Resolution doubling for position-sensitive sensors in shock wave and detonation-driven experiments

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Article

Improving Chirped fiber Bragg grating resolution for position-sensitive sensors in shock and detonation-driven experiments

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Abstract

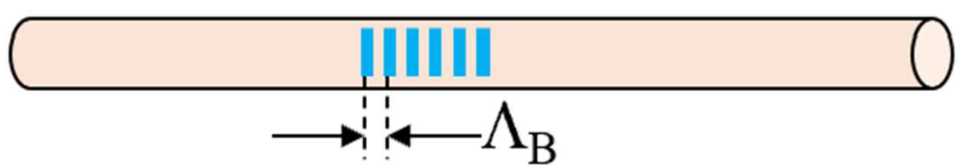
Chirped fiber Bragg gratings (CFBG) are robust diagnostic sensors that are widely used to track detonation-driven and shock wave propagation. The CFBG gratings are inscribed with linearly-chirped periodic index of refraction changes that alter the Bragg wavelength along the length of the probe. The light return of each individual Bragg element is captured by a detector at a unique time to map the full reflected spectrum. The CFBG spectrum is measured with a dispersive Fourier transform of the reflected light that temporally stretches the spectrum to increase spatial resolution and make a one-to-one map of wavelength onto a time axis. Here, we proposed an improvement of the CFBG temporal and spatial resolution by incorporating two co-linear, laser pulses with orthogonal polarization states (XP-CFBG) and a 5 ns time offset. The two separate signals were split and tracked by two separate detectors. An oscilloscope captured good separation of the signals, and two separate spectrograms were generated and interleaved in post-processing of the data. This novel technique doubled the CFBG spatial and temporal resolution. As a proof-of-concept of this technique, the resolution improvement was compared between standard CFBG measurements and the two polarization states method on a position-sensitive CFBG sensor. The CFBG resolution doubling will advance sensor capabilities and will have a direct impact on improving capture and analysis in dynamic, high-explosive experiments.

Keywords: chirped fiber Bragg gratings, cross polarization chirped fiber Bragg gratings, spatial resolution, temporal resolution, shock waves

Fiber Bragg gratings (FBG)

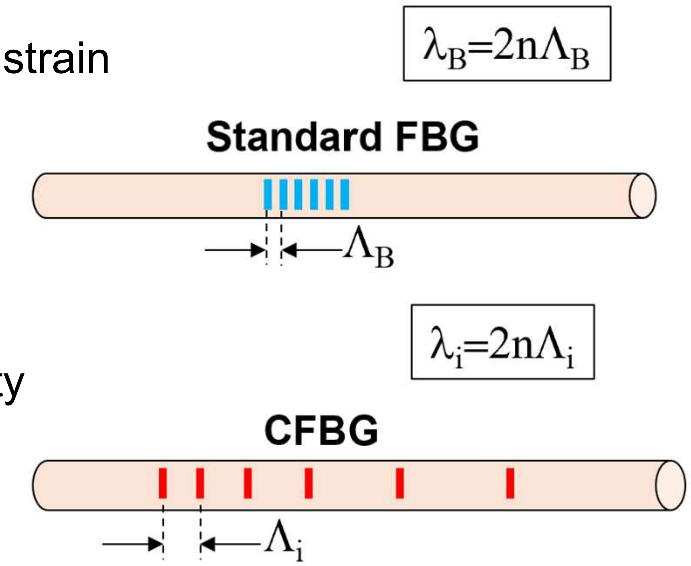
- Used to track and measure shock waves and high explosive detonation
- Widely adopted in technology for many years, particularly in monitoring bridges, aerospace, environmental testing
- Provide measurement of changes in static and dynamic strain, displacement, pressure, and temperature in real time
- **Main advantages**: flexibility, light weight, compact size, quick response, electromagnetic resilience

Standard FBG

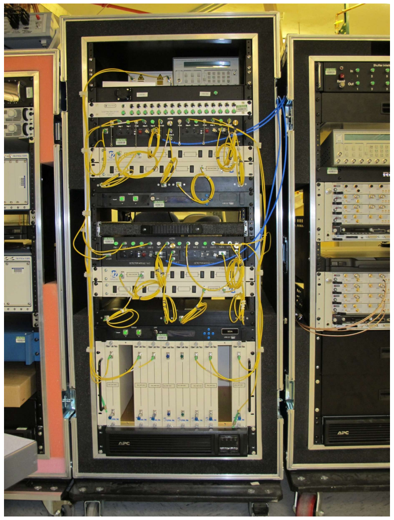


Chirped Fiber Bragg Gratings (CFBG)

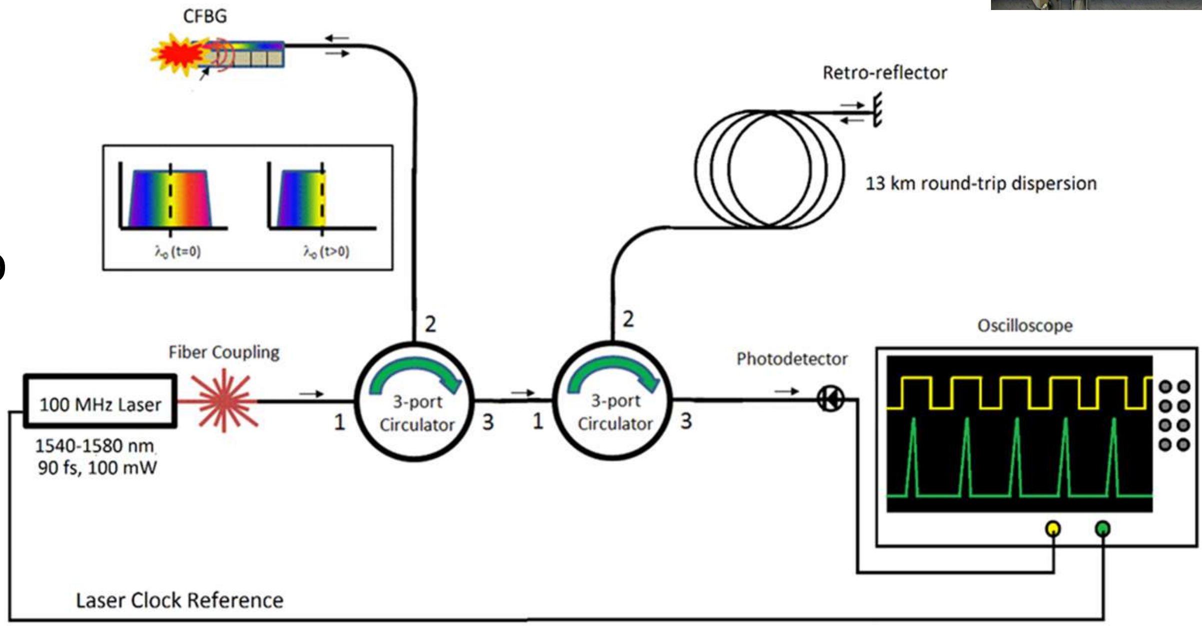
- Grating period changes along its length. Reflected spectrum changes linearly with the grating length
- CFBG reflects different wavelengths of light at different points along its length
- Grating variations allow for modulations in the Bragg wavelength and refractive index along the grating length
- CFBG response relies on the individual chirps, temperature, and strain
- More sensitive than standard FBGs
- CFBG consumption in detonation and shock wave experiments
- Commonly used in fiber-optic communications, detonation velocity tracking, dispersion compensation, shock wave measurements, healthcare, mechanical engineering, and broadband sensing
- **Limitations**: complex design, low durability in harsh environment, and higher costs



Time Domain Chirped Fiber Bragg Grating (TD-CFBG)

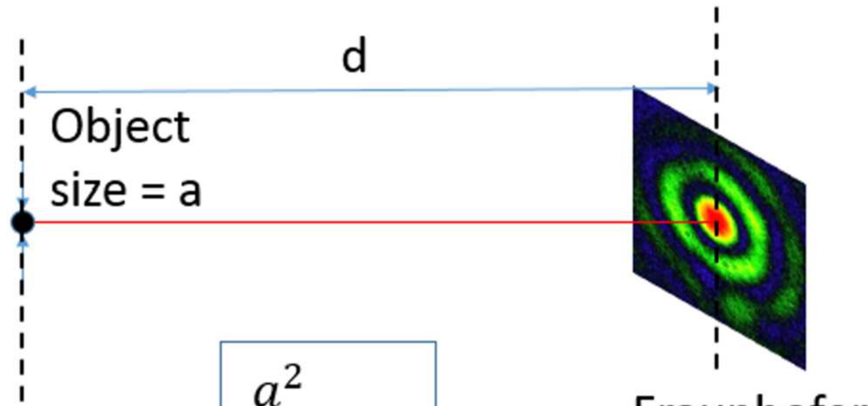


- Continuous measurement of detonation wave position and velocity
- Also measures lower-amplitude shock wave spectrum
- Dispersive Fourier Transform converts wavelength spectrum to time



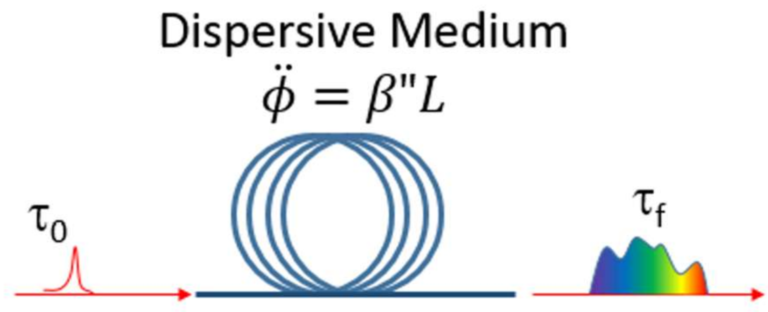
Dispersive Fourier Transforms (DFT) as a Frequency Swept Source

Aperture Diffraction



$$\frac{a^2}{\lambda d} \ll 1$$

Temporal Analogue

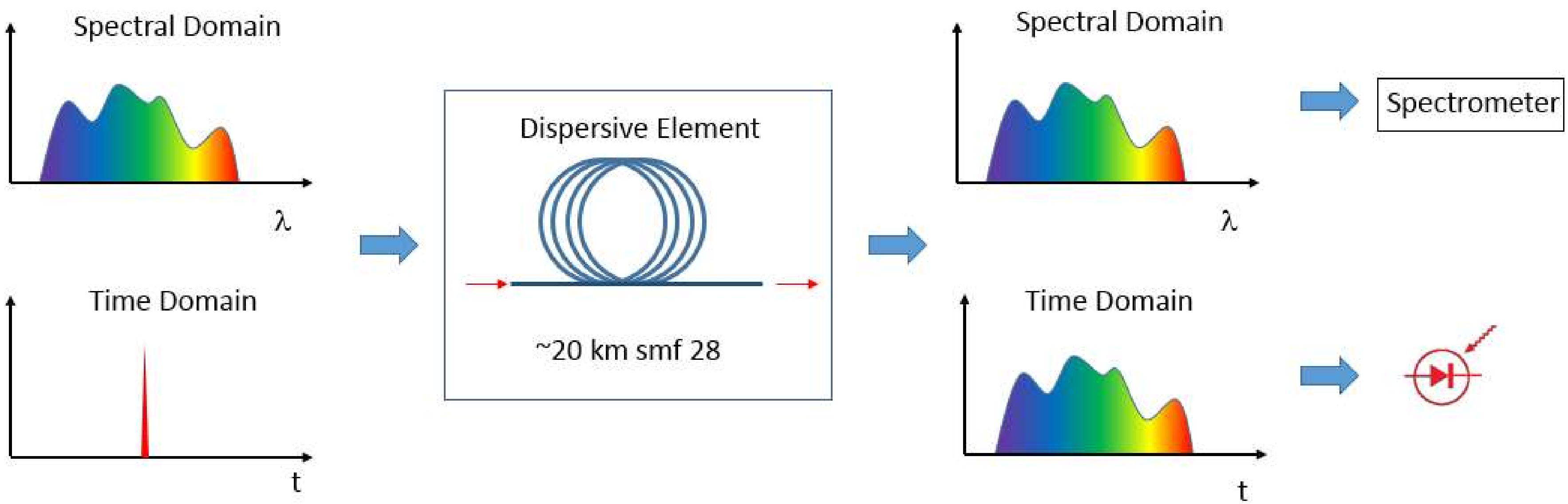


$$\left|\frac{\tau_0^2}{\ddot{\phi}}\right| \ll 1$$

Assumptions:

- Temporal dispersion conditions are met
- Spectral phase is linear or at least well-characterized

Dispersive Fourier Transforms (DFT)

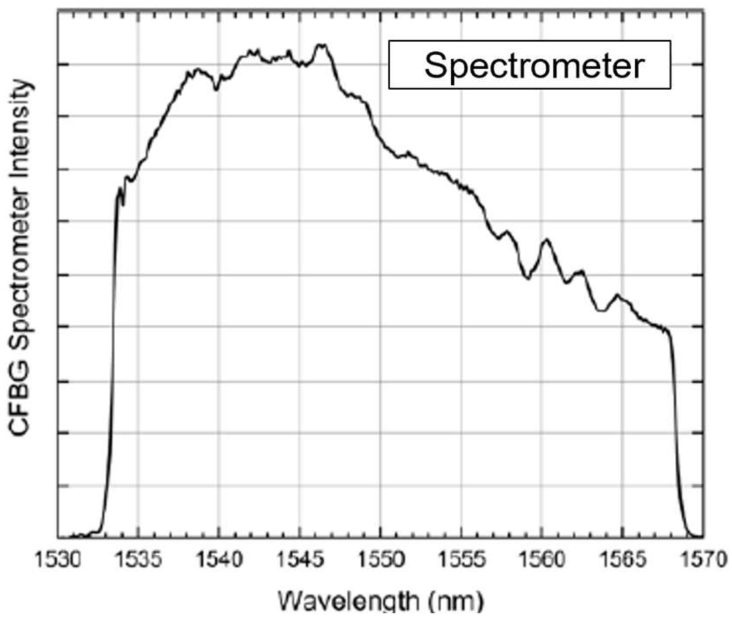


K. Goda and B. Jalali, Nature Photonics 7, 102 (2013)

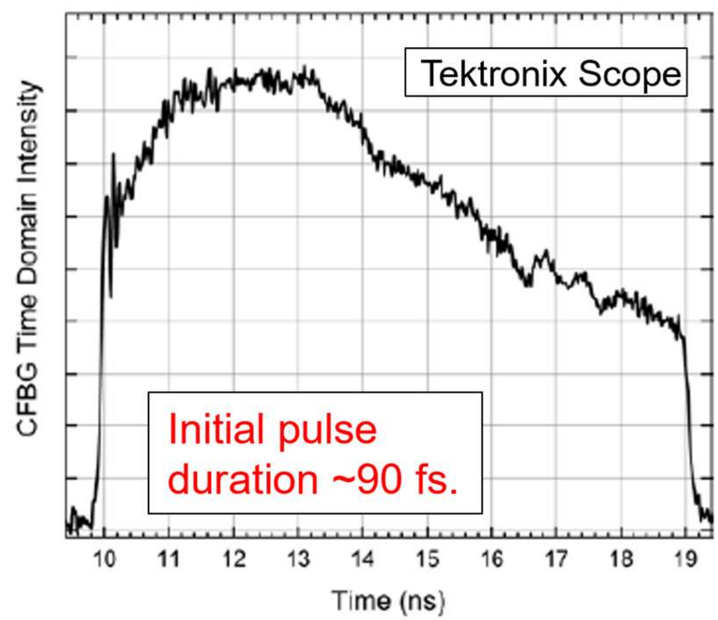
- Allows the measurement of the spectral content of a pulse with a fast photodetector – basically an FSL.
- Useful with high rep-rate lasers (100 MHz)
- Achievable with several km of standard smf 28 fiber

DFT Experimental Example

Spectrum of CFBG before and after dispersive element

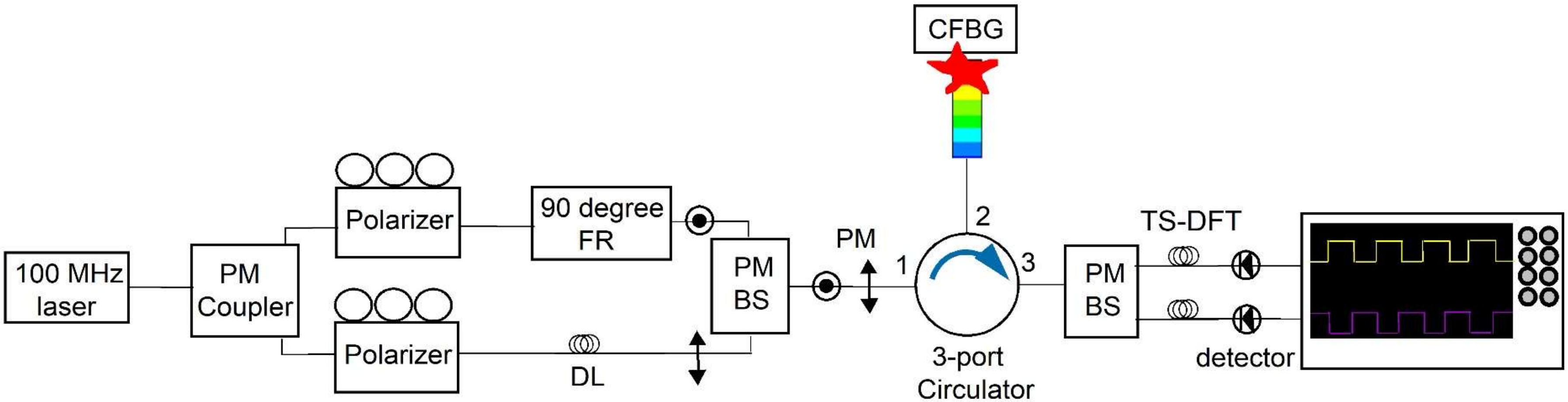


Temporal profile of pulse after dispersive element.



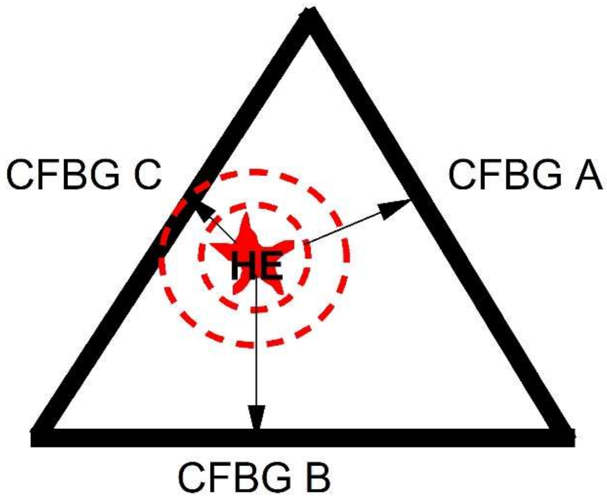
1 to 1 mapping of spectrum onto a time axis

Schematic representation of cross polarization (XP-CFBG) CFBG



- All fibers were polarization maintaining (PM)
- A 50:50 split of laser energy was achieved by sending a polarization maintaining (PM) laser into a 50:50 beam splitter
- Each half of the light was directed into polarizers, with one leg going into a 90-degree Faraday rotator to obtain perpendicular polarization states
- The signals from two orthogonal states were recombined using a circulator and are directed to CFBG
- Two separate detectors transmitted two orthogonal signals

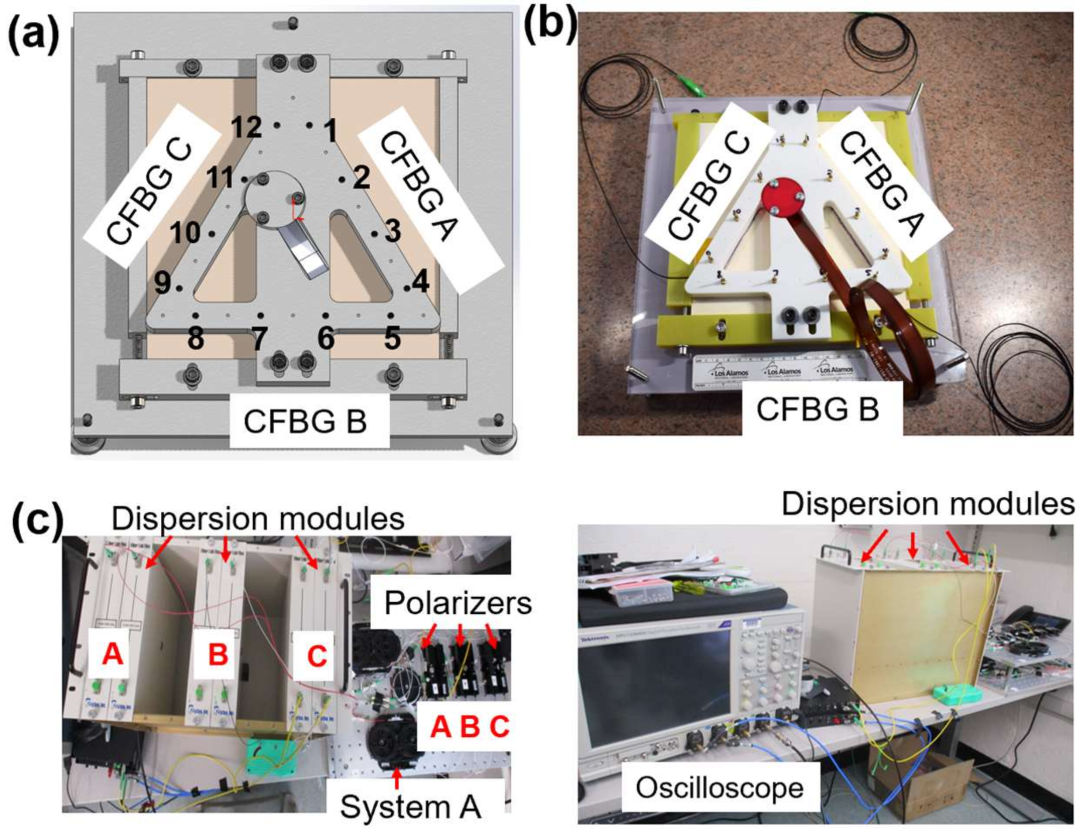
Position-sensitive sensors assembly



CFBG #	Length (mm)	Chirp rate (nm/mm)	Distance to detonator (mm)
A	144.97	0.2331	39.68
B	138.97	0.2331	70.82
C	145.11	0.2331	17.68

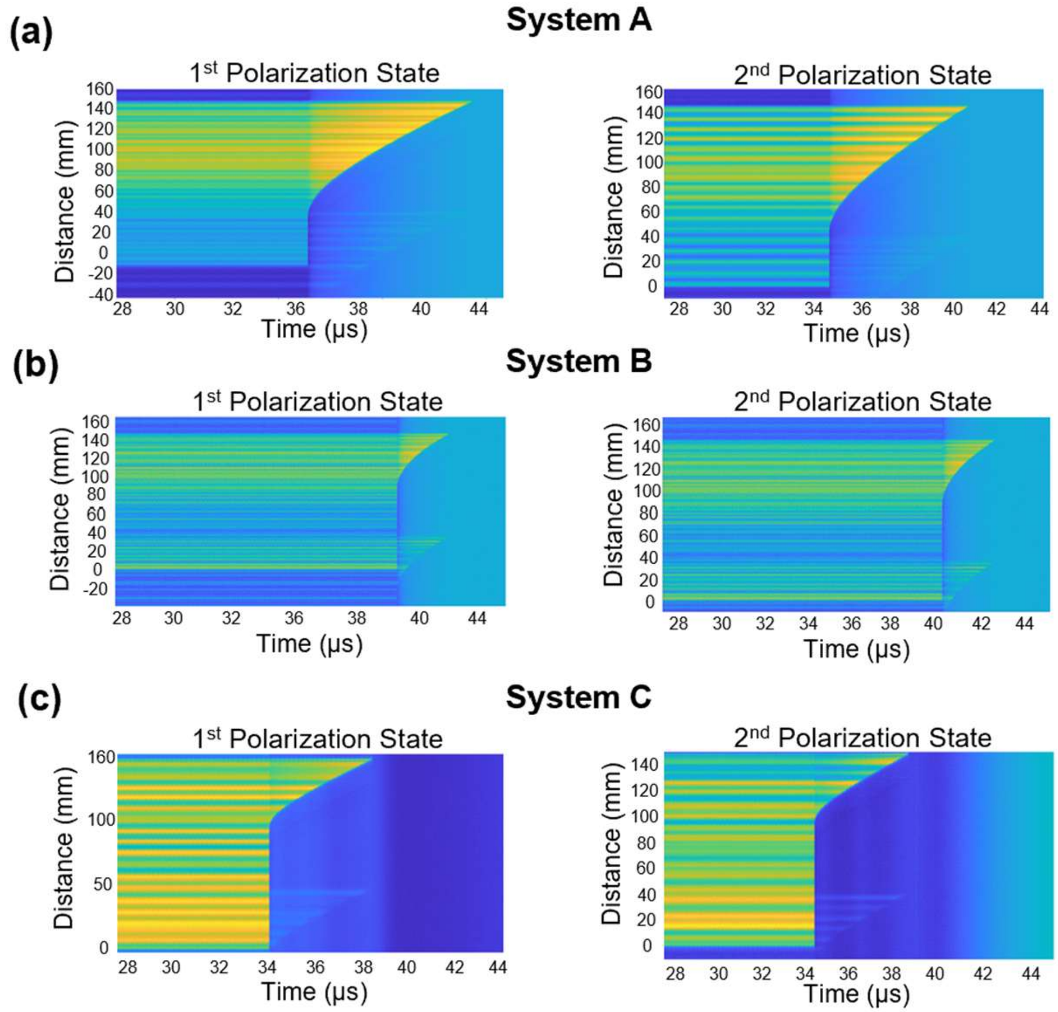
- Three CFBG systems: CFBG A, B, and C
- A single detonator was positioned off the center to compare shock wave propagation from three various points
- Shock pressure amplitude was high enough to completely consume the grating

High explosive slab shot



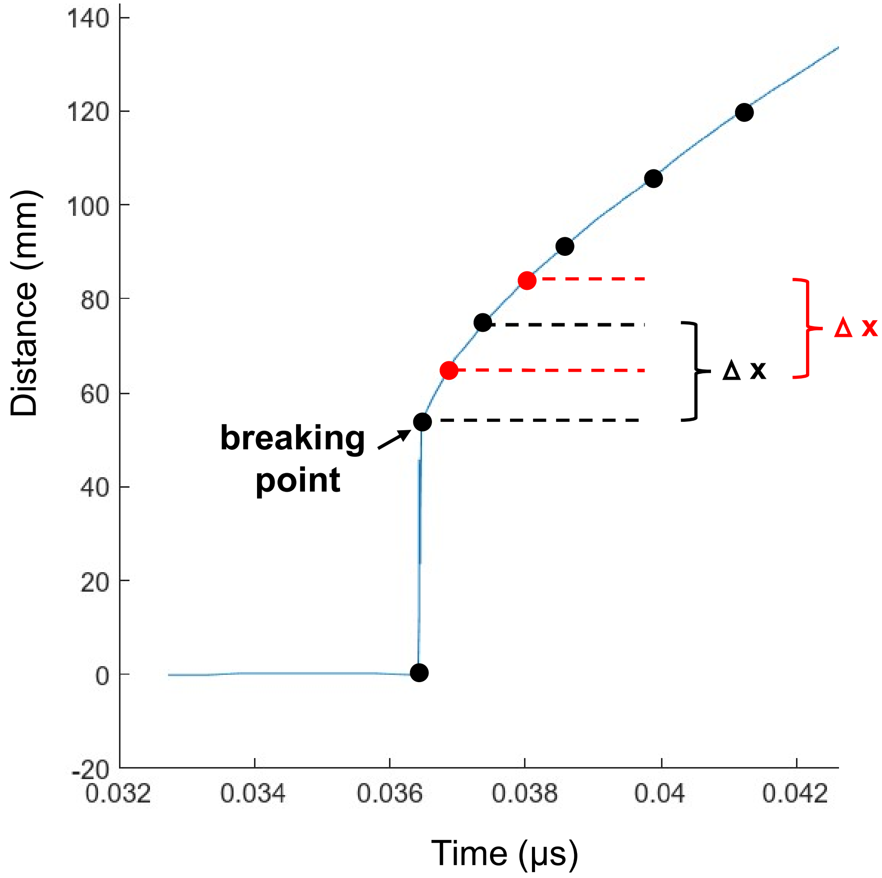
- Twelve piezo pins were used for secondary diagnostics
- Three systems were built on two breadboards: system A and all the polarizers (top breadboard), systems B and C (bottom breadboard)

Spectrograms of the two polarization states



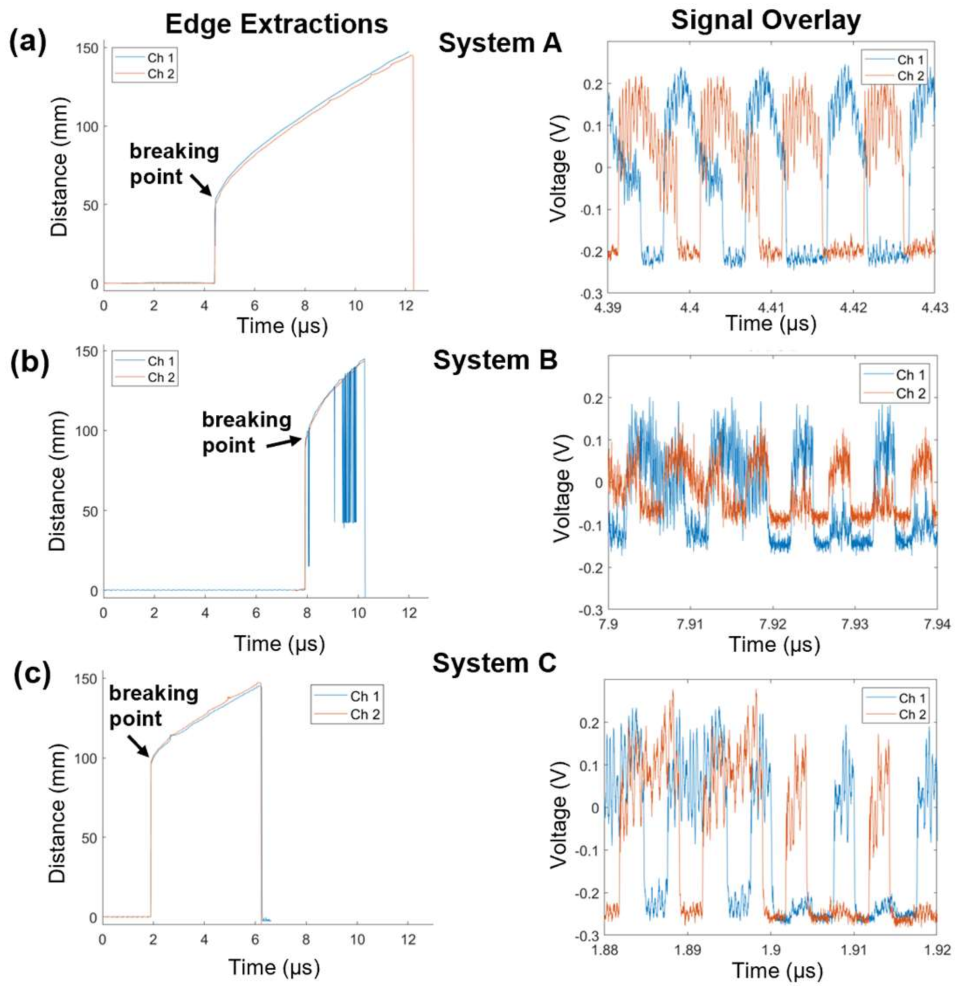
- Each CFBG system detected the presence of two polarization states

Determining the breaking point and the highest/lowest value



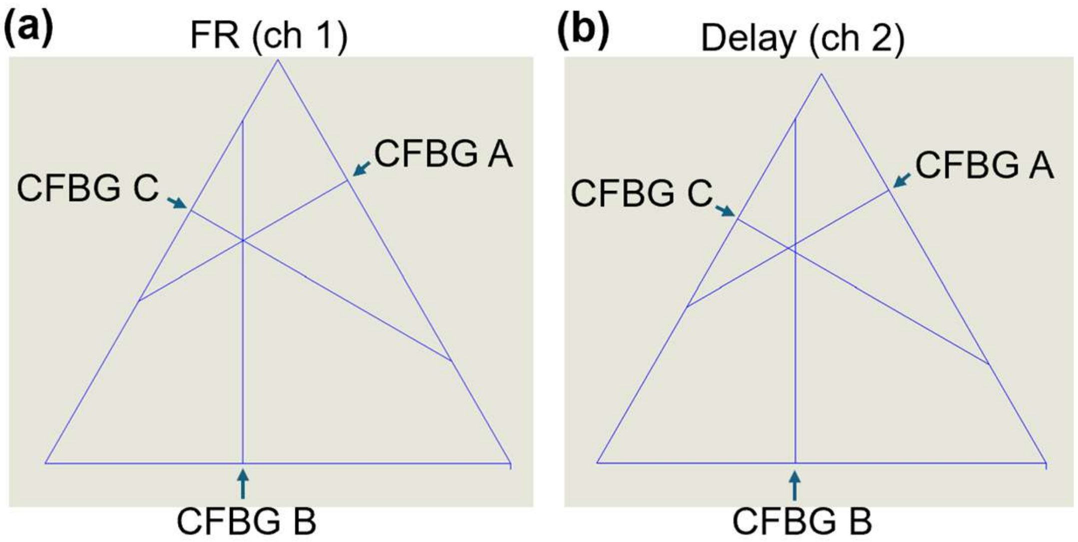
- XP-CFBG doubles the resolution and provides data points every 5 ns instead of every 10 ns

Edge extraction and signal overlay diagrams



- Signal overlap between the two signals was graphed for better visualization of the signal separation
- Time was corrected to a common timing fiducial for each CFBG system

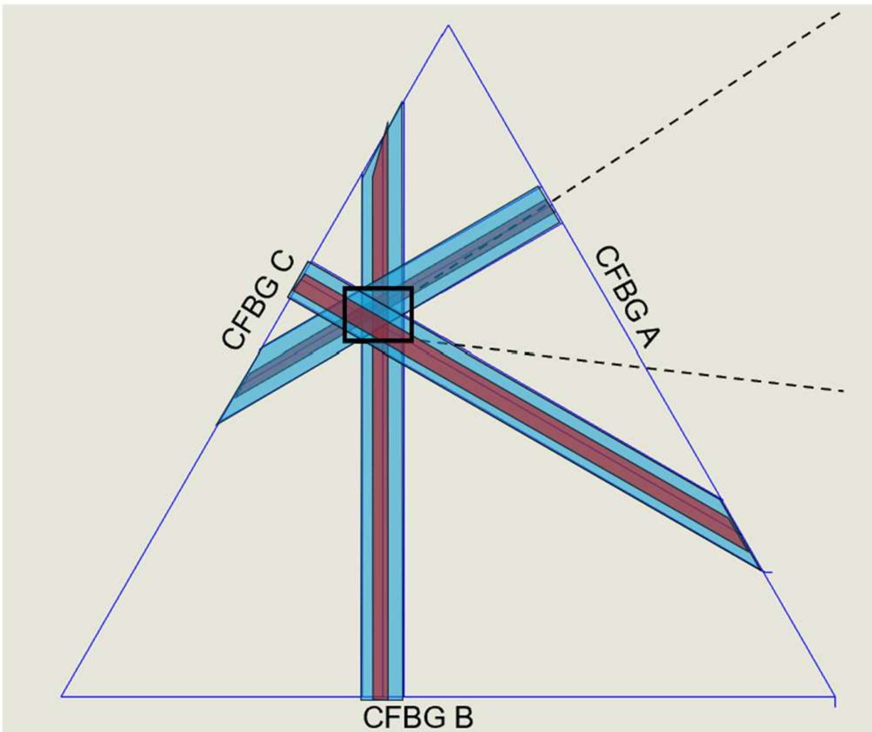
CFBG breaking point

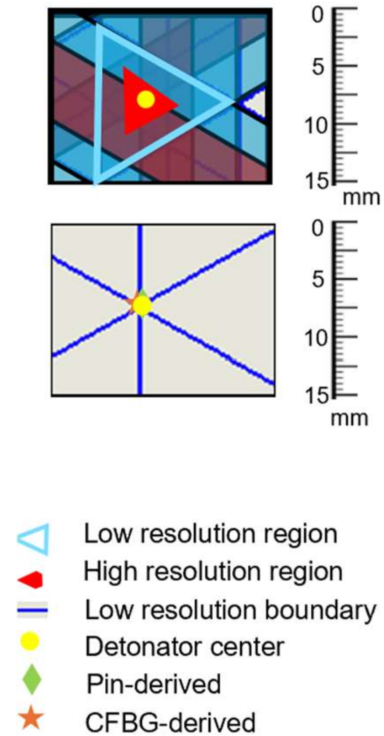


Count	Distance from fiducial (mm) for 145 mm CFBG	Corrected breaking point time (us)
System A ch 1	44.2964	4.6241
System A ch 2	44.368	4.416574
System B ch 1	85.124	7.924954
System B ch 2	82.593	7.956356
System C ch 1	92.7092	1.900466
System C ch 2	92.7092	1.904716

- Lines from the calculated breaking points were graphed at 90° angle towards the triangle center
- The exact breaking point time and distance of each CFBG were measured

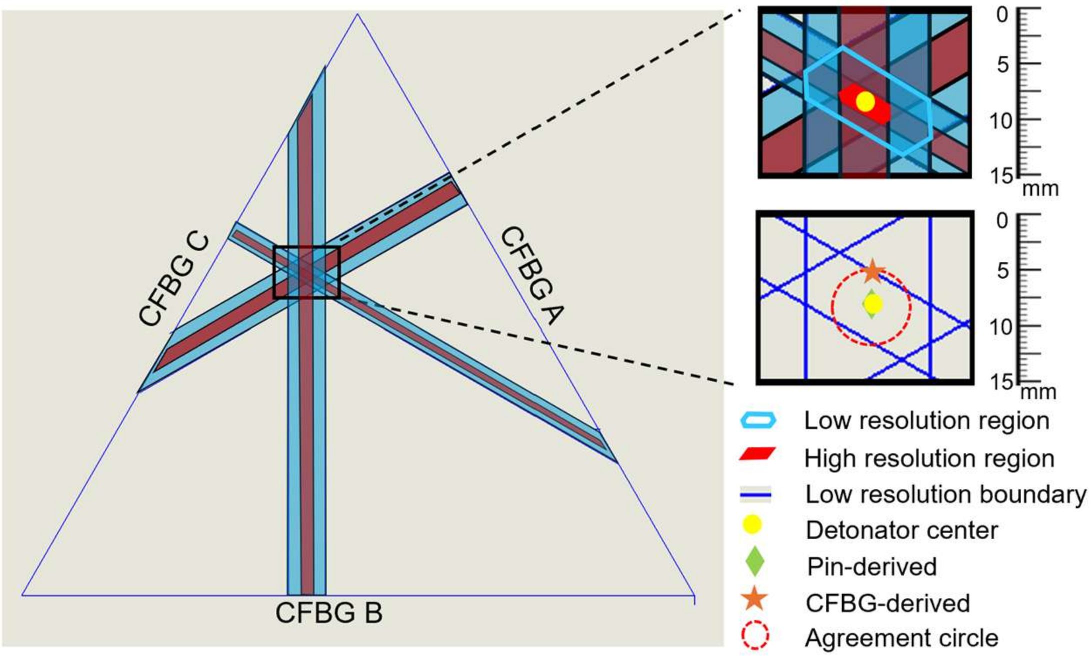
Ideal scenario





- Area of equilateral triangle would be $A = \frac{\sqrt{3}}{4} s^2$
- For high resolution (red), the area would be half of the low resolution (blue) area

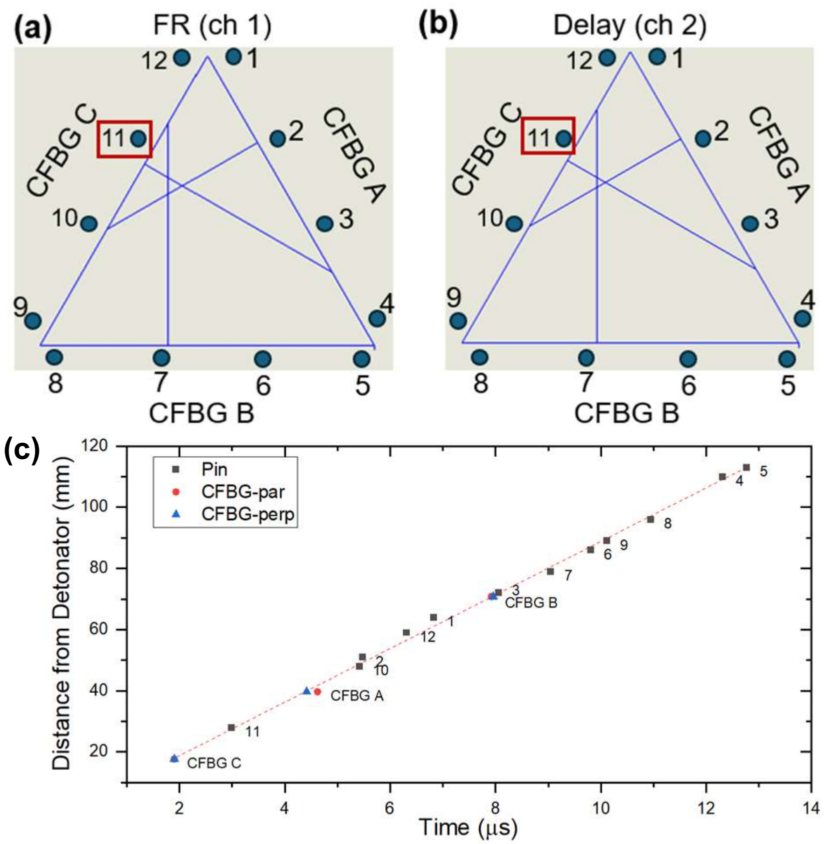
Low and high resolution



Count	Distance from fiducial (mm) for 145 mm CFBG	Higher value (mm)	Distance from the break point to the next value (mm)	Lower value (mm)
System A ch 1	44.30	48.30	4.00	40.30
System A ch 2	44.37	45.97	1.60	42.77
System B ch 1	85.12	89.13	4.00	81.12
System B ch 2	82.59	83.59	1.00	81.59
System C ch 1	92.71	94.71	2.00	90.71
System C ch 2	92.71	93.50	0.79	91.92

- Confidence area was generated by using the higher and lower values from the breaking point
- Blue area - low resolution, red area - high resolution
- The exact breaking points, higher and lower values are shown in the table
- Multilateration technique was used to locate the detonator initiation point

CFBG and piezo pins measurements

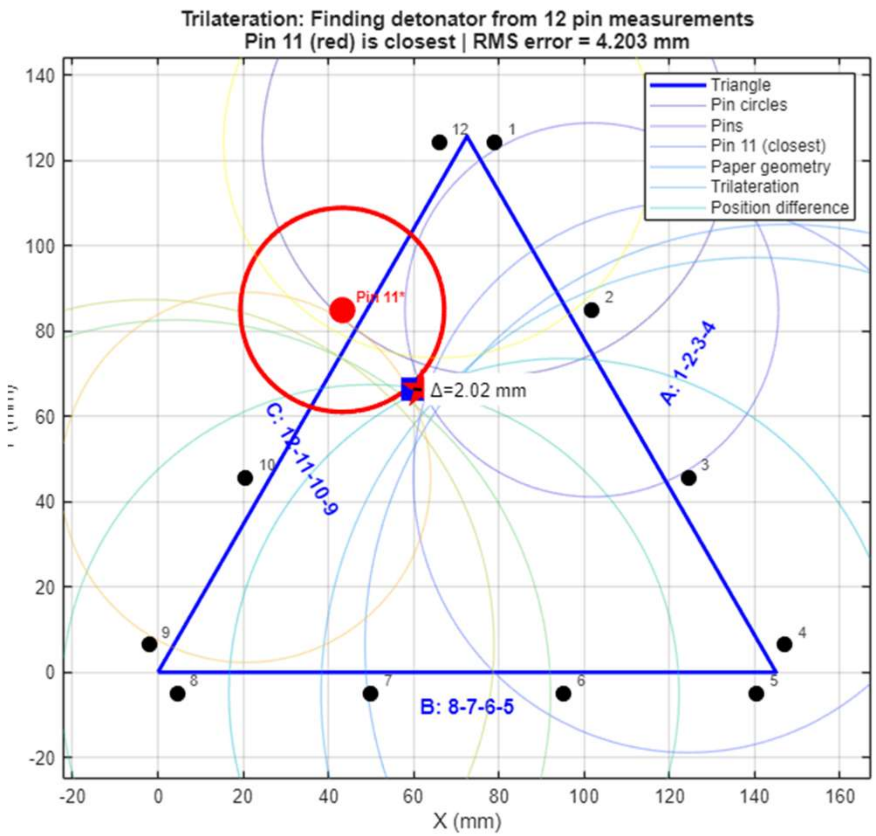


Pin number	Time (us)	Scope number	Voltage (V)	Attenuation (dB)
1	6.8289	1	0.016	26
2	5.4753	1	0.032	26
3	8.0616	1	0.032	26
4	12.3115	1	0.024	26
5	12.7716	2	0.056	26
6	9.8117	2	0.04	26
7	9.0495	2	0.04	26
8	10.9436	2	0.048	26
9	10.1095	3	0.032	26
10	5.4217	3	0.04	26
11	2.9879	3	0.056	30
12	6.3076	3	0.048	30

- Pin #11 (red box) – closest to the detonator
- CFBG and pins were plotted as function of distance to detonator versus time
- Overall, good agreement between CFBG and pin data

Trilateration

- Purpose: inversely estimate the location of the detonator initiation
- When more than three distances are involved, it may also be called **multilateration**
- For XP-CFBG, the velocity of the detonation wave was determined using the timing offset and distance to the closest pin (8.8 mm/us)
- As the detonation velocity could be unknown, particularly for curved geometries, multilateration may not be available for analysis in all experimental conditions (the break points alone can be used, but higher uncertainties)



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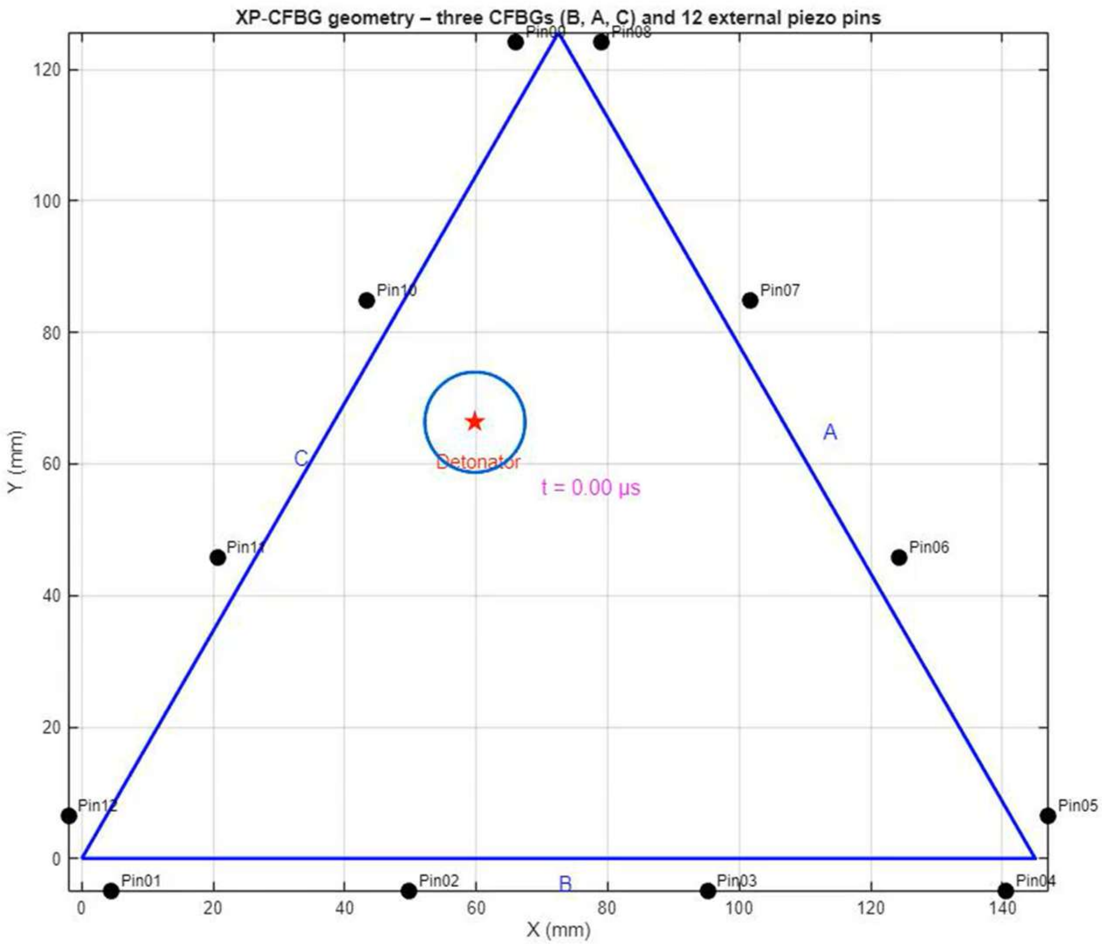
Trilateration



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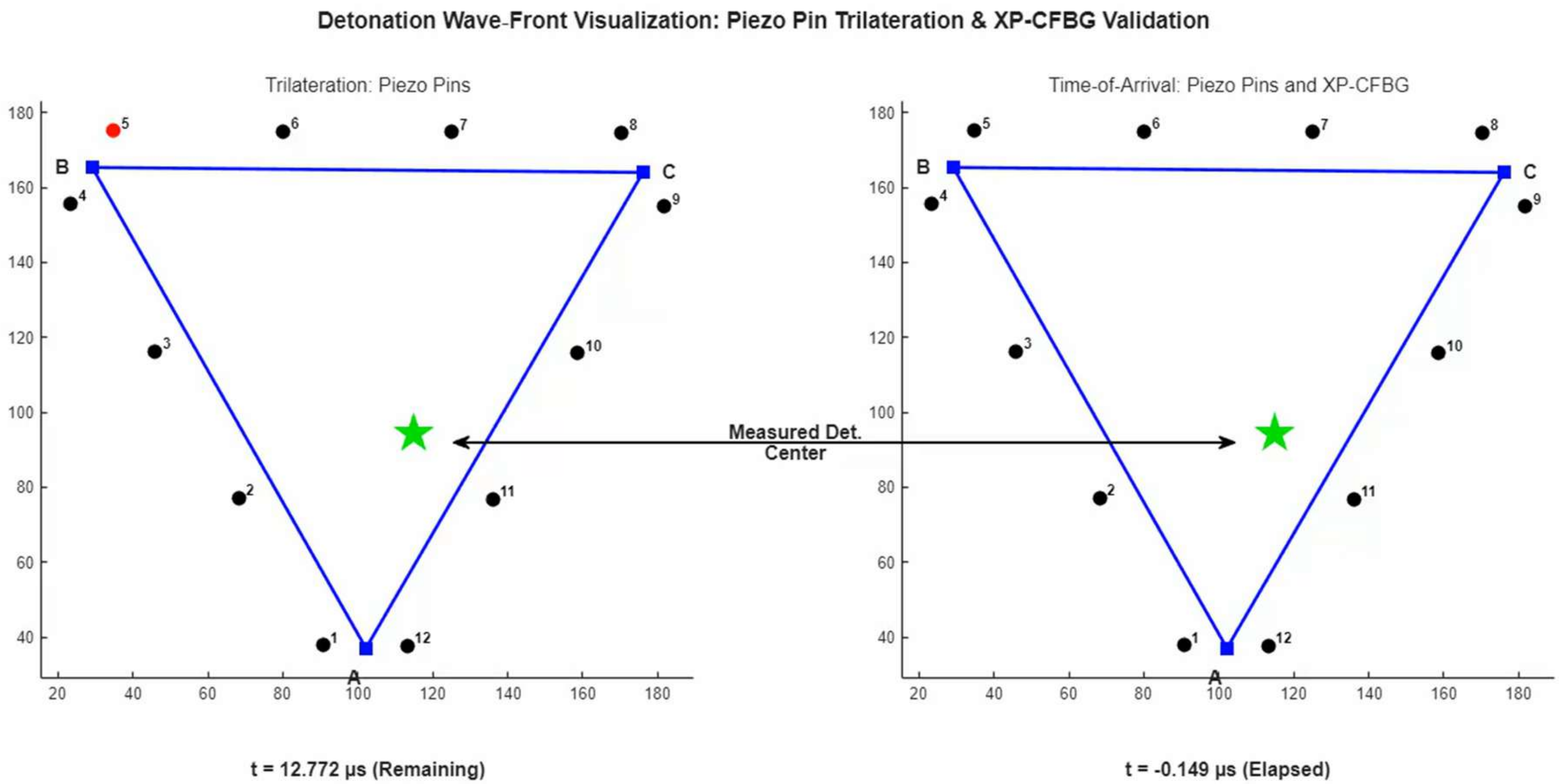
Trilateration



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Conclusions and future directions

- Increase of spatial and temporal resolution of CFBG by incorporating cross polarization and separating two signals with orthogonal polarization
- Separate signals had a 5 ns offset achieved by addition of a 1.1 m fiber
- Two CFBG signals were tracked separately by two independent detectors that were further transmitted to an oscilloscope on two separate channels
- This technique doubled CFBG spatial and temporal resolution
- We expect this novel cross polarization CFBG technique to improve shock and detonation measurements
- Future directions include refinement of the analysis method for alignment of the pulses in time, including further improving CFBG resolution by several factors of magnitude

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