Femtosecond direct space-to-time pulse shaping in an integrated-optic configuration

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Received January 20, 2004

We demonstrate femtosecond operation of an integrated-optic direct space-to-time pulse shaper for which there is a direct mapping (no Fourier transform) between the spatial position of the masking function and the temporal position in the output waveform. The apparatus is used to generate trains of more than 30 pulses as an ultrafast optical data packet over approximately an 80-ps temporal window. © 2004 Optical Society of America

OCIS codes: 320.5540, 130.3120.

Femtosecond pulse shaping[1] has become a frequently used tool in many ultrafast-optics laboratories because of the large range of pulse shapes that can easily be generated with high fidelity by use of that technique. The most commonly utilized configuration is one in which there exists a Fourier-transform relationship between the output temporal profile and the spatial pattern impressed onto the optical spectrum in the apparatus. To achieve any general output pulse shape requires simultaneous control of both spectral amplitude and phase. For applications for which the Fourier-transform relationship is inconvenient or both spectral amplitude and phase control cannot be simultaneously implemented, an alternative geometry, which we call the direct space-to-time (DST) pulse shaper, can be used.[2] This apparatus is particularly well suited to applications in which the desired pulse shape is a pulse packet consisting of a series of discrete pulses separated in time. In this case there is a direct mapping, rather than a Fourier-transform relationship, between the spatial masking elements and the output temporal waveform. The generation of arbitrary millimeter-wave wave forms[3] is an example of one area to which this pulse-shaping technique can be applied.

Although the bulk-optic DST pulse shaper is not significantly more complex to align than the Fourier-transform pulse shaper, an essentially alignment-free, integrated-optic configuration can greatly simplify the implementation of the technique, particularly in the optical communications band near 1550 nm in which integrated-optic devices and techniques are well developed. Although Fourier-transform pulse shaping by use of integrated-optic devices was demonstrated previously,[4,5] our current research is the first demonstration to our knowledge of an integrated-optic DST pulse shaper. In this Letter we demonstrate an integrated-optic implementation of the femtosecond DST pulse shaper based on a modified arrayed waveguide grating (AWG) structure.

The standard AWG structure, shown schematically in Fig. 1(A), is commonly used in optical communications as a wavelength (channel) multiplexer–demultiplexer.[6] The device consists of at least one input guide, an input slab waveguide, an array of waveguides with a constant length difference between adjacent guides, an output slab, and one or more output waveguides. When the input pulse that is used to excite the AWG is shorter than the delay increment per guide in the waveguide array, the AWG can be used to generate bursts of femtosecond pulses on multiple spatially separated, wavelength-shifted

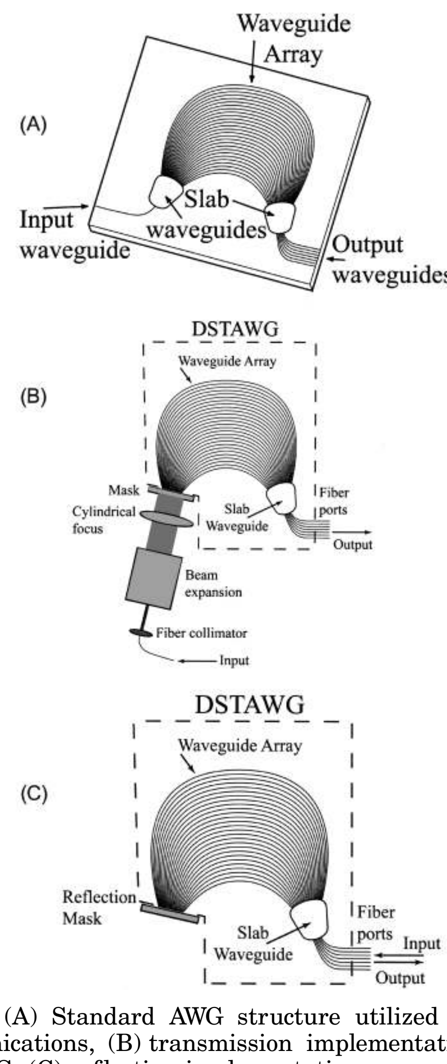

Fig. 1. (A) Standard AWG structure utilized in optical communications, (B) transmission implementation of the DSTAWG, (C) reflection implementation.

output channels, as was shown previously.[7] In this case, each guide within the waveguide array contains a pulse that is temporally separated from its nearest neighbor by the constant delay increment per guide, which is equal to the inverse of the filter's (AWG) free spectral range. The temporal positions of pulses in the output train that arise from the delay increment per guide in the waveguide array can be understood by means of a one-guide, one-pulse design methodology. As an example of this design methodology, the amplitudes of individual pulses within the burst can be controlled by loss engineering to generate a flat-topped output train.[8] Here, for the first time to our knowledge, we extend the one-guide, one-pulse methodology to generate arbitrary pulse packets from a modified AWG structure. One obtains direct access to the waveguide array and hence control of the excitation of each guide in the array by removing one of the slab waveguide sections of a standard AWG and utilizing a spatially patterned mask coupled directly to the waveguide array, as shown in Fig. 1(B). Because of the direct analogy between this device and the bulk-optic DST pulse shaper,[2] we refer to the current device as the DSTAWG.

In Fig. 1(B) the transmission configuration of the DSTAWG is demonstrated.[9] In this arrangement an input femtosecond pulse is cylindrically focused through a spatially patterned mask to directly control the excitation profile of the guides in the waveguide array. The spatially patterned mask consists of sections that are either clear to permit excitation of an individual guide or opaque to block light from entering that guide. Each guide in the waveguide array that is excited, which corresponds to a clear section in the mask, can be identified with a specific pulse in the output temporal profile.

Here we concentrate on an alternative arrangement that uses a reflection geometry, as shown in Fig. 1(C). Here the input femtosecond pulse is focused into one of the single-mode guides, the pulse spatially spreads (laterally) in the slab waveguide section to fill the aperture of the waveguide array exciting a pulse in each of the guides in the array, and the waveguide array delays each of these pulses with respect to its neighbor. A spatially patterned reflection mask is placed at the end of the waveguide array to manipulate the amplitude of each delayed pulse and to reflect the light back through the device. Each pulse experiences additional delay with respect to its neighbor as it double passes the waveguide array. On retraversing the slab waveguide section, light from each guide of the waveguide array combines at the aperture of the single-mode guides in a manner similar to that of a standard AWG structure. As in the previous research on the short-pulse response of AWGs,[7,8] multiple spatially separated outputs with identical temporal intensity profiles are available via the single-mode guides. We changed the details of the output-pulse burst in the research reported here by manipulating the spatially patterned mask at the end of the waveguide array. We anticipate replacing the fixed mask with an optoelectronic modulator array to permit programmable control of the output temporal profile. Both transmission and reflection geometries have output temporal profiles in which each pulse can be identified with a single guide in the waveguide array. However, the reflection geometry simplifies the alignment radically compared with that of the transmission geometry. The difficult and vibration-sensitive large-aspect-ratio cylindrical focusing operation utilized in the transmission geometry is eliminated in the reflection geometry. Further, in reflection, the delay increment per guide is double passed, increasing the temporal window of the output pulse sequence.

We performed an experimental demonstration of the DSTAWG device, using ~75-fs pulses at a 50-MHz repetition rate from a passively mode-locked erbium fiber laser[10] centered at 1575 nm. The output of the fiber laser is split into signal and reference arms, and all fiber paths were constructed to be dispersion compensated with an appropriate combination of single-mode and dispersion-compensating fiber. The reference arm goes directly to a free-space cross correlation apparatus where it is used to measure the temporal profile of the signal arm after going through the DSTAWG device. Figure 2 shows three examples of output pulse shapes obtained from the DSTAWG device in reflection mode. Figure 2(A) shows a periodic pulse train obtained by use of a mask that reflects light from every guide in the waveguide array. The ~1.2-ps spacing between pulses is consistent with the expected ~600-fs delay increment per guide in the waveguide array and with the fact that the array is double passed. The reflection mask is a standard microlithographically patterned chromium mask as used in the semiconductor industry; many different patterns of reflective and clear sections are present on

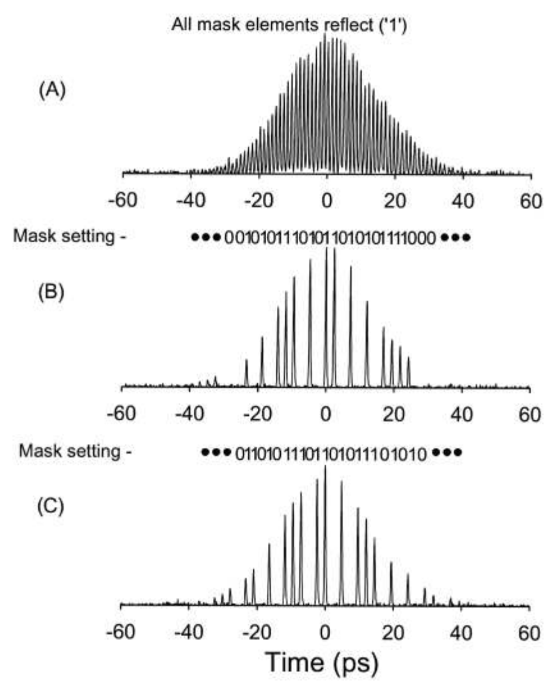

Fig. 2. Output temporal intensity profile of the DSTAWG device measured by cross correlation for (A) periodic and (B), (C) aperiodic—i.e., data packet representation—masking functions.

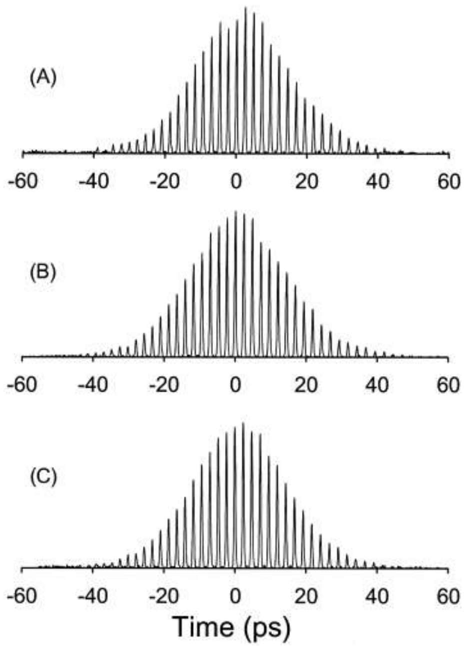

Fig. 3. Temporal intensity profile of output channels (A) 3, (B) 9, and (C) 17 for light input onto channel 10, demonstrating invariant output temporal intensity profiles.

the mask to facilitate demonstration of significantly different pulse patterns. Excellent interpulse extinction is present because the reflection mask is butt coupled to the DSTAWG device with index-matching fluid such that unwanted reflections are essentially eliminated. Figures 2(B) and 2(C) show two additional examples of aperiodic pulse packets intended to simulate a data stream as might be generated when an optoelectronic modulator array is used to control the temporal output pulse sequence programmatically; to clarify the contrast between adjacent pulses, every other guide is utilized to generate the data packet, resulting in a pulse repetition rate that is half that of Fig. 2(A).

Figure 3 shows output temporal profiles obtained from several single-mode guides while the DSTAWG was excited in a central guide (number 10) and the reflection mask was fixed. The DSTAWG has 18 single-mode guides for use as the input–output guides. The output temporal profiles obtained from guides 3, 9, and 17 are displayed in Figs. 3(A), 3(B), and 3(C), respectively, as representatives of the output of the fiber-connected ports. The mask used in this case blocks every other guide, demonstrating a periodic pulse train with twice the pulse spacing of that shown in Fig. 2(A). The invariant temporal profile across the different output guides is identical to the character noted previously[7,8] in short-pulse excitation of AWGs. The ~25-dB measured fiber-to-fiber insertion loss is dominated by the splitting loss incurred by use of only one of the 18 available fiber ports in addition to the ~3-dB loss that is expected when a broadband excitation source is used.

In summary, we have demonstrated, for the first time to our knowledge, an integrated-optic implementation of a direct space-to-time pulse shaper. This planar light wave circuit configuration not only simplifies alignment and considerably decreases the apparatus's footprint but has the potential to be directly integrated with an optoelectronic modulator array to permit programmable configuration of the output temporal profile. Such an apparatus, with a full high-speed modulator array, could serve as a high-speed parallel electrical-to-ultrafast serial optical conversion apparatus.

This material is based on research supported by, or in part by, the U.S. Army Research Office under contract DAAD19-00-0497 and by the National Science Foundation under contract 0100949-ECS; the DSTAWG device was obtained with funding from the Defense Advanced Research Projects Agency and the National Science Foundation through the Joint Optoelectronics Project administered by the Optoelectronics Industry Development Association. D. E. Leaird's e-mail address is leaird@purdue.edu.

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