TECHNOLOGICAL AND METHODOLOGICAL ADVANCES IN MEASUREMENT

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AKADÉMIAI KIADÓ, BUDAPEST

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ACTA IMEKO 1982

Proceedings of the 9th IMEKO CONGRESS of the International Measurement Confederation held from the 24th to the 28th May 1982 Berlin-West

VOL. II.

MEASUREMENT OF MECHANICAL AND PHYSICAL QUANTITIES, METROLOGY

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AKADÉMIAI KIADÓ, BUDAPEST 1983

ISBN 963 05 3256 5 (Series)
ISBN 963 05 3258 1 (Vol. 2)

Joint edition published by Akadémiai Kiadó, The Publishing House of the Hungarian Academy of Sciences, Budapest, Hungary and North-Holland Publishing Co., Amsterdam, The Netherlands

Printed in Hungary

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Plenary Lectures
Liquid and Flow Measurement
Measurement of Electrical Quantities
Analytic Measurements
Bio-Medical Applications
Standards, Metrology

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PLENARY LECTURES

APPLICATIONS OF FIBRE-OPTIC WAVEGUIDES IN THE MEASURING ART

by

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Abstract: Fibre-optic waveguides are of threefold interest in the measuring art: 1. In conventional measuring systems they are capable of noise-immune transmission of digital data at large bitrates.
2. To measure their properties (attenuation, bandwidth, etc.), completely new equipment has to be developed.
3. Sensors of both simple and sophisticated design for measuring various physical quantities (mechanical forces, temperature, electric current, rotation, etc.) can be built using fibre-optic waveguides.

Keywords: Optical fibres, data transmission, fibre property measurements, fibre-optic sensors

1. Introduction

During recent years fibre-optic waveguides have become increasingly interesting as a transmission medium for communications due to their attractive properties:

- long repeaterless links
- large transmission bandwidth
- thin, flexible, lightweight cables
- no electrical interference or crosstalk
- electrical isolation, no ground-loops.

Most of these properties are also desirable in both measuring and control systems where the noise-immune transmission of digital data is important. With fibre-optic waveguides the bit rates and transmission distances can be much larger than in conventional systems (Fig. 1) and problems with ground-loops, shielding and high voltage differences are avoided. In addition, sensors for analog measurement of various physical quantities (mechanical forces, temperature, electric current, rotation, etc.) can be built using fibre-optic waveguides.

2. Optical fibres as a transmission medium

There are mainly three types of fibre-optic waveguides:

step-index fibres
graded-index fibres
monomode fibres.

They all consist of a core made of low-loss glass that is surrounded by a cladding of glass with a slightly lower refractive index and a typical outer diameter of 100...250 μm. In step-index fibres the core diameter is 50...200 μm, which is much more than the optical wavelength of about 1 μm, and light is guided within the core by total internal reflection. These fibres are widely applicable in simple and low-cost systems, and sometimes they are made of cheap glass with a medium loss of 10...20 dB/km. Their main disadvantage is their limited bandwidth-length product which is 50·MHz km at most. In graded-index fibres this problem is solved by a parabolic refractive index profile in the core region which allows bandwidth-length products of up to 1 GHz·km. As these fibres are made of high-quality glass, their typical loss is 2...5 dB/km at optical wavelengths below 1 μm, and less than 1 dB/km at 1,3 μm. A further improvement of bandwidth-length product is possible by reducing the core diameter to a few microns. Fibres of that type carry only a single propagation mode and are called monomode fibres. They are used for wideband long-distance transmission and for sophisticated sensors.

Two types of light sources are used in fibre-optic systems: light emitting diodes (LED) and laser diodes. The optical wavelength of these sources is usually between 0.8 and 0.9 µm, but recently sources for 1.3 µm have been introduced to utilize the low fibre attenuation in that region. With LEDs an optical power of 10...100 µW can be launched into graded-index fibres, and slightly more into step-index fibres. (A special case is that of thick-core step-index fibres that are used for short-distance transmission. These are capable of collecting several mW from LEDs.) From laser diodes several mW can be launched into graded-index fibres, as the radiance of these diodes is much higher than that of LEDs. In addition, the radiation of laser diodes is highly monochromatic and coherent, and they can be modulated at extremely high bit rates ($>$ 1 GBit/s).

In fibre-optic receivers either PIN-photodiodes or avalanche photodiodes are used. Due to their high sensitivity optical powers of a few nanowatts are sufficient for receiving digital signals. As this is much less than the power launched by the transmitter, fibre lengths of several kilometers can easily be bridged. Fig. 1 shows some examples for low-cost data transmission links with LED and PIN-diodes. (The dashed lines show the influence of a 10 dB reduction in receiver sensitivity.) In telecommunication systems more expensive equipment is used which allows both longer repeater spans and higher bitrates. Fibre-optic transmission systems need not only be point-to-point connections of one transmitter and one receiver, but also complex networks of numerous transmitters and receivers (Fig. 2). This is possible by adding optical tapping and branching elements and allows, for example, the use of fibre-optic transmission in distributed process control systems.

3. Measuring optical fibre properties

If optical fibres are used in practice, their properties, e.g. mechanical dimensions, attenuation and bandwidth, have to be known. Initially, measuring these properties caused a lot of problems that could not be solved by conventional measuring equipment. New methods had to be developed and these fall mainly into two classes. In the first class (Fig. 3a) light is launched into one end of the fibre and measured at the other end, whereas in the second class (Fig. 3b) launching and measuring is done at the same end.

The most important end-to-end method is attenuation measurement: White light from an incandescent lamp is filtered by a variable monochromator and launched into the fibre. From the optical power at both fibre ends the attenuation of the fibre can be calculated. The main problems of this method are the choice of suitable launching conditions and the detection of very low light levels. With modifications, this method can also be used to measure other fibre parameters e.g. core diameter and refractive index profile. For bandwidth measurement a laser diode is used as an optical source that emits short pulses of high peak power. While travelling down the fibre these pulses are both broadened and distorted and this is observed by a wideband detector. By mathematical analysis of the received pulse shape not only the bandwidth of the fibre but also detailed information about its complex transfer function is obtained. In addition, the fibre length can be calculated from the delay of the observed pulse.

Measurements of the second class (Fig. 3b) need access to one fibre end only and are therefore especially important for testing optical fibre cables during and after installation. They are based on backscattering: A small fraction of the optical power of a pulse travelling down the fibre is scattered in the reverse direction from every point of the fiber and is observed at the launching end by means of a beam splitter.

From the temporal behaviour of the backscattered light information is obtained about total fibre attenuation, distribution of attenuation along the fibre, position and loss of connectors and splices, and fibre length.

4. Optical fibres as sensors

Some of the fibre properties can be influenced from outside, and if these properties are measured in a sensitive setup, the fibre will act as a sensor. One example is the increase of attenuation by mechanical bending or undulating of the fibre. By adding simple mechanical devices this can be used to measure mechanical pressure or vibration, mechanical forces caused by magnetic fields or temperature changes, and similar effects. Another example is the elongation of fibres under tensile stress which can be sensed via the delay of pulses transmitted through the fibre. Optical fibres can also be used as light barriers: Light is fed from one fibre into another and in the separating gap between the two endfaces an opaque medium, liquid or solid, is inserted or removed.

Whereas the sensors just mentioned are relatively simple and can be made of multimode fibres and incoherent optical sources, e.g. LEDs, there is yet another group of sensors. These are much more sophisticated and operate with monomode fibres and coherent light from laser diodes.

One example is the group of sensors that use changes in the polarization of transmitted light due to either elasto-optic birefringence (mechanical forces) or the Faraday effect (magnetic fields). Other sensors are built as interferometers. A typical example is the Mach-Zehnder interferometer (Fig. 4) consisting of two nearly identical fibres. One of these fibres is exposed to the physical effects to be measured (mechanical forces etc.), the other is isolated from them. By means of beam splitters light is symmetrically launched into both fibres and recombined at the far end of the fibres. If the effect to be measured is stationary, a stable pattern of interference fringes is obtained, but each change can be sensitively observed as a movement of these fringes. Another example is the Sagnac-interferometer for sensing mechanical rotations. A long monomode fibre is wound on a coil and is fed symmetrically from both ends. The two waves are recombined after having travelled through the coil in opposite directions and form an interference pattern which is stable as long as the coil is not moved. A rotation of the coil causes a phase shift between the two waves and this effect is so sensitive that rotations slower than the earth rotation can be measured.

Presently most of these sensors are in the development stage and some of them are rather complicated. For the future it is hoped that progress in integrated optic techniques will lead to new components which can help to build compact and reliable fibre-optic sensors for practical use.

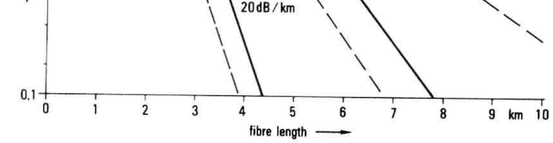

Fig. 1 Achievable bitrate vs. fibre length for point-to-point links with LED transmitters and PIN receivers

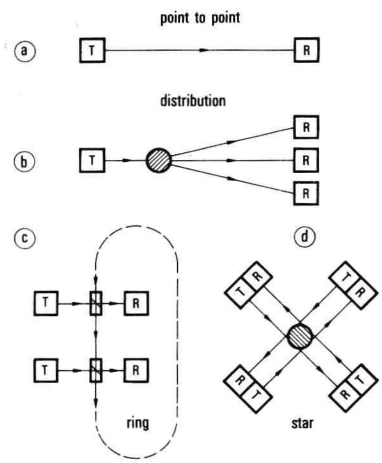

Fig. 2 Structures of fibre-optic transmission systems

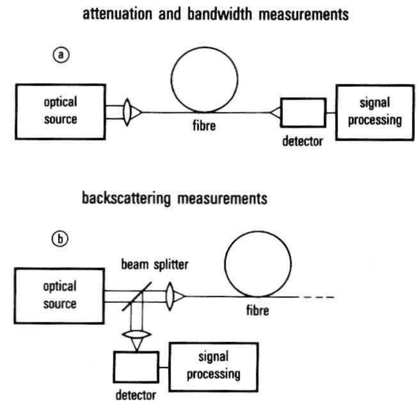

Fig. 3 Principles of measuring optical fibre properties

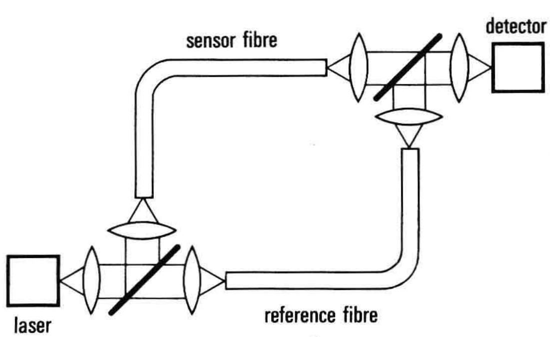

Fig. 4 Fibre optic Mach-Zehnder interferometer