Optical Fiber Sensor Technology

Advanced Applications – Bragg Gratings and Distributed Sensors

Edited by
K.T.V. Grattan and B.T. Meggitt

Kluwer Academic Publishers

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Preface

Advanced Applications in Optical Fiber Sensor Technology

The maturity in the subject of fiber optic sensors, seen in work presented at recent Conferences in the field and in the previous four volumes of this series on *Optical Fiber Sensor Technology* is reflected in the number of new, or enhanced applications of sophisticated fiber-based sensor systems which are continuing to appear. Indeed it is fiber sensor *systems*, rather than individual, relatively unsophisticated devices which have made the difference and opened up applications in the fields of environmental monitoring, measurement in civil engineering situations and in major industries such as petroleum and energy production. This has been brought about by combining the use of the best and most suited of the essential optical interactions concerned, coupled with sophisticated signal processing and data handling to make better measurements with optical fiber sensor systems than with conventional technology, often in special situations In this, the fifth text in the current series, the aim is to focus strongly on these application aspects, and to build upon the foundation of work reported in previous volumes.

The text comprises a series of commissioned chapters from leading experts in the field, the first of which discusses in some detail both the principles and applications of multimode optical fiber sensors. It draws upon the experience of three authors, coincidentally all having the same surname. Gordon Jones of the University of Liverpool, UK has co-ordinated the input of his colleagues in industry, Robert Jones and Roger Jones to include in the discussion a wide variety of multimode fiber systems. Following that Andreas Othonos draws upon his wide experience, including time spent with Ray Measures' group in Canada which had pioneered the application of fiber Bragg gratings in structural monitoring, in writing a chapter on fundamentals and applications of what are now key components of most optical fiber sensor systems. The chapter gives the essential groundwork for the subject, and then discusses a number of interesting applications which show the versatility of Bragg grating-based sensor systems. Alan Rogers' expertise in the fundamentals and applications of non-linear optics in fiber sensor systems has been known since his foundation work in the mid-1970s and he brings this to bear upon a chapter discussing both the basics and a range of topical uses of non-linear optical effects, enhanced by modern signal processing techniques. Arthur Hartog of York Technology was one of the pioneers of the use of non-linear optics in temperature measurement and in his chapter, again following a discussion of the key fundamentals of the subject, he emphasises the wide range of new applications of this sensor technology which has opened up in recent years. These devices, commercialized in the 1980s, represent some of the most successful of optical fiber sensor systems, and his discussion of the breadth of uses in industry is both fascinating and informative. Intensity-based fiber optical systems have required effective referencing to compete with other schemes, and Ghulam Murtaza and John Senior discuss in their chapter a wide range of such referencing schemes which are applicable to a number of different types of sensor systems and measurands. The key principles underpinning the wide range of optical fiber chemical sensors are discussed by John Norris, and seminal examples of the methods are discussed. The subject has grown rapidly over the years and European, American and other International Conferences regularly bring reports of the latest developments and applications which rely upon the key principles outlined herein.

The reputation of the authors as publishers in the leading international journals and key presenters at major Conferences gives then the basis upon which their contributions have been made and their authority to write as they do. They are the developers and users of the technology – in industry and from academia. The coverage of the subject is wide, and the material discussed will have a lasting impact upon both the fundamental understanding and applications of this sensor technology.

The editors are very grateful to Dr Tong Sun for her tireless efforts in typesetting this manuscript from the authors' original material and in preparing the diagrams from a wide range of sources for publication.

The editors hope that the readers of this fifth volume in the *Optical Fiber Sensor Technology* series will find, together with the companion four volumes, a valuable source of reference and information in what is a comprehensive series on devices, applications and systems.

Contents

1

Multimode Optical Fiber Sensors

G. R. Jones, R. E. Jones and R. Jones

1.1 INTRODUCTION

Multimode optical fiber is widely used in a range of sensor systems. Such multimode optical fiber sensors have advantages of:

- operating with substantial optical power over moderate distances inexpensively;
- utilizing the multiplicity of propagation modes within the fiber for sensing purposes;
- providing a means of sensing spectral signature changes over considerable wavelength ranges;
- relatively large dimensions so improving tolerances with respect to end effects and interconnections.

Thus whereas multimodal and polychromatic effects may lead to dispersion-based limitations to the high data rate demands of telecommunications, they may be used to advantage for sensing systems operating at lower data rates ($\leq$ MHz).

Since phase and polarization are not easily maintained in multimode fibers, the transmission of sensor information through the fiber needs to be by light intensity variations (although the sensing elements themselves may provide phase or polarization information). As a result, the evolution of multimode fiber sensing is concerned with:

- producing various intensity modulation sensor outputs for transmission (including phase and polarization modulating elements);
- overcoming the problems associated with the lack of intensity conservation in optical fiber systems.

Arguably multimode optical fiber sensors are capable of deployment for measuring a greater variety of measurands than other fiber systems, encompassing not only physical parameters (e.g. pressure, temperature etc.) but also chemical (e.g. impurity contamination etc.) parameters and non specific parameters (e.g. color, acoustical vibrations etc.). Both analog and

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digital systems are available and their cost effectiveness for bulk applications has long been recognized [1].

The approach taken here is to establish the performance criteria and to formalize a general systems description within which framework transducer, data acquisition and signal processing requirements can be considered. These are discussed in section 1.2. Section 1.3 considers the implications of the system requirements upon the optical source and fiber transmission. Some important optical modulation principles are considered in section 1.4. Section 1.5 relates to signal processing and system architecture matters, whilst the present state of the technology and its future potential are is summarized in the conclusion

1.2 FORMAL SYSTEMS APPROACH

The systems approach to fiber sensing needs to establish how the system performance is to be judged and how the various system components interact to affect the overall performance. The former aspects may be addressed through specific performance criteria, whereas the latter require the formulation of a mathematical model from which the coupling of various terms representing the different components can be identified.

1.2.1 Performance criteria

The performance criteria for a measurement system may be identified from a consideration of the characteristic which relates the output of the measurement system to the measurand value (fig. 1.1). These are the sensitivity, noise, signal-to-noise ratio, resolution, dynamic range and accuracy. Consideration is also needed of transient response.

1.2.1.1 Sensitivity

The sensitivity (or scale factor), s, is the proportionality between the input (measurand) and output of the measurement system, i.e.

$$V_0 = sx \qquad (1.1)$$

where V_0 is the output of the measurement system (e.g. volts) and x is the measurand value (e.g. pressure in pascals). Ideally, s should remain constant over the entire operating range of the transducer and should be independent of external conditions such as environmental temperature. Variations in s

for a given system are known as 'fading'. However, the value of s may be changed for different systems by varying either the transducer designs or system operation (section 1.2.2).

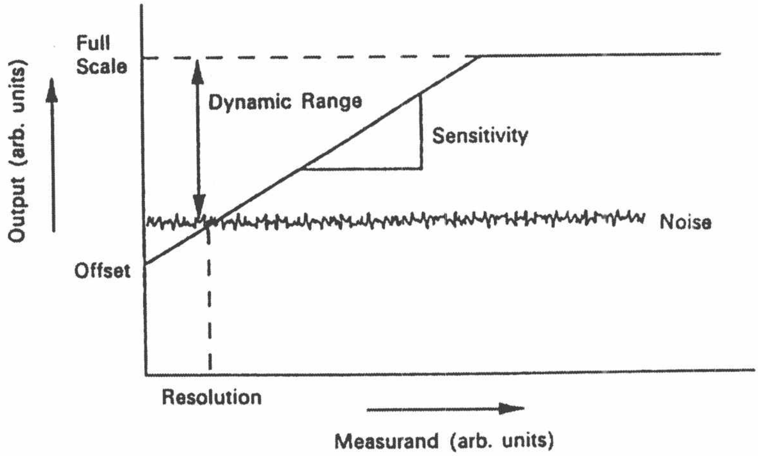


Figure 1.1. Relationship between sensor parameters

1.2.1.2 Noise

In electrically-based measurement systems, a fundamental limitation is due to electronic noise produced either in resistors or active devices, or by electromagnetic pick-up via connecting leads.

A noise is characterized by its frequency spectrum $V_n(f)$ (units $VHz^{-1/2}$). Two important cases are Johnston noise (produced by random electron motion in resistive elements) and flicker noise. The former is independent of frequency whereas the latter is inversely proportional to frequency (fig. 1.2). $V_n(f)$ at a given frequency is the sum of all noise components $\sum V_n(f)$. Thus the total r.m.s output noise voltage from a system is

$$V_n = \int \left[\sum V_n(f) \right] df \qquad (1.2)$$

which corresponds to the area under the curve of fig. 1.2.

This is merely a formalization of the fact that the r.m.s noise voltage depends upon the bandwidth (frequency range) of the measurement. For instance, for a system with only Johnston noise at 10 $nVHz^{-1/2}$ (fig. 1.2) the r.m.s. output noise for a bandwidth up to 100 Hz would be 100 nV and would increase to 316 nV for a bandwidth up to 1 kHz.

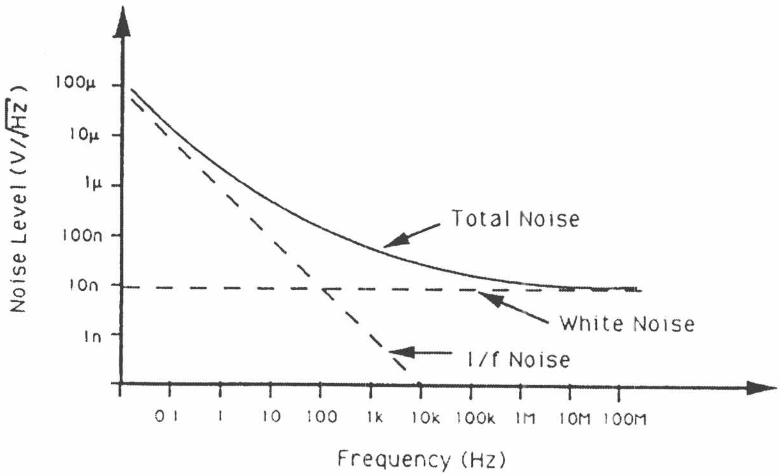


Figure 1.2. Spectra of white and 1/f noise

The discrimination of a signal against a noise background is quantified by the signal-to-noise ratio (S/N)

$$S/N = \frac{V_0}{V_N} = \frac{sx}{V_N} \tag{1.3}$$

1.2.1.3 Resolution

Clearly, the above noise considerations govern the smallest change in a measurand which a system can discern or resolve.

Thus the system resolution (R_s) is the value of the measurand which produces an output voltage equal to the noise voltage. From equation (1.3)

$$R_s = \frac{s}{V_N} \tag{1.4}$$

Since V_N is bandwidth dependent the implication of equation (1.4) is that for a fixed sensitivity s, resolution can only be improved at the expense of transient response.

1.2.1.4 Dynamic range

At the other extreme of the measurement range is the highest output signal that may be limited either by the transducer (e.g. length of travel of a displacement transducer), the system (e.g. output voltage reaching the supply rail) or the user requirement (e.g. unacceptable departure from linearity). This represents the full scale (FS) of the system. Thus the scale length which is available for measurement is the ratio between the full-scale and the noise voltage (fig. 1.2). This is known as the **dynamic range** and may be written as:

$$\Delta R = \frac{(FS)}{V_N} \tag{1.5}$$

1.2.1.5 Accuracy

The accuracy of a measurement system is the extent to which the output deviates from that of a calibrated standard. Thus although accuracy is related to the resolution of the system, the accuracy will in general be poorer than the resolution.

1.2.2 Formal representation of a fiber system

To relate the performance criteria described above to an optical fiber measurement system it is necessary to establish a formal theoretical description of the system. The general structure of such a system is shown in fig. 1.3. It consists of an optical source, optical fibers, a modulator element (which transduces the measurand to an optical signal), an optical detector and processing electronics. The output voltage, V_o, of the system depends upon the optical properties of each system component combined according to the mathematical expression

$$V_o = q\left\{\sum_{l,m} \int_\lambda \left[\int_l p(\lambda)F(\lambda)M_2(\lambda)dl \right] M_l(\lambda)R(\lambda)d\lambda \right\}^P \tag{1.6}$$

where $P(\lambda)$ is the spectral power distribution of the source, $F(\lambda)$ is the spectral transmission of the optical fiber, $M_l(\lambda)$ is the spectral modulation produced by the sensor element, and $R(\lambda)$ is the spectral responsivity of the detector. The optical signal may be polychromatic in nature, hence the need for integration with respect to wavelength λ. Propagation may occur over variable lengths of transmitting fiber, so integration of fiber-related aspects needs to be over the fiber length, l. In addition, the multimode nature of the fibers requires summation over all propagation modes designated by l, m (section 1.3.3). Intermodal power exchange caused by system components (connectors, modulator etc.) is taken into account by the factor $M_2(\lambda)$. The parameter q represents electronic signal processing effects of the circuitry which provides the voltage output V_o. The proportionality between voltage output and received optical power (which is the term in curly brackets) may be nonlinear, which leads to the exponent P.

Equation (1.6) provides an insight into several aspects of fiber monitoring. It embodies not only power conservation considerations but also spectral information which can be used for optimizing the spectral matching of components.

A special case which leads to a simplified description and which corresponds to an optical system which is most closely analogous to an electronic system involves intensity modulation with monochromatic light ($\lambda=\lambda_1$) and monomode fibers ($m = 0, l = 1$).

Here the amplitude of $M_1(\lambda_1)$ is proportional to the measurand X_i, i.e.

$$X_i = q_m M_1(\lambda_1) \tag{1.7}$$

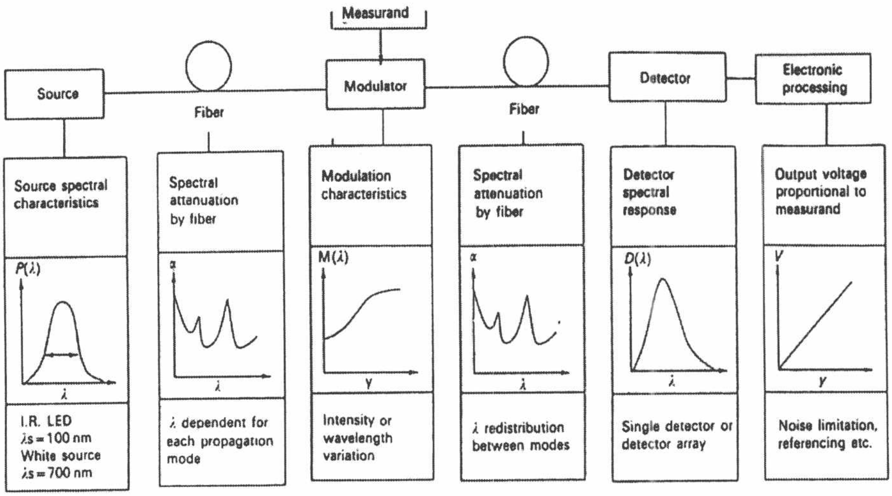
with the additional assumption that $P = 1$, equation (1.6) reduces to a power budget expression from which the system sensitivity (eq.(1.1)) is more easily determined:

$$s = qP(\lambda_1)F(\lambda_1)M_2(\lambda_1)q_m R(\lambda_1) \tag{1.8}$$

This expression has several implications with regard to system limitations.

The ultimate resolution (section 1.2.1.3) is determined by additive electronic noise in the receiver via the parameter q. For a photodetector sensitivity of 0.5AW^{-1}, a transimpedance amplifier with a feedback resistor of $1\text{M}\Omega$, a bandwidth of 1 kHz and an input current noise density of 0.2 $\text{pAHz}^{-1/2}$ (section 1.2.1.2), the minimum detectable change in optical power is 1.2 pW. Hence, for a typical received optical power of 1.2 μW the intensity resolution predicted is 1 in 10^6. In practice, it is difficult to achieve this level of resolution with intensity modulation. In the shot noise limit, increasing the intensity of the received signal is not advantageous since the shot noise is proportional to intensity.

However, in practice the dominant limitations are due not so much to q but to the fiber transmission, $F(\lambda)$, and fiber-related effects $M_2(\lambda)$. Firstly, changes can occur to these parameters due to aging or environmental temperature variations which produce fading (section 1.2.1). Secondly, although fiber systems are immune to electromagnetic interference, they are instead susceptible to mechanical noise and fluctuations caused by fiber microbending. It is the fading and fiber noise susceptibility which constitute the greatest barrier to the commercialization of optical fiber sensors and much research is concerned with overcoming these deficiencies.



$$\left\{ \sum_{lm} \int_{\lambda} \int_{t} P(\lambda) \cdot F(\lambda) \cdot M_1(\lambda) \cdot M_2(\lambda) \cdot R(\lambda) \mathrm{d}/\mathrm{d}(\lambda) \right\}^{P} \quad q = V$$

Figure 1.3. Structure of a multimode fiber sensor system

In the case of the more general formulation (equation (1.6)) the situation is made more complicated not only by the complex integrated interdependence of the component parameters ($P(\lambda)$, $F(\lambda)$ etc.) but also because of the intermodal coupling via $\sum_{lm}$. The implication of this is that it is impossible to obtain a universally applicable simple analytical expression for the sensitivity, s. Instead equation (1.6) needs to be evaluated for each individual case and this involves detailed knowledge of not only the modulator characteristics but also each system component. It is for this reason that a rigorous systems description is essential for considering multimode fiber sensors.

Such an approach provides a powerful basis for exploring possible methods for overcoming system limitations of the type indicated above. It enables system components to be better optimized with regard to matching the spectral transmission windows of the interconnected optical elements of the system. It also allows various signal multiplexing (e.g. wavelength based) and system architecture possibilities to be assessed. The remainder of this chapter is based upon the implications of equation (1.6) for such considerations. The approach taken is to consider the mathematical form of each of the components representing parameters in equation (1.6) separately.

1.3 SOURCE AND FIBER EFFECTS

1.3.1 Spectral emission of source (P(λ))

The use of multimode sensors is, in general, less restrictive with regard to the type of optical source used than in the single mode case, so the mathematical form of the parameter $P(\lambda)$ may differ significantly depending upon systems and sensor requirements. Two simplifying extreme cases may be identified which correspond to a purely monochromatic source and an ideal white light source respectively. In the former case

$$P(\lambda) = P(\lambda_1) \tag{1.9}$$

so the wavelength integration in equation (1.6) becomes redundant, leading, for monomode propagation, to equation (1.8).

At the opposite extreme, corresponding to an ideal white light source,

$$P(\lambda) = p \text{ constant} \tag{1.10}$$

so equation (1.6) reduces to

$$V = q\left[\sum_{l,m} P \int_{\lambda}\left(\int_{l} F(\lambda)M_2(\lambda)dl\right)M_1(\lambda)R(\lambda)d\lambda\right]^p \tag{1.11}$$

In practice equation (1.8) is a good approximation for systems activated by laser sources, whilst there are situations in which equation (1.11) can apply to broadband sources. This latter category includes tungsten halogen, conventional LED and 'white light' LED sources. Conventional LED sources refer to moderate spectral width sources up to about 100 nm. Tungsten halogen sources are extremely wideband ranging from about 450 nm to the near infrared at 1.1 μm; they have proved to be reliable for providing a very wide spectral output with high spectral stability and capable of energizing up to eight sensors economically. The most recent addition to this group of broad band sources is the white LED covering the intermediate spectral range from 400 - 600 μm with a pronounced emission at the shorter wavelengths (figure 1.4). Early indications are that such sources have good power output, spectral stability and aging characteristics without the infrared heating effects of the tungsten halogen source, making them good candidates for optical fiber spectral and chromatic modulation systems.

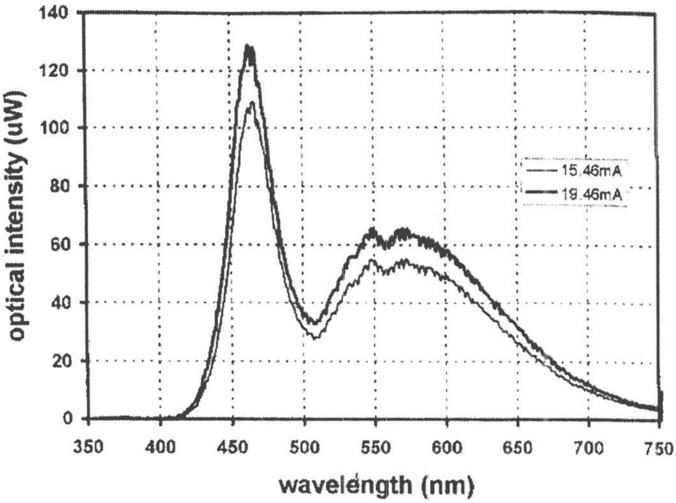


Figure 1.4. Change in spectrum of white LED with forward current

1.3.2 Wavelength-dependent fiber attenuation (F(λ))

The parameter F(λ) (equation (1.6)) takes account of both the attenuating and optical filtering action of the optical fiber and as such embodies the influence of several physical processes. These include the effect of Rayleigh scattering due to the structure of the optical fiber material, the optical absorption due to particular ionic/molecular impurities (such as OH) and residual effects such as losses associated with fiber bending (fig. 1.3). Conventionally these effects are incorporated via an attenuation coefficient and defined by (e.g. [2])

$$F(\lambda) = F_o \exp(-\alpha l) \qquad (1.12)$$