3.8-THz Wavelength Conversion of Picosecond Pulses Using a Semiconductor Delayed-Interference Signal-Wavelength Converter (DISC)

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***Abstract*—A new all-optical semiconductor-band-filling-based wavelength converter, named delayed-interference signal-wavelength converter (DISC), is proposed. Its speed is not restricted by the carrier lifetime and its structure is very simple: it consists of only two essential components, namely, a semiconductor optical amplifier and a passive split-delay. Using this converter, 3.8-THz-shifted (from 1530 to 1560-nm) 14-ps-long pulses are generated from 1530-nm 140-fJ 0.7-ps pulses with high-conversion efficiency.**

***Index Terms*—All-optical, carrier lifetime, conversion efficiency, delay, interference, semiconductor optical amplifier, wavelength conversion.**

I. Introduction

PARTLY due to recent progress in wavelength-division-multiplexing (WDM) devices such as multiwavelength laser sources and tunable narrow-spectrum filters, WDM transmission experiments even at an ultrahigh throughput of 2.6 Tb/s [1], which nearly covers the entire optical bandwidth of Er-doped fiber amplifiers, have reached a realistic level. For cross-connecting such high-speed WDM signal streams, all-optical wavelength converters are attracting a significant amount of attention. To date, cross-phase-modulation (XPM) wavelength converters have shown high-conversion efficiency for both up- and down-conversion [2]. The response speed of this XPM wavelength converter is, however, limited to 10–20 Gb/s due to a carrier lifetime of around 50 ps because the converter mechanism is based on a carrier-induced band-filling effect in the incorporated semiconductor waveguides. Nevertheless, it has already been shown that response of band-filling-based all-optical devices is not necessarily limited by the carrier lifetime. Two examples are the symmetric Mach–Zehnder switch (SMZ) [3], [4] and the teraherz optical asymmetric demultiplexer (TOAD) [5], both proposed in 1993. The SMZ was shown to respond even within 1 ps [6]. This lack of limitation originates from their operating principle: a slow phase decay of one signal component is cancelled with the decay in the other component when those two components combine and interfere at the output. It should be noted that these switches function as wavelength converters in principle, because a control pulse input at λ_1 switches on and off a continuous-wave (CW) light having a different wavelength λ_2; thus there is a $\lambda_1 \rightarrow \lambda_2$ wavelength conversion.

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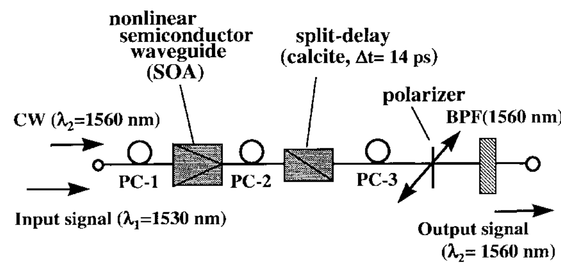

Fig. 1. Schematic view of the delayed-interference signal-wavelength converter (DISC). As the λ_1 input signal, 0.7-ps-long 82-MHz pulses were used. The polarizer and bandpass filter (BPF) are optional, as described in the text. PC: polarization controllers.

In order to do this, the SMZ switch originally required a relatively complicated structure including two nonlinear waveguides in two arms. The SMZ structure was, however, simplified drastically in 1995: the new structure (polarization-descriminating symmetric-Mach–Zehnder; PD–SMZ) includes only one nonlinear waveguide [7], [8]. An input signal in PD–SMZ is split into two orthogonally polarized signal light, they co-propagate through the nonlinear waveguide, then they interfere with each other at the output. The authors noticed, based on the above progress, that the PD–SMZ can be further simplified, specifically for wavelength-conversion.

This letter describes this new wavelength converter, named delayed-interference signal-wavelength converter (DISC). This converter consists of only two essential components: a nonlinear semiconductor waveguide and a passive split-delay. Our results demonstrate that this converter operates with a mechanism exactly the same as the SMZ switch. An ultrafast response for 3.8-THz-shift (30-nm-shift) wavelength conversion at high efficiency, is successfully demonstrated.

Fig. 1 shows a schematic view of the DISC structure. First of all, each λ_1 input pulse signal excites the nonlinear semiconductor waveguide. The carrier density inside the waveguide changes almost instantaneously [6] due to either absorption (in a passive semiconductor waveguide) or stimulated recombination [in a semiconductor optical amplifier (SOA)]. The carrier density change induces a refractive-index change due to the band-filling effect, and gives rise to a transient phase shift at t_0 for the copropagating λ_2 CW input light, as schematically shown in Fig. 2(a). The rise time is determined by the input pulsewidth, while the fall time is determined by the relatively long carrier lifetime. Secondly, the split-delay in Fig. 1 splits the λ_2 CW light into two orthogonally polarized copropagating components having the same amplitude E_1 and gives a delay time Δt between them [Fig. 2(b)]. These two components interfere as

$$\hat{E}_{\text{out}}(t) = \hat{e}_1 E_1 \cdot \exp[i\Psi_f(t)] + \hat{e}_2 E_1 \cdot \exp[i\Psi_s(t)], \quad \hat{e}_1 \perp \hat{e}_2. \tag{1}$$

The polarizer is set 45° off the fast-component polarization ($\hat{e}_1$). Both a 45°-off-polarized component of the $\hat{e}_1$-polarized fast component and that of the $\hat{e}_2$-polarized slow component cross the polarizer. The polarizer output intensity is thus written as

$$\begin{aligned} |\hat{E}_{\text{out}}(t)|^2 &= \left| \frac{1}{\sqrt{2}} E_1 \cdot \exp[i\Psi_f(t)] \right. \\ &\quad \left. + \frac{1}{\sqrt{2}} E_1 \cdot \exp[i\Psi_s(t)] \right|^2 \\ &= 2 \cdot |E_1|^2 \times \cos^2 \left[\frac{\Psi_s(t) - \Psi_f(t)}{2} \right]. \end{aligned} \tag{2}$$

The direction of a quarter-wave plate (in PC-3) is initially determined, so that the 45°-off polarizer blocks the interference component when no λ_1 input pulse excites the SOA. This quarter-wave plate biases the phase difference in (2) to $+\pi$ at $t < t_0$ [Fig. 2(b)]. Once the initial phase difference is thus biased to $+\pi$ at $t < t_0$, the difference remains $+\pi$ at $t > t_0 + \Delta t$ as well [Fig. 2(c)]. It is because carrier-induced phase recoveries of the two components are cancelled with each other, in a manner exactly the same as the SMZ switch. The polarizer output has, therefore, a finite intensity only between t_0 and $t_0 + \Delta t$ [Fig. 2(d)]. As a consequence, each input pulse generates an output pulse. Its pulsewidth is determined by the split-delay, regardless of the relatively long carrier lifetime. In contrast to the previous PD-SMZ switch, only one split-delay realizes the above ultrafast response. It was possible in DISC because two different CW components emitting from a laser source at two separate times (t_0 and $t_0 + \Delta t$) interfere with each other, when the interval Δt is shorter than a coherent time t_c of the laser source of an order of $\Delta\nu^{-1}$ ($\Delta\nu$: laser line width). Typical DFB laser line widths of around 1 MHz suggests their coherent times to be of the order of 1 μs.

In our experiment, a 1.5-μm SOA was used as a nonlinear medium, to reduce the input pulse energy [5]. The SOA has a 240-nm-thick, 360-nm-wide, 400-μm-long, bulk InGaAsP active layer [9], [10]. The small-signal CW gains of the SOA at 1530 and 1560 nm were measured to be +9 and +6 dB @ $I_{op} = 60$ mA, respectively. A 24-mm-long calcite, a birefringent crystal, was used as the split-delay. Its C-axis was set perpendicular to the light-beam direction. For the input signal, 700-fs-long 1530-nm pulses were used. These pulses were prepared by limiting the spectrum width of 130-fs pulses, generated by a 82-MHz LiB_3O_5 optical parametric oscillator system, down to 2.2 nm. A 1560-nm CW input was generated by an external-cavity tunable laser. The linewidth is less than 1 MHz. Both the 1530-nm pulse and 1560-nm CW light were lens-coupled into the SOA, where both polarizations were controlled to be TE-polarized for the SOA by the polarization controller, PC-1. The lens-coupling constant was measured to be 7%. After the SOA, the PC-2 controlled the 1560-nm light polarization to 45° off the calcite's C-axis. Finally, a 0.6-nm-wide 1560-nm-centered bandpass filter was used to eliminate the 1530-nm input from the output.

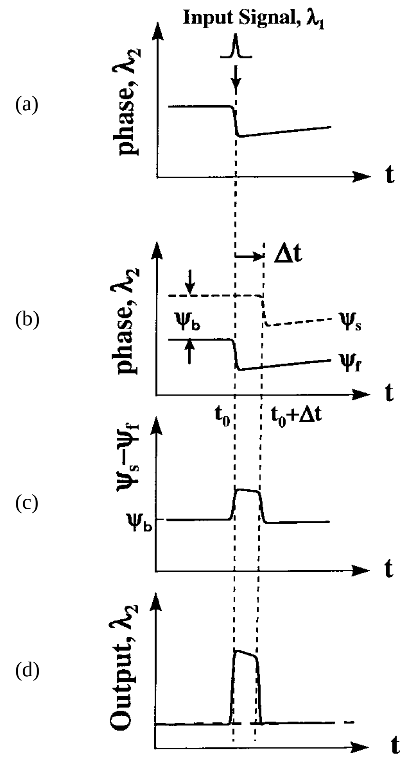

Fig. 2. Wavelength-conversion mechanism. (a) Band-filling-induced transient phase change for the λ_2 CW after the SOA. (b) Time delay between phase changes for the two split components after the split-delay. (c) The time-dependent phase components after $t_0 + \Delta t$ are cancelled with each other. (d) Output intensity.

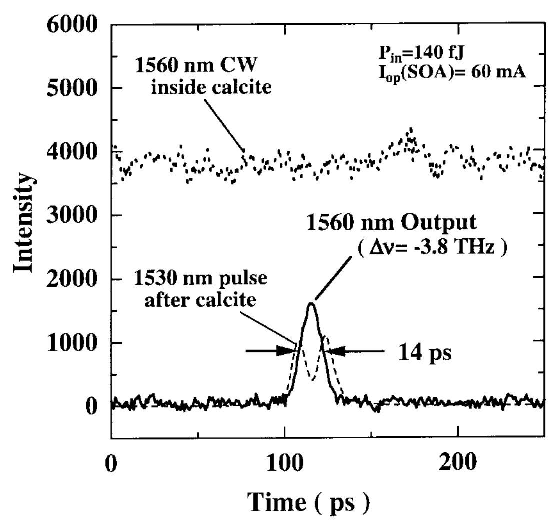

Fig. 3. Streak-camera trace (resolution = 8 ps) for the 1560-nm output (solid line). The output pulsewidth matched the calcite delay time of 14 ps indicated by the dashed line. This pulsewidth was much shorter than the separately measured carrier recovery time of 200 ps in this SOA.

Fig. 3 shows a typical streak-camera (resolution = 8 ps) trace for the 1560-nm output signal, wavelength-converted from the 1530-nm input signal. The input pulse energy was

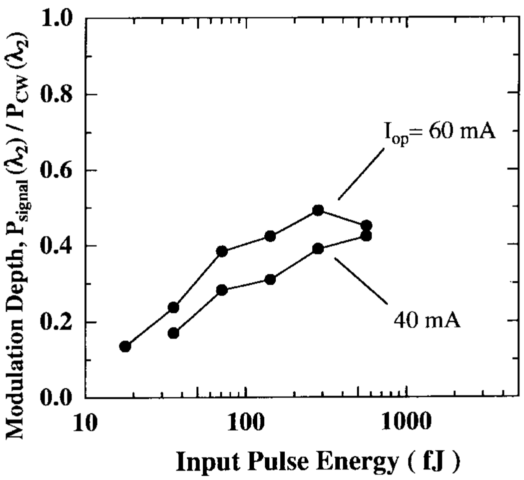

Fig. 4. Modulation depth (ratio of the output pulse intensity to the 1560-nm intensity inside the calcite) as a function of input pulse energy. The saturation originates from pulse-gain saturation in the SOA.

140 fJ. An operating current (Iop) of 60 mA was injected into the SOA. The output pulsewidth was measured to be approximately 14 ps. For comparison, the dashed line shows the trace of a 1530-nm pulse separately detected after the calcite, which consists of components parallel and perpendicular to the calcite C-axis and whose peak distance indicates the delay time given by the calcite. Clearly, the wavelength-converted output pulsewidth matched the delay time. The gain recovery time of this SOA was measured to be 200 ps in a separate experiment. The above output pulsewidth was therefore much shorter than the carrier lifetime. Fig. 3 also shows −10-dB extinction, currently limited by the streak-camera's dark noise, both before t_0 and after $t_0 + \Delta t$.

An apparent conversion loss, namely, the intensity ratio of the 1560-nm output (−32 dBm) to the 1560-nm CW input (−9 dBm) was −23 dB (0.5%). Most of the conversion loss, however, came from our poor lens coupling in the present experiment. The conversion efficiency of the DISC part excluding coupling losses, defined as an intensity ratio of the 1560-nm output signal to the 1560-nm SOA input, was estimated to be +2 dB. This was partly indicated in Fig. 4 by the ratio (modulation depth) of the output pulse peak to the 1560-nm CW intensity inside the calcite (dotted line). The intensity inside the calcite was detected by temporarily rotating the output polarizer by 90° so that the two orthogonal components interfere constructively. The conversion efficiency (+2 dB) corresponds to a sum of the modulation depth in Fig. 3 (−4 dB) and the small-signal gain at 1560 nm (+6 dB). This high-conversion efficiency is an advantage common to interferometric all-optical wavelength converters. Fig. 4 shows the modulation depth as a function of the input pulse energy. The saturation in modulation depth was consistent with a pulse-gain saturation energy of the SOA, which was seperately measured to be 0.5–0.7 pJ. In such a saturation regime, not only the nonlinear phase shift but also the pulse gain saturation contributes to the wavelength conversion. It should be noted here that not only the slow recoveries in phases [Fig. 2(c)] but also those in intensities, of the amplified λ_2 components, are cancelled with each other after $t_0 + \Delta t$ in DISC.

In practical applications, first of all, the output and input pulsewidths can be equalized, by tuning the delay time with respect to the input pulsewidth. It is possible because both of the rise and fall times of the output pulse are determined by the input pulsewidth. Second, the fact that the two optical components experience the same SOA's refractive index before interference should significantly improve operational stability, as compared with wavelength-converters experiencing indices in different SOA's. Third, the calcite split-delay used in this experiment can be replaced by a pair of 50 : 50 fiber couplers (having unbalanced arm lengths) or a planar lightwave circuit. Then, the output polarizer is no longer required. Fourth, the DISC also works in a counterpropagating configuration, where the λ_1 input pulse signal counterpropagates through the SOA (from the right-hand side in Fig. 1). In this case the BPF is no longer required if it is acceptable that the wavelength-conversion response is now limited to an input-pulse's transit time through the SOA (e.g., 4 ps for 400-μm-long SOA).

In summary, a new wavelength converter was proposed. Its structure is the simplest one, to the authors' knowledge, of all ultrafast interferometric devices which are not restricted by the carrier lifetime. A 14-ps-long pulse generation, wavelength-converted from 1530 to 1560 nm, was successfully demonstrated at high-conversion efficiency.

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