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Design and Interface of a Photonic PBG-Based Pressure Sensor with Fiber-Optic/Onboard Data Logging for Aerospace Monitoring: A Comprehensive Review

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Abstract: *Photonic crystal fibers (PCFs) are a revolutionary technology in pressure sensing especially in tough environments in aerospace applications. Their structural topology is special and the photonic bandgap characteristics are used to achieve unprecedented sensitivity, resistance to electromagnetic interface, and tolerability to adverse environments. This review examines the advances in PCF-based pressure sensors with some emphasis on how the sensors may be designed with fiber optic and onboard data logging to eliminate the challenge of wireless transmission of data in aerospace environment.*
Keywords: *Photonic crystal fibers (PCFs), Aerospace, Optical fiber*

1. INTRODUCTION:

The part of the pressure sensing in aerospace systems is to control the cabin pressure, structural loading, propulsion units and the pneumatic subsystems, where reliability and precision directly impact the safety and performance. The classical electrical types of pressure sensors are susceptible to electromagnetic interference, thermal drift and minimized miniaturization, and are less adaptable to hard aerospace. As a result, two photonic crystal (PC)-based and micro-opto-electro-mechanical system (MOEMS) pressure sensors have been of great concern due to miniature size, sensitivity and absence of electromagnetic noise and its high stability. Explicitly, experimental results have demonstrated that silicon diapers bonded with photonic crystal cavities or ring resonators can be employed in converting mechanical deformation caused by pressure to optical resonances by taking advantage of stress-induced variations in refractive-index, as a consequence of alterations in stress [1]-[3].
Recent studies have aimed at improving photonic pressure sensor performance by optimization of structures, defect engineering, and other material platforms. Enhanced sensitivity and linearity in broad pressure regimes have been demonstrated with high-Q two-dimensional PCs with photonic crystals, nanostructured resonators, polymer-defect annular PCs, and micro-ring-based designs [4] -7. Simultaneously, fiber-optic and fiber Bragg grating-based sensor technologies have been investigated to be used in distributed pressure and structural health monitoring applications, especially in aerospace and in civil structures [6], [9]. In more recent work, numerical simulations of multiphysics that have been combined with artificial intelligence and machine-learning methods have become a promising solution to virtual prototyping, performance prediction, and intelligent interpretation of optical sensing data [8], [9]. Inspired by these breakthroughs, this paper provides a systematic review of photonic crystal and fiber-optic pressure sensing technologies, examines the performance features of these technologies, and identifies the existing challenges, gaps in the literature, and future opportunities to develop AI-enabled photonic pressure sensors in aerospace

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monitoring.

2. METHODOLOGIES:

2.1. MOEMS-Based Circular Silicon Diaphragm with Ring Resonator Methodology

The article gives a simulation study on a circular diaphragm MOEMS pressure sensor that incorporates photonic crystal hexagonal ring resonator to sense pressure high-sensitivity. The proposed design uses a silicon diaphragm with a hole-based ring resonator system, which is triangular shaped photonic crystal lattice, and allows high interaction between mechanical deformation and optical modulation. Stress and strain on the diaphragm center cause changes in refractive index of silicon through elasto-optic effect and consequently change the resonant wavelength of the ring resonator. One of the strong points of the work is the fact that ANSYS Multiphysics is used to model the mechanical aspect and MEEP (FDTD) is used to model the optical aspect in order to have the ability to couple both the mechanical and optical responses correctly.

The outcomes of the simulation show that the diaphragm can be detected to deform at ultra-low pressures up to 6 MPa and the resonance wavelength varies between 1.5979 1.6380 1.5979 1.6380 1.5979 1.6380 1.5979 1.6380 1.5979 1.6380 1.5979 1.6380 1.59 The sensor has a high sensitivity (316.15 nm/RIU) and a high Q-factor of 12245, which implies that the resonance is sharp, and the signal quality is excellent. Geometric parameters, lattice structure and modeling processes are described in detail, making them more reproducible and understandable. All in all, the paper demonstrates the usefulness of all-optical, electrically passive sensing of pressure and provides some future advancement of the method including the optimization of packages and coupling with machine learning strategies, rendering the method effective in aerospace, biomedical and environmental sensors.

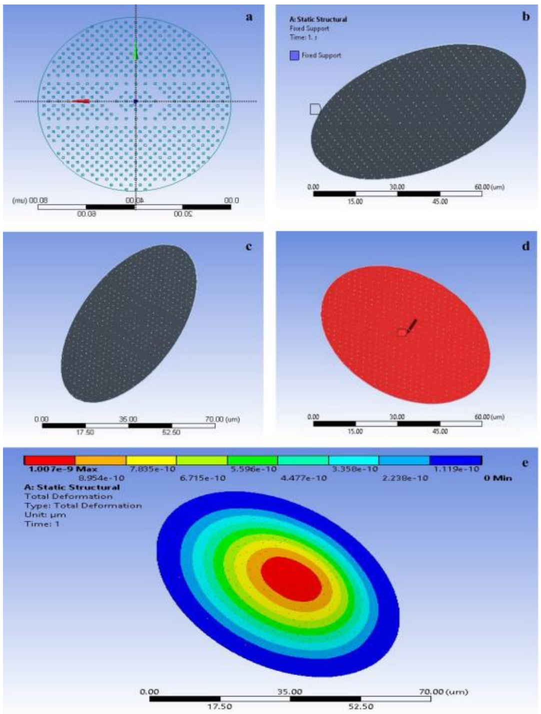

Fig.1 a. Sketch of the proposed design(2D). b.Model of proposed design (3D). c. Model with its circumference as fixed support. d. Load applied at the center of the Diaphragm. e. Deformation observed for pressure=6.3µPa

2.2 High-performance 2D photonics MOEMS pressure sensors

This paper provides a thorough review of new pressure sensor architectures using Micro Opto-electro-mechanical systems (MOEMS) and Photonic Crystal (PhC) technology. The authors aim to discuss the challenges in measuring high-pressure ranges with special reference to the sensitivity and quality factor of the sensors. Through simulation and comparison of two resonator structures namely ring and triangular with silicon as the material, the study employs the finite-difference time-domain (FDTD) method for effective two-dimensional modeling and simulation.

A major contribution of this study is in-depth examination of pressure-induced deformation on the resonant wavelength, which is of utmost significance to sensor performance. The authors meticulously explain their procedure, for example, the use of Bragg resonance wavelength shift (BRWS) simulation by Ansys Multiphysics and the computation of mechanical parameters at various loads. The results are that the triangular resonator structure exhibits better performance in the lower pressure range (0-2 GPa), while the ring resonator is better at higher pressures (2-3 GPa). Bragg resonance wavelength shift (BRWS). This two-performance feature is all the more remarkable, as this makes more varied uses of the sensors possible.

The resulting Quality factors (Q-factors) of 1634 for the ring resonator and 1047 for the triangular structure clearly surpass the already published Q-factors with an average of around 150. This improvement speaks to the uniqueness of the suggested designs and their applicability to high sensitivity in practical uses. The paper also includes a well-rounded literature review, situating the current study in the context of previous studies and indicating progress towards the development of photonic crystal sensors.

Moreover, authors provide implications of the results for future research, such as that further tuning of design parameters could lead to even higher sensitivity and Q-factors. They emphasize the prospects of real-time applications of their sensors, which would find application in numerous industries, including biomedical, environmental, and process industries. As a whole, this paper is doing much for photonic sensors, providing a solid foundation for further work and development of high-performance pressure sensing technologies. The clarity of exposition, combined with conclusive experimental and simulation support, renders this book a valuable source of reference for practitioners and researchers eager to advance the evolution of sensor technology.

2.3 Pressure Sensing Using a Two-Dimensional Photonic Crystal Sensor

The paper titled "Pressure Sensing Using a Two-Dimensional Photonic Crystal" by Yashaswini P.R., Gowthami M., and P.C. Srikanth gives a complete overview of advanced pressure sensing technology using two-dimensional photonic crystals (2DPC). The authors give a well-structured study beginning with a strong introduction to the basics of photonic crystals and their use in optical sense applications. Using a "holes in slab" configuration, the scientists can enhance the sensitivity and quality factor of the pressure sensor and correct shortcomings found in traditional sensing methods. The use of finite difference time domain (FDTD) simulations makes it possible to conduct an in-depth evaluation of the sensor performance within a pressure range of 0 to 4 GPa with a linear dependence of applied pressure on resonant wavelength shifts, making the precise measurement of pressure crucial.

The values are particularly noteworthy as the Q-factor derived at 1 GPa is more than that of the works published earlier by a wide margin, affirming an appreciable improvement in sensing capability. The study offers thorough information regarding changes in refractive index and transmission spectra, not only validating the results but also illustrating the function of the sensor in unequivocal terms. The authors carefully describe the simulation process, design parameters, and the reason why the "holes in slab" design is chosen over other designs, enriching the study.

In addition, the context of discussion clearly describes the results in the broad context of research on photonic crystals and sets forth the potential applications of the sensor so designed for monitoring process, clinical diagnosis, and environmental monitoring. The authors also suggest avenues of future work with calls for optimization to increase sensitivity and Q-factor even higher. Overall, this article is a significant contribution to the study of photonic sensors in terms of both theoretical principles and practical uses. The ease and accuracy of expression, coupled with good experimental and simulation evidence, make this article a valuable resource for researchers and practitioners who want to pursue sensor technology. The identification of institutional support further enhances the transparency and credibility of the research and makes it an outstanding addition to photonic crystal-based sensing technology literature.

2.4 Photonic Skins for Optical Sensing

The PHOSFOS (Photonic Skins for Optical Sensing) is a technology focused project, and was an initiative by the European Commission, to produce flexible, stretchable photonic skin. They are optoelectronic foils that are very thin and they are filled with sophisticated optical sensors that are utilized to measure mechanical parameters like strain, deformation, pressure and stress. The most essential components of such technology are the Fiber Bragg Gratings (FBGs) that may be integrated into any type of optical fibers such as the normal silica fiber, the birefringent microstructured fibers (MSFs) and the polymer optical fibers (POFs). The establishment of the temperature-sensitive sensors utilising the MSFs is one of the project achievements.

These are high pressure sensitive sensors that do not respond to any variation of temperature and therefore can be used in highly stressful and changing environment. Another interesting invention was the successful splicing of polymer optical fibers to silica fibers that made practical the utilization of polymer based FBGs in laboratory. This was further enhanced at the 800 nm spectral region which had substantially less fiber losses and long and effective sensors could be constructed. Also, it was found out that POFs wavelength division multiplexing (WDM) can be achieved as well as thermal annealing can be utilized to control the reflective wavelength and saturate a multiplicity of sensors using a single phase mask. Moreover, the FBGs inscription using the femtosecond lasers was the possibility to create the localized birefringence at the identical spatial position of the grating to allow the creation of the vectorial sensors.

PHOSFOS developed flexible built-in circuits to support the sensing fibres. Photodetectors and sources of light were reduced so thin (to 20 micrometers) and can be fabricated in transparent and flexible polymers that are highly transmitted and highly flexible. Secondly, UV-curing polymer and monomer were also developed to come up with new formulations that would give it mechanical flexibility, transparency and compatibility with the sensors laid inside of it.

Using PHOSFOS technology can be applied in many varieties, both civil (to map infrastructures, such as bridges and tunnels), aerospace (i.e. aircraft wings and rotor blades), to the medical (i.e. wearable sensors and pressure sensors in a human body). One of which is that these sensors are used to keep track of the strain on old tapestries where age-old sensors were too inquisitive and invasive. Overall, PHOSFOS has played a major role in the development of the flexible optical sensing due to the incorporation of photonic and electronic component

in stretchable materials. The breakthroughs in the fiber technology field, minimization of sensors and material ensure smart and adaptive systems in the broad spectrum of scientific and industry.

2.5 FBG Based High Sensitive Pressure Sensor and Its Low-Cost Interrogation System With Enhanced Resolution

The paper presents a very sensitive Fiber Bragg Grating (FBG) pressure sensor, which has been greatly enhanced by the integration of a metal bellows structure and has a very high sensitivity of 90.6 pm/psi, which is almost 4000 times more sensitive compared to that of a bare FBG. The sensor shows excellent linearity (99.86%), repeatability and low hysteresis (±0.29 psi) and is a significant improvement in optical pressure sensing technologies.

One of the contributions of the work is the creation of a low cost and small size of the interrogation system with the use of the Long Period Grating (LPG) and a photodiode, which enhances the resolution of the system to 0.025 psi. This is a low-cost design that will improve the applicability of the sensor in the real-world scenarios, without affecting its performance.

The authors use a special reference FBG to facilitate cross-sensitivity due to temperature, thus ensuring a correct and faithful pressure reading at different temperatures. The theoretical predictions are in excellent agreement with the experimental results as they support the design of the sensor and the analytical models.

The article is also admirable in its clear schematics, strict methodology and thorough data analysis that all contribute to the validity of the results. The research can however be improved by further research on the operational permanence of the sensor in the long run and its functionality in extreme or dynamic environmental conditions like changing humidity, pressure cycling or mechanical wear.

2.6 Design and Experimental Validation of a Fiber Optic Pressure Sensor with FBG Technology

The article is called Design and Experimental validation of Fiber optic pressure sensor using FBG Technology, it is an innovative and technically valid addition to the topic of smart sensing system and aerospace and industrial in particular. The paper shall be founded on the development of a pressure sensor which involves the application of Fiber Bragg Grating (FBG) technology into silicone resin platform. The sensor has been created by additive manufacturing and in this instance, stereolithography or 3D printing, which enables the creation of precise, customizable geometries, low cost of production and high versatility. The plan will ensure that it possesses a tiny, lightweight and chemically inert sensor architecture that is hardly obtrusive and can be integrated in embedded systems in harsh environments.

His experimental system is well planned and involves the Smart Scan laser interrogator to measure the wavelength changes with regards to the manipulated pressure changes. The sensor had been subjected to 0 to 200 mbar pressure pressure in a hermetic tank and sampled at the charging, and the discharging cycles. The results were very sensitive and the sensor could detect the changes in pressure of a minimum of 50 mbar. The statistical analysis of MATLAB and MINITAB established the presence of linear and reproducible response and distributions of the data were comparable to the characteristics of the Gaussian which helps to verify the authenticity and efficiency of the sensing mechanism.

In addition, the paper is also able to establish a calibration curve between the variation in the wavelengths and the values of pressure which enhances the useful practicality of the sensor. Another similarity that the authors develop to justify the findings of their research is the comparison of their outcomes with the current designs of FBG-based sensors based on the flexibility and possibilities of their solution. The present study is concluded by suggesting that more research should be conducted on the topic by using alternative resources and refined geometries in order to enhance the pressure spectrum and sensitivity. Overall, the article is a good show of the concept, and the successful synthesis of fiber optic pressure sensors, which is a concerted effort by material science, synthesis of manufacturing, and rigorous testing in experiments.

2.7 Hybrid Photonic-Crystal Fiber

The paper, Hybrid Photonic-Crystal Fiber, provides a critical and detailed overview of the history, operation, and future perspectives of the hybrid photonic crystal fibers (PCFs), which is one of the most vibrant fields of current photonics studies. The paper is authored by the best scientists in the best institutions and presents the novel merger of the materials science with the optical fiber technology in order to develop versatile and tunable fiber systems. The key assumption is based on the hybridization of PCFs, that is, the incorporation of various materials, including both liquids and solids and gases, into their microstructured cores, and thus, their linear and nonlinear optical characteristics have been greatly improved. The article is logically organized, the author begins with a historical review of how PCF technologies have developed, starting with the standard step-index fibers, to the more sophisticated construction such as hollow-core PCFs and broadband-guiding ones. This historical account establishes a firm base on the reasons and discoveries that resulted in hybrid PCFs.

The authors carefully explain the mechanisms that guide in PCFs including total internal reflection, photonic bandgap, anti-resonance, inhibited coupling, and more recent mechanisms such as twist-induced guidance. These elaborate physical descriptions have an important role to play to readers who are interested in understanding the underlying optics of these technologies. Much of the review is devoted to functionalization of solid-core PCFs using high-index materials such as liquid crystals, semiconductors and chalcogenide glasses. In particular, liquid crystal-filled PCFs are pointed out due to their ability in tunable optical devices, with thermal and electrical tuning. Such hybrid constructions have led to production of fiber based filters, sensors, modulators and even tunable lasers.

2.8 Fiber Optic Sensing Technology and Vision Sensing Technology for Structural Health Monitoring

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Moreover, the paper discusses physics and use of gas-filled hollow-core PCFs. It is demonstrated that these fibers are transformative to ultrafast nonlinear optics which enables the control of light-matter interactions at intensities and durations never seen before. The authors overview the experimental setups, dispersion properties, nonlinear coefficients, as well as the nonlinear phenomena including the soliton propagation, supercontinuum generation, plasma effects, and harmonic generation. They also brush on applications in quantum optics with the emphasis applied on the versatility of the gas-filled PCFs in the state-of-the-art applications.

To sum up, the review manages to provide a comprehensive overview of the hybrid PCF environment. It is also not just technical progress and theoretical knowledge but also takes into account such practical factors as the ways of fabrication and the indicators of performance. This article is an important reference to the researchers in the field of photonics by merging various scientific fields, hence providing depth and breadth of the analysis. The perspective of the future suggests an optimistic future of hybrid PCFs in the next-generation optical technologies, in the high-resolution spectroscopy perspective, up to fiber-integrated quantum systems.

3.RESULTS:

Recent studies show that photonic crystal (PhC) and fiber-optic pressure sensing technologies have made huge progress with respect to improved sensitivity, Q-factor, and versatility of application. Silicon-based MOEMS pressure sensors based on photonic crystal ring resonators have ultra-high sensitivity (up to 316.15 nm/RIU) and are characterized by an excellent stability of wavelengths, which is much higher than previous models due to the precision of opto-mechanical interactions which are being modeled using ANSYS and FDTD/MEEP simulations [1]. A comparative analysis of PhC resonator geometries has shown that ring resonators could be more efficient in high-pressure (2 -3 Gpa) regimes and triangular resonators in low-pressure regimes, with Q-factors in each geometry that are significantly higher than using more traditional designs and structures [2].

Their application to high-accuracy sensing is supported by further optimization with L3 defect-based 2D photonic crystals which verify linear changes in wavelength shifts with pressure, and constant Q-factors between 0 and 4 Gpa [3]. The PHOSFOS project is not just a breakthrough in chip-scale sensors, but in flexible optical sensing skins, and 20 times better pressure sensitivity than the best fiber sensors to date, as well as multifunctional, temperature-insensitive and biomedical-safe optical fiber Bragg grating sensing using polymer optical fibers [4].

At the fiber-device scale, FBG-based pressure sensors in combination with mechanical transducers like metal bellows or silicone matrices exhibit a very high sensitivity, good linearity, low hysteresis and a high repeatability, and are therefore suitable to the low-pressure and structural monitoring applications [5][6]. Along with these innovations, hybrid photonic crystal fibers are being developed that broaden sensing and tunability to include functional materials and extensive reviews show the increasing importance of fiber optic and vision-based sensing in structural health monitoring [7][8].

3.CONCLUSION:

The paper is a case study of the latest trend in photonic crystal and fiber-optic based pressure sensing technology and it highlights the heightened value of the technology in high-precision and harsh environmental applications. The research papers analyzed in it have shown a definite trace that optical pressure sensors are better than the traditional electrical sensors in terms of their sensitivity, electromagnetic interference resistance, miniaturization, and stability.

The MOEMS pressure sensors using photonic crystal resonator simulation of silicon diaphragms have exhibited sensitive pressure sensors with the highest sensitivities and Q-factors ever reported and proves their application in sensing changes in pressure on the MPa to GPa regimes. Comparative studies on resonator geometry have shown that optimal designs can be adjusted to a specific range of pressure, all of which ring, triangular and defect-based resonators have their own advantage in sensitivity as well as wavelength stability. These results draw attention to the fact that the resonator engineering and the opto-mechanical coupling should be paid attention to in order to enhance the sensor performance.

At the same time, a fiber-optic pressure sensor, in particular, Fiber Bragg Grating (FBG)-type sensors, have demonstrated a phenomenal enhancement of mechanically amplified sensors through polymer embedding and novel polymer interrogation procedures. These are further expanded by large scale projects such as the PHOSFOS project that talks of flexible, skin like optical sensing systems that have the ability to give multi-parameter monitoring capabilities enabling it to be used in aerospace, biomedical engineering, civil infrastructure and energy systems.

In addition, development of hybrid photonic crystal fiber and integrated sensing systems expands the functional ability of optical sensors since they are tunable, nonlinear and sophisticated in sensing. The combination of these technologies with other complementary technologies such as those of vision-based sensing result in intelligent and distributed structural health monitoring systems of the future which will be more accurate and robust.

4.References:

[1] Yashaswini P. R., Mamatha N., and Srikanth P. C., "Circular diaphragm-based MOEMS pressure sensor using ring resonator," *2020 International Conference on Photonics and Optical Engineering*, 2020, pp. 1–5.

[2] Yashaswini P. R., Gayathri H. N., and Srikanth P. C., "High-performance 2D photonics MOEMS pressure sensor," *Proc. International Conference on Emerging Electronics and Microsystems*, 2022, pp. 1–6.

[3] Yashaswini P. R., Gowthami M., and Srikanth P. C., "Pressure sensing using a two-dimensional photonic crystal sensor," *IEEE International Conference on Smart Sensors and Systems*, 2022, pp. 1–5.

[4] M. Ali and H. Shalaby, "High-sensitivity all-optical pressure sensor based on photonic-crystal nanotechnology," *Journal of Russian Laser Research*, vol. 44, no. 2, 2023, pp. 113–119.

[5] M. S. Rahman and M. K. Uddin, "Modeling and analysis of all-optical pressure sensor using photonic crystal

based micro ring resonator," *International Journal of Numerical Modelling*, vol. 34, no. 5, 2021, Article ID e2879.

[6] X. Zhang and H. Wang, "Investigation of a high-performance pressure sensor employing a polymer-defect-based 1D annular photonic crystal," *Photonics*, vol. 10, no. 2, 2023, p. 123.

[7] R. Das and S. Sen, "Numerical modelling of 1-dimensional silicon photonic crystal sensor for hydrostatic pressure measurement," *Zeitschrift für Naturforschung A*, vol. 78, no. 4, 2023, pp. 255–263.

[8] C. Markos, J. C. Travers, A. Abdolvand, B. J. Eggleton, and P. S. J. Russell, "Hybrid photonic-crystal fiber," *Reviews of Modern Physics*, vol. 89, no. 4, 2017, pp. 045003-1–045003-28.