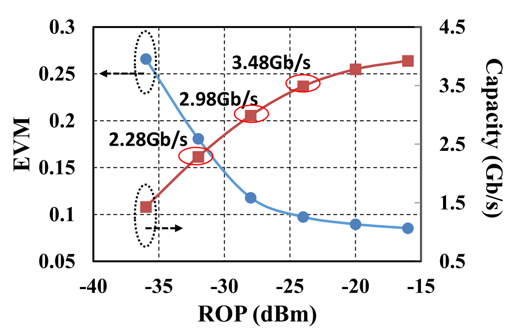

Fig. 10. Receiver sensitivity and maximum achievable capacity measured for delta-sigma modulated OFDM-PON after the transmission over 20-km SSMF.

Fig. 11 shows the curve of BER versus ROP, with those capacities of 2.28-Gb/s, 2.98-Gb/s, and 3.48-Gb/s, in which a 3.8×10^{-3} BER threshold is used. The inset of Fig. 11 also shows the retrieved constellations during the measurements.

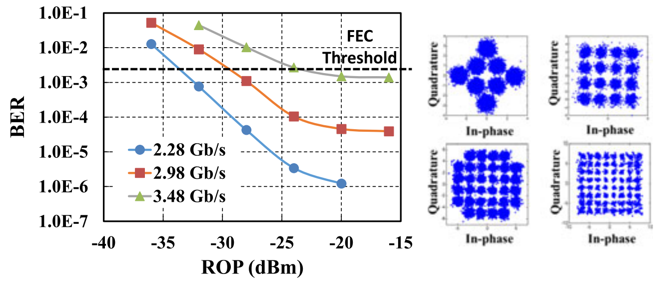

Fig. 11. Measured BER vs. ROP curves with capacities of 2.28-Gb/s, 2.98-Gb/s, and 3.48-Gb/s, respectively.

5. Conclusion

A delta-sigma modulation has been proposed to enable the transmission of OFDM signals by cost-effective binary IM-DD channel. Neither ADC/DAC nor linear RF driver and modulator/detector were required in the proposed OFDM-PON system. The proposed delta-sigma modulated OFDM-PON can offer excellent robustness against noises and nonlinearity distortions by using the 10/40-Gbps binary optics/electronics. Investigations have been made by experimental demonstrations of end-to-end transmission of OFDM-PON with and without delta-sigma modulation. It has been found that around 4-dB improvement in receiver sensitivity can be achieved using proposed digital transmission scheme of OFDM-PON, with the 20% average EVM.

References

[1] E. Wong, "Next-generation broadband access networks and technologies," *J. Lightw. Technol.*, vol. 30, no. 4, pp. 597–608, Feb. 2012.
[2] *Gigabit-Capable Passive Optical Networks (G-PON)*, ITU-T recommendation G.984.5 series, 2007.
[3] F. Effenberger, "The XG-PON system: Cost effective 10 Gb/s access," *J. Lightw. Technol.*, vol. 29, no. 4, pp. 403–409, Feb. 2011.
[4] A. Banerjee *et al.*, "Wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access: A review [Invited]," *J. Opt. Netw.*, vol. 4, no. 11, pp. 737–758, 2005.
[5] K. Y. Cho, Y. Takushima, and Y. C. Chung, "Demonstration of 11-Gb/s, 20-km reach WDM PON using directly-modulated RSOA with 4-ary PAM signal," in presented at the Opt. Fiber Commun. Conf., 2010, San Diego, CA, USA, Paper OWG1.
[6] R. Hu *et al.*, "A cost-effective 2.5 Gb/s/λ bi-directional coherent UDWDM-PON with computationally-efficient DSP," presented at the Eur. Conf. Opt. Commun. Conf., Cannes, France, 2014, Paper Th.2.6.4.
[7] N. Cvijetic, "OFDM for next-generation optical access networks," *J. Lightw. Technol.*, vol. 30, no. 4, pp. 384–398, Feb. 2012.
[8] D. Y. Qian, N. Cvijetic, J. Hu, and T. Wang, "108 Gb/s OFDMA-PON with polarization multiplexing and direct detection," *J. Lightw. Technol.*, vol. 28, no. 4, pp. 484–493, Feb. 2010.
[9] R. Hu *et al.*, "Direct-detection optical OFDM superchannel for long-reach PON using pilot regeneration," *Opt. Exp.*, vol. 21, no. 22, pp. 26513–26519, 2013.
[10] P. Ossieur *et al.*, "Hybrid DWDM-TDMA PONs for next generation access," presented at the Opt. Fiber Commun. Conf., 2012, Los Angeles, CA, USA, Paper OW1B.7.
[11] N. Cvijetic *et al.*, "1.92Tb/s coherent DWDM-OFDMA-PON with no high-speed ONU-side electronics over 100 km SSMF and 1:64 passive split," *Opt. Exp.*, vol. 19, no. 24, pp. 24540–24545, 2011.
[12] J. Tang *et al.*, "Real-time optical OFDM transceivers for PON applications," presented at the Opt. Fiber Commun. Conf., 2011, San Diego, CA, USA, Paper OTuK3.
[13] R. P. Giddings, E. Hugues-Salas, X. Q. Jin, J. L. Wei, and J. M. Tang, "Experimental demonstration of real-time optical OFDM transmission at 7.5 Gb/s over 25-km SSMF using a 1-GHz RSOA," *IEEE Photon. Technol. Lett.*, vol. 22, no. 11, pp. 745–747, Jun. 2010.
[14] J. L. Wei, C. Sánchez, R. P. Giddings, E. Hugues-Salas, and J. M. Tang, "Significant improvements in optical power budgets of real-time optical OFDM PON systems," *Opt. Exp.*, vol. 18, no. 20, pp. 20732–20745, 2010.
[15] R. M. Gray, "Oversampled sigma-delta modulation," *IEEE Trans. Commun.*, vol. COMM-35, no. 5, pp. 481–489, May 1987.
[16] S. A. Jantzi *et al.*, "A fourth-order bandpass sigma-delta modulator," *IEEE J. Solid-State Circuits*, vol. 28, no. 3, pp. 282–291, Mar. 1993.
[17] J. Wang *et al.*, "Delta-sigma modulation for digital mobile fronthaul enabling carrier aggregation of 32 4G-LTE/30 5G-FBMC signals in a single-λ 10-Gb/s IM-DD channel," presented at the Opt. Fiber Commun. Conf., 2016, Anaheim, CA, USA, Paper M1H.2.