Generation of Flat-Topped 500-GHz Pulse Bursts Using Loss Engineered Arrayed Waveguide Gratings

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***Abstract*—A specially engineered arrayed waveguide grating is demonstrated. The 500-GHz repetition rate bursts of femtosecond pulses with a flat-topped temporal intensity profile window are shown here for what we believe is the first time.**

***Index Terms*—Optical planar waveguides, optical pulse generation, optical pulse shaping, optical waveguide filters, waveguide arrays.**

DUE TO INCREASING optical communication network demands, significant research effort has been expended in the development of high repetition rate optical clock sources. One attractive methodology is repetition rate multiplication of a lower rate source to generate very high repetition rate pulse bursts and/or trains. The arrayed waveguide grating (AWG) [1], [2], frequently used in optical communication systems as channel multiplexers/demultiplexers, has also seen limited use in time-domain applications. An AWG has been used to spectrally slice supercontinum sources in order to generate pulse trains on multiple output channels [3], [4]. Alternatively, using a mode-locked source laser permits the generation of trains of tens of picosecond pulses at the repetition rate of the source laser [5]. Recently, we demonstrated a technique whereby a single low-repetition rate short pulse source laser can be used with a specially designed AWG to generate bursts of pulses with repetition rates in the terahertz regime, but with the same pulsewidth as the source laser [6]. The high rate bursts were contained under a Gaussian temporal window. Here, we demonstrate that the temporal intensity profile may be equalized, ideally to generate a flat-topped output pulse train, by introducing loss engineering into the design of the AWG structure. Loss engineering has been previously demonstrated for controlling or flattening the spectral passbands of the AWG [2], [7]. Here, we apply this technique for the first time applied for time-domain waveform shaping.

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As discussed previously [6], the key requirement for utilizing an AWG for the generation of very high repetition rate pulse trains and/or bursts is that the delay increment per guide within the waveguide array must be greater than the pulsewidth of the input laser. When the input pulses are bandwidth limited, this means that the free spectral range (FSR) of the filter is less than the bandwidth of the source laser. The small FSR regime as a design condition is opposite to that typically employed for AWG devices used as channel multiplexers/demultiplexers in optical communications networks. For use in optical communication networks, the AWG should have a large FSR in order to ensure that a unique output wavelength is present at each output. Conversely, the small FSR regime utilized here ensures that the power spectrum of each output of the AWG is multiply peaked.

We briefly review the temporal response of the small FSR AWG. When the input pulsewidth is less than the delay increment per guide within the waveguide array, the AWG can essentially be envisioned as an array of delay lines with a constant length difference from one guide to the next. In this case, each guide within the waveguide array that is excited by the input pulse will be associated with a specific pulse in the output pulse train—one guide one pulse. The Gaussian temporal window observed in our previous work [6] demonstrates a measure of the guide excitation pattern within the waveguide array. This Gaussian window arises from both input and output guide contributions—the input guide leads to distribution of power among the different guides in the waveguide array; the output guide has an angular acceptance function that also leads to rolloff in the temporal profile. The following scheme compensates for both.

In order to equalize the amplitude of the pulses in the output pulse train, the "one-guide one-pulse"' methodology is utilized to calculate the amount of additional loss to be inserted into each of the central guides so that their effective excitation amplitudes are the same. The waveguide array is truncated outside a prespecified number of central guides. Fig. 1 shows both a schematic diagram of the "one-guide one-pulse" design methodology, and an example of the additional loss inserted on a guide-by-guide basis in order to equalize the temporal output profile. The "one-guide one-pulse" methodology shown in Fig. 1(a) was recognized by drawing on the analogy between an AWG (with small FSR), and the direct space-to-time (DST) pulse shaper previously demonstrated in bulk optics [8], [9]. The loss engineering gives a modified spatial profile at the output of the waveguide array, leading to a modified time domain profile—very similar to the DST [9].

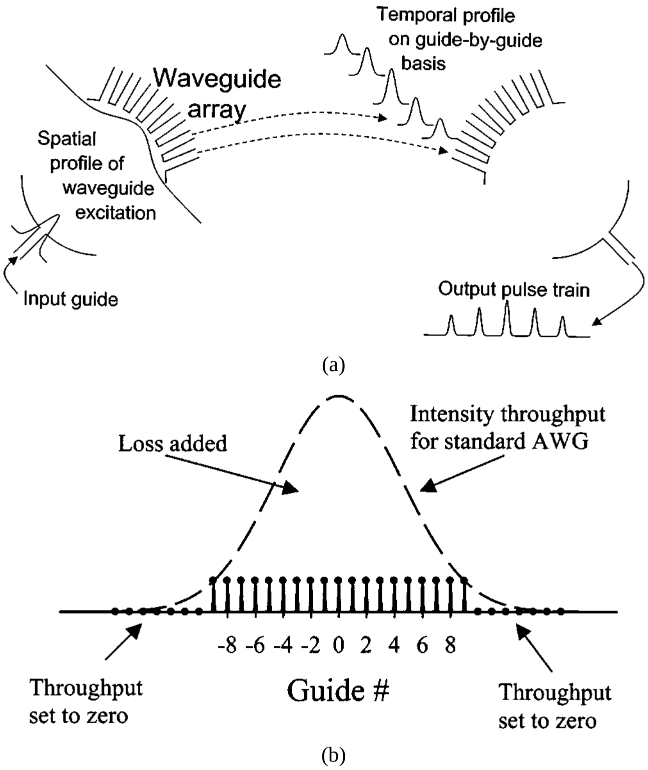

Fig. 1. (a) "One-guide one-pulse" design methodology. (b) Excess loss on a guide-by-guide basis.

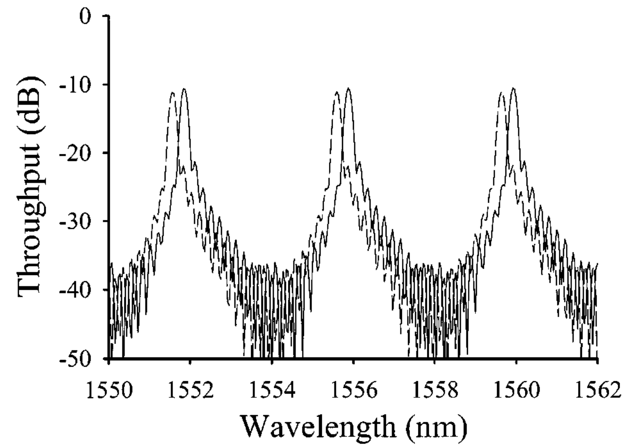

Fig. 2. Measured spectral filter function of two adjacent channels.

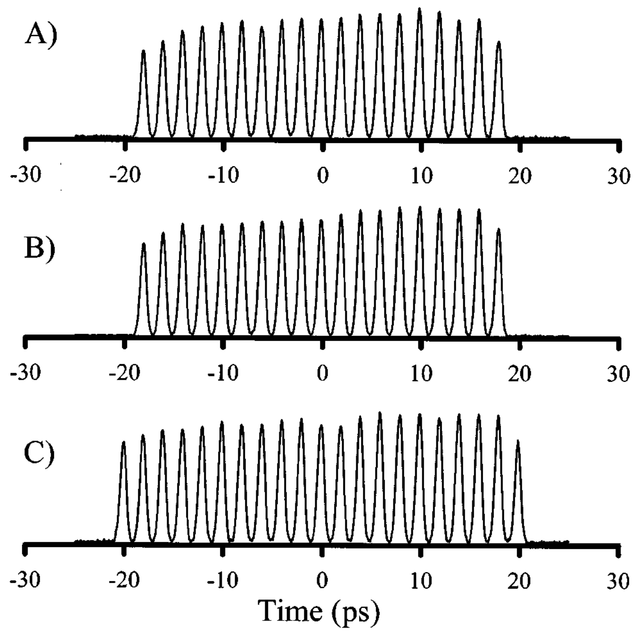

Fig. 3. Intensity cross-correlation measurements of two outputs of the 19-guide device (a) and (b), and one output of the 21-guide device (c).

Fig. 1(b) demonstrates the loss-engineering scheme utilized to generate the flat-topped output temporal intensity profile. The output temporal window of the unmodified AWG is calculated via inverse Fourier transform analysis of a single spectral passband. Individual pulses within the temporal window are spaced by the FSR^{-1} of the AWG. The amount of additional loss per guide that is necessary to flatten the output temporal profile is determined by reducing the height of each pulse in the output train to a level equal to that of the outer-most pulse in the desired square train. In Fig. 1(b), the dashed line indicates the temporal window, $\mathrm{FWHM} = 21.5$ ps, expected from a non-loss engineered AWG with a 20.7 GHz 3-dB passband width. The solid line and circles indicate the designed throughput on a guide-by-guide basis for the central 19 guides which would yield a 19 pulse flat-topped output pulse train with 2-ps pulse spacing.

In our experiments, a short pulse erbium-fiber laser producing a 40-MHz train of ~200-fs pulses centered at 1558 nm is used as the source. The laser output is split with a 50/50 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 signal arm is launched into an AWG that has been designed to have a relatively small FSR of 500 GHz (~4 nm at 1558-nm center wavelength). This FSR corresponds to a relatively large delay increment per guide, $\Delta\tau = 2$ ps. The temporal profile of the AWG outputs are recorded via intensity cross correlation in a free-space apparatus using the second port of the fiber splitter as a reference pulse. Power spectra of the AWG outputs are recorded using an optical spectrum analyzer. Two different AWGs were investigated, both with 40-GHz output channel spacing and four outputs fiber connectorized. One AWG has 19 guides within the waveguide array while the other has 21 guides. For reference, a similar device designed to be a low-loss channel demultiplexer would typically utilize 50 guides within the waveguide array.

Fig. 2 shows the measured spectral filter function, using a tunable narrow-line laser source and an optical spectrum analyzer of the 19-guide AWG for two adjacent output channels. The 500-GHz FSR is evident from the periodic passband structure with 4-nm spacing between peaks. The shift in output center wavelength from one output to another is apparent as well. The individual passbands of the AWG spectral filter function have a sinc-like appearance, consistent with the expected rectangular shape of the output burst in time.

Fig. 3(a) and (b) show intensity cross-correlation measurements of two output channels of the 19-guide AWG. As expected, the data indicate bursts of pulses with a 2-ps period, corresponding to the AWG delay increment, and with a pulse duration comparable to that of the input pulse. The number of pulses in the output train (19) is equal to the number of guides in the waveguide array, as expected from the "one-guide one-pulse" methodology indicated above. Similar profiles are observed for the other two fiberized outputs of the same AWG. The output intensity profile is the same for different output channels of a single device, even though the filter function is shifted. This property of identical temporal profiles at different outputs but with a center wavelength shift is an exact analog to the behavior observed earlier for the bulk optics DST pulse shaper [9]. Although the output pulses have nearly the same amplitudes, there are small deviations, which explains why the spectral filter function shown in Fig. 2 is not an ideal sinc function. Fig. 3(c) shows data from one output of the 21-guide AWG, demonstrating generation of a nearly flat-topped 21-pulse burst.

As these AWGs rely on loss engineering to achieve a flat-top temporal intensity profile, it is important to consider the effect of the excess loss. In our previous work, where no loss engineering was employed [6], the small FSR AWG exhibited quite good insertion loss when viewed as a traditional channel demultiplexer—$\sim$3.5 dB. In the current work, the measured insertion loss from the perspective of a standard channel demultiplexer, is approximately 10.5 and 11.0 dB for the 19 guide and 21 guide AWG devices, respectively, corresponding to excess losses of $\sim$7.0 and 7.5 dB. An approximate analytic expression for the excess loss of a flat-top pulse train design compared to a "standard" Gaussian output pulse train is possible assuming a Gaussian filter function for the standard AWG and assuming the filer bandwidth is much less than the FSR. For a square train of width 2τ (i.e., runs from $-\tau$ to τ) and 3-dB filter passband width δf, the efficiency relative to that of a standard AWG design is given by

$$\eta = \frac{2}{\sqrt{\pi}}\frac{\tau}{T}\exp\left[\frac{-\tau^2}{T^2}\right] \tag{1}$$

where

$$T = \frac{\sqrt{\ln 2}}{\pi}\frac{1}{\delta f} \cong 0.265\frac{1}{\delta f}. \tag{2}$$

The calculated excess loss for the 19-pulse and 21-pulse flat-top train devices are 7.3 and 9.0 dB respectively, in good agreement with the measured values.

In summary, we have shown for the first time to our knowledge that loss-engineering in a small FSR AWG can equalize the pulse amplitudes in the temporal output train obtained upon femtosecond readout. The key requirements are that the FSR of the device must be tailored so that multiple filter passbands fit within the input laser bandwidth, and the waveguide array should be viewed as a collection of delay lines with one output pulse for each guide. 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 pulsewidth of the individual pulses in the output train is determined by the input pulsewidth. 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 gigahertz), which should lead to very closely spaced or even continuous pulse bursts in the range of 100 GHz to greater than 1-THz repetition rate.

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