The generation of arbitrary sequences of femtosecond pulses at very high repetition rates is critical to the implementation of optical code division multiple access (O-CDMA) and optically assisted internet routing networks. Among the different approaches that are used to generate fixed or arbitrary output optical waveforms the direct space-to-time (DST) pulse shapers (PSs) are of particular importance. This technique does not require Fourier transform computation of masks, making the DST-PS a suitable approach for applications where the fast response of the pulse shaper is a critical requirement. Integrated-optic versions of the DST-PSs involving specially designed arrayed waveguide gratings (AWG) (de)multiplexers and external fixed masks or conventional AWGs and an external programmable mask were demonstrated recently. Arbitrary sequences of ultrafast pulses demonstrated thus far with the DST-PS approach rely on amplitude modulation. We propose and demonstrate here, to the best of our knowledge for the first time, an integrated-optic version of the DST-PS based on phase modulation.

In this work we investigate the spectral and temporal response of DST-PSs based on the combination of a reflective (R) AWG and a patterned mask used as an external reflector. The mask consists of corrugated reflective pixels with a corrugation depth equal to $\lambda/4$. This approach allows for spatial modulation of the phase of light travelling individual waveguides, or groups of waveguides, in the grating of the AWG. We show that sequences of ultrashort pulses with different repetition rates within the burst can be obtained by varying the period of the pattern in the corrugated mask.

The details of the design and performance of the R-AWGs used in this work were described previously. Our R-AWGs, designed for wavelength division multiplexing (WDM), operate with 40 channels separated from each other by 100 GHz. The AWGs have a Gaussian passband response. High reflectivity is obtained by placing a specially designed external mirror at the surface terminating the R-AWG. Phase modulation at this reflector is accomplished by fabricating a patterned mask with spatial features of different depths. The phase mask is fabricated on a silicon wafer by using conventional optical photolithography. The pattern consists of an array of pixels with variable length and separation with a fixed pixel height of 1.0 mm. To produce a phase change of $\pi$ radians the pixel regions are etched down to $-269 \text{ nm}$. After etching, a thin film of gold is deposited on the entire wafer. With an ultrafast pulsed laser as the input source, pulses propagating through different groups of waveguides in the grating are reflected back to the patterned mask with different phases. Constructive interference at the output channels of the R-AWG occurs only among groups of pulses traveling through the grating with the same phase. Reflection at a corrugated mask results in a modification of the free spectral range (FSR) of the device similar to that observed for an integrated-optic pulse shaper with amplitude masks.

The temporal experiments presented here were performed using a passive mode-locked fiber laser generating 500 fs pulses at the repetition rate of 50 MHz and a center wavelength of 1560 nm (Femto-master laser, Fianium). The temporal characteristics of the R-AWG output were determined using free-space intensity autocorrelation.

Figure 1 shows the spectral and temporal output profiles of a single output channel of a R-AWG with a simple (not corrugated) external mirror and with a periodically corrugated external mirror that produces a phase change of $\pi$ rad for eight consecutive waveguides ($N_{wg}^\pi=8$) and no phase change for the adjacent eight waveguides ($N_{wg}^0=8$) after reflection. The spectrum and the autocorrelation intensity profiles of the input laser are shown as references. Similar spectral and temporal profiles are obtained at other output channels of the same R-AWG. As expected, when a single mirror is used as the external reflector the spectrum [Fig. 1(a)] of a single output channel of the integrated-optic DST-PS is a highly monochromatic peak centered at 1560.6 nm with a 3 dB bandwidth of 0.38 nm. When a corrugated external mirror with $N_{wg}^\pi=8$ and $N_{wg}^0=8$ is used instead, additional trans-
mission peaks are observed at the same output channel of the device. These peaks are located symmetrically at 4.1 nm at both sides from the main peak position. By analogy to the output response of a R-AWG with an amplitude mask used as the external reflector, the additional peaks observed in Fig. 1(a) are attributed to the modification of the FSR of the R-AWG from its original design value of $\frac{\Delta \lambda}{H_{11011}} = 67$ nm.\(^8\)

The temporal response of a single channel of the R-AWG with a single mirror corresponds to a broad, structureless transform-limited output pulse with a pulse width approximately 13.5 times larger than that of the input laser [Fig. 1(b)]. In contrast, when grating waveguides are sampled with a periodic structure of $N_{wg}^\pi + N_{wg}^0 = 8$ and $N_{wg}^\pi = N_{0wg}^0 = 8$ for the same output channel of the device, the intensity autocorrelation trace consists of nine pulses with a pulse-to-pulse separation of 2 ps, an individual pulse width of $\approx 1.2$ ps, and a duty cycle, within the sequence, of approximately 50%.

The spectral and temporal output characteristics of the integrated-optic DST–PS depend on the path-length increment ($\Delta L$) between adjacent waveguides in the grating. In multiplexers designed for WDM applications the $\Delta L$ is quite small, of the order of a few micrometers.\(^8\) This results in corresponding waveguide-to-waveguide delay times that are smaller than the temporal width of the input pulse. When a single mirror is used as the external reflector, pulses returning from each waveguide in the grating overlap, resulting in constructive interference. This produces a single elongated pulse at each output channel of the R-AWG, as observed in Fig. 1(b). When a phase mask is used as the external reflector, pulses traversing consecutive groups of waveguides with different phases also overlap. However, they interfere destructively, resulting in intensity minima in the temporal output response. This results in a sequence of pulses as shown in Fig. 1(b).

The pulse repetition rate and the width of each pulse within the burst can be controlled by varying the period and the width of the pixels in the patterned external mirror, respectively. Figure 2 shows the temporal output response of a single output channel of a R-AWG for patterned mirrors with periods of $N_{wg}^\pi = 8$, 16 and $N_{0wg}^0 = 8, 16$. When the period $N_{wg}^\pi + N_{wg}^0$ is increased from 16 to 32, the pulse separation increases from $\sim 2$ to $\sim 4$ ps, respectively. As can also be observed in Fig. 2, the width of each pulse in the sequence is increased by a factor of $\sim 2$ when the period $N_{wg}^\pi + N_{wg}^0$ is increased from 16 to 32. The number of pulses in the train also depends on the period $N_{wg}^\pi + N_{0wg}^0$. Shorter pattern periods result in a larger number of pulses in the train (Fig. 2). However, the length and the envelope of the output sequence are

Fig. 1. (a) Spectrum and (b) intensity autocorrelation measurements of a single output channel of a R-AWG with a corrugated external mirror with period $N_{wg}^\pi = N_{0wg}^0 = 8$ and with a single external mirror. The spectrum and the intensity autocorrelation of the input laser source are shown as references.

Fig. 2. (a) Spectrum and (b) intensity autocorrelation measurements of a single output channel of a R-AWG with corrugated external mirrors of different periods.
essentially independent of the sampling period. The R-AWGs used in this work are designed for a Gaussian passband output response. Consequently, the electric field intensity distribution in the grating also has a Gaussian profile. This results in a Gaussian output pulse sequence envelope profile (or a single pulse with a single external mirror). The total length of the pulse sequence is related to the inverse of the passband width of the peaks in the output spectra. Peaks with a 3 dB bandwidth of ~60 GHz were measured [Fig. 2(a)]. This results in a pulse sequence length of the order of ~17 ps, in agreement with the results shown in Fig. 2(b).

When the phase of the pulses traversing the grating waveguides is spatially modulated with an external patterned mirror, the time separation between consecutive pulses in the burst and the peak wavelength separation in the spectrum can be calculated with the following expression for the FSR:

\[ \text{FSR} = \Delta \tau^{-1} = \frac{c \Delta \lambda}{\lambda_0} = \frac{c}{2n_c (N_{wg}^\pi + N_{wg}^0) \Delta L}, \]

where \( c \) is the speed of light, \( n_c \) is the refractive index of the grating waveguides, and \( \lambda_0 \) is the central channel wavelength. When \( N_{wg}^0 = 1 \) and \( N_{wg}^\pi = 0 \), Eq. (1) is reduced to the conventional definition of a FSR, with the additional factor of 2 to account for the folded device design. From Eq. (1) we see that \( \Delta \tau \) and \( \Delta \lambda \) are directly and inversely proportional, respectively, to the pattern period \( N_{wg}^\pi + N_{wg}^0 \). We calculate in Eq. (1) that \( \text{FSR} = 5.0 \) (2.5) nm and \( \Delta \tau = 1.9 \) (3.8) ps for pattern periods of 16 (32) waveguides, in excellent agreement with the measured experimental values obtained from Fig. 2.

In summary, we have demonstrated pulse shaping by using a DST-PS that combines a R-AWG designed for WDM applications with an external phase mask. The spatial modulation of the phase was obtained by creating corrugated pixels in the external reflector. Output sequences with a variable pulse width and pulse repetition rate within the burst were obtained by using patterned mirrors with different periods. The intensity minima in the output sequence of the DST-PS were attributed to destructive interference between pulses traversing groups of waveguides in the grating with opposite phases.

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References