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Isolated fiber-optic transmission of IGBT U_{CE} signals for precise HV switching analysis

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***Abstract*—This work presents the design and implementation of an isolated fiber-optic transmission system for real-time monitoring of collector-emitter voltage (U_{CE}) in IGBT-based high-voltage (HV) stacks, with a focus on applications in industrial and accelerator environments. The system, named LaserLink, addresses the need for galvanic isolation, operator safety, and high-fidelity signal acquisition under challenging conditions such as ionizing radiation, strong electromagnetic interference, high temperatures, and restricted operator access.**

The architecture employs analog signal transmission using modulated laser diodes and fiber-optic links, with each IGBT monitored by a dedicated optical transmitter (HiBox) and a ground-referenced receiver (LowBox). The solution enables broadband observation of dynamic $U_{CE}(t)$ waveforms with a bandwidth from DC to at least 50 MHz, supporting precise analysis of switching events, detection of anomalies, and implementation of advanced timing correction algorithms. The paper discusses the rationale for avoiding local A/D conversion at the measurement point, highlighting environmental, diagnostic, and scalability constraints that favor analog transmission. The LL system demonstrates that robust analog optical transmission for HV measurement can be achieved using cost-optimized components when paired with targeted compensation strategies and careful architectural design.

***Keywords*—laser diode; light modulation; signal transmission band; self calibration; thermal conditions**

I. Introduction

POWER systems based on IGBT transistors operating in series configurations (HV stack) require precise control and diagnostics of switching parameters. The key measurement signal is the collector-emitter voltage (U_{CE}), observed locally on each transistor. To ensure operator safety and enable analyses from the system ground level (GND), galvanically isolated transmission of these signals to a safe potential area is necessary.

A. Justification for Transmitting UCE to Ground Level

In cascade systems, the U_{CE} voltage is locally measured relative to the emitter, which is at a high and variable potential—often ranging from several hundred volts to several kilovolts. Direct measurement of this voltage relative to earth is impossible without introducing an isolation system.

Transmission of the $U_{CE}(t)$ signal to the GND level enables:
- Precise determination of switching times (Ton, Toff);
- Identification of asymmetric switching between transistors in the stack;
- Observation of saturation voltage U_{CESAT};
- Detection of anomalies such as desaturation, tail current, ringing;
- Application of switching time correction algorithms (timing correction).

B. Environmental Requirements and Limitations of Classical Methods

1) Ionizing Radiation (X-ray)

In accelerator applications, the HV system may be exposed to ionizing radiation. Consequences include degradation of electronic components (integrated circuits, converters, capacitors), interference with light detectors, and potential scintillation of optical fibers. The use of optical isolation with radiation-resistant components (e.g., rad-hard LD/FAP) reduces the risk of failure.

2) Strong Electromagnetic Fields (EMI)

Fast switching of IGBTs at high voltage and current (tens of kV/µs, kA/µs) generates strong interference pulses. Classical HV differential probes based on coaxial cables may be susceptible to common-mode interference and capacitive coupling. Optical transmission eliminates ground loops and provides high immunity to EMI.

3) High temperature

System elements located in the immediate vicinity of IGBT transistor heat sinks must operate reliably at temperatures exceeding 85 °C. This requires the use of industrial components with low temperature drift and provision of locally stable power supply.

4) Limited operator access

Under HV system operating conditions, direct access to measurement points is dangerous. Measurement solutions must provide complete galvanic isolation and enable remote monitoring from the operator level—including during service and integration tests.

II. LaserLink Fiber-Optic System considerations

In response to the above requirements, the LaserLink system was developed, in which each IGBT transistor cooperates with a local optical module (HiBox) containing:
- Voltage divider for U_{CE};
- Analog laser modulator (LD 650 nm, 10 mW);
- Local power supply at the emitter potential of the currently monitored transistor;
- Switchable measurement ranges and input modes AC/DC/GND;

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- Optically controlled channel for sync/range relay control (separate digital fiber with slow transmission rate).

The analog signal is transmitted via fiber optic cable to the receiver (LowBox) at the GND level. The system bandwidth is ≥50 MHz, enabling observation of fast transitions and voltage oscillations.

A. *Abandoning Local A/D Processing in the LaserLink System: Environmental and Architectural Constraints*

1) *System and Functional Assumptions*

The LaserLink (LL) system aims to enable broadband observation of dynamic $U_{CE}(t)$ voltage waveforms on individual IGBT transistors in high-voltage stacks, with full galvanic isolation and minimal signal distortion from the transmission path. Information transfer is analog-based, using a modulated laser diode (LD) and unidirectional optical fiber. A concept for local signal digitization at the HiBox level (i.e., at each transistor) was considered but ultimately rejected due to technical, environmental, and diagnostic constraints—outlined below.

2) *Environmental Requirements: Radiation and Interference*

- *X-ray Radiation*

In systems like radiation sources, accelerators, or HV circuits used in industrial/research settings, IGBT environments may be exposed to ionizing radiation. This radiation:

- Degrades digital circuits (microcontrollers, FPGAs, ADCs) faster than analog components;
- Causes latch-up, bit-flip, and SEU (Single Event Upset) effects;
- Requires costly "rad-hard" components, often with limited availability.

The analog LD modulation path is significantly more radiation-tolerant and eliminates error-correction processes.

- *Electromagnetic Interference (EMI)*

Local A/D processing requires high-bandwidth data buses and ultra-short signal paths vulnerable to interference. Near operating IGBTs, extreme voltage/current slopes (dU/dt > 30 kV/µs, dI/dt > 1 kA/µs) generate:

- Conducted/radiated emissions;
- Impulsive noise coupled through power and local grounds;
- Uncontrolled A/D conversion errors.

3) *Bandwidth and Digital Transmission Limitations*

For a signal sampled at 200 MSPS (Mega Samples Per Second) with 10-bit resolution, the data rate per channel is:

- 200 MSPS × 10 bits = 2 Gbit/s;

In an 8-channel system (for 8 transistors in a stack):

- 8 × 2 Gbit/s = 16 Gbit/s.

This bandwidth:

- Exceeds plastic optical fiber (POF) capabilities (max. ~1 Gbit/s at short lengths, even with high error margins);
- Demands QSFP+/SFP+ high-speed links—prohibitively expensive and difficult to integrate with HV isolation;
- Increases transceiver complexity, requiring synchronization protocols, error correction, and reconfiguration.

4) *Diagnostic and Reliability Challenges*

- Local Digitization Complicates Debugging

If A/D processing, transmission, or decoding fails, distortion sources become untraceable. Verification with standard oscilloscopes is impossible, as signals remain in the digital domain within galvanically isolated structures.

- Remote Diagnostics Become Non-Trivial

Requires frame logging, CRC analysis, and clock synchronization systems. Increases computational load and memory requirements on the receiver side. Demands separate debug interfaces for each HiBox module—challenging at potentials of tens of kV.

5) *Complexity ×8 Mismatches System Objectives*

LaserLink was designed as an auxiliary tool for dynamic switching analysis, intended to provide:

- Simple, reliable real-time $U_{CE}(t)$ observation;
- Scalability and configurability;
- Interference and radiation resilience.

Implementing local digitization across 8 channels would introduce nonlinear complexity growth. The system would evolve into a diagnostic platform requiring its own diagnostics—contradicting the core purpose. LaserLink exists to analyze HV systems, not to become a standalone digital oscilloscope with clock synchronization.

6) *Benefits of proposed solution*

Rejecting local A/D processing in LaserLink resulted from a deliberate analysis of bandwidth, reliability, environmental resilience, and complexity trade-offs. Adopting analog transmission via modulated LD ensures:

- X-ray/EMI immunity
- Minimal local complexity (no clocks, ADC, FPGA);
- Ease of scaling and servicing;
- Compatibility with standard oscilloscopes for $U_{CE}(t)$ analysis

Consequently, LL's current architecture maximizes functionality within minimal infrastructure, aligning with its role as a supportive—not dominant—tool in HV IGBT measurement systems.

B. *Optimization of Laser Diode Current Modulation: An Engineering Approach for Precision Applications*

1) *Operating Point Selection (Bias Current)*

The diode's operating point should be slightly above the threshold current (Ith) to ensure stimulated emission and enable linear optical response. Values of 1.2–1.5 × I_{th} achieve high bandwidth without excessive thermal loading.

2) *Modulation Depth*

Modulation amplitude must avoid driving the current below the lasing threshold. Otherwise, spontaneous emission regions increase noise, delay ignition, and intensify nonlinear chirp effects. Modulation amplitude should be limited to <50% above I_{th}.

3) *Dynamic Effects and Modulation Bandwidth*

The laser's resonance frequency (fr) increases with bias current per: $fr \propto \sqrt{I - Ith}$ [1]. Over-provisioning bias current extends modulation bandwidth to GHz-range, provided thermal management is effective.

4) *Gain Compression Effect*

At high optical intensities, gain compression limits linearity due to carrier saturation and active-medium nonlinearities. Gain (g) relates to optical power (P) as:

$g(N, P) = g_0(N - Ntr)/(1 + \varepsilon P)$, where ε is the compression coefficient. This flattens L–I characteristics at high currents, complicating precise modulation—especially at high frequencies/large signals. Optimization requires limiting modulation amplitude.

5) Thermal Stabilization

Temperature directly impacts threshold current (Ith), slope efficiency, and wavelength (typical dλ/dT ≈ 0.3 nm/°C). Active cooling, thermistors, or TECs ensure spectral stability and linear L–I responseGain Compression Effect

6) Chirp Minimization

Chirp (optical frequency modulation via refractive index changes) critically limits spectral-coherence applications. Mitigation strategies:

- Limiting modulation depth:
- Using external modulation (EOM/MZM):
- Temperature stabilization and higher bias.

However, in systems with bandwidth requirements below 100 MHz (such as the 50 MHz LaserLink system), chirp effects are generally negligible for intensity-based detection applications.

III. Engineering Aspects of LaserLink System

A. Role, Characteristics, and Requirements for Monitor Photodiodes in Laser Diode Systems

The monitor photodiode (PD) is an integral component in many laser diode (LD) systems [2], especially in applications that demand stable optical emission, precise linearity of light output, or long-term optoelectronic reliability, as its primary function is to provide feedback signals for LD current regulation or modulating amplifier circuits.

Functionally, the monitor PD enables measurement of the actual optical power emitted by the LD in DC mode, facilitates long-term brightness stabilization through a feedback loop, compensates for thermal drift of the LD threshold voltage, allows for analog path voltage calibration (such as SPAN adjustment), and supports diagnostics of LD status and degradation, for example by monitoring current-to-light conversion efficiency.

The electrical and optical characteristics required of the PD depend on the application, but typically include spectral sensitivity matched to the LD emission range (e.g., 630–650 nm), low dark current (in the nA or pA range) to ensure DC readout stability, low junction capacitance (less than 10 pF) for maintaining loop stability and bandwidth, minimal bandwidth (usually under 100 kHz) sufficient for DC measurements without limiting the open-loop response, a minimal temperature coefficient of sensitivity to ensure that photocurrent is largely independent of ambient temperature (or can be compensated), and long-term stability, which is essential in industrial or precision environments.

Closed-loop operation should generally be restricted to warm-up phases or synchronized with system pauses, such as 2 ms intervals between pulses. However, practical limitations must be considered: many low-cost PDs show significant photocurrent temperature drift even in DC mode, their current-voltage characteristics may be nonlinear or vary with aging, and high capacitance can restrict loop bandwidth and cause instability in dynamic regulation; moreover, PD-based systems are typically unsuitable for fast optical modulation and are best used for DC-level regulation.

Ultimately, the monitor photodiode is critical for LD systems that require precise establishment and correction of the operating point over time, temperature, and operational cycles; in systems like LaserLink, its role is focused on providing a stable light bias (LD DC current component) during warm-up or synchronized idle periods, and careful selection of PDs with consideration for their limitations allows for simplified regulation design while maintaining high reliability and repeatability of the optical signal.

C. Characteristics and Requirements for Receiver Photodiodes in Analog Laser Transmission Systems

The receiver photodiode (Rx PD) is a critical component in analog optical transmission systems utilizing modulated laser diodes, as it is responsible for converting variable-intensity light signals into electrical signals with maximum fidelity in amplitude, linearity, and bandwidth. In analog applications, photodiodes are subject to more stringent requirements [3] for noise, bandwidth, and stability compared to their digital counterparts.

To ensure optimal performance, the Rx PD must support the system's maximum modulation frequency—such as 50 MHz in the LaserLink system—which is fundamentally determined by the junction capacitance and the value of the load resistance; applying a reverse bias (typically around 5 V) is recommended to minimize capacitance and enhance response speed. The photodiode's sensitivity and spectral responsivity [4] should be matched to the emission wavelength of the laser diode, usually within the 630–650 nm range, and should maintain a high and thermally stable responsivity (A/W) throughout this spectrum.

Low noise and offset stability are vital for analog transmission, with key parameters including a dark current below 10 nA, minimal combined current and thermal noise, and negligible offset drift over temperature variations. From an integration standpoint, the Rx PD should allow straightforward connection to receiver circuits—such as through transimpedance resistors or voltage-controlled amplifiers (VCAs)—and, provided the optical signal is sufficiently strong (for example, with a 1 kΩ load), may not require a dedicated transimpedance amplifier.

Additionally, the photodiode must be capable of accurately receiving short optical pulses in the 10–20 ns range without introducing distortion. For practical implementation, components such as the OSRAM SFH250, a fast PIN photodiode [5] optimized for 650 nm with a 50 MHz bandwidth at 5 V bias and a rise time of approximately 5 ns, are well suited, while lower-cost alternatives like the BPW34 may be considered where speed is less critical. It is essential that the reverse bias supply is well filtered to prevent noise, the photodiode is shielded from ambient light to avoid interference, and, in high-sensitivity analog paths, magnetic shielding is recommended to minimize external disturbances.

D. Laser Biasing and Feedback Loop

The core of the HiBox transmitter (Fig. 1) is a circuit built around amplifiers with an integrated Shutdown function, which is used as a Track-and-Hold (T/H) element to activate or deactivate specific circuit branches. The FBA (LD Feedback Amplifier) operates as an active current source biasing the laser diode (LD) with 10 mW power and a wavelength of 650 nm.

In closed-loop feedback mode, the FBA is controlled by an error signal generated by the TIA (PD Trans-Impedance Amplifier). The purpose of this loop is to stabilize the LD's quiescent current as a function of the PD response, regardless of LD forward voltage variations or thermal drifts. The voltage established in the loop during its active operation serves as a reference point for the analog part of the circuit, marked as AGND (Artificial GND) This eliminates the problem of shifting input-output signal potentials and enables the system's bandwidth to extend down to DC.

Since the monitoring PD has a very limited bandwidth (typically with a pole at several tens of kHz), the stabilization loop is designed with filtering limited to DC and very low AC. Its bandwidth is determined by time constants, meaning the loop cannot react to fast modulation—it only provides stabilization of the basic LD bias current. The closed-loop mode is maintained only for a few minutes after system startup, during the "warm-up" phase. During this time, the microcontroller monitors the voltage via the local ADC input.

Once the operating point stabilizes, the system switches to open-loop mode, where only the modulation path is active. During operation, the loop can be briefly reactivated to recall the operating point, e.g., during 2 ms breaks between pulses in the HV switching system.

Signal modulation is achieved by adding a modulation component to the established LD current (set by the FBA) via the LMA (LD Modulation Amplifier).

E. Signal Modulation

The SigIn input supplies the measurement signal (e.g., the U_{CE} voltage from the IGBT, divided as determined by the microcontroller μC), which, after passing through the T/H buffer, reaches the LMA. When T/H is active, the LMA injects the modulation current into the LD through a passive filter that introduces a zero in the transfer function, thereby extending the modulation bandwidth and setting the modulation depth of the LD current.

The potential of the entire signal path is "floating"—referenced to the local GND established by the feedback loop. The FBA cannot be turned off (no shutdown), which means the LD bias current is always present, and modulation is achieved by superimposing additional current from the LMA

F. Compensating LD Pole for Bandwidth Extension

In the analog optical transmission system LaserLink (LL), the transmitter unit (HiBox) employs a laser diode (LD) as the optical source, modulated via a current driver based on EL8300 and supported by high-speed analog amplifiers such as VCA821. A critical factor limiting the high-frequency response of such systems is the intrinsic low-pass behavior of the LD and its associated circuit, introducing a dominant pole typically in the 10–20 MHz range.

In the present configuration, the native frequency pole of the laser diode was identified at approximately 16 MHz. This pole arises due to the combined effects of the LD junction capacitance, the impedance of the driver circuitry, and parasitic elements from the PCB layout and packaging.

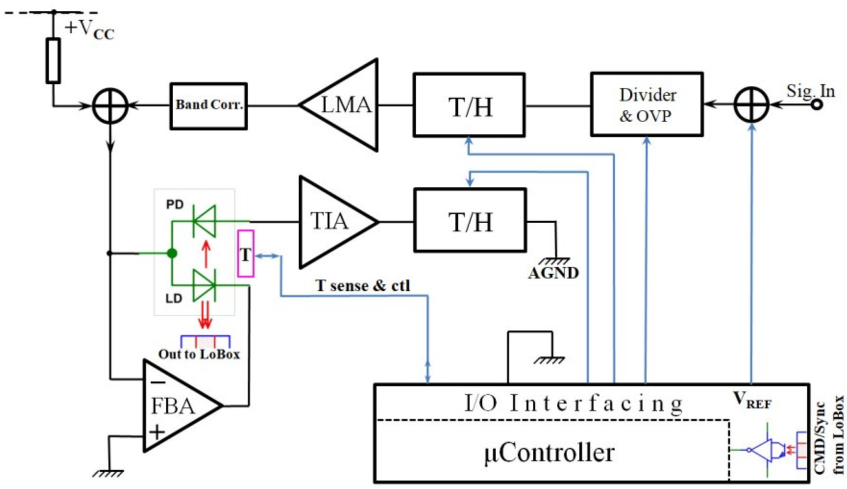

Fig. 1. Simplified functional diagram of LaserLink transmitter unit - HiBox

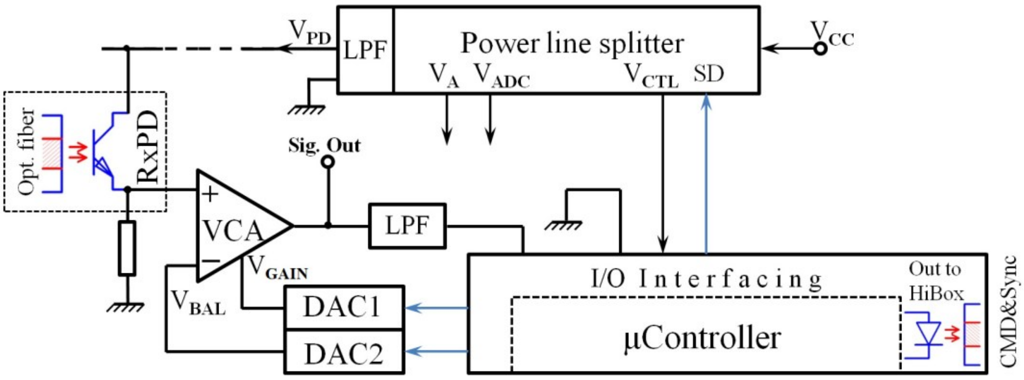

Fig. 2. Simplified functional diagram of LaserLink receiver - LoBox

The presence of this pole introduces a phase lag and reduces signal amplitude for higher frequencies, effectively limiting the system bandwidth.

To extend the bandwidth, a variable capacitor (trimmer) was introduced in the biasing network of the LD. By carefully tuning this capacitor, a transmission zero was placed near the frequency of the dominant pole. This configuration resulted in effective pole-zero cancellation, reducing the overall phase lag and flattening the frequency response over a wider range. The practical outcome of this compensation was a significant improvement in the bandwidth of the system — from a limited 16 MHz up to approximately 50 MHz.

This technique exemplifies a classic compensation strategy in analog circuit design, particularly effective in systems where a single dominant pole dictates performance. However, beyond this improved bandwidth, a second limitation appears. At frequencies beyond 50 MHz, the cumulative effect of additional poles becomes apparent. These arise from the transmission medium (plastic optical fiber), the response time of the photodiode [6] (SFH250), the input characteristics of the differential amplifier, and the parasitic inductance and capacitance of the PCB traces

G. *Thermal Stabilization and Startup Management for Laser Diode*

To minimize stabilization time and ensure repeatable performance characteristics, active thermal management of the LD package is implemented through a precision temperature sensor and SMD power resistor bonded directly to the LD's metal housing, functioning as a localized heater controlled by a microcontroller (µC). The µC continuously monitors the LD temperature and activates the heating resistor until the target operational temperature range (typically 40–45°C) is achieved and maintained.

This approach delivers rapid thermal stabilization while enabling cyclic temperature monitoring during normal operation, which allows for temporary transmission suspension or recalibration if deviations occur, providing full thermal state control, eliminating unpredictable drifts, and significantly reducing optical transmission preparation time. Future enhancements include developing a thermally isolated LD capsule and implementing a PID loop within the µC firmware for improved regulation.

Key advantages of this solution include its favorable cost-to-efficiency ratio, elimination of modifications to the transmission path, and minimal hardware changes—requiring only a small additional component on the HiBox.

H. *Calibration Procedures*

1) *SPAN Calibration*

The HiBox generates a reference voltage via its Vref circuit. The µC output normally remains high-impedance but activates during calibration, setting the reference voltage fed to the Divider and OVP (Overvoltage Protection) circuit. The LoBox reads the optical level corresponding to this value and calibrates its response (V_{GAIN} channel) to achieve the target voltage SPAN.

Activation Conditions:

- Calibration is only permitted when HV stack voltage is absent (safety/reliability requirement).
- The CMD/SYNC line transmits calibration commands and synchronizes bias refreshing during operation.

2) *Zero Correction*

In the LoBox, the Vpd voltage from the LPF (Low-Pass Filter) power supply output is referenced to the local signal ground. The HiBox's optical output level corresponding to 0 V input (Sig.In) is detected by the receiver photodiode, generating a voltage drop across a 1 kΩ resistor fed to the VCA input. The µC reads the zero level via its ADC input. If needed, it applies offset correction (V_{BAL}) via DAC2, which supplies V_{BAL} to the VCA's -Vin input. Sequence: Zero correction precedes SPAN calibration. Both parameters are stored in µC memory post-calibration.

3) *Bias Refreshing*

To compensate for slow thermal drifts in the PD (affecting LD bias readings), a bias refreshing procedure is executed periodically (e.g., every 60 s). The HiBox enters closed-loop mode for ~100 µs to recall the original operating point.

Implementation Modes:

- Asynchronous: Triggered by the HiBox's µC local clock.
- Synchronous: Activated by a SYNC pulse at the µC interrupt input.
- Mixed-mode: If SYNC is absent within a set time, local bias refreshing initiates via timeout.

I. Final Remarks

Designed for precise $U_{CE}(t)$ measurements in HV systems, LaserLink balances implementation simplicity with transmission quality:

- Receiver design: A 1 kΩ resistor replaces a transimpedance amplifier in the LoBox, leveraging sufficient optical signal levels and preserving wide bandwidth.
- Performance: The SFH250 diode (5 V bias) achieves:
- Rise time: 5–10 ns;
- Bandwidth: ≥50 MHz;
- Output: Directly compatible with oscilloscopes or signal acquisition systems.

IV. EXPERIMENTAL

A) Experimental Setup

For the experimental evaluation of the transmission parameters of the LaserLink (LL) analog optical path, a complete transmitter–receiver setup was assembled. This setup included a HiBox module with a laser diode (LD) integrated with current modulation circuits, and a receiver LoBox equipped with an SFH250V PIN photodiode in a shielded optical enclosure.

The connection between the modules was realized using single- or multi-meter lengths of plastic optical fiber, corresponding to typical laboratory or industrial applications of the system.

B) Test Signal

For testing purposes, an electrical signal generated by a function generator was applied to the HiBox analog input. The generator was carefully selected with respect to:

- Amplitude and DC offset – to simulate voltages observed at the Uce voltage divider of the IGBT transistor,
- Signal shape – including square pulses, triangular waves, and continuous waveforms, reflecting real $U_{CE}(t)$ variations,
- Frequency range – the bandwidth was tested from several tens of Hz up to tens of MHz, in accordance with the switching dynamics of modern power transistors.

V. RESULTS

A. Input–Output Transfer Characteristics

All measurements were carried out with consideration of oscilloscope limitations (including ADC resolution and acquisition length), which were accounted for in the analysis of result accuracy and repeatability.

Comparison of input and output signals in terms of linearity, attenuation and offset is shown in Fig. 3. Since the total gain of the signal transmission system is 5, the input and output waveforms were superimposed for a visual assessment of the path’s linearity. The transmitted signal shows good agreement, with any differences attributable to the delay introduced by the system.

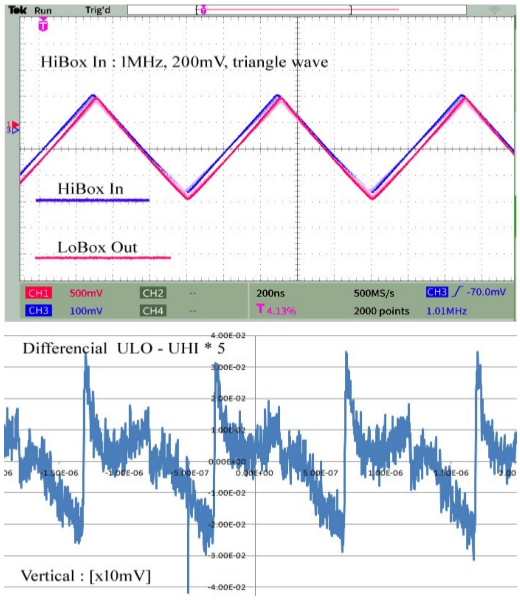

Fig. 3. Comparison of input and output signals in terms of linearity, attenuation and offset,

The result plotted below the waveforms is based on numerical values of signals obtained from the oscilloscope. After eliminating the time shift, the signals were subtracted from each other. The resulting plot is typical for quantization errors of AD converters [7]. Conclusion: the linearity testing of the path is unfortunately limited by the signal processing within the oscilloscope itself (8-bit, 500 MSPS).

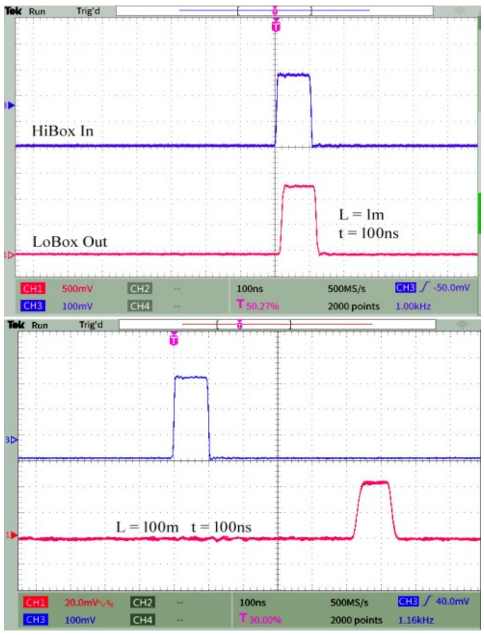

Fig. 4. Comparison of input and output signals collected with different optical fiber length

Figure 4 compares signals transmitted through optical fibers of different lengths. The per-meter delay introduced by the fiber and the fixed electronic circuit delay can be estimated from these measurements:

1 m measurement: 13 ns total delay,

100 m measurement: ~530 ns total delay,

hence the difference for 99 m is 517 ns,

so: 99 m ≈ 5.22 ns/m - this aligns with the nominal propagation delay of ~5 ns/m in plastic optical fiber (reflecting a refractive index of ~1.5)

Additionally, observation of pulse "smearing" aligns with chromatic dispersion effects, where high-frequency components arrive later than low-frequency ones, causing temporal broadening without amplitude loss.

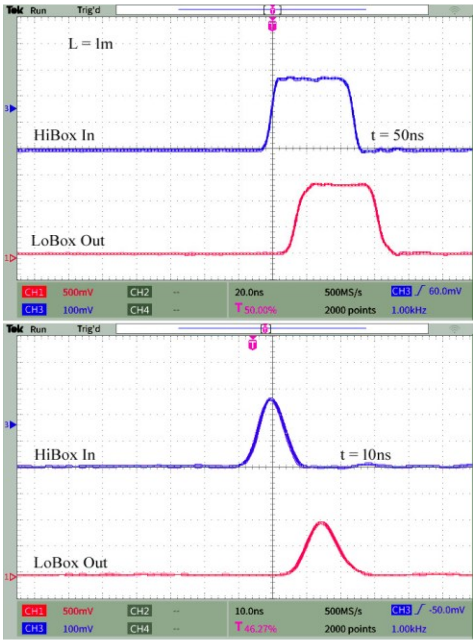

Fig. 5. Frequency-domain pulse parameter comparison (input vs. output) with fixed-delay estimation data for electronic circuits.

From the pulse comparison in Figure 5, the total delay introduced by electronic circuits in the path can be determined. Given that 1 m of optical fiber contributes 5.22 ns delay and the total measured delay is 13 ns, the fixed electronic delay can be calculated as approximately 7.8 ns. Additionally, analysis of 50 ns pulse raising edge t_R= 6.5ns (BW ≈ 0.35/t_R = 54 MHz) and an independent sine signal sweep measurement indicate a bandwidth exceeding 50 MHz.

VI. CONCLUSIONS

The LaserLink analog optical transmission system has achieved its engineering objectives for signal bandwidth and linearity while maintaining consistency with component quality and operating within budget constraints. Despite utilizing cost-effective components—including an economical-grade laser transmitter diode, EL8300/VCA821 amplifiers, and an SFH250V optical receiver—the LL path delivers an effective transmission bandwidth exceeding 50 MHz and high input-output linearity within the ±SPAN range.

Implemented compensation techniques (notably local elimination of the LD frequency pole) and a well-considered biasing/calibration architecture fully leveraged the potential of analog transmission over plastic optical fiber at minimal unit costs. The system is validated as optimally tuned—both in dynamic performance and economic implementation efficiency.

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