Broadband photonic arbitrary waveform generation based on spatial-spectral holographic materials

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We discuss an approach for the practical implementation of photonic arbitrary waveform generation of microwave signals. We describe and demonstrate an approach using spatial-spectral (S2) holography in rare earth ion doped crystals that has the potential to achieve extremely wide bandwidths (>40 GHz) using conventional electro-optic phase modulators and low bandwidth (<100 MHz) control electronics. We provide analysis of this approach, show simulations, and perform experimental demonstrations of the technique. We show a pulse compression factor of ~15,000 and demonstrate the largest effective bandwidth of 3.9 GHz to date for pulse compression using S2 holography. We also show control and manipulation of up to 30 independent compressed pulses for the creation of arbitrary waveforms. © 2007 Optical Society of America

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1. INTRODUCTION

A wide variety of applications rely upon the rapid synthesis and use of arbitrary waveforms including ultrahigh resolution radar, microwave and millimeter-wave communication devices, and data storage, as well as the probing and manipulation of quantum and molecular processes. Many of these applications require arbitrary waveform generation (AWG) with bandwidths well over 10 GHz and with high signal-to-noise ratios. AWG up to a few gigahertz of bandwidth has traditionally been performed with electronic equipment comprised mainly of fast memory containing a digital representation of the waveform desired and a digital to analog converter (DAC), which converts the waveform into its appropriate voltage at the desired sample rate. High-end, commercially available electronic AWG devices create arbitrary waveforms with sample rates of up to 10 gigasamples per second (GSPS) and 8 bits of vertical resolution with a maximum bandwidth of 3.5 GHz and ~2 ps root mean square (rms) delivery jitter [1,2]. Utilizing a specially developed two channel mixing device, these electronic AWGs can also achieve a sample rate of 20 GSPS and a maximum bandwidth of 5.8 GHz [2]. Unfortunately electronic DACs suffer from a loss in dynamic range or vertical resolution as their sample rates are increased. The current state of the art demonstrated ~3 bits at 40 GSPS [3]. The lack of an electronic solution for extremely high bandwidth AWG has lead to interest in photonic approaches to AWG.

With photonic AWG, hundreds of gigahertz to terahertz bandwidths are possible using the well-developed optical approach of femtosecond (fs) pulse shaping. These pulse-shaping techniques have predominantly used mode-locked pulsed lasers in conjunction with diffraction gratings and spatial light modulators to create arbitrary waveforms [4,5]. The spatial light modulators used to shape the pulse’s spectrum typically limit the spectral resolution of these devices to >10 GHz, and thereby limit the arbitrary optical waveforms to a maximum duration of <100 ps. There have been some recent improvements upon these approaches with the use of virtually imaged phased arrays [6]. These devices allow for finer frequency resolution than conventional approaches, providing the potential for arbitrary waveforms with somewhat larger time bandwidth products. There are also other novel approaches to photonic AWG that have been proposed [7–10]. While all these approaches show some promise, many do not address the need to create user-defined waveforms that have both tens to hundreds of gigahertz of bandwidth and nanoseconds to microseconds of duration.

The approach described in this paper, termed spatial-spectral (S2) holographic material based photonic arbitrary waveform generation (S2-PAWG), has the ability to create waveforms with tens of gigahertz of bandwidth and tens of microseconds of duration allowing for time-bandwidth products (TBPs) over 106 and with spatial multiplexing enables potentially continuous AWG. In this paper, we describe and demonstrate the use of S2 materials to perform chirp compression, and how simple, low-cost, low-bandwidth electronics can be used to control and shape these compressed pulses for AWG, extending the results of Barber et al. [11] by 2 orders of magnitude in bandwidth. To achieve high-bandwidth AWG, we used the high-bandwidth pulse compression approach first described by Reibel et al. [12]. Here, the high-bandwidth optical chirps are created with an electro-optic phase modu-
lator (EOPM) driven with an rf chirp. Frequency agile (chirped) lasers can also create wideband optical chirps and have been used to engrave true time delay gratings [13], compressive filters for AWG [14], and for rf spectrum analysis [15].

This approach for broadband AWG has several advantages compared to using frequency agile lasers [14,15]. First, it can take advantage of low-cost, commercially available parts such as telecom modulators, which have 3 dB bandwidths up to 40 GHz [16], low-cost frequency swept rf sources (described below), and narrow linewidth, frequency stable distributed feedback fiber lasers (subkilohertz linewidths over millisecond time scales). The approach utilizes cotemporal engraving of compressive filters into the holographic material, which provides large holographic efficiencies along with the ability to leverage low-bandwidth electronics for control of high-bandwidth outputs, among its other advantages (see [17]). In spectral holography, frequency stability and accuracy of the optical pulses is very important, and AWG is no exception. The approach utilizes frequency stable laser sources in conjunction with swept rf sources, providing for very accurate and precise frequency control of the optical engraving and probe pulses. This stability ultimately translates into very stable outputs from the system in terms of amplitude, and temporal jitter. Both this approach and those using frequency agile laser sources have the common goal of achieving the most economical, efficient, wideband, amplitude, and phase stable outputs as possible.

In this paper, we provide background on this new approach, including its differences as compared to other high bandwidth approaches, and discuss the additional complexities introduced when an EOPM is utilized in the AWG process. In particular, we describe the process by tracking the two first-order Bessel terms created by driving an EOPM. We also present simulation results of this new approach and provide the latest experimental results, showing to our knowledge the shortest duration individual compressed pulse of any S2 holographic approach, with a full-width, half-maximum (FWHM) duration of 260 ps. This compressed pulse was created from a 4 μs probe pulse and achieved a very large compression factor of ~15,000. Additionally, we show experimental results of the full S2-PAWG process, where 15–30 sub-ns compressed pulses were controlled to approximate several arbitrary waveforms and were captured without averaging.

2. BACKGROUND

The S2-PAWG technique is conceptually similar to that of a conventional DAC. However, S2-PAWG operates in the optical domain, while a DAC works in the electrical domain. Like digitally controlled samples from a DAC, compressed pulses are formed and positioned by an S2-PAWG device to approximate an arbitrary waveform. The ability of an S2-PAWG device to create an arbitrary waveform accurately depends upon how accurately it can set the amplitude, phase, and timing of each compressed pulse. It is important to note that while this process described in this manner sounds like a digital approach, the process is fully analog and has both the advantages and disadvantages associated with such signal processing. We will first consider how a S2-PAWG device forms the compressed pulses, and then we will look at how it controls those compressed pulses to create an arbitrary waveform.

A. Pulse Compression

S2-PAWG creates narrow pulses, known as compressed pulses, by temporally compressing linearly frequency modulated or chirped optical pulses, analogous to that done in the microwave regime [18]. The chirped pulses are compressed using a compression filter, which is engraved into the absorption profile of a S2 material. While many suitable S2 materials exist, thulium doped yttrium aluminum garnet (Tm:YAG) was used as the S2 material in this paper [19]. When Tm:YAG is cooled to ~4 K, each Tm ion has a ~30 kHz homogeneous linewidth, which corresponds to the spectral resolution of the S2-PAWG. Tm:YAG has an inhomogeneously broadened linewidth of ~30 GHz, which corresponds to the instantaneous operating bandwidth of the S2-PAWG. The ratio of the homogeneous to inhomogeneous linewidths is a figure of merit (10° for Tm:YAG) that is equivalent to the maximum TBP achievable with this approach.

The compression filter is a periodic spectral grating, also termed a compression grating, which is optically etched into the inhomogeneous broadened absorption profile of the S2 material. When forming a single compressed pulse, the filter works by delaying each instantaneous frequency component of a broadband chirped probe pulse such that each instantaneous frequency component of the probe leaves the filter at the same time. These delayed components form a compressed pulse, also known as a compressed echo [20–23]. The programmed filter persists for the population lifetime of the bottleneck state of the S2 material, which for Tm:YAG is ~10 ms, and can be reprogrammed on this time scale or maintained in a quasi-steady state [24].

Figure 1 is a timing diagram for the optical input and output pulses of the S2-PAWG technique with a single sideband (SSB) approach. Time is graphed horizontally while instantaneous frequency (dashed lines) and amplitude (solid lines) are graphed vertically (note: not to scale). While there are several ways of creating a compression grating, here we describe the creation of a chirped compression grating with an optical programming pulse that consists of two temporally overlapped linear frequency chirps (TOLFCs), as shown on the right side of Fig. 1. The duration of the programming pulse was τc and the spectral coverage of the pulse is the spectral overlap of the two TOLFCs, which defines the bandwidth of the compression filter, B. The chirp rate (hertz per second) of the upper and lower frequency chirps was α1 and α2, respectively, and the upper chirp was initially offset from the lower chirp by a frequency f0. The frequency-dependent group delay programmed into the S2 material for a particular frequency is equal to the temporal separation of the TOLFCs at that particular instantaneous frequency. Hence, in the case of Fig. 1, the delay given to an instantaneous optical frequency at fs1+f0 is τc Min = f0/α2, where fs1 is the start frequency of the lower chirp.
The FWHM temporal duration, $\tau_{cp}$, of this compressed pulse’s intensity is $\approx 0.89/B$.

There are several ways of creating the programming and probe pulses necessary for S2-PAWG. The timing diagram in Fig. 1 shows S2-PAWG input pulses that were formed by SSB modulation or swept frequency sources. One straightforward method of obtaining SSB modulation is to use an acousto-optic modulator (AOM) driven by an rf chirp. AOMs provide stable linear modulation. However, in practice they are typically bandwidth limited to less than 1 GHz. Previous experiments have used AOMs in an S2-PAWG device to perform chirped pulse compression, pulse train creation, self-convolution, and autocorrelation at an AOM limited bandwidth of $\sim 20$ MHz [11]. To obtain larger bandwidth SSB modulation, frequency agile laser sources such as chirped external cavity diode lasers have been developed [27,28], used to program 2 GHz wide spectral gratings [13,29], and also used to perform pulse compression over $\sim 1.5$ GHz of bandwidth [14,15].

The success of broadband S2 holographic processing relies upon the capability to produce extremely linear chirped optical pulses for engraving spectral gratings and/or for probing these spectral structures. Thus there has been a push to improve the performance of frequency agile lasers by providing active stabilization of the optical chirp. Using active feedback for chirp control was first suggested by Greiner et al. [30]. A similar system has been described by Crozatier et al. [31] and used in the pulse compression demonstrations described above [15]. A modification to the approach was discussed by Gorju et al. [32]. The improvement in chirp linearity is notable, and these approaches show between 2–3 orders of magnitude suppression of laser frequency error. Residual frequency errors are reported to be between 65–100 kHz on time scales ranging from 50 $\mu$s to 4 ms.

To achieve full compression of the pulses and achieve AWG at bandwidths up to the chirp bandwidth, frequency errors on the optical chirp must be kept less than the inverse of the temporal duration of the optical chirp. The duration of engraving pulses has ranged from as short as 50 $\mu$s [15] to as long as 1 ms [11], requiring frequency errors on such chirps to be less than 20 and 1 kHz, respectively. Given the current reported frequency errors of actively controlled chirped sources, these sources will not produce true Fourier transform limited performance unless relatively short duration optical chirps are used, subsequently requiring higher power lasers to engrave efficient spectral gratings. The results of such residual frequency errors on the compressed pulse are discussed in [15].

The approach utilized here for S2-PAWG involves driving an EOPM or electro-optic amplitude modulator with an rf chirp [12], which produces optical chirps with better frequency stability than that reported with frequency ag-
ile lasers, though chirped lasers have the potential to create chirps with significantly larger bandwidth. Figure 2 is a timing diagram that shows how an EOPM is used to create the programming and probe chirps (note: not to scale). The first and second rf chirps have starting frequencies $f_{S1}$ and $f_{S2}$, respectively. The overlap of the two chirps defines the compression filter bandwidth $B$. As seen in Fig. 2, this technique produces sidebands symmetrically around the optical frequency of the laser, $f_L$. We will term this technique the double sideband (DSB) approach, because we limit our discussion to only the two first-order symmetric sidebands. The DSB approach, unlike the SSB approach, creates two compression filters in the S2 material; the upper one centered at $f_L + (f_{S2} + B/2)$, and the lower one centered at $f_L - (f_{S2} + B/2)$. When the DSB approach is used to produce a compressed pulse (see the middle of Fig. 2) with a probe pulse whose chirps are symmetric about $f_L$, two temporally overlapped compressed pulses (TOCPs) are produced; one from the higher frequency sideband and one from the lower frequency sideband. Provided the chirps in the probe pulse spectrally overlap the compression filter entirely, the center frequencies of the compressed pulses are $f_{L} + (f_{S2} + B/2)$ and $f_{L} - (f_{S2} + B/2)$, respectively. These center frequencies are indicated by dashed lines above or below $f_{L}$. Assuming that the experimental geometry of the input pulses results in these two compressed pulses leaving the crystal with the same spatial direction and assuming a high-bandwidth photodiode is used for their detection, then a beat frequency equal to the frequency separation of the compressed pulses ($2f_{S2} + B$) will be observed.

This approach is not immune to frequency errors and must still meet the requirement that the frequency error on either optical chirp remain less than the inverse of the optical chirp pulse duration. Here the combination of residual frequency errors from the rf frequency chirps applied to the EOPM and the source laser must meet the requirement over the chirp duration. However, this is easily accomplished even for millisecond long duration optical chirps with subkilohertz linewidth frequency stable lasers such as those used in this experiment [33] in combination with the negligible errors introduced from the rf electronics.

This approach does require that a stable, low-cost rf chirping source be found and that it works on the time scales of these experiments. In the current experiment, 12.5 GSPS pulse pattern generators (PPGs) are used for the creation of wideband analog chirps for proof-of-concept demonstrations. This solution is not deployable due to the cost of the commercial pulse pattern generators and a lower-cost solution must be found. We suggest two possibilities for low-cost, wideband rf chirped pulse creation. First, one could utilize low-cost, wideband direct digital synthesis boards in conjunction with frequency multipliers to achieve this goal. Second, rapidly tunable microwave oscillators, for example, yttrium iron garnet (YIG) oscillators, could be frequency swept with the linearity being controlled by phase-locked loops; the microwave equivalent to the active control for the frequency agile laser sources described above. This approach has seen some success with the creation of a 2.5 ms, 6 GHz rf chirp with adequate linearity [34]. If this technique is to succeed on extremely wide bandwidths, more efforts in identifying such a broadband rf chirping source are required.

B. Manipulating Compressed Pulses for Arbitrary Waveform Generation

In addition to the compressed pulse’s temporal duration being determined by the bandwidth of the compression filter (provided the probe spectrally overlaps the filter entirely), the compressed pulse’s amplitude and phase are also controllable, being proportional to the amplitude and phase of the chirp(s) that make up the probe pulse. This control enables multiple compressed pulses to approximate an arbitrary waveform. In essence, the output of the system is still described by Eq. (3). Here we choose to describe the probe pulse as being constructed of multiple, frequency-shifted, cotemporal optical chirps. The output of the system is fully analog, and will respond linearly to $E_{s}(\omega)$, provided the probe pulse does not saturate the S2 material. In the case of multiple, frequency-shifted cotemporal chirps, the outputs are several temporally separate compressed pulses. To indicate that compressed pulses’ amplitudes and phases are controllable and inde-
pendent, the five compressed pulses on the right side of Fig. 2 are drawn with varying heights.

Each compressed pulse in the S2-PAWG’s output arbitrary waveform is individually controlled acting analogous to the digitally controlled samples from a DAC. The S2-PAWG device can be made to output a sequence of N compressed pulses by sending N chirped probes through the compression filter (see the far right of Figs. 1 and 2). Because the N probes can be temporally overlapped, they can be produced simply by creating frequency-shifted copies of a single chirped probe. An additional chirped probe that is frequency shifted by \( f_n \) relative to the original chirped probe will create an additional compressed pulse that is delayed by \( \tau_n \) relative to the original compressed pulse, where \( \tau_n \) is given by the formula: \( \tau_n = f_n^\frac{1}{c} \). In the typical implementation of such a technique, where \( c \) is \( \sim 10^{15} \text{Hz/s} \), a delay time, \( \tau_n \), of 250 ps can be created by a frequency shift of 250 kHz. A delay of 100 ns can be created by a frequency shift of 100 MHz. These frequency shifts are easily achieved with an AOM and low-bandwidth driving electronics. Hence controlling multi-gigahertz compressed pulses comes down to controlling electronic signals in the 100 kHz to 100 MHz range, a region in which the high dynamic range, low-cost DACs exist. In addition, the amplitude and phase control of the probes is also easily handled by controlling the RF tones that drive the AOM. Thus an S2-PAWG device has bandwidth leverage, because it uses low-bandwidth modulators and electronics to control its high-bandwidth outputs. This makes the S2-PAWG a practical means of creating high-bandwidth arbitrary waveforms.

Note that due to the finite duration of the spectral overlap of the probe pulse with the compression filter, \( \tau_B = B/|c| \), the minimum, Fourier-limited differential frequency offset of probe pulses that create distinct outputs is \( \sim 1/\tau_B \). Hence the temporal control resolution, \( \Delta \tau \), is \( (1/\tau_B)/|c| \approx 1/B \), which is comparable to the calculated FWHM of a compressed pulse, \( \tau_c \approx 0.89/B \). We note that the vertical resolution of the S2-PAWG device relies upon a variety of parameters including but not limited to the intensities and fidelity of the input pulses, the dynamic range of the detection device, the detection scheme, the S2 material’s purity, the higher-order sidelobes created from the pulse compression process, the stability of the chirp and laser sources, and the optical shot noise on the programming pulses as well as during waveform detection.

When using an AOM to control the compressed pulses in DSB S2-PAWG, each frequency shift of the original probe pulse creates two shifted chirped pulses, resulting in an output waveform that has temporal symmetry, as illustrated on the right side of Fig. 2. In the DSB approach, the original probe pulses are created from an EOPM modulated carrier, whose sidebands have mirror symmetry about the laser source frequency. The unshifted probe creates dual overlapping compressed pulses labeled c and f in Fig. 2. The multiple frequency offset probe pulses on the right of Fig. 2 are labeled a and b on the upper frequency sideband and d and e on the lower frequency sideband, where a and d are the result of one AOM frequency shift and b and e are the result of a different AOM frequency shift. Since the AOM shifts both sidebands of the probe in the same direction (higher in case of Fig. 2), the mirror symmetry about the laser frequency is broken. Thus the two sidebands and their frequency shifted copies produce two pulse sequences (such as pulse sequence a,b,c and pulse sequence d,e,f in Fig. 2) that are mirror images (in time) around a temporal point of symmetry, \( \tau_{B, \text{Min}} \), after the end of the probe pulse. Each compressed pulse in Fig. 2 is labeled with the same letter as the temporally overlapped probe chirp from which it was compressed. Due to the temporal symmetry of the pulse sequence produced by the DSB S2-PAWG technique, one might think that only symmetric waveforms can be created, but this is not the case. The two mirror-symmetric pulse sequences are temporally and frequency offset, so they can be gated or spectrally filtered so that only one of the pulse sequences is generated.

3. EXPERIMENTAL DEMONSTRATIONS

A. Experimental Setup

Figure 3 shows the experimental setup for the DSB S2-PAWG device. The solid arrows indicate the path of the laser light and the dotted arrows indicate an electronic path. Here the stabilized laser source was a New Focus Vortex laser operating at 793 nm that was frequency locked to a spectral hole within the S2 material [33]. The

![Fig. 3.](image-url) Schematic of the experiment setup used in the DSB S2-PAWG experiments. Definitions of the acronyms are as follows: beam splitter (B.S.), electro-optic phase modulator (EOPM), pulse-pattern generator (PPG), injection-locked diode amplifier (ILA), low-bandwidth electronic arbitrary waveform generator (E-AWG), acousto-optic modulator (AOM), New Focus 1580 photodiode (NF 1580), and avalanche photodiode (APD).
optical programming and probe chirps were created first as digital, electrical signals by two 12.5 GSPS PPGs. These electrical frequency chirps were summed and converted into optical sideband chirps on the stabilized laser source via an EOspace 12 GHz bandwidth EOPM. Since the EOPM could only output a few milliwatts of optical power, its output was amplified with an injection-locked diode amplifier (ILA) [35] and a tapered semiconductor amplifier. These amplifiers increased the optical power of the programming and probe pulses to over 100 mW. The last modulator in the optical path before the S2 material was an AOM, which created the frequency-shifted copies of the original probe chirp. The AOM was controlled by a low-bandwidth electronic arbitrary waveform generator (E-AWG). The laser light was focused into the cryogenically cooled S2 material (Tm:YAG 0.1% at. doping), which was held at ~4 K in a cryostat (CRYO). The average electric field strength in the crystal had a measured Rabi frequency of ~600 kHz. When the TOLFCs of the programming pulse passed through the S2 material, they created the compression filter in the S2 absorption profile. These programming pulses typically lasted for ~1 ms with a difference in chirp rates such that $\tau_{S2,Max}$ was kept at ~7 $\mu$s, and $\tau_{S1,Max}$ was ~1.5 GHz unless otherwise stated. The probe pulses, which typically lasted for 4 $\mu$s, were then compressed as they interacted with this filter in the S2 material. The compressed pulse sequence that was produced passed through a gating AOM, where the programming pulses and probe pulse were rejected and the compressed pulse or arbitrary waveform sequence was allowed to pass. This signal was subsequently detected by a high-speed photodetector (either a 1 GHz Hamamatsu APD or a 12 GHz New Focus 1580 photodiode) and captured by a 3 GHz bandwidth oscilloscope (Tektronics TDS-694C) and a computer.

B. Low-Bandwidth Simulations and Demonstrations

To verify that the S2-PAWG device worked according to the theory, simulations and low-bandwidth experiments were performed. First, we simulated the SSB and DSB S2 pulse compression techniques using a Maxwell–Bloch simulator [36]. When the creation of a single compressed pulse using the SSB approach (such as in the middle of Fig. 1) was simulated, a compressed pulse was seen, shown as the dashed curve in Fig. 4(a). When the DSB approach was simulated, the compressed pulse contained a beat frequency close to $2f_{S2}+B$ indicating that there were indeed two overlapping compressed pulses as expected. To experimentally verify the existence of this beat frequency, DSB S2 pulse compression experiments were performed at low bandwidths ($B=100$ MHz) and start frequencies ($\nu_{S1}, \nu_{S2} \sim 200$ MHz) such that this beat note would be within the bandwidth of the 3 GHz oscilloscope. Figure 4(b) shows this expected beat signal and confirms that the two frequency offset compressed pulses occur at the same time. In our high-bandwidth experiments described below, this beat frequency ranges from 4 to 6 GHz and was unable to be seen with our 3 GHz bandwidth oscilloscope.

Simulations of DSB S2-PAWG were also run for a multiple pulse output to simulate arbitrary waveform generation. In this simulation, a half-period of a sine wave was approximated with nine compressed pulses as can be seen in Fig. 4(c). Note that in this simulation the probe chirp's frequency offsets were created on the rf chirps that drove the EOPM causing a beat frequency on each compressed pulse.

C. High-Bandwidth Experimental Results

Figure 5(a) shows on the left a 4 $\mu$s probe pulse with a bandwidth of 1.25 GHz, and on the right the resulting compressed pulse (magnified) with a measured FWHM duration of 0.90 ns. This result is close to the theoretical, Fourier-limited duration (0.89/B) of 0.71 ns. A figure of merit for a pulse compression technique is the compression factor (CF), which is the duration of the probe pulse, $\tau_{pb}$, divided by the duration of the compressed pulse, $\tau_{cp}$, (i.e., $CF = \tau_{pb}/\tau_{cp}$). The CF in Fig. 5(a) is ~4400. We subsequently increased the bandwidth of the 4 $\mu$s probe pulse to 4 GHz producing a compressed pulse with a 260 ps FWHM, shown averaged 16 times in Fig. 5(b). This result is close to the expected 0.89/B duration of 220 ps marked as the vertical lines in Fig. 5(b). The CF in this experiment was ~15,000. The effective bandwidth of ~3.8 GHz is the largest that has been achieved using S2 materials for pulse compression, nearly three times larger than any other demonstration to our knowledge.

Figure 6 shows arbitrary waveforms that were produced by DSB S2-PAWG. The waveforms shown in Fig. 6 are composed solely of pulses that were compressed from
4 μs probe pulses with 1.25 GHz of bandwidth. All these waveforms are single shot captures. Note that although all the waveforms we show in Fig. 6 are symmetric, this is not the result of the temporal symmetry of DSB PAWG outputs. All the waveforms shown were created from only the upper sidebands of the programming and probe pulses. The waveform created by the lower sideband’s pulses was gated and does not appear in the data. Figure 6(a) shows 15 separate compressed pulses that were programmed to synthesize a single period of a raised sine wave (i.e., a sine wave that is offset from zero). These compressed pulses are each 0.8 ns in duration and are spaced by 3.2 ns. Figure 6(b) shows the synthesis of the single same period of a raised sine wave, except the number of compressed pulses was doubled to 30 while the spacing between the pulses was halved to 1.6 ns. A single period of a square wave was created in Fig. 6(c) by 15 compressed pulses, each 0.8 ns in duration and spaced by 3.2 ns. Finally in Fig. 6(d) three periods of a square wave were formed. Each of the three periods was comprised of five 0.8 ns pulses that were spaced by 1.6 ns. The 0.8 ns duration of all these compressed pulses is in good agreement with the 0.89/B Fourier minimum duration of 0.71 ns. As seen in (c) and (d) of Fig. 6, there was issue with the linearity of the compressed pulses’ amplitudes, which may be due to saturation and could be improved by calibration. The data in Fig. 6 exemplify the abilities of an S2-PAWG device to create any arbitrary waveform and represent to our knowledge the first demonstrations of using low-bandwidth control electronics to control the width, amplitude, phase, and timing of 30 independent compressed pulses.

4. CONCLUSION

In conclusion we have demonstrated S2-PAWG using a DSB approach at bandwidths greater than 1 GHz. A compression factor of ~15,000 was achieved by compressing a 4 μs probe pulse to a 260 ps FWHM, demonstrating the largest effective bandwidth (3.8 GHz) to date. Up to 30 independent compressed pulses were produced and controlled using low-bandwidth electronics enabling the creation of unique arbitrary waveforms. To practically implement PAWG in the millimeter-wave regime, future work should focus on utilizing currently available, next-generation S2 materials that have ~300 GHz absorption features.
Such wideband materials will require the creation of optical chirps of comparable bandwidth to perform the engraving and probing of spectral holographic gratings. It appears that there are two possibilities for the generation of such optical chirps. First, highly linear, broadband, stabilized frequency agile laser sources similar to those used in [15, 27–32] should be developed with frequency errors much smaller than the inverse of the optical chirp duration. Or, second, low-cost, highly linear, broadband rf swept sources should be developed and used in conjunction with next generation ~100 GHz bandwidth EOPMs such as those described in [37, 38]. These stable rf chirps in combination with the frequency stable laser source must then meet the same frequency error requirements. Other hurdles to overcome include the tremendous increase in required optical power for engraving and probing such broad bandwidths, the increase in instantaneous spectral diffusion as more atoms are excited, and keeping the whole S2-PWAG system, including the cryogenic cooler, cost effective with performance equivalent to or better than that of the competing digital approach.

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