Fiber Optic Sensors in Brazil: a Contemporary Review

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***Abstract*—The authors present a short review about the development of fiber optic sensors (FOS) since its appearance in Brazilian institutes by the 1980's.**

***Index Terms*—Fiber optic sensors, Fiber Bragg grating sensors, Long-period grating sensors**

I. Introduction

This paper reviews the development in Brazil in the field of fiber optic sensors (FOS). The evolution of the field is separated in time spans, just to establish a timeline easy to follow. For the sake of simplicity, sensors were classified into two broad types: non-grating and grating based FOS. It is not the goal of this review to discuss their advantages and issues, but instead to follow their development in Brazil. We also consider a wide definition of FOS as the ones where the fiber can be either the transducer itself or a constituent of the sensing system.

II. Evolution of the Field

A. Starting Years, before 1989

In the current year, the Annual Meeting of the Brazilian Society for Microwaves and Optoelectronics (SBMO) comemorates the 40^{th} anniversary of the society, as well as the 25^{th} anniversary of the Journal of Microwaves, Optoelectronics and Electromagnetic Applications (JMOe), whose first issue appeared in May, 1997.

It is noteworthy that early developments on optical fiber sensors in Brazil started almost together with SBMO. In fact, the first conference paper about a sensor based on liquid-core optical fiber appeared in 1984 [1]. Around this period, researchers based at the CTA - Centro Tecnológico da Aeronáutica - caught attention to fiber optic gyroscopes. As a part of their effort, Brazilian researchers moved to obtain Ph.D. in other countries, working in that subject. At the 3^{rd} International Conference on Optical Fiber Sensors (OFS–3, Washington, 1985), S.L. Carrara authored a paper resulting from that exchange [2].

In the first quarter of 1986 L.C. Guedes Valente and H.J. Kalinowski attended an ICTP Winter College (Trieste, Italy) where two talks about FOS were delivered by A.M. Scheggi, the pioneer on biomedical fiber sensors. Soon after, Kalinowski attended a two week NATO Advanced School Institute on Optical Fiber Sensors (Erice, Italy). Both events influenced the group at Universidade Federal Fluminense (UFF) to start working on FOS. At the Pontifícia Universidade Católica do Rio de Janeiro (PUC-RIO) there was also work on length/strain measurements in optical fibers using an optical fiber interferometer [3], whereas at UFF the focus was temperature [4], voltage and current sensors for transmission and distribution lines [5], in a joint agreement with Centro de Pesquisas em Energia Elétrica (CEPEL). CTA keep fiber gyros as one main goal [6]

B. Early Developments along 1990-1995

The efforts of the CEPEL-UFF partnership lead to prototypes that were lab tested. A few of them also were field tested at a power station (Adrianópolis, RJ). CEPEL looked for attracting from industry partners through the realization, within their premises, of the first Brazilian meeting on optical fiber sensors (Encontro Brasileiro de Sensores a Fibra Ótica), organized by L.C. Guedes Valente and N.L. Brooking in 1991. By that time, other research groups were involved in FOS for electrical energy applications as, e.g., M. Werneck at the Universidade Federal do Rio de Janeiro (UFRJ), whereas at ITA the work followed on fiber gyros and associated devices. There was continuing interest at PUC-RIO and a new group started to work on FOS at the Centro Federal de Eduação Tecnológica do Paraná (CEFET/PR), now UTFPR - Universidade Tecnológica Federal do Paraná, after Prof. Kalinowski joined their faculty; a short bend sensor using a temperature sensitive polymer jacket was demonstrated [7]. An international cooperative project was established between CEFET/PR and Universidad Nacional de Colombia under auspices of the CNPq-COLCIENCIAS agreement to develop modelling techniques applied to optical fiber devices and sensors.

A special session on optical fiber sensors was organized during the XVI National Meeting of Condensed Matter Physics (ENFMC, Caxambú, 1993) having Prof. Brian Culshaw (Strathclyde University, Scotland) – one of the pioneers in FOS – as an invited speaker. This contributed to spread the

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work on fiber sensors among the physicist community, which, in turn, were joined by colleagues of other scientific branches.

Non-Grating based sensors were first studied both experimentally and theoretically, comprehending interferometric, polarimetric, fluorescence, reflectance/absorbance interrogation systems [8]–[15]. The proposed applications included strain, temperature, pH and carbon monoxide monitoring. Such works, although are not grating-based fiber sensors, were the first efforts to consolidate the development, by Brazilian researchers, of optical fiber sensors. Grating sensors in optical fibers started to be developed in other countries right after the demonstration of photosensitivity in optical fibers in 1978 [16]. However, the first papers about grating-based sensors in Brazil only appeared almost two decades afterward [17], [18].

C. Building the Grounds on FOS, 1996-2000

The first attempt to establish some comparison methodology applicable to FOS in order to improve their readability was done in [19] by defining a figures of merit for the detectors. Several other propositions appeared in the following years, seeking for standardization of the FOS and modelling of particular classes of devices [20]. A high resolution bend-based FOS for temperature measurements in microwave hyperthermia applications was described by this time [21]. The first Fiber Bragg Grating (FBG) sensors were developed to measure temperature in transmission lines [22], strain in power systems and to monitor the respiratory spectrum . New pH sensors with modified optodes were developed aiming for better resolution and accuracy [23]. New infrastructure related to FOS was installed in UFRJ [24]. The phenomenon of Surface Plasmon Resonance (SPR) was explored in FOS with possibilities of improved responses [25]–[27]. Multiple sensors for distributed monitoring using multiplexed transducers were described [28], [29].

An application where the FOS showed to be very advantageous relatively to the traditional mechanical options is the fiber-optic gyroscope (FOG) [30]. Without moving parts, they are commercially available and its use ranges from space applications to military inertial navigation systems.

Along this time slot the first phase-mask interferometers to inscribe Bragg gratings in optical fibers were assembled in Brazil. One of them at PUC-RIO, using an Ar^{3+} laser doubled at $244\,\mathrm{nm}$ in the group of L.C. Guedes Valente and the other at Instituto de Estudos Avançados (IEAv), using a similar light source, with C.L. Barbosa as the research leader. Both facilities cooperated with researchers of other centers, by providing fiber Bragg gratings (FBG) to be used as sensing devices The availability of FBG enhanced the Brazilian research on fiber sensors in the next years. Partnership with companies from the Oil, Gas and Energy sectors started to provide field tests for FOS.

D. Consolidating FOS Research, 2001-2005

From this time on, the number of works focusing on fiber grating sensors attracted an increasing number of groups and researchers. Also, Brazilian researchers started to play a more important role in conferences with extended versions of Proceedings published in special issues of Journals. As a result, about 10% of the Brazilian Proceedings papers were also accepted for publication in peer reviewed Journals, further contributing for the international recognition of Brazil in the field. At the end of this time interval, cooperative work started in grating based FOS, involving Brazilian research groups with their counterpart in Portugal, particularly at Universities of Aveiro and Porto, as well as the Instituto de Telecomunicações – Aveiro. The group at CEFET/PR received grants that permitted to assemble two phase-mask interferometers using a frequency doubled Nd:YAG laser $(266\,\mathrm{nm})$ and also started to provide FBG sensors to researchers in other universities and institutes.

Techniques involving Optical Time Domain Reflectometry (OTDR) allowed interrogating several sensors in the same optical link, for distributed strain measurements using FBGs [31]. OTDR was also used to demonstrate the possibility of measuring curvature of structures, by using long period gratings (LPGs) for the first time in Brazil [32].

Attempts devoted to decrease the costs of the overall sensor, focusing in the interrogation system by replacing expensive commercial interrogators by fixed optical filters were demonstrated for monitoring respiratory movements with FBGs [33], a work that also pioneered FBG *in vivo* biomechanical applications.

Trying to offer a solution for monitoring the quality of hydrocarbons-based fuels, a new type of sensing method was proposed by using LPGs [34], [35]. The possibility of discriminating oxidation states of chemical compound was also demonstrated with the same fiber transducer [36]. Sill in the oil-gas industry, FBGs are good candidates for applications in the oil-gas industry related with corrosion [37].

In another approach, FOS can be tailored allowing for multi-parameter measurements. By writing superimposed FBGs in a highly birefringent fiber, authors were able to measure up to three parameters in point-sensor [38]. FBG sensor are also suitable due to its small size to access bio-mechanical systems, where traditional sensors do not perform adequately [39].

Although grating sensors became a well established technology, non-grating fiber sensors still showed to be an import branch of optical sensors. Among them, it is worth to mention plasmonic structures with noble metal films, [40], interferometric structures based on multimode (MM) - singlemode (SM) cavities [41], polymeric optical fibers (POF) [42] , Raman and Brilloin sensors in Hi-Bi fibers [43] and evanescent field sensors [44], [45].

The cooperative work with the Portuguese groups induced strong exchange of students, pos-docs and researchers, consolidating the Brazilian partnership within Europe and attracting attention both of other Brazilian researchers as well as from European research institutes. As a result of the increased participation of Brazilian authors in high quality FOS papers, a position in the Technical Program Committee of the International Conference on Optical Fibre Sensors was assigned to a Brazilian researcher in 2004.

Gavea Sensors, the first Brazilian company to industrialise and commercialize optical fiber sensors started its operation in 2003, as a successful spin-off from the Laboratório de Sensores de Fibra Ótica at PUC-RIO, with strong ties to Petrobras and other companies of the energy sector.

E. Dissemination of FOS related Work along 2006-2010

In part owing to the increasing international cooperation, FOS experienced an important expansion within this 5-year time span. The number of published papers surpassed by 33 % the total number of papers co-authored by Brazilians between 1995 an 2005. Another consequence was the increased variety of applications addressed by the authors. New facilities for FBG and LPG devices were implemented along this (and the next) quinquennium in different geographical regions of Brazil, allowing samples to a large group of researchers. Apart from frequency doubled $Nd:YAG$ and Ar^{3+} lasers illuminating Talbot interferometers, under the phase-mask method was alto assembled with *KrF:eximer* lasers.

Among the new developments in 2006 can be mentioned the measurement of ambient ozone [46], salinity [47], dental biomechanics [48], current leak in transmission lines [49] and sulfur dioxide in wines [50]. Specialty optical fibers also received attention from the researchers, making use of the evanescent field to promote the interaction with the measurands [51], [52].

The use of long period gratings (LPG) were further extended to analyze the quality of renewable Brazilian fuels like biodiesel and ethanol, as well as fossil fuels [53], [54]. Mechanical properties of dental resins [55] were studied with FBGs, consolidating the Brazilian Group in dental biomechanics. It is also worthy to mention the use of FBGs in the study of drying process of latex paintings [56], magnetic field detection [57], as well as fiber sensors for partial electrical discharge detection [58] and hydrostatic pressure [59].

F. Widespreading FOS Subjects, 2011-2015

Along 2011, the main Brazilian contributions to the field were related to improvements in peak detection of FBG with computational intelligence [60], FBG-based sensing of high-voltage [61] and biosensing with plastic optical fibers [62].

In the next year, the search for increased sensitivity led to the development of a technique using Photonic Crystal Fiber (PCF) with 70pm/degree temperature sensitivity [63], and about 10 pm/microstrain using microcavities in optical fibers [64]. As the optical fiber grating sensors evolved from laboratory to field applications, the need for standards was the object of a metrological characterization of FOS [65].

New developments to be mentioned in the following years include the detection of tropical diseases like dengue [66] or Escherichia coli [67]. Also, a new plasmonic technique to increase the sensitivity of fiber grating sensors in water environments was first proposed [68], resulting in new developments further carried in other countries. Concerning FBG applications in biomechanics, one singular result was the *in vivo* monitoring of food ingestion in ruminants, using implanted sensors [69], that has been enhanced in following years. The use of FBG sensors for the study of dental materials and related clinical procedures also grew along this quinquennium [70], [71]. Such applications in veterinary and dentistry attracted researchers from the living sciences branches to the interdisciplinary work using FOS, a trend that is observed up today.

The facilities for grating production had some remarkable improvements with shorter UV sources *(ArF:Excimer)* and femtosecond pulsed lasers [72].

G. Brazil and OFS-24 Conference

The history behind the organization of the 24^{th} International Conference on Optical Fibre Sensors, OFS-24, starts back in 2003, when the conference (OFS-16) took place at Nara (Japan). The Brazilian attendees (A. Braga, H.J. Kalinowski, L.C. Guedes Valente, M.F. Silva) discussed how it would be helpful to the Brazilian community having one of the OFS conference edition within Brazil. An informal proposal was directed to the OFS International Steering Committee (ISC) through the help of Anna Mignani and Dick Claus.

OFS-17 (Brugges, 2005) assigned Prof. Kalinowski to act in the Technical Program Committee, which allowed another proposition to realize OFS in Brazil. The proposal gained momentum after OFS-19 (Perth) and, along 2008 – 2009, Brazil submitted a formal plan, disputing with Canada the organization of OFS-21 (2011), finally assigned to this country. However, the Brazilian proposal induced the OFS community to nominate Prof. Kalinowski as a member of the ISC, as well as others Brazilian researchers in the Technical Program Committee. A proposal to organize the OFS-24 was negotiated and approved by the Steering Committee in that year (2011) with Prof. J.L. Fabris appointed as the TPC Chair and Prof. H.J. Kalinowski as General Chair.

Previous activities for the OFS-24 were organized along the IMOC 2013 and SBMO 2014, which included special dedicated sessions to Optical Fiber Sensors and related technology. The JMOe also published a special issue on OFS.

In September 2015, OFS-24 attracted around 350 participants, 250 from outside Brazil. A large number of Brazilian students attended the meeting, providing manpower for future generations of researchers in the fields of optical and photonic sensing. In fact, Brazil held the second position in the number of submitted papers, after China – the best performance of the country in the history of the conference. Dr. L.C. Guedes Valente received a Lifetime Achievement Award from SBMO, in recognition of his achievements in setting FOS research and development in Brazil. An special issue of the IEEE/OSA Journal of Lightwave Technology was published with selected papers from the conference [73].

OFS-24 provided a major impact on FOS research in Brazil, leading to the organization of two Latin American Workshop on Optical Fiber Sensors (LAWOFS), the first at Porto Alegre (2016) – along the annual meeting of SBMO – and the second at Rio de Janeiro (2019); the third edition was postponed due to the CoVID-19 pandemic.

H. FOS Brazilian Bubble Growth after 2016

Along the most recent years FOS research continued to receive enhanced attention from Brazilian groups. A search in the Web of Science database shows more than 300 articles published in their indexed journals in the last six years, and it is expected that a large number of articles appeared in non-indexed journals and conferences. The geographical distribution of the authors now spreads from the South to the North regions. Due to length limitation, it is not possible to present in this manuscript a fairy reasonable description of the achieved results without prejudice to a large number of researchers authoring all those articles. Impressing results were obtained in biomedical, hydraulic and aerospace engineering, as well as improvements in electrical and electronic engineering. New materials were studied for FOS sensing, including polymers, nanoparticles, and magnetorestrictive coatings, among others. Fiber sensors were demonstrated using structured fibers and distributed Raman or Acoustic sensors also claimed several interesting applications. Brazilian researchers presented invited papers on FOS work both at international conferences as well as webinars organized by the leading optics and photonic societies.

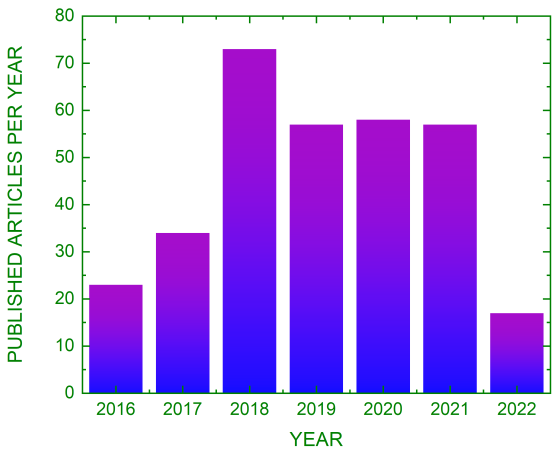

Fig. 1. Number of FOS related articles published in Web of Science indexed journals from 2016. Data for 2022 covers only January – February.

III. JMOe and FOS

As initially mentioned, the starting issue of the Journal do Microwaves, Optoelectronics and Electromagnetic Applications was published in 1997. It take a few years in order to the first article on FOS subjects to appear in the journal, which occurred in June, 2000 [74] – the 50^{th} article published by JMOe. In the next ten years the publication of FOS related articles showed a shy performance, with an average of 1.85 papers per year, a figure that increased to an average of 3.6 papers per year after 2012. The graph on Fig. 2 displays the evolution of the articles along the full time interval since that initial publication.

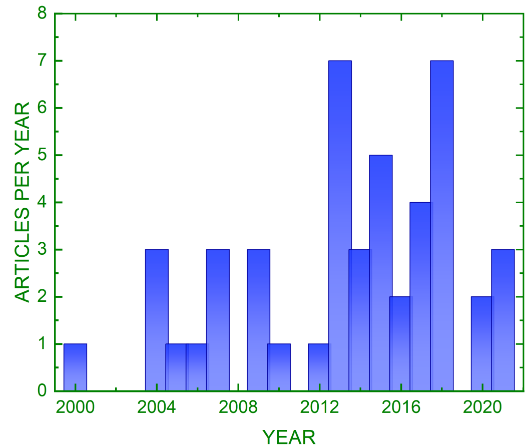

Fig. 2. Number of JMOe published articles on FOS related subjects along time.

IV. Conclusion

This short review highlights the development achieved by Brazilian researchers in the field of FOS. Thanks to its unique properties that for many applications make them advantageous over their electrical counterpart, the field is still attracting new adepts since the first developments in the 1990's. It is also important to note that the history o FOS in Brazil is closely connected to the Brazilian Society for Microwaves and Optoelectronics (SBMO) and its Scientific Annual Meetings. The importance of the theme can be followed along the Proceedings from those Meetings, no matter if is the national version (MOMAG, SBMO) or international (IMOC).From the presented data, it is possible to verify the increasing number of publications, only impacted during the biennium 2020-2021 owing to, among other things, the COVID-19 pandemics. At last, such trend can also be verified by observing the number of published papers appearing per year in the JMOe (Journal of Microwaves, Optoelectronics and Electromagnetic Applications), a joint publication between the scientific societies SBMO and SBMag.

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