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Citation for published version (APA):

Jansen, S. L., Chayet, H., Granot, E., Ben Ezra, S., Borne, van den, D., Krummrich, P. M., Chen, D., Khoe, G. D., & Waardt, de, H. (2005). Wavelength conversion of a 40-Gb/s NRZ signal across the entire C-band by an asymmetric Sagnac loop. *IEEE Photonics Technology Letters*, 17(10), 2137-2138.
<https://doi.org/10.1109/LPT.2005.854427>

DOI:

[10.1109/LPT.2005.854427](https://doi.org/10.1109/LPT.2005.854427)

Document status and date:

Published: 01/01/2005

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.
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Wavelength Conversion of a 40-Gb/s NRZ Signal Across the Entire C-Band by an Asymmetric Sagnac Loop

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Abstract—A compact integrated all-optical wavelength converter based on an asymmetric Sagnac loop is demonstrated. We show that a 40-Gb/s nonreturn-to-zero data signal can be converted over the entire C-band employing an asymmetric Sagnac loop. Compared to the back-to-back configuration, a receiver sensitivity power penalty of less than 2.1 dB is measured for both up- and down-conversion.

Index Terms—All-optical devices, fiber-optics communications, semiconductor optical amplifiers (SOAs).

I. INTRODUCTION

ALL-OPTICAL wavelength conversion is a key feature for reducing wavelength blocking in wavelength-division-multiplexing all-optical networks. It enhances routing options and enables wavelength reuse [1]. Extensive research has been devoted to various schemes of all-optical wavelength converters; Mach-Zehnder interferometers [2], [3], nonlinear optical loop mirrors [4], periodically poled lithium-niobate (PPLN) [5], and Sagnac loops [6]–[8]. For the nonreturn-to-zero (NRZ) modulation format, only the PPLN has achieved successful conversion at 40 Gb/s [5]. All other devices capable of operating with the NRZ format were limited to a data rate of 10 Gb/s. The asymmetric Sagnac loop wavelength converter with a semiconductor optical amplifier (SOA) is one of the schemes that received significant interest in the last few years [6]–[8]. Originally, the Sagnac loop was proposed for return-to-zero (RZ) modulation [9]. However, recently, the scheme was extended to 10-Gb/s NRZ operation [6].

In this letter we are, to the best of our knowledge, the first to present an asymmetric Sagnac-loop-based wavelength converter for 42.7-Gb/s NRZ signals. We show that the Sagnac loop is capable of converting wavelengths over the entire C-band

Manuscript received April 4, 2005; revised June 22, 2005. This work was supported by the University of Technology Eindhoven, The Netherlands, by Siemens AG, Munich, Germany, by MCI, Richardson, TX, and by KaiLight, Rehovot, Israel.

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Digital Object Identifier 10.1109/LPT.2005.854427

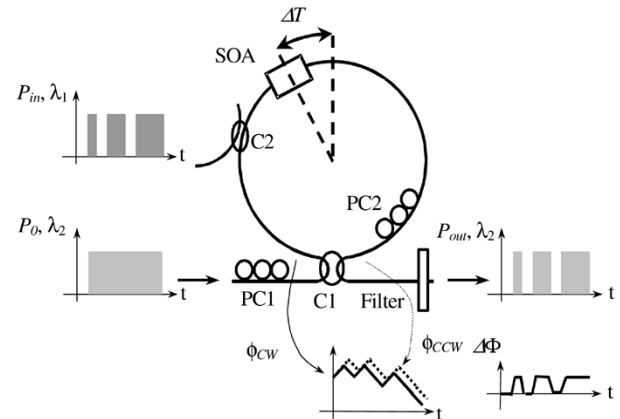


Fig. 1. Sagnac schematic; P_{in} is the input signal at the original wavelength λ_1 , P_0 is the continuous wave signal at wavelength λ_2 . PC1 and PC2 are polarization controllers, and C1 and C2 are optical couplers; ϕ_{CLW} and ϕ_{CCLW} are the phases of the CLW and CCLW propagating signal components, respectively. The spectral bandpass filter is used to block the incoming signal wavelength λ_1 .

with a sensitivity penalty of less than 2.1 dB compared with back-to-back operation.

II. PRINCIPLE OF OPERATION

The Sagnac loop is shown schematically in Fig. 1. The Sagnac loop used in this experiment has an asymmetric configuration; the SOA is moved ΔT from the center of the loop, where ΔT is a propagation time interval. A 50 : 50 coupler (C1) splits the incident signal P_0 into clockwise (CLW) and counter-clockwise (CCLW) propagating components. A data signal is input into the device through the 20% port of a 20 : 80 coupler (C2). Both the CLW and the CCLW components experience cross-gain modulation (XGM) and cross-phase modulation (XPM) inside the SOA. Signal P_0 and the data signal will have, in general, different polarizations. Since the effective refractive index of the transverse-electric and transverse-magnetic modes change differently, they will also experience cross-polarization modulation [10].

As mentioned in the introduction, the Sagnac loop was originally introduced for RZ operation. In RZ operation [9], a pulse rather than a continuous wave is introduced into the Sagnac loop through coupler C1 (Fig. 1). Due to the high peak power of this pulse, the SOA is saturated. The CLW and the CCLW part pass the SOA before and after the data pulse and, therefore, experience a different phase shift. Interference is altered by the nonlinearity of the SOA. For NRZ operation, the original data signal

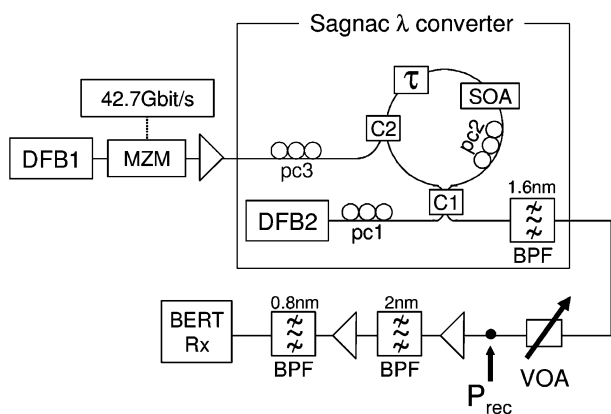


Fig. 2. Experimental setup.

is converted to a continuous wave instead of a pulsed signal. As a result, a faster SOA is required since the pulse shaping finds place inside the Sagnac loop. The XPM-induced phases of CCLW and CLW are shifted in time, as shown in the inset of Fig. 1. Here in addition to the time shift, a constant difference between the φ_{CLW} and the φ_{CCLW} is introduced by the birefringence of the loop. Thus, when the SOA is offset from the center the interference at the output coupler is determined both by XPM and cross-polarization modulation. By adjusting the PC2 and the delay line (ΔT), it is possible to improve the extinction ratio (ER) of the output signal. A more detailed description of this principle and the general operation of the Sagnac loop in combination with the NRZ data format can be found in [7].

III. EXPERIMENTAL SETUP

In Fig. 2, the experimental setup is depicted that was used to measure the performance of the wavelength converter. A distributed feedback (DFB) laser (DFB1) generated a continuous-wave signal at 1552.1 nm. This continuous-wave signal was NRZ modulated with a $2^{31}-1$ pseudorandom binary sequence at 42.7 Gb/s by a Mach-Zehnder modulator. Before the wavelength converter, an erbium-doped fiber amplifier (EDFA) boosted the signal to a power level of 10 dBm. After the EDFA, the signal was inserted in the Sagnac loop. The 700- μm -long SOA used in the Sagnac loop had a response time of approximately 65–75 ps and was operated at an injection current of 220 mA. The gain peak was present at ~ 1540 nm and the saturation power was 9.0 dBm. The saturated and nonsaturated gain was 3 and 27 dB, respectively. A continuous-wave signal at a different wavelength was created by a second DFB laser (DFB2). This signal was inserted into the Sagnac with a power of 9 dBm.

The performance of the wavelength converter was optimized by adjusting the polarization of the inserted continuous-wave signal (PC1) and the polarization within the Sagnac loop (PC2). Another parameter to be set is the delay of the loop (ΔT). The SOA used in this setup had a polarization dependence of about 1 dB, hence, a third polarization controller (PC3) was used to control the polarization of the incoming data channel. With a polarization-independent SOA, this polarization controller will no longer be required. In order to measure the receiver sensitivity of the system, a variable optical attenuator was inserted before the receiver. In the receiver, the signal was amplified by

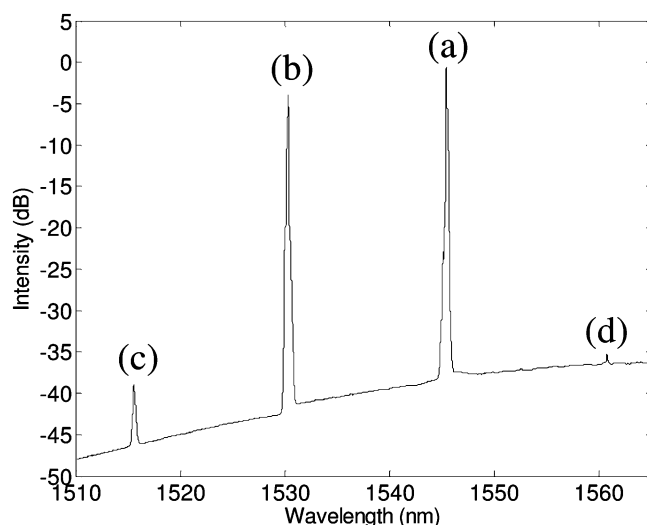
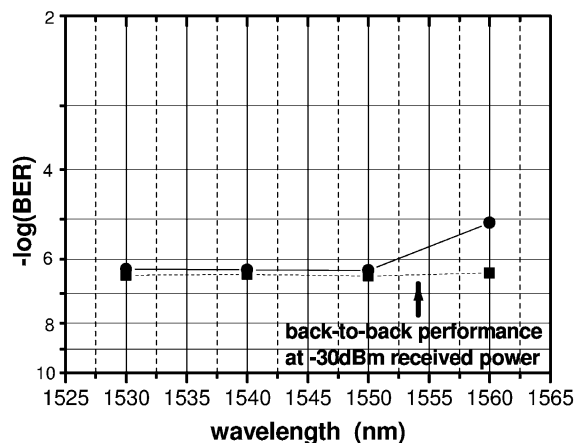


Fig. 3. Optical spectrum after conversion, before the bandpass filter (resolution bandwidth of 0.1 nm).

Fig. 4. BER as a function of the converted wavelength at -30 -dBm optical power at the receiver. The original data signal was present at 1545 nm.

an EDFA and band-limited by a 0.8-nm (full-width at half-maximum) bandpass filter. Finally, the signal was received by a bit-error-rate (BER) tester.

IV. RESULTS

The optical spectrum after conversion, before the 1.6-nm bandpass filter, is depicted in Fig. 3. The original data signal [Fig. 3(a)] can be seen at 1545 nm. The continuous-wave signal [Fig. 3(b)] can be seen at 1530 nm. At 1515 [Fig. 3(c)] and 1560 nm [Fig. 3(d)] small four-wave mixing (FWM) products are present. The FWM products are blocked by the 1.6-nm bandpass filter after the wavelength converter and, hence, do not affect the performance of the conversion.

In this Sagnac structure, the incoming signal with wavelength λ_1 can be converted to any wavelength λ_2 within the C-band as long as the original and converted channels do not overlap. Fig. 4 shows the back-to-back BER performance of the 42.7-Gb/s NRZ signal for wavelength conversion from 1545 nm to wavelengths across the entire C-band.

The received optical power in these measurements was -30 dBm. The back-to-back performance without wave-

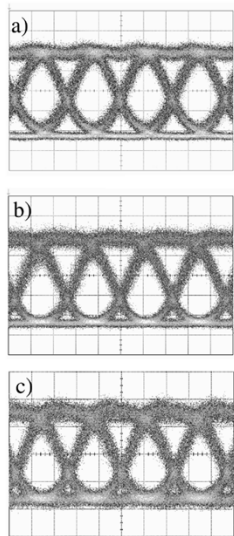


Fig. 5. Eye diagrams of the 40-Gb/s data; (a) without wavelength conversion, (b) with conversion from 1545 to 1540, (c) with conversion from 1545 to 1560.

length conversion (the dashed line) was $\sim 3.5 \times 10^{-7}$. With the Sagnac-based wavelength converter, the BER increased to 4.5×10^{-7} and 8.3×10^{-6} for the best and the worst conversion, respectively. Wavelength conversion from 1530 to 1560 nm and from 1560 to 1530 nm was measured as well. The BER from 1560 to 1530 nm was 4.2×10^{-7} , the BER from 1530 to 1560 nm was 5×10^{-6} .

From Fig. 4, we conclude that the performance of up-conversion, i.e., conversion from lower to higher wavelengths, is worse than the performance of down-conversion. We believe that the performance difference between up-conversion and down-conversion is due to a decreased XGM efficiency for up-conversion. As a result, the extinction ratio of the output signal is lower for up-conversion. This wavelength dependence of the XGM is attributed to the spectral dependence of the differential gain of the SOA, which decreases monotonically with increasing wavelength [11].

In Fig. 5, the eye diagrams of the back-to-back operation, and for the best (from 1545 to 1540 nm) and the worst (from 1545 to 1560 nm) conversion settings are depicted. It can be seen that the eye diagram of the worst conversion is noisier and has a lower extinction ratio than the eye diagram of the best conversion. From both the best wavelength and worst wavelength conversion eye diagrams, it can be concluded that the crossing point between the bits is slightly lowered. However, the "one" level is constant in the eye diagram. A faster SOA could help maintain the level of the crossing point in the middle.

The optical power at the receiver as a function of the BER with and without wavelength conversion is shown in Fig. 6. In this plot, the best (from 1545 to 1540 nm) and the worst (from 1545 to 1560 nm) conversion settings are depicted. For the best wavelength conversion, the receiver power penalty compared to back-to-back is smaller than 0.4 dB. The worst wavelength conversion setting results in a receiver power penalty of less than 2.1 dB. Error-free conversion (BER of lower than 1×10^{-12}) was measured for all wavelength configurations.

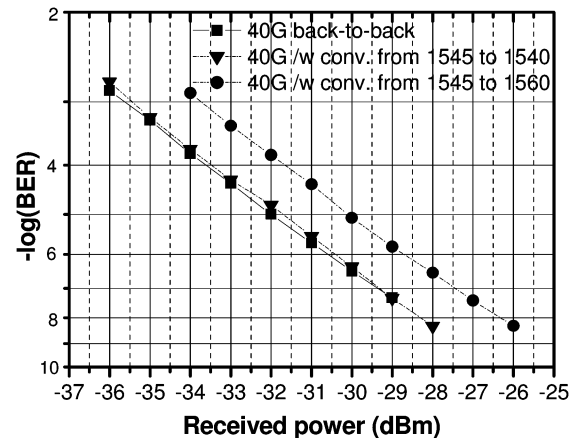


Fig. 6. BER as a function of the optical power at the receiver for the back-to-back 42.7-Gb/s system, with and without optical wavelength conversion.

V. CONCLUSION

We have shown for the first time that a Sagnac loop can be employed for wavelength conversion of a 42.7-Gb/s NRZ signal across the entire C-band. Compared to back-to-back operation, the receiver sensitivity power penalty was less than 2.1 dB for all measured wavelength conversion configurations.

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