Double-Passed Arrayed Waveguide Grating for 500-GHz Pulse Burst Generation

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***Abstract*—500-GHz repetition rate pulse bursts on multiple wavelength shifted channels are generated via femtosecond readout of an arrayed waveguide grating (AWG). These bursts are combined onto a single channel by double-passing the AWG, resulting in a substantially increased number of output pulses.**

***Index Terms*—Optical planar waveguides, optical pulse generation, optical pulse shaping, optical waveguide filters, waveguide arrays, wavelength division multiplexing.**

THE arrayed-waveguide grating (AWG) has undergone significant development in recent years with a focus on wavelength-division-multiplexed (WDM) channel multiplexers and demultiplexers [1]. Time-domain application of these devices, in contrast, has seen only limited exploration. For example, modelocked pulse inputs have been spectrally sliced to yield pulses in the tens of picoseconds range at the repetition rate of the modelocked source laser [2], and supercontinuum sources have been sliced to yield multiple optical wavelengths for high-speed systems studies [3]. Recently, we demonstrated a mechanism by which an AWG can be used to generate multiple wavelength shifted, spatially separated bursts of short optical pulses with repetition rates on the order of 1 THz using a single lower repetition rate source laser [4]. Here, we report that these spatially separated high repetition rate bursts may be combined onto a single optical channel, with a variable delay between the bursts, by double-passing the AWG device. Compared to the single-pass configuration, the total number of output pulses is substantially higher. In the experiments reported here, a single femtosecond pulse input into the double-pass AWG produces more than 100 output pulses on a single output fiber in four distinct bursts. These results point to intriguing new possibilities for manipulating ultrafast time-domain signals via mixed time-frequency processing.

Fig. 1 shows a schematic representation of the experimental apparatus. A modelocked erbium fiber laser producing a 40-MHz train of ∼200-fs pulses at 1560 nm is used as the source laser. The laser output is split with a fiber splitter into signal and reference paths, and all fiber links are constructed to be dispersion compensated using an appropriate combination of single mode fiber and dispersion compensating fiber. The signal arm is launched through a circulator into an AWG that has been designed to have a relatively small free spectral range (FSR) of 500 GHz (corresponding to a relatively large delay increment of 2 ps per guide in the waveguide array) and an output channel spacing of 40 GHz. The AWG we used in our experiments was loss-engineered to produce a nearly flat-top burst of pulses on each output [5]. Although a standard AWG could also be used for double-pass operation, the loss engineered device allows us to explicitly demonstrate the difference between single-pass and double-pass temporal profiles. Four outputs of the AWG are fiber coupled, and each of these is directed independently to a free-space section consisting of coupling optics and a retroreflecting mirror on a translation stage (labeled Λ_1 to Λ_4 in Fig. 1).

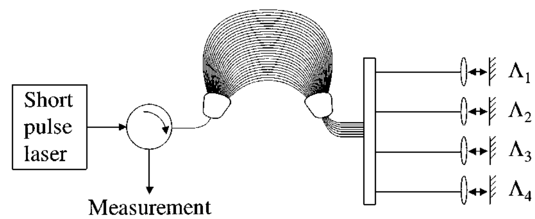

Fig. 1. Experimental apparatus showing four independently variable free-space delay sections.

Before describing the double-pass results, it is important to review the operation of this AWG in single pass. When the FSR of an AWG is less than the bandwidth of the source laser, a multiply peaked output power spectrum is generated on each output. The peaks are separated by the FSR, as shown in Fig. 2(A) for a single selected output. All of the AWG outputs will have similar power spectra—all the same overall shape, but shifted in wavelength from one output to the next by the output channel spacing of the AWG (40 GHz in the current work). The multiply peaked nature of the power spectra implies that the output temporal profile is a burst of pulses with the repetition rate equal to the FSR. Alternatively, one can consider that the input femtosecond pulse is split into a train of pulses—one pulse per guide within the waveguide array. The waveguide array delay increment gives the interpulse separation in the output train. The AWG is loss-engineered in order to control the transmission amplitude for each guide within the waveguide array. Fig. 3(A) shows the measured output temporal intensity profile of a nearly flat-topped

Manuscript received April 30, 2002; revised June 19, 2002. This work was supported in part by the U.S. Army Research Office under Contract DAAD19-00-0497, in part by the National Science Foundation under Contract 0100949-ECS, in part by Intel Corporation, and in part by by sponsors of the Center for Education and Research in Information Assurance and Security.

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Publisher Item Identifier 10.1109/LPT.2002.802395.

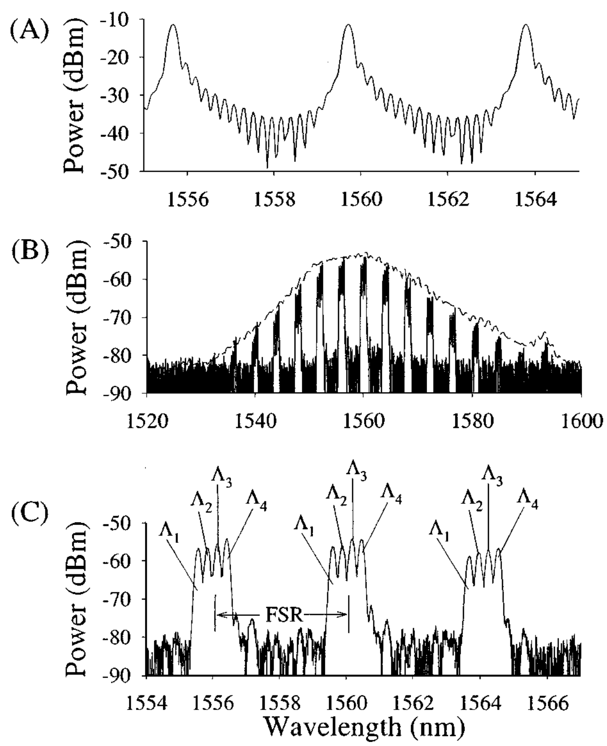

Fig. 2. Experimental power spectra. A) Single passed, loss-engineered AWG. B) Double-passed, loss-engineered AWG (solid), and input laser spectrum (dashed). C) Expanded horizontal scale showing the character of each output passband in the double-passed AWG. Four discrete spectral peaks are evident in each passband labeled Λ_1 to Λ_4 corresponding to the four free-space delay sections.

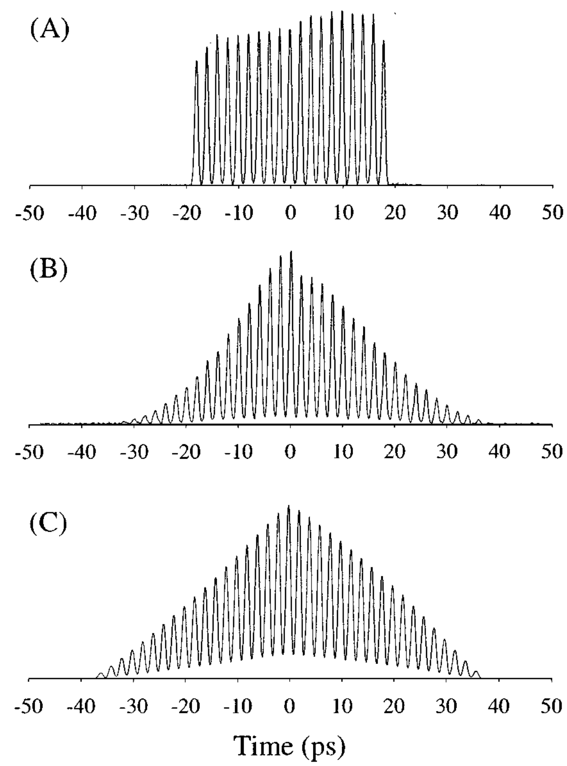

Fig. 3. Output pulse trains. A) Single pass though the AWG. B) Double pass. C) Calculated output train obtained by autoconvolving the single-pass temporal response.

pulse burst generated by a single pass through the loss-engineered AWG. All AWG outputs exhibit identical temporal intensity profiles. Guides in the waveguide array outside the central 19 were eliminated in the mask design, and additional loss was inserted in the central guides to generate the quasi-flat topped output pulse train. The total added insertion loss is ~7 dB.

Let us now explain what is expected by double-passing the device. 1) All of the wavelength-shifted outputs will be recombined back into a single fiber. 2) Each output of the single-pass AWG will contribute a burst of pulses to the recombined channel. 3) Independent control of the delays between bursts is possible by using the free-space delay sections shown in Fig. 1. 4) On a single pass, the one input pulse is split into 19 output pulses. On a double pass, each of these 19 pulses is split again. These pulses add with delays determined by the waveguide array in the AWG—the end result is that the output temporal profile is the autoconvolution of the single-pass temporal response. In principle, recombining all of the single pass wavelength-shifted outputs onto a single fiber could lead to fundamentally lower loss than in single pass pulse sequence generation with the added feature of dramatically increasing the number of pulses in the output pulse train.

Fig. 2 shows the power spectra recorded at the output of the circulator. Fig. 2(B) demonstrates the periodic spectral passbands within the spectra of the source laser similar to that demonstrated in our previous work. Fig. 2(C) expands the wavelength scale to examine the character of each passband in more detail. Each spectral passband, separated by the FSR of the AWG, consists of four discrete spectral peaks, each associated with a specific AWG output with its corresponding free-space delay section. The spectral peaks are labeled Λ_1 to Λ_4 to make the connection to the apparatus schematic shown in Fig. 1.

The temporal profile of the double-passed AWG is recorded by intensity cross correlation of the circulator output with the reference arm directly from the source laser. Fig. 3(A) shows the intensity profile of one output of the AWG in single pass as was recently demonstrated [5]. When this single output is redirected back through the AWG, the temporal profile of Fig. 3(B) is obtained. The envelope of the pulse bursts is roughly triangular, as expected from the autoconvolution of a nearly flat-topped train. Furthermore, the data are in good agreement with the theoretical trace [Fig. 3(C)] calculated by autoconvolving the single-pass data.

In order to demonstrate individual manipulation over each pulse burst, in Fig. 4 we show the output of the double-passed AWG as seen by a 50-GHz detector and oscilloscope. Each of the curves in Fig. 4 show pulse bursts associated with different free-space delay sections. The individual pulses within the bursts occur at a 500-GHz repetition rate (as shown by the cross-correlation traces of Fig. 3) and are not resolved in this measurement. However, the envelopes of the pulse bursts are clearly observable. Fig. 4(A) shows three pulse bursts corresponding to AWG outputs 1, 2, and 4, the free-space section associated with AWG output 3 is blocked. Multiple distinct pulse bursts are evident. In Fig. 4(B), the free-space delay section corresponding to AWG output 4 is moved by ~15 mm, and the output pulse burst corresponding to that output shifts by ~100

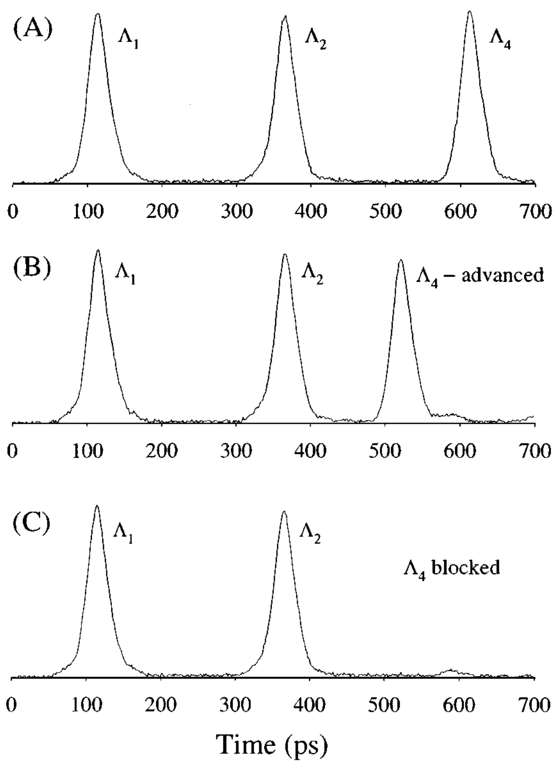

Fig. 4. Pulse train bursts recorded with a 50-GHz detector and oscilloscope. Each burst contains a 500-GHz pulse substructure as on the left. A) Free-space sections 1, 2, and 4 output, 3 blocked. B) free-space section 4 advanced $\sim$100 ps. C) Block free-space section 4.

ps as expected. For Fig. 4(C), free-space section Λ_4 is blocked, and the resultant output with an additional missing pulse burst is shown. These data clearly show the ability to individually manipulate the pulse bursts associated with each AWG output. Further, additional AWG outputs could be utilized, each with its own free-space delay section, to permit the generation of several hundred output pulses.

We comment briefly on the insertion loss. For a standard (not loss engineered) AWG with broadband input, the overall loss as seen by a single output guide is the sum of the basic insertion loss of the AWG at its peak wavelengths (typically a few decibels) and the spectral slicing loss (determined by the ratio of the FSR and the AWG filter bandwidth, $\sim$13 dB in our experiments). The spectral slicing loss can be largely eliminated if all of the wavelength-shifted outputs demultiplexed into separate output guides upon single pass are recombined into a single output fiber upon double pass. For loss-engineered devices, there is an extra single-pass insertion loss, which is incurred twice in double-pass operation. We emphasize, however, that the use of loss-engineered devices is not critical for our double-pass pulse train generation concept.

In summary, we have shown that very high repetition rate pulse bursts can be generated with an increased number of pulses by double-passing a small-FSR AWG. Equivalently, two identical AWGs could be interconnected back-to-back to generate the same functionality in transmission. The output temporal profile is determined by the autoconvolution of the temporal profile of an output channel in a single pass. This scheme shows promise for manipulating ultrafast optical waveforms via hybrid WDM/TDM optical processing. For example, with further engineering of the AWG structure, it may be possible to generate continuous very high repetition rate pulse trains, as would be desired for a repetition-rate multiplication scheme of a lower rate source.

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