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RF-Photonic Wideband Measurements of Energetic Pulses on NIF Enhanced by Compressive Sensing Algorithms

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ABSTRACT

At the National Ignition Facility (NIF), home of the world's largest laser, a critical pulse screening process is used to ensure safe operating conditions for amplifiers and target optics. To achieve this, high speed recording instrumentation up to 34 GHz measures pulse shape characteristics throughout a facility the size of three football fields—which can be a time consuming procedure. As NIF transitions to higher power handling and increased wavelength flexibility, this lengthy and extensive process will need to be performed far more frequently. We have developed an accelerated high-throughput pulse screener that can identify nonconforming pulses across 48 locations using a single, real-time 34-GHz oscilloscope. Energetic pulse shapes from anywhere in the facility are imprinted onto telecom wavelengths, multiplexed, and transported over fiber without distortion. The critical pulse-screening process at high-energy laser facilities can be reduced from several hours just seconds—allowing greater operational efficiency, agility to system modifications, higher power handling, and reduced costs. Typically, the sampling noise from the oscilloscope places a limit on the achievable signal-to-noise ratio of the measurement, particularly when highly shaped and/or short duration pulses are required by target physicists. We have developed a sophisticated signal processing algorithm for this application that is based on orthogonal matching pursuit (OMP). This algorithm, developed for recovering signals in a compressive sensing system, enables high fidelity single shot screening even for low signal-to-noise ratio measurements.

Keywords: RF signal processing, RF photonics, single-shot, real-time, FM-AM conversion, compressive sensing

1. INTRODUCTION

High-energy laser facilities have become a modern workhorse for scientific discovery in such disciplines as astrophysics, materials science, nuclear science, the use of lasers in medicine, radioactive and hazardous waste treatment, particle physics, and eventually, abundant energy from fusion energy. At the National Ignition Facility (NIF), 192 intense laser pulses direct nearly two million joules of ultraviolet light onto a small, pill-sized, target creating extreme pressures and temperatures found only in stars. These unprecedented conditions could soon allow controlled fusion gain to safely generate electricity fueled by hydrogen—the most abundant element in the universe.

A critical aspect in operating a high-energy laser is ensuring that the laser does not exceed safe operating conditions for optics. The energetic beams of light are so powerful that, when left uncontrolled, they can shatter the extremely valuable glass inside the laser. In order to protect these optical surfaces from destructive acoustic waves (known as stimulated Brioullin Scattering), the laser pulse is conditioned by a rapid wavelength variation, a process known as wideband frequency modulation (FM). FM is also important for smoothing the illumination spot on the laser target (known as smoothing by spectral dispersion).

Ideally, this unseen modulation does not alter the temporal profile of the laser pulse intensity. In practice, however, the facility is susceptible to non-idealities that arise from small defects found in the many optics throughout the laser. When the laser's delicate gain and phase spectrum is perturbed, the once harmless FM can quickly transform into a rapid and harmful variation in laser peak power, a process known as frequency modulation to amplitude modulation (FM–AM) conversion. This newly formed ripple on the pulse profile can cause the intensities near the target (where peak power is the highest) to cross a threshold at which filamentation may occur inside valuable optics. This phenomenon is associated with intense light fields in matter and may cause hot spots on the beam that can exceed the safe operating intensity limits of the optics. Since filamentation is a function of laser power, identifying and solving the problem allows NIF to operate at higher power without increasing the risk for hot spots.

The first—and most critical—step in safeguarding a high-energy laser facility from harmful pulses is to locate them. Once they are screened, operators can quickly mitigate the AM using several established solutions. Unfortunately, capturing high-frequency ripple across many checkpoints has been a difficult and time consuming task. NIF currently uses 48 screening locations to identify harmful pulses. At each checkpoint, the fast-pulse ripple must be sampled by a state-of-the-art 34-GHz digital oscilloscope. While low-bandwidth digitizers are more economical, they are not fast enough to capture the high-frequency ripple. Moreover, the digitizer must be placed as close as possible to the checkpoint in order to minimize the use of lossy RF cables. These impediments in the screening process previously required transporting the recording equipment from location to location throughout the facility—an intrusive and lengthy process that can take up to 12 hours on NIF.

This time-consuming bottleneck of measuring AM has been overcome by a wideband RF-photonic network known as Laser Screening at High-throughput to Identify Energetic Laser Distortion (SHIELD). As a fully operational system, Laser SHIELD is capable of screening rapid variations in pulse peak power across 48 locations, using one 34-GHz-bandwidth oscilloscope. For the first time, accurate knowledge of AM can be obtained simultaneously at 48 checkpoints.

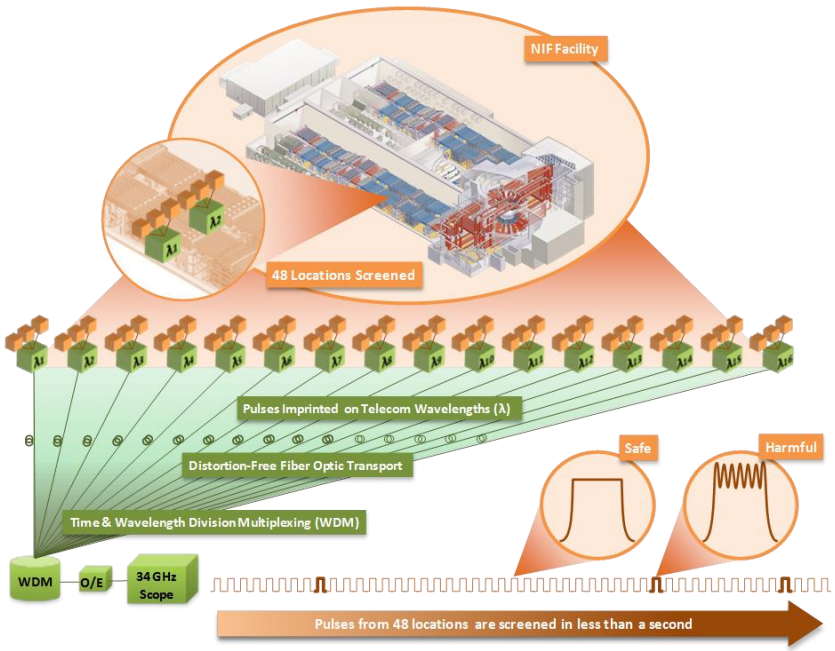


Figure 1. An overview of Laser SHIELD at the National Ignition Facility (NIF) where 48 laser-pulse checkpoints are screened in less than a second to ensure safe operating conditions for optics. (O/E: optical to electrical converter)

The reduction in the screening process from 12 hours to less than a second offers several advantages for high-energy lasers. First, the facility is able to fire more shots in less time—an efficiency gain that amounts to saving NIF millions of dollars per year. It might one day help safeguard fusion power plants that will require up to 15 target shots each second. Second, high-energy lasers are more flexible to the wavelength changes requested by target physicists. Changing the laser wavelength, ever so slightly, allows researchers to adjust the amount of energy that reaches different locations of the target. Third, high-energy lasers are able to achieve greater power handling without increasing the risk of filamentation. Finally, high-energy lasers can identify harmful beams before they can exceed safe operating intensities at the valuable optics near the target—potentially saving NIF hundreds of thousands of dollars per year.

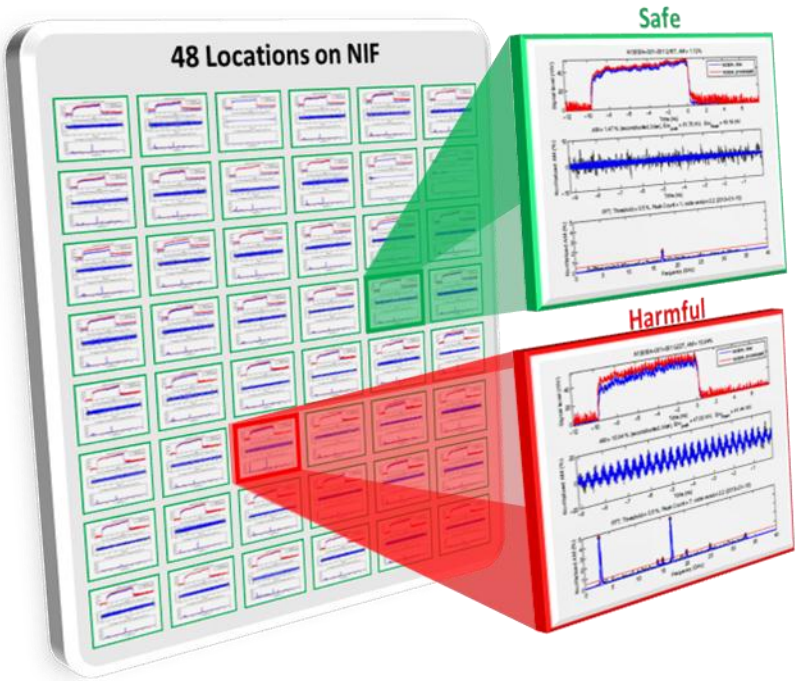


Figure 2. Pulse screening results captured by NIF's Laser SHEILD showing 48 laser-pulse checkpoints measured with the push of a button. Pulse shapes, frequency content of the AM (amplitude modulation), and total AM are reported to determine whether pulse intensities have exceeded safety margins for optics.

In practice, FM–AM conversion is a universal problem faced by high-energy lasers worldwide. Conditioning light pulses with wideband FM is necessary to avoid the buildup of harmful acoustic waves within the laser. The need to quickly and cost-effectively screen FM-AM conversion throughout the laser is a vital tool for any high energy laser. Facilities worldwide will immediately benefit from our technology: the OMEGA laser at the University of Rochester, GEKKO XII facility in Japan, new HiPER laser in the European Union, Shen Guang II laser system in China, and LMJ facility in France. One day, a fusion power plant could harness heat from this reaction to drive a steam-turbine generator and produce electricity with no pollutants or climate-changing gasses. These powerful lasers must fire at rapid rates (up to 15 times per second) for continuous energy production. As a result, the high throughput capability offered by Laser SHIELD will play an important role in making commercial fusion power plants economical, by lowering refurbishing costs and improving operational efficiency.

2. PRINCIPLE OF OPERATION

Laser SHIELD is a custom-designed high-throughput screening system built from low-cost and commercially available components. Its all-fiber design makes it amenable to the unique needs of high-energy laser facilities, for instance, routing to intricate pick-off locations, immunity to electromagnetic interference, and low-loss transport (up to several kilometers). To understand Laser SHIELD's operation, we will walk through the five-step screening process.

STEP 1: Pulse Freezing

Optical components used in a screening system have the potential to introduce additional FM-AM conversion. For example, filters, lengthy fibers, amplifiers, couplers, etc. can exhibit spectral distortion (amplitude and phase) that can artificially increase or decrease the reported AM value. To avoid this problem, Laser SHIELD "freezes" the pulse shape as close as possible to the screening location. This is performed by a wideband photodetector that converts the input light

at 1053-nm into an electrical signal. Since these devices are square-law detectors, responding to the square of the electric field strength, only AM passes through while FM is rejected. As a result, this step ensures a snapshot of the pulse shape is “frozen” in time and FM-AM conversion can no longer occur in the screening process.

STEP 2: Shape Imprinting

Once in the electrical domain, the pulse shapes are imprinted onto a wavelength near 1550 nm. This important step allows cost-effective components in the telecommunications industry to perform long range transport and low-loss multiplexing. FM-AM conversion will not take place at telecom wavelengths since FM modulation has been removed in Step 1. The pulses are imprinted onto a telecom laser operating near 1550 nm using a broadband radio frequency (RF) amplifier to boost the signal, followed by a wideband electro-optic modulator to carve the pulse shape. If additional screening locations are required in the future, the system may be scaled using dense wavelength division multiplexing (DWDM) technology, which can screen up to several hundred channels at once.

STEP 3: Transporting, Multiplexing, and Digitizing

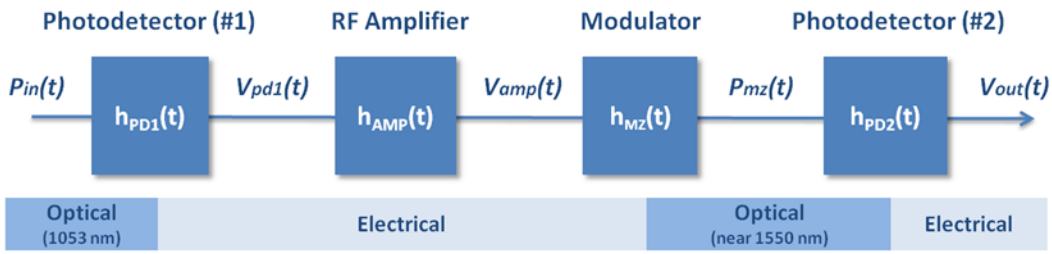
Lengthy optical transport fibers are used to route pulses away from the pick-off locations and ensure the 48 pulses do not overlap in time. The use of optical fiber allows pulses to be transported throughout the facility without attenuation restrictions (exhibited by RF cables). When the pulses reach their final destination (e.g., a control room), a wavelength division multiplexer (WDM) combines all 48 pick-off locations. The low-loss nature of WDM components keeps power levels in the transport fiber away from the nonlinear regime, which could alter the AM result. Next, a real-time wideband digitizer with up to 34 GHz bandwidth captures all 48 locations in a 5-microsecond single-shot acquisition.

STEP 4: Data Processing

After digitization, raw data is parsed and processed off line to compute the AM result. An end-to-end mathematical model accounts for well known component responses within Laser SHIELD through a self-calibration procedure (described below). The calibration includes the amplitude and phase response of the components (e.g., photodetectors, patch cords, amplifiers, modulators, and digitizers) as well as the sinusoidal transfer function of the electro-optic modulator. A signal processing algorithm compensates for these responses to yield an accurate AM result.

STEP 5: Self-Validation and Self-Calibration

An end-to-end validation and calibration system has been built to ensure optimal performance and reliability over the life of the system. At any point in time, a test pulse with predetermined AM can be created and distributed to all high speed photodetectors described in Step 1. These test pulses undergo Steps 1-4, like ordinary NIF pulses, and the AM result is validated by comparing to the predetermined AM setting. If discrepancies arise from system changes (e.g. from environmental fluctuations or sub-component degradation), an automatic calibration is performed and applied to the data processing algorithm (Step 4). This “in-situ” self-validation and self-calibration capability helps guarantee accurate results. Moreover, it reduces the need to go out into the field and individually test and recalibrate Laser SHIELD components over time.



Forward direction: $$V_{out}(P_{in}) = \frac{V_{\max}}{2}\left\{1-\cos\left[\frac{\pi}{V_{pi}}\left(G\Re_1 R_1[P_{in}(t) * h_{PD1}(t) * h_{AMP}(t) * h_{MZ}(t)] + V_{bias}\right)\right]\right\} * \Re_2 R_2 h_{PD2}(t)$$

Reverse direction: $$P_{in}(V_{out}) = \frac{V_{pi}}{G\Re_1 R_1 \pi}\Im^{-1}\left\{\frac{\operatorname{acos}\left[1-\left(2/\left(V_{\max}\Re_2 R_2\right)\right)\cdot \Im^{-1}\{V_{out}(f)/H_{PD2}(f)\}\right]-V_{bias}}{H_{PD1}(f)\cdot H_{AMP}(f)\cdot H_{MZ}(f)}\right\}$$

Variable	Description	Units
$P_{in}(t)$	Optical signal from pick-off	Watts
$V_{pd1}(t)$	Electrical signal after first photodetector	Volts
$V_{amp}(t)$	Electrical signal after RF amplifier	Volts
$P_{mz}(t)$	Optical signal after modulator	Watts
$V_{out}(t)$	Electrical signal after final photodetector	Volts
$R_{1,2}$	Photodetector impedance	Ohms
$R_{1,2}$	Photodetector responsivity	Amps/Watt

Variable	Description	Units
V_{max}	Power of telecom laser	Volts
V_{pi}	Voltage for modulator to see π phase shift	Volts
V_{bias}	Bias voltage for modulator	Volts
G	Gain of RF amplifier	-
$\mathcal{F}^{-1}$	Inverse Fourier transform	-
h(t)	Impulse response of component	-
H(f)	Frequency response of component	-

Figure 4 illustrates a mathematical model describing the evolution of a NIF pulse as it travels through four key components (first photodetector, RF amplifier, modulator, and final photodetector) prior to the oscilloscope. The data-processing algorithm discussed in Step 4 uses this model in a reverse direction to calculate the AM result for all 48 checkpoints. Calibration data corresponding to each channel is used to recover the input optical signal. At any time, an automatic calibration can be performed to measure the numerical constants and frequency responses found in the Laser SHIELD model.

Prior to Step 1, a series of three pulses is formed by time multiplexing three neighboring pick offs. The triplet is captured by one of 16 photodetectors having 60-GHz bandwidth at 1053 nm. In Step 2, pulses are imprinted onto fiber-coupled telecom lasers using 16 RF amplifiers at 55-GHz bandwidth, 16 electro-optical modulators at 40-GHz bandwidth, and 16 laser diodes operating at various DWDM channels. In Step 3, the pulses are transported through large effective area fiber (LEAF) before reaching one of two 8-channel WDMs. The WDMs feed 2 1550-nm, 60 GHz photodetectors, which in turn enter 2 channels of a 34-GHz, real-time oscilloscope. In Step 4, the data processing algorithm performs calculations on an off-line PC that provides AM results to the shot director for immediate feedback. In Step 5, a 1550-nm test pulse is created using a low-speed modulator to carve a 10-ns, flat-in-time envelope as well as a high-speed modulator to create a pre-determined AM ripple. An AM signal is generated by superimposing several RF voltage controlled oscillators (VCOs) at various frequencies and amplitudes. The signal is amplified by an erbium-doped fiber amplifier (EDFA) and distributed among 16 photodetectors used in Step 1.

3. COMPRESSIVE SENSING ENHANCEMENTS

Typically, the sampling noise from the wideband oscilloscope places a limit on the achievable signal-to-noise ratio of the measurement, particularly when highly shaped and/or short duration pulses are required by target physicists. In order to improve the single-shot performance of Laser SHIELD, we investigated several digital signal processing algorithms based on compressive sensing. In the study, we modeled a typical AM signature modulated on a synthetic NIF pulse. The AM signal and shape of the pulse envelop shown are only for simulation purposes and not representative of actual measurements. The AM signature can be described as set of RF frequency tones which exist on a fixed integer frequency grid from 1-34 GHz. The number of tones depends on the degree of FM-AM conversion used in the model.

Our simulation consists of a set of 5 sinusoids superposed on a ~4 ns laser pulse. The signal is digitized by a 100 GS/s digitzer and the goal is to correctly derive the 5 frequencies and complex amplitudes at the lowest possible signal level relative to the intrinsic noise of the digitizer (see preceding section). Fig. 5a shows the un-modulated laser pulse, Fig. 5b shows the pulse plus 5 sinusoid, Fig. 5c shows the same for a case where the sinusoids are at the edge of the detection limit, and Fig. 5d is a blow up of the noise free case (5c). We investigate 4 separate methods for recovering the sine waves: (1) discrete Fourier transform (DFT), (2) multiple signals classification (MUSIC), (3) basis pursuit de-noising (BPD) and (4) orthogonal matching pursuit (OMP). We make use of additional information: the number of sinusoids is exactly 5, the sinusoids have frequencies that are integral multiples of 1 GHz and the maximum possible frequency is 34 GHz. Before applying the recovery methods, it is useful to remove the laser pedestal and select a time window. The pedestal can be removed by subtracting the waveform shown in Fig. 5a from those in Figs. 5b and 5c or by dividing that waveform into those in Figs. 5b and 5c. Since the sinusoids modulate the laser pulse, they are not present before and after the laser pulse. Thus before about 6 ns and after about 12 ns, the signal consists primarily of noise and the time window should be chosen appropriately.

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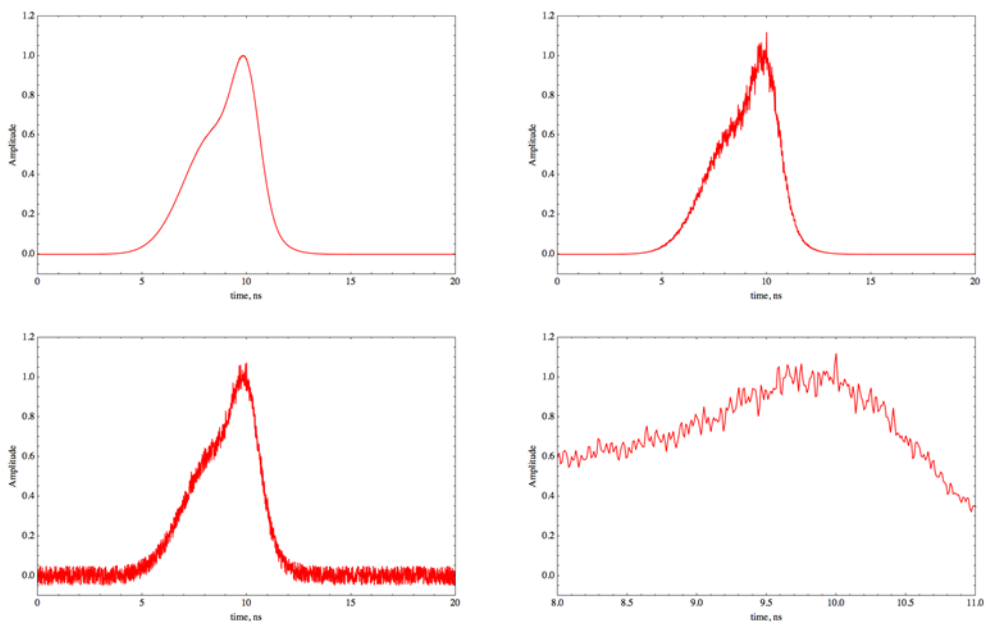

Fig. 5. Amplitude as a function of time. (a) Laser pulse, (b) laser pulse plus large signal (signal amplitude = 0.03) , (c) laser plus small signal (signal amplitude = 0.01) and high noise (noise level = 0.1), (d) blow up of (b).

Use of a DFT to find frequencies needs no more explanation. Fig. 6a shows the absolute value of the DFT of the signal in Fig. 5c over the 600 to 1200 ps window with the pedestal subtracted out. The 5 sinusoids are clearly visible at both positive and negative frequencies (because the sinusoids are real).

Basis Pursuit Denoising (or alternatively, the penalized ell-1 norm method) has been widely used in work on compressive sensing (Baraniuk 2007, Gill et al. 2001 and Loris 2008) to recover sinusoids and a wide range of other signals. It relies on finding the vector argument that minimizes a functional that is the sum of two terms: the first term enforces that the vector satisfies the measurement while the second term promotes a sparse vector solution. If the penalty parameter that controls the relative weight of the sparsity-promoting term compared to the measurement term is set properly, basis pursuit will recover just the unknown frequencies even in the presence of noise as shown in Fig. 6b.

Multiple Signals Classification (MUSIC) (Schmidt 1986) uses a subspace method to recover the frequency content of signals composed of the sum of sinusoids plus noise. An autocorrelation matrix is formed from the time series and the first n eigenvectors of this matrix correspond to the n sinusoids present in the time series while the remaining eigenvectors correspond to the noise. If n is known, this provides a natural separation between the signal and the noise and leads to a well-known frequency estimator (Schmidt 1986) that gives the result shown in Fig. 6c. Note that unlike

the DFT and basis pursuit, MUSIC is a super-resolution method that can be used to find frequencies off the DFT grid. Since our frequencies are known to like on the DFT grid, this aspect of MUSIC is unnecessary for our problem.

Orthogonal Matching Pursuit (OMP), another technique widely used in compressive sensing and elsewhere (Tropp and Gilbert 2007; Kunis and Rauhut 2008; Huang and Zhu 2011, Valley and Shaw 2011) uses a different approach to find the frequency and amplitude of sinusoids (or other waveforms). First, a dictionary matrix for the system is calculated. Each column of the dictionary corresponds to a time series for a sine wave at a frequency of interest. Second, the dictionary is correlated with the measurement vector and the position of the maximum in the correlation gives an estimate of the frequency of the largest sinusoid present in the signal. If the dictionary is the same as the matrix used in the discrete Fourier transform, then this correlation process is the same as taking the DFT. Third the amplitude of the first sinusoid is estimated directly form the data and a time series is synthesized for the first sinusoid. This can then be subtracted from the data and the process repeated for the 2nd through 5th sinusoids. In our case, we know that all the frequencies are integral multiples of 1 GHz up to 34 GHz so the dictionary only has 34 columns. This gives OMP an advantage over the other methods for our problem. The spectrum calculated with OMP is shown in Fig. 6d.

Fig. 7 shows the same 4 spectra for conditions in which the signal is 4 times smaller and the noise is the same as in Fig. 6. Note that nothing is discernable in the DFT spectrum, the Basis Pursuit and MUSIC spectra are completely wrong and only the OMP recovers almost all of the frequencies (4 of 5 correct).

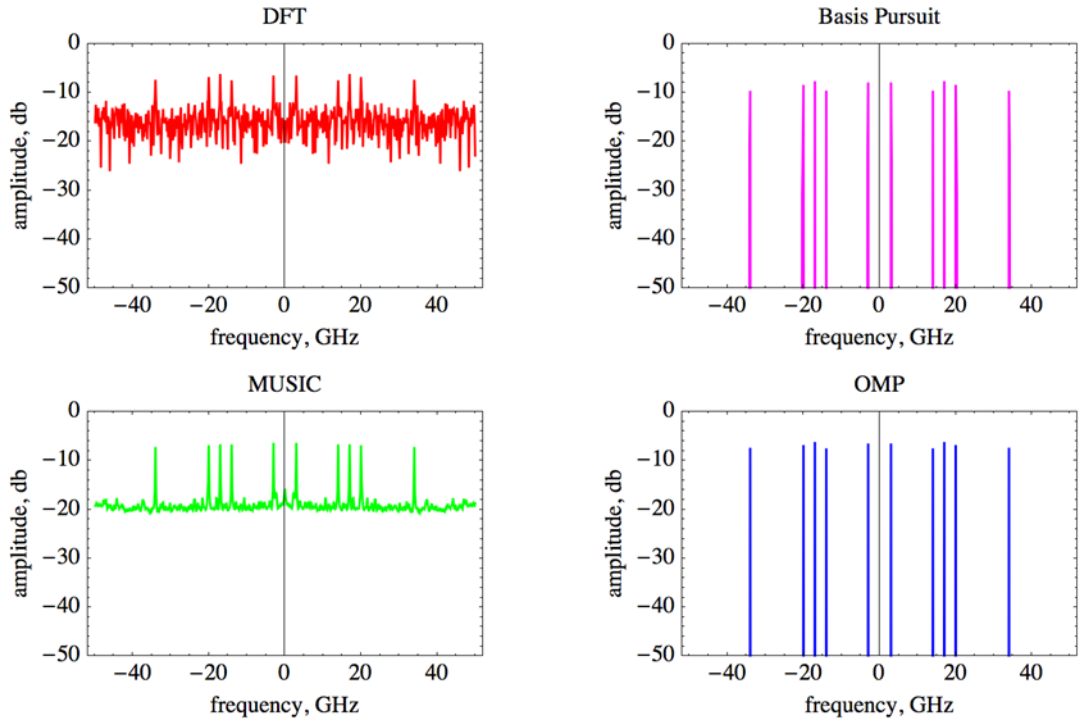

Fig. 6. Spectra for signals recovered by DFT, BPD, MUSIC, and OMP for signal with signal amplitude = 0.03 and noise level = 0.1.

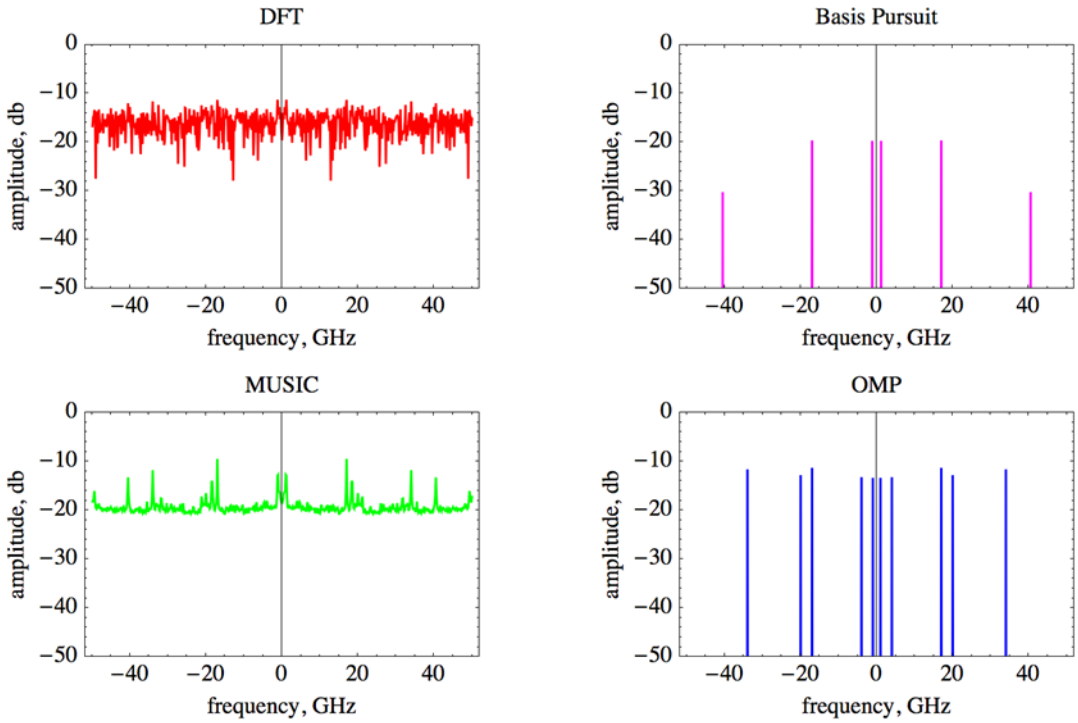

Fig. 7. Spectra for signals recovered by DFT, BPD, MUSIC, and OMP for signal with signal amplitude = 0.0075 and noise level = 0.1.

The spectra shown in Figs. 6 and 7 are derived for single realizations of the noise and thus the result that the OMP provides better performance than the other methods might simply be due to use of a lucky realization of the noise. Therefore, we performed calculations comparing OMP and DFT for 100 and 1000 realizations of the noise. The results for 1000 realizations were essentially the same as for 100 realizations so we present in Fig. 8 a plot of the number of correct frequencies recovered with OMP and the DFT averaged over 100 realizations. These calculations were performed for a signal that consisted solely of the sum of 5 unit amplitude sine waves and Gaussian distributed noise with standard deviation σ.

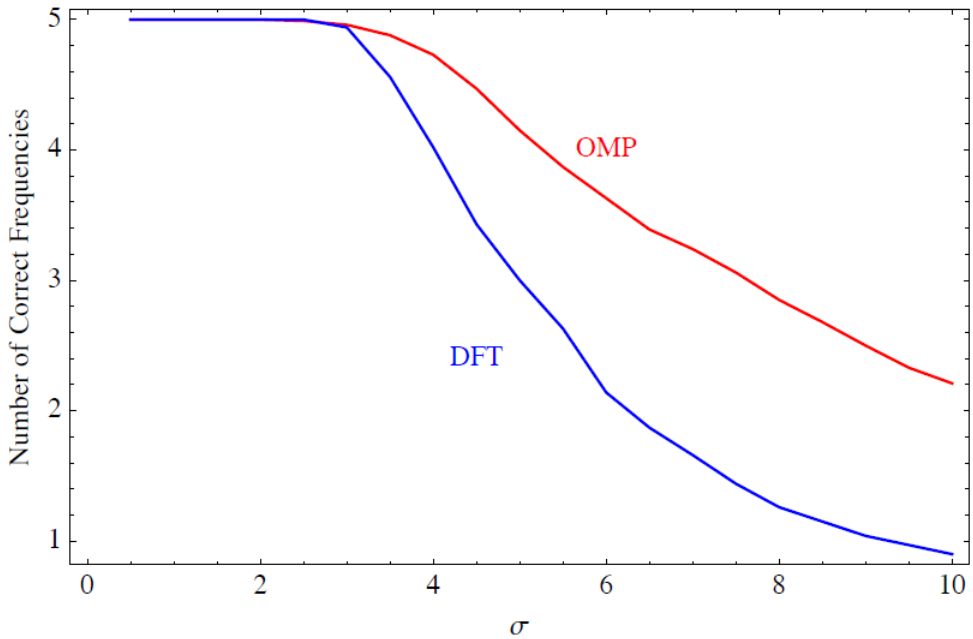

Fig. 8. Number of correct frequencies as a function of the standard deviation of Gaussian noise applied to each of 500 time points.

4. CONCLUSION

We have developed an accelerated high-throughput pulse screener that can identify nonconforming pulses across 48 locations using a single, real-time 34-GHz oscilloscope. Energetic pulse shapes from anywhere in the facility are imprinted onto telecom wavelengths, multiplexed, and transported over fiber without distortion. The critical pulse-screening process at high-energy laser facilities can be reduced from several hours just seconds—allowing greater operational efficiency, agility to system modifications, higher power handling, and reduced costs. Typically, the sampling noise from the oscilloscope places a limit on the achievable signal-to-noise ratio of the measurement, particularly when highly shaped and/or short duration pulses are required by target physicists. We have developed a sophisticated signal processing algorithm for this application that is based on orthogonal matching pursuit (OMP). This algorithm, developed for recovering signals in a compressive sensing system, enables high fidelity single shot screening even for low signal-to-noise ratio measurements.

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