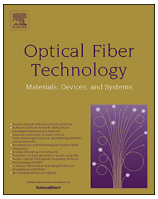
Optical Fiber Technology 43 (2018) 6–19

Contents lists available at ScienceDirect

Optical Fiber Technology

journal homepage: www.elsevier.com/locate/yofte



Invited Papers

Fiber optic sensors for sub-centimeter spatially resolved measurements: Review and biomedical applications

Daniele Tosi[a,b,*], Emiliano Schena[c], Carlo Molardi[a], Sanzhar Korganbayev[a,b]

[a] *Nazarbayev University, Department of Electrical and Electronic Engineering, 53 Kabanbay Batyr, 010000 Astana, Kazakhstan*
[b] *National Laboratory Astana, Laboratory of Biosensors and Bioinstruments, 53 Kabanbay Batyr, 010000 Astana, Kazakhstan*
[c] *Università Campus Bio-Medico di Roma, Laboratory of Measurements and Biomedical Engineering, 00128 Rome, Italy*

ARTICLE INFO

Keywords:
Fiber optic sensors (FOS)
Fiber Bragg Grating (FBG)
Distributed sensors
Chirped Fiber Bragg Grating (CFBG)
Optical Frequency-Domain Reflectometry (OFDR)
Biomedical sensors

ABSTRACT

One of the current frontier of optical fiber sensors, and a unique asset of this sensing technology is the possibility to use a whole optical fiber, or optical fiber device, as a sensor. This solution allows shifting the whole sensing paradigm, from the measurement of a single physical parameter (such as temperature, strain, vibrations, pressure) to the measurement of a spatial distribution, or profiling, of a physical parameter along the fiber length. In the recent years, several technologies are achieving this task with unprecedentedly narrow spatial resolution, ranging from the sub-millimeter to the centimeter-level. In this work, we review the main fiber optic sensing technologies that achieve a narrow spatial resolution: Fiber Bragg Grating (FBG) dense arrays, chirped FBG (CFBG) sensors, optical frequency domain reflectometry (OFDR) based on either Rayleigh scattering or reflective elements, and microwave photonics (MWP). In the second part of the work, we present the impact of spatially dense fiber optic sensors in biomedical applications, where they find the main impact, presenting the key results obtained in thermo-therapies monitoring, high-resolution diagnostic, catheters monitoring, smart textiles, and other emerging applicative fields.

1. Introduction

Fiber optic sensors (FOS) have undergone a substantial expansion through their decades of history [1]. FOS make use of an optical fiber or an optical fiber device as the sensing element. The sensing mechanism is enclosed within the modification of the properties of the lightwaves transmitted through or, as in most implementations, reflected by the sensing element(s): the measurand affects the sensing region by altering the power, reflection/transmission spectrum, phase, polarization, or guided modes of the incoming light.

From the late ‘80s, FOS have attracted interest in biomedical applications [2]. In this field, FOS have been employed in the detection of biophysical and biological parameters, such as changes of temperature, pressure, strain, pulsatile signals, glucose, hemoglobin. Compared to more traditional sensing technologies, FOS offer a plurality of advantages that are significant for biomedical applications: lightweight and compact form factor, with the possibility to be packaged within the smallest medical catheters and needles [3–5]; biocompatibility, according to the ISO 10993 [6] standard in use by Food and Drug Administration and the European Union; chemical and biological inertness; immunity to electromagnetic interference, which makes FOS compatible with MRI (magnetic resonance imaging), CAT (computed tomography) and other procedures which make use of high-intensity electromagnetic fields; instantaneous response to biophysical variations, limited only by the catheterization.

Thanks to these characteristics, FOS have established as a key sensing element in several medical applications [7], including cardiovascular diagnostic [8], femoral artery pressure detection [9], intra-aortic balloon pumping [10], prostatic implants [11], ventricular assist [12], intra-cranial pressure [13], blood temperature detection [14], and urology [15] among others.

Modern approaches to FOS technologies, however, contribute to a new sensing feature, potentially a breakthrough in terms of sensing possibilities: recent advances allow not only to use an optical fiber as a sensing element but to enclose a plurality of sensing element within the same optical fiber. This possibility gives FOS the possibility to spatially resolve physical parameters, by detecting and localizing temperature or strain variations in space [16]. This is an unprecedented feature, because it enables the detection of *maps* or *profiles*, whereas strain or temperature variations are mapped in space and time [17]. The spatial resolution is defined as the distance between two sensing points that can be resolved by the sensing system. For advanced biomedical

---

* Corresponding author at: Nazarbayev University, Department of Electrical and Electronic Engineering, 53 Kabanbay Batyr, 010000 Astana, Kazakhstan.
E-mail address: daniele.tosi@nu.edu.kz (D. Tosi).

https://doi.org/10.1016/j.yofte.2018.03.007
Received 29 January 2018; Received in revised form 3 March 2018; Accepted 26 March 2018

applications, it is important to resolve high-resolution sensors, whereas the spatial resolution ranges between the centimeter and the fraction of millimeter.

Two approaches enable sensing with a high spatial resolution. The first method makes use of a set of several sensors, multiplexed in a single fiber in an inline configuration. This approach is used in modern Fiber Bragg Grating (FBG) arrays [18], which exploit wavelength division multiplexing [19] principle. An FBG is an inline sensor that exhibits a narrow resonant spectrum, having bandwidth hundreds of time smaller than the spectral range of interrogation devices. This enables the possibility of fabricating several FBGs on a single optical fiber, each having a different wavelength. The advances in FBG fabrication allow reducing the distance between each element of the FBG array, reducing the spatial resolution to 3–10 mm [20]. In FBG arrays, strain or temperature maps are discrete maps, whereas each FBG element constitutes a sensing point. Chirped FBG (CFBG) sensors extend the FBG concept from a discrete to a continuous dataset [17]. A CFBG behaves as a continuous set of FBGs, and thus its spectrum is inherently dependent on the temperature or strain variation experienced in every point of the sensing element.

The second approach relies on distributed sensing: in this approach the sensing element is not fabricated on the fiber, but the fiber itself acts as the sensor [21]. Due to Rayleigh backscattering events occurring in every section of the optical fiber, an infinitesimal fraction of the power input to an optical fiber is reflected in every section of the waveguide, each component arriving at the photodetector with a different time and phase. The genesis of distributed sensing to high-resolution detection dates to the mid 1990s, where Froggatt et al. [22] demonstrated that inverse Fourier transform of the wave back-reflected by an optical fiber through Rayleigh scattering corresponds to the fiber spectral signature, which shifts by effect of temperature and strain [21]. This is the principle of optical frequency-domain reflectometry (OFDR), which is applied in distributed sensing [23]. An alternative approach to OFDR makes use of microwave photonics (MWP) [24]: in this case, reflected waves are detected in the microwave domain by a vector network analyzer, simplifying part of the signal demodulation. MWP have been recently applied even in multi-core fibers, extending sensing capacity [25].

The possibility of reducing spatial resolution to the cm-level or below has opened a set of biomedical applications, in which this sensing feature is a key asset. A major field that requires spatially dense fiber optic thermometry is in the real-time monitoring of thermal ablation based therapies [26,27]. Other applications are in medical catheterization for diagnostic through gastroscopy [28] and colonoscopy [29]. FOS can also serve as optical guidance and force/bending detection in medical catheterization [30], such as in epidural anesthesia [31] and in robotic surgery [32]. Emerging applications are in high resolution urology diagnostic and in smart textiles [33]. The applications where high spatial resolution FOS are employed are sketched in Fig. 1.

In this paper, we review and compare the technologies for high spatial resolution fiber optic sensors (Section 2). The emphasis is on technologies capable of sub-millimeter to centimeter-level spatial resolution, including the system architecture, working principle and theoretical standpoints, and sensor demodulation. Subsequently, we review the biomedical applications of high resolution sensors (Section 3), explaining the impact of sensors and their spatial resolution on the possibility to perform each detection.

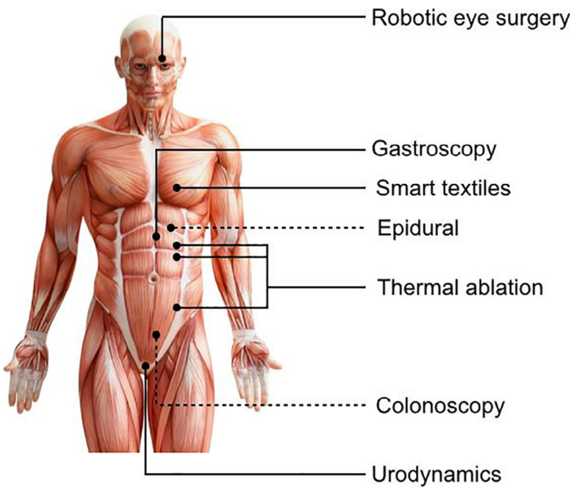


Fig. 1. Overview of high-resolution biomedical applications of fiber optic sensors.

2. High spatial resolution sensors

2.1. Fiber Bragg Gratings

Introduced in the late '90s [34], FBGs constitute one of the major pillars of recent FOS. The FBG is the fiber-optic implementation of a grating structure and is obtained through generating a periodic modulation of the refractive index of a single-mode optical fiber [35]. The resulting structure is a resonant spectrum, centered at the so-called Bragg wavelength $\lambda_{B,0}$:

$$\lambda_{B,0} = 2n_{eff}\Lambda, \tag{1}$$

where Λ is the period of the refractive index modulation, and n_{eff} is the effective refractive index of the fiber core. The coupled-mode theory (CMT) introduced by Erdogan [36] provides a closed-form expression for the reflection spectrum of an FBG. The reflection spectrum of an FBG can be approximated as:

$$R(\lambda) = \frac{\sinh^2(L\sqrt{\kappa^2-\sigma^2})}{\cosh^2(L\sqrt{\kappa^2-\sigma^2})-\frac{\sigma^2}{\kappa^2}} \tag{2}$$

where λ is the wavelength; R is the reflectivity; L is the length of the grating; κL is the grating strength coefficient, a unitless number that defines the maximum reflectivity as $\tanh^2(\kappa L)$. The coefficient σ has the following expression:

$$\sigma = \frac{\pi}{\lambda}\delta n_{eff} + 2\pi n_{eff}\left(\frac{1}{\lambda}-\frac{1}{\lambda_B}\right) \tag{3}$$

where δn_{eff} is the amplitude of the refractive index modulation.

The physical sensitivity of an FBG is enclosed in Eq. (1), as both Λ and n_{eff} are dependent on the variation of strain ($\Delta\varepsilon$) and temperature (ΔT). If strain and temperature variations are low or moderate, according to [34] we observe a linear shift of the Bragg wavelength $\Delta\lambda$:

$$\Delta\lambda = 2\left(\Lambda\frac{\partial n_{eff}}{\partial \varepsilon} + n_{eff}\frac{\partial \Lambda}{\partial \varepsilon}\right)\Delta\varepsilon + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial \Lambda}{\partial T}\right)\Delta T \tag{4}$$

which can be rewritten as:

$$\Delta\lambda = k_\varepsilon \varepsilon + k_T\Delta T \tag{5}$$

highlighting the strain sensitivity (k_ε) and temperature sensitivity (k_T). For FBGs operating on standard telecom fibers in the third optical window, the sensitivity coefficients have values of ~1 pm/με and ~10 pm/°C respectively [35].

The spatial distribution capability emerges when a sequence of FBGs, each having different Bragg wavelength, is inscribed on the same optical fiber. In this wavelength-division multiplexing (WDM) condition, it is possible to design an array of sensors each occupying a different spectral portion. Using FBGs having a sharp spectrum (typical bandwidth 0.1–0.3 nm), the cross-talk between each FBG is substantially negligible when the wavelength spacing between two adjacent FBGs is > 1.8 nm. Typical FBG arrays have 2 nm spacing between adjacent FBGs. In WDM conditions, there is a one-to-one correspondence between the location of the FBG within the array, and