Generation of Arbitrary Sequences of Ultrafast Pulses With Integrated-Optic Space-to-Time Optical Processors and Phase-Only Masks

A. Krishnan, L. Grave de Peralta, V. Kuryatkov, H. Temkin, *Fellow, IEEE*, and A. A. Bernussi

***Abstract*—We report a new approach to the generation of arbitrary sequences of ultrafast pulses using an integrated optics space-to-time optical processor. The processor combines a reflective arrayed waveguide grating multiplexer with a phase-only mask containing sets of pixels of constant phase separated by sets of pixels with phases alternating between 0 and π rad.**

***Index Terms*—Optical pulse shaping, planar waveguides, ultrafast optics, waveguide arrays, wavelength-division multiplexing.**

THE GENERATION of arbitrary sequences of femtosecond pulses at very high repetition rates, with its potential for applications in high-speed telecommunications systems, has been a subject of considerable interest in the last few years [1]–[3]. Integrated optics space-to-time optical processors are of particular importance in addressing this problem [3]–[6]. The integrated-optic approach offers advantages, compared to equivalent bulk-optic implementations, of reduced footprint, the absence of assembly and alignment, and the ease of integrating other passive or active components on the same platform. Prior demonstrations of arbitrary sequences of ultrafast pulses using integrated optics space-to-time optical processors relied on arrayed waveguide grating (AWG) multiplexers and amplitude masks, resulting in relatively high losses [5], [6]. In order to overcome this difficulty, we have recently demonstrated an integrated-optic processor based on reflective (R)-AWGs and binary phase masks [7]. However, that approach only allows for the generation of periodic sequences of ultrafast pulses. In order to generate arbitrary sequences of ultrafast pulses using space-to-time optical processor with phase modulation, a new approach is needed.

In this work, we describe for the first time a space-to-time optical processor based on R-AWGs and phase-only masks, used as external reflector, which allows for the generation of arbitrary sequences of ultrafast pulses. The mask consists of linear arrays of corrugated pixels, with sets of constant phase pixels separated by sets of pixels with alternating phases of 0 and π rad. We show that arbitrary sequences of ultrafast pulses, including removal of specific pulses, can be formed by replacing sets of constant phase pixels with sets of pixels with alternating phases. Our experimental results are supported by simulations of the R-AWG response taking into account the phase and intensity values at each waveguide of the grating.

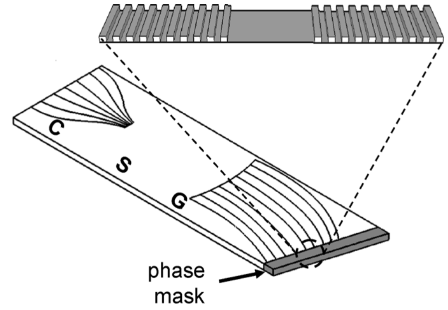

Fig. 1. Schematic of the optical processor with a phase mask used as the external reflector. The inset shows a selected region of the corrugated mask. C, S, and G stand for coupler, slab, and grating, respectively.

A schematic representation of the R-AWG-phase mask apparatus is shown in Fig. 1. R-AWGs used here are 40-channel 100-GHz Gaussian passband response with typical insertion loss of ~3.5 dB [8]. In order to generate arbitrary sequences of ultrafast pulses, an external reflector is placed close to the surface terminating the R-AWG. The reflector, fabricated on a silicon wafer, incorporates a phase mask prepared by conventional photolithography and dry etching. The mask pattern consists of an array of pixels with a fixed height and width of 1.0 mm and 25 μm, respectively. To produce a phase change of π rad, the pixels are etched down ~269 nm. After etching, a thin film of gold is deposited over the entire mask. The pattern was designed to match the number ($N_{\text{wg}} = 330$) and the spatial separation (31 μm) of individual waveguides of the grating, at the surface terminating the R-AWG. The temporal characteristics of the R-AWG output channels were measured using intensity cross-correlation and a passively mode-locked fiber laser generating $\tau_{\text{laser}} = 500$-fs pulses with the repetition rate of 50 MHz, at a center wavelength of 1561 nm (Femtomaster laser from Fianium).

With an ultrafast laser used as the input source, pulses propagating through different waveguides in the grating are reflected back by the patterned mask with modified or preserved phases. In order to obtain arbitrary sequences of pulses, we fabricated masks consisting of periodic groups of N pixels with a constant phase, where N^0 and N^π represent the number of pixels of either 0 or π rad, respectively, separated by a group of pixels (N^π/N^0) with alternating phases of 0 and π rad.

Manuscript received September 21, 2006; revised November 30, 2006. This work was supported in part by the Jack F. Maddox Foundation. The work of L. Grave de Peralta was supported by SBIR-NSF under Grant 0450072.

A. Krishnan, V. Kuryatkov, H. Temkin, and A. A. Bernussi are with the Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, TX 79409 USA (e-mail: ayrton.bernussi@ttu.edu).

L. Grave de Peralta is with Multipass Corporation, Lubbock, TX 79401 USA.

Digital Object Identifier 10.1109/LPT.2006.890046

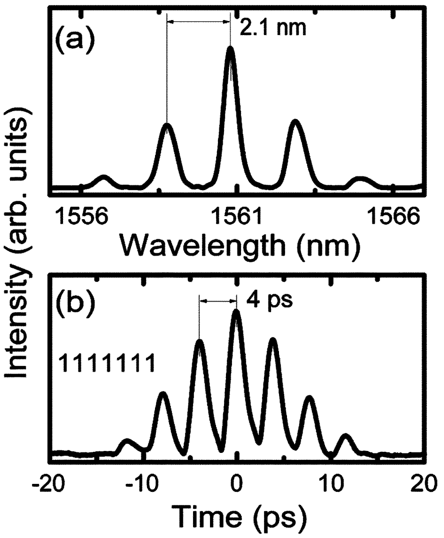

Fig. 2. Measured (a) spectrum and (b) intensity cross-correlation trace obtained with a periodic phase mask $N^0 = 13$ and $N^\pi/N^0 = 19$.

Fig. 2 shows the spectral and the temporal output profiles of a single output channel of an R-AWG using a mask with period $(N^o + N^\pi/N^o) = 32$, where $N^0 = 13$ and $N^\pi/N^0 = 19$. The spectrum Fig. 2(a) consists of peaks located symmetrically, at multiple integers of ~2.1 nm, at both sides of the central peak at ~1561 nm. These peaks are attributed to the effective modification of the free-spectral range (FSR) of the R-AWG from its original design value of ~67 nm [7]. A loss increase of ~6 dB was observed for the main peak in the data shown in Fig. 2(a). This is attributed to a redistribution of intensity among all peaks in the modified spectrum. However, a small difference (<0.2 dB) of the total intensity of the selected channel was observed when a continuous mirror or the patterned masks were used as the external reflectors. The corresponding temporal response Fig. 2(b) consists of a periodic sequence of seven pulses (1111111) with pulse repetition rate within the sequence of ~250 GHz.

The spectral and temporal output characteristics of the optical processor depend on the path-length increment (ΔL) between adjacent waveguides in the grating. R-AWGs used in this work were designed with $\Delta L = 12.3\ \mu$m [8]. This results in waveguide-to-waveguide delay times ($\tau_{\Delta L} \sim 119$ fs) smaller than the temporal width of the input pulse [6]. When a phase mask is used as the external reflector, pulses traversing adjacent waveguides with alternating 0- or π-rad phases overlap and interfere destructively, resulting in intensity minima in the temporal output response. This results in a sequence of pulses shown in Fig. 2(b). The maximum number of pulses in the output sequence is determined by the ratio $N_{\mathrm{wg}}/(N^o + N^\pi/N^o)$. In order to ensure no overlap between consecutive pulses in the sequence Fig. 2(b), the number of pixels with alternating phases were chosen such that $(N^\pi/N^o) > \tau_{\mathrm{laser}}/\tau_{\Delta L}$.

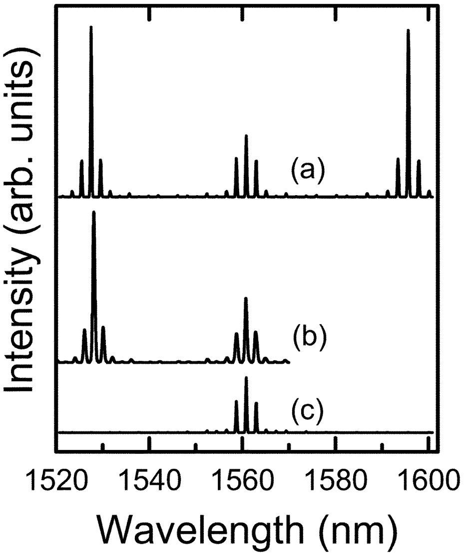

Fig. 3. (a) Simulated and (b) measured spectra from a single channel of the R-AWG using as the external reflector a phase-only mask consisting of $N^0 = 13$ and $N^\pi/N^0 = 19$. (c) Simulated spectrum using an amplitude-only external mask consisting of $N^R = 13$ and $N^T = 19$.

When the grating waveguides of the R-AWG are sampled periodically, the FSR is reduced from its original value $\mathrm{FSR}_o = c/2n_c\Delta L$ to $\mathrm{FSR}_o/(N^0 + N^\pi/N^0)$, where c is the speed of light and n_c is the refractive index of the grating waveguide. When $N^\pi/N^0 = 0$ and $N^0 = 1$, the original FSR is recovered. Thus, the time separation between consecutive pulses in the sequence $(\Delta\tau)$ and the peak wavelength separation $(\Delta\lambda)$ in the spectrum can be calculated as [6], [7]

$$\Delta\tau^{-1} = \mathrm{FSR} = \frac{c\Delta\lambda}{\lambda_o^2} = \frac{c}{2n_c\,(N^0 + N^\pi/N^0)\,\Delta L} \tag{1}$$

where λ_o is the channel center wavelength. Using the R-AWG design parameters, $\Delta\tau = 4.0$ ps and $\Delta\lambda = 2.0$ nm were calculated from (1), in excellent agreement with the data of Fig. 2. The length of the pulse sequence is inversely proportional to the bandwidth of the peak in the spectrum. Using (1) and measured peak bandwidth Fig. 2(a), we calculated a pulse length sequence of ~32 ps in agreement with the result shown in Fig. 2(b).

In order to obtain detailed information about the effect of the periodic phase mask on the output characteristics of the optical processor, we simulated the response of the R-AWG using a single Gaussian approximation and taking into account the phase and intensity values at each waveguide of the grating [8]. The phase information was converted into delay times for the calculation of time-dependent intensity for each output waveguide. The total electric field arriving at the output channel of the device is obtained by summing up the contribution from all waveguides. Fig. 3(a) shows the simulated spectrum of the optical processor using a periodic phase mask with $N^0 = 13$ and $N^\pi/N^0 = 19$. The spectrum consists of three sets of multiple peaks: the maximum of the central set is located at ~1561 nm with the peak-to-peak wavelength separation within the set of 2.0 nm. This result is consistent with the spectrum shown in Fig. 2(a) and (1) and it corresponds to the modification of the FSR of the R-AWG by the external phase mask with a pattern period of $N^0 + N^\pi/N^0 = 32$. The maxima of the other two sets of peaks are located symmetrically at ±33.5 nm from the central maximum (at ~1561 nm). This corresponds to the half of the original FSR of the R-AWG. The peak-to-peak separation of ~2.0 nm within each group corresponds to the regular period of 32 pixels in the mask. The larger spectral separation

(33.5 nm) between the sets of peaks in the phase modulated response spectrum of the R-AWG is attributed to a short period $N^0 + N^\pi = 2$ corresponding to the spatial regions with alternating phases in the patterned mask. This interpretation is supported by the data of Fig. 3(b), where a mask with the same period ($N^0 = 13$ and $N^\pi/N^0 = 19$) was used as the external reflector [see Fig. 2(a)], but the spectrum is now measured over a wider wavelength span. The spectrum consists of two sets of multiple peaks with the signature of each set similar to those measured in Fig. 3(a). The absence of a set of peaks at longer wavelengths in Fig. 3(b) is due to the wavelength span limitations of our experimental setup. In order to confirm that the additional sets of multiple peaks of Fig. 3(a) and (b) are due to phase modulation, we simulated the spectrum of the R-AWG using periodic amplitude-only. The modulation corresponding to groups of $N^R = 13$ consecutive reflecting pixels separated by $N^T = 19$ consecutive transmitting pixels. The amplitude simulated spectrum is shown in Fig. 3(c) and it consists of a single central set of peaks located at $\sim$1561 nm with the peak-to-peak wavelength separation within the set of $\sim$2.0 nm. This confirms that the additional sets of peaks shown in the spectra of Fig. 3(a) and (b) are indeed due to the short period modulation in the patterned phase mask.

Arbitrary sequences of ultrafast pulses could be obtained by replacing sets of pixels with constant phase with sets of pixels with alternating 0- and π-rad phases in the mask. We fabricated different phase masks designed to remove one or several pulses from the output sequence. All masks used a modulated pattern with $N^0 = 13$ and $N^\pi/N^0 = 19$. Fig. 4 shows a series of arbitrary sequences of pulses obtained with different masks. The corresponding simulated pulse sequences are included in the same figure. As can be seen in Fig. 4, symmetric and asymmetric output pulse sequences can be obtained with our approach. Sequences with different number of pulses (ranging from one to seven) in the output channel of the R-AWG device were clearly observed. Pulse-to-pulse extinction ratios of 20 and 5 were determined for the central and outmost pulses of the sequence, respectively [e.g., for the sequence (1110111)]. Simulated spectra are in good agreement with those obtained experimentally. Some deviations between simulated and experimental data, due to phase mask fabrication errors, are expected. Results shown in Fig. 4 demonstrate the effectiveness of the optical processor described here.

In summary, we demonstrate the generation of arbitrary sequences of ultrafast pulses using an optical processor based on R-AWGs and phase-only masks. The mask contains a periodic array of sets of corrugated pixels with constant phase separated by sets of pixels with alternating phases. The phase mask modifies the FSR of the device resulting in the spectrum consisting of sets of multiple peaks at each output channel of the R-AWG. Arbitrary sequences of ultrafast pulses were obtained by substituting sets of pixels with constant phase with sets of pixels with alternating phases. The spectral features are attributed to fast and slow periodic modulation of the phase of light traversing the waveguide grating. Our results were verified by simulations of the R-AWG response that take into account the phase and intensity of light at each waveguide in the grating. Sequences of pulses could be dynamically reconfigured by substituting a fixed mask with a phase-only spatial light modulator.

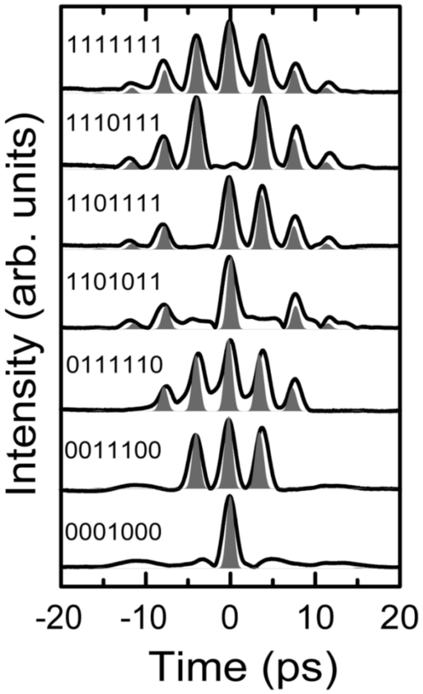

Fig. 4. Measured (lines) and simulated (gray shaded curves) intensity cross-correlation traces obtained with different patterned masks. In all masks, $N^0 = 13$ and $N^\pi/N^0 = 19$ were used.

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