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Abstract
We present what we believe to be the first demonstration of femtosecond pulse train generation from an arrayed waveguide grating. THz rate bursts of femtosecond pulses are produced with the rate determined by the arrayed waveguide delay spacing.

Index terms: Optical pulse generation, optical pulse shaping, optical waveguide filters, optical planar waveguides, waveguide arrays, wavelength division multiplexing

The Arrayed-Waveguide Grating (AWG) has seen considerable development in the past few years [1,2] primarily in the development of devices for use as Wavelength Division Multiplexed (WDM) channel demultiplexers and routers. In contrast AWG devices have seen only limited use in time domain applications. For example, modelocked pulse inputs have been spectrally sliced to yield pulses in the tens of picoseconds range at the repetition rate of the modelocked source laser [3], and supercontinum sources have been sliced to yield multiple optical wavelengths for high-speed systems studies [4,5]. Modified AWG devices have also been used for Fourier transform optical pulse shaping [6]. Here we present a completely new functionality, in which the AWG produces bursts of femtosecond pulses repeating at a THz rate, with the pulse repetition rate determined by the AWG design rather than the input pulse repetition rate. Each input pulse to the AWG produces a burst of very-high repetition rate pulses. In principle, if a high repetition rate short pulse source is used as the input, continuous, or quasi-continuous trains of very-high repetition rate short pulses may be generated as in a rate multiplication scheme. Furthermore, identical femtosecond pulse bursts with slightly shifted center wavelength are obtained at different output channels of the AWG, very much like the direct space-to-time (DST) pulse shaper [7-9], previously investigated only in bulk optics.

For short pulse applications, the important AWG parameter determining the character of the output is the free spectral range (FSR), which is equal to the inverse of the delay increment per guide ($\Delta\tau$):

$$\mathrm{FSR} = \Delta\tau^{-1} = \frac{c}{n_{eff}\ \Delta L} \qquad (1)$$

where n_{eff} is the effective index of the waveguide, c is the speed of light in vacuum, and ΔL is the physical path length difference from one guide to the next in the waveguide array section of the AWG. In traditional AWG devices, the FSR is typically required to be large to ensure that a unique output wavelength within the DWDM system is present at each AWG output. For the generation of THZ rate trains of femtosecond pulses, we work in the opposite regime, where the optical bandwidth, $\Delta\nu$, exceeds the FSR. If the input pulses are bandwidth limited, this means the input pulse width, t_p, is less than the delay increment per guide:

$$t_p < \Delta\tau \qquad (2)$$

In this limit, the output spectrum on a single output guide is multiply peaked, with the spectral peak spacing equal to the FSR. Accordingly, in the time domain, this corresponds to a pulse train with a pulse separation, Δt, equal to the waveguide delay increment:

$$\Delta t = \mathrm{FSR}^{-1} = \Delta\tau \qquad (3)$$

Thus, the waveguide array acts as 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, while the duration of the envelope of the burst of pulses, T, varies inversely with the AWG passband width, Δf. For a Gaussian passband,

$$T = 0.44\ \Delta f^{-1} \qquad (4)$$

where T and Δf are expressed in terms of the FWHM of intensity. From equations (3) and (4), the number of output pulses within the FWHM is given by

$$N = \frac{T}{\Delta t} = \frac{0.44\ \mathrm{FSR}}{\Delta f} \qquad (5)$$

Finally, the bursts repeat at the repetition period of the modelocked laser, T_{rep}, provided this period is larger then the duration of the bursts themselves (in the frequency domain, this means that each AWG passband contains many of the discrete laser modes separated by T_{rep}^{-1}). A schematic representation of the output spectrum and temporal profile is shown in Fig. 1.

These considerations apply to any of the output guides of an AWG. Therefore, an identical pulse train is expected at each output, but with a wavelength shift from one guide to the next consistent with the AWG channel spacing.

In contrast, when the AWG is used as a simple spectral slicer [3], the optical bandwidth should be less than the FSR, i.e., $\Delta\nu$ < FSR, which implies $t_p > \Delta\tau$. Thus, in this standard mode of operation, successive delayed output pulses corresponding to neighboring guides in the array are not resolved. The overall output from all the array guides merge to form a simple unstructured output pulse of duration 0.44 Δf^{-1} (considering a single output guide). This is very different than our current mode of operation.

In the experiments described here, a short pulse erbium fiber laser producing a 50 MHz train of ~200 fs pulses centered at 1560 nm is used as the source (a Femtolite from IMRA America). The laser output is split with a 10/90 fiber splitter, and all fiber links are constructed to be dispersion compensated using an appropriate combination of single mode fiber and dispersion compensating fiber. The 90% arm is launched into an AWG that has been designed to have a relatively small FSR of 1 THz (~8.1 nm at 1560 nm center wavelength). This FSR corresponds to a relatively large delay increment per guide $\Delta\tau$ = 1 ps. The temporal profile of the AWG outputs are recorded via intensity cross correlation in a free-space apparatus using the 10% port of the fiber splitter as a reference pulse. Power spectra of the AWG outputs are recorded as well with an optical spectrum analyzer. Two different AWG's were investigated. One device has 100 GHz channel spacing and 10 output channels, while the second has 40 GHz channel spacing and 25 output channels. The 3 dB passband widths are 51 GHz and 21 GHz respectively. In both these devices, the 1 THz FSR is equal to the output channel spacing multiplied by the number of output channels.

Fig. 2 shows power spectra recorded from the 40 GHz output channel spacing device. In Fig. 2A, the power spectrum of the source laser is overlaid with the output power spectra recorded from channels 1 and 4. The 1 THz FSR is evident from the periodic passband structure with 8.1 nm spacing between peaks. The spectra consist of six discrete output frequencies within the bandwidth of the source laser for each output channel. The shift in output center wavelength from one output to another is apparent as well. In order to more clearly show the shift in output center wavelength across the output guides, Fig. 2B shows an expanded version of the central passbands. The ~0.95 nm spacing between the two output channels corresponds to an average 39.1 GHz channel spacing per output. Note that the individual longitudinal modes of the mode locked laser, with a 50 MHz spacing, are not resolved. The multiply peaked nature of the power spectra demonstrate that $\Delta\nu$ > FSR; therefore, the output temporal profile is expected to be a train of pulses where the temporal period of the pulses in the output train is given by the inverse of the FSR.

Fig. 3 shows intensity cross correlation measurements of two different output channels for both AWG devices. As expected from the power spectrum presented above and eqn. (3), the temporal profile consists of a train of pulses with a 1 ps period, corresponding to the AWG delay increment, which is the inverse of the FSR, and with a pulse duration comparable to that of the input pulse. The degraded extinction ratio between pulses within the train is primarily due to incomplete dispersion compensation in the fiber links and the fact that the measurements are made by intensity cross correlation. The temporal window (or number of pulses), as predicted in eqn. (5), is inversely proportional to the AWG filter bandwidth and therefore increases by 2.5 times from the 100 GHz device to the 40 GHz device. The form of the output intensity profile is the same for different output channels of a single device, even though the spectrum is shifted. In Fig. 3C, the calculated pulse train envelope for the 100 GHz output channel spacing device is indicated by the dashed line. The envelope is calculated from a measurement of a single passband in the power spectrum. If we denote the form of the passband as $\left|A(\omega)\right|^2$, the envelope, $\left|a(t)\right|^2$, is taken as

$$\left|a(t)\right|^2 = \left|\frac{1}{2\pi}\int d\omega\,\sqrt{\left|A(\omega)\right|^2}\,\exp(j\omega t)\right|^2 \qquad (6)$$

The actual envelope is in excellent agreement with this calculation confirming eqn. (4) and the Fourier transform relationship between the spectral properties of the AWG and its temporal behavior.

As mentioned earlier, the femtosecond response of the AWG is quite similar to that of the DST pulse shaper [7-9], also used to generate very high rate bursts of femtosecond pulses [8,9]. The DST shaper consists of a diffraction grating, lens, and a thin output slit with a spatially patterned mask on top of the grating. This apparatus gives an output temporal waveform which is a directly scaled version of the input spatial profile at the grating; in particular, a periodically peaked input spatial profile produces an evenly spaced burst of pulses. The AWG can be considered to be an integrated DST pulse shaper where the waveguide array corresponds to the grating/lens combination in the bulk apparatus, and the AWG output waveguide corresponds to the bulk optics output. The spatial waveguide pattern at the output of the AWG array section is analogous to the periodically modulated spatial beam on the bulk optics grating; this explains the close similarity between the very high rate pulse bursts generated here via femtosecond illumination of an AWG and earlier using DST pulse shapers [8]. Also, the bulk optics DST, like the AWG, is capable of generating multiple spatially separated and wavelength shifted but otherwise identical copies of femtosecond pulse bursts [9].

As this methodology for utilizing an AWG is previously unexplored, it is important to briefly address the optical power efficiency. Referring to Fig. 1, the efficiency for a single output channel is approximately given by the passband width divided by the FSR (Δf/FSR). When the device is designed so that output channels are spaced by δf, the number of output channels is approximately FSR/δf. So, the total optical power efficiency is given by the efficiency for a single channel times the number of channels with the result $\eta_{total} \sim \Delta f/\delta f$.

In summary, we have shown for the first time, to our knowledge, that generation of trains of femtosecond pulses at terahertz repetition rates is possible from an AWG. The key requirements are that the FSR of the device must be tailored so that multiple filter passbands fit within the input laser bandwidth. The output pulse repetition frequency is equal to the free spectral range, or equivalently to the inverse of the delay increment per guide in the array waveguide region. The output temporal profile is invariant across different outputs of the same device, but the center wavelength shifts from one output to the next with the amount of shift given by the channel spacing of the device. The pulse width of the individual pulses in the output train is determined by the input pulse width. These unique properties allow generation of identical, wavelength shifted, very high rate pulse trains for hybrid TDM/WDM communications and photonic signal processing. In the future we anticipate that similar experiments may be performed with a high repetition rate femtosecond source (tens of GHz), which should lead to very closely spaced or even continuous THz pulse bursts.

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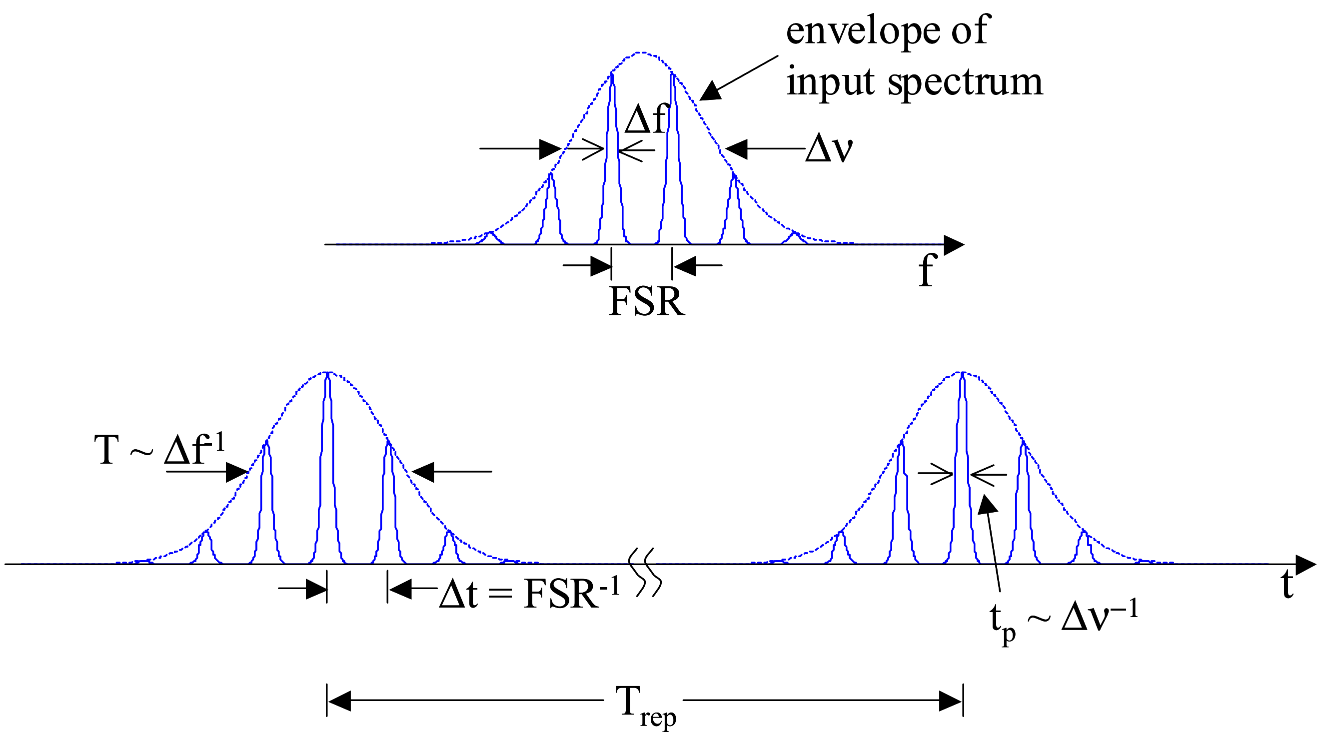
Figure captions

Figure 1: Expected output spectrum and temporal profile for an arbitrary output guide of the AWG.

Figure 2: Power spectra measured from the source laser (solid) and outputs of the 40 GHz output channel spacing device (Channel 1 – dash, Channel 4 – dot).

Figure 3: Intensity cross-correlation measurements of the output of both the 100 GHz channel spacing (left side, A and C), and 40 GHz channel spacing (right, B and D) devices on output channels #3 (top, A and B) and #4 (bottom, C and D). The dashed line in 3C is the calculated pulse train envelope.


envelope of
input spectrum
Δf
Δν
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FSR
T ~ Δf-1
Δt = FSR-1
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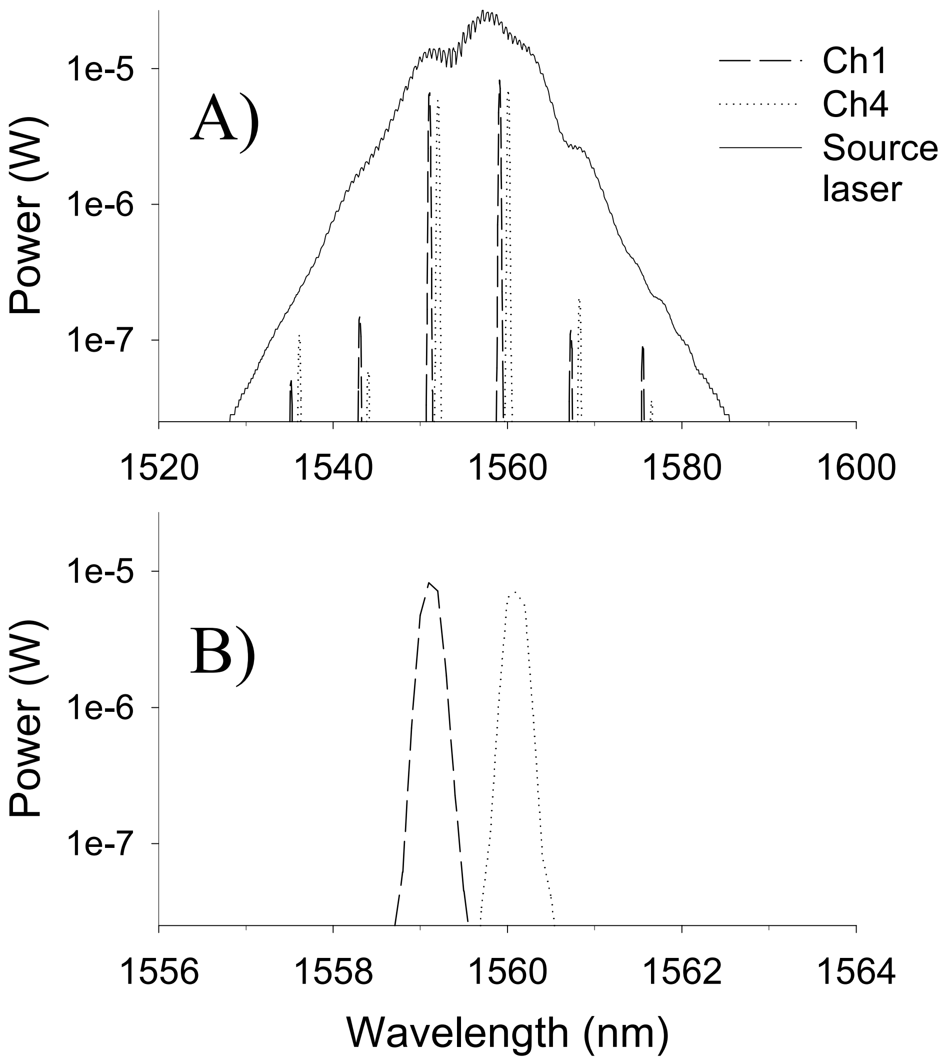
A)
B)
Ch1
Ch4
Source laser
Power (W)
1e-5
1e-6
1e-7
1520
1540
1560
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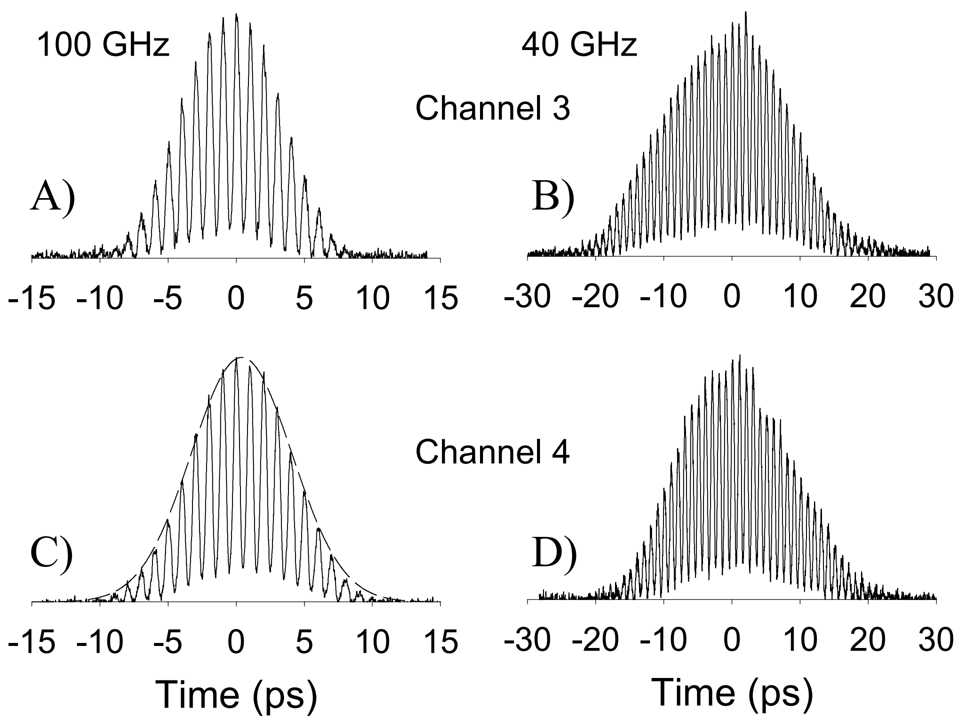
1560
1562
1564
Wavelength (nm)


100 GHz
40 GHz
Channel 3
A)
B)
-15 -10 -5 0 5 10 15
-30 -20 -10 0 10 20 30
Channel 4
C)
D)
-15 -10 -5 0 5 10 15
-30 -20 -10 0 10 20 30
Time (ps)
Time (ps)