

PAPER • OPEN ACCESS

Laser system for remote 3D registration and measurement of vibration and translational movements of objects

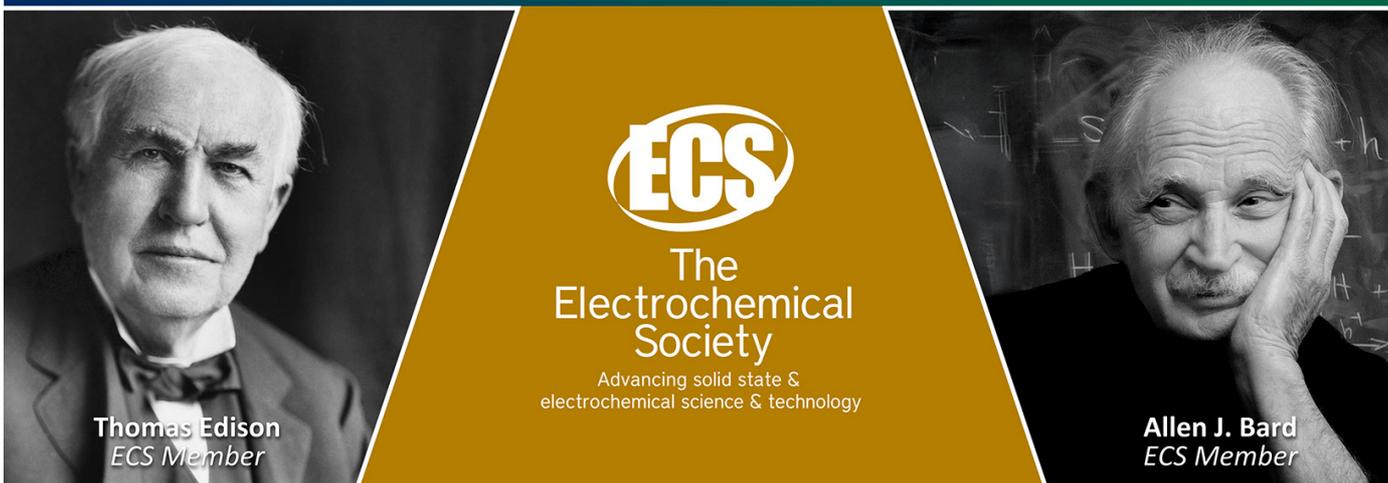
To cite this article: Margarita Deneva and Marin Nenchev 2025 *J. Phys.: Conf. Ser.* **2994** 012011

View the [article online](#) for updates and enhancements.

You may also like

- [Formulation and characterization of Benzylamine loaded casein/chitosan nanocomplexes](#)
M Marudova, S Milenkova, N Zahariev et al.
- [Curcumin loaded casein submicron-sized gels as drug delivery systems](#)
S Milenkova, I Manolov, B Pilicheva et al.
- [Comparative analysis of sorption characteristics of Bulgarian grape seeds and flours and flakes produced by them](#)
A G Durakova, A L Bogoeva, A P Krasteva et al.

Join the Society
Led by Scientists,
for *Scientists Like You!*



Thomas Edison
ECS Member

ECS
The
Electrochemical
Society
Advancing solid state &
electrochemical science & technology

Allen J. Bard
ECS Member

Laser system for remote 3D registration and measurement of vibration and translational movements of objects

Margarita Deneva* and Marin Nenchev

Sci.Lab. "Quantum and Optoelectronics" and Sci.Lab. "Optical and laser technologies in the automotive industry" at IMEESST, Technical University of Sofia, Branch Plovdiv, 25 Tcanko Djustabanov Str., 4000 Plovdiv, Bulgaria

*E-mail: deneva@tu-plovdiv.bg

Abstract. The article presents a physic-technical solution in which a laser interference-wedge-based system is implemented for remote optical registration and measurement from a distance of metres or tens of metres of mechanical vibrations and translations of objects in three perpendicular directions: horizontally along the X-axis, vertically along the Y-axis, and in the direction of the incident laser beam, along the Z-axis. This enables purely 3D measurement of the object, which can be separately measured in each of these directions. The measured vibrations and translations amplitude range from units of mm up to 10-15 cm on concrete structures, bridges, subways, buildings, and rocks.

1. Introduction

In a previous work [1], the authors introduced a device for remotely registering object size changes during heating [1], by tracking resonance shifts in a wedged interference structure attached to the object. This device could detect changes at a distance (~ 30 m) using reflected radiation from the wedge. In this paper, we present an advancement of this method for remote 3D vibration registration using Interference Wedges (IWs). These structures, previously detailed in our papers [2, 3], including their properties, variants, and computational approach, are briefly described below. Other authors [4] describe an alternative interference structure for tracing resonance in unidirectional object vibrations. Various devices for measuring mechanical vibrations are mentioned, including magnetic-inductive, piezoelectric, Fabry-Perot interferometric, and graphene sensors, as well as Doppler effect and Talbo interferometers [5–7]. However, these devices have limitations: they mainly measure unidirectionally, require direct contact or close proximity, use wired or radio connections, and are prone to misalignment and signal loss. Crucially, they cannot measure 3D vibrations and over long distances, which is a major drawback. Commercial laser devices, e.g. laser distance measures, can perform optical distance measurements but are limited to one direction, along the incident beam, and to distances of only a few meters. They do not provide 3D registration. Additionally, some devices can detect vibrations from acoustic noise at close range (up to 1 m) from specialized motors, registering general vibrations and identifying specific sources based on prior knowledge of the vibration type [8].

In this paper, we present a novel purely optical remote sensing system for 3D vibration measurements over distances from meters to hundreds of meters. To the best of our knowledge, none of the existing vibrometry applications use optical devices with IWs in this way, as our competing solution does.



2. Physical-technical nature of the presented solution

The scheme of the developed measurement system is presented in Figure 1(a). The structure comprises two blocks A and B. Block A is composed of two sub-blocks: A1, which emits the working radiations, and A2, designed to receive and process the vibration information of the investigated object. Sub-block A1 incorporates an integrated laser source with a meter, a beam expander and a forming unit comprising three laser beams 1, 2 and 3. These beams have a wavelength of 594 nm (He-Ne CW Yellow Laser) and a total power of 200 mW, distributed equally among the three beams. The diameter of each beam is ~ 2 cm. The emitted radiation is directed and incident on the second block B, which is coupled in a direct rigid connection to the vibrating object under study. The block B modifies the 1, 2 and 3 beams with the object vibration information and reflects them back as the 4, 5 and 6 beams to the sub-block A2. This block is configured to both receive and process the emissions and to thereby register information about the vibrations. Block B incorporates three IWs, each as a basic element and as a reflector, for each of the three directions X, Y and Z, respectively. An illustrative example, based on our developed earlier approach [2, 3] and computations of the resonant transmission lines for the used IWs is presented on Figure 1(b). The parameters displayed were selected to constitute the IW employed in our experimental investigations. The advantage of using an IW in our application is shown in Figure 1(d), where the IW, consisting of dielectric layer mirrors and separators, produces distinct clear resonance lines, dark-in-reflection, without diffraction (left). In contrast, Figure 1(d) (right) shows how the insertion of a 0.8 mm diameter filament leads to diffraction blurring at the edges, illustrating an undesirable effect that compromises the measurements.

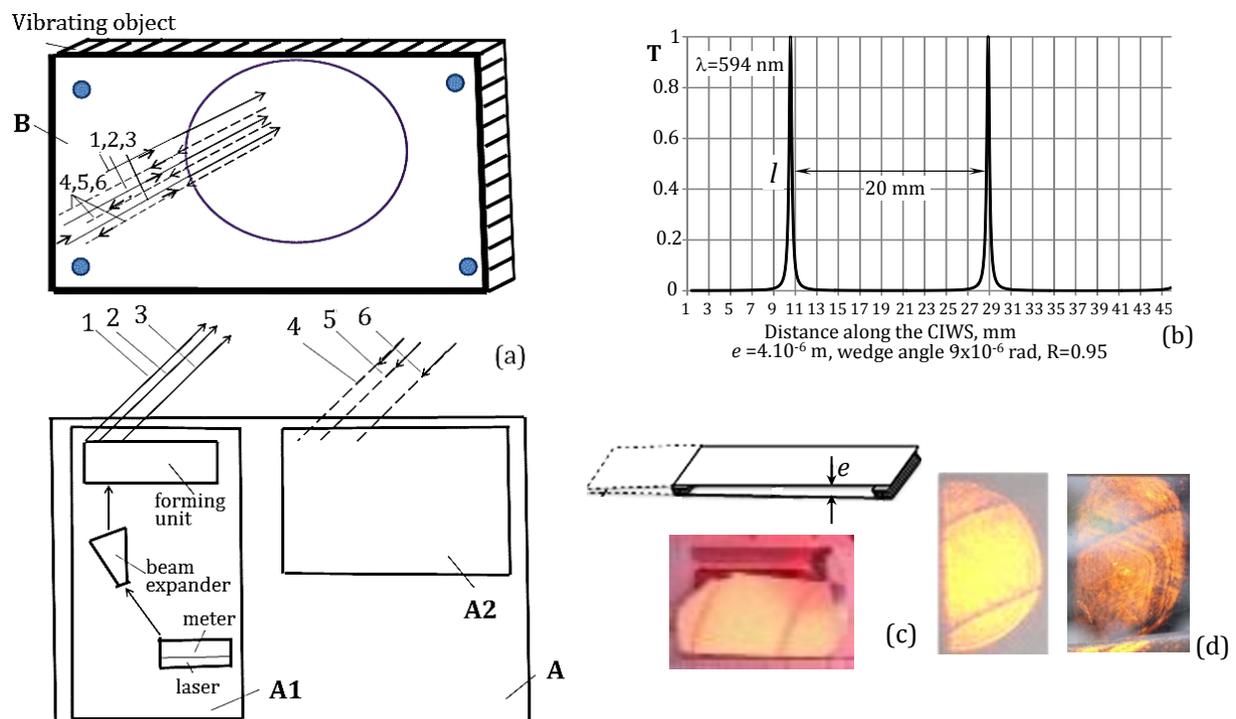


Figure 1. (a) Block diagram of the 3D vibration registration system. (b) Example of computed resonant transmission lines for the integrated IW, detailed in references [2, 3], where a comprehensive understanding of its essence, operation and computation, as well as building complex structures with it is provided (CIWS – complex interference wedged structure). (c) Schematic (top) and laser-illuminated element (bottom) of the superimposed dielectric layers forming the IW. (d) IW configuration with stacked dielectric layer mirrors and separators (left), and an image (right) showing a 0.8 mm diameter filament insertion effect.

3. The vibration registration approach

The reflection of each incident beam 1, 2, and 3 from its corresponding IW on Block B forms a spot where the displacement of dark-in-reflection resonance line registers vibration. This displacement, caused by the IW's movement, reflects changes in the beam position, indicating vibrations. Each IW acts as a highly reflective mirror (over 90%) for beams with narrow resonance lines ($\sim 1\text{mm}$), enabling vibration registration along the X, Y, and Z axes. Figure 2 illustrates this process, showing the shift in resonance line positions as the IWs vibrate. The marking may be accomplished by tracking the distance of the spot from the apex of the IW, but with sufficient precision of more than mm.

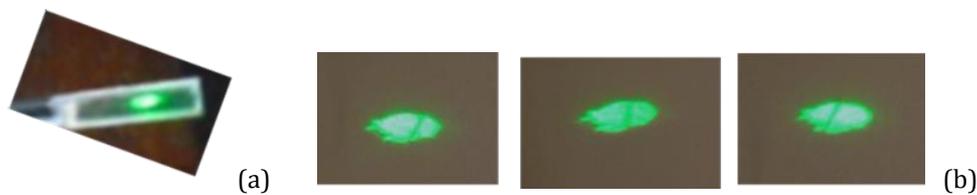


Figure 2. (a) Example of IW realisation with incident laser beam (light spot) on it. (b) Series of reflected spots from the IW when the element vibrates along the Z-axis, resulting in change in the resonance line position.

Block B is rigidly attached to the vibrating object and is composed of three sub-blocks (Figure 3), each of which is arranged in an optical configuration to separately capture vibration information of the object in its three directions: in B1 single IW₁, in B2 - IW₂, which are suitably placed for reflection operation. The wedges are designed to register movement transverse to the direction of beam incidence, in particular vibration, with IW₁ registering movement in the X direction and IW₂ registering movement in the Y direction. The third IW₃, comprising the sub-block B3, is for monitoring the vibration in the beam incidence direction, Z. In a state-of-the-art implementation, the IW is performed as a quartz plate with a micron smoothness surface finish and dimensions typical for the application: thickness of $\sim 2\text{ mm}$, length of $\sim 40\text{-}50\text{ mm}$, and width of $\sim 20\text{-}25\text{ mm}$. On each plate, the cathode sputtering technique is employed to deposit a series of dielectric layers, comprising a mirror layer with a reflection of $\sim 90\%$ (transmittance of $\sim 5\text{-}7\%$), and a separating transparent wedged layer of $2\text{-}3\ \mu\text{m}$ thickness with an angle at the apex of $(1\text{-}5)\times 10^{-5}\text{ rad}$. On top, a second layer mirror, as the first one, with $\sim 90\%$ reflection is placed.

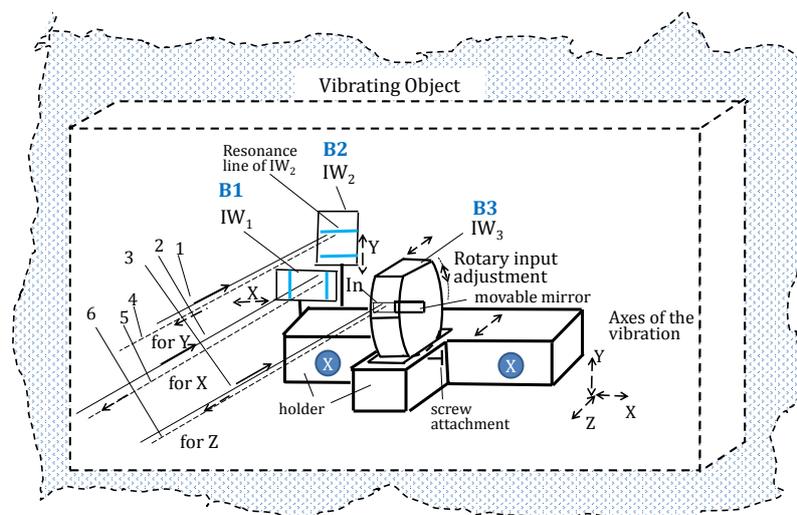


Figure 3. Block B rigidly attached to the vibrating object with its three sub-blocks, each of which with the corresponding IW for registration: in B1 single IW₁ for X-axis, in B2 - IW₂ for Y-axis, in B3 - IW₃ for Z-axis.

4. Principal and technical solution of the system

The system employs three beams to create a 3D registration of object movement, with the positions of the reflected beams in Block B being used to determine the vibrations. For the beams directed to and reflected from IW_1 and IW_2 the information on the position of the resonance line, in X and Y vibration direction, is provided directly. In the direction of beam incidence (along Z), there is no change in registration as a result of the vibration of IW_1 and IW_2 . The wedges simply translate along X and Y, parallel to itself and along an equally reflecting mirror surface. The position of the spot remains unchangeable relative to the resonance lines.

In order to register the movement along the Z direction, it is necessary to include the main element IW_3 in a complex optical-mechanical system. This system is shown in detail in Figure 4, where its action is explained. The starting position of the elements is indicated by a solid line and the letter "a". When the position is changed, this is indicated by a dashed line and the letters "b" and "c".

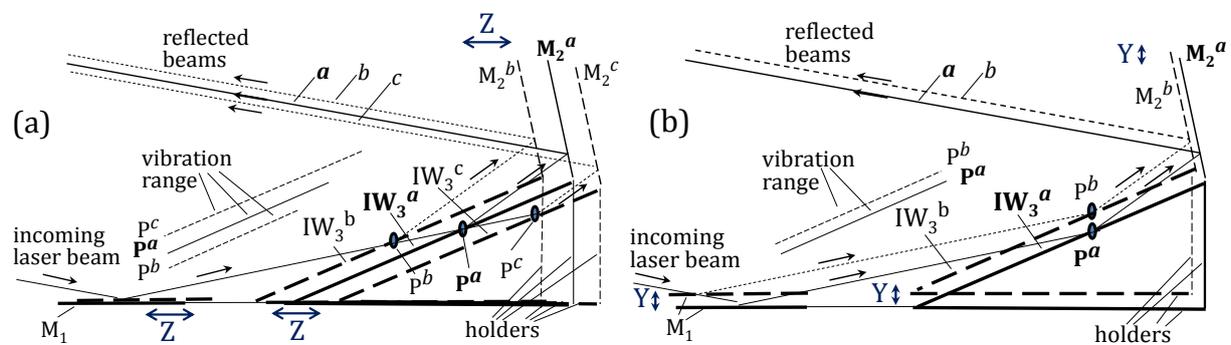


Figure 4. Optical diagram of Z-axis vibration registration: incident beam and optical paths. (a) Beam trajectory for Z-registration. (b) Beam path for Y-registration. $P_{a,b,c}$ - incident beam positions on IW_3 surface.

The incoming laser beam is first reflected by an external horizontal mirror M_1 , which is rigidly connected to the IW_3 . After reflection from IW_3 , the beam spot marks the resonance line of IW_3 (or its distance from the resonance line) in the reflected spot. The beam is then deflected by an additional mirror M_2 towards its emitting Block A and enters the receiving component, sub-block A2, where the position of the beam's initial contact with IW_3 is registered.

The movement of IW_3 along the Y-axis within the vibrating sub-block B3 will result in the mirror M_1 moving in the same direction. The incoming incident beam will be reflected by M_1 from its other position on the surface (for the Z displacement, the level of M_1 is preserved and the reflective position of M_1 is maintained). As mirror M_1 and IW_3 vibrate in the same manner at the same height on the Y-axis, it may be observed that the incident beam falls on the same initial position of IW_3 . Thus, sub-block B3 does not detect any Y-axis vibrations of IW_3 , as no vibrational movement is registered along the Y-axis. It only captures vibrations in the Z-axis.

Figure 5(a) shows the resonance line's position change relative to the bottom of the incident beam spot. These variations indicate the vibration of the IW and the system. The change in distance between the two resonant lines, which remains constant for large beam spots, allows a quantitative measurement of the vibration. For example, assuming a maximum line translation variation of $\sim 30\%$ and a constant distance of 20 mm between the resonance lines, which can be used as a scale for the present measurements, the vibration value is ~ 7 mm.

Figure 5(b) shows a photo example of the oscilloscope registration system detecting 5 Hz vibrations at distances of up to 40 metres. This system effectively measures low frequency vibrations (10-20 Hz) by tracking the movement of the resonance lines. In addition, oscilloscope measurements using a 250 MHz Rigol with a fast optical receiver allow registration of vibrations in the hundreds of Hz. The dual-channel oscilloscope also allows vibration to be captured along

both the Z-axis and Y-axis, as shown in Figure 5(b) right. The minima in the oscilloscope recorded signals correspond to the passage of the reflected IW dark-in-reflection resonance line.

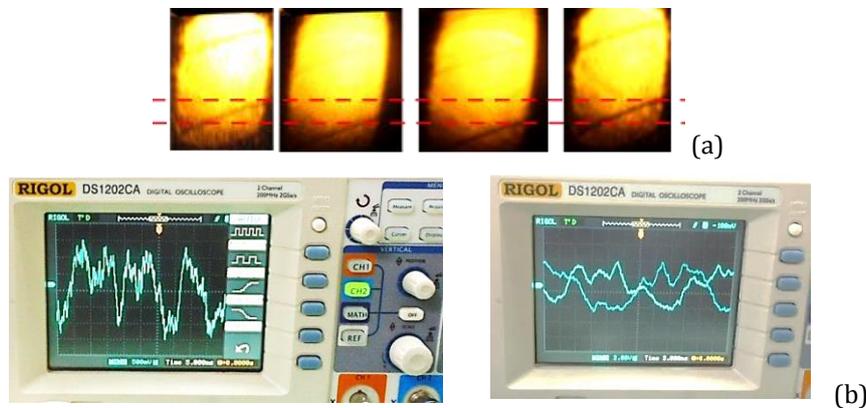


Figure 5. (a) Four images showing the visual registration system detecting 5 Hz vibrations at distances up to 40 meters. The system provides approximate vibration assessment for low frequencies (10-20 Hz). (b) Oscilloscope registration of return signals from 40 m, demonstrating high-frequency (300 Hz) vibration detection, with measurements of frequency, amplitude, and acceleration.

5. Conclusion

In this work, we presented a novel system for remote 3D laser registration of mechanical vibrations, building upon our prior research and experience. The system employs interference wedge structures and demonstrates significant effectiveness and originality in its design. We have validated its practical applicability, particularly in monitoring vibration activity in rock formations near transportation infrastructure, such as highways and railways. This system offers a valuable tool for enhancing the safety and stability of such critical structures through precise vibration monitoring.

Acknowledgments

The authors would like to thank the Competence Center "Intelligent mechatronic, eco- and energy-saving systems and technologies", Lab. C8-4 "Optical and laser technologies in the automotive industry" and Sci. Lab. QOEL for the opportunities to perform the experiments, as well as the Research and Development Sector at the Technical University of Sofia for the financial support.

References

- [1] Nenchev M N, Deneva M A, Kissov Ch T and Stoykova E V 2015 *Patent BG 66490 B1* A laser device for remote measurement of object-slip translation using a wedged interference structure
- [2] Stoykova E V and Nenchev M N 2001 Fizeau wedge with unequal mirrors for spectral control and coupling in a linear laser oscillator–amplifier system *Appl. Opt.* **40** 5402–12 <https://opg.optica.org/ao/abstract.cfm?URI=ao-40-30-5402>
- [3] Nenchev M, Stoykova E and Deneva M 2018 Composite wavelength tunable wedged interference structures with increased free spectral range *Opt. Quant. Electron.* **50** 433 <https://doi.org/10.1007/s11082-018-1668-9>
- [4] Kim M, Yoon D-Y and Pahk H 2015 *J. Opt. Soc. Korea* **19** 494–502 <https://doi.org/10.3807/JOSK.2015.19.5.494>
- [5] IRIDA 22 Company Vibrodiagnostics Prospectus materials, available online
- [6] VM-6360 Hand Held Vibration Meter, Digital vibrometer with external accelerometer and magnetic base <https://www.omniinstruments.co.uk/vm-6360-hand-held-vibration-meter.html>
- [7] BOSCH GLM 250 VF Professional Laser Tape Measure <https://www.euromarket.bg/bg/product/lazerna-roletka-bosch-glm-250-vf-professional>
- [8] Wu B and Qiao M 2022 A review of the research progress of motor vibration and noise *Int. Trans. Electr. Energy Syst.* **2022** 5897198 <https://doi.org/10.1155/2022/5897198>