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FIBER OPTIC SENSORS

Joachim Hesse and W. Sohler

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2. Fiber Optics Sensors with Multiwave Fibers

2.1 "External" fiber optics sensors

The optical sensor itself is an "external" component which is supplied with light through a glass fiber and which is "interrogated" through a second fiber. In most cases, here the "external" optical sensor varies the transmission in the supply fiber/signal fiber pathway. A simple light barrier, the position of which is detected with optical fibers, can thus be termed an optical sensor of this type. It is utilized for position determination or for measurement of fill status.

A reflecting membrane which hooks up the pressure - dependent light from the supply fiber with the signal fiber is a further example [2]. This kind of sensor, even with fiber bundles, still remains so small that, installed in a catheter, it makes possible pressure /90
measurements within the living heart [3]. Fluid crystals [4] or semi-conductors [5] between the two fibers serve for temperature determination; thereby use is made of the fact that the arrangement of the fluid crystal and the spectral location of the band-edge absorption of the semi-conductor are temperature dependent. Very small and sensitive sensors have then already been manufactured; a possible area of application is hyperthermal cancer therapy [6]. A phosphor optically activated by UV light through the supply fiber can also be termed an "external" optical sensor. Its temperature-dependent luminescent radiation is conducted out through the signal fiber and analyzed to determine temperature [7]. A device with this kind of a sensor is already commercially offered in the USA; the almost punctiform measuring with disappearing heat capacity makes possible quite a variety of applications.

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The actual optical sensor, in the case of this class, is a specially treated segment of fiber between the supply and the signal fiber. It can be a "naked" fiber section (consisting of the fiber

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SUMMARY /89*

As always, there exists a great demand for new and improved sensors. The requirements set for them are above all reliability, insensitivity to interference by electrical fields and a reasonable price. One of the most recent developments in this direction is the fiber optics sensor, a by-product of light guide technology. Meanwhile, ways have been found with which one can in this way measure all kinds of physical values, in some cases with extraordinarily high accuracy. This area has already become quite complex; this paper is intended to provide a survey of the field.

1. Introduction

The significant progress in the manufacture of low attenuation glass fibers has made a decisive contribution to the development of fiber optics sensors [1]. A fiber optics sensor is an optical detector which is supplied with light through a glass fiber, and which conducts an optical signal, suitably coded according to the measured magnitude, to a detector, and thereby to signal processing with displays or regulators, this being done through another fiber (which under certain circumstances can be identical to the supply fiber), (Figure 1).

In this way, one exploits, for one thing, the advantages of optical signal transmission through glass fiber cables which are also more and more being put to work in commercial transmission routes.

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The insensitivity of optical transmission circuits to electromagnetic field interference and their isolation from electrical potentials have here the greatest significance for fiber optics sensors. In addition, the use of an optical sensor makes possible the direct conversion of the measured magnitude into an optical signal without a second electro-optical conversion as in the case of electronic sensors with optical signal transmission. Moreover, (fiber) optical sensors open up new capabilities for measurement; in many cases they can be more accurate, more rugged and cheaper than the usual electronic sensors.

The term "fiber optics sensor" nevertheless does not describe a completely unitary concept: The actual optical sensor (Figure 1) can, for example, "externally" modulate, as a function of the measured magnitude, the transmission in the supply fiber/signal fiber pathway; but it can also be "internally" a part of a specially prepared fiber. While most of these sensors are made with multiwave fibers (multimode), there are also fiber optics measurement systems with single-wave (monomode) fibers--in general of complicated design. In the latter, the phase location or the polarization state is changed by the effect of the measured magnitude on the fiber, while, in the sensor with multimode fibers, the light amplitude (and thereby the intensity) is usually a function of the measured amplitude. These two types of fiber optics sensors will be presented below, using some examples.

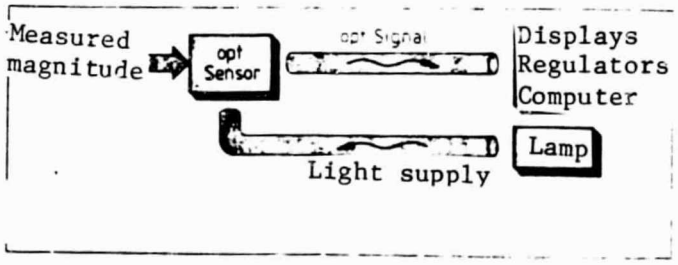

Figure 1. Schematic representation of a fiber optics sensor.

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core only), the aperture of which, and hence the transmission, is dependent on the refraction index of the surrounding medium. Such a sensor is suitable for the determination of the level of a liquid [8] and/or for the measurement of its refraction index (Figure 2) [9]. Another example is represented by a segment of fiber which is deformed by an external force. Thus are created curvature losses (light decoupled from the fiber) which are a measure of the applied force (or pressure) [10]. Such a sensor also makes possible indirectly very exact measurement of a displacement. In addition, there are fibers specially doped (for example with ions of rare earths such as neodymium and europium) whose optically activated luminescence and transmission are a measure of temperature [10].

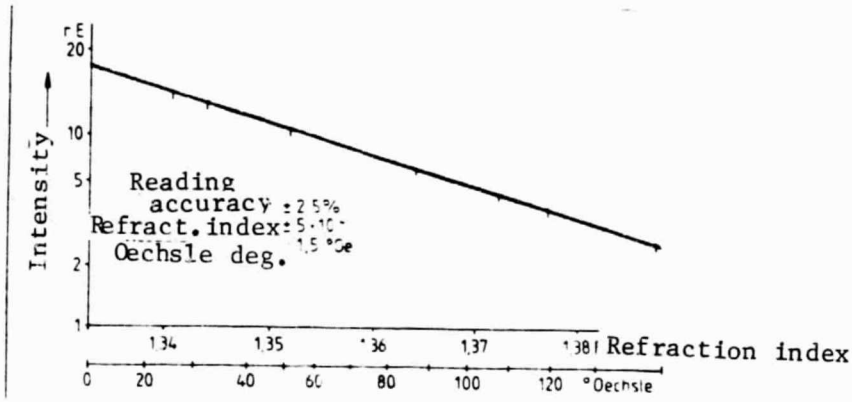

Figure 2. Light stream of a fiber optics refractometer as a function of refraction index or of sugar content (Oechsle degree) of a solution.

3. Fiber Optics Sensors with Monowave Fibers

This group of sensors, the sensitivity of which increases proportional to the length of the measurement fiber, has in recent times been further developed with particular intensity [11]. In this way measurement sensitivity has been enormously improved through the employment of ever longer fibers, possibly due to their extremely low attenuation up to < 1 dB/km. Many of these sensors (or sensor systems) promise to become interesting with respect to their performance and their price.

3.1 Mach-Zehnder and Michelson Interferometers

With a fiber optics Mach-Zehnder interferometer (Figure 3), temperature differences [12], changes in length [13] and pressure differences [12] can be detected with particular sensitivity as a phase difference between measurement and comparison fiber. For example, a fiber optics hydrophone with long fibers attains such a high sensitivity that one can measure "sea state zero", the frequency dependent background noise in underwater sonar technique [14]. Here it is of great interest that, on account of the flexibility of quartz glass fiber, sensors and sensor systems with directional characteristics can be built.

By means of a special "coating" of the fibers it is possible not only to increase the sensitivity of pressure measurements [15]; but it also makes possible measurement of other magnitudes such as magnetic field and current which do not directly affect the phase position of the light in the quartz glass fiber (there is an exception in the case of large magnetic fields and special sensor arrangements due to Faraday effect; see also Paragraph 3.4). For example, the measurement fiber can be coated with a magnetostrictive material (e.g., nickel) [16] which when in a magnetic field exercises forces on the fiber which then gives rise to changes in length and in refractive index. The corresponding phase change can be easily measured. In experiments sensitivities of 10^{-7} Oe/meter of fiber

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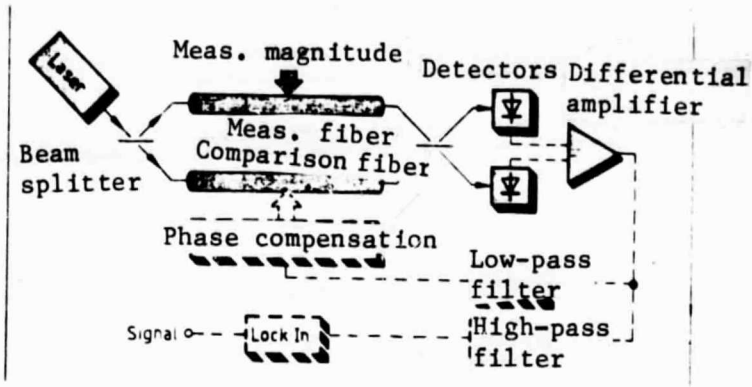

Figure 3. Design of a fiber optics Mach-Zehnder interferometer.

length have been attained [17]. Through the known relationship between magnetic field and current (e.g., in a coil), the current strength can then be determined. The induced phase difference can amount to up to 100 rad/A x meters of fiber length. Sensors have /91 been manufactured with 10 cm long fibers which show a linear relationship beween sensor signal and current strength in the range between 0.5 μA and 5 mA [17].

A further possibility for measuring current strength consists in the analysis of a corresponding change in temperature. For this, the current is conducted directly to the measurement fiber by a metal coating. The temperature change generated thereby again varies the optical length of the measurement fiber, thus produces a phase change proportional to the current strength. At 1 Hz sensitivities were achieved of 100 rad/A x meters of fiber length and at 100 Hz still 1 rad/A x meters fiber length [17].

All these measurement capabilities are also present with a fiber optics Michelson interferometer which operates with reflective fiber ends (Figure 4). In many cases with this a simpler, more compact sensor is possible.

3.2 Sagnac Interferometer (fiber optics gyroscope)

One of the most extensively developed fiber optics sensor systems is a gyroscope which analyzes as a measurement value the angular-velocity-dependent phase difference between the oppositely directed light waves in a fiber optics Sagnac interferometer [34,35]. The sensitivity of the gyroscope can be immensely increased by the use of longer fiber lengths on account of the extremely small attenuation in modern quartz glass fibers. Today detection sensitivities have already been attained which permit measurement of the rotation of the earth. Despite these impressive results, we are still a long way from the theoretically possible detection limit of the fiber optics gyroscope. Estimates have shown that sensitivities of up to around 10^{-3}°/hr should be possible [20]. For this reason, the fiber optics gyroscope will certainly soon start competing with the expensive mechanical gyroscope systems which are many times more costly.

3.3 Wave-guide resonators

A special kind of interferometric measuring instrument is the fiber resonator (Figure 6) [21]. It semi-integrates both arms of the interferometer into itself. It is possible, through the choice of the mirror reflectivity, to set in any desired condition between "two beam" and "multibeam" interference. In this way an increase in sensitivity can be achieved which roughly corresponds to the acuteness of the resonator (to about 100).

3.4 Polarimetric sensors

Polarimetric sensors form a further class of fiber optics sensors with monomode wave-guides. They can be also considered as interferometers which unit both arms into a single fiber. The measurements are of the relative phase differences between the

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orthagonally polarized components of the transmitted light. Thus, the physical field to be measured must generate and/or modify a birefringence in the fiber. Thereby, the sensitivity is normally considerably smaller than with the classical interferometer; but the measurement with a single fiber permits the design of much simpler sensors, for example, for temperature [22] or pressure [23] measurement.

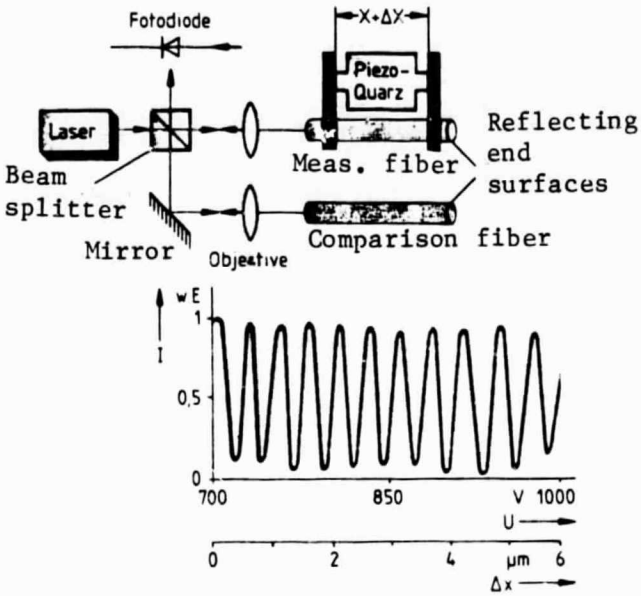

Figure 4. Schematic representation of a fiber optics Michelson interferometer with the experimental results of a rotation measurement.

Also, the rotation of the polarization plane of linearly polarized light in a longitudinal magnetic field (Faraday effect) can be used for measurement of the current. For this, a long glass fiber is wound as a coil around a conductor carrying a current. The rotation of the polarization plane is proportional to the linear integral $\oint \vec{H}\, d\vec{r}$, and thereby to the current strength in /92
the enclosed conductor. Figure 7 shows the comparison of conventional and fiber optics transformers [24]. Prototypes of this kind of sensor have already been installed in power plants for current measurement on high tension lines (no insulation problem) [25].

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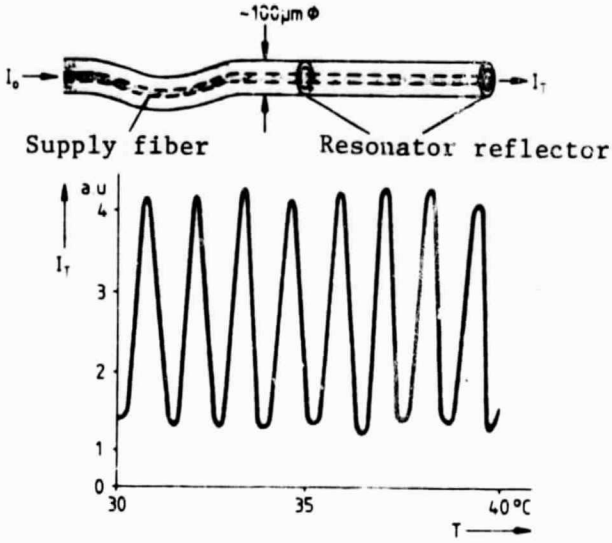

Figure 5. Fiber optics resonator (1 cm long) as a temperature sensor.

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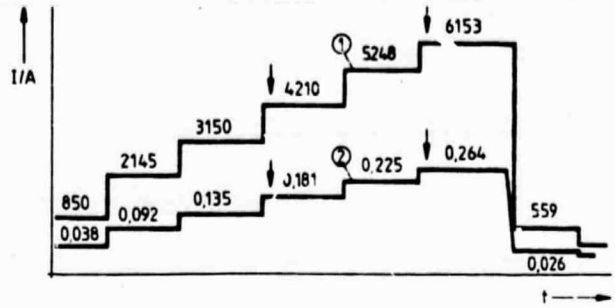

Figure 6. Comparison between conventional [1] and fiber optics transformers with staged alteration of current strength.

4. Outlook

A series of specialized components have been developed for the realization of fiber optics sensors. To be mentioned here are fiber-fiber couplers [26], fiber polarizers [27], fiber phase shifters [28], polarization stabilizers [29] and birefringent fibers [20]. Alongside these of course are used the components already extensively developed in optical signal technology such as semi-conductor lasers, luminescent diodes, fiber jacks, wave length multiplexers, filters and detectors. Also, the components of the integrated optics, which preferably have been developed as monomode structural elements, offer great potential for purely optical or electro-optical signal processing. To be mentioned as an example would be an integrated polarization regulator which can transform an arbitrary polarization condition of the light entering into any other polarization condition at emission [31]. Pure integrated optical sensors have also already been manufactured; an example is the integrated optical spectrum analyzer for very high resolution spectroscopy [32].

With all of these components and with the multiplicity of concepts for fiber optics sensors, a series of useful new measurement devices can be expected in the foreseeable future. Fiber optics gyroscopes, hydrophones, transformers, and temperature sensors already stand on the threshold of industrial use. A wider palette of sensors will follow; their preferred employment will be in electromagnetically disturbed, chemically aggressive or explosive environments.

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Hobbies: Family, Music

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Hobbies: Family, skiing, hiking

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