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>500 GHz repetition rate WDM pulse train generation via direct space-to-time pulse shaping – bulk & integrated optics implementations

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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. In one example of previous work, tapped delay line structures have been used to generate picosecond pulse trains at rates up to several hundred GHz [1]. Arrayed waveguide grating (AWG) structures, popular for wavelength demultiplexing and routing in WDM communication systems [2], have been used for spectral slicing of supercontinuum [3] and modelocked pulse [4] sources, which results in trains of ~tens of picosecond pulses at the same repetition rate as the modelocked laser. We have recently demonstrated a completely 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. Unlike previous work, the pulse repetition rate is determined by the AWG design parameters (not by the modelocked laser) and can be in the range of 500 GHz and greater [5].

For our high rate pulse train generation application, the AWG is closely analogous to the direct space-to-time (DST) pulse shaper previously demonstrated only in bulk optics [6-9]. Our previous work on this bulk optics approach furnishes important insight relevant to this new integrated implementation using an AWG. Fig. 1 shows schematic diagrams of both the bulk optics DST pulse shaper and the AWG. For the DST pulse shaper, the output temporal intensity profile is then a directly scaled representation of the input spatial profile. As an example, if the spatial profile 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. 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 [8].

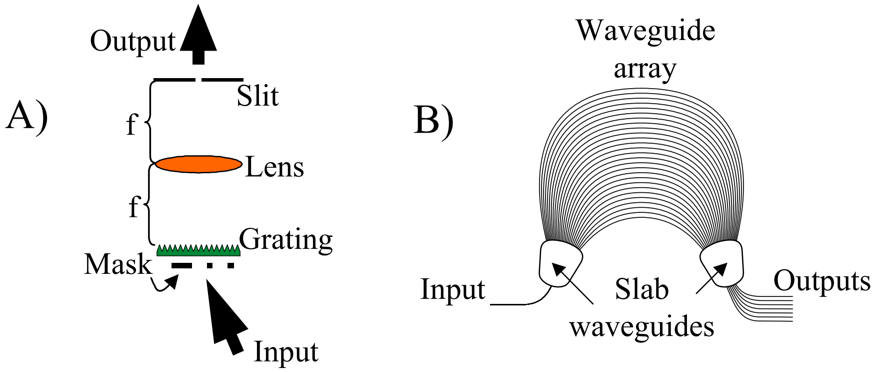

Fig. 1. Schematic diagrams of the bulk optics DST pulse shaper (A), and the integrated AWG (B).

In the standard integrated AWG structure 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.

Although the operation of the DST pulse shaper and of the AWG for this application will be shown to be similar, the use of the integrated AWG device represents a significant step towards the practical implementation of such technologies. This is evident from Fig. 2, which shows photographs of our bulk optics DST pulse shaper setup and of the AWG used in our experiments. The reduction is the physical footprint is clearly shown.

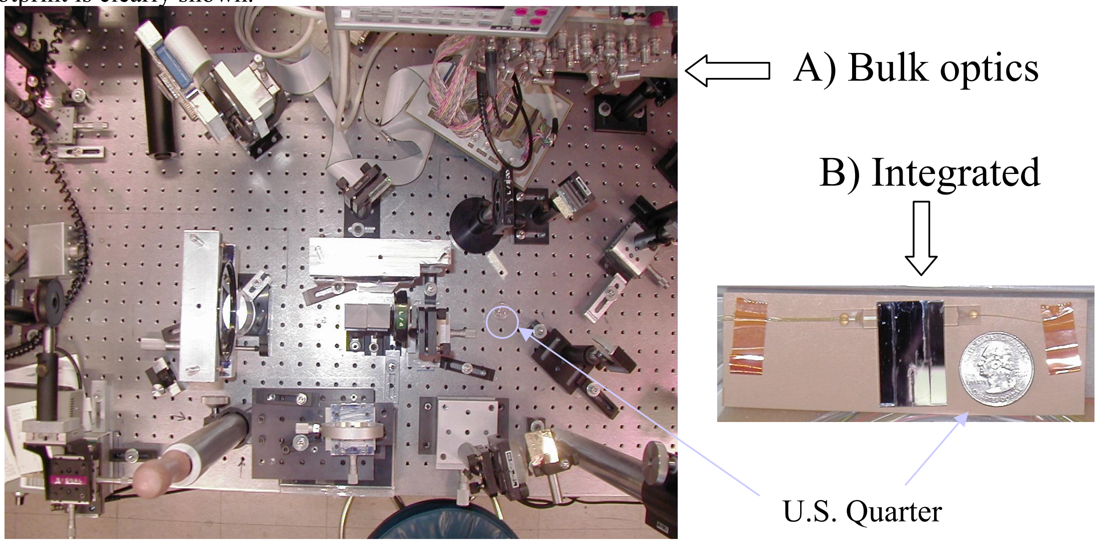

Fig. 2 Photos of the experimental apparatus for both the DST pulse shaper (A) and the AWG (B).

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 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. We note that the requirement that FSR $< \Delta\nu$ is opposite to the normal usage in DWDM systems, where the free spectral range must exceed the range of wavelengths employed.

Our DST pulse shaper experiments relied on a modelocked Ti:S laser producing ~100 fs pulses at an 850 nm center wavelength as the source. In the AWG experiments, a modelocked erbium fiber laser producing a 50 MHz train of ~200 fs pulses at 1560 nm is utilized. In principle, similar experiments can also be performed using much higher rate (e.g. >10 GHz) modelocked pulse sources. 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 [7], and the apparatus is configured to be chirp-free [9]. The AWG device has a 1 THz FSR corresponding to a 1 ps delay increment per guide in the waveguide array.

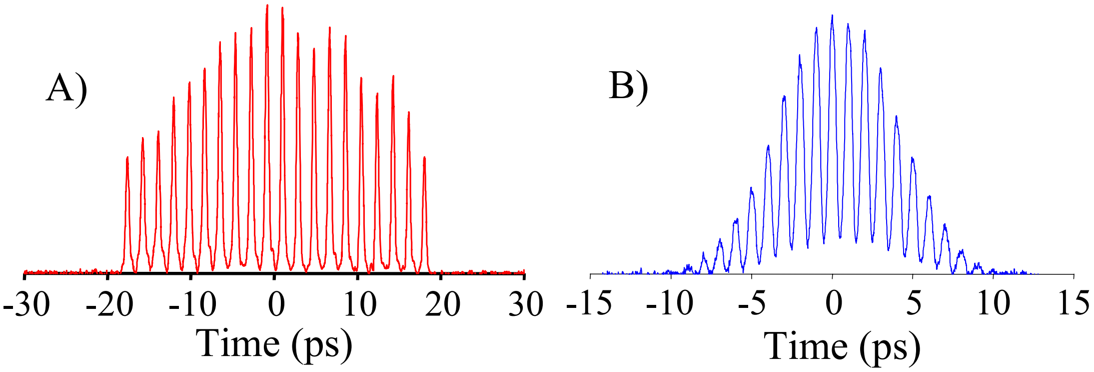

Fig. 3. Output temporal profiles recorded by intensity cross correlation for the DST pulse shaper (A), and AWG (B).

The periodic 'masking function' (transmission mask in the DST, periodic waveguide array apertures in the AWG) implies that both experiments should yield high rate bursts of evenly spaced pulses. This is confirmed in Fig. 3, which shows intensity cross correlation measurements from both the DST and the AWG devices. As expected, both devices exhibit a high repetition rate pulse train burst (530 GHz and 1 THz respectively). In the DST pulse shaper case, the repetition rate is determined by the spatial period of the periodic transmission mask, while the pulse spacing within the AWG output burst corresponds to the 1 ps delay increment in the waveguide array.

Fig. 4 shows output power spectra from both the bulk optics DST pulse shaper and the AWG. The spectra both exhibit a series of evenly spaced peaks, as expected for an evenly spaced pulse burst. Interestingly, the general form of the output spectrum is invariant for different spatially separated outputs of each apparatus (different output waveguides in the AWG, different output slit positions in the DST). In each case, the output spectrum simply shifts from one output to the next; further, the output temporal intensity profiles are invariant.

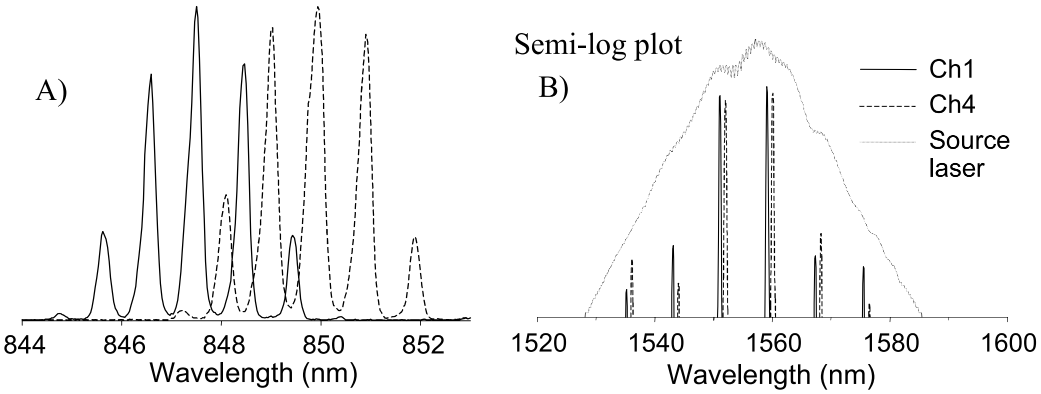

Fig. 4. Output power spectra recorded for two different outputs of the DST pulse shaper (A), and AWG (B).

In summary, 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. Each device generates high repetition rate (500 GHz – 1 THz) bursts of femtosecond pulses simultaneously on multiple spatially separated output channels with varying center wavelengths. In principle, continuous high repetition rate trains (~ THz) of short pulses are possible by appropriatly tailoring the apparatus design (either DST or AWG) while extending these experiments to utilize a moderate repetition rate (10's of GHz) short pulse source laser.

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References

1. S. Kawanishi, "Ultrahigh-speed optical time-division-multiplexed transmission technology based on optical signal processing," IEEE J. Quant. Electron., **34**, 2064-2079 (1998).
2. K. Okamoto, "Recent progress of integrated optics planar lightwave circuits," Opt. and Quant. Electron., **31**, 107-129 (1999).
3. S. Kawanishi, H. Takara, K. Uchiyama, I. Shake, and K. Mori, “3 Tbit/s (106 Gbit/s x 19 channel) optical TDM and WDM transmission experiment,” Electron. Lett. **35**, 826-827 (1999).
4. I.Y. Khrushchev, J.D. Bainbridge, J.E.A. Whiteaway, I.H. White, and R.V. Penty, "Multiwavelength pulse source for OTDM/WDM applications based on arrayed waveguide grating," IEEE Photon. Tech. Lett., **11**, 1659-1661 (1999).
5. D.E. Leaird, S. Shen, A.M. Weiner, A. Sugita, S. Kamei, M. Ishii, and K. Okamoto, "1 THz Repetition Rate WDM Pulse Train Generation from an Arrayed-Waveguide Grating," in *Conference on Lasers and Electro-Optics Postdeadline Papers*, CPD18 (2000).
6. B. Colombeau, M. Vampouille, and C. Froehly, “Shaping of Short Laser Pulses by Passive Optical Fourier Techniques,” Opt. Comm., **19**, 201-204 (1976).
7. D.E. Leaird, and A.M. Weiner, “Femtosecond optical packet generation by a direct space-to-time pulse shaper,” Opt. Lett. **24**, 853-855 (1999).
8. D.E. Leaird, and A.M. Weiner, "Wavelength tunable femtosecond pulse trains from a direct space-to-time pulse shaper," in *Conference on Lasers and Electro-Optics*, OSA Technical Digest, 410-411 (2000).
9. D.E. Leaird and A.M. Weiner, "Chirp control in the direct space-to-time pulse shaper," Opt. Lett. , 850-852 (2000).