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Realization of Optical OFDM System Using Frequency Combs and Optical Modulators

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Abstract: At both the ends of transmitter and receiver the realization of terabit per second high speed and high spectral-efficiency optical transmission is required. This paper describes the use of much lower speed electronics and optoelectronics through parallel processing of coherent optical frequency combs .The coherent and parallel processing enables electrical-to-optical and optical-to-electrical (E/O and O/E) conversion of wide-bandwidth optical signals which would otherwise exceeds the capability of conventional optoelectronics. As given in this research paper, an optical frequency comb (OFC) generator provides 16 comb lines with less than 3.5-dB power variation. Subsequently, 1.115-Tb/s modulation capability is realized on 32 106 OFDM subcarriers with 16-QAM modulation in a 318-GHz seamless optical bandwidth.

1. INTRODUCTION

Now a days orthogonal frequency division multiplexing (OFDM) has drawn significant research interest owing to its large dispersion tolerance and high spectral efficiency (1-4). Recently, Refs. 5 and 6 have proposed to realize Fourier transform (FT) and inverse Fourier transform (IFT) in optical domain. In Ref. 5, FT and IFT are realized using a time lens which is nothing but a cascade of dispersive element (such as optical fiber or fiber grating), phase modulator and a dispersive element. It is well known that for a conventional lens, the optical field distribution at the back focal plane is the Fourier transform of the field distribution at the front focal plane. Replacing the diffraction by dispersion and spatial chirp of a conventional lens by a temporal chirp introduced by a phase modulator, Fourier transformation of a temporal signal by a time lens is discussed in Ref. 7. The advantage of the optical domain realization of FT is that high speed digital signal processing needed for FFT and IFFT implementation is now replaced by optical signal processing by time lens which has inherently high bandwidth. Ref. 5 has demonstrated the feasibility of 320 Gb/s transmission over a 400 km fiber-optic link. However, fiber nonlinear effects are ignored in the study of Ref. 5. In this paper, we study the nonlinear tolerance of such an optical OFDM system. One of the drawbacks of the scheme proposed in Ref. 5 is that to realize inverse FT, one would need a dispersion compensating fiber (with normal dispersion) 8 and therefore, the dispersion tolerance of such a scheme becomes questionable. Therefore, in this paper, we propose to implement FT at the transmitter instead of IFT so that the standard SMF can be used as a dispersive element of the time lens set up. As a result, the received sequence gets time reversed within a frame. But it can be easily corrected using the digital signal processing at the receiver. A wide variety of systems require reliable personal recognition schemes to determine the identity of an individual requesting their services. Identity verification (authentication) in computer systems has been traditionally based on something that one has (key, magnetic or chip card) or one knows (PIN, password) [1]. Things like keys or cards, however, tend to get stolen and passwords are often forgotten or disclosed. To achieve more reliable verification or identification one should use something that really characterizes the given person. Biometrics offer automated methods of identity verification or identification on the principle of measurable physiological or behavioral characteristics like face, voice, fingerprints etc. Due to non intrusive and user friendly nature of the face biometric it is most commonly used in surveillance applications, crime investigations, security etc.

2. COHERENT OPTICAL OFDM SYSTEMS USING OPTICAL FREQUENCY COMBS

An optical frequency comb is a large number of precisely spaced spectral lines. It is desirable to have a flat optical frequency comb with independent adjustment of center wavelength and comb spacing [12], [13]. In general, there are two approaches for optical frequency comb generation: mode-locked lasers [10], [14] and strong E/O modulation on a continuous-wave (CW) laser [12], [13]. The former approach has been demonstrated for 10-Tb/s signal generation [10]. This paper chooses the latter because it can independently configure the comb center frequency and comb frequency spacing. This method is capable of generation of more than 30 comb lines [2], [13] and therefore it enables the Tb/s signal generation in Section III, which is ten times faster than the previous report [8].

Figure 1 shows the architecture of Tb/s coherent optical OFDM systems using optical frequency combs. At the transmitter side, the comb generator converts a single laser line to multiple comb lines, which are inherently coherent with each other. This coherent characteristic facilitates optical OFDM generation across the entire bandwidth of the multiple comb lines. The comb lines pass through a spectral demultiplexer (demux), optical in-phase/quadrature (IQ) modulators, and a spectral multiplexer (mux) for the data encoding on individual comb lines. The optical IQ modulators may include the power equalization of comb lines with proper power level controls of RF driving signals, or may be followed by tunable optical attenuators to equalize the power of individual comb lines.

The subsequent broad optical signal can be seamless if the frequency spacing of the comb lines is an integral multiple of the OFDM subcarrier spacing and therefore all of the OFDM subcarrier from different comb lines are orthogonal to each other [8]. This is readily achievable once the comb generator and OFDM modulators are frequency synchronized. Therefore, the inherently coherent comb lines enable the generation of much wider bandwidth optical OFDM signals than that of the state-of-the-art ADC/DAC and optoelectronics. This method resembles the RF OFDM generation using oscillator banks and filter banks which were used before the introduction of FFT/IFFT using digital signal processing (DSP) [15], [16]. The optical frequency comb replaces the usual bank of lasers, not only reducing the cost but also maintaining the coherence among the comb lines. In principle, since the optical frequency comb consists of orthogonal comb lines, this transmitter structure will still generate an optical OFDM signal regardless of the modulation format on individual comb lines [10]. However, using OFDM modulation on every comb line enables the system to mitigate fiber dispersion impairments using a reasonable amount of overhead [17]. For convenience, comb lines after OFDM modulation are called OFDM bands. The key feature of the receiver architecture is the O/E conversion of very wideband or high-speed signals via optical spectrum slicing and electronic spectrum synthesis. Based on Figure 1(b), Figure 2 further illustrates this feature for O/E conversion of three comb lines with OFDM modulation. Optical spectrum slicing is achieved primarily by the demultiplexer and secondarily by electrical antialiasing filters that can have much sharper frequency responses (edges) than the optical demuxes. Here, unlike conventional WDM systems which require frequency guard bands, the multiplexer at the transmitter and the demux at the receiver for the optical OFDM signal need to be gapless or strongly overlapping [2], [18], to pass all of the spectral components.

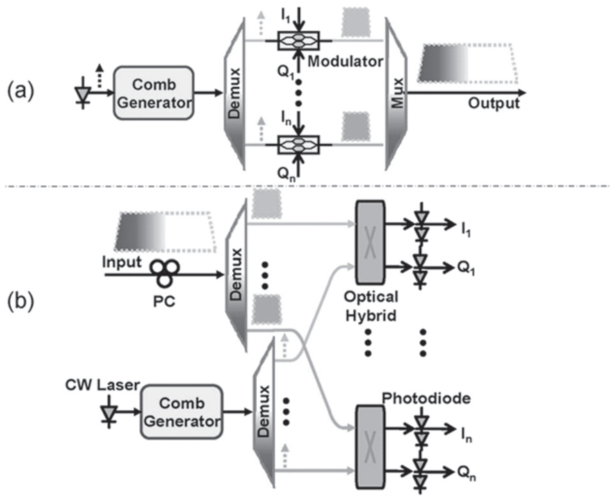

Figure 1: (a) Transmitter and (b) Receiver of Tb/s Coherent Optical OFDM Systems Using Optical Frequency Combs. Dashed Arrows and Boxes Illustrate the Optical Spectra at Various Stages. PC: Polarization Controller

In the next Figure (2a), the frequency components of the three OFDM bands are seamless. Each demultiplexed OFDM band has unwanted frequency components at the slice edges from the neighboring OFDM bands, e.g., the dashed frequency components in Figure 2(b). In a carefully designed system, these frequency components are still orthogonal to the demultiplexed OFDM band and consequently cause no interference.

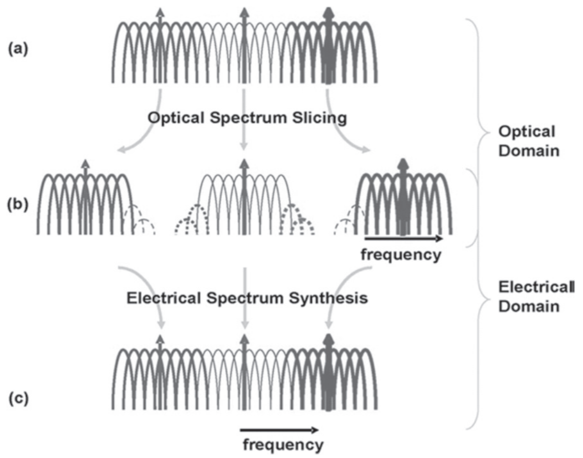

Figure 2: Optical-to-electrical conversion of three OFDM bands via optical spectrum slicing and electrical spectrum synthesis. (a) The three OFDM bands in the optical domain; (b) OFDM bands after gapless optical spectrum slicing; (c) The three OFDM bands in the electrical domain after electrical spectrum synthesis. The arrows stand for the position of the comb lines. The dashed spectral components are eliminated through electrical spectrum synthesis

The utilization of an optical frequency comb in place of multiple local lasers guarantees that the phase relationship among optical spectral slices is preserved afterO/E conversion. For these two reasons, the DSP can eliminate the unwanted frequency components in the frequency domain and can stitch the spectra of multiple OFDM bands together to recover the original data (referred to as electrical spectrum synthesis). From this perspective, the receiver structure is similar to the frequency interleaved ADC [15] and a photonic sampled and demuxed ADC [16], since the optical frequency comb is the optical sampling pulse source in the time domain.

The report in [11], [12] demonstrated the real-time measurement of 160-GHz wide arbitrary optical signals. In comparison, Section IV will show that optical OFDM signals have a less stringent requirement on the frequency response of the receiver structure since OFDM is resilient to the irregularity/distortion in the frequency domain. In Figure 1, the Tb/s capability requires an array of optical devices, DACs/ADCs and DSPs for parallel processing. The feasibility relies on optical and electrical integration. In fact, a chip-scale device with a configuration very similar to Figure 1(a) has shown the capability of manipulation of individual comb lines for optical arbitrary waveform generation [2], [12], [13]. Already a chip-scale device has implemented all the required demuxes and optical hybrids in Fig. 1(b), which is detailed in the other reports for optical arbitrary waveform measurement (OAWM) [18], [11]. The experiment in Section IV employs the identical chip in a coherent optical OFDM receiver.

3. SYSTEM MODELING AND SIMULATION

Figure 3 shows a block diagram of fiber-optic communication system based on optical OFDM, in which the FT blocks are implemented in optical domain using the Fourier transforming property of time lenses. In the proposed scheme, the message signals from various channels are combined using electrical time division multiplexing (ETDM) and the combined signal drives the Mach-Zehnder modulator (MZM). In contrast, in the case of electrical OFDM1-4, message signals from various channels modulate the sub-carriers through IFFT.

The output of the fiber-optic link passes through a FT. Since Fourier transform of a Fourier transform leads to time reversal within a OFDM frame, the transmitted signal can be recovered by introducing time reversal using digital signal processing. In the case of coherent optical/ electrical OFDM, a phase chirp is introduced across the frame due to fiber dispersive effects which can be cancelled using equalization algorithms4. However, in the case of direct detection, equalizer is not needed since the output of the direct detection receiver is proportional to the absolute square of the field envelope.

To investigate the performance of the optical OFDM, both coherent and direct detection schemes are simulated and the bit error rate (BER) is calculated at the receiver as a function of optical signal-to-noise ratio (OSNR). The OSNR is calculated based on 0.1 nm noise bandwidth. Fiber nonlinearity and amplified spontaneous emission (ASE) noise are both taken into account in the simulation. The number of sub-channels is 2048 and the cyclic prefix of length 512 is added as the guard interval between OFDM frames. Each of the sub-channel consists of a BPSK signal at a bit ate of 19.5 Mb/s and the total information rate is 40 Gb/s. In the case of direct detection OFDM, a constant bias voltage is added at the input of MZM so that the output of MZM is an OOK signal. The transmission fiber is a standard single-mode fiber (SSMF). The parameters of the fiber and other system components are listed in Table 1. There is no dispersion compensating module (DCM) placed in the fiber link. The amplifier span is 80 km with 5 spans, so the total transmission distance is 400 km. A De Bruijin sequence of length 211 is used in each of the sub-channel in the Monte-Carlo simulation and the total number of OFDM frames is 50. The accumulated dispersion β2*F* in time-lens-based Fourier transformer is 0.1019 ns2, where *F* is the fiber length and β2 is the dispersion of the standard SMF used in the time lens setup.

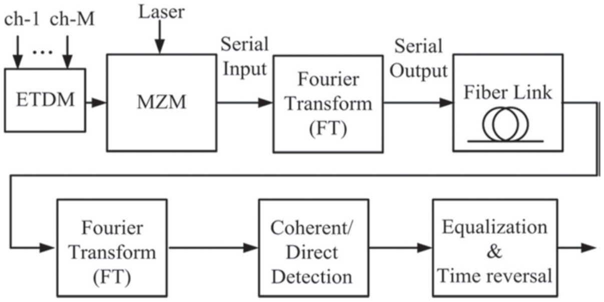

Figure 3: Block Diagram of an Optical OFDM System. MZM = Mach-Zehnder Modulator, ETDM= Electrical Time Division Multiplexer

4. THE FUTURE: COMMERCIALIZATION OF OPTICAL OFDM

Optical OFDM for fiber-optic applications has not yet been commercialized. In this section three applications will be discussed for potential commercialization of Optical OFDM in metro and/or long-haul applications. 100 Gigabit Ethernet (100 GbE) is considered to become the next generation Ethernet standard for high-capacity backbone networks. It has recently been shown that PDM-OFDM is a suitable modulation format for this application. However, the dominating modulation format for 100GbE is single-carrier PDM-QPSK. For PDM-OFDM to break through it must offer significant advantages with respect to PDM-QPSK. PDM-OFDM offers similar performance to PDM-QPSK, but requires in addition the development of DACs at the transmitter. It has as well been shown that PDMOFDM is not very well suited for deployment on legacy systems as XPM generated by OFDM disturbs its neighboring channels.

As such we conjecture that for 100GbE backbone PDM QPSK will be the dominating modulation format.

As described in the previous section, one of the strengths of OFDM is that it is easy to scale to higher level modulation formats. An interesting application space for optical OFDM is to realize 100GbE transponders for Metro applications. Cost is here the dominating factor and by using a 16-QAM constellation instead of QPSK (4-QAM), 100GbE PDMOFDM can be realized with 10G electronics. A higher constellation size reduces the reach of the transponder, but the reach should be sufficient for both metro and regional applications (up to ~800km). This would significantly reduce transponder costs while still offering a large tolerance with respect to chromatic dispersion and PMD.

Finally, one can take advantage of the fact that with OFDM it is possible to dynamically set the constellation size of the payload. Taking advantage of this feature one can realize a transponder that can operate at either 100GbE or 400GbE by changing the constellation size from 2QAM to 16QAM. Using a PDM-OFDM modulation format, the required bandwidth would be about 60 GHz and as such it would not be suitable for a 50 GHz channel spacing. However, it would provide reach dependent throughput scaling from the ultimate reach with BPSK (2QAM) modulation to the highest data rate with 16 QAM. The main challenge might be that at the client side an interface must be defined that can support both a 100 Gb/s and 400 Gb/s throughput.

5. CONCLUSION

In this paper we have discussed the past, present and future applications of optical OFDM. The main advantages of optical OFDM are its tolerances to linear impairments, scalability to higher constellation sizes, low oversampling requirements and negligible linear crosstalk. Thereby optical OFDM offers distinct advantages for certain metro and long-haul applications in next generation fiber-optic transmission systems.

REFERENCES

[1] B.J.C. Schmidt, A. J. Lowery, and J. Armstrong, "Experimental Demonstrations of Electronic Dispersion Compensation for Long-Haul Transmission Using Direct-Detection Optical OFDM", *Journal of Lightwave Technology,* Vol. 26, Issue 1, pp. 196-203.

[2] I. B. Djordjevic and B. Vasic, "Orthogonal Frequency Division Multiplexing for High-speed Optical Transmission", *Optics Express,* Vol. 14, pp. 3767-3775, 2006.

[3] W. Shieh, X. Yi and Y. Tang, "Transmission Experiment of Multi-gigabit Coherent Optical OFDM Systems Over 1000 km SSMF Fibre," *Electronics Letters,* Vol. 43, No. 3, pp. 183-184, 2007.

[4] S.C.J. Lee, F. Breyer, S. Randel, O. Ziemann, H.P.A. van den Boom, A.M.J. Koonen, "Low-Cost and Robust 1 Gbit/s Plastic Optical Fiber Link Based on Light-Emitting Diode Technology," in Proc. Opt. Fiber Commun. Conf., San Diego, CA, 2008, Paper OWB3.

[5] S.L. Jansen, I. Morita, T.C.W. Schenk, and H. Tanaka, "Long-haul Transmission of 16x52.5-Gb/s Polarization Division Multiplexed OFDM Enabled by MIMO Processing," *OSA Journal of Optical Networking,* Vol. 7, pp. 173-182, 2008.

[6] D. Qian, N. Cvijetic, J. Hu, and T. Wang, "108Gb/s OFDMA-PON with Polarization Multiplexing and Direct-Detection", in proc. OFC 2009, OMV3, 2009.

[7] Hidenori Takahashi, Abdullah Al Amin, Sander L. Jansen*, Itsuro Morita and Hideaki Tanaka, "DWDM Transmission with 7.0-bit/s/Hz Spectral Efficiency using 8x65.1-Gbit/s Coherent PDM-OFDM Signals," in Proc. Opt. Fiber Commun. Conf., San Diego, CA, 2009, Paper PDPB7.

[8] E. Ip, A.P.T. Lau, D.J. F. Barros, J.M. Kahn, "Coherent Detection in Optical Fiber Systems", *Optics Express,* Vol. 16, pp. 753-791, 2008.

[9] T.C.W. Schenk, "RF Imperfections in High-rate Wireless Systems," Springer 2008.

[10] C.R.S. Fludger, T. Duthel, D. van den Borne, C. Schulien, E-D. Schmidt, T. Wuth, J. Geyer, E. de Man, G.D. Khoe and H. de Waardt, "10x111 Gbit/s, 50 GHz spaced, POLMUX-RZ-DQPSK Transmission Over 2375 km Employing Coherent Equalisation," *Journal of Lightwave Technology,* Vol. 26, No. 1, pp. 64-72, 2008.

[11] S. Adhikari, S.L. Jansen, V.A.J.M. Sleiffer and W. Rosenkranz, "On the Nonlinear Tolerance of 42.8-Gb/s DPSK with Co-propagating OFDM Neighbors", In proc. LEOS Annual Meeting 2009, Paper ME 1.A. K. Jain, A. Ross and S. Prabhakar, An Introduction to Biometric Recognition, IEEE Transactions on Circuits and Systems for Video Technology, *Special Issue on Image-and Video-Based Biometrics,*Vol. 14, No. 1, pp. 4-20, 2004.

[12] R. P. Scott, N. K. Fontaine, J. P. Heritage, B. H. Kolner, and S. J. B. Yoo, "3.5-THz wide, 175 Mode Optical Comb Source," in *Proc. OFC*, 2007, Paper OWJ3.

[13] P. J. Delfyett, S. Gee, M. T. Choi, H. Izadpanah, W. Lee, S. Ozharar,F. Quinlan, and T. Yilmaz, "Optical Frequency Combs from Semiconductor Lasers and Applications in Ultrawideband Signal Processing and Communications," *J. Lightw. Technol.*, Vol. 24, No. 7, pp. 2701–2719, July 2006.

[14] S. Weinstein and P. Ebert, "Data Transmission by Frequency-division Multiplexing Using the Discrete Fourier Transform," *IEEE Trans. Commun. Tech.*, Vol. COMM-19, No. 5, pp. 628–634, Oct. 1971.

[15] L. Hanzo and T. Keller, *OFDM and MC-CDMA: A Primer*. New York: Wiley, 2006.

[16] W. Shieh and C. Athaudage, "Coherent Optical Orthogonal Frequency Division Multiplexing," *Electron. Lett.*, Vol. 42, pp. 587-589, 2006.

[17] R. P. Scott, N. K. Fontaine, L. Zhou, J. P. Heritage, and S. J. B. Yoo, "Continuous, Real-time, Full-field Waveform Measurements via Spectral Slicing and Parallel Digital Coherent Detection," in *Proc. OFC*, 2010, Paper OWB7.

[18] G. Ding, C. Dehollain, M. Declercq, and K. Azadet, "Frequency-interleaving technique for high-speed A/D conversion," in *Proc. IEEE Symp. Circuits Syst. (ISCAS)*, 2003, pp. 857-860.

[19] G. C. Valley, "Photonic Analog-to-digital Converters," *Opt. Exp.*, Vol. 15, pp. 1955-1982, 2007.