Mach-Zehnder Fiber-optic Links for Reaction History Measurements at the National Ignition Facility

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Abstract. We present the details of the analog fiber-optic data link that will be used in the chamber-mounted Gamma Reaction History (GRH) diagnostic at the National Ignition Facility (NIF) located at the Lawrence Livermore Laboratory in Livermore, California. The system is based on Mach-Zehnder (MZ) modulators integrated into the diagnostic, with the source lasers and bias control electronics located remotely to protect the active electronics. A complete recording system for a single GRH channel comprises two MZ modulators, with the fiber signals split onto four channels on a single digitizer. By carefully selecting the attenuation, the photoreceiver, and the digitizer settings, the dynamic range achievable is greater than 1000:1 at the full system bandwidth of greater than 10 GHz. The system is designed to minimize electrical reflections and mitigate the effects of transient radiation darkening on the fibers.

1. Introduction

Traditionally, time-domain signals have been transmitted from high-bandwidth detectors to data recorders, such as oscilloscopes or digitizers, using coaxial cables. With coaxial cables, transmission bandwidth is maximized by (a) using high-quality cable, (b) keeping cable lengths as short as possible and (c) equalizing the cables, at the expense of signal amplitude. With short-pulse experiments like laser-driven inertial-confinement fusion (ICF) entering a new regime of energy and radiation emission, recording systems must be located 100 feet or more from the detectors [1]. At this length, preserving bandwidth above a few gigahertz for detectors with modest voltage output is not possible, so the National Ignition Facility (NIF) will use analog fiber-optic links to transmit data from the Gamma Reaction History (GRH) detectors to the digitizers [2].

The fiber links at NIF will initially be based on Mach-Zehnder (M-Z) modulators, commonly used in digital telecommunications because of their high bandwidth (> 10 GHz) and compatibility with low-loss single-mode optical fiber. M-Z transmission links are well suited to analog signal transmission and recording of pulsed power diagnostics for a few key reasons:
Bandwidth is preserved over arbitrarily long fibers (kilometers or more).
The M-Z modulator can tolerate large voltage pulses (> 500 V) without damage, thus optically isolating sensitive digitizer inputs from detector outputs.
Modern digitizers, unlike their tube-based counterparts, have high-gain input amplifiers that are well matched to high-bandwidth photoreceivers which typically output less than one volt.

2. NIF Gamma Reaction History Mach-Zehnder System
Engineering an M-Z system for pulsed-power experimentation requires careful consideration of several details in order to optimize the use of commercially available components into a modestly priced system. In particular, we have optimized the NIF GRH system for low-noise, signal accuracy and tolerance to electromagnetic pulse (EMP) effects. The important steps to system optimization were:

- Eliminating switching power noise in the laser diodes, as off-the-shelf laser modules are typically designed for digital telecommunications systems which are insensitive to noise below 10 MHz
- Controlling the modulator bias before the shot with no RF signal on the input using components specifically designed for analog fiber-optic systems
- Shielding and isolating DC bias voltage from EMP by shunting high frequencies to ground through a 50 Ohm resistor using a bias tee

The system for the NIF GRH diagnostic has a modular design, with the active electronics (laser diode, bias controller, and recording system) on the diagnostic mezzanine, and only the modulator located at the target chamber wall. The default configuration for the NIF GRH M-Z system will use two M-Z modulators per detector, with a 10x difference in attenuation to provide a dynamic range of 1000:1 at the full system bandwidth. The system schematic is shown in Figure 1(a), with the corresponding digitizer channel coverage shown in part (b), as measured during the OMEGA high-yield campaign in July 2009.

![Figure 1: NIF GRH M-Z system. The schematic is shown in (a), with two M-Z modulators running to four digitizer channels. The system dynamic range is shown in (b), as measured during the high-yield shot campaign at OMEGA in July 2009.](image)

Each M-Z optical signal is split using fiber couplers, and recorded on two photoreceivers attached to the digitizer. The noise in the laser diode ultimately determines the noise floor of the system; that noise level, however, is below the digitizer noise only if the signal is kept fully on scale. To achieve high dynamic range, one channel records the signal at the level of the laser noise and clips when the signal rises above a certain level, while the other channel records the full modulation amplitude of the
M-Z, though with higher noise floor due to the digitizer. This strategy is repeated for the second M-Z, giving overlapping coverage across three decades of signal level.

Four digitizer traces from one OMEGA shot are shown in Figure 2. The photomultiplier tube used on this shot has higher sensitivity and somewhat slower response than the tube more commonly used on the GRH for burn width measurements. However, this shot data shows the intrinsic dynamic range of the recording system, going from the 26 mV noise floor up to 27.5 V at the peak of the gamma signal. The data are composited using a noise-weighted spline fit, so that the traces with the lowest noise are most heavily weighted in the fit, until they go off-scale [3].

![Figure 2: M-Z composite data from a high-yield shot at OMEGA, showing dynamic range of the M-Z recording system. The delay is engineered into the GRH to separate the Cherenkov signal from the prompt, scattered gamma signal.](image)

3. Timing Measurement Considerations

One of the top-level requirements of the GRH diagnostic at NIF is precise measurement of so-called “bang time,” which is the timing of the peak fusion reaction rate relative to the laser drive. For quantitative error estimation, we must consider the effect of peak width and noise level on the estimate of timing.

One strategy for determining peak time to better than one digitizer period is to fit a function to data, for example a Gaussian. With real data, such a strategy is always executed under circumstances of (a) finite sample intervals in the recorded data and (b) noise in the record. For additive white Gaussian noise on a Gaussian peak, the uncertainty in peak location due to least-squares fitting can be expressed as:

\[ \text{RMS}_{-\text{Error}} \approx 0.007 \times N \times \sqrt{W} \]

Where \( N \) is the ratio of the RMS noise to the peak height, and \( W \) is the full-width-half-max of the peak, measured in digitizer samples.

Simulations were performed to verify this conclusion using 100 noisy Gaussian records at values of \( N \) from 0 to 20% (1% increments) and \( W \) from 4 to 20 (increments of 1). The results from the value \( N=0.1 \) are shown in Figure 3(a), and good fits were obtained for all values of \( N \). We analyzed peaks in the M-Z records from the May 2009 high-yield campaign at OMEGA with this formalism, using peaks from the timing fiducial, precursor peaks, the gamma peak and the first peak after the gamma peak.
The results show very good agreement in the slope of the curve, though with some noise due to the much smaller number of samples, since each data point in (a) represents 100 simulated curves.

![Graph showing simulated peak RMS error](image)

**Figure 3:** Peak uncertainty from Gaussian fitting. Simulation results for $N=0.1$ are shown in (a), and measured data from the OMEGA high-yield campaign in May 2009 are shown in (b).

4. Conclusion
The Mach-Zehnder transmission and recording system for the NIF GRH diagnostic provides dynamic range of greater than 1000:1 at the full system bandwidth of 12 GHz. The system has a modular design based on low-noise electronics located on the diagnostic mezzanine and the optical modulator co-located with the detector on the target chamber wall. Results at OMEGA over the last three years show that the system is very reliable and that measurement of peak timing is robust, even at the subsample-interval timescale.

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