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Abstract: High repetition rate WDM pulse burst generation from a single lower rate femtosecond source laser is demonstrated with both a bulk optics direct space-to-time pulse shaper, and an integrated arrayed waveguide grating (AWG). The critical AWG design parameters, free spectral range and path length difference between adjacent guides, are discussed.

OCIS codes: (130.3120) Integrated optics devices; (320.5540) Pulse shaping

High repetition rate pulse sources are a critical component in current and future optical networks. One attractive methodology is to use lower rate short pulse sources to generate higher repetition rate pulse bursts and/or trains. For example, previous work has been demonstrated in the use of tapped delay lines [1], filtering of supercontinuum with arrayed waveguide gratings (AWG) [2], and spectral slicing [3]. In our current work, we demonstrate a new scheme utilizing an AWG to generate a high repetition rate burst of short pulses, or in principle a continuous train, at multiple, spatially separated, output wavelengths from a single lower rep rate femtosecond pulse source. The key design parameters of the AWG for this application will be explored, and experimental verification of the design premises will be presented. The AWG will be shown to be analogous to the direct space-to-time (DST) pulse shaper previously demonstrated only in bulk optics [4-6].

Fig. 1 shows schematic diagrams of both the bulk optics DST, and the AWG. For a complete description of the space-time mapping of the DST pulse shaper, refer to [5]. For this bulk optics configuration, the end result is that the field just before the slit is given by

$$e_2(x,t) \propto \int d\omega \;\; E_{in}(\omega)\, S\left(\frac{x}{\beta\lambda f} - \gamma\omega\right) \;\exp\left(j\omega t\right) \tag{1}$$

This equation assumes that the separations between the pulse shaping lens and grating, and the pulse shaping lens and output slit are both equal to the focal length of the pulse shaping lens, f. S(k) is the spatial Fourier transform of the one-dimensional spatial pattern s(x) present just before the diffraction grating, $\gamma = \lambda/[c\ d\cos(\theta_d)]$ is the spatial dispersion of the diffraction grating, λ is the center wavelength of the input spectrum, c and d are the speed of light and the period of the diffraction grating (1800^{-1} mm) respectively, and the $\beta = \cos\theta_i / \cos\theta_d$ term [7] arises from the beam size change upon diffraction from the grating. $\theta_d \cong 53°$ and $\theta_i \cong 47°$ are the diffraction and incident angles respectively. The thin output slit samples the spatially dispersed frequency components, for example around $x = x_s$. For a sufficiently thin slit the output field $e_{out}(t)$ is given by the input pulse $e_{in}(t)$ convolved with a scaled representation of the spatial profile at the grating:

$$\begin{aligned} e_{out}(t) &\propto \int d\omega\; S\left(\frac{2\pi x}{\beta\lambda f} - \frac{\gamma\omega}{\beta}\right) E_{in}(\omega)\; \delta\left(x - x_s\right)\; \exp\left(j\omega t\right) \\ &\propto\; e_{in}(t) \;*\; \left\{ s\left(\frac{-\beta\, t}{\gamma}\right) \exp\left[\frac{j\, 2\pi x_s}{\gamma\lambda f}\; t\right]\right\} \end{aligned} \tag{2}$$

For example, if the spatial profile of the at the diffraction grating is given by a Gaussian input beam multiplied by a periodic spatial masking function, then the output is a high repetition rate pulse train under a Gaussian envelope. The shift term, $\exp\left[\frac{j\,2\pi x_s}{\gamma\lambda f}\,t\right]$, results in a change in output center wavelength as the output slit is translated transversely across the output plane. Equivalently, a multiple element output slit can be utilized so that multiple spatially separated outputs with varying center wavelengths but identical temporal intensity profiles will be generated.

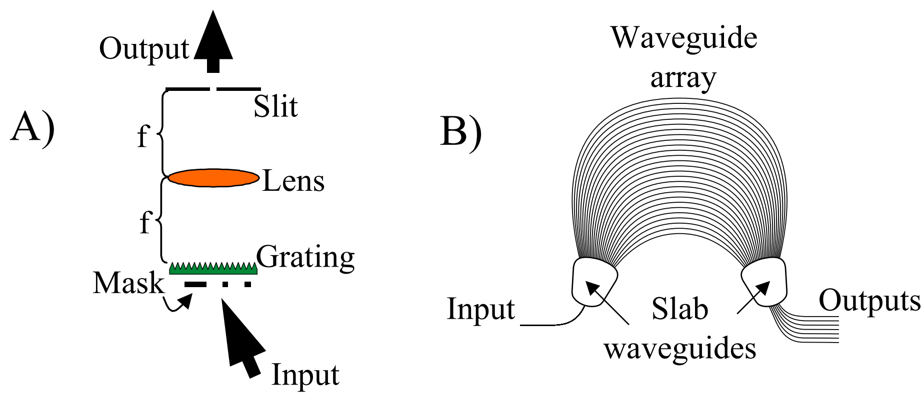

Fig. 1. Schematic diagrams of the bulk optics DST pulse shaper (A), and the integrated AWG (B).

In the integrated AWG shown in Fig. 1B, the waveguide array is equivalent to a curved diffraction grating, analogous to the grating/lens combination of the DST, and the output waveguides of the AWG are analogous to a multiple element output slit in the DST pulse shaper. The spatially modulated field pattern at the output of the waveguide array section is equivalent to a periodically modulated spatial pattern in the DST. By analogy, under appropriate conditions an AWG read out by a femtosecond pulse should lead to a very high repetition rate femtosecond pulse train.

The key design constraint of the AWG is that the free spectral range (FSR) must be less than the optical bandwidth, $\Delta\nu$, of the source laser. In this case, the output spectrum of any single waveguide in the AWG is multiply peaked, with the spectral peak spacing equal to the FSR. Conversely, this means that the bandwidth limited input pulse width, t_p, is less than the delay increment per guide, $\Delta\tau$, in the waveguide array. The time domain output then consists of a train of pulses with pulse separation, Δt, equal to the waveguide array delay increment. The waveguide array can be considered to be a series of delay lines, and each pulse in the output train can be identified with propagation through a specific guide in the array. The duration of the individual output pulses is the same as the input pulse, and the duration of the envelope of the pulse train varies inversely with the AWG passband width.

Fig. 2 shows output power spectra from both the bulk optics DST, and the AWG. In the DST experiments, a modelocked Ti:S laser producing ~100 fs pulses at an 850 nm center wavelength is used as

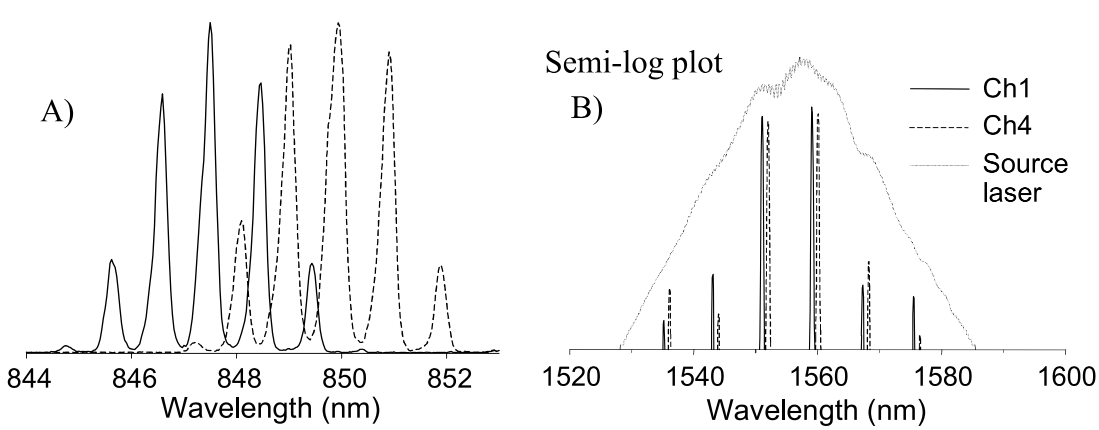

Fig. 2. Output power spectra recorded for two different outputs of the DST pulse shaper (A), and AWG (B).

the source; while, in the AWG experiments, a commercial modelocked erbium fiber laser (Femtolite from IMRA America) producing a 50 MHz train of ~200 fs pulses at 1560 nm is utilized. A periodic spatially patterned amplitude mask and imaging lens configuration is used in the DST to produce a one-dimensional array of spots at the diffraction grating [5], and the apparatus is configured to be chirp-free [8]. The AWG device has a 1 THz FSR corresponding to a 1 ps delay increment per guide in the waveguide array.

The periodic 'masking function' (transmission mask in the DST, periodic waveguide array apertures in the AWG) implies that the spectrum should have a periodic nature in each case as demonstrated in the figure. Also, note that the general form of the output spectrum is invariant for different outputs of each apparatus (output waveguides in the AWG, output slit positions in the DST) – the output spectrum simply shifts from one output to the next.

Fig. 3 shows intensity cross correlation measurements (with an unshaped reference pulse directly from the source laser) from both the DST and the AWG devices. Both devices exhibit a high repetition rate pulse train burst (530 GHz and 1 THz respectively), and although not shown here, identical intensity profiles are generated at each output position of both devices. The pulse spacing within the AWG output burst corresponds to the 1 ps delay increment in the waveguide array.

An AWG designed to have a small FSR (less than the bandwidth of the source laser), has been shown to be equivalent to a bulk optics DST pulse shaper with a periodic pixelation mask. High repetition rate bursts of femtosecond pulses are generated from both devices on multiple spatially separated output channels with varying center wavelengths. In principle, continuous high repetition rate trains (~ THz) of short pulses are possible by tailoring the apparatus design (DST or AWG) utilizing a moderate repetition rate (10's of GHz) short pulse source laser.

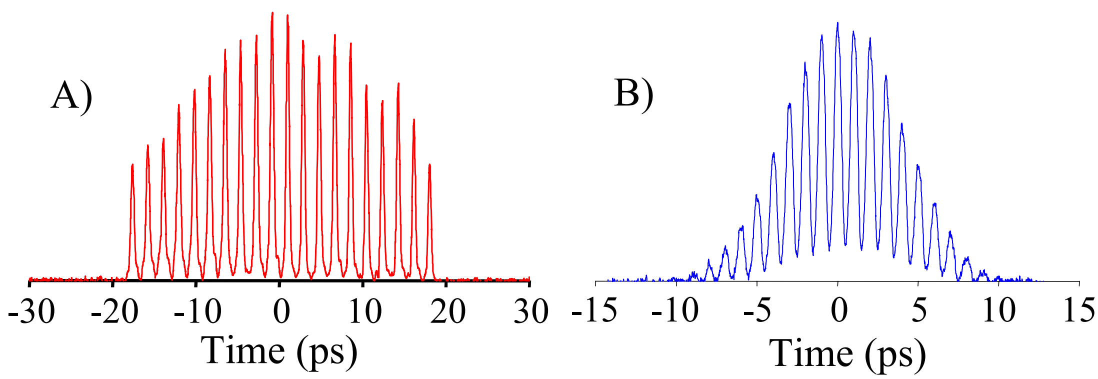

Fig. 3. Output temporal profiles recorded by intensity cross correlation for the DST pulse shaper (A), and AWG (B).

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