frequency will become $f/4$, $f/2$ or f as determined by external light injection. This scheme of optically controlled multistage frequency division greatly enhances the flexibility of the applications in OTDM networks.

Conclusion: All-optical clock frequency division from 10 to 5 GHz has been demonstrated with an FP-LD using the effect of period doubling. The division process can be optically controlled through an adjustment on the relaxation oscillation frequency. A fast switching response within tens of picoseconds has been obtained.

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K.K. Chow and C. Shu (*Department of Electronic Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong*)

E-mail: ctshu@ee.cuhk.edu.hk

H.F. Liu (*Photonics Technology Operation, Intel Corporation, 300 Enzo Drive, San Jose, CA 95138, USA*)

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Continuous 500 GHz pulse train generation by repetition-rate multiplication using arrayed waveguide grating

D.S. Seo, D.E. Leaird, A.M. Weiner, S. Kamei, M. Ishii, A. Sugita and K. Okamoto

The use of a specially designed arrayed waveguide grating as a repetition-rate multiplier is demonstrated for the first time. A continuous 500 GHz pulse train is generated by multiplying the repetition rate of an 11.9 GHz short-pulse source at 1.5 μm by a factor of 42.

Introduction: Ultrafast pulse sources are very attractive for future high capacity optical and millimetre-wave communication systems as well as ultrafast data processing. Passive modelocking with monolithic semiconductor lasers has been explored to generate several hundreds GHz to THz pulse trains [1]. However, a passively modelocked laser has inherent repetition-frequency instability (hence timing jitter) due to the simultaneous excitation of higher-order supermodes by spontaneous emission [2]. An attractive method to generate such high-speed pulses with reasonably good frequency stability is repetition-rate multiplication of a lower-speed but stable and easily manageable pulse source, especially using a fixed passive device. Several multiplication methods based on dispersive fibres [3] or superstructured chirped fibre Bragg gratings [4] have been implemented and showed promising results up to ~100 GHz pulse trains. The latter method requires only a ~1 cm-long fibre, which assures better stability than the former requiring ~1 km of fibre. One drawback of the latter method is that each of the multiplied pulses has a different spectrum from pulse to pulse and has a narrower spectral width than the original input pulse, resulting in pulse broadening. Repetition-rate multiplication can also be achieved by spectral filtering using a Fabry–Perot interferometer with passband spacing equal to a multiple of the input repetition frequency. However, this requires a strictly stable system with almost perfect frequency-matching between the filter and input pulse train, which practically lowers the achievable multiplication factor significantly [5].

Integrated planar lightwave components (PLCs) have been used to obtain considerably higher repetition-rate multiplication factors for ultra-high-speed optical time domain multiplexing experiments, e.g. multiplexing of a 10 Gbit/s source to generate a 640 Gbit/s output [6]. The PLCs used for this repetition-rate multiplication function are usually based on a cascaded 2×2 power splitter/combiner geometry, which is inherently a time-domain delay-line approach. However, PLCs have also seen extensive application for wavelength-division multiplexing (WDM) applications. Arrayed-waveguide grating (AWG) PLCs are a very popular component in WDM for wavelength multiplexing, demultiplexing, and routing [7]. In recent work Leaird *et al.* demonstrated for the first time that upon femtosecond read-out, AWGs can also provide interesting time-domain functionalities, such as generation of isolated bursts of very high repetition-rate pulses [8, 9], which may also contain user-defined intensity substructure [10]. In this Letter, for the first time we report the use of an AWG as a repetition-rate multiplier, producing a 500 GHz continuous pulse train output from an 11.9 GHz repetition-rate short-pulse source.

Our work is important for two principal reasons: (i) this is the first application of this well-known WDM technology for ultra-high-speed time-domain repetition-rate multiplication; and (ii) the AWG approach has the potential to yield a higher repetition-rate multiplication factor than the cascaded 2×2 delay-line approach, as explained below.

Experiment: Fig. 1 shows a schematic diagram of our experiments. An actively modelocked fibre laser followed by a dispersion decreasing fibre soliton compressor producing ~0.4 ps pulses at ~11.9 GHz repetition-rate centred near 1545 nm is used as a pulse source. All fibre links are dispersion compensated using an appropriate combination of singlemode and dispersion compensating fibre. The AWG has 21 guides in the waveguide array, a free spectral range (FSR) of 500 GHz, and has four fibre-pigtailed output channels with ~40 GHz spacing. Fig. 2 shows the measured optical power spectra of the four channels. Each output channel consists of a series of narrow peaks, with a slight spectral shift of ~40 GHz from one channel to the next. The envelope of the spectra follows exactly that of the input pulse, ensuring that the individual output pulses have the same pulse width as the input pulse. The periodic passband structure with 4 nm spacing between peaks reflects the 500 GHz FSR. This FSR corresponds to a 2 ps delay increment per guide, which is equal to the output pulse spacing in the time domain. Each passband has ~20 GHz bandwidth, which passes two or three spectral spikes, corresponding to the individual frequency modes of the 11.9 GHz modelocked laser. Theoretically, the AWG can provide up to 12 different, spectrally resolvable channels with identical pulse bursts and the same spectral envelope.

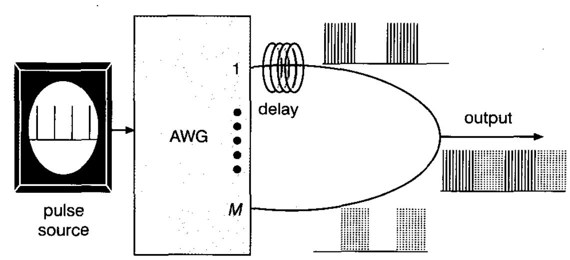

Fig. 1 *Schematic diagram of experimental setup*

The AWG has been modified via loss-engineering so that each output channel produces an approximately equal intensity, 21 pulse, 500 GHz pulse burst repeating at the repetition rate of the input modelocked laser, as described in detail in [9]. In principle, all of the outputs of the AWG should produce pulse trains with identical intensity profiles, as also expected from the optical spectra shown in Fig. 2. This opens up the potential use of all of the output channels, which would reduce insertion loss and increase the overall repetition-rate multiplication factor. To demonstrate this point, here we use two of the output channels. Each output channel produces a 21 pulse, 500 GHz pulse burst covering a time aperture of 42 ps. This is half of the 84 ps period for the 11.9 GHz repetition-rate modelocked laser, corresponding to 50% duty factor. Fig. 3*a* shows the intensity cross-correlation measurements of two output channels with a reference signal split from the compressed modelocked laser output. As expected, nearly flat-topped 500 GHz pulse bursts with a pulse width comparable to that of the input pulse are generated at the source repetition-rate, leading to a 50% duty ratio for the pulse bursts. The other two channels also show very similar traces as predicted. The 21 pulse burst corresponds to one pulse for each guide in the waveguide array of the AWG. As shown schematically in Fig. 1, we combine the two AWG output channels which are given complementary time delays for seamless stitching, resulting in a continuous, 100% duty factor, high repetition rate pulse train. Fig. 3*b* shows the combined output of the two channels demonstrating that a continuous 500 GHz pulse train is generated from a lower repetition-rate source by 42 times of the repetition-rate multiplication. Comparing Figs. 3*a* and *b*, no noticeable change in the flatness of the pulse tops has been induced by the combining process. Note that, if desired, a polarisation multiplexing scheme can be applied to eliminate the 3 dB loss involved in the combining process.

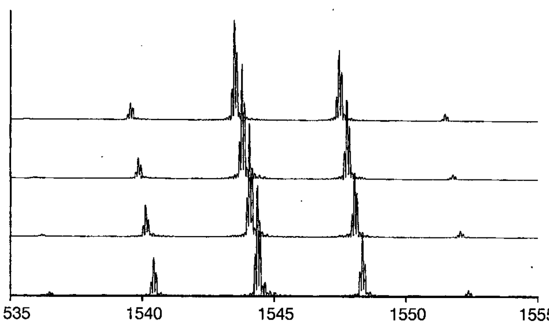

Fig. 2 *Measured optical power spectra of four AWG output channels*

40 GHz spectral shift between adjacent channels and 11.9 GHz mode separation of laser easily observable

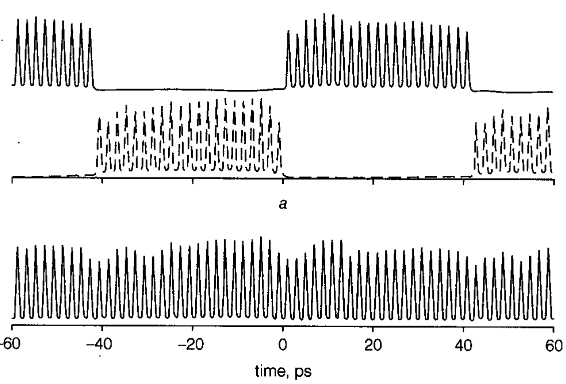

Fig. 3 *Intensity correlation measurements showing 500 GHz continuous waveform generation*

a 500 GHz pulse bursts from two separated channels at 11.9 GHz repetition-rate, leading to 50% duty ratio for the pulse bursts

b Continuous 500 GHz pulse train obtained by combining two complementary channels shown in Fig. 3*a*

Discussion: A cascaded delay-line PLC used for *N*-fold time-domain multiplexing scales the source repetition-rate by *N*. In our experiment, we achieved 2*N*-fold repetition-rate multiplication by using two outputs of an AWG, each of which provided a pulse spacing reduced by a factor of 2*N*, but with a 50% burst duty ratio. In principle, this concept can scale to an *M*-output AWG, with each output providing a pulse spacing reduced by a factor of *MN*, but with $1/M$ burst duty ratio. In this case the overall source repetition-rate after the various outputs are combined would scale as *MN*, which can be substantially larger than the cascaded 2×2 splitter/combiner geometry. In addition, a properly designed AWG can provide spectrally resolvable channels with user-defined intensity modulation within each output pulse burst [10].

Conclusion: We have reported 500 GHz continuous pulse train generation at 1545 nm from an 11.9 GHz repetition-rate short-pulse source by combining two of the output channels of an AWG functioning as a 42 (21×2) times repetition-rate multiplier. This demonstrates a new repetition-rate multiplication functionality for AWGs in addition to their well-known wavelength demultiplexing application.

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D.S. Seo (*School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907-1285, USA*)

E-mail: dseo@purdue.edu

D.E. Leaird and A.M. Weiner (*School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907-1285, USA*)

S. Kamei and M. Ishii (*NTT Photonics Laboratories, Morinosato Wakamiya, Atsugi, Kanagawa Pref., 243-0198, Japan*)

A. Sugita (*NTT Electronics Corporation, Naka-gun, Ibaraki Pref., 311-0122, Japan*)

K. Okamoto (*Okamoto Laboratory Ltd., Higashihara Mito, Ibaraki, 310-0035, Japan*)

D.S. Seo: Also with Department of Electronics, Myongji University, Yongin, Kyonggido, 449-728, Korea

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Gain-clamped semiconductor optical amplifier based on compensating light generated from amplified spontaneous emission

Joon Tae Ahn, Jong Moo Lee and Kyong Hon Kim

A gain-clamped semiconductor optical amplifier (SOA) scheme based on automatic power control of a compensating light generated from amplified spontaneous emission by a reflector is proposed. Experimental demonstrations using an SOA with fibre Bragg grating at the input fibre show the proposed amplifier has a low noise figure as well as good gain clamping characteristics.

Introduction: Because of constant gain characteristics up to some level of input signal power, gain-clamped (GC) semiconductor optical amplifiers (SOAs) have shown enhanced performances as amplifiers and fast space switches for optical communications compared to conventional SOAs [1, 2]. Most GC-SOAs are based on optical feedback using a distributed Bragg reflector (DBR)-type laser cavity [3]. However, due to the lasing-based gain-clamping the DBR GC-SOAs have two drawbacks. One is high noise figure (NF) and the other is frequency dependent amplification and switching characteristics resulting from relaxation oscillation (RO) [4]. A linear optical amplifier (LOA) based on a vertical cavity surface emitting laser is thought to be a good solution for the RO problem [5]. However, somewhat high NF may be inevitable because it is still based on the lasing mechanism.

In this Letter, we propose a GC-SOA scheme based on reflecting amplified spontaneous emission (ASE) into the SOA and experimentally demonstrate the proposed GC-SOA scheme using an SOA with a fibre Bragg grating (FBG) at the input or output fibre. The proposed GC-SOA is expected to be free from the lasing-induced drawbacks since it is not based on the lasing mechanism.

Principle: Figs. 1*a* and *b* show two schematic diagrams of the proposed GC-SOA, input FBG-type and output FBG-type. Consider the input FBG-type. Partial backward ASE out of the SOA is reflected by the FBG, goes back into the SOA, and is amplified while passing through the SOA. The SOA has two input signals, the reflected ASE and the externally applied optical signal to be amplified. Total input power of the two signals determines the characteristics of the proposed GC-SOA. The reflected ASE power is strongly dependent on the applied signal power. It is maximum in the case of no external signal. When the external signal is launched into the SOA, it consumes a part of the amplifier gain, then backward ASE power decreases. As a result, reflected ASE power decreases. Because of this all-optical complementary property between the two signal powers the total input power remains constant automatically up to some input power level of the externally applied signal. Therefore, the amplifier gain can be fixed regardless of the externally applied signal power. The principle of the proposed GC-SOA is similar to the compensation light scheme in [6] for gain clamping in an erbium-doped fibre amplifier except that the intensity control of a compensating light is automatically accomplished not by electronic/optical hybrid method but by all-optical method.

Experiment: The SOA is an Alcatel 1901 SOA. Driving current was fixed at 150 mA during the experiment. Band rejection characteristics of the FBG are 1551.8 nm of centre wavelength chosen around the peak gain wavelength of the SOA, 0.6 nm of flat-top bandwidth, and 35 dB of rejection ratio. Each isolator is used to suppress lasing at wavelengths within the FBG reflection band due to high reflectivity of the FBG.

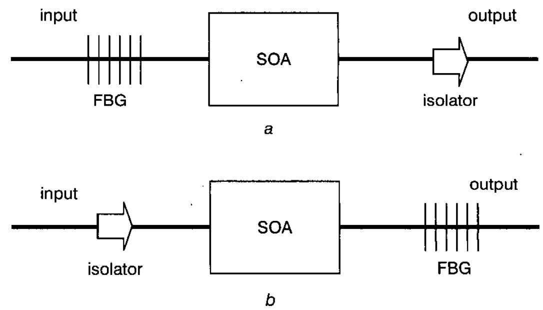

Fig. 1 *Input FBG and output FBG schemes for proposed GC-SOA*
a Input FBG
b Output FBG

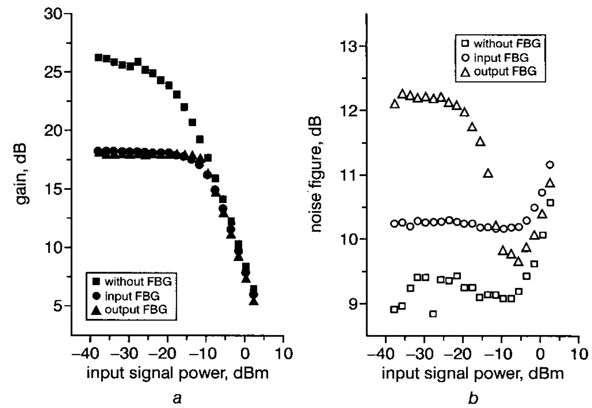

Fig. 2 *Gain and NF of conventional SOA and the two proposed GC-SOAs with respect to input signal power*
a Gain
b NF

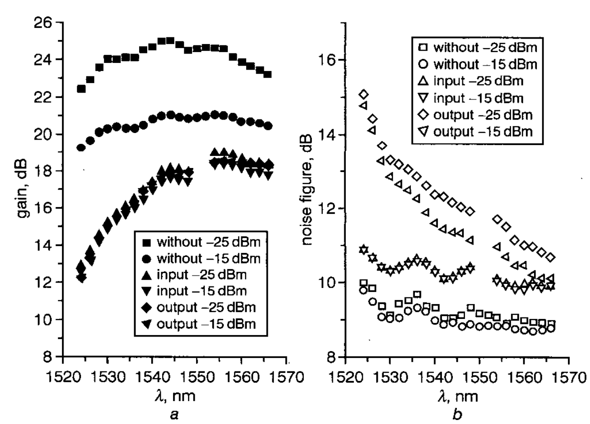

Fig. 3 *Gain and NF of conventional SOA and the two proposed GC-SOAs with respect to input signal wavelength*
a Gain
b NF

Fig. 2 is the measured gain and NF for the conventional SOA (without FBG) and the proposed GC-SOAs (input and output FBG) with respect to input signal power with 1545 nm of wavelength. Gain of the conventional SOA decreases gradually as input signal power increases. Conversely, those of the two proposed GC-SOAs are clamped at about 18 dB till the input signal power increases up to about −11 dBm, then decrease gradually as input signal power increases further. Therefore, the proposed GC-SOA scheme based on the ASE reflector has good gain-clamping characteristics. The NF of the DBR GC-SOA is usually a few dB higher than that of a conventional SOA [2]. Conversely, the input FBG GC-SOA has NF just 1 dB higher than