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International Frequency Sensor Association (IFSA).

Foreword

The 10th annual NSTI Nanotech Conference and Trade Show was held this year during 20-24 May at the Santa Clara Convention Center, in Santa Clara, California. The conference has grown this year to host 3000 attendees and 250 exhibitors, while the resulting proceedings boasts over 3000 pages of peer-reviewed micro and nanotechnology research.

A number of authors publishing in the Joint Electronics and Microsystems Symposia track were invited to submit a revised version of their papers to this special issue. Papers were selected from a number of symposia within the track, including: MEMS & NEMS, Sensors & Systems, Micro & Nano Fluidics, and MSM – Modeling Microsystems. These symposia brought together researchers from a number of disciplines to discuss topics ranging from theoretical developments, to design and fabrication, through to industrial applications of MEMS and NEMS sensors, devices and systems.

The joint symposia are motivated by the dream of smarter, smaller, and more complex systems that integrate micro and nano system technologies with intelligence, power and communication ability at the same micro or nano scale. The resulting increase in complexity poses an enormous challenge to engineers when designing, modeling, and fabricating such integrated micro and nano systems. The joint symposia aimed at bringing together researchers from different disciplines to exchange ideas about how to best develop such systems.

As with the joint symposia, this special issue includes papers ranging from those with a higher level focus to those covering low-level physical aspects of MEMS and NEMS devices and their modeling and fabrication. Four of the papers presented in this special issue correspond to invited talks: Sanna et al., examine miniaturization trends in preventative medicine and include some results from the EU project ANGEL; Adams et al., describe the results of the NASA funded GEMSTONE project, which involved creating and field-testing a small system of atmospheric probes; French and Yang explore the opportunities and pitfalls of scaling, whilst Nieva presents a number of new trends for using MEMS sensors in harsh environments.

We are very thankful both to the NSTI directors and Nanotech chairs (Dr. Matthew Laudon and Dr. Bart Romanovicz) and to the *Sensors & Transducers Journal* for offering the opportunity to publish this special issue.

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Fabry-Perot Diaphragm Fiber Optic Sensor (DFOS) for Acoustic Detection

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Abstract: A diaphragm fiber optic sensor (DFOS) solely based on Fabry-Perot multiple beam interference has been designed and fabricated with micro-electric mechanical system (MEMS) technology. The silicon diaphragm with an embossed center was designed with an interference gap width kept accurately. The DFOS was verified to be a truly and purely Fabry-Perot device via a critical test. Parallel testing with a Piezoelectric (PZT) sensor showed that the DFOS had high sensitivity. The Fabry-Perot DFOS also demonstrated excellent performance in on-line monitoring of Partial Discharge (PD) in power transformers. *Copyright © 2007 IFSA.*

Keywords: MEMS, Fabry-Perot, Fiber optic, Acoustic, Diaphragm with embossed center

1. Introduction

A diaphragm fiber optic sensor (DFOS) utilizes a diaphragm as the sensing element to detect static and dynamic pressure (acoustic wave). The fiber is used to deliver a steady probing light and to receive the reflected light modulated by the signals under detection. In recent years a great deal of efforts have gone into developing diaphragm-based fiber optic sensors for static pressure and acoustic signal detection to take advantage of optic sensors' high sensitivity, flexibility, versatility of diaphragm-fiber structure, resistance to electromagnetic interference (EMI) caused noise, and easiness for multiplexing and integration [1-4]. In this research, the silicon diaphragm was designed to have an embossed center in order to improve efficiency, alignment, linearity, and Q-point stability, which are critical issues in diaphragm-based fiber optic sensor design.

Currently an imminent application of DFOS is detecting partial discharge (PD) in high voltage transformers in the power industry. PD is an electrical discharge that occurs in an insulation system where the discharge does not completely bridge the electrodes. It is a well-known phenomenon and a precursor to complete insulation failure. Partial discharge within the power transformer could lead to degradation of the insulation system that may result in catastrophic failures [5-9]. It is a big concern for the power industry. As a consequence, there is a strong need for a capable sensor to detect and study PD.

2. Sensor System Design

The developed DFOS acoustic detection system is illustrated schematically in Fig. 1. It consists of a DFOS, a 1527 nm DFB laser, a 3-port fiber circulator, a photodiode, a filter & amplification circuit, and an oscilloscope. Light from the DFB laser propagates along the single mode fiber to the DFOS through the circulator and interferes inside the DFOS. The modulated light propagates back in the third leg of the circulator and is detected by the photodiode. The optical signal is turned into electric signal, which is then filtered and amplified, and finally processed and collected by the oscilloscope.

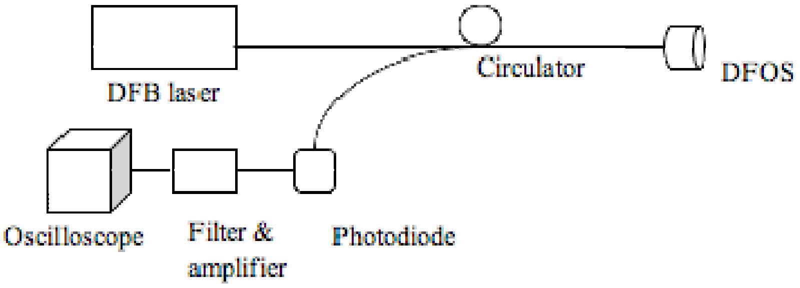


Fig. 1. Schematic of DFOS system.

A Fabry-Perot interferometric device is based on the interference of multiply reflected beams. The interference gap L corresponding to the applied pressure is determined by measuring the inference spectrum. The ratio of optical power output and input is defined as

$$\frac{I^{(0)}}{I^{(i)}} = \frac{2R_a - 2R_g \cos\phi}{1 + R_g{}^2 - 2R_g \cos\phi}, \tag{1}$$

where R_a is the arithmetic mean reflectance of the interfaces, R_g is the geometric mean reflectance of the interfaces, and ϕ is the phase shift of the light propagating across the interference gap L.

The mechanism of DFOS is usually described by the Fabry-Perot interference of multiply reflected beams between the diaphragm surface and the fiber end surface. The structure of a DFOS is shown in Fig. 2. The diaphragm, as the sensing element, is batch fabricated on a silicon wafer with MEMS technology and soldered to a single mode optic fiber to keep the sensor cavity at Q-point. Fabry Perot interferemetry is formed between the fiber end face and diaphragm inner surface. The incident light is partially reflected at the end face of the fiber. The remainder of the light crosses the air gap, gets partially reflected at the inner surface of the diaphragm and transmitted back to the fiber. The acoustic pressure changes the air gap and modulates the light transmitted back through the fiber. Sensitivity, efficiency and frequency response etc. are determined by the geometry of the diaphragm. Therefore the diaphragm is a critical part of sensor design.

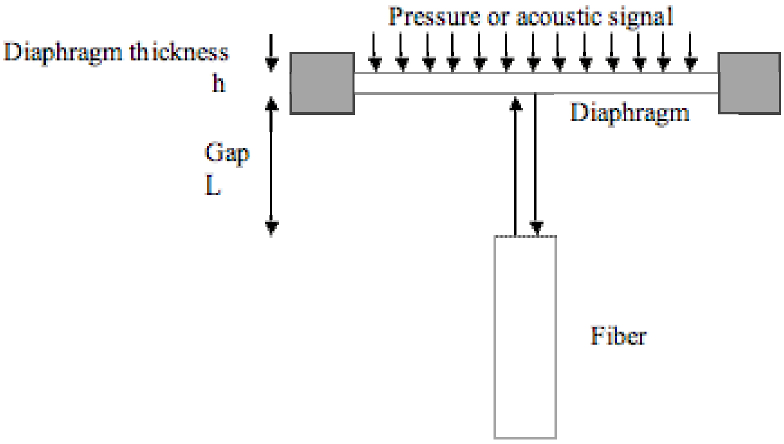


Fig. 2. Principle of Diaphragm Fiber Optic Sensor (DFOS).

The selection of diaphragm thickness and side length is based on the pressure range and acoustic frequency at which the device is required to operate. The center deflection y_0 (m) of a flat square diaphragm under pressure may be expressed by Equation 2 [10, 11]:

$$y_0 = \alpha \frac{Pa^4(1-\nu^2)}{Eh^3}, \tag{2}$$

where a is half side length of the square diaphragm, h is thickness, P is applied pressure, E is Young's modulus, and ν is Poisson ratio.

For the diaphragm clamped at its circumference, the resonant frequency is

$$f = \frac{\pi}{a^2} \cdot \left[\frac{gD}{hw}\right]^{\frac{1}{2}}, \tag{3}$$

where D is flexural rigidity, and w is the diaphragm density.

In this research, an embossed center was designed in the diaphragm of DFOS to make the sensor structure and operation more stable and more efficient. The gap between the embossed center and the fiber tip must be kept within several micrometers for near field operation. One advantage of the embossed center is that it prevents lateral misalignment between the diaphragm and the fiber end. Another important advantage is that while the gap between the embossed center and the fiber tip is only a few micrometers, the distance between the diaphragm and the fiber is considerably larger (60 μm). This geometry increases the air cavity volume, and significantly reduces the air cavity back pressure during diaphragm movement. Diaphragm movement is easier under reduced air pressure, resulting in increased sensor sensitivity. Furthermore, according to mirror symmetry of the electromagnetic wave, the coupling coefficient of the electromagnetic wave back into the fiber increases in reverse proportion to the air gap distance and in proportion to how may times the light is reflected. Therefore, a smaller interference gap between the embossed center and the fiber increases sensor efficiency and sensitivity.

Femlab software was used for simulation of center-embossed diaphragm deflection for a sensor of 100 kHz resonant frequency for PD acoustic detection. The simulation yielded a diaphragm of 1.9-mm side length and 60-µm thickness with a 0.35mm x 0.35 mm embossed center and a 2-µm interference gap as the optimum parameters.

3. Sensor Fabrication

The diaphragm fabrication steps using MEMS technology are shown in Fig. 3. A 220-µm silicon wafer was etched sequentially on both sides in KOH to give a 60-µm thick diaphragm. The embossed center was protected by a layer of silicon oxide to ensure that it remained intact in the etching process. As a result, both ends of the Fabry-Perot cavity (the embossed center and fiber tip) were perfect flat surfaces to reduce speckle noise. The surrounding wall on the embossed-center side of the diaphragm was coated with gold by evaporation. The 2-µm gap between the embossed center and fiber end was accurately determined by the gold film thickness.

(1) (2)

(3) (4)

Fig. 3. Schematic of diaphragm fabrication steps.

The diaphragm and fiber tip were first clamped together mechanically. The gap between the diaphragm and the fiber was then adjusted while measuring the interference light signal output until it reached linear operation and the highest detection sensitivity, defined as Q-point. After the sensor operation had reached Q-point, the diaphragm and the fiber ferule were soldered together with Ag-Sn-Pb175 under microscope.

4. Experimental Results

4.1. Static and Dynamic Pressure Testing

This was the first time that static pressure testing was successfully demonstrated in diaphragm-based Fabry-Perot sensors. The static pressure was gradually increased to 9000 Pa. The output signal intensity vs. pressure curve is shown in Fig. 4. Good agreement between the theoretical curve calculated from Equation (1) and experimental data was achieved. Therefore, our DFOS has proven to be a truly and purely Fabry-Perot device.

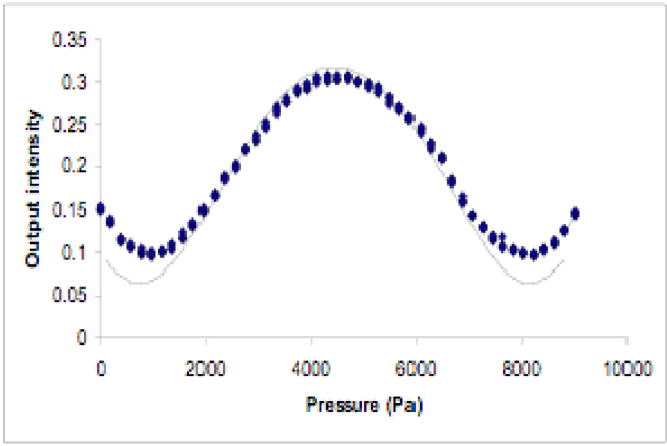


Fig. 4. Static characterization of optic output (dotted line) as a function of pressure, in comparison with calculated curve from Equation (1).

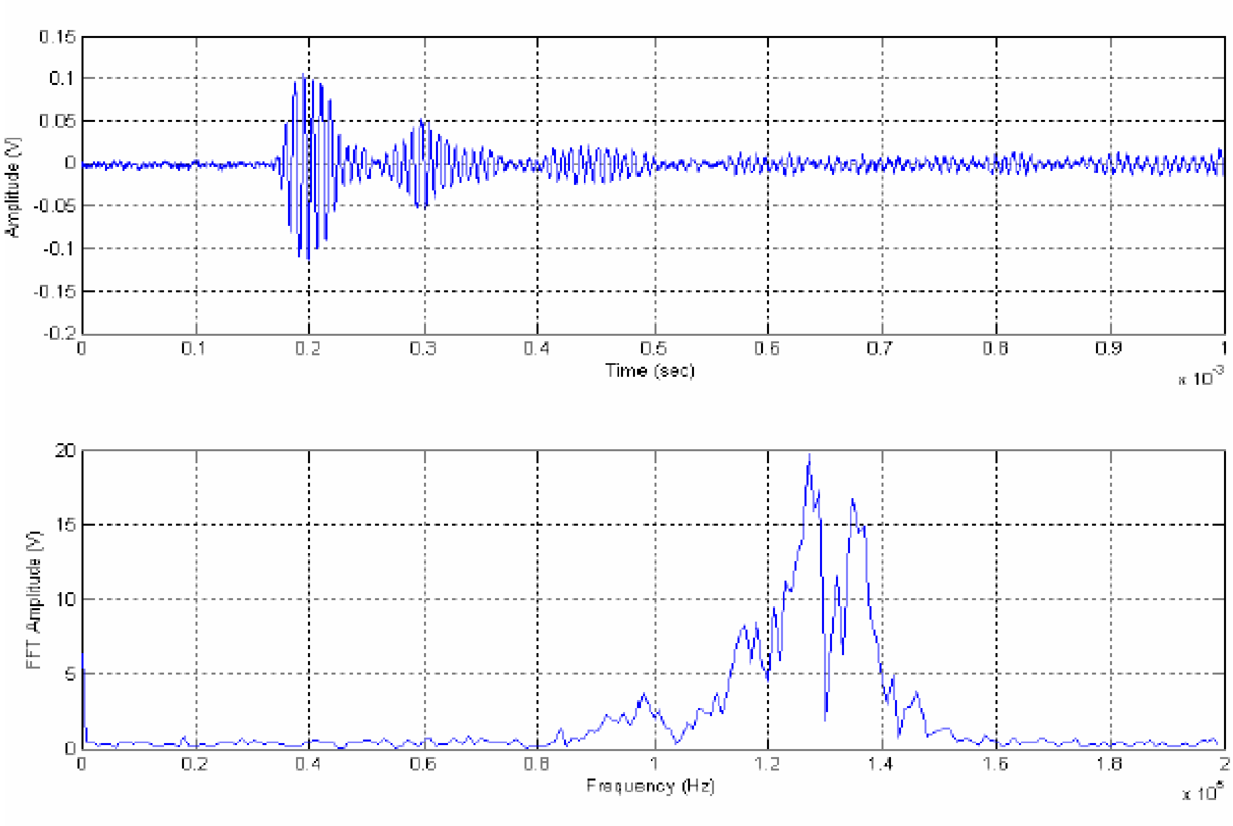
In dynamic pressure testing, the DFOS and a PZT sensor were tested in parallel under identical conditions. DFOS and R15 (PZT sensor made by Physics Acoustic Corporation) were immersed in water. The acoustic waves were created by an emitter (pulser R15) placed approximately eight inches away from both sensors. The pre-amp gain of the R15 sensor was set to 20 dB. The DFOS was connected directly to the oscilloscope without any amplification.

The pulser frequency was increased in 5 kHz increments from 75 kHz to 300 kHz. The R15 sensor with 20 dB gain had two bandwidths with peak frequencies at 150 kHz and 230 kHz. The maximum amplitude was about 145 and 185 mV respectively. The DFOS without amplification had a bandwidth with peak frequency at approximately 105 kHz and maximum amplitude of about 140 mV. Fig. 5 (a) and (b) show the waveforms and frequency spectra of the DFOS and R15 when the pulser frequency was 130 kHz. Both sensors exhibited very similar waveform profiles and frequency spectra. The DFOS has shown comparable high sensitivity as the PZT sensor even without signal amplification.

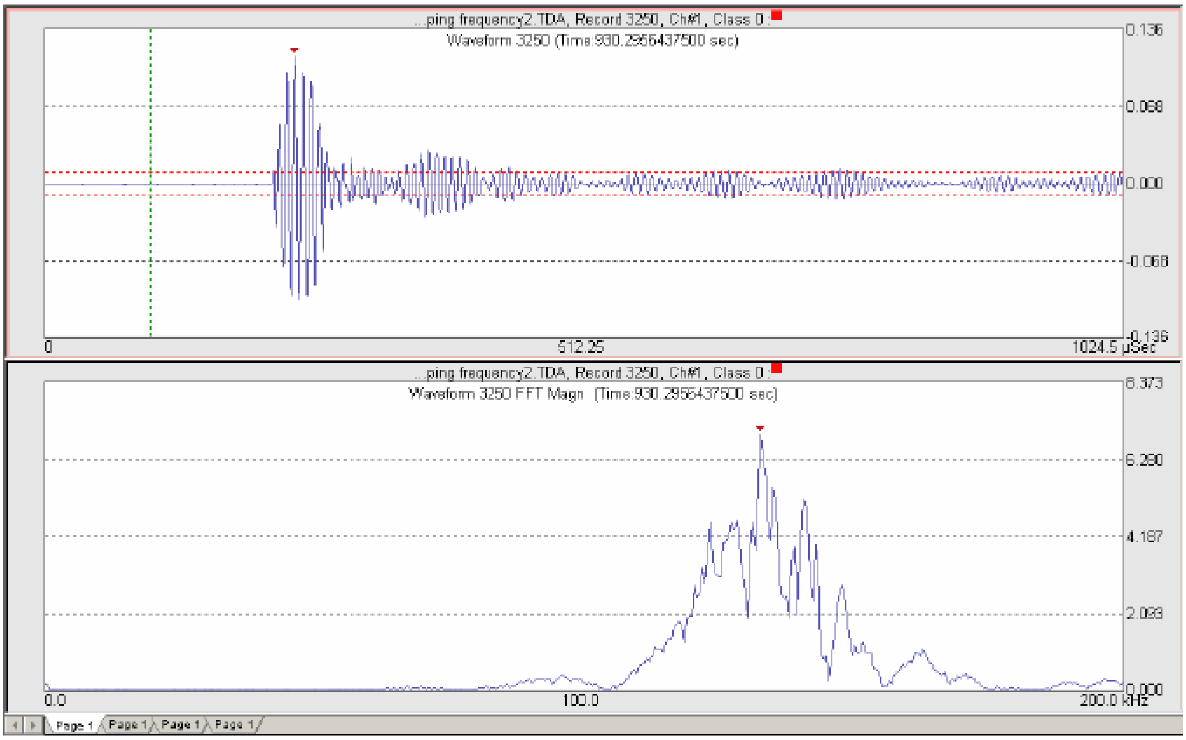
4.2. Partial Discharge Acoustic Detection

The DFOS was placed in the oil inside a retired real utility transformer at various distances from the partial discharge (PD) spark. The PZT sensor was attached to the external tank wall.

In Fig. 6, the purple curves of extremely high frequency are the triggering signals of the PD, which served as the starting point of the PD occurrence. The yellow signals were from the DFOS sensor, and the green signals from the PZT sensor. In the left graph, the PD was far from the two sensors, while it was close to both in the right graph. The time difference between the PD peak to the onset of the yellow/green acoustic signal is the time of flight. Fig. 6 clearly shows the time of flight increased as the sensors were farther away from the spark. The magnitude (sensitivity) of the DFOS signal was higher than the PZT signal.



(a)



(b)

Fig. 5. Waveform and frequency spectra when the pulser frequency is 130 kHz.
(a) DFOS; (b) PZT sensor.

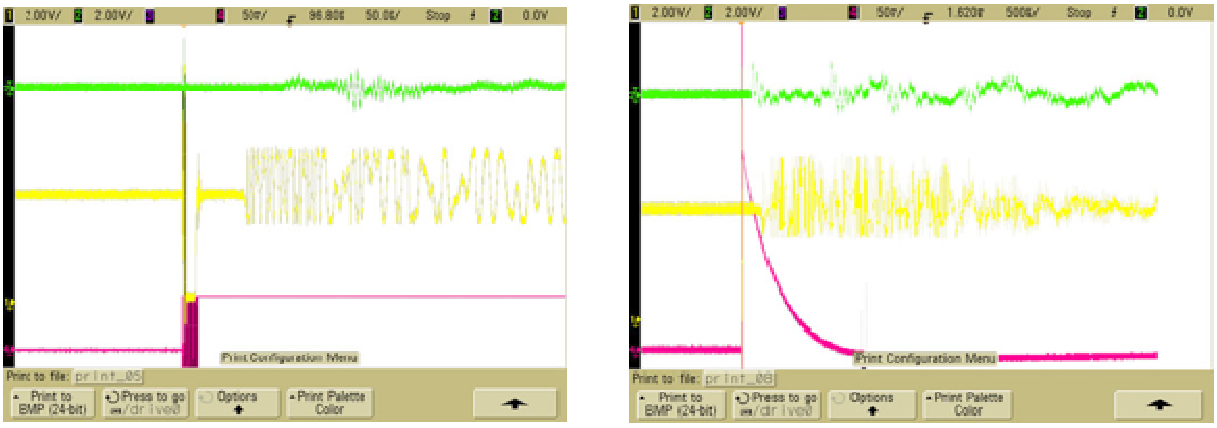


Fig. 6. PD in the oil tank of a transformer detected by DFOS and PZT sensor.

5. Conclusion

The Diaphragm Fiber Optic Sensor is based on extrinsic Fabry-Perot interferemetry. A center embossed diaphragm was designed to serve as the sensing element of the sensor. The bonding and diaphragm processing methods by MEMS technology ensured that the diaphragm and the fiber were aligned both laterally and angularly. The novel DFOS design and fabrication led to better alignment and Q-point stabilization, high efficiency, and reliability. Experimental results from static pressure and dynamic acoustic measurements demonstrated excellent sensor efficiency and stability. High frequency (100 kHz) DFOS showed high sensitivity in comparison testing with commercial PZT sensors.

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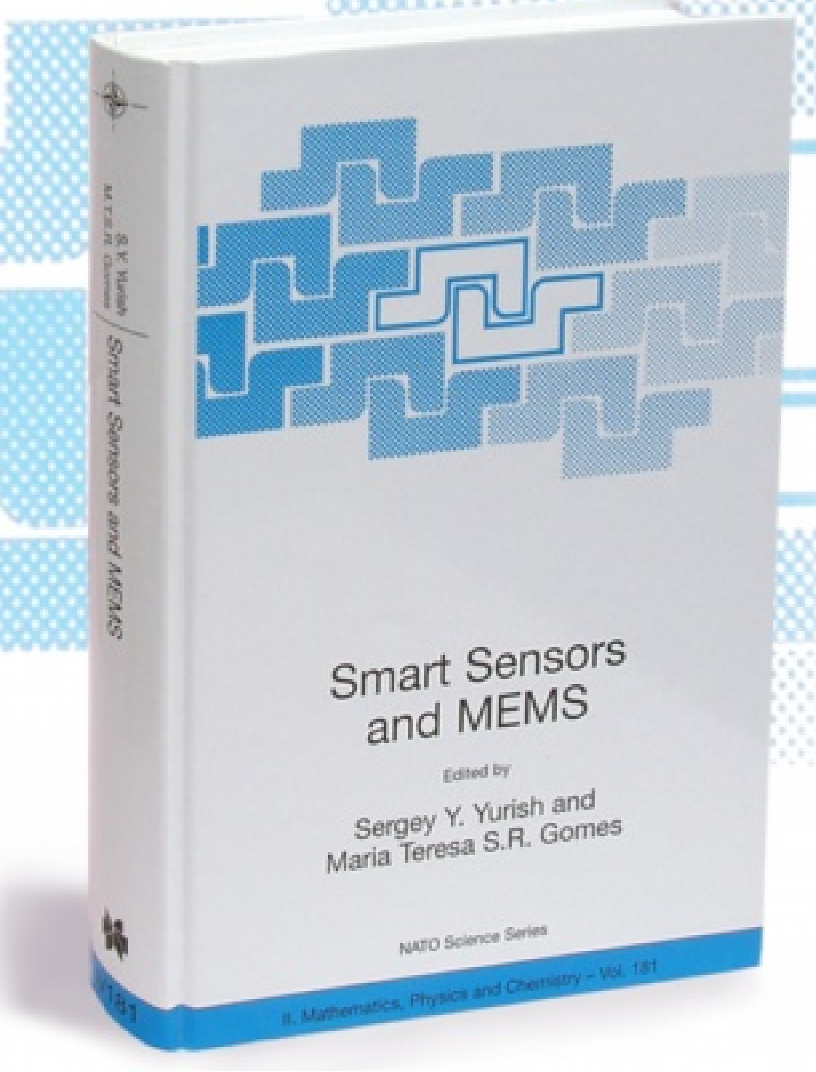

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