40-Gb/s all-optical wavelength conversion based on a nonlinear optical loop mirror

Yu, Jianjun; Zheng, Xueyan; Peucheret, Christophe; Clausen, Anders; Poulsen, Henrik Nørskov; Jeppesen, Palle

Published in:
Journal of Lightwave Technology

Link to article, DOI:
10.1109/50.850746

Publication date:
2000

Publisher Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
40-Gb/s All-Optical Wavelength Conversion Based on a Nonlinear Optical Loop Mirror

Jianjun Yu, Xueyan Zheng, Christophe Peucheret, Anders T. Clausen, Henrik N. Poulsen, and Palle Jeppesen, Member, IEEE

Abstract—All-optical wavelength conversion based on a nonlinear optical loop mirror (NOLM) at 40 Gb/s is demonstrated for the first time. The effect of walkoff time between control beam and signal beams is investigated when the NOLM is used as an all-optical wavelength converter or an all-optical demultiplexer.

Index Terms—All-optical demultiplexing, cross-phase modulation (XPM), nonlinear optical loop mirror (NOLM), optical time domain multiplexing (OTDM), wavelength conversion, wavelength-division multiplexing (WDM).

I. INTRODUCTION

WAVELENGTH conversion has been suggested as a method of enhancing routing options and network properties like reconfigurability, nonblocking capability and wavelength reuse [1], [2]. Cross-gain modulation (XGM) [3], [4], cross-phase modulation (XPM) [5], [6], and four-wave mixing (FWM) [7]–[9] in semiconductor optical amplifiers (SOA’s) have been demonstrated for 40 Gb/s wavelength conversion. But up to now, 40 Gb/s wavelength conversion using a nonlinear optical loop mirror (NOLM) has been reported. In fact, NOLM based on silica fiber has the potential of attaining terahertz per second switching operation due to the ultrafast optical nonlinearity [10]–[13]. Reference [14] has demonstrated that the pulsewidths can be maintained, and even compressed when the walkoff between the continuous-waves (CW’s) and the control pulses is small. So, wavelength conversion based on an NOLM will be suitable for return-to-zero (RZ)-based networks. In this paper, we will realize wavelength conversion based on an NOLM at 40 Gb/s, and investigate the walkoff effect when the NOLM is used as a wavelength conversion or demultiplexing media.

II. EXPERIMENT

The full-width at half-maximum (FWHM) pulsewidth of the control pulse measured by an autocorrelator is 8.2 ps, so the duty cycle is 0.33. In this case, the nonlinear phase of the counterpropagating wave will have some effect on the ER of the converted signal. Like nonreturn-to-zero (NRZ), this problem can easily be solved by adjusting the state of polarization controller in the NOLM [11], [14]. In order to obtain a switching efficiency of 1, the peak power of the control pulse should be 242 mW; it means an average power of about 40 mw. The output power of the erbium-doped fiber amplifier (EDFA) in our experiment can satisfy this requirement.

A. Experimental Setup

The experimental setup is shown in Fig. 1. It consists of two NOLM’s, one is used for wavelength conversion (WC-NOLM), and the other is used for all-optical demultiplexing (D-NOLM) [15] The WC-NOLM consists of 3 km of dispersion shifted fiber (DSF) with a nonlinear index \( n_2 = 2.67 \times 10^{-20} \text{ m}^2/\text{W} \), an effective cross sectional area \( A_{\text{eff}} = 50 \mu \text{ m}^2 \), zero dispersion wavelength of 1550.7 nm and dispersion slope of 0.08 ps/nm²/km. The on-off ratio defined between maximum and minimum transmission of the NOLM is 30 dB without the control signal [14].

The control pulses for the WC-NOLM at 1546.8 nm (\( \lambda_1 \)), which are generated by a gain-switched DFB-LD followed by DCF for compression, are externally modulated by a LiNbO\(_3\) intensity modulator at 10 Gb/s using a 2\(^{23}-1\) pseudorandom bit sequence (PRBS) before passive multiplexing to 40 Gb/s. The control pulses for the D-NOLM are also obtained from a gain-switched laser followed by a dispersion compensated fiber (DCF) (compressed pulsewidth \( \sim 10 \) ps and center wavelength \( \lambda_2 = 1553.0 \) nm) and injected into D-NOLM from OC4. The average optical power of the control pulses for demultiplexing the optical time division multiplexed (OTDM) signals is 18 dBm; the relative timing between the control pulses and the converted signals is adjusted by using a variable optical delay line.

Fig. 2. Relative total group delay and total dispersion as a function of signal wavelength measured in the two DSF’s. (a) DSF used for wavelength conversion. (b) DSF used for demultiplexing.

Fig. 3. Control signal at 1546.8 nm (20 ps/div). (a) 10 Gb/s and (b) 40 Gb/s.

B. Experimental Results

Fig. 4 shows some typical optical eye diagrams of the converted signals at different wavelengths. Almost the same eye diagrams are obtained at converted wavelengths from 1540 to 1563 nm. Fig. 5 shows the numerical simulation results with FWHM of control pulse of 8.2 ps; the numerical model is described in [14]. From Fig. 5, we can see that the pulsewidths of the converted signals are smaller or equal to that of the control pulses when the CW wavelengths are chosen from 1541 to
Fig. 4. Optical eye diagrams of converted signals at different wavelengths (20 ps/div). (a) 1535 nm, (b) 1540 nm, (c) 1557 nm, (d) 1563 nm, and (e) 1569 nm.

1561 nm, and the variation of the pulsewidths in this range is small. When the CW wavelength is 1561 nm, the walkoff time is 11.8 ps. The reason for the pulsewidth compression of the converted pulses is explained in [14]. Because the pulsewidth of the converted signal is maintained or compressed, there is no intersymbol interference (ISI) as shown in Fig. 4(b)–(c). Even when the CW wavelength is 1563 nm, in which case the walkoff time is 17.7 ps, ISI cannot be observed, as shown in Fig. 4(d). This is because the pulsewidth of the converted signals is only a little wider than that of the control pulses, and the duty cycle of the control signals is small. The converted signals at 1535 and 1569 nm are severely broadened because of a large walkoff between the control signals and CW lightwaves, which leads to an obvious ISI in the converted signals, as shown in Fig. 4(a) or (e).

Without wavelength conversion means that the WC-NOLM is not used, but we demultiplex the 40 Gb/s OTDM signal (1546.8 nm) using the control pulses (1553.0 nm). The eye diagram of
the demultiplexed signal is shown in Fig. 6(a). The BER performance (40 Gb/s back to back) is measured and shown in Fig. 8. As an example, Fig. 6(b) shows the eye diagram at 1557 nm after wavelength conversion and demultiplexing. The clean eye diagram of the de-multiplexed signals can be seen. Fig. 7 shows the optical spectrum around 1557 nm after wavelength conversion and demultiplexing in the time-domain; a sidemode suppression ratio (SMSR) larger than 30 dB is obtained. The second peak in Fig. 7 is the remaining control pulse at 1553 nm because of the finite suppression of the optical filter.

Fig. 8 shows the bit-error rate (BER) performance. \( \tau \) represents the walkoff time between control pulses and signals in D-NOLM. There is a power penalty of 3.2 dB for the 40-Gb/s OTDM signal without wavelength conversion (40 Gb/s back to back). The penalty is due to a large walkoff between the control pulses (1553.0 nm) and the 4 x 10 Gb/s signals (1546.8 nm). The power penalties are dependent on the wavelengths of the converted signals, because there is a different walkoff time when signals at different wavelengths are demultiplexed in the D-NOLM. Because there exists a timing jitter in both control pulses and signals, and the D-NOLM uses the interaction between control pulses and signals through the optical Kerr effect, timing errors result in fluctuations in the switching efficiency and thus degradation of the BER performance. One effective way to improve the jitter tolerance is to take advantage of the walkoff between control pulses and signals. Reference [18] has found that a proper walkoff time can suppress the BER degradation due to timing jitter, and the optimal walkoff depends on the value of pulse timing jitter. The eye diagrams in Fig. 4(b)–(e) are almost the same, demonstrating that the converted signals at 40 Gb/s in Fig. 4(b)–(e) have almost the same performance. From Fig. 8, we can see that when the walkoff time between the control pulses and signals is 2 ps, then the power penalty is smallest and equal to 4 dB at BER of \( 10^{-9} \). It shows that the optimal walkoff is 2 ps. When the walkoff is 0 ps and 2.7 ps, there is almost the same power penalty, and that power penalty is approximately 6 dB at BER of \( 10^{-9} \). When the walkoff is 7 ps and 15 ps, error floors appear at BER’s of \( \sim 10^{-7} \) and \( 10^{-6} \), respectively, although the eye diagrams of the converted signals at the wavelengths of 1540 nm and 1563 nm are very clear. It shows that the walkoff plays an important role when the NOLM is used as a demultiplexer. Because of the SNR reduction of converted signals, the tolerance of the walkoff time will be reduced when the OTDM signals are demultiplexed by the D-NOLM. Even if there is a walkoff time of 7.5 ps between the original OTDM signals (1546.8 nm) and control pulses (1553.0 nm), the original OTDM signals can be demultiplexed, however, after wavelength conversion, the OTDM signals with a walkoff time of 7 ps can not be demultiplexed and there is an error floor at BER of \( 10^{-7} \).

III. CONCLUSION

We have demonstrated 40-Gb/s RZ wavelength conversion based on an NOLM. Because the pulsewidths of the converted
signals can be maintained and even compressed, there is no evi-
dent ISI in the converted signals at center wavelengths from
1540 nm to 1561 nm. The pulsewidth of the converted signals
can be maintained even if the walkoff time is 11.8 ps when the
CW wavelength is 1561 nm. However, when the NOLM is used
as a demultiplexer and when the walkoff time is larger than 4 ps,
there is an obvious effect on the demultiplexed signals, which
shows that the walkoff plays a more important role when the
NOLM is used as a demultiplexer.

ACKNOWLEDGMENT

The authors gratefully acknowledge Lucent Denmark and
France Telecom for providing, respectively, the optical fibers
and the gain-switched laser used in this work.

REFERENCES

sign and implementation of a fully reconfigurable all-optical crossconnect
for high capacity multi-wavelength transport networks,” J. Lightwave

J. F. Morrison, R. Ohshansky, R. Ramaswami, and E. H. Smith, “All-
optical packet-switched metropolitan-area network proposal,” J. Light-

length conversion at 10 Gbit/s using a semiconductor optical amplifier,”

wavelength conversion by semiconductor optical amplifiers,” Electron.

Guillemet, F. Gaborit, F. Pointg, B. Dagens, and M. Renaud, “20 Gbit/s
optical wavelength conversion in all-active maczehnder interferom-

A. Kloch, A. P. B. Hansen, K. E. Stubkjaer, K. Wunstel, K. Daub, E.
Lach, G. Laube, W. Idler, M. Schilling, and S. Bouchoule, “40 Gbit/s all-
optical wavelength converter and RZ-NRZ format adapter realized by
monolithic integrated active Michelson interferometer,” Electron. Lett.,

standard fiber using midspan spectral inversion for dispersion compensa-

“Wavelength conversion at 40 Gbit/s via four wave mixing in semicon-
ductor optical amplifier with integrated pump laser,” Electron. Lett.,

version over 24.6 nm using FWM in a semiconductor optical amplifier
with an optimized MQW active region,” Electron. Lett., vol. 33, no. 25,

C. Sonne, “Simultaneous wavelength conversion and optical phase
conjugation of 200 Gbit/s (5 × 40 Gbit/s) WDM signal using a highly
nonlinear fiber four-wave mixing,” in Proc. ECOC’97, 1997, Paper

of NRZ and RZ signals using a nonlinear optical loop mirror,” J. Light-

conversion at 10 Gbit/s with nonlinear optical loop mirror,” Electron.

pulse width and wavelength conversion at 10 Gbit/s using a nonlinear

P. Jeppesen, All-optical wavelength conversion of short pulses and
NRZ signals based on a nonlinear optical loop mirror, in J. Lightwave
Technol., submitted for publication.

linear fiber loop mirror as an ultrafast all-optical demultiplexer,” Elec-

A. Morton, T. Tanbun-Ek, R. A. Logan, and K. W. Wecht, “64 Gbit/s
all-optical demultiplexing with the nonlinear optical-loop mirror,” IEEE

Jianjun Yu was born in Hunan, China, 1968. He received the B.S. degree in op-
tics from Xiangtan University, China, in 1990 and the M.E. and Ph.D. degrees
in optical communications from Beijing University of Posts & Telecommuni-
cations, Beijing, China, in 1996 and 1999, respectively.

In June 1999, he joined Research Center COM, Technical University of Den-
mark as a Postdoctoral Fellow, where he has been engaged in research on high-
speed optical communication systems and networks. Since December 1999, he
has been an Assistant Research Professor.

Xueyan Zheng was born in Hebei, China, in 1969. He received Ph.D. degree
from Beijing University of Posts and Telecommunications, China, in 1998 and
the M.S. degree in optics from Changshun Institute of Optics and Fine Ma-
 churnery, China, in 1995. He received the B.S. degree in physics from Hebei
Normal University, China, in 1992.

Currently, he is an Assistant Research Professor in Research Center COM
at Technical University of Denmark. He has been engaged in wavelength con-
version, regeneration and DWDM transmission system. He is also interested in
WDM network architecture and planning.

Christophe Peucheret was born in Bar-sur-Aube, France, in 1970. He received
the Diplome d’Ingenieur degree from Ecole Nationale Superieure des Telecom-
unications de Bretagne, Brest, France, and the M.Sc. degree in microwaves
and optoelectronics from University College London, U.K., both in 1994.

Since 1997, he has been with the Department of Electromagnetic Systems,
then Research Center COM at the Technical University of Denmark. His current
interests are filtering effects in WDM systems and dispersion management.

Anders Clausen received the M.Sc.E.E from the Technical University of Den-
mark (DTU) in 1997 from the Department of Electromagnetic Systems, now
Research center COM. Since June 1999, he has been pursing the Ph.D. degree
with a project entitled “Experimental and Theoretical Investigations of Systems
with Potential for Terabit Capacity.”

He worked at the Department of Electromagnetic Systems, now Research center COM from 1997 to 1999 as a Research Associate at System Group funded
by the European projects HIGHWAY and REPEAT. His research activities in-
cludes high-speed optical time division multiplexed systems in terms of clock-
recovery (optical and electrical), synchronization, transmission, all-optical re-
generation, and signal-processing.

Henrik N. Poulsen was born in Copenhagen, Denmark. In 1995, he received the M.Sc.E.E degree from the Electromagnetics Institute of Technical
University of Denmark, and is currently working towards the Ph.D. degree at
Research Center COM at the Technical University of Denmark.

His field of interest is high bit rate signal processing in semiconductor
devices; in particular, all-optical techniques for demultiplexing and add-drop
functions and their applications in telecommunication systems based on
combinations of OTDM and WDM.
Palle Jeppesen (M'69) was born in Vordingborg, Denmark, on August 6, 1941. He received the M.Sc., Ph.D., and Dr. Sc. degrees in electrical engineering from Technical University of Denmark, Lyngby, in 1967, 1970, and 1978, respectively.

From 1968 to 1969, he was a Research Associate at Cornell University, Ithaca, NY, and from 1969 to 1970, he was a Project Engineer at Cayuga Associates, Ithaca; at both places he did research in the field of GaAs Gunn effect microwave oscillators. From 1970 to 1998, he was an Assistant, Associate, Research and Full-Professor at EMI, Technical University of Denmark, first in microwave electronics, and since 1974, in optical communications. At EMI, he was Head of Optogroup from 1974 to 1988 and Head of Center for Broadband Telecommunications from 1988 to 1998. From 1982 to 1984, he also worked as a part-time Manager of R&D at NKT Elektronik, now Draka Denmark Optical Cable, Lucent Technologies Denmark and Tellabs Denmark. From 1995 to 1998, he coordinated the participation of Technical University of Denmark in the EU ACTS project METON (METropolitan Optical Network). Since 1999, he has been Professor in optical communications at Research Center COM where he is heading the Systems Competence Area. His current research interests are high-speed WDM optical communication systems; in particular, dispersion maps and WDM devices.