

Generation of Ultrafast Pulse Sequences With Arrayed Waveguide Grating Multiplexers Subjected to Modulated External Stress

A. Krishnan, L. Grave de Peralta, H. Temkin, and A. A. Bernussi

Abstract—We demonstrate a novel approach to generation of sequences of ultrafast pulses in which external stress is applied to arrayed waveguide grating multiplexers using a corrugated pattern. Stress applied to the grating region modifies the free spectral range resulting in modulation of the response spectrum with the corresponding sequence of ultrafast pulses at each output channel of the device. The repetition rate, number, and width of the pulses within the sequence are determined by the corrugation length and the period of the pattern.

Index Terms—Optical pulse shaping, planar waveguides, stress, ultrafast optics, wavelength-division multiplexing (WDM).

PULSE shapers based on free-space [1], [2] and integrated optics devices [3]–[8] are of interest in a variety of applications. Integrated optics pulse shapers can be made using stable and cost-effective processing technologies, eliminate the need for complex optical alignment, and can be integrated with other passive or active components to perform multiple tasks. However, integrated optics pulse shapers demonstrated thus far require specially designed devices, nonstandard postprocessing procedures, and external amplitude or phase masks [3]–[8]. In this study, we demonstrate a simple approach to generation of ultrafast pulses with an integrated optics pulse shaper. The proposed method relies on the application of an external stress to the grating of an arrayed waveguide grating (AWG) (de)multiplexer designed for wavelength-division multiplexing (WDM). We demonstrate that pulse sequences with different repetition rates and pulsewidths within the sequence can be readily obtained with this technique.

A schematic representation of the pulse shaper is shown in Fig. 1. Our approach relies on silica-based reflective (R)-AWG (de)multiplexers subjected to modulated external stress. R-AWGs used in this work were designed for WDM applications with 100-GHz channel-to-channel separation and Gaussian passband response. Devices were designed with length increment (ΔL) between consecutive grating waveguides of $12.44 \mu\text{m}$, diffraction order (m) of 23 and separation (d_{wg}) between consecutive waveguides at the reflecting surface terminating the device of $30 \mu\text{m}$. The waveguide dimensions are $5 \mu\text{m}$ high and $6 \mu\text{m}$ wide. High-reflectivity at the reflecting

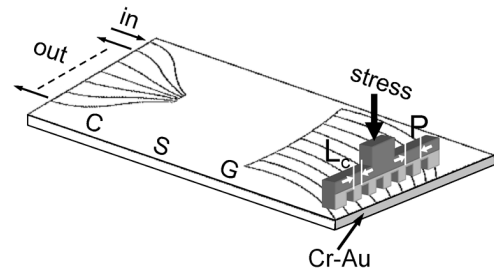


Fig. 1. Schematics of the pulse shaper apparatus that consists of an R-AWG and a corrugated pattern subjected to external stress. *C*, *S*, and *G* stand for coupler, slab, and grating, respectively.

surface of the R-AWG was provided by the deposition of a Cr–Au film. Details of the device performance were described previously [9]. Compressive stress was applied to the grating through a screw-loaded beamlet with a periodic corrugated pattern (see Fig. 1) machined in either stainless steel or sapphire. The beam dimensions were $\sim 12 \text{ mm}$ long, 2 mm wide, and 2 mm high. The depth of the corrugation was about 0.5 mm . We fabricated patterns with different periods (P) and corrugation (teeth) lengths (L_c). The pattern was positioned over the R-AWG grating, close to the reflecting surface terminating the device (Fig. 1). Spectral and temporal output profiles were measured with an optical spectrum analyzer and a free-space intensity autocorrelation apparatus, respectively. Spectral and temporal measurements shown in this work were obtained with a fixed polarization state corresponding to the TE mode of the waveguides. In all temporal experiments presented here, a passive mode-locked fiber laser (Femtomaster laser from Fianium) generating 500-fs pulses at the repetition rate of 50 MHz and the center wavelength at 1560 nm was used as the ultrafast input source.

Spectral and temporal output profiles of a single output channel of the R-AWG with and without stress are shown in Fig. 2. A beamlet with the pattern of $P = 1.3 \text{ mm}$ and $L_c = 0.8 \text{ mm}$ was used in this experiment. The period and the corrugation length of this pattern correspond to 43 and 27 consecutive grating waveguides, respectively. As expected, in the absence of external stress the output spectrum of the R-AWG [Fig. 2(a)] showed a single transmission peak centered (for the selected channel) at 1560.4 nm . When an external stress was applied to the waveguide grating, additional transmission peaks were observed at the same output channel. These peaks were located symmetrically at multiple integers of $\sim 1.6 \text{ nm}$, at both sides of the central peak. A loss increase of $\sim 6 \text{ dB}$ was

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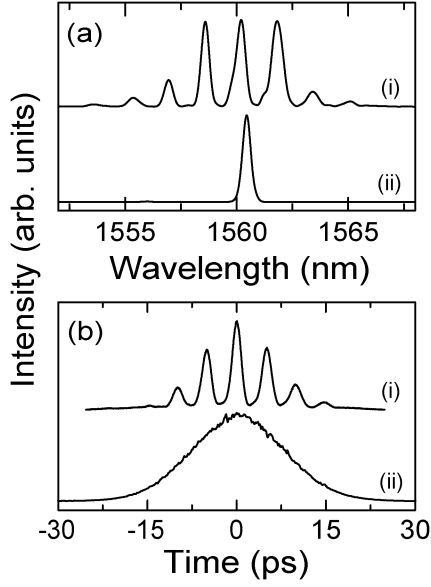


Fig. 2. (a) Spectra and (b) intensity autocorrelation traces obtained from a single output channel of the R-AWG with (i) and without (ii) external stress, using the pattern $P = 1.3$ mm and $L_c = 0.8$ mm.

observed for the main peak in the spectrum shown in Fig. 2(a) when the device was subjected to the external stress. This is attributed to a redistribution of intensity among all peaks in the modified spectrum. However, negligible difference in the integrated intensity of the selected channel was observed with or without external stress application.

The presence of multiple peaks in the response spectrum of a single channel of the R-AWG is attributed to stress-induced modification of the free spectral range (FSR) of the device [10]. Similar results were obtained on other output channels of the device. Our data indicate negligible dependence of the polarization state on the FSR of the device under stress conditions. The multiple peaked spectrum observed in Fig. 2(a) is similar to that obtained with amplitude modulation of light traversing the waveguides in the grating of an R-AWG [10]. With stress applied to the device [Fig. 2(a)], we also observed a 0.2-nm blue shift of the entire response spectrum. This stress-induced shift is attributed to increased birefringence of the device [9]. Indeed, a polarization-dependent wavelength shift of 0.17 nm was measured under stress. In the absence of external stress, the device exhibits very low birefringence with a polarization-dependent wavelength shift of only 0.01 nm [9]. The birefringence (Δn) can be estimated from the polarization-dependent wavelength shift measured under external stress using the expression [11]

$$\Delta n = m \cdot \frac{\Delta \lambda}{2\Delta L}. \quad (1)$$

Without stress, the intrinsic birefringence of our R-AWGs is 9.2×10^{-6} . When the external stress is applied to the device a birefringence value of 1.5×10^{-4} is determined. This corresponds to a stress of ~ 40 MPa applied to the grating waveguides [11].

The stress applied to the grating waveguides was completely reversible. This was verified in a set of experiments (not shown) where the device was subjected to stress cycling. In these experiments, a total of 50 cycles were performed. In each cycle,

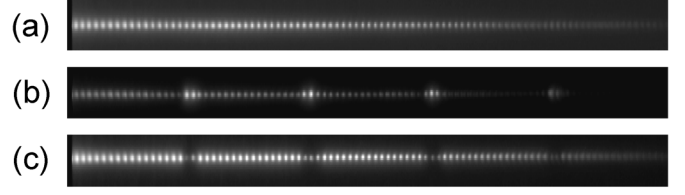


Fig. 3. Near-field images from part of the reflecting surface terminating the device subjected to the stress using the pattern $P = 1.3$ mm and $L_c = 0.8$ mm (a) without the linear polarizer, (b) with the linear polarizer at 0° , and (c) with the linear polarizer at 90° . TE input was used in the polarization measurements.

when the stress was removed, the device insertion loss, center peak wavelength and polarization-dependent wavelength shift resumed their original values.

The temporal response of the device without external stress [Fig. 2(b)], measured at the same selected channel, consists of a single broad pulse. In multiplexers designed for WDM applications, the path length difference between consecutive waveguides in the grating is only $12.44 \mu\text{m}$ [9]. This results in corresponding waveguide-to-waveguide delay times smaller than the temporal width of the input pulse. As a result, pulses traversing adjacent waveguides in the grating overlap at the output channel, giving rise to the broad pulse shown in Fig. 2(a). However, with a periodic external stress applied to the grating waveguides, a pulse sequence with pulse-to-pulse separation of 5.0 ps was observed at the same output channel of the R-AWG.

When the waveguide grating is subjected to a periodic stress, the time separation ($\Delta\tau$) between consecutive pulses within the burst and the peak wavelength separation ($\Delta\lambda$) in the spectrum can be calculated using the expression for the FSR as [10]

$$\text{FSR} = \Delta\tau^{-1} = \frac{c\Delta\lambda}{\lambda_o^2} = \frac{c}{2n_c(P/d_{\text{wg}})\Delta L} \quad (2)$$

where λ_o is the peak wavelength, c is the speed of light in the vacuum, and n_c is the effective refractive index of the waveguide. This equation shows that the time separation between pulses $\Delta\tau$ is directly proportional while the wavelength separation $\Delta\lambda$ is inversely proportional to the number of waveguides within the corrugation period (P/d_{wg}). Measured $\Delta\tau$ and $\Delta\lambda$ for the pattern with period $P = 1.3$ mm (see Fig. 2) are 5.0 ps and 1.6 nm, respectively. Using the nominal parameters for the pattern and the device we calculated $\Delta\lambda = 1.6$ nm and $\Delta\tau = 5.2$ ps, in excellent agreement with measured values.

In order to obtain more complete information about the effect of the external stress on the output response of the R-AWG pulse shaper, we monitored the output intensity of a selected group of waveguides at the reflecting surface terminating the grating. In these experiments, the Au-Cr reflector film was removed by diamond polishing and an infrared-camera-lens-polarizer apparatus was used to monitor the output intensity. A continuous-wave laser centered at 1560 nm was used as the input source. Fig. 3 shows near-field images from a selected region of the reflecting surface terminating the R-AWG under stress induced using a pattern of $P = 1.3$ mm and $L_c = 0.8$ mm. Without the polarizer [Fig. 3(a)], all the waveguides within the selected spatial region contribute to the near-field image. This indicates that the amplitude modulation is not the mechanism responsible for the appearance of multiple peaks in the spectrum and the pulse

sequence observed in Fig. 2. However, when a linear polarizer at 0° polarization state (perpendicular to the waveguides) is inserted between the camera and the device [Fig. 3(b)], periodic intensity modulation is clearly observed. A 90° polarization rotation [Fig. 3(c)] resulted in complementary intensity modulation. The results shown in Fig. 3 confirm that light propagates with different polarizations through groups of waveguides subjected to external stress.

Spectral modulation and the corresponding pulse sequence at the output channel of an AWG can be obtained by periodically sampling the amplitude [6], phase [8] and polarization of light traversing groups of waveguides in the grating. As shown in Fig. 2(a), the external stress produces extrinsic birefringence in the device. Stress-induced changes in the refractive index of the waveguides in the grating result in modifications in the optical path length, and consequently the phase of light traversing these waveguides. In addition, in Fig. 3, we observed that light travels with different polarization states through groups of grating waveguides with and without stress. Constructive interference at each output channel of the R-AWG occurs only between pulses traveling through individual or groups of grating waveguides with the same phase and polarization states. In the absence of external stress, light traversing all waveguides in the grating has the same phase and polarization states and therefore interferes constructively at each output channel of the device. With periodic stress applied to the grating, light traversing groups of waveguides with or without stress experiences different phases and polarizations. Within each group, constructive interference still occurs for light traversing adjacent waveguides. However, light traversing different groups of waveguides with different phases and polarizations produces intensity minima in the temporal output response of the device. This produces a sequence of pulses as shown in Fig. 2(b).

The repetition rate, the number and width of individual pulses within the sequence, can be varied by changing the periodicity of the applied stress. Fig. 4 shows the temporal output response at the same output channel of an R-AWG subjected to an external stresses with similar magnitude but using patterns with different periods and corrugation lengths. When the period was increased from $P = 0.3$ to 3.0 mm, the separation between consecutive pulses within the sequence increased from 1.5 to 10.5 ps, respectively. As shown in Fig. 4, the width of each pulse and the number of pulses in the sequence depend on the number of nonstressed waveguides and inversely on the period of the pattern, respectively.

In summary, we demonstrate a new approach to generation of sequences of ultrafast pulses by applying an external periodic stress to the grating waveguides of R-AWG (de)multiplexers. The modulated stress resulted in phase and polarization changes for light traversing different groups of waveguides. Intensity minima in the output sequence of the device were attributed to pulses traversing distinct groups of waveguides in the grating with different phases and polarization states. For se-

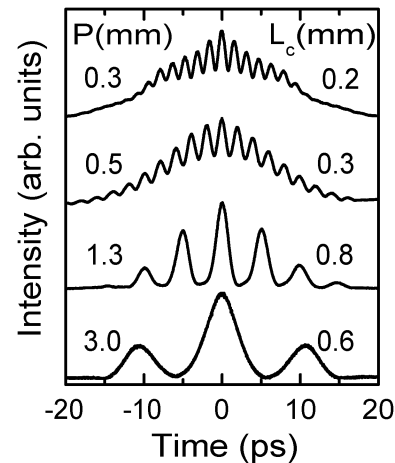


Fig. 4. Intensity autocorrelation traces obtained from a single output channel of an R-AWG subjected to an external stress using patterns with different periods and corrugation lengths.

quences with different repetition rates, the number of pulses and pulsewidths within the sequence were obtained using patterns with different periods and corrugation lengths. We anticipate that this technique can also be applied to conventional unfolded AWG (de)multiplexers.

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