Modulation Index Boosting (MiBo) and Enhanced PDV Sensitivity for Unconventionally High-Velocity Objects

David Borlaug,[1,2] **Bill Seng**,[2] **Crystal Glen**,[2] **and Bahram Jalali**[1]

[1]University of California, Los Angeles

[2]Sandia National Laboratories

Tuesday, June 7, 2016, 2:20 PM – 2:40 PM

Photon Dopler Velocimetry Workshop, 2016

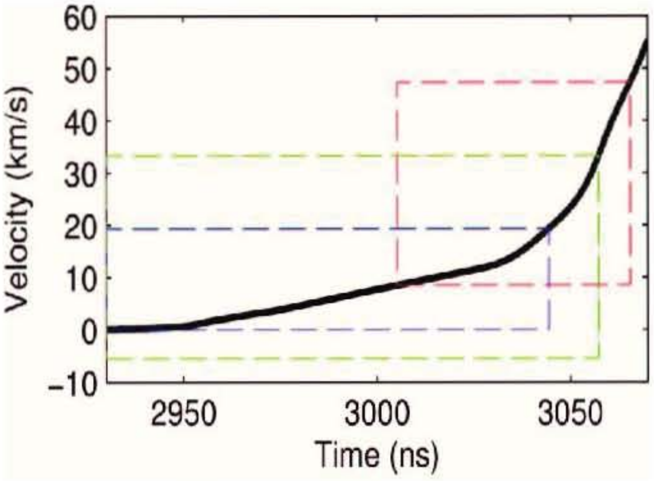
The Bankhead Theater -- Livermore, California

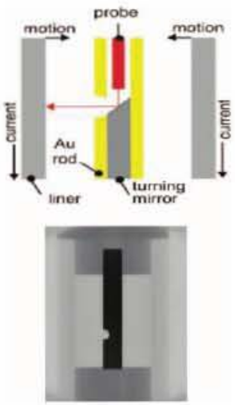
Outline

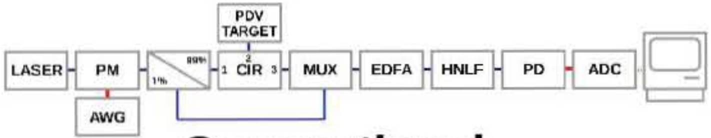
- Modulation Index Boosting (MiBo)
  - Concept, Principles, Simulations, Experiments, Prototype
- PDV at Sandia's Z-Machine, one example from 2013
- General PDV Model & Waveform Synthesis
- MiBo & PDV
- Future Enhancements: MiBo + Time-Stretch
- Summary / Discussion

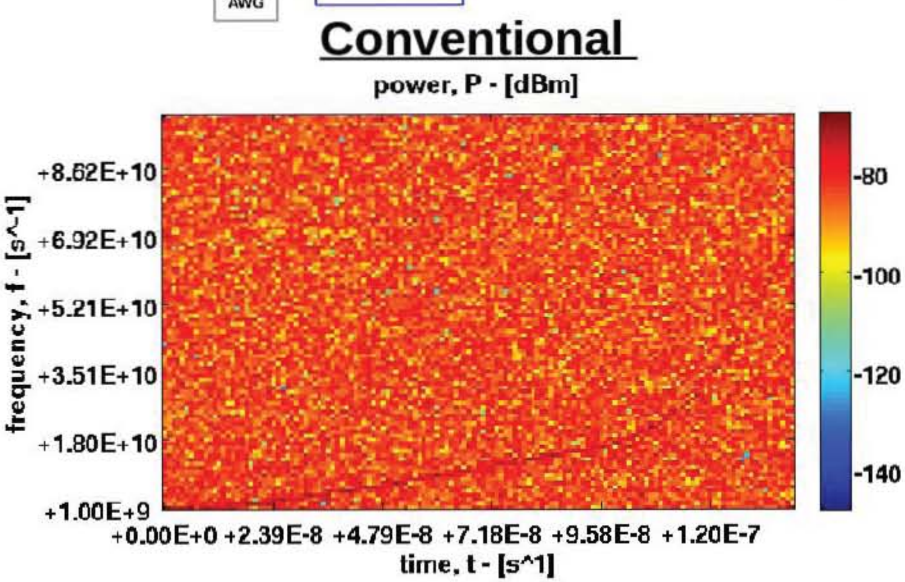
Photon Doppler Velocimetry

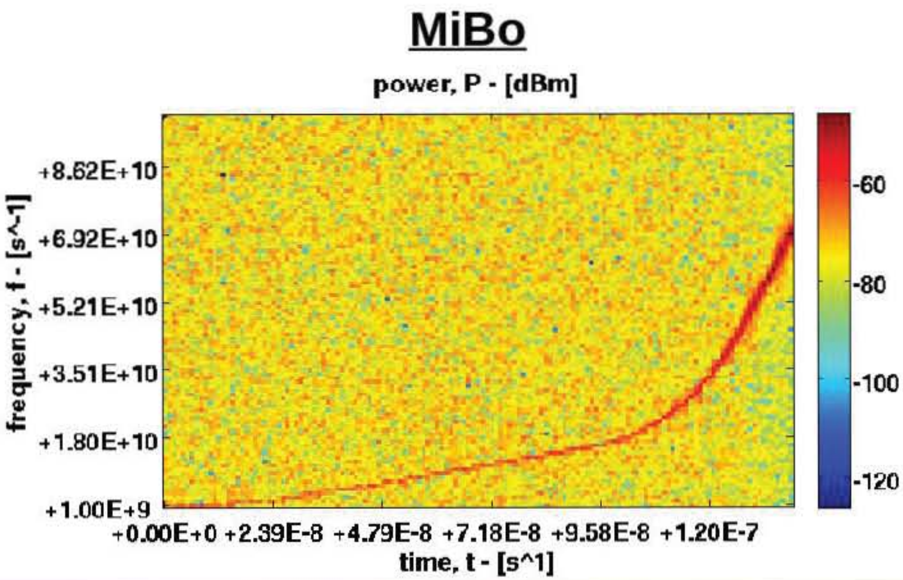
- Photon Doppler Velocimetry (PDV), developed by Sandia, utilizes Doppler velocimetry to track unconventionally high-velocity objects.
- PDV waveforms contain broadband 1-70 GHz content.
- Simulation show MiBo improves PDV detection sensitivity by 10 dB in general, and by 20 dB for signals beyond 40 GHz.
- Jalali-Lab's Time-Stretch Technology already deployed at DoE facility





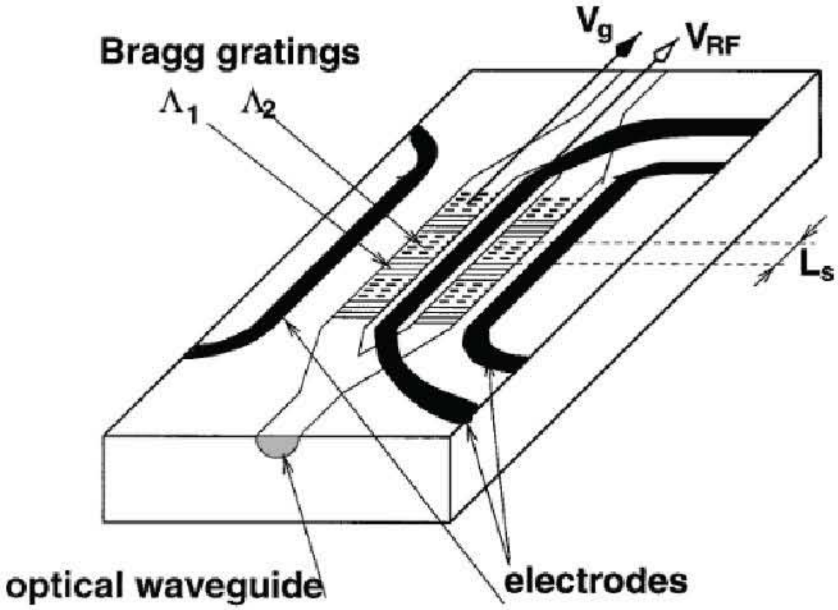






Traditional Approaches to Vpi Reduction

- **Velocity matching**
- **High r33 material**
  Lithium niobate ($LiNbO_3$), d_{33} = 30.9 pm/V
- **Resonant modulators**

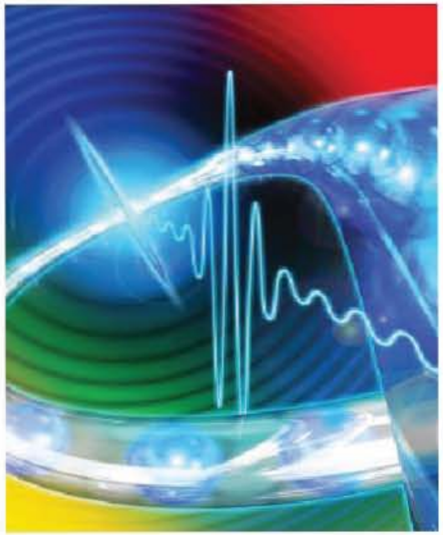


- **Distributed RF amplification along the waveguide**

Are there other, previously unexplored approaches for Vpi reduction?

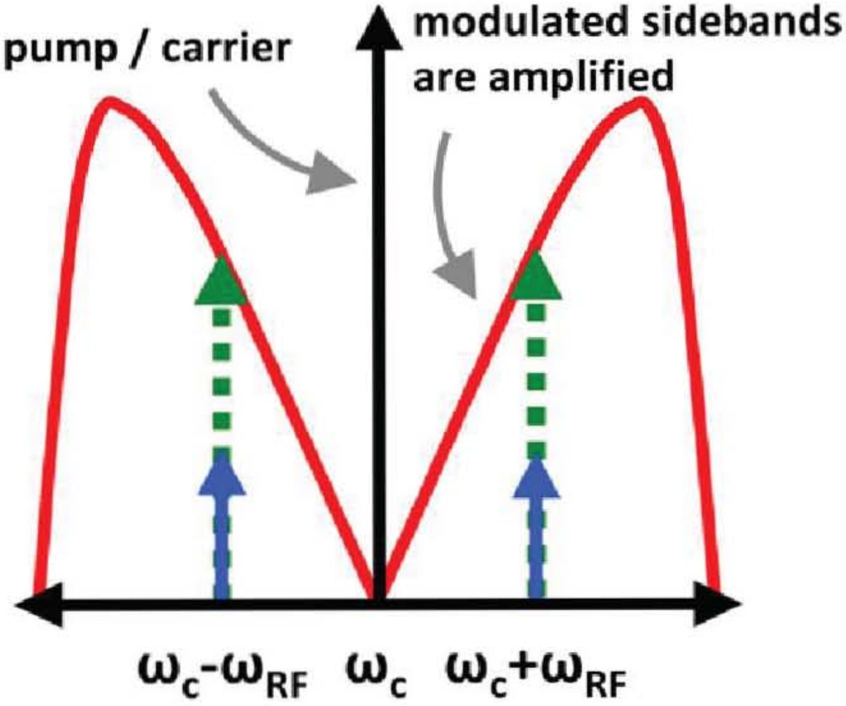
Benjamin Feir Sideband Amplification

- **Responsible for spontaneous pattern formation**
- **Sand ripples, cloud formations, water waves, coupled pendula, queues**
- **Optical rouge waves**
  Jalali-LAB, 2007
- **Solitons & supercontinua**
- **Amplifies Sideband-only**
  (at the expense of the carrier)



MiBo exhibits high-pass frequency amplification, g(ω). Modulated sidebands are amplified at the expense of the pump/carrier to increase modulation depth and lower V_π.

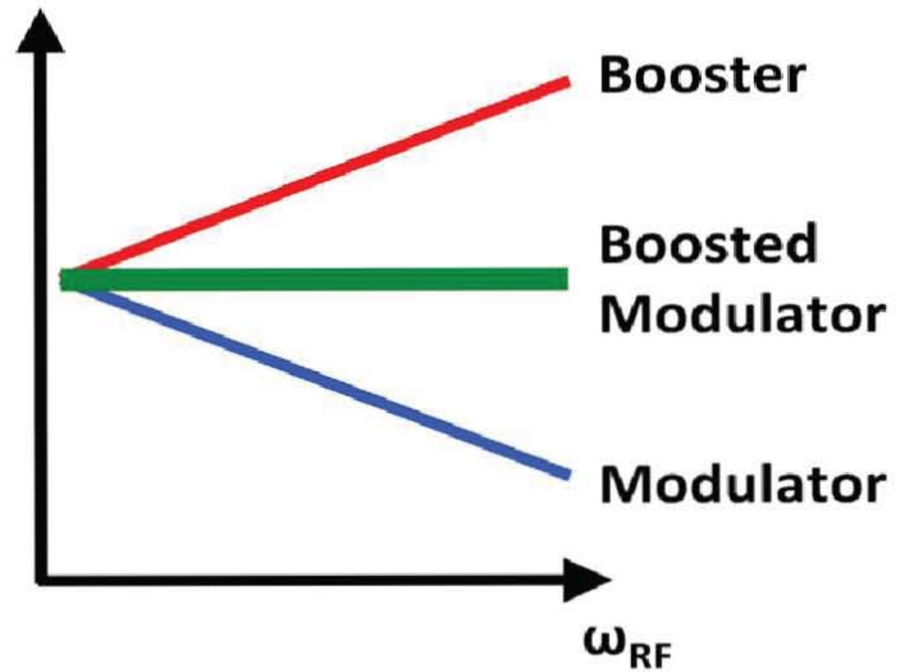
Gain Spectrum



$$g(\omega) = |\beta_2 \omega| [(4\gamma P/|\beta_2|) - \omega^2]^{1/2}$$

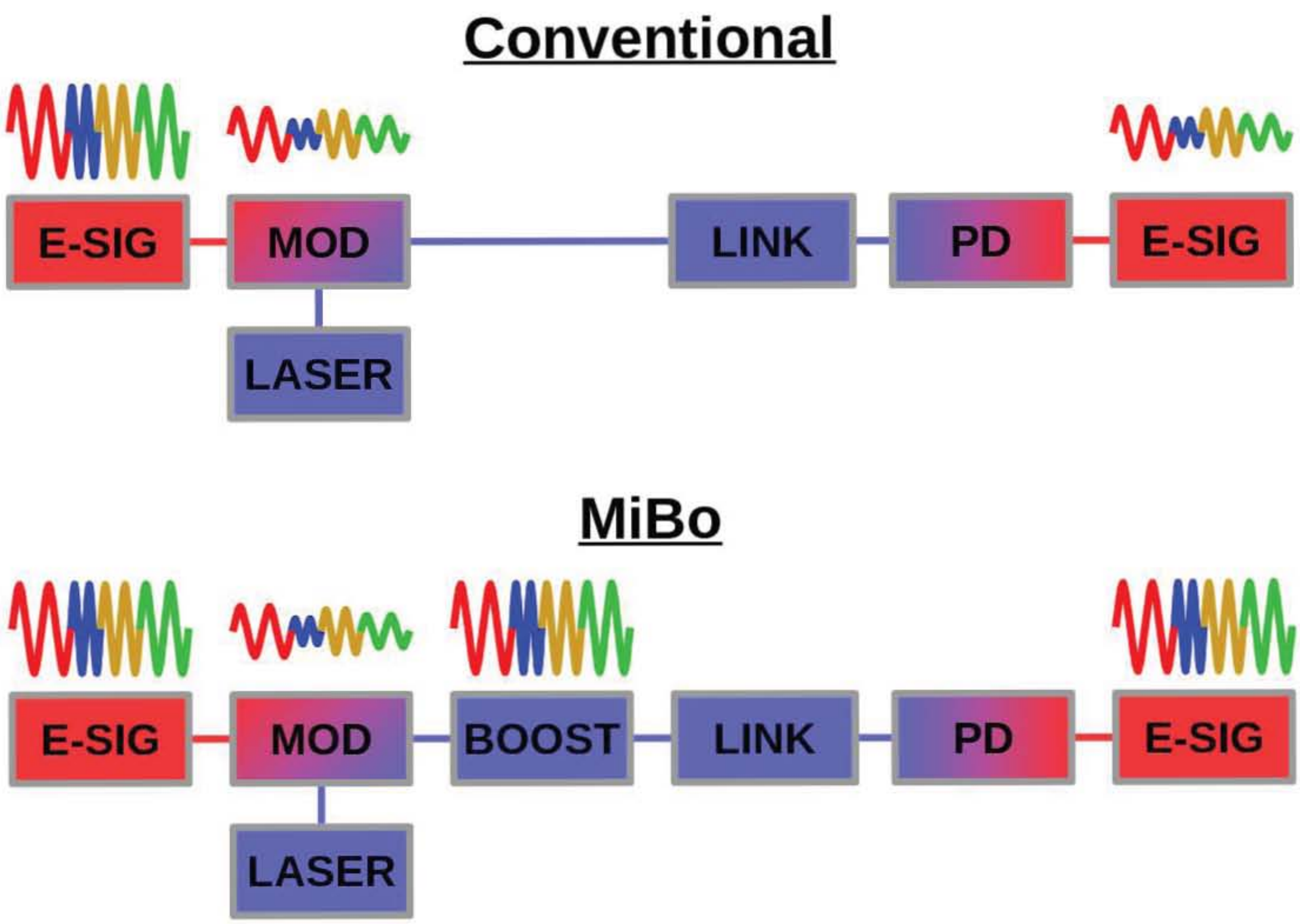
$\Omega_c = 4\gamma P/|\beta_2|$ $\quad V_{\pi,eff}(\omega) = V_\pi(\omega)/\sqrt{G_{MI}(\omega)}$

Modulation Depth

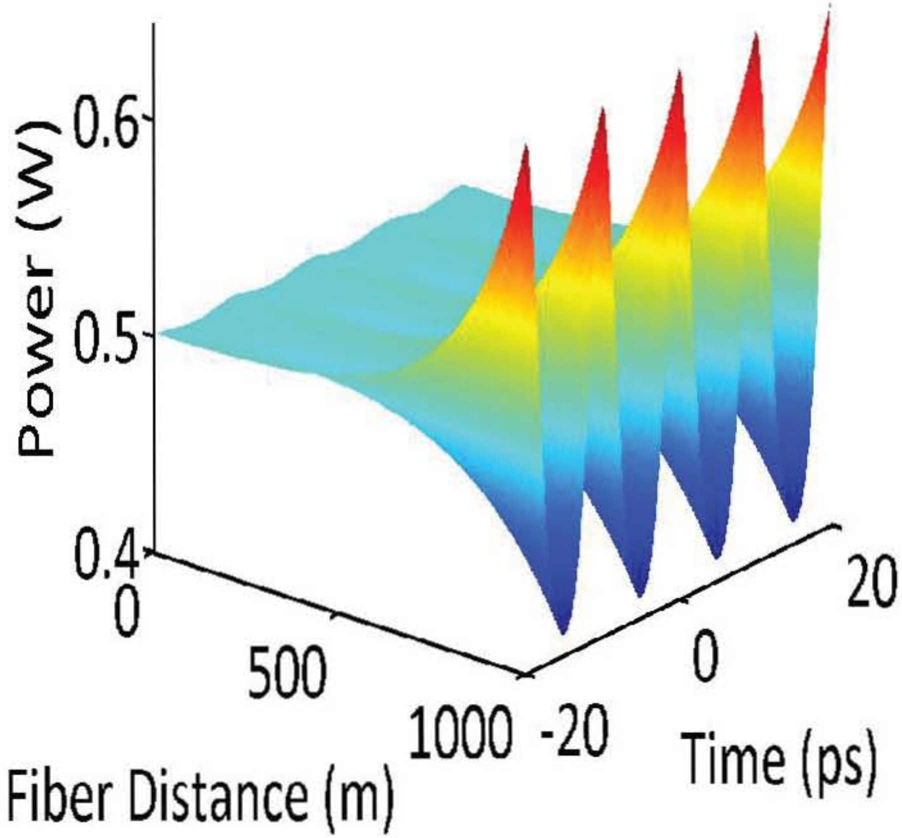


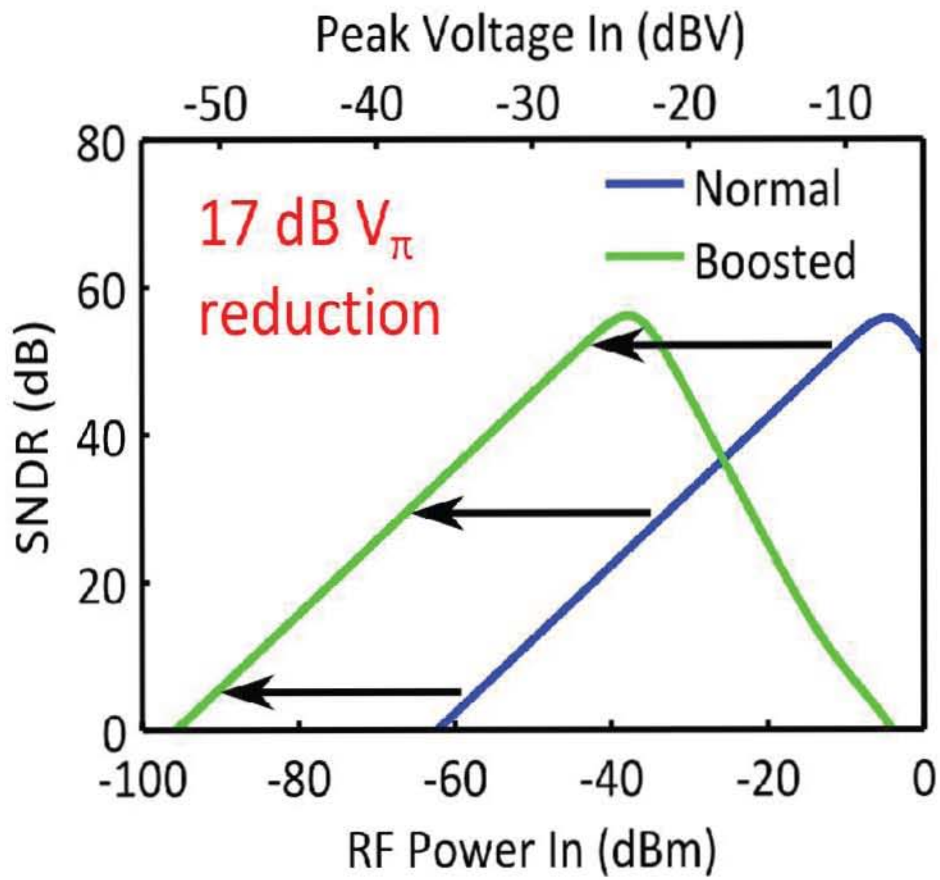
Boosted Modulator

MiBo Concept



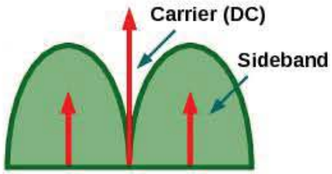
Modulation Index Booster (MiBo)





$$SNR \propto P_{RF,out} \propto \frac{1}{V_{\pi,eff}^2}$$

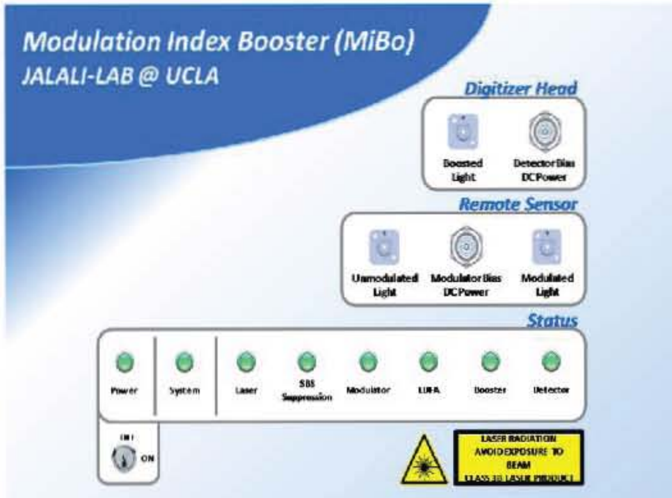
Approach Comparison

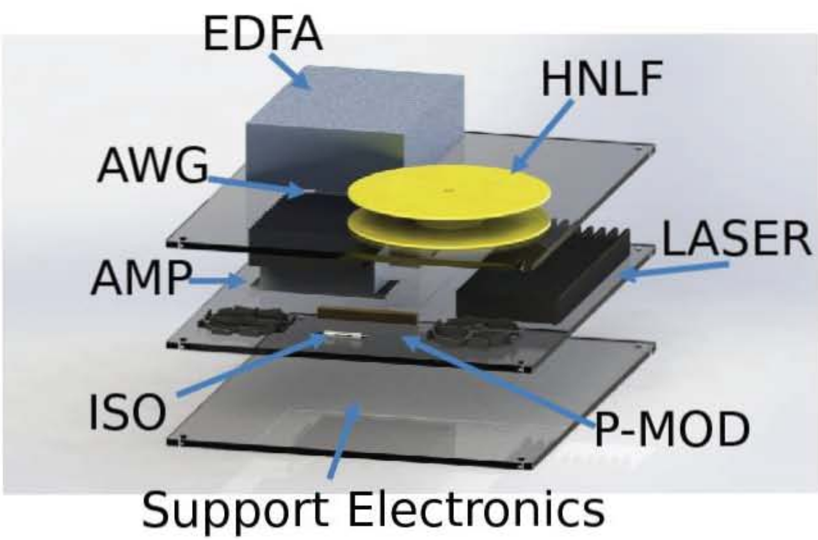


	Carrier Filtering vs MiBo	
	Carrier Filtering	MiBo
Sideband Response	Net Loss: Passive Filter Insertion Loss	Net Gain: 15 dB @ 50 GHz
Carrier Response	Strongly Attenuated	Negligible Propagation Attenuation
Sideband:Carrier Specificity	Strong	Strong
Active Filter Tuning & Locking	Yes: Required	No: Self-Aligned
Temperature Drift	Yes	No

	EDFA vs MiBo	
	EDFA	MiBo
Sideband Response	Strongly Amplified	Net Gain: 15 dB @ 50 GHz
Carrier Response	Strongly Amplified	Negligible Propagation Attenuation
Sideband:Carrier Specificity	Poor	Strong
Active Filter Tuning & Locking	No: Self-Aligned	No: Self-Aligned
Temperature Drift	No	No

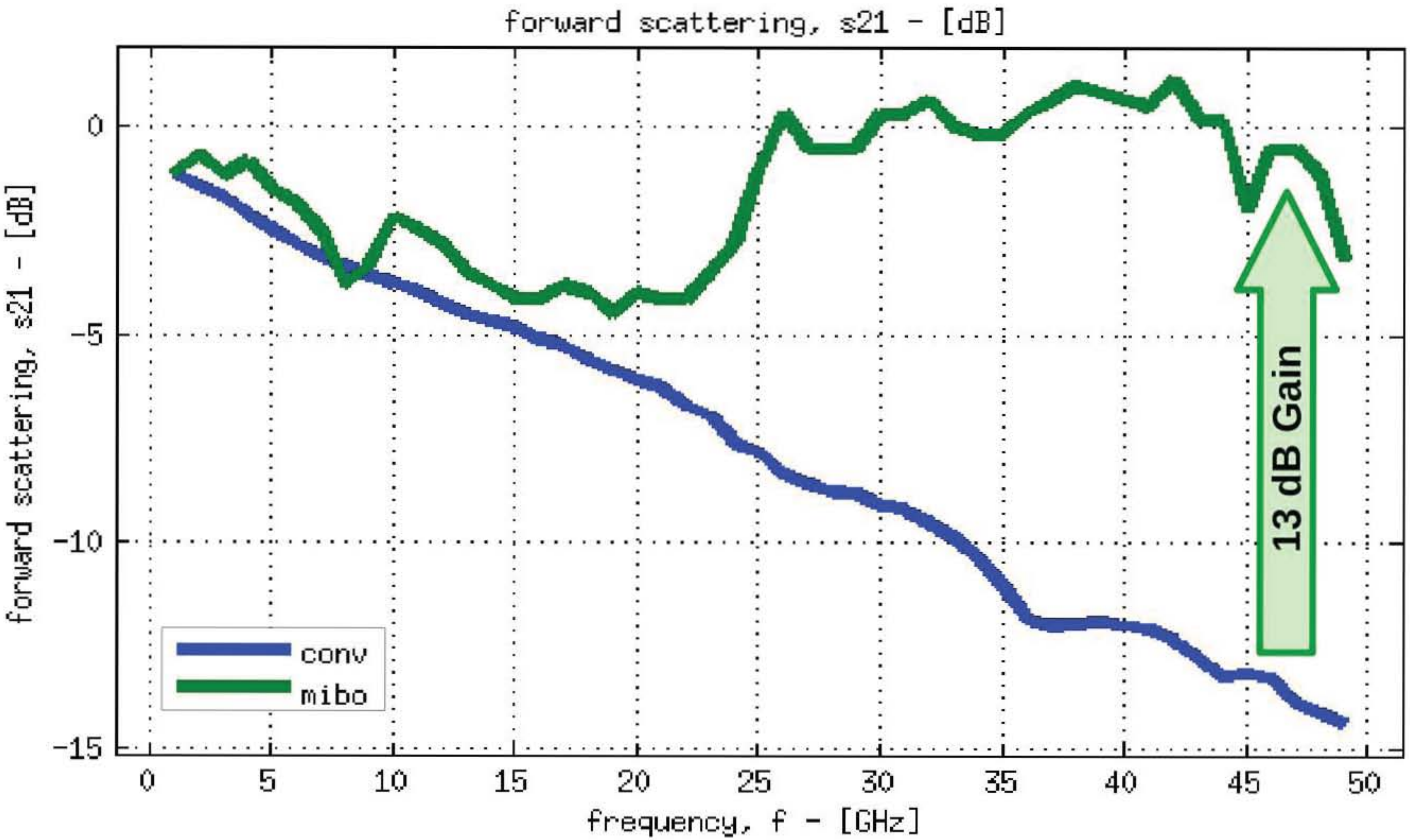
MiBo Prototype
(Components Ordered and Received – Assembly underway)



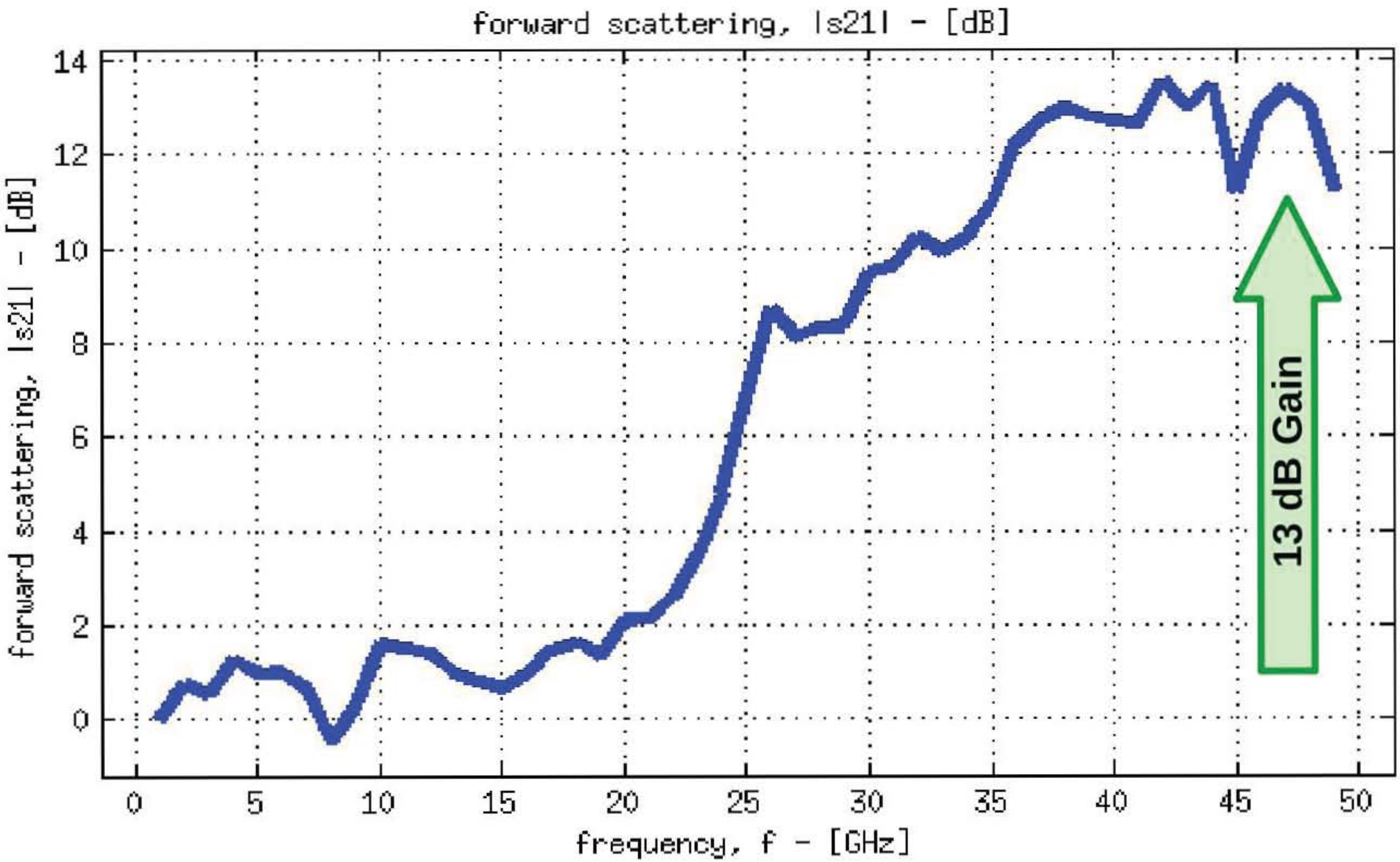


Gen-2 MiBo Prototype

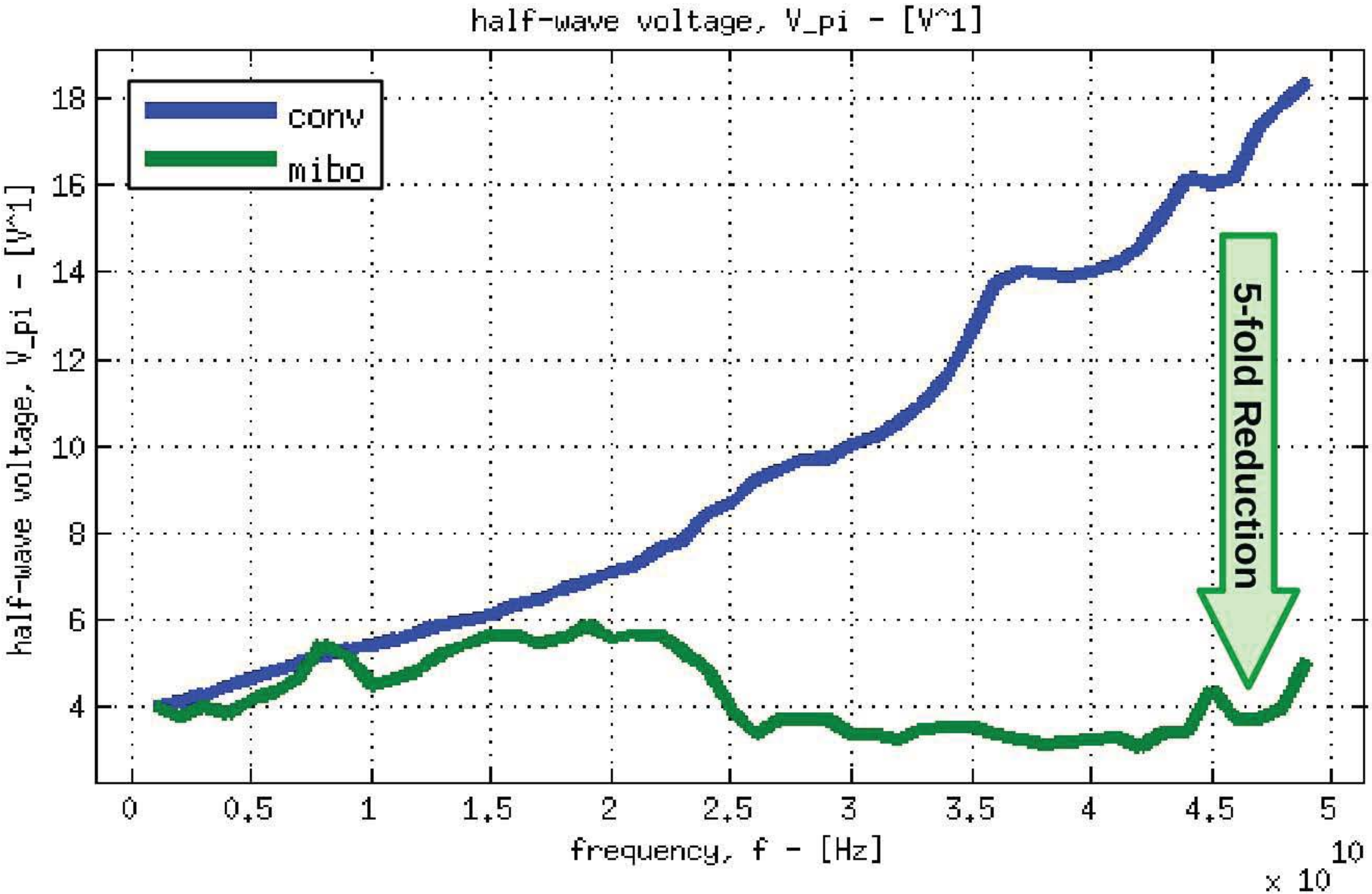
Gen-2 MiBo Prototype -- Experimental Data
S_21 {MiBo; Conventional}



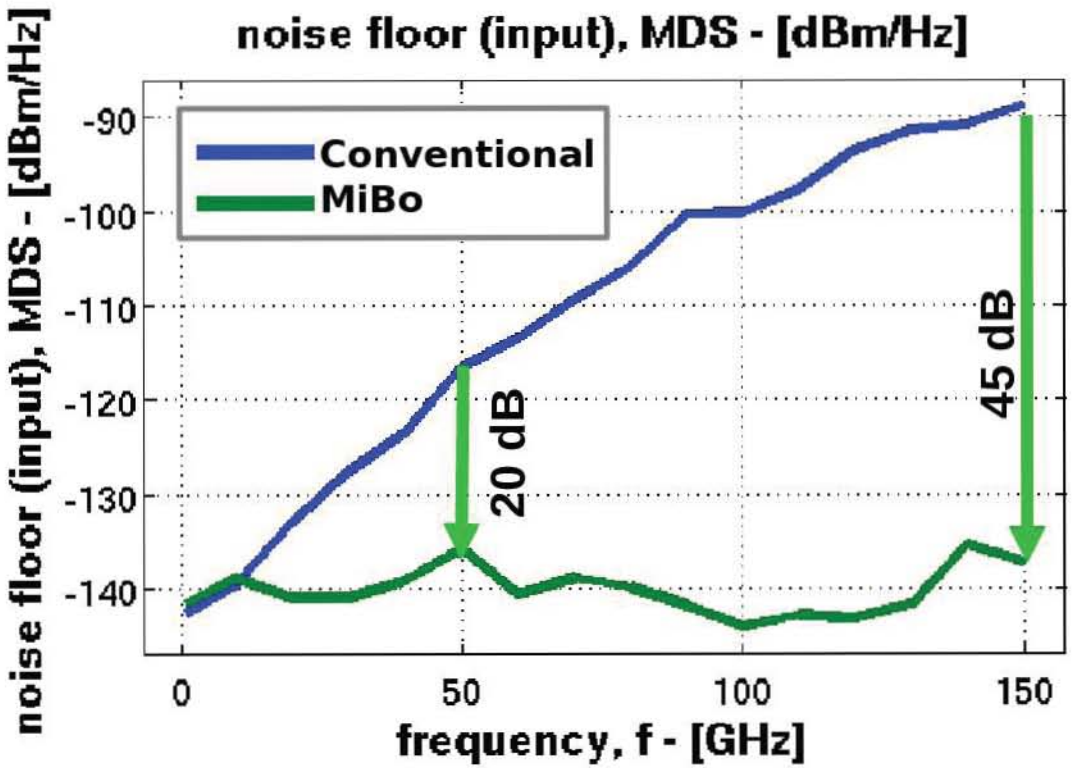
Gen-2 MiBo Prototype -- Experimental Data
MiBo Gain



Gen-2 MiBo Prototype -- Experimental Data
Half-Wave Voltage



Weak Signal Detection



MiBo improves electrical Minimum Detectable Signal (MDS) by:
20 dB @ 50 GHz
45 dB @ 150 GHz

Simulations show MiBo can remotely sense signals as weak as -140 dBm/Hz from 1-150 GHz

Theoretical limit: -145 dBm/Hz Cox, IEEE Trans. MTT 2006, RIN=-175 dB/Hz.

REVIEW OF SCIENTIFIC INSTRUMENTS **84**, 055102 (2013)

Tracking an imploding cylinder with photonic Doppler velocimetry

D. H. Dolan,[1,a)] R. W. Lemke,[1] R. D. McBride,[1] M. R. Martin,[1] E. Harding,[1] D. G. Dalton,[1] B. E. Blue,[2] and S. S. Walker[3]
[1]*Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*
[2]*General Atomics, San Diego, California 92121, USA*
[3]*National Security Technologies, Albuquerque Operations, Albuquerque, New Mexico 87185, USA*

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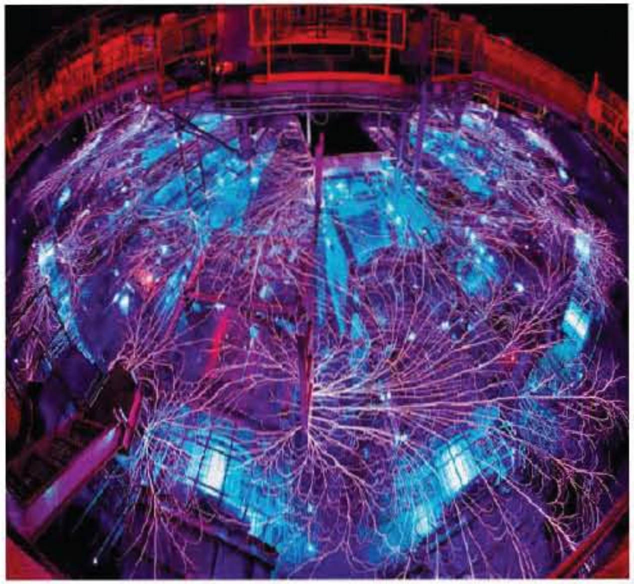
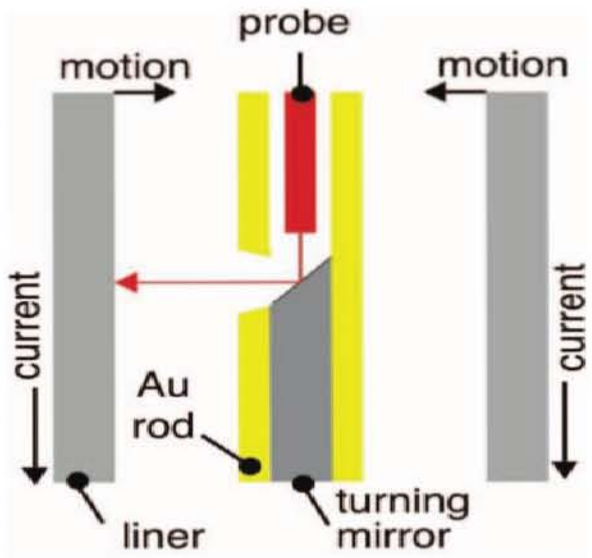
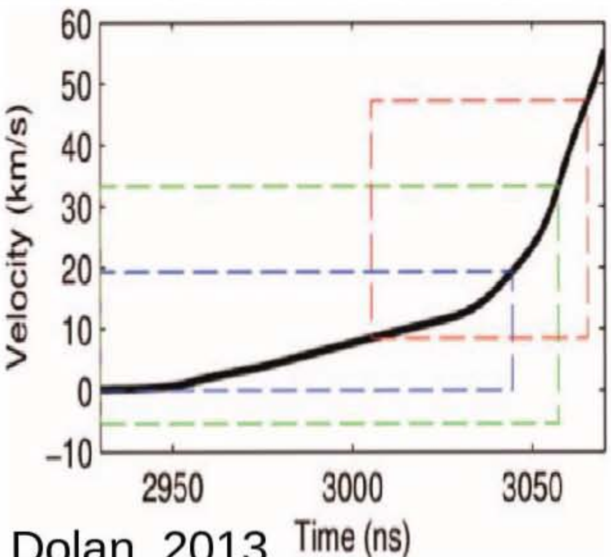
Cylindrical implosion offers a path to extreme material states, reaching considerably higher pressures than planar geometry. However, diagnosing compressed material in cylindrical geometry is challenging. Time-resolved velocimetry, a standard technique in planar compression, is difficult to incorporate into cylindrical experiments. This paper describes the use of photonic Doppler velocimetry (PDV) in magnetically driven cylindrical compression experiments at the Sandia Z machine. With this diagnostic, it is possible to track the interior of an imploding cylinder beyond 20 km/s. A "leapfrog" implementation is described to support velocities well above the bandwidth limits of standard PDV measurements. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4803074]

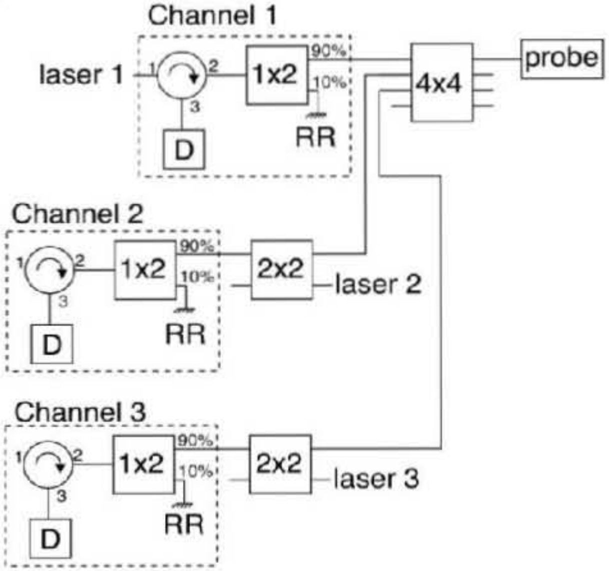
PDV Example, Sandia Imploding Cylinder, 2013

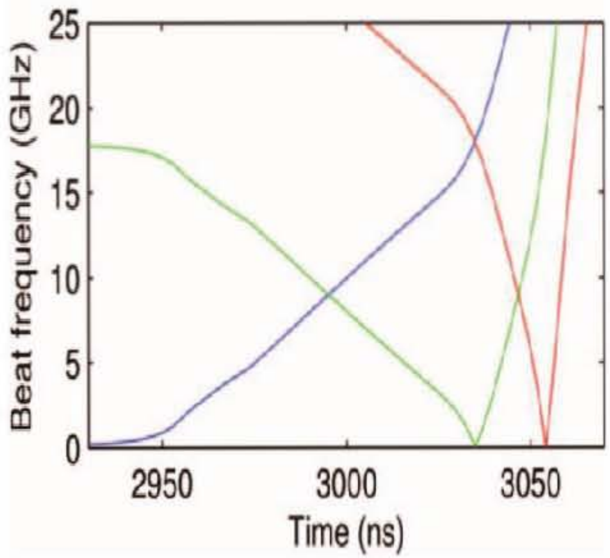






Dolan, 2013





Digitized PDV Velocity Profile

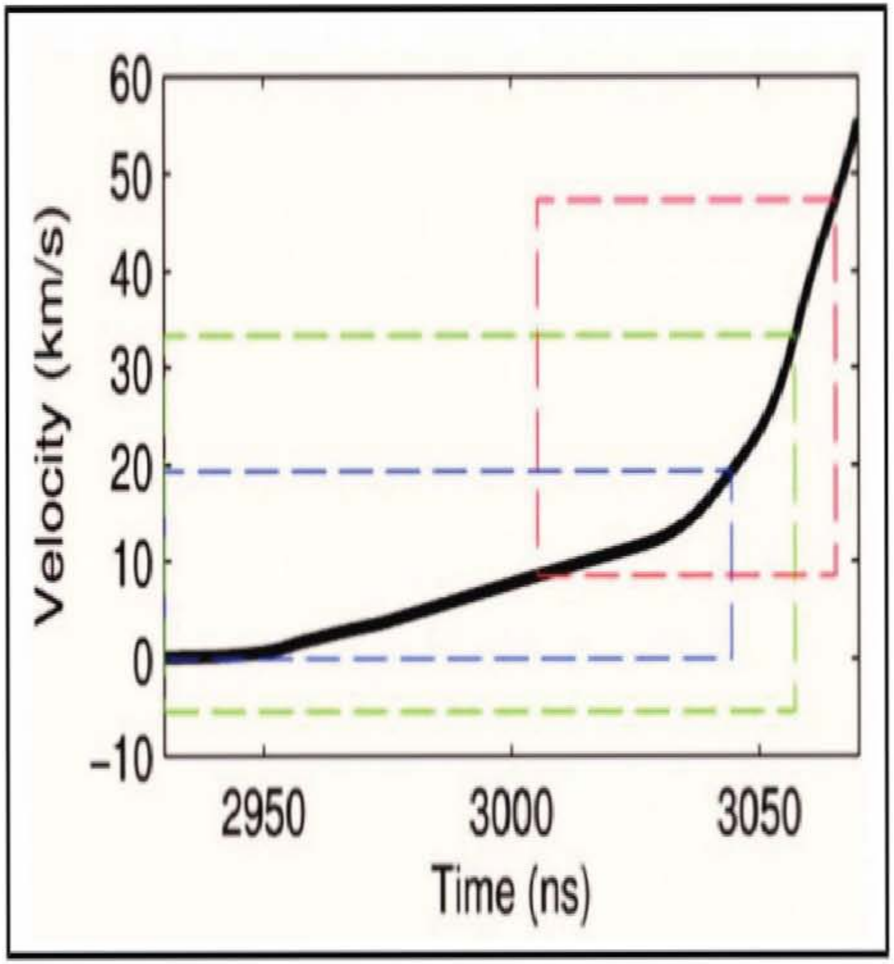


Figure 1: PDV data of Sandia target.[1]

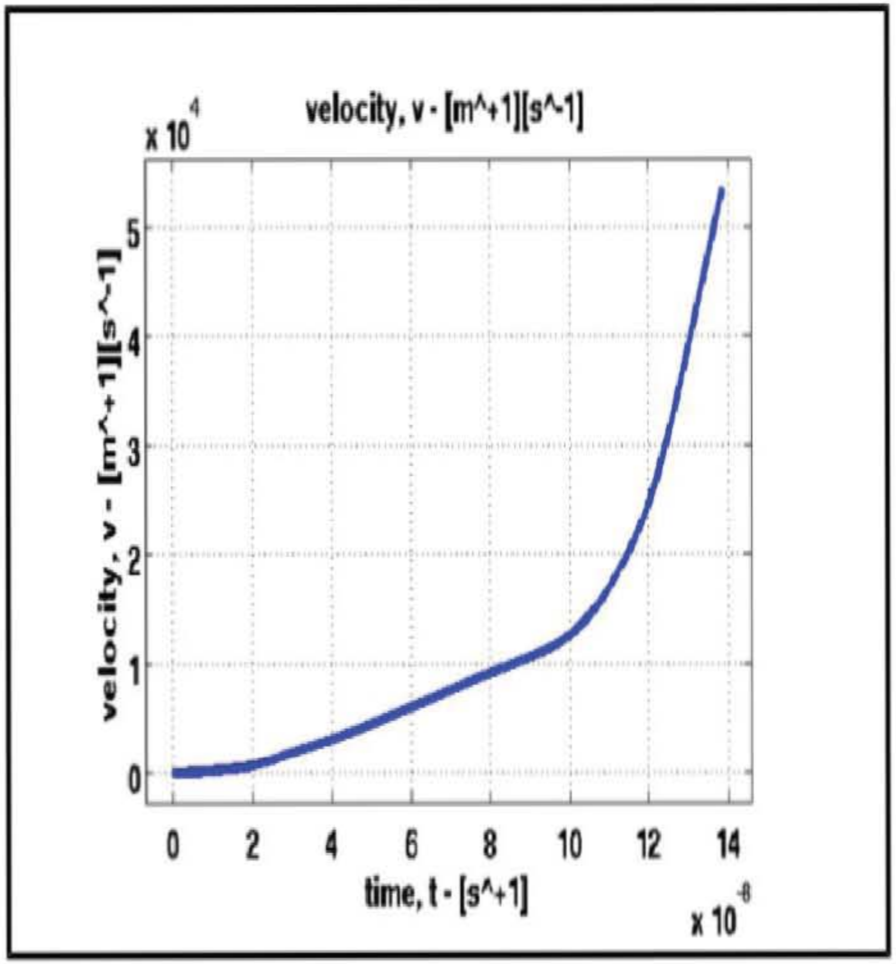


Figure 2: Digitized PDV data of Sandia target.

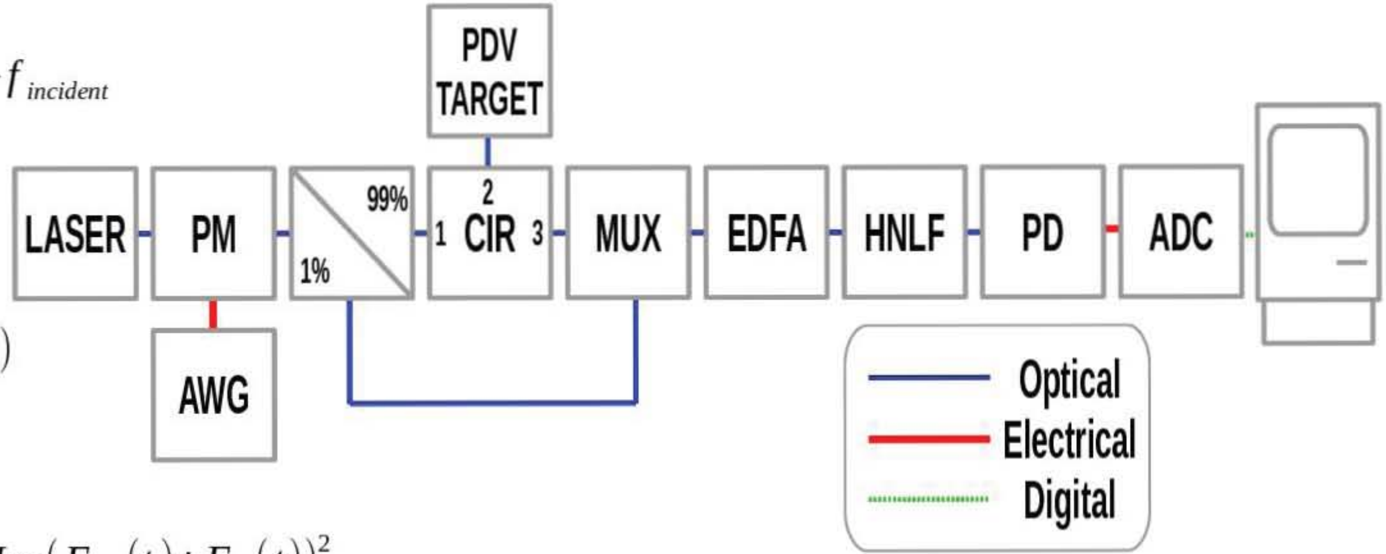
PDV Basics & Waveform Synthesis

$$\Delta f = \frac{2\Delta v}{c} f_{incident} = f_{reflected} - f_{incident}$$

$$f_{reflected} = f_{incident}\left(1 + \frac{2\Delta v}{c}\right)$$

$$E_{sig}(t) = E_{sig}\cos(\omega_{sig} t + \phi_{sig})$$

$$E_{lo}(t) = E_{lo}\cos(\omega_{lo} t)$$



$$I \propto (E_{sig}(t) + E_{lo}(t))^2$$

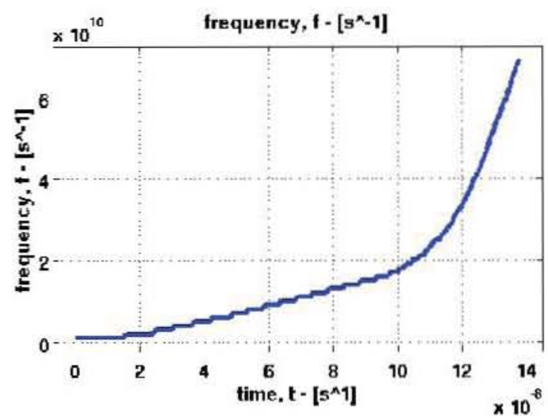
$$= (E_{sig}\cos(\omega_{sig} t + \phi_{sig}) + E_{lo}\cos(\omega_{lo} t))^2$$

$$= \frac{E_{sig}^2}{2}(1 + \cos(2\omega_{sig} t + 2\phi_{sig})) + \frac{E_{lo}^2}{2}(1 + \cos(2\omega_{lo} t))$$

$$+ E_{sig} E_{lo}[\cos((\omega_{sig} + \omega_{lo})t + \phi_{sig}) + \cos((\omega_{sig} - \omega_{lo})t + \phi_{sig})]$$

$$= \underbrace{\frac{E_{sig}^2 + E_{lo}^2}{2}}_{constant\ component} + \underbrace{E_{sig} E_{lo}\cos((\omega_{sig} - \omega_{lo})t + \phi_{sig})}_{beat\ component}$$

$$\underbrace{+ \frac{E_{sig}^2}{2}\cos(2\omega_{sig} t + 2\phi_{sig}) + \frac{E_{lo}^2}{2}\cos(2\omega_{lo} t) + E_{sig} E_{lo}\cos((\omega_{sig} + \omega_{lo})t + \phi_{sig})}_{high-frequency\ component}$$



Waveform Synthesis

$$I \propto \underbrace{\frac{E_{sig}^2 + E_{lo}^2}{2}}_{\text{constant component}} + \underbrace{E_{sig} E_{lo} \cos((\omega_{sig} - \omega_{lo}) t + \phi_{sig})}_{\text{beat component}}$$

$$\omega_{sig} = \omega_{reflected} = \omega_{incident}\left(1 + \frac{2\Delta v}{c}\right)$$

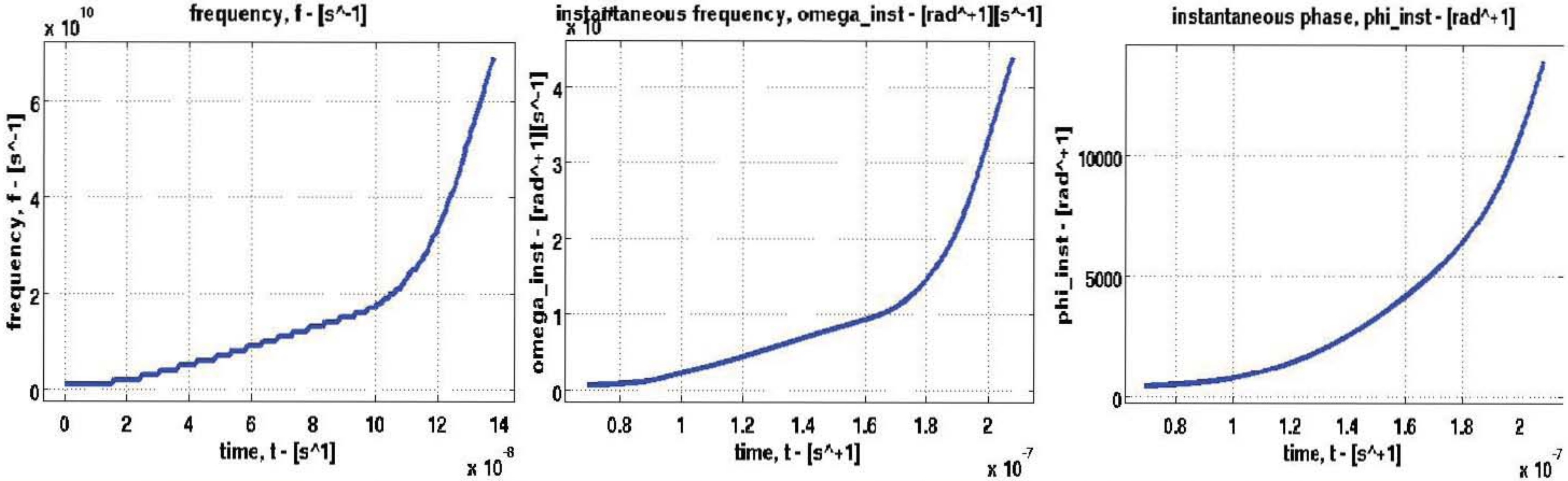
$$\Delta\omega_{offset} = \omega_{incident} - \omega_{lo}$$

$$P(t) = \frac{P_{sig} + P_{lo}}{2} + \sqrt{P_{sig} P_{lo}} \cos\Big(\Big(\underbrace{\frac{(\omega_{lo} + \Delta\omega_{offset}) 2\Delta v}{c} + \Delta\omega_{offset}}_{\omega_{inst}(t)}\Big) t + \phi_{sig}\Big)$$

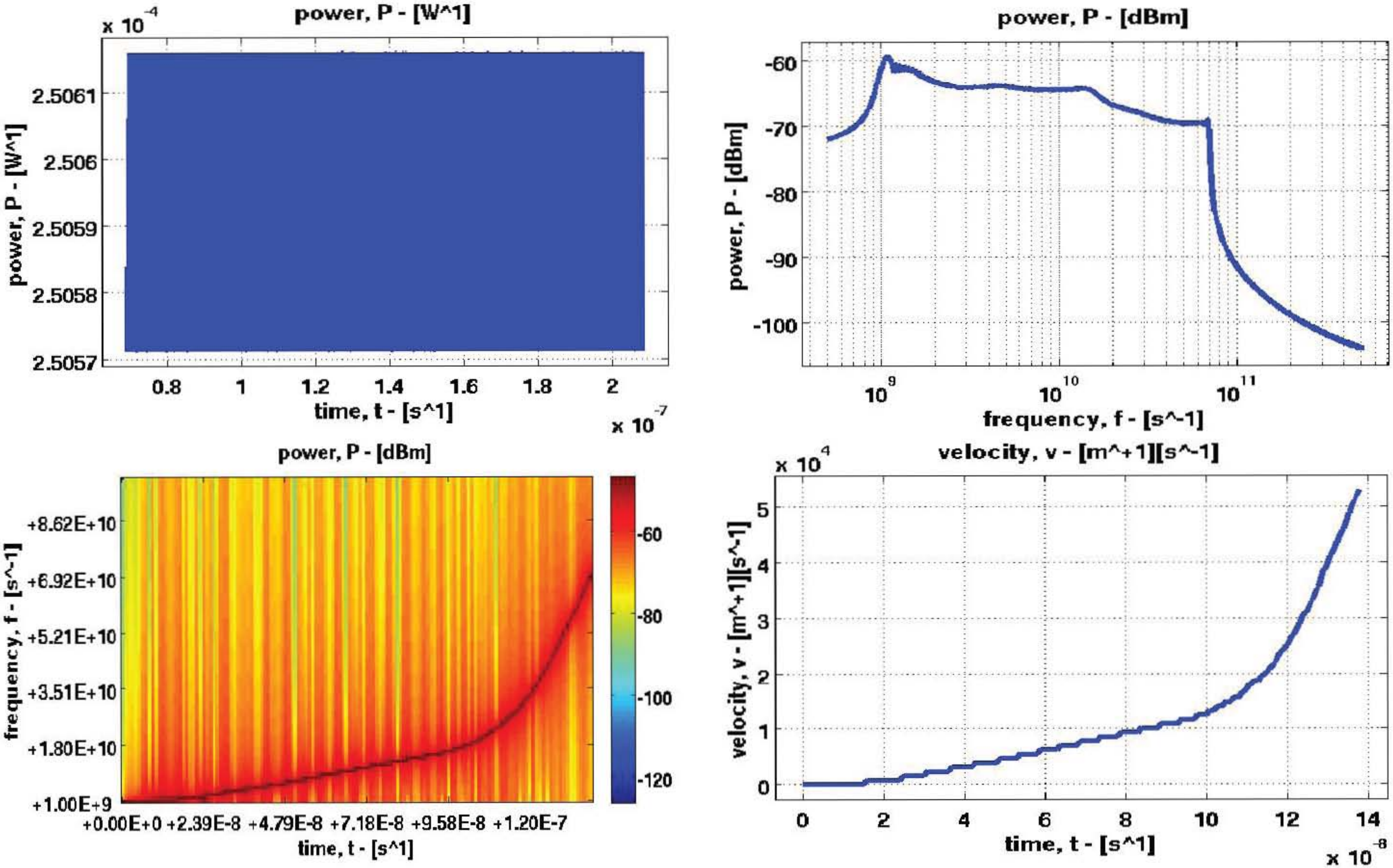
$$\omega_{inst}(t) = \frac{(\omega_{lo} + \Delta\omega_{offset}) 2\Delta v}{c} + \Delta\omega_{offset}$$

$$\phi_{inst}(t) = \int_{-\infty}^{t} \omega_{inst}(t')\, dt'$$

$$P(t) = \frac{P_{sig} + P_{lo}}{2} + \sqrt{P_{sig} P_{lo}} \cos(\phi_{inst}(t))$$



Waveform Synthesis



Conventional

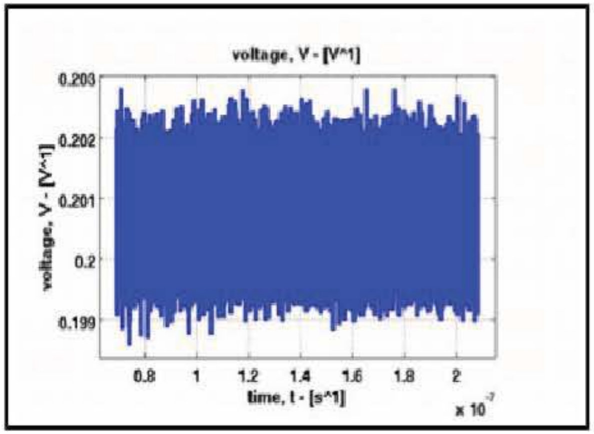


Figure 13: PD waveform.

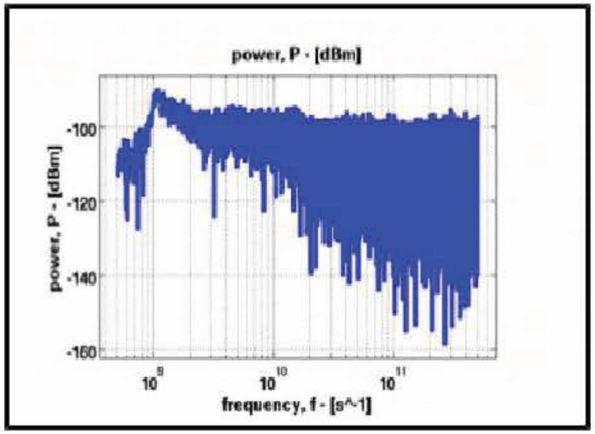


Figure 14: PD spectrum.

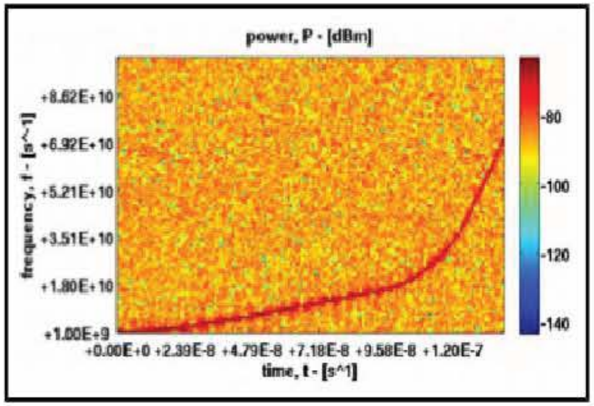


Figure 15: STFT of PD waveform.

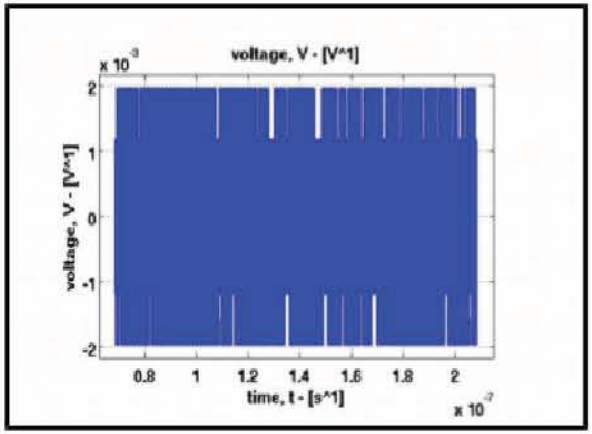


Figure 16: Digitized waveform

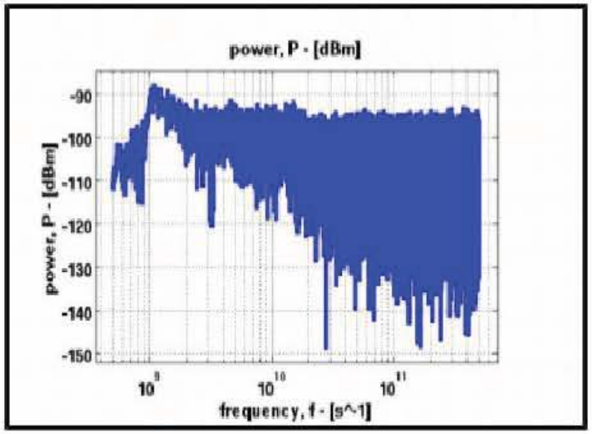


Figure 17: Digitized Spectrum

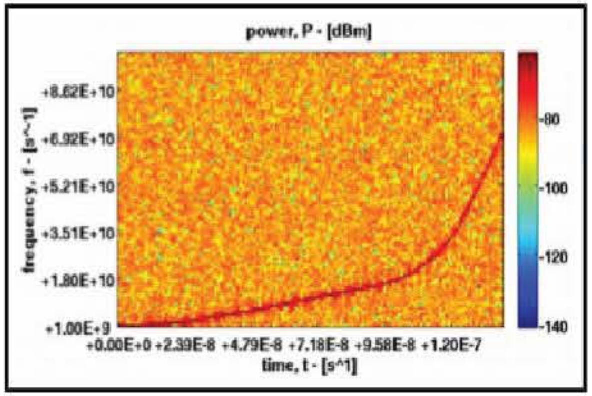


Figure 18: STFT of Digitized waveform.

MiBo

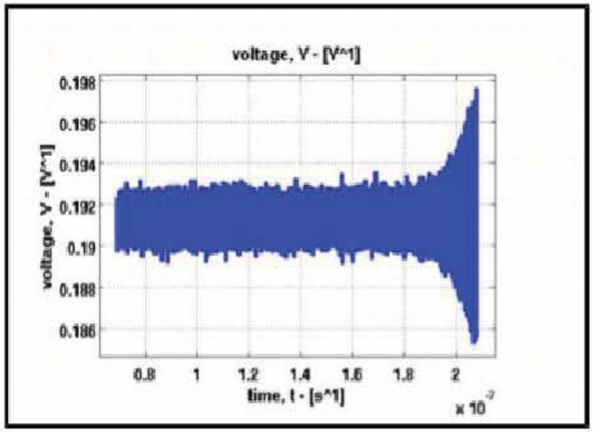


Figure 22: PD waveform.

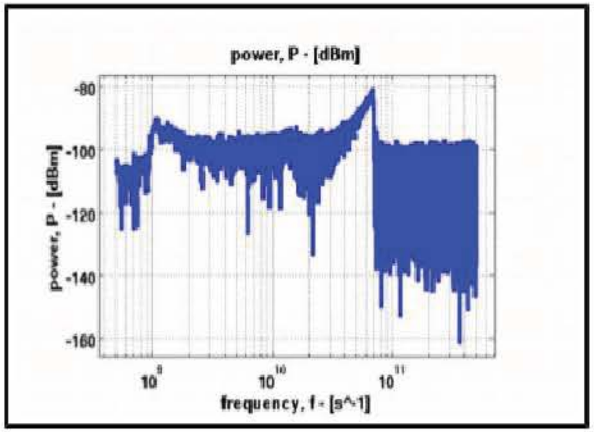


Figure 23: PD spectrum.

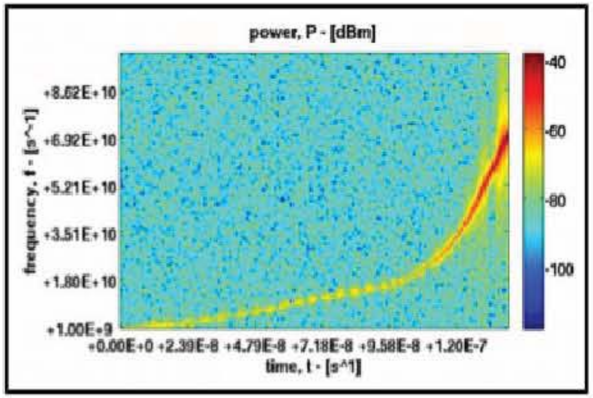


Figure 24: STFT of PD waveform.

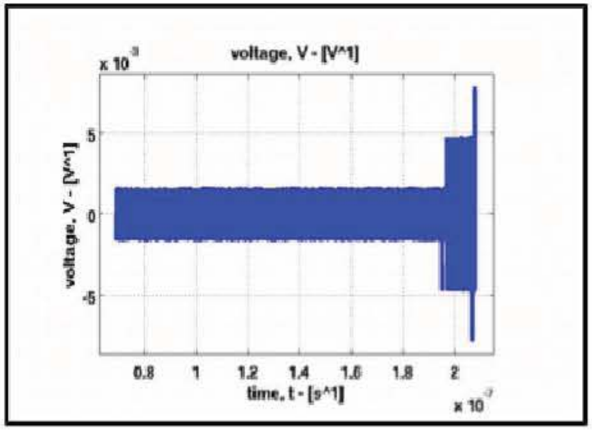


Figure 25: Digitized waveform

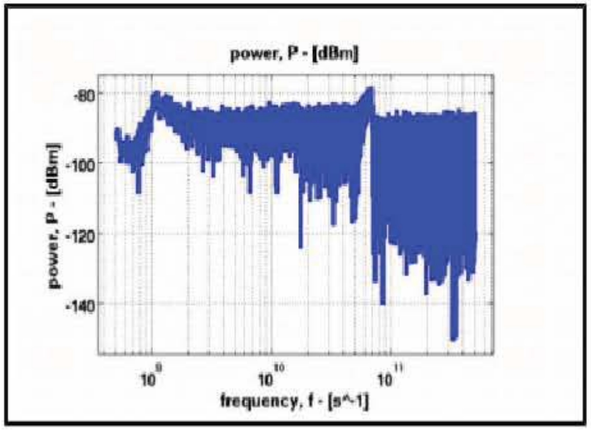


Figure 26: Digitized Spectrum

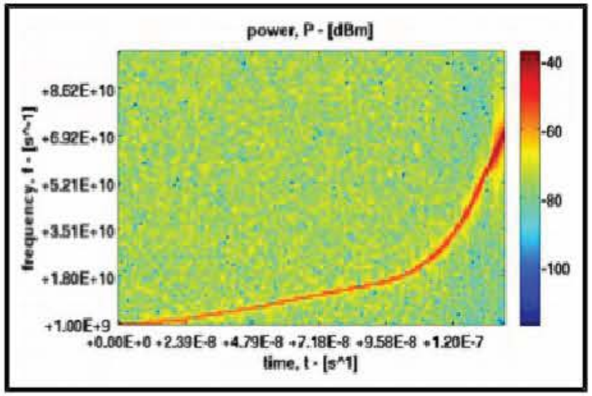
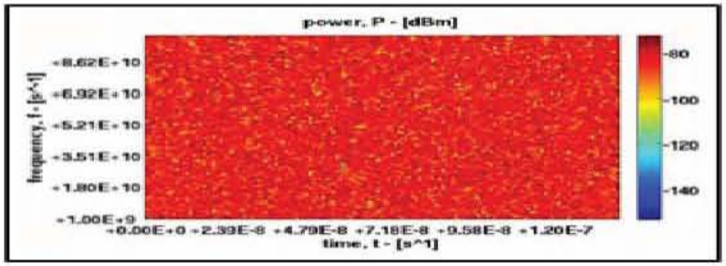
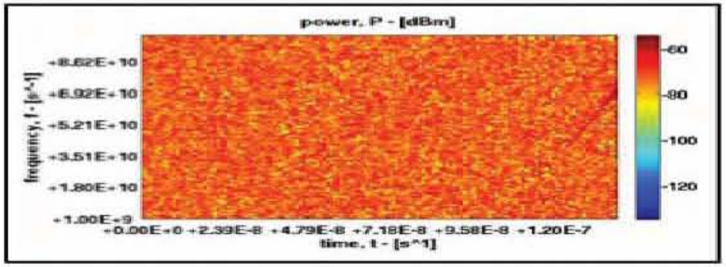
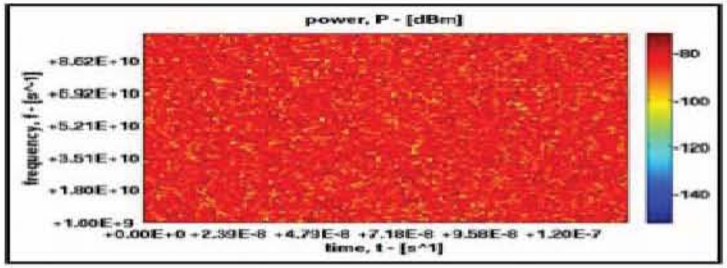
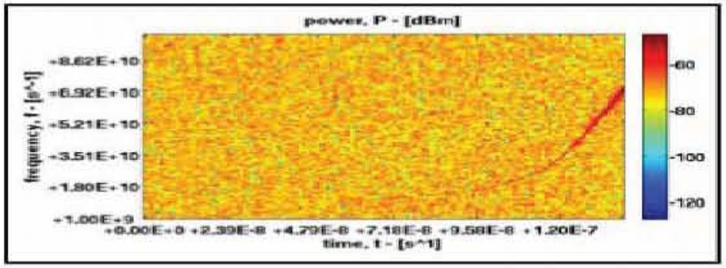
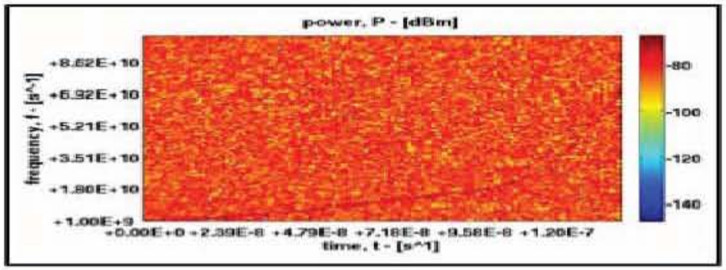
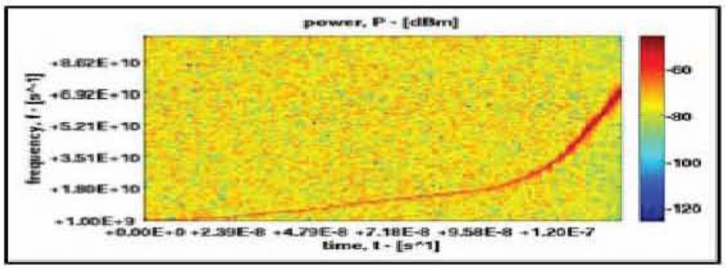
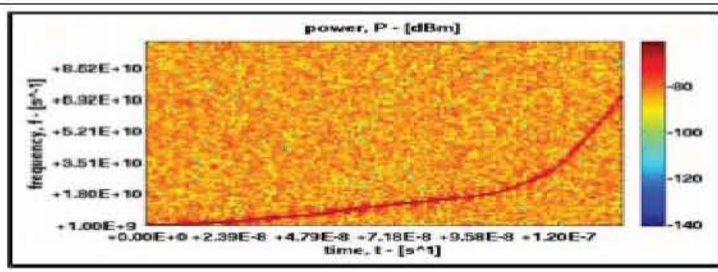
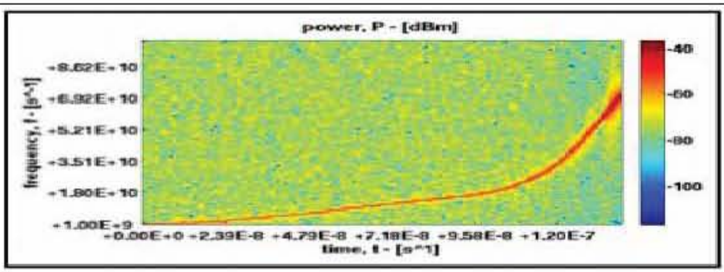


Figure 27: STFT of Digitized waveform.

Comparison

$P_{sig}\,[dBm]$	Conventional	MiBo
-100		
-90		
-80		
-70		

Study

2015-09-03T10:24:16 201509031014-pdv-mibo-study

Photon Doppler Velocimetry & Modulation Index Boosting

A Proof-of-Principle Study

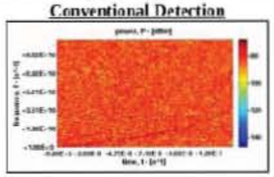
David Borlaug, Bill Seng, Crystal Glen, and Bahram Jalali

Table of Contents

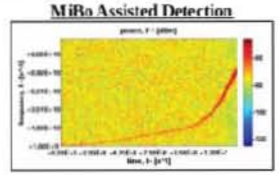
Executive Summary

The purpose of this study is to investigate the potential for performance enhancement by combining two mature techniques, Photon Doppler Velocimetry (PDV), developed by Sandia, and Modulation Index Boosting (MiBo), developed at UCLA in collaboration with Sandia. PDV utilizes Doppler velocimetry to track unconventionally high velocity objects. In the course of operation, PDV generates high-frequency broadband waveforms with spectral content from 1-70 GHz. MiBo is a technique that preferentially boosts or amplifies high-frequency signals by as much as 15 dB at 50 GHz. MiBo gain extends up to 150 GHz, making the technique especially relevant to PDV. This proof-of-principle study analyzes the expected performance impact of inserting a MiBo module in to a PDV system. The unoptimized results presented here show that MiBo is able to improve PDV detection sensitivity by 10 dB in general, and by as much as 20 dB for challenging Doppler frequency shifts beyond 40 GHz. These results offer a compelling case for further development of MiBo assisted PDV systems.

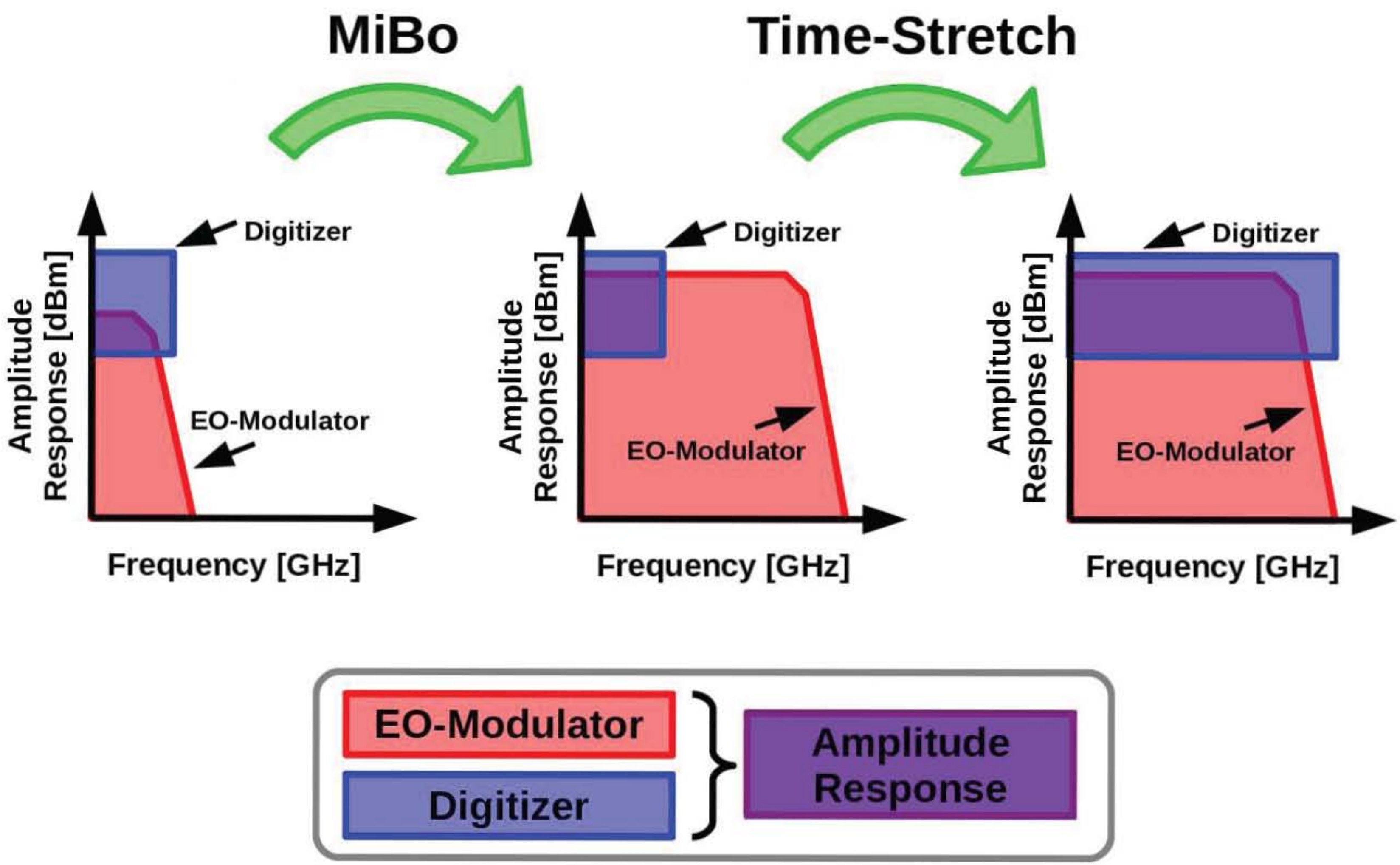
Conventional Detection



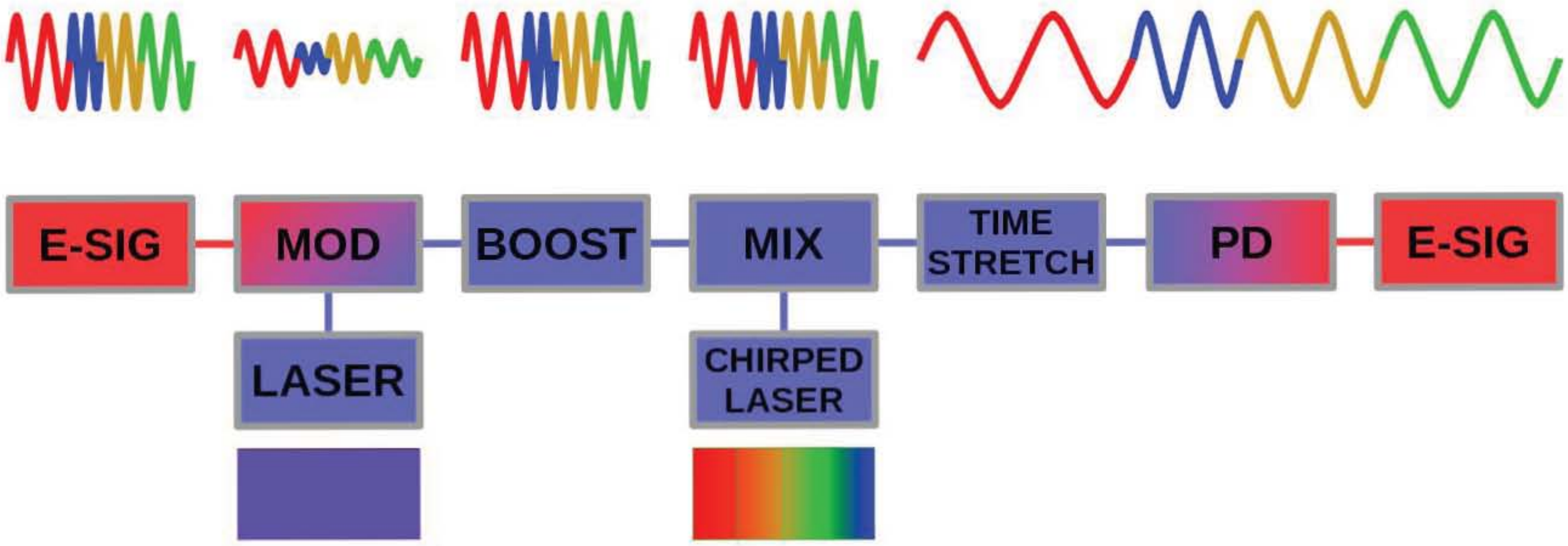
MiBo Assisted Detection



Time-Stretch MiBo



Time-Stretch MiBo



Summary

- MiBo has a high pass gain profile into the 100s of GHz -- can boost signals to overcome the information bottleneck.
- MiBo delivers 15 dB electrical signal power gain at 50 GHz.
- MiBo increases signal detectivity by 15 dB at 50 GHz.
- Time-Stretch MiBo enables high-sensitivity broad-band digitization using fair-sensitivity narrow-band digitizers.
- PDV can utilize MiBo in all-optical and electro-optical systems to capture fast moving velocimetry data.

Thank You