ANALOG OPTICAL U-SHAPED FIBRE TRANSDUCER BASED ON INDEX MODULATION FOR QUASIDISTRIBUTED SENSING

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I.- INTRODUCTION

Optical time domain reflectometry (OTDR) is a very useful tool used in optical fibre communications and in sensor networks. The cost of an OTDR instrument prohibits sometimes its use in fibre optic sensor networks. Desforges et al[1] presented a scheme that allows the monitoring of 10 to 50 on/off microswitches along a fibre in industrial environments using retroreflected light. Detection of retroreflected rather than backscattered light improves the number of multiplexed sensors[2]. In this communication we present a retroreflecting analog optical fibre transducer for measuring physical parameters by OTDR. This transducer has a U-shaped single curve fibre optic. It is made of silica glass fibres in order to realise long distance measurement capability as well as to provide durable sensors. This transducer is all optical, it does not have any mechanical moving parts. It is analog, not on/off. It is low cost and easy to implement. First, the transducer structure, the principles of operation and preliminary experimental results in a transmissive scheme are presented. Then the transducer in a retroreflective scheme is evaluated. Finally, a prospective of use in quasidistributed measurements employing automated and optimised OTDR techniques is done.

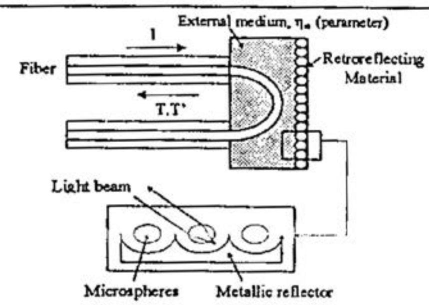

Fig. 1. Retroreflective analog all-optical transducer.

II.- TRANSDUCER DESCRIPTION. PRINCIPLES

Fig. 1 shows the transducer structure and principle of operation in which the fibre is stripped of its cladding along a certain length and the stripped section is further bent into a U shape. A retroreflecting material[3] is placed opposite to the bend. This material is composed of glass microspheres (3M) that reflect the incident optical radiation in a direction that goes parallel to the incident one. Therefore, by introducing between the bent fibre and the retroreflector an external optical medium with a refractive index n_m depending of the measurand, the light can be extracted from the core to the external medium, and then retroreflected into the fibre core, even if the retroreflector is not perpendicular to the incident light. The very low lateral offset between incident and retroreflected rays, due to the very small diameter of the glass microspheres, allows the light to be launched back into the fibre core. Since the critical angle is given by $\psi_c=\sin^{-1}(n_m/n_{co})$, assuming n_{co} and n_m are the refractive indices of the fibre core and the surrounding material, respectively, the light output from the fibre and after launched back into the fiber core is a function of n_m.

III.- TRANSMISSIVE TRANSDUCER: EXPERIMENTAL RESULTS

Transmissive transducer without retroreflection was previouly studied[4], and following that analysis the transmissive transducer was simulated, constructed and experimentaly evaluated. In order to verify its performance in the retroreflective scheme, a transducer using a material with temperature index dependence was made. A 350 µm radius transducer was fabricated with the aid of a conventional fusion splicer, by means of controlling the stress applied to the fibre and the electric arc lapse time. The fiber cladding was removed and covered with silicone and its performance was verified in transmission. The experimental set-up is shown in Fig. 2. The Anritsu MG9002A laser diode launched the light at 820 nm into the transducer placed inside a climatic chamber HIGROS-15.

The output light was measured with a HP8153A power meter. The set up equipment was fully automatically controlled using the GPIB bus by a computer, which also worked as an automatic data acquisition unit. Several series of temperature cycles from 0 to 80 °C, and viceversa were done.

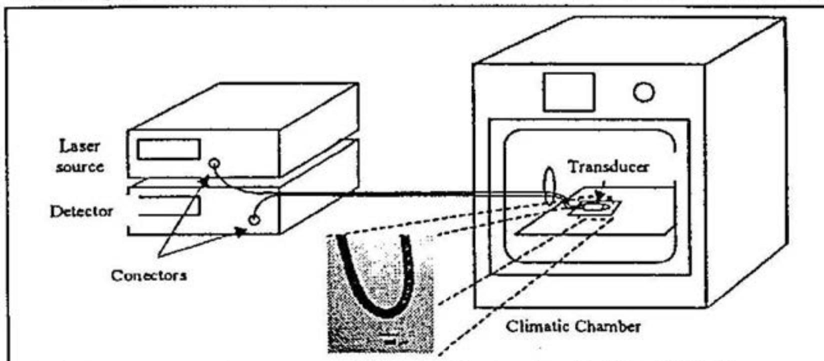

Fig 2. Set up to measure the temperature with the transmision transducer in which a detail of the developed transducer in the climatic chamber is shown.

The experimental results and their comparison with the theoretical ones, both normalised to 0 °C, are shown in the Fig. 3. In this figure the lack of hysteresis in the transducer can be seen. As the refractive index of the silicone decreases when temperature increases, n(T) = 1.4155-0.000475T (T is the temperature in °C), light loss decreases with temperature increments. The bending losses are inversely proportional to the relative increment of indices. Experimental results present a greater temperature dependence, giving a better sensitivity than the theoretical simulations.

IV.- TRANSDUCER THEORETICAL ANALYSIS IN RETROREFLECTIVE SCHEME.

Because multimode fibres are to be used for the transducer fabrication, we can analyse their characteristics using geometric optics methods. For simplicity, the transducer is assumed to have an ideal U shape, to consist of a fibre that is bent into a semicircle stripped of its cladding. The light retroreflected by the sensor head, i.e., the ratio of the retroreflected to the input light, can be obtained by tracing ray paths and calculating the reflectivities at reflection points in the transducer. It was assumed that most of the optical power of each ray is lost in the first point of intersection with the bend, P_1, the reflectivity of the retroreflector is considered to be unity, and the optical media are homogeneous and lossless. After being reflected on the retroreflector this power is launched into the fibre core going backwards to the optical input. By means of the Fresnel coefficients[5] the reflectivity and the optical power that comes out of the fibre in each point is calculated. Following the Snell law and after several complex

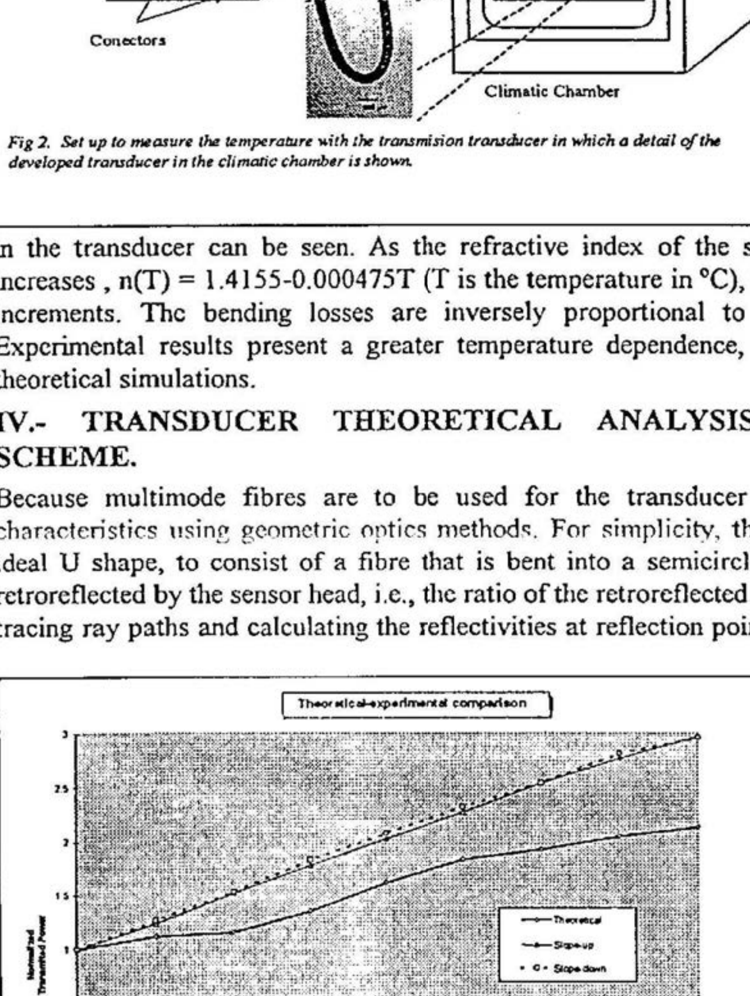

Fig. 3. Theoretical and experimental comparison for the temperature transmission sensor.

algebraic and trigonometric operations the direction vector $\mathbf{r}_i$ of the first refraction (see Fig. 4.a) is calculated as:

$$\mathbf{r}_i = \frac{n_{co}}{n_m} \cdot (\mathbf{s}_i - \mathbf{n}_i \cdot (\mathbf{n}_i \cdot \mathbf{s}_i)) + \mathbf{n}_i \cdot \sqrt{\left(1 - \left(\frac{n_{co}}{n_m}\right)^2 \cdot \left[1 - (\mathbf{n}_i \cdot \mathbf{s}_i)^2\right]\right)} \quad (1)$$

Where $\mathbf{s}_i$ an $\mathbf{n}_i$ are the unitary vectors in the direction of the incident and the normal to the core material interface, respectively. Then, it is possible to calculate the amount of the optical power lost and it is given by the transmitance T. After been reflected by the retroreflector placed at the distance d_i from the fibre bend the optical power that comes from the core in a direction $\mathbf{r}_i$ will be coupled again with an apposite direction $\mathbf{r}'_i = -\mathbf{r}_i$ to the exit one, see Fig. 4b. The reflected light will be incident into the optical fibre, in a point near to P_i. The percentage of optical power that is coupled in the fibre core and its direction after this reflection can be calculated. In a similar way to (1) an expression for the direction vector $\mathbf{s}'_i$ of the second refraction is obtained as

$$\mathbf{s}_i' = \frac{n_{co}}{n_m} \cdot (\mathbf{r}_i' - \mathbf{n}_i' \cdot (\mathbf{n}_i' \cdot \mathbf{r}_i')) + \mathbf{n}_i' \cdot \sqrt{\left(1 - \left(\frac{n_{co}}{n_m}\right)^2 \cdot \left[1 - (\mathbf{n}_i' \cdot \mathbf{r}_i')^2\right]\right)} \quad (2)$$

Where $\mathbf{r}'_i$ and $\mathbf{n}'_i$ are the incident and the normal unitary vectors to the external medium-core interface, respectively. For this new refraction, the Fresnel coefficients are used again to calculate T', obtaining the retroreflected power for each ray as TT'. The scheme for ray tracing in the bend is illustrated in the Fig. 4.a. Assuming that, from a small area dS on one endface of the bend, a light pencil is emitted to the direction represented in spherical coordinates (θ,ϕ). The intensity of this ray is given by $dI = i_r(r) i_\theta(\theta) \cdot dS \cdot d\Omega$, where $dS = r \cdot dr \cdot d\alpha$, $d\Omega = \sin\theta \cdot d\theta \cdot d\phi$, and $i_r(r)$ and $i_\theta(\theta)$are light intensities as functions of r and θ, respectively. Assuming the intensities of the ranges in relation to the spherical coordinates given by

$$i_r(r) = \text{constant}, \quad (0 < r < b) \quad (3a)$$

$$i_\theta(\theta) = \cos(\pi\theta/2\chi_c), \quad (0 < \theta < \chi_c) \quad (3b)$$

where $\cos \chi_c = n_{cl}/n_{co}$, and n_{cl} is the cladding refractive index. Thus, by summing up the light for all rays the expression for the total retroreflection coefficient of the transducer R_R becomes

$$R_R = \frac{\iint T \cdot T' \cdot i_r(r) i_\theta(\theta) dS d\Omega}{\iint i_r(r) i_\theta(\theta) dS d\Omega} \quad (4)$$

This retroreflection coefficient R_R, has been obtained for a step-index 100/140 multimode optical fibre, with n_{co}= 1.457 and a numerical aperture 0.28 as a function of different curvature radius. As it is shown in Fig. 5, the retroreflected power increments as the refractive index of the external medium increases and approximates to the n_{co}. It is verified that for small curvature radius the losses also increase in the transducer. Therefore, an adequate selection of this external medium, this transducer can be applied in the measurement of physical parameters. Particularly, its application to temperature measurement was proved. Fig. 6 shows the variation of the retroreflected power with the temperature using silicone as external material. The same statement is applied to the changing of R_R with the bend radius.

The measurement of this retroreflected light instead of the backscattered by means an OTDR is more advantageous because it introduces a figure of merit M, inversely proportional to the pulse with τ and there is no trade-off between dynamic range and spatial resolution[1], but it presents the drawback of a worst resolution in commercial equipment. At present, we are working on the development of techniques that permit us, by means of getting and processing of the OTDR trace in a computer through the bus GPIB, automatise the measurements and improve the performance of these equipment in the monitoring of both reflective and retroreflective optical fibre sensors networks. Previous results have shown that up to 50 quasidistributed measurement points can be reached with a proper design.

V. CONCLUSION

A retroreflective intrinsic optical fibre probe with intensity modulation for the measurement of physical parameters has been designed. It is based in the bend losses of a multimode optical fibre immersed in a external medium with a refractive index dependent on the mesurand, and a retroreflector. The retroreflected optical power is index dependent and also dependent on the bending radius of the fibre. Its behaviour for the measurement of temperature with silicone as external medium, has been simulated and demonstrated. To increase the sensitivity of the transducer it is important to have an optical fibre without cladding and small bending radius. Experimental results obtained by the transmissive transducer are satisfactory and validate the theoretical model of the transducer.

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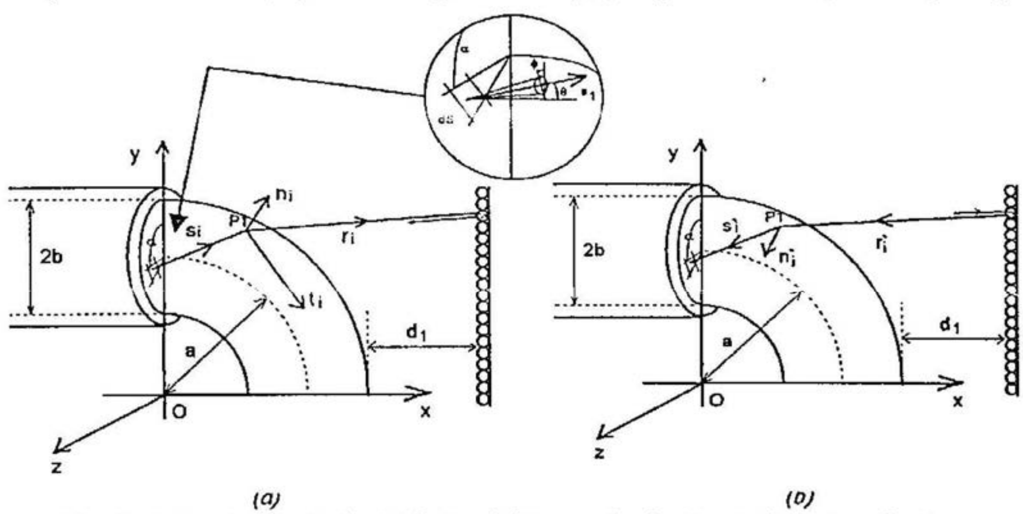

Fig. 4 a,b. Ray tracing in the (a) first and (b) second refraction in the retroreflective sensor.

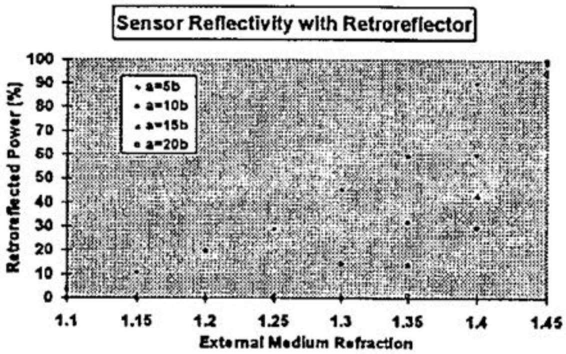

Fig. 5. Retroreflected power vs. refractive index of the external medium for several bending radius.

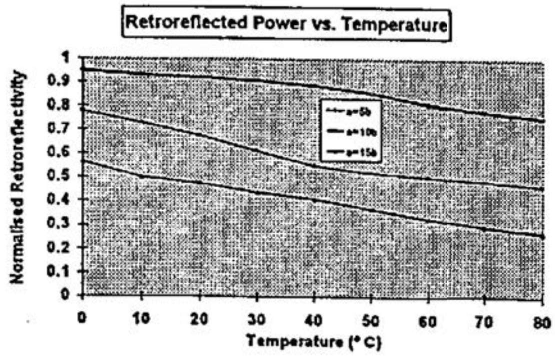

Fig.6. Retroreflected power vs. temperature for silicone.