# Error-free all-optical wavelength conversion at 160 Gbit/s using a semiconductor optical amplifier and an optical bandpass filter

# Error-Free All-Optical Wavelength Conversion at 160 Gb/s Using a Semiconductor Optical Amplifier and an Optical Bandpass Filter

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*Abstract*—Error-free and pattern-independent wavelength conversion at 160 Gb/s is demonstrated. The wavelength converter utilizes a semiconductor optical amplifier (SOA) with a recovery time greater than 90 ps and an optical bandpass filter (OBF) placed at the amplifier output. This paper shows that an OBF with a central wavelength that is blue shifted compared to the central wavelength of the converted signal shortens the recovery time of the wavelength converter to 3 ps. The wavelength converter is constructed by using commercially available fiber-pigtailed components. It has a simple configuration and allows photonic integration.

*Index Terms*—All-optical switch, nonlinear optics, semiconductor optical amplifier (SOA), ultrafast, wavelength conversion.

## I. INTRODUCTION

ALL-OPTICAL wavelength converters (AOWCs) are considered as important building blocks in wavelength-division-multiplexed networks [1], [2]. AOWCs that utilize nonlinearities in semiconductor optical amplifiers (SOAs) have attracted considerable research interest due to their integration potential and their power efficiency [3], [4]. A number of SOA-based AOWCs have been demonstrated [5]–[7]; however, the slow SOA recovery, determined by the electron–hole recombination time (typically several tens to hundreds of picoseconds), can cause unwanted pattern effects in the converted signal. This sets a limit to the maximum operation speed of the wavelength converter.

Many approaches have been tried to increase the operation speed of SOA-based AOWCs. Some approaches focus on reducing the carrier recovery time of the SOA. It has been shown in [8] that SOAs with a long active region recover faster compared to SOAs with a short active region. The SOA recovery can also be reduced by saturating the SOA using an external holding beam. The holding beam can be either continuous-wave (CW)

light [9]–[11], or modulated light [12]. However, it is difficult to achieve full recovery of the SOA in the order of 10 ps.

Some methods have been proposed to increase the frequency response of an SOA-based AOWC. An increased operation speed has been achieved by employing a fiber Bragg grating (FBG) [13], or a waveguide filter [14]. Wavelength conversion at 100 Gb/s has been demonstrated by using a long SOA (2 mm) in combination with an FBG [7]. In [15], a switch using a differential Mach–Zehnder interferometer with SOAs in both arms has been introduced. The latter configuration allows the creation of a short switching window (several picoseconds), although the SOA in each arm exhibits a slow recovery. A delayed interferometric wavelength converter, in which only one SOA has been implemented, is presented in [6]. The operation speed of this wavelength converter can reach 160 Gb/s [6] and this approach also allows photonic integration [16]. This concept has been analyzed theoretically in [17]. The delayed interferometer also acts as an optical filter. Nielsen and Mørk [18] present a theoretical study that reveals how optical filtering can increase the modulation bandwidth of SOA-based switches.

Optical filtering of chirped wavelength-converted output light of an SOA has been utilized to achieve polarity-preserved wavelength conversion at 40 Gb/s [19]–[21]. It has been shown in [19] that the red-chirped component of the converted output light, filtered by an optical step filter (with a sharp frequency response), can be used to obtain noninverted wavelength conversion. Similarly, Nielsen *et al.* [20] shows that filtering of the blue-chirped part of the converted output pulse can lead to noninverted wavelength conversion. In [21], both the blue- and red-chirped components of the converted signals are filtered by a pulse reformatting optical filter to achieve noninverted wavelength conversion.

In this paper, we show that it is possible to make the wavelength converter fully recover in 3 ps, while the employed SOA has a recovery time greater than 90 ps. Speeding up of the AOWC recovery is realized by placing an optical bandpass filter (OBF) at the SOA output. The central wavelength of the OBF is blue shifted with respect to the wavelength of the converted signal. This concept can be used to achieve error-free and pattern-independent wavelength conversion at a bit rate of 160 Gb/s, with a low power penalty [22]. The signal filtered by the bandpass filter is injected into a delayed interferometer, which is used to convert the inverted signal into a noninverted
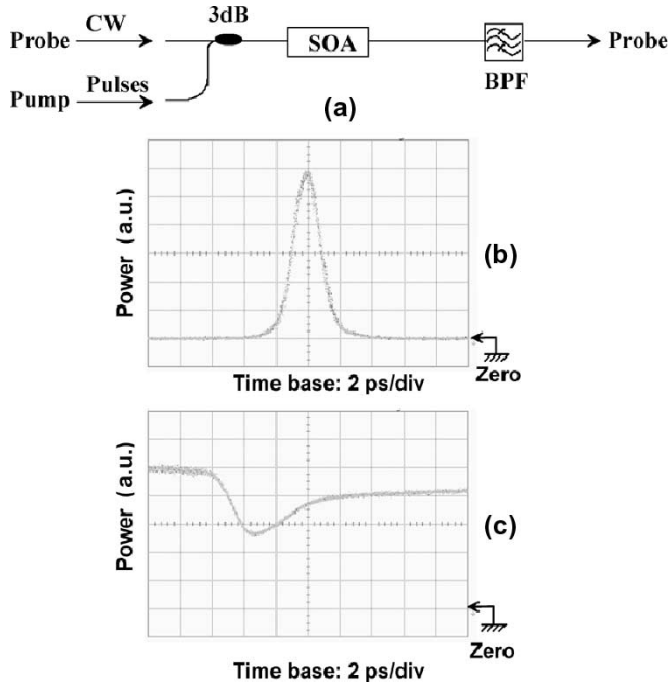
Fig. 1. (a) Setup for testing the SOA gain recovery. (b) Input pump pulse. (c) SOA gain recovery measured by an optical sampling scope. BPF is (optical) bandpass filter.



Fig. 2. SOA gain recovery. Solid line: experimental result. Dashed line: simulation result.

signal. It should be noted that, in contrast to [5] and [6], differential operation in the delayed interferometer is not essential for realizing error-free 160-Gb/s operation, since the input of the delayed interferometer already shows a clear open eye.

This wavelength converter allows high-speed wavelength conversion without using sophisticated custom-made devices such as differentially operated SOA-Mach–Zehnder interferometers. This concept also has the potential to be used in other all-optical switches, such as in optical demultiplexers. We obtained our results using commercially available fiber-pigtailed components. The system is easy to implement since the configuration is very simple. Moreover, the concept allows photonic integration.

The paper is organized as follows. In Section II, the operation principle for ultrafast recovery is explained. Experimental results are presented in Section III. Finally, conclusions are given.

## II. OPERATION PRINCIPLE

A setup for measuring the recovery time of the SOA is depicted in Fig. 1(a). A pulsed pump signal is combined with a CW probe signal, and the signals are simultaneously launched into the SOA. At the output of the SOA, an OBF is used to select the probe light, and to block the pump signal. The probe light that outputs the OBF is monitored by an optical sampling scope (Agilent 86119A) with an optical bandwidth up to 700 GHz. The pulsewidth of pump signal is 2.2 ps, as shown in Fig. 1(b).

We first use the optical sampling scope to measure the SOA recovery if the central wavelength of the OBF is located at the center wavelength. The OBF in this measurement has a 3-dB bandwidth of 10 nm. The experimental result is shown in Fig. 1(c). Fig. 1 summarizes some well-known results. The
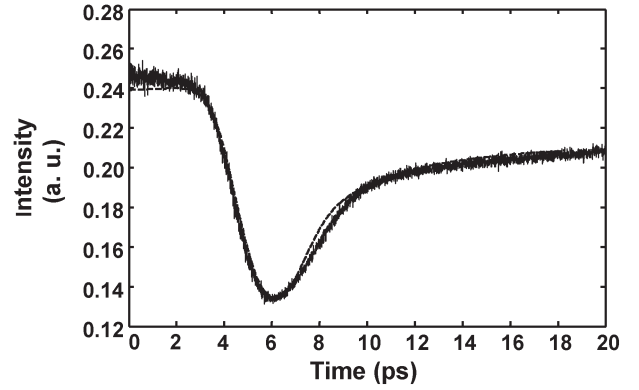
input optical pump pulse causes stimulated emission and leads to a reduced SOA gain. The SOA gain saturation time is determined by the pulse duration; the SOA gain approximately reaches its minimum at the time that the input pump pulse reaches its maximum intensity.

Roughly speaking, the SOA recovers on three different timescales. Ultrafast gain recovery, driven by carrier–carrier scattering takes place at subpicosecond timescales [23]. Furthermore, carrier–phonon interactions contribute to the recovery of the amplifier on a timescale of a few picoseconds [23]. Finally, on a nanosecond timescale, there is a contribution driven by electron–hole interactions. We have utilized a model that accounts for all these effects [24]. A simulation result for the SOA recovery is given by the dashed line in Fig. 2, which shows good agreement with the experimental curve (solid line).

The injected pulses not only modulate the gain of the SOA, but also modulate the refractive index. This results in chirp on the output signal. The leading edges of the (inverted) converted probe pulses are red shifted, whereas the trailing edges are blue shifted [19]–[21]. We also used our model to simulate the chirp on the converted pulse. The simulation result is presented in the lower panel of Fig. 3(a), whereas for reasons of comparison, the gain recovery is shown in the upper panel. A similar result can be found in [21].

If the central wavelength of the OBF is blue shifted with respect to the central wavelength of the probe beam [Fig. 3(b)], the converted signal recovers much faster compared to the case that the central wavelengths of the filter and the probe beam coincide. The operation of the wavelength converter is schematically presented in Fig. 3(c). The dotted and dashed lines in Fig. 3(c) are the SOA gain and chirp, respectively, and also shown in Fig. 3(a). The fast recovery of the wavelength converter can be explained as follows. When the pulse appears at point A, the SOA carriers deplete and the gain drops, reaching its minimum at point B. The SOA gain saturates during timeslot A–B. Furthermore, in timeslot A–B, the wavelength of the probe light moves to a longer wavelength (red chirp) and thus receives more attenuation by the filter. As a result, the transmittance of the probe light through the filter is reduced. At point B, the chirp becomes 0, and the SOA starts to recover. From this point onwards, the wavelength of the probe light is blue shifted, leading to an increased transmittance. If the OBF is
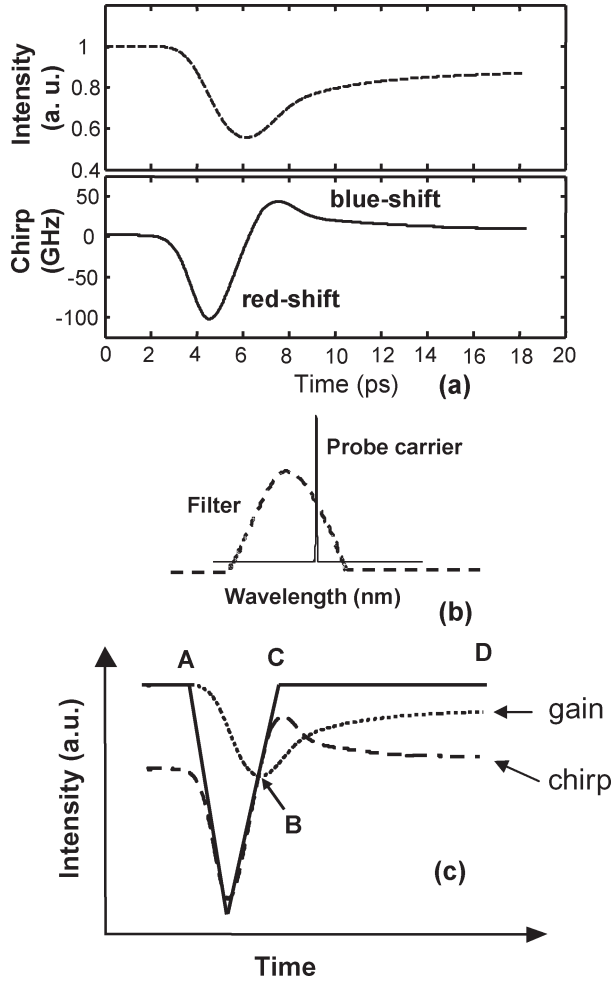
Fig. 3. Operation principle of the wavelength converter. (a) SOA gain (upper panel) and chirp response (lower panel) as a function of time. (b) Schematic of the optical spectrum of the input probe light and the filter characteristic. (c) Transmittance through the OBF as a function of time. The dotted and dashed lines are the SOA gain and chirp, respectively, the same as the curves in (a).

properly selected (the slope of the OBF is especially essential), the enhancement of transmittance due to the blue chirp can compensate the gain saturation. Thus, the transmittance at point C is equal to the transmittance at point A. From points C to D, the wavelength of the probe light slowly moves back to the probe carrier wavelength, leading to a decreased transmittance. However, the SOA gain starts to recover, leading to an increased amplification of the probe light. These two effects take place on the same timescale and cancel each other out. As a result, the net intensity at the filter output is constant. This means that the system effectively recovers much faster than the SOA gain. It should be noted that these effects can be utilized with low-energy optical pulses. In our experiment, the input pump pulse energy was about 60 fJ. We will show that an OBF is sufficient to utilize these ultrafast effects for wavelength conversion at 160 Gb/s.

## III. EXPERIMENT AND RESULTS

The experimental setup for 160-Gb/s wavelength conversion is shown in Fig. 4(a). The setup was constructed by using com-

mercially available fiber-pigtailed components. A 10-Gb/s data stream with 1.9-ps-wide optical pulses, generated by an actively mode-locked fiber ring laser (MLFRL), is modulated by an external modulator at 10 Gb/s to form a $2^7 - 1$ return-to-zero (RZ) pseudorandom binary sequence (PRBS). This 10-Gb/s RZ-PRBS data stream is multiplexed to 160 Gb/s by using a passive fiber-based pulse interleaver. The 160-Gb/s data signal is combined with a CW probe light and fed into an AOWC via a 3-dB coupler. As shown in the dashed box of Fig. 4(a), the AOWC is composed out of an SOA, a 1.4-nm OBF, and a delayed interferometer. The delayed interferometer consists of two polarization controllers (PCs), a polarization maintaining fiber (PMF) with 2-ps differential delay, and a polarization beam splitter (PBS). The operation principle of the delayed interferometer can be found in [5], [6], and [16]. Note that the delayed interferometer allows photonic integration [16]. The SOA in the AOWC is a commercial product from Kamelian and is designed as an optical preamplifier. The SOA is pumped with 250 mA of current. The center wavelengths of the 160-Gb/s data signal and the CW probe beam are at 1549.98 and 1560.77 nm, respectively. The average optical power of the 160-Gb/s data signal is 4.8 and 2.6 mW for CW probe light, measured at the pigtail at the SOA input.

The injected 160-Gb/s data signal modulates the SOA carriers, and thus, the SOA gain. As a result, the CW probe light is modulated via cross-gain modulation, causing inverted wavelength conversion. Moreover, the injected data signal modulates the refractive index of the SOA, resulting in a chirped converted signal. As discussed before, the leading edges of the (inverted) converted probe light are red shifted, whereas the trailing edges are blue shifted. Thus, the spectrum of the probe light at the SOA output is broadened as shown in Fig. 5(a) (measured by an optical spectrum analyzer with 0.02-nm resolution). A 1.4-nm OBF, which is placed at the SOA output, selects the blue-shifted sideband of the probe light. The OBF characteristic is indicated by the dashed line (experimental result) in Fig. 5(a). The center wavelength of the OBF is detuned 1.23 nm to the blue side with respect to the probe carrier wavelength. The insertion loss of the detuned OBF is about 13 dB. Fig. 5(b) shows the optical spectrum of the probe light at the output of the OBF.

The converted probe light is monitored by using the optical sampling scope. Fig. 4(c) shows that an inverted 160-Gb/s signal with a clear open-eye pattern is obtained, which indicates that the wavelength converter recovers in less than 3 ps. This ensures pattern-independent wavelength conversion at 160 Gb/s.

The inverted 160-Gb/s signal is subsequently injected into the delayed interferometer, where the polarity of converted signal is changed, i.e., the inverted signal is changed into a noninverted signal. It is noted that differential operation in the delayed interferometer is not essential for realizing 160-Gb/s operation because the input (inverted) pulses have already been fully recovered within 3 ps.

The transmittance of the delayed interferometer is presented in Fig. 5(c), which shows that the delayed interferometer operates as a "notch" filter. Since the role of the delayed interferometer is to change the polarity of converted signal, we align the wavelength of the notch with the center wavelength
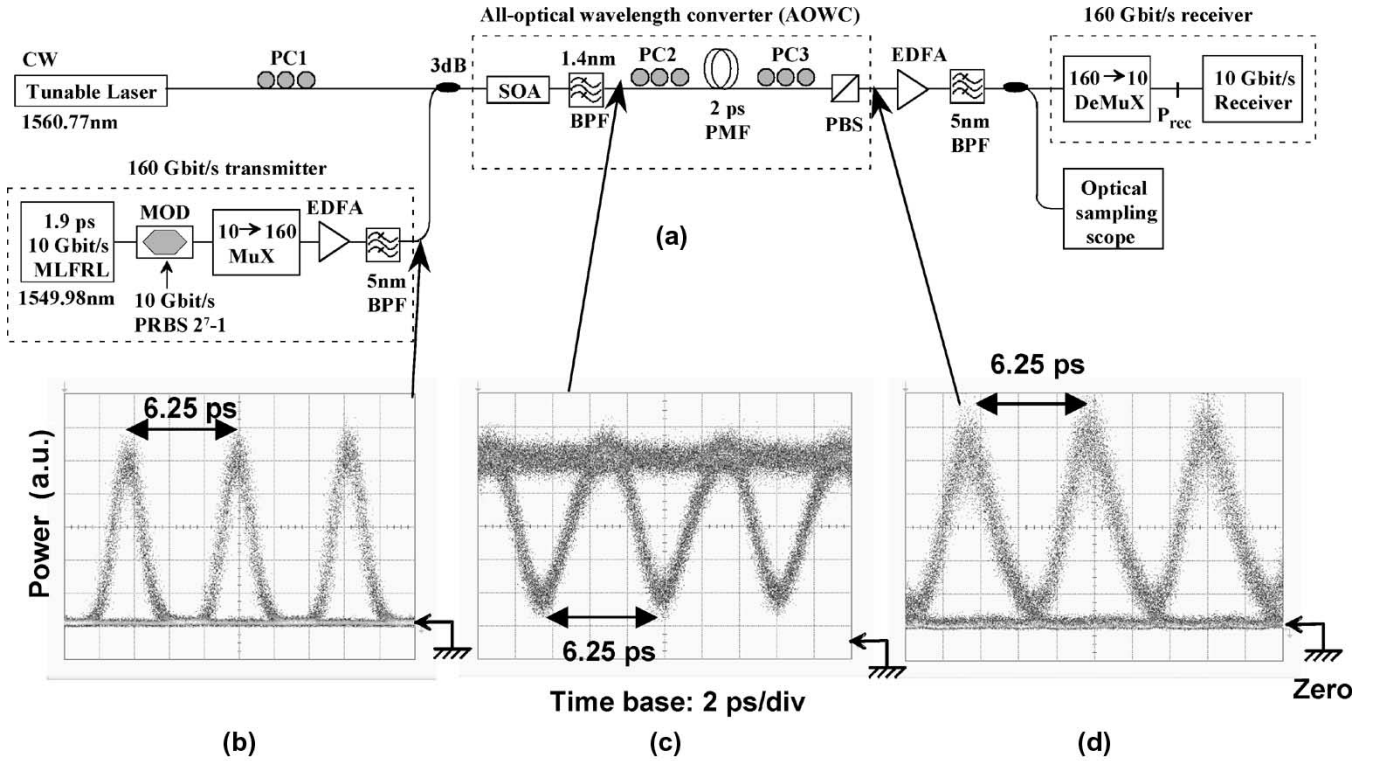
Fig. 4. (a) 160-Gb/s all-optical wavelength-conversion setup. (b) Eye diagram of the 160-Gb/s input pump signal. (c) Eye diagram of the converted light at the output of the bandpass filter. (d) Eye diagram of the converted light at the output of the delayed interferometer. PC: polarization controller; MLFRL: mode-locked fiber ring laser; BPF: (optical) bandpass filter; PBS, polarizing beam splitter; PMF: polarization maintaining fiber; EDFA: erbium-doped fiber amplifier.

of the converted light. This ensures a high attenuation of the dc component corresponding to the "1" level in the inverted signal [see Fig. 4(c)] and a larger transmittance of the "0" level. Hence, the polarity of the signal that outputs the SOA is inverted [Fig. 4(d)]. The optical spectrum at the output of the delayed interferometer is shown in Fig. 5(d).

After wavelength conversion, the converted signal is demultiplexed from 160 to 10 Gb/s by using a gain transparent ultrafast nonlinear interferometer [25]. The demultiplexed 10-Gb/s data signal is fed into a 10-Gb/s receiver and a bit error rate (BER) tester. Fig. 6 shows BER measurements of the 160-Gb/s input signal and the converted signal. All the 16 10-Gb/s tributaries are presented in Fig. 6(a). In addition, the 10-Gb/s basic channels that are multiplexed to the 160-Gb/s data stream is also presented. It can be observed that the average sensitivity penalty for wavelength conversion at a BER = $10^{-9}$ is about 2.5 dB with respect to that of the original 160-Gb/s signal. The input dynamic range is about 6 dB to keep BER values under $10^{-9}$. Moreover, it is visible that no error floor is observed, which indicates excellent performance of the proposed wavelength converter.

The polarization dependence of our 160-Gb/s wavelength conversion has also been investigated. We find that the wavelength converter is polarization insensitive for the optical pump signal because the SOA is polarization independent ($< 0.3$ dB). However, we need to precisely control the polarization of the CW input light. The main reason for this is that our scheme requires exact control of the detuning between the center wavelength of the OBF and the CW carrier frequency. The

OBF used in the experiment has a polarization-dependent transmittance, resulting in a polarization-dependent performance of the system. Thus, this wavelength-conversion concept can, in principle, be made polarization independent if a polarization-independent OBF is used.

It should be noted that the SOA used in the experiment has a recovery time of more than 90 ps. In wavelength conversion based on cross-gain/phase modulation, an SOA with a recovery time of 90 ps allows operation at bit rates less than 40 Gb/s. We have achieved error-free wavelength conversion at 160 Gb/s. Simulations show that operation at higher bit rates is feasible.

As a last point, we discuss the speed of this wavelength converter. Fig. 7 shows a numerical simulation of the SOA gain saturation and chirp if an optical pulse is injected in the SOA. The dashed line shows the result for the case that the pulse had duration of 2.2 ps [full-width at half-maximum (FWHM)] and the solid line represents the case for which the pulse has duration of 1 ps. In the latter case, the peak power is reduced such that the maximum gain saturation introduced by both pulses is almost the same. It is visible that in both cases the SOA recovery has a fast and a slow component. Simulations indicate that the fast component of the recovery is determined by the duration of the pulse, whereas the slow component is determined by the SOA carrier dynamics. This means that for pulses with duration as short as 1 ps, the recovery of the wavelength converter is limited by the pulsewidth and not by the carrier dynamics in the SOA. Simulations also show that if the pulsewidth is decreased further (to about 200 fs), ultimately, the recovery of the wavelength converter is limited by
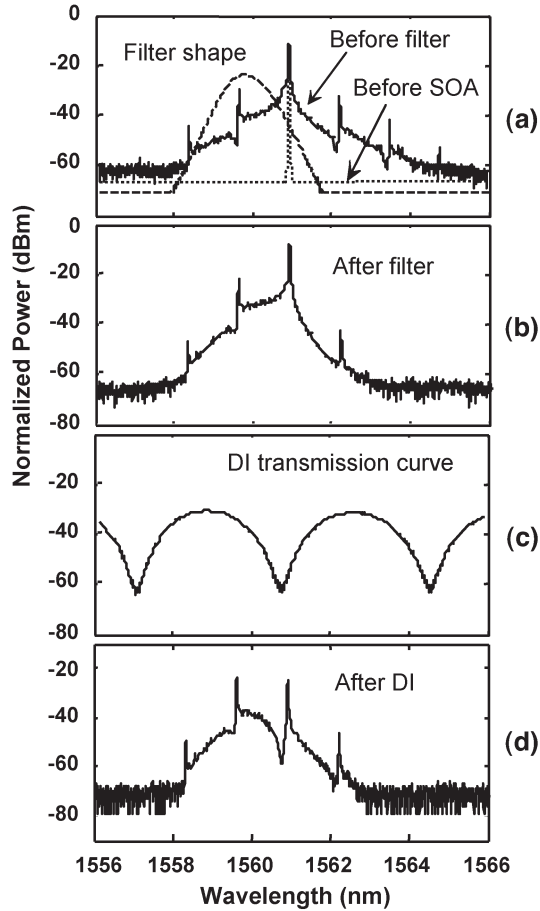
Fig. 5. Optical spectra and the 1.4-nm OBF shape. (a) Optical spectrum of the probe light at the input and output of the SOA; the dashed line shows the shape of the 1.4-nm OBF. (b) Spectrum after filtering the SOA output. (c) Transmission characteristic of the delayed interferometer. DI: delayed interferometer. (d) Spectrum at the output of the delayed interferometer.
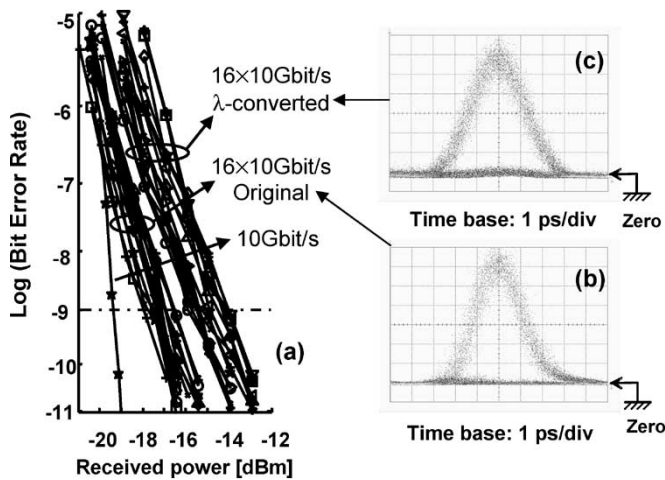


Fig. 6. (a) BER performance of 160-Gb/s wavelength conversion. (b) and (c) Eye diagrams of the demultiplexed 10-Gb/s input and wavelength-converted signal, respectively.

ultrafast carrier dynamics in the SOA (carrier–carrier scattering and carrier–phonon interactions) [22], [23]. These simulations suggest that this approach can be potentially used to achieve wavelength conversion at bit rates higher than 160 Gb/s.
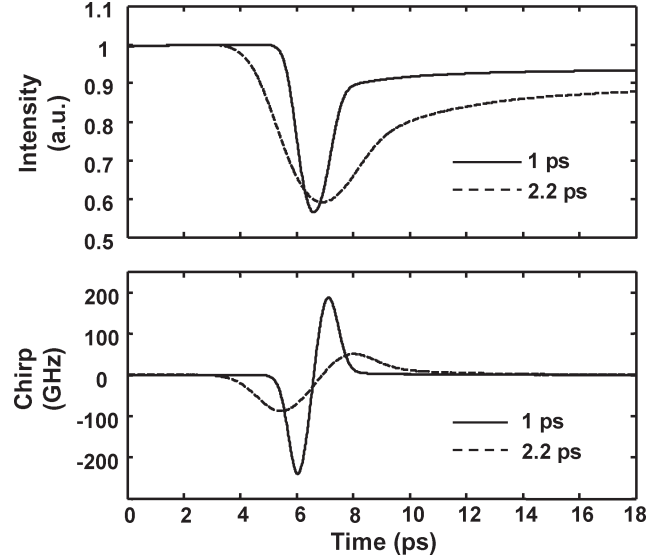


Fig. 7. Simulated gain response (upper panel) and the chirp response (lower panel) of probe light versus time in the case of the input pump pulses with different pulsewidth. Solid line: 1.0-ps pump pulse; dashed line: 2.2-ps pump pulse. Note that all the input pump pulses have the same optical peak power.

## IV. CONCLUSION

We have demonstrated pattern-independent wavelength conversion at 160 Gb/s with a low power penalty by employing an SOA with a gain recovery time greater than 90 ps. The essential point in our approach is to employ an OBF with a center wavelength that is blue shifted with respect to the center wavelength of the probe light. We have explained how detuning of the OBF can be utilized to speed up the recovery time of the wavelength converter. In our approach, the gain recovery of SOA is still very slow, but chirp dynamics in the SOA is very fast. The detuned OBF is used to extract the fast chirp dynamics, which leads to high-speed wavelength conversion. Numerical simulations indicate that by using shorter optical pulses, the response time of the wavelength converter can be further increased. Ultimately, the response time of the wavelength converter is limited by ultrafast carrier dynamics in the SOA, i.e., carrier–carrier interaction and carrier–phonon interactions. In our experiments, the wavelength converter has been demonstrated by using low-power optical pulses and commercially available fiber-pigtailed components. The wavelength converter has a simple configuration and allows photonic integration.

Our approach does not constrain to a specific device. Similar results have been obtained by using other SOAs. However, the performance of the wavelength converter is better if the SOA produces more chirp (this is an SOA with a large linewidth enhancement factor). We observe a similar performance if the wavelength of the probe light is changed. However, it is desirable to use a probe light with a wavelength for which the linewidth enhancement factor is large, which means the probe wavelength is located at the "longer" wavelength side of the SOA bandwidth. In fact, in this wavelength area, the gain saturation is also smaller. Therefore, the required detuning of the OBF is smaller, which leads to a better optical-signal-to-noise ratio (OSNR). However, if the probe wavelength is too

long, the SOA is not capable of producing sufficient gain, which causes a degradation of the OSNR.

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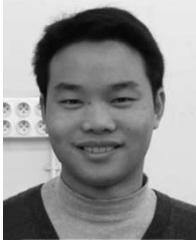
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**G. D. Khoe** (S'71–M'71–SM'85–F'91) was born in Magelang, Indonesia, on July 22, 1946. He received the degree of electrical engineering (*cum laude*) from the Eindhoven University of Technology, Eindhoven, The Netherlands, in 1971.

He began his research career at the Dutch Foundation for Fundamental Research on Matter (FOM) Laboratory on Plasma Physics, Rijnhuizen, The Netherlands. In 1973, he moved to the Philips Research Laboratories in order to research into the area of optical fiber communication systems. In 1983, he was appointed as Part Time Professor at Eindhoven University of Technology, became a Full Professor at the same University in 1994, and is currently Chairman of the Department of Telecommunication Technology and Electromagnetics (TTE). Most of his work has been devoted to single-mode fiber systems and components. Currently, his research programs are centered on ultrafast all-optical signal processing, high-capacity transport systems, and systems in the environment of the users. He has more than 40 U.S. patents and has authored and coauthored more than 100 papers, invited papers, and chapters in books. His professional activities include many conferences, where he has served in technical committees, management committees, and advisory committees as a Member or Chairman. Recently, he was General Cochair of ECOC 2001. He has been involved in journal activities, as Associate Editor, as a Member of the Advisory Board or as Reviewer. In Europe, he is closely involved in Research Programs of the European Community and in Dutch national research programs, as a Participant, Evaluator, Auditor and Program Committee Member. He is one of the Founders of the Dutch COBRA University Research Institute. In 2001, he brought four groups together to start a new international alliance called the European Institute on Telecommunication Technologies (eiTT).

Mr. Khoe is one of the three recipients of the prestigious "Top Research Institute Photonics" grant, which is awarded to COBRA in 1998 by the Netherlands Ministry of Education, Culture and Science. He is the past Junior President of the IEEE Lasers & Electro-Optics Society (LEOS). He has served in the IEEE/LEOS organization as European Representative in the Board of Governors (BoG), VP Finance & Administration, BoG Elected Member, and member of the Executive Committee of the IEEE Benelux Section. He was a founder of the LEOS Benelux Chapter. He received the Micro-Optics Conference/GRadient INdex optical systems (MOC/GRIN) award in 1997.

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