1.25-Gb/s incoherent spectral OCDMA transmission using integrated en/decoders

Citation for published version (APA):
Huiszoon, B., Spuesens, T., Tangdiongga, E., Zantvoort, van, J. H. C., Khoe, G. D., Waardt, de, H., & Koonen, A. M. J. (2008). 1.25-Gb/s incoherent spectral OCDMA transmission using integrated en/decoders. *IEEE Photonics Technology Letters*, *20*(24), 2189-2191. https://doi.org/10.1109/LPT.2008.2006405

DOI:
10.1109/LPT.2008.2006405

Document status and date:
Published: 01/01/2008

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 20. Oct. 2021

1.25-Gb/s Incoherent Spectral OCDMA Transmission Using Integrated En/Decoders

B. Huiszoon, *Student Member, IEEE*, T. Spuesens, *Student Member, IEEE*, E. Tangdiongga, J. H. C. van Zantvoort, G. D. Khoe, *Fellow, IEEE*, H. de Waardt, *Associate Member, IEEE*, and A. M. J. Koonen, *Fellow, IEEE*

***Abstract*—The performance of an incoherent spectral optical code-division multiple-access system using integrated en/decoders is experimentally evaluated. Results are shown for a 1.25-Gb/s transmission over 2.25-km standard single-mode fiber in case of a single and two active users. Additionally, the optical and electrical correlation values as well as the crosstalk factors are measured.**

***Index Terms*—Code-division multiaccess, coding, decoding, integrated optics, optical fiber communication, passive filters.**

I. INTRODUCTION

THE primary application domain of optical code-division multiple-access (OCDMA) is the access network because it offers cost-effective network deployment and management combined with physical layer security [1]. Researchers employing the various OCDMA techniques currently focus on the increase of the transmission performance. Cost-effectiveness is a key issue in the access domain which make the properties of an incoherent spectral OCDMA system particularly interesting. It uses incoherent broadband sources, the coding rate thus the system bandwidth (BW) is in the order of the bit rate and complementary en/decoding effectively suppresses interferers [2], [3].

Recently demonstrated systems employ fiber-based en/decoders (E/Ds) and bit rates below 1 Gb/s [4], [5]. Integrated E/Ds are preferred to fully exploit the potential of monolithic or hybrid integration. Future BW demands in access are largely fuelled by peer-to-peer networking and user-generated content such as digital video. Therefore, the access network should anticipate and provide at least gigabit speeds symmetrically [6].

This work considers Mach–Zehnder interferometer (MZI)-based integrated E/Ds first used in a cascade or ladder configuration by [7] which presented single-user transmission results at 100 Mb/s in a back-to-back (BTB) configuration. A parallel or tree E/D has been developed to process the code set with a single device which is typically done at the central office (CO) of a passive optical network (PON). Recently, both E/D types have been integrated in the low-loss Si_3N_4–SiO_2 material system [8]. To the best of the authors' knowledge, the first multiple-user transmission results are presented in this letter. The system operates at 1.25 Gb/s and a standard single-mode fiber (SSMF) of 2.25 km is used without dispersion compensation.

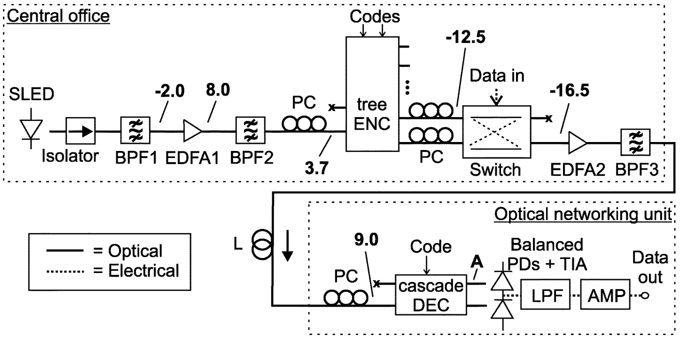

Fig. 1. Experimental setup, downstream PON configuration.

The remainder of this letter is organized as follows. Section II describes the experimental setup in detail after which Section III presents measured values of the correlation and crosstalk within the code set. The transmission performance is shown in Section IV. Finally, conclusions are drawn in Section V.

II. EXPERIMENTAL SETUP

The experimental setup is depicted in Fig. 1 for a downstream PON configuration. The output of the superluminescent light-emitting diode is filtered by a bandpass filter (BPF) which is placed after an isolator and has a -3-dB cut-off frequency of 5 nm. This value is equal to the free-spectral range (or periodicity) of the MZI-based E/Ds. Then an erbium-doped fiber amplifier (EDFA) is used to amplify the spectral slice before it is encoded and modulated. A second BPF filters the amplified spontaneous emission (ASE) noise generated by the EDFA and has a -3-dB cut-off frequency of 12 nm. This value should be closer to 5 nm in order to rigorously filter ASE noise but such filters were not available. A performance degradation was observed if BPFs of 5 nm were used after the EDFA because the edges of the passband affect the shape of the spectral slice.

The optical power is optimized for the transverse-electric (TE) mode via a polarization controller in front of the polarization-dependent tree encoder (ENC). The MZI-based tree ENC passively splits and filters the spectral slice and, as a result, multiple 5-nm-wide amplitude distributions appear at all its outputs which represent the spectral codes. Obviously, such parallel coding occurs at the expense of a power penalty.

Manuscript received June 30, 2008; revised September 05, 2008. First published October 31, 2008; current version published December 12, 2008. This work was supported by the Dutch Ministry of Economic Affairs, by the Netherlands Organization for Scientific Research (NWO), and by the Technology Foundation STW via the NRC Photonics Research Grant and the Valorisation Grant I. This work has been carried out in the COBRA SWOOSHING Project.

The authors are with the COBRA Institute, Eindhoven University of Technology (TU/e), NL-5600MB Eindhoven, The Netherlands (e-mail: b.huiszoon@ieee.org).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2008.2006405

1041-1135/$25.00 © 2008 IEEE

Authorized licensed use limited to: Eindhoven University of Technology. Downloaded on December 15, 2008 at 09:11 from IEEE Xplore. Restrictions apply.

TABLE I
MEASURED STATIC CORRELATION OF TWO-STAGE E/DS, OPTICAL [mW]

	Code ENC			
Code DEC	$\mathrm{A}(\omega)/\overline{\mathrm{A}}(\omega)$	$\mathrm{B}(\omega)/\overline{\mathrm{B}}(\omega)$	$\mathrm{C}(\omega)/\overline{\mathrm{C}}(\omega)$	$\mathrm{D}(\omega)/\overline{\mathrm{D}}(\omega)$
$\mathrm{A}(\omega)/\overline{\mathrm{A}}(\omega)$	0.52/-0.35	0.08/0.10	0.08/0.07	0.10/0.14
$\mathrm{B}(\omega)/\overline{\mathrm{B}}(\omega)$	0.08/0.02	0.61/-0.39	0.08/0.08	0.10/0.12
$\mathrm{C}(\omega)/\overline{\mathrm{C}}(\omega)$	0.04/0.08	0.09/0.07	0.57/-0.39	0.13/-0.09
$\mathrm{D}(\omega)/\overline{\mathrm{D}}(\omega)$	0.05/0.06	0.11/0.05	0.09/0.05	0.55/-0.29

TABLE II
MEASURED DYNAMIC CORRELATION OF TWO-STAGE E/DS AT 1.25 Gb/s, ELECTRICAL [dBm]

	Code ENC			
Code DEC	A	B	C	D
A	-2.7	-19.5	-19.2	-20.0
B	-19.3	-2.0	-19.7	-20.0
C	-19.7	-20.0	-2.3	-20.1
D	-20.6	-19.0	-18.8	-3.4

Tunable phase shifters in the ENC enable modification of the filter patterns such that orthogonal codes can be produced. An integrated MZI naturally has two complementary optical outputs which are used in a modulation format referred to as spectral shift keying (SSK). SSK transmits $T(\omega)$ as a logical "0" and $\overline{T}(\omega)$ as a logical "1" such that a binary data stream is represented by a sequence of complementary filter patterns.

Here, a 2 × 8 tree ENC is used which is able to generate four complementary sets of spectral codes [8]. The insertion losses are 16.5 dB for each output. As shown in Fig. 1, a polarization-dependent high-speed 2 × 2 optical switch is used for the SSK modulation and a second EDFA compensates for the experienced losses at the ENC and switching. A third BPF ($\mathrm{BW} = 12$ nm) filters the ASE noise and the optical stream is launched into an SSMF with a length L.

At the receiver side, the optical stream is again optimized for the TE-mode after which it is launched into a 2 × 2 cascade decoder (DEC) with an insertion loss of 8.5 dB. Then, a 12-GHz balanced photodetector (PD) unit with a transimpedance amplifier detects the optical intensity. The electrical signal is filtered by a 938-MHz low-pass filter and amplified by a 12-GHz broadband amplifier with a gain of about 20 dB. The polarization-dependency of the ENC and DEC can be significantly reduced [8].

III. CORRELATION AND CROSSTALK EVALUATION

The available code set is characterized via the auto- and cross-correlation peaks (ACP, CCP) similar to [3] in case of a BTB configuration, i.e., $L = 0$ in Fig. 1. The ACP and CCP are determined for the static and dynamic operation of the setup using any of the four codes. Regarding the former, the optical powers are measured at position A in Fig. 1 when either $T(\omega)$ or $\overline{T}(\omega)$ is launched in the DEC. Regarding the latter, an encoded 1.25-Gb/s bit stream is decoded by the DEC and the electrical power is measured at the output of the optical networking unit (ONU) in Fig. 1. The results are shown in Tables I and II. In the static case, two values are shown when either the spectral code (left) or the complementary (right) is selected. The "row"-codes are set at the ENC while the "column"-codes are set at the DEC. The values in Table I represent the optical power difference between the upper and the lower output of the DEC. As shown, the ACP has a high and bipolar output while the CCP remains low. In the dynamic case, the measured values in Table II indicate that a contrast ratio of more than 16 dB can be achieved between decoding with a matched and mismatched code.

TABLE III
MEASURED CROSSTALK FACTORS OF TWO-STAGE E/DS

Code	Inbound	Outbound
$\mathrm{A}(\omega)/\overline{\mathrm{A}}(\omega)$	0.20/0.40	0.15/0.23
$\mathrm{B}(\omega)/\overline{\mathrm{B}}(\omega)$	0.16/0.31	0.18/0.26
$\mathrm{C}(\omega)/\overline{\mathrm{C}}(\omega)$	0.23/0.23	0.15/0.20
$\mathrm{D}(\omega)/\overline{\mathrm{D}}(\omega)$	0.20/0.20	0.20/0.49

The static correlation values in Table I can be used to calculate the inbound and outbound crosstalk values for each code [9]. The outbound crosstalk value indicates to which extent a code generates crosstalk at other users while the inbound crosstalk indicates to which extent a user is affected by crosstalk from other codes. Let us take Code A as an example. Then, with respect to the values in Table I, its outbound crosstalk values are determined by dividing the maximum CCP value found for either the spectral code (0.08 at Code B) or the complementary (0.08 at Code C) in the column of Code A by its ACP (0.52 and -0.39). Its inbound crosstalk value is determined by a similar procedure in the row of Code A. The (absolute) crosstalk factors are shown in Table III.

The values in Table III differ significantly from the values determined via analysis in [9]. However, the analysis was done considering ideal components and, therefore, represents the optimal case. The measured crosstalk values exhibit discrepancies and in some cases a factor two difference may be observed within a set of complementary spectral codes. Most likely device imperfections cause this difference. Regarding the inbound crosstalk, Codes C and D display an equal response both for the spectral code and the complementary. Considering the outbound crosstalk of these two, D generates a large amount of crosstalk (at Code A). Therefore, in the transmission experiments, Code C is preferred using these devices.

IV. TRANSMISSION PERFORMANCE

The transmission performance of the setup shown in Fig. 1 is evaluated. The optical switch is operated by a pulse pattern generator which generates a $2^7 - 1$ pseudorandom bit sequence (PRBS) at a bit rate of 1.25 Gb/s. A higher order PRBS was not allowed due to a poor low-frequency response of the amplifier driving the switch. An SSMF with $L = 2.25$ km is inserted between the CO and the ONU which is close to the dispersion limit of this system. The measured optical powers are shown in dBm at various positions in Fig. 1. The decoded and detected data stream is processed by a bit-error-rate (BER) tester. A time gating of 100 s has been employed during the measurements.

In case of a single active user, the BER versus the received optical power is depicted in Fig. 2 for all four codes. Note that the received optical power at the input of the ONU is taken and not the decoded optical power at the input of the balanced

Authorized licensed use limited to: Eindhoven University of Technology. Downloaded on December 15, 2008 at 09:11 from IEEE Xplore. Restrictions apply.

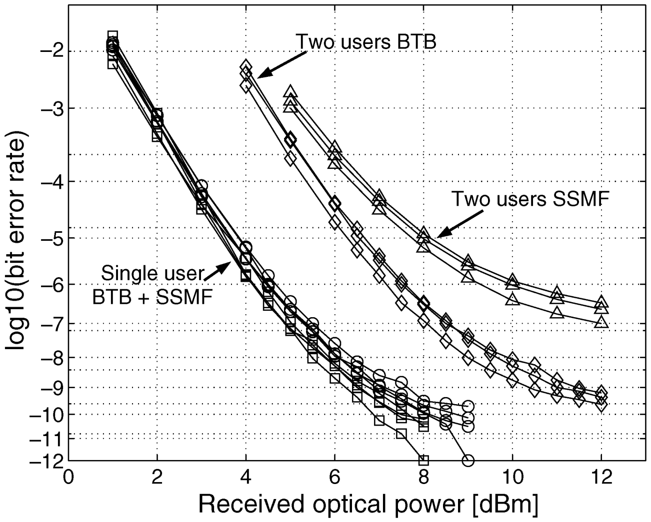

Fig. 2. BER versus received optical power, 1.25 Gb/s and PRBS $= 2^7 - 1$.

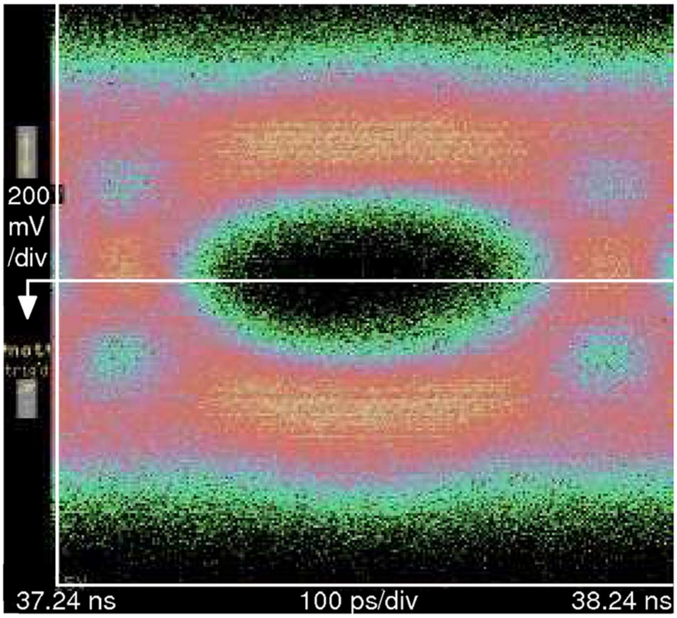

Fig. 3. Eye diagram measured after 2.25-km SSMF transmission with two active codes, BER $= 10^{-7}$ and PRBS $= 2^7 - 1$.

PDs. Error-free transmission $(\text{BER} \leq 10^{-9})$ is clearly shown in Fig. 2 with a transmission penalty smaller than 1 dB; no significant difference is observed between the four codes and no error-floor is present. The relatively poor receiver sensitivity of +7 dBm is merely caused by the losses of the DEC and a low sensitivity of the balanced PD unit with respect to the ACPs shown in Table I. If these values are improved, a significant improvement can be expected.

In case of two active users, an additional switch is placed at the tree ENC in Fig. 1 and Code C is combined with any of the three other available codes. Fig. 2 clearly shows the effect of adding a second channel by a roughly 3-dB increase of received power. Error-free transmission is only determined in case of the BTB because the received optical power level was not raised higher than +12 dBm to prevent damage to the equipment. Given that no error-floor exists for BTB prior to the error-free BER level and the low transmission penalty for a single user transmission, error-free performance may be expected for two users at higher received power levels. However, a multiple-user interference penalty has to be taken into account. The eye diagram in case of two active users after 2.25-km SSMF transmission is shown in Fig. 3 at 12 dBm.

V. CONCLUSION

This work presents the first multiple-user transmission experiments at a bit rate of 1.25 Gb/s for an incoherent spectral amplitude encoded OCDMA system using integrated E/Ds. Error-free transmission over 2.25-km SSMF is clearly shown for a single user and up to a BER of 10^{-7} could be measured in case of two active users for a $2^7 - 1$ PRBS. The latter is expected also to perform error-free under improved conditions. The measured correlation and crosstalk values confirm orthogonality of the code set.

REFERENCES

[1] K. Fouli and M. Maier, "OCDMA and optical coding: Principles, applications, and challenges," *IEEE Commun. Mag.*, vol. 45, no. 8, pp. 27–34, Aug. 2007.

[2] M. Kavehrad and D. Zaccarin, "Optical code-division-multiplexed systems based on spectral encoding of noncoherent sources," *J. Lightw. Technol.*, vol. 13, no. 3, pp. 534–545, Mar. 1995.

[3] L. Nguyen, T. Dennis, B. Aazhang, and J. F. Young, "Experimental demonstration of bipolar codes for optical spectral amplitude CDMA communication," *J. Lightw. Technol.*, vol. 15, no. 9, pp. 1647–1653, Sep. 1997.

[4] G. A. Magel, G. D. Landry, R. J. Baca, D. A. Harper, and C. A. Spillers, "Transmission of eight channels ×622 Mbit/s and 15 channels ×155 Mbit/s using spectral amplitude encoded optical CDMA," *Electron. Lett.*, vol. 37, no. 21, pp. 1307–1308, 2001.

[5] Z. A. El Sahn, M. Zeng, B. J. Shastri, N. Kheder, D. V. Plant, and L. A. Rusch, "Dual architecture uplink demonstration of a 7 × 622 Mbps SAC-OCDMA PON using a burst-mode receiver," presented at the Proc. OFC2008, San Diego, CA, Mar. 2008, Paper OMR3.

[6] K.-I. Kitayama, X. Wang, and N. Wada, "OCDMA over WDM PON—Solution path to Gigabit-symmetric FTTH," *J. Lightw. Technol.*, vol. 24, no. 4, pp. 1654–1662, Apr. 2006.

[7] C. F. Lam, R. Vrijen, D. T. K. Tong, M. C. Wu, and E. Yablonovitch, "Experimental demonstration of spectrally encoded optical CDMA systems using Mach–Zehnder encoder chains," presented at the Proc. CLEO'98, San Francisco, CA, May 1998, Paper CThU4.

[8] B. Huiszoon, A. Leinse, D. H. Geuzebroek, L. M. Augustin, E. J. Klein, H. de Waardt, G. D. Khoe, and A. M. J. Koonen, "Multi-stage cascade and tree en/decoders integrated in Si_3N_4–SiO_2 for spectral amplitude OCDMA on PON," presented at the Proc. OFC2008, San Diego, CA, Feb. 2008, Paper OMR4.

[9] B. Huiszoon, H. de Waardt, G. D. Khoe, and A. M. J. Koonen, "Performance analysis of an integrated spectral OCDMA technique including coupler imbalance," *IEEE Photon. Technol. Lett.*, vol. 20, no. 4, pp. 276–278, Feb. 15, 2008.

Authorized licensed use limited to: Eindhoven University of Technology. Downloaded on December 15, 2008 at 09:11 from IEEE Xplore. Restrictions apply.