Low-Cost Quasi-Distributed Fiber-Optic Sensors for Structural Health Monitoring Using 650 nm Lasers

Raushan Aimagambetova, Ali Mekhtiyev, and Aliya Alkina

***Abstract*—**Structural health monitoring (SHM) demands durable, sensitive sensors embedded in infrastructure. Fiber-optic sensors (FOS) are ideal due to their small size, flexibility, and immunity to electromagnetic interference. These passive, all-optical sensors are intrinsically safe in hazardous environments where electrical sensors may fail or ignite. However, conventional FOS systems use expensive 1310/1550 nm lasers and interrogators, making them costly. We develop a quasi-distributed FOS system using low-cost 650 nm diode lasers and silicon photodetectors. We show that a properly chosen 650 nm diode laser can achieve sensing performance comparable to infrared systems while drastically reducing hardware cost. Experiments on concrete beams demonstrate a nearly linear increase in fiber attenuation with load, validating quantitative strain sensing. Despite higher fiber loss at 650 nm, practical SHM lengths are short enough that this is acceptable. The all-optical design ensures intrinsic safety and immunity to interference, with the visible wavelength enabling easy alignment and inexpensive detectors.

***Index Terms*—**fiber-optic sensors, laser diode, optical attenuation, safety, structural health monitoring

I. Introduction

Fiber-optic sensors (FOS) are attractive for structural health monitoring (SHM) because of their small size, lightweight, and immunity to electromagnetic interference [1]. As passive, all-optical sensors they are intrinsically safe in hazardous environments [2]. Distributed and quasi-distributed configurations allow spatially resolved measurements along long fiber paths, yielding a comprehensive picture of strain or deformation in large structures. However, widespread deployment of FOS has been limited by the high cost of telecommunication-band sources and interrogators at 1310–1550 nm, which typically require narrow-linewidth lasers and precise interferometric receivers [3]. This work explores a low-cost alternative based on commodity 650 nm laser diodes. Such diodes, commonly found in consumer products, can provide tens of milliwatts at visible wavelengths and are paired with inexpensive silicon photodetectors. Although standard telecom fiber exhibits higher attenuation at 650 nm, many civil-infrastructure sensing applications involve meter-scale lengths where this loss is acceptable. We evaluate the stability of several red diodes and demonstrate a quasi-distributed fiber sensor embedded in concrete elements.

II. Materials and Methods

Several off-the-shelf 650 nm laser modules (nominal outputs 10–30 mW) were characterized. Each module was powered by batteries and allowed to warm up for at least one hour before testing. Optical power was measured with a silicon photodiode power meter, and wavelength stability was evaluated by heterodyning the diode output with a stabilized 633 nm reference using a fiber-coupled optical spectrum analyzer. A standard G.652 single-mode fiber was epoxied into a groove along a concrete beam to form the sensing element. The beam was loaded in four-point bending, and the transmitted power was logged to quantify strain-induced attenuation. An optical time-domain reflectometer (OTDR) at 650 nm was used in supplementary tests to localize induced bends.

III. Results and Discussion

Among the tested lasers, one 30 mW 650 nm diode (Laser B) exhibited the best stability. After warm-up, its output power was approximately 36.4 mW with only about 0.5% standard deviation over 30 minutes. To quantify wavelength stability, each 630–650 nm diode was heterodyned with a stabilized 633 nm reference and 10 000 frequency samples were recorded at steady state. Fig. 1 shows the frequency-versus-time trace (top) and the Allan variance versus integration time (bottom) for a representative 650 nm diode laser heterodyned with the 633 nm reference.

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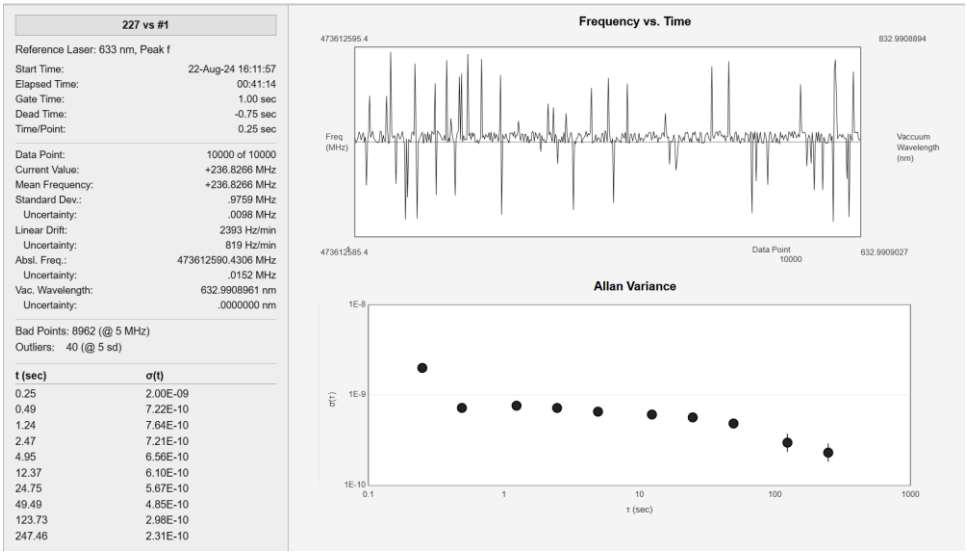


Fig. 1. Frequency-versus-time trace and Allan variance for laser #1 measured against a 633 nm stabilized reference (10 000 data points).

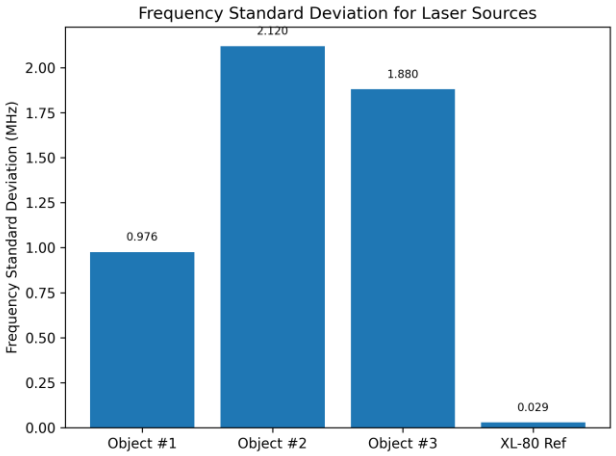


Fig. 2. Frequency standard deviation (MHz) for Object #1–#3 and the stabilized 633 nm reference (10 000-point heterodyne runs).

The trace reveals short-term fluctuations that average down with integration time, whereas the Allan variance decreases consistently, indicating predominantly white-frequency noise over the short term. From the same 10 000-point run, the representative diode exhibited a frequency standard deviation of 0.976 MHz and a linear drift of +2.393 kHz·min⁻ ¹, values used as acceptance thresholds when screening low-cost sources for SHM. Table I compiles the frequency-stability metrics for all sources under identical 10 000-point acquisitions, reporting the standard deviation (MHz) and linear drift (kHz·min⁻ ¹) obtained from a least-squares fit to the frequency-versus-time data.

TABLE I
FREQUENCY STABILITY OF 630–650 NM LASERS VERSUS STABILIZED 633 NM REFERENCE (10 000-POINT HETERODYNE RUNS)

Source (λ)	Frequency standard deviation (MHz)	Linear drift (kHz·min⁻ ¹)	Points
Object #1 (≈633–650 nm)	0.9759	+2.393	10 000
Object #2 (≈633–650 nm)	2.12	−64.984	10 000
Object #3 (≈633–650 nm)	1.88	+1.412	10 000
XL-80 stabilized ref (633 nm)	0.029	+0.401	10 000

The stabilized 633 nm reference outperforms the low-cost diodes by more than an order of magnitude in short-term frequency noise and drift, which becomes decisive for phase-sensitive or interferometric sensing where source fluctuations map directly into phase error [4]. For intensity-modulated sensing in concrete, the observed stability of the best low-cost unit is typically sufficient when coupled with basic thermal management, whereas the broader suitability of fiber-optic sensors for civil infrastructure SHM is well established [5]. Fig. 3 compares the linear drift across all sources, highlighting the markedly lower drift of the stabilized reference.

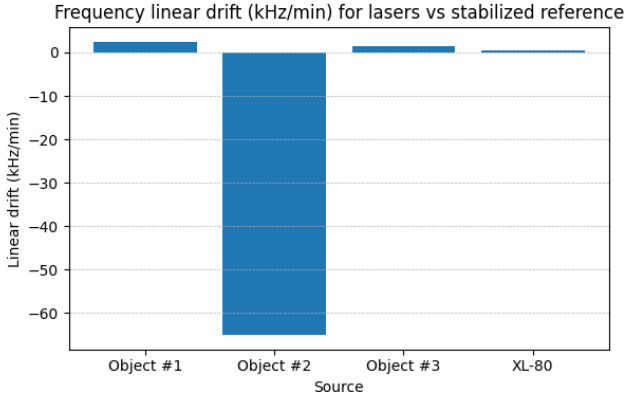


Fig. 3. Frequency linear drift (kHz·min⁻ ¹) for Object #1–#3 and the stabilized 633 nm reference (10 000-point heterodyne runs).

Under monotonic load increase (beam loaded to failure), the fiber loss increased nearly linearly with applied force. For example, raising the load to ≈35 kN produced ≈8 dB of additional loss (attenuation). The loss-versus-load curve had $R^2 \approx 0.99$, indicating a highly linear sensor response. This linearity and sensitivity (resolvable power changes <0.1 dB) confirm that the quasi-distributed fiber sensor can quantify

structural deformation. The fiber remained intact up to ultimate load, demonstrating robustness. The embedded sensor and electronics-free design mean the system is intrinsically safe in explosive or EMI-heavy environments [6]. The visible wavelength also simplifies handling: the beam path can be aligned visually and low-cost silicon photodiodes suffice as detectors [7].

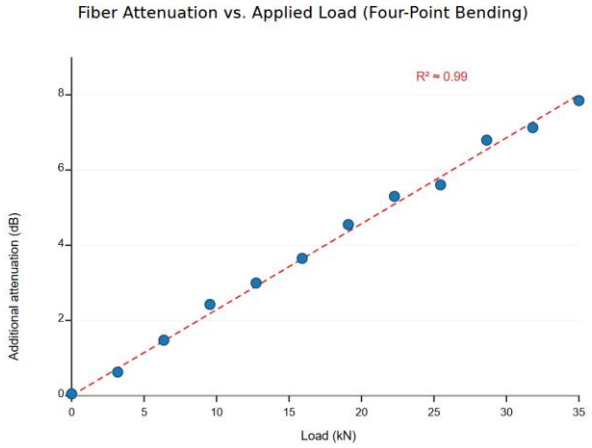


Fig. 4. Additional fiber attenuation versus applied bending load for the concrete beam under four-point bending, showing a near-linear response (≈8 dB at ≈35 kN, $R^2 \approx 0.99$).

It is true that fiber attenuation at 650 nm is higher than at 1310 nm (≈1–2 dB·km^{-1}), but in our meter-scale tests this was not limiting. For longer runs (up to a few kilometers), one can use 650 nm sections for local sensing and then splice to telecom-wavelength fiber for long-haul links. Combining the sensor with an OTDR enables damage localization: in separate tests we simulated a crack by introducing a defined bend at a known position, and the 650 nm OTDR successfully located the event, confirming that standard fiber-interrogation techniques remain effective with visible lasers [8].

Overall, the results demonstrate that mass-produced red lasers enable low-cost FOS networks without sacrificing essential performance [9]. The inexpensive components reduce system cost and complexity, addressing a key barrier to field deployment. In applications such as mining or remote infrastructure, this affordability is critical [10]. Future work will involve field trials on real structures and the integration of automated signal processing (e.g., machine-learning-based anomaly detection) for real-time SHM based on these low-cost fiber sensors [11].

TABLE II
ESTIMATED PER-CHANNEL COMPONENT COST: 650 NM DIODE-LASER SENSING HARDWARE VERSUS CONVENTIONAL 1310/1550 NM TELECOM-GRADE INTERROGATION HARDWARE. FIGURES ARE INDICATIVE CATALOG-PRICE RANGES, NOT ITEMIZED SUPPLIER QUOTES

Component	650 nm system (est., USD)	1310/1550 nm system (est., USD)
Laser source	15–40	800–3 000
Photodetector	5–15	150–500
Driver / power supply	5–10	200–600
Interrogator / data acquisition	30–80	3 000–15 000
Fiber & connectors	10–20	20–40
Alignment / packaging	10–20	100–400
Total	75–185	4 270–19 540

IV. LIMITATIONS AND RECOMMENDED EXTENSIONS

The present study establishes proof-of-concept feasibility but leaves several gaps that should be closed before field deployment. First, wavelength-stability measurements should be repeated with a heterodyne or wavemeter method validated specifically for 630–650 nm sources, rather than instrumentation designed for stabilized He-Ne (633 nm) calibration. Second, the loss-versus-load relationship (Fig. 4) is based on a single beam loaded once to failure; multiple beam specimens and repeated load cycles are needed to establish confidence intervals and assess fatigue/repeatability. Third, the fiber choice for 650 nm operation warrants re-examination: standard G.652 fiber is single-mode only above its ~1260 nm cutoff and is multimode at 650 nm, so a step-index or plastic-clad multimode fiber selected for the visible band — with attenuation recalculated from Rayleigh scattering's λ^{-4} dependence — would better represent achievable performance.

Further work should also include: (i) long-term and temperature-dependent stability trials (days to weeks, varying ambient temperature) beyond the 30-minute warm-up window reported here; (ii) OTDR reflectogram data showing the actual localization profile of an induced defect, rather than a textual summary; (iii) a co-located reference sensor (strain gauge or linear variable differential transformer) on the same beam to validate absolute strain readings; (iv) assessment of ambient-light and temperature sensitivity of the visible-wavelength channel under field conditions; (v) field trials on an in-service structure (bridge or building) rather than a laboratory specimen; (vi) a lifecycle cost model that accounts for diode replacement/maintenance intervals alongside the initial component costs in Table II; and (vii) a pilot demonstration of the proposed machine-learning-based anomaly detection, currently listed only as future work.

TABLE III
IDENTIFIED GAPS AND RECOMMENDED EXTENSIONS FOR FOLLOW-UP STUDY

Gap	Recommended extension	Expected benefit
Stability data borrowed from 633 nm calibration instrumentation	Heterodyne/wavemeter method validated for 630–650 nm	Credible source-noise figures
Single beam, single load-to-failure run	Multiple specimens, repeated load cycles	Confidence intervals, fatigue behavior
G.652 fiber assumed single-mode at 650 nm	Step-index/plastic optical fiber suited to visible band; recompute loss (λ^{-4})	Physically consistent loss budget
Only 30-min stability window	Multi-day, temperature-varied trials	Realistic long-term drift estimate
OTDR result reported only as text	Published reflectogram of defect localization	Verifiable localization accuracy
No independent strain reference	Co-located strain gauge / LVDT	Validated absolute strain values
Lab-only specimen	Field trial on in-service structure	Real-world performance evidence

Cost model excludes maintenance	Lifecycle cost incl. diode replacement	Realistic total cost of ownership
Machine-learning anomaly detection unproven	Pilot machine-learning demonstration on collected data	Evidence for real-time SHM claim

V. Conclusions

We developed a low-cost fiber-optic structural monitoring system built around inexpensive 650 nm laser diodes and silicon detectors. By careful selection of the laser source, the system achieved performance comparable to standard infrared-based sensors. The 650 nm laser produced stable output with <1% power variation, and the fiber sensor exhibited a clear linear response to applied load (≈8 dB over ~35 kN), with high sensitivity. These results indicate that visible-light fiber sensors can reliably quantify strain [12]–[14].

The all-optical design is intrinsically safe and immune to EMI, making it well-suited for hazardous environments such as mines or areas with strong electromagnetic fields. Moreover, the use of visible lasers simplifies implementation (visible beam, cheap photodiodes) and drastically lowers cost: the optical components used here cost on the order of tens of dollars, rather than thousands [15], [16].

Our findings suggest that quasi-distributed fiber sensors based on 650 nm diodes are a viable, low-cost alternative for SHM. Future work will focus on deploying this system on actual infrastructure and enhancing the signal analysis (e.g., automated pattern recognition) for real-time SHM based on these low-cost fiber sensors.

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