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# THE DETERMINATION OF THE EFFICIENCY OF OPTICAL FIBRE SENSORS

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The paper presents a calculation method for the determination of the efficiency of temperature probes with optical fibre and fluorescent crystal. An equivalent model is firstly defined, starting from the probe effective structure, based on geometrical optics rules and applying the superposition principle. The computation relations for the value of the fluorescence optical flux collected by the receiving fibre were developed as part of the equivalent model. From the value of the fluorescence optical flux related to the excitation optical flux of the emitting fibre, the optical efficiency of the probe can be obtained. The computation of the effective optical efficiency was made numerically, using a computation program elaborated in MATLAB language. The analysis of the values for the efficiency for a probe with cube shaped crystal allowed to find important conclusions regarding the optimum dimensions of the crystal and the maximum value of the efficiency. These conclusions are useful for getting an optimal temperature sensor.

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## 1. Introduction

The diversity of optical phenomena and the unlimited possibilities of coupling these ones with mechanical, electrical and magnetic phenomena lead to the spectacular evolution of optical fibre sensors. These sensors represent nowadays a field in full expansion, more and more solutions being transferred from laboratory to industry.

Optical fibre sensors are no longer a subject of laboratory research only [1], but a very attractive solution for different industrial applications, because of their advantages: small size, immunity to interference with electrical and magnetic fields, total safety in explosive environments, chemical inertness, intrinsic galvanic isolation.

The general structure of an optical fibre sensor is presented in Fig. 1.

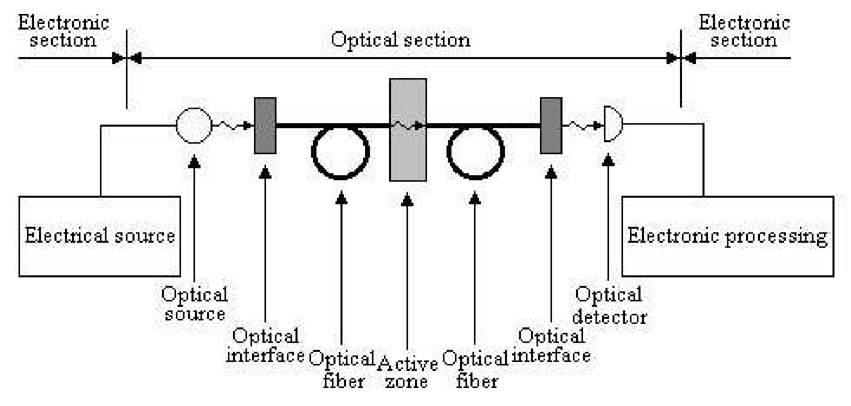

Fig. 1. The general structure of an optical fibre sensor.

Two sections can be delimited: optical section, where the measurement produces the variation or the modulation of one of the light parameters and the electronic section, where the optical modulated signal is converted to an electrical signal which may be further electronically processed. This delimitation is achieved by two interfaces: electro-optical and opto-electronic interfaces, which ensure the coupling of optical transmitter to optical fibre, respectively, the coupling of optical fibre to optical receiver.

There is an active zone in the optical section on which the size of measuring will act, creating changes on the propagation of the light radiation. The active zone may be a section of the optical fibre or other optical medium outside the fibre. That is why is prefered the name of “optical fibre sensors” to other variants as “optical sensors” or “sensor of optical fibres”.

## 2. Computation method of the efficiency of the sensing head by modelling the probe with optical fibre and fluorescent crystal

The active part of the optical fibre and fluorescent crystal probe is the sensing head, which represents the sensor active zone, being in contact with the measured factor (the temperature).

The sensing head consists of a fluorescence crystal volume and one or two optical fibres stickled of this. The optical fibres have the role to perform the excitation optical pumping and to collect the fluorescence radiation emitted in the crystal volume. Until now it was proposed several constructive solutions for the sensing head regarding the positioning of the optical fibres on the crystal. The sensing head has a major contribution to the global energetic balance of the sensor. In Fig. 2 are illustrated the solutions presented in the literature on this subject [2], [3], [4]. The fibres used are made from glass, with gradual variation of the refractive index, and of various diameters, from 100 µm to 1 mm.

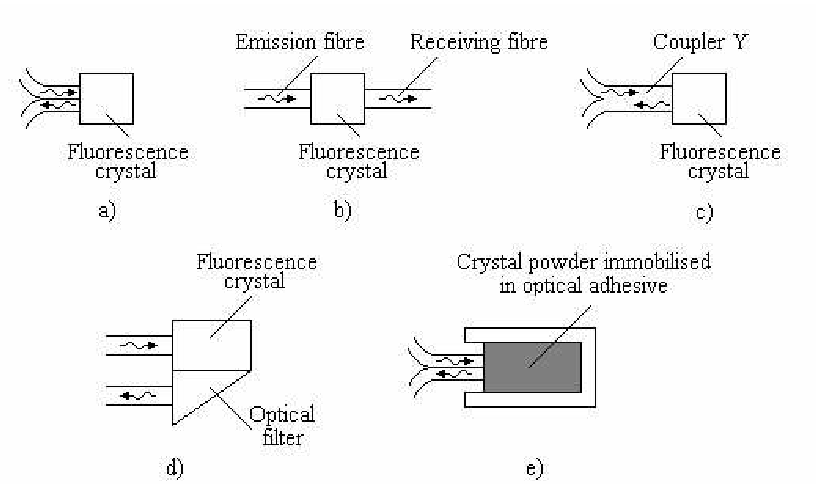

Fig. 2. Sensing head structures: a) with the fibres of the some part of the crystal; b) with the fibres on opposite sides of the crystal; c) with a fibre and coupler Y; d) with optical filter in the sensing head; e) with crystal powder immobilised in optical adhesive.

In the optical section of the sensors using fluorescence, the sensing head has the lowest efficiency. The design of the sensor is, therefore, strongly influenced by the efficiency of the sensing head. Using the method presented in this paper, it is possible to compute accurately the sensing head efficiency, and following this, the optical power of the source required for a safe operation of the sensor. An optimised design of the sensing head and sensor can be done. The computation process includes two steps: the generation of an equivalent model for the sensing head and the computation of the efficiency using the equivalent model.

The equivalent model is built starting from real structure of the sensing head.

In the real structure (Fig. 3) the emissive fibre illuminates a volume of the fluorescent crystal, of the frustum of cone shape, defined by the numerical aperture of the fibre and the crystal refractive index. As a result of the absorption, each point of the illuminated crystal volume emits fluorescence radiation. The emission by fluorescence is isotropic (under a solid angle of $4\pi$). A part of this radiation can be collected by receiving fibre, either directly, $(\lambda_f)_d$, or as a reflection produced on the crystal walls, $(\lambda_f)_r$.

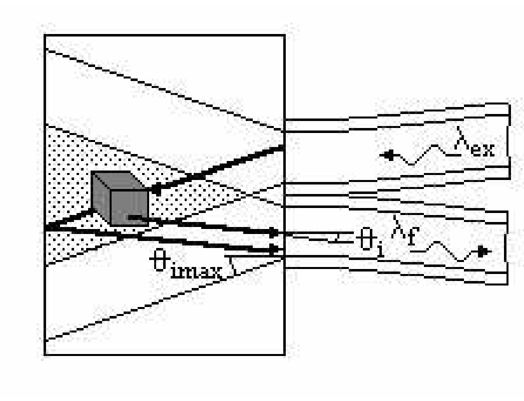

Fig. 3. The fluorescence emission in the sensing head real structure.

In order to be collected and guided to the detector, the fluorescence radiation must be directed on the fibre core, under an incidence angle $\theta_i$ ($\theta_i \le \theta_{imax}$, where $\theta_{imax}$ is the maximal incidence angle defined by the numerical aperture of the receiving fibre). The emergent rays from a point which fulfils the mentioned conditions fills a solid angle, named acceptation solid angle of the fluorescence elementary source, $\theta_{sa}$.

In order to calculate the collected fluorescence optical flux, it must be evaluated the acceptation solid angle value of each point from illuminated crystal volume.

A first stage in the analysis relief is the separation of the phenomena of directly collected radiation reception $(\lambda_f)_d$, from the collected radiation as a result of reflection on the crystal walls $(\lambda_f)_r$. This can be obtained using the effects of the superposition principle and the geometrical optical properties. The fluorescence crystal, whose faces are mirrors of reflectivity R for the radiation within the crystal, is replaced by a homogeneous transparent medium, with the same refractive coefficient as the crystal, in which are placed the fibres. The radiation loss by refraction at the crystal faces is modulated with absorbent screens without thickness and total transmittance T, numerically equal to the reflectivity R. In this medium the emission fibre and receiving fibres are placed in the position established according to the crystal geometry.

Each receiving fibre collects the fluorescence radiation for which the combined optical routes of the excitation light and fluorescence light suffer the same number of reflections. The number of the receiving fibres increases as more reflections occur.

The equivalent model of a temperature probe, built and used in experiments is presented in Fig. 4.

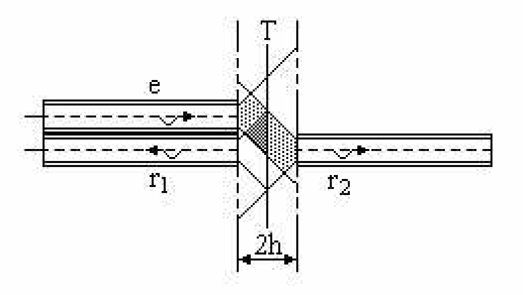

Fig. 4. The temperature probe equivalent model with parallelepiped fluorescent crystal.

The model of temperature probe has two receiving fibres. The fibre $r_1$, placed in the same position as the real receiving fibre, collects the fluorescence light for which the combined path of excitation light and fluorescence light has no reflection on crystal faces. The fibre $r_2$, placed in mirror configuration with respects to screen T, collects the fluorescence light for which the combined path of excitation light and fluorescence light has one reflection on crystals faces.

Using the equivalent model the fluorescence optical flux collected by receiving fibre can be calculated and consequently, the crystal dimensions that ensure the required value of the sensing head efficiency can be determinated.

The optical efficiency of the sensing head $\eta_{cp}$, is defined as:

$$\eta_{cp} = \frac{\Phi_f}{\Phi_0} \tag{1}$$

where:

$\Phi_f$ is the flux of fluorescence light coupled by receiving fibre;

$\Phi$ is the optical excitation flux launched in the crystal.

Between the emitted fluorescence radiation and absorbed radiation exists the relation:

$$\phi_{fe} = \eta(\lambda)\cdot\phi_a \tag{2}$$

where:

$\phi_{fe}$, $\phi_a$ are the total fluorescent and absorbed fluxes of radiation, respectively, and $\eta(\lambda)$ is the fluorescence efficiency, defined as the ratio between the number of photons emitted by fluorescence and the number of photons absorbed which produce excitations followed by radiation emission by fluorescence [3].

The absorbed radiant flux $\phi_a$ can be determined on the base of radiation absorption rules in substance. Thus, considering a substance layer of thickness *dz* on which falls a radiation beam of wavelength $\lambda$ and flux $\phi_0$ from which come out an emergent beam of flux $\phi$, the absorbed flux $d\phi_a$, is equal with the flux decrease due to absorption that verifies the relation:

$$d\phi_a = -k(\lambda)\cdot\phi\cdot dz \tag{3}$$

Using in the Lambert law (3):

$$\phi = \phi_0 \cdot e^{-k(\lambda)z} \tag{4}$$

it results that the absorbed flux into a layer of dz thickness, at the distance z in substance, $d\phi_a(z)$ is:

$$d\phi_a(z) = -k(\lambda)\phi_0 \cdot e^{-k(\lambda)z}dz \tag{5}$$

where k (λ) is the substance absorption coefficient of the layer, for the radiation of wavelength λ.

If S(z) is the surface of the incident flux at the distance z in the substance layer, then the elementary flux absorbed by a surface element ds, $d\phi_{0a}(z)$ is:

$$d^2\phi_a(z) = \frac{d^2\phi_a ds}{S(z)} = -\frac{k(\lambda)}{S(z)}\cdot\phi_0\cdot e^{-k(\lambda)z}dzds \tag{6}$$

Replacing in relation (2) the expression for the elementary absorbed flux from (6) the value of the fluorescence elementary flux, $d\phi_{0f}(z)$ is obtained:

$$d^2\phi_{0f}(z) = -\frac{\eta(\lambda)\cdot k(\lambda)}{S(z)}\cdot\phi_0\cdot e^{-k(\lambda)z}dzds \tag{7}$$

In this way each volume element $dv=dz\cdot ds$ can be considered as a radiation source. The fluorescence flux is emitted isotropically and only a fraction corresponding of the acceptance solid angle of the elementary source, $\theta_{sa}$, is collected. Consequently, the collected fluorescence elementary flux, $d\phi_{0f}$, can be defined as:

$$d^2\phi_{0fc} = \frac{d^2\phi_{0f}}{4\pi}\cdot\theta_{sa}(\vec{r}) \tag{8}$$

where r is the position vector of the volume element, having as origin the receiving fibre centre.

The difficulty consists in determination of the value of $\theta_{sa}(r)$ for each volume element of emission cone.

Considering of the definition the elementary source acceptation solid angle, previously shown, it is defined a calculation elementary source, which emits a conical beam in the perpendicular direction on the end plane of the receiving fibre, of solid angle $\theta_c$, equal with the acceptation solid angle of the receiving fibre for a given medium. For a fibre with numerical aperture NA, the maximum incidence angle sinus value of the guided rays, $\varphi$, (Fig. 4) is:

$$\sin\varphi = \frac{n_1}{n_r}\cdot\sin\varphi = \frac{n_1}{n_r}\cdot\frac{NA}{n_1} = \frac{NA}{n_r} \tag{9}$$

where NA is the numerical aperture of the fibre:

$$NA = \sqrt{n_1^2 - n_2^2} \tag{10}$$

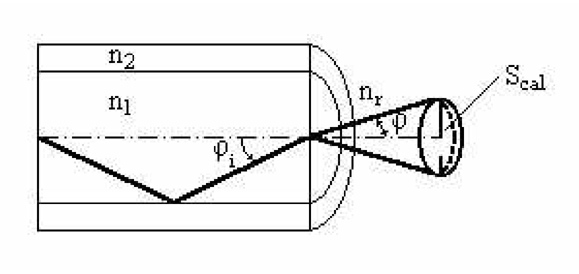

Fig. 5. The acceptance angle of the fibre in a medium with refractive index $n_r$.

For the defined cone of angle φ corresponds the solid angle $\theta_c$:

$$\theta_c = \frac{S_{cal}}{r^2} = 2\pi \cdot \left[ 1 - \sqrt{1 - \left( \frac{NA}{n_r} \right)^2} \right] \tag{11}$$

where:

$S_{cal}$ is the understretched spherical calotte surface of the cone;

R is the sphere radius with the centre in the cone top, which includes the calotte $S_{cal}$.

Computation elementary source illuminates a circular surface $S_i$ in the plane of the receiving fibre. If the superposition surface of illuminated surface $S_i$ and fibre core surface $S_c$, is $S_s$, then the acceptation solid angle of the elementary calculation source is:

$$\theta_{sa}(\vec{r}) = \theta_c \cdot \frac{S_s}{S_i} = \theta_c \cdot F \tag{12}$$

Based on the relation (7), (8), (11), (12) and on fluorescence elementary flux emitted from an element of volume and collected by the receiving fibre, it results that the collected elementary fluorescence flux is given by the relation:

$$d^2\phi_{0fc}(\vec{r}) = -\frac{\eta(\lambda)\cdot k(\lambda)}{2S(z)} \cdot \phi_0 \cdot e^{-k(\lambda)z} \cdot \left[ 1 - \sqrt{1 - \left( \frac{NA}{n_r} \right)^2} \right] \cdot F \cdot dzds \tag{13}$$

where $n_r$ is the refraction index of the exterior medium and $F$ is a ratio that can be determined by geometrical analysis.

Because the sensing head models take in consideration the optical routes with successive reflections, with the inclusion of some screens with transmissivity $T$, the expression of the collected elementary fluorescence flux must be corrected, becoms:

$$d^2\phi_{0fc}(\vec{r}) = -\frac{\eta(\lambda)\cdot k(\lambda)}{2S(z)} \cdot \phi_0 \cdot e^{-k(\lambda)z} \cdot \left[ 1 - \sqrt{1 - \left( \frac{NA}{n_r} \right)^2} \right] \cdot F \cdot T^n \cdot dzds \tag{14}$$

where n is the reflection number of the considered route.

The total fluorescence flux collected of receiving fibre $r_i$ of a equivalent model, $(\phi_{0fc})_I$ is obtained by integration of expression (14) on the volume from the equivalent model of the considered fibre:

$$\left(\Phi_{0fc}\right)_i = \int V_i d\Phi_{0fc} \tag{15}$$

For a sensing head whose equivalent model contains p receiving fibres, the fluorescence collected flux of the real receiving fibre, $\phi_f$ is:

$$\Phi_f = \sum_{i=1}^{p}\left(\Phi_{0fc}\right)_i \tag{16}$$

If in relation (4) the excitation flux, $\phi_0$ is taken as:

$$\phi_0 = 1 \tag{17}$$

then relation (17) represents the sensing head efficiency, according to the relation (1):

$$\eta_{cp} = \sum_{i=1}^{p}\left(\Phi_{0fc}\right)_i \Big|_{\Phi_0=1} \tag{18}$$

## 3. Results

The determination of the value of the optical probe efficiency, which uses fluorescence phenomena, can be done only by numerical calculation.

In order to perform the calculation program it can be used diverse program media, as FORTRAN, PASCAL, C, $C^{++}$ languages or specialised programmes for scientific calculations, developed in the last period.

In this case it was used MATLAB language, which allow the reduction of the required time for writing the programs, using the specialised existent functions and graphic facilities.

The method developed was applied for the computation of the efficiency of probes with parallelepipedic shaped crystal, a geometry frequently used in applications.

The numerical calculation of the efficiency supposes the cummulation of collected fluorescence elementary fluxes emitted by all elementary volumes in the illumination cone of the emission fibre. For each elementary volume can be decided if this is included or not in the emission fibre illumination cone and for the cone inside can be determined the geometrical coordinates at the centre of the receiving fibre, needed for the computation of the collected fluorescence flux.

A system of orthogonal axes, with the origin in the plane of emission fibre end and axes x=0, y=0, tangent to the emission cone in the plane of receiving fibre (Fig. 6) is used for discretisation. The active volume is divided in a number of layers of height *dz*, parallel with the emission fibre end. The surface of each layer illuminated by the excitation light is divided in $N_s^2$ square elements, each of them of *ds* area.

Due to the discretisation procedure described above all layers have the same number of illuminated (and, therefore, active) elements.

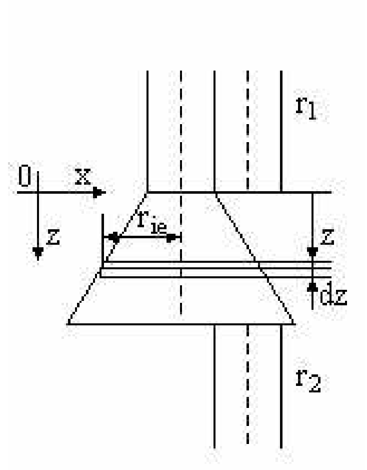

Fig. 6. The discretisation of the equivalent model.

The effect of the increase of the volume elements is compensated by the decrease of excitation flux, due to absorption. The analysis of the influence of the dimensions of the volume element upon the computed value of the efficiency, independently performed for *dz* and ds, shows a stabilisation trend both dz and ds decrease.

For simulation it was used the following input data were used:

– the fibre numerical aperture NA = 0.47;

– the fibre core refraction index $n_1 = 1.492$;

– the ruby fluorescence efficiency $\eta = 0.8$ for $\lambda = 550$ nm;

– the ruby absorption coefficient $k = 14$ mm$^{-1}$ for $\lambda = 550$ nm;

– the ruby refraction index $n_r = 1.762$ for $\lambda = 550$ nm.

In order to study the influence of the crystal dimensions on with the efficiency value, the programme was run for the thickness values of it between 0.5 and 3 mm. The results obtained for the crystal surface reflectivity R = 0.9, are presented in Table 1, where it is distinctly emphasised the contribution of the routes without reflection and with one reflection on the efficiency total value.

Table 1. Calculated values of the sensing head efficiency as a function of the crystal thickness.

| The crystal thickness (mm) | The contribution of the routes without reflection | The contribution of the routes with one reflection, R = 0.9 | The total efficiency |
|---|---|---|---|
| 0.5 | $0.1503 \cdot 10^{-4}$ | $0.6069 \cdot 10^{-4}$ | $0.7572 \cdot 10^{-4}$ |
| 1 | $0.6078 \cdot 10^{-4}$ | $2.0870 \cdot 10^{-4}$ | $2.6948 \cdot 10^{-4}$ |
| 1.5 | $0.9112 \cdot 10^{-4}$ | $2.9180 \cdot 10^{-4}$ | $3.8292 \cdot 10^{-4}$ |
| 2 | $1.9355 \cdot 10^{-4}$ | $5.0009 \cdot 10^{-4}$ | $6.9364 \cdot 10^{-4}$ |
| 2.5 | $2.5947 \cdot 10^{-4}$ | $5.5367 \cdot 10^{-4}$ | $8.1314 \cdot 10^{-4}$ |
| 3 | $3.1685 \cdot 10^{-4}$ | $5.5556 \cdot 10^{-4}$ | $8.7241 \cdot 10^{-4}$ |

In Fig. 7 is presented the dependence of the sensing head efficiency as a function of the crystal thickness, for a reflectivity value of R = 0.9.

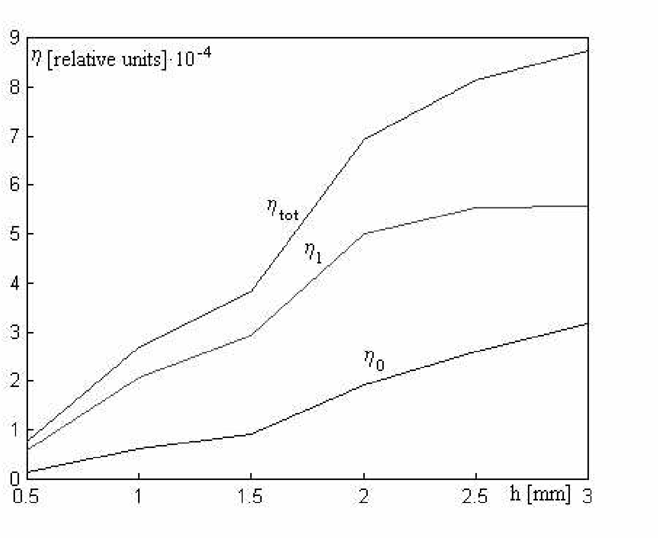

Fig. 7. The sensing head efficiency versus the crystal thickness.

## 4. Discussion

One observes that the optical head efficiency has reduced values, situated in the range $10^{-4}$ and $9 \times 10^{-4}$. The dependence of the efficiency on the crystal thickness is more pronounced up to 2 mm thickness. Then a tendency to limitation is observed. Fig. 6 shows that this effect is due to the contribution of the routes with one reflection and appears for a crystal thickness for which the receiving fibre is completely included in the emission fibre cone. It can be seen the important contribution of one reflection routes that represent approximately 70% of the total efficiency value, this value depending on the reflectivity of crystal faces.

The efficiency strongly depends on the reflectivity value of the crystal faces too. But the reflectivity is a parameter that can be improved by simple procedures, as e.g. the polishing of the crystal faces and the placement of the crystal into a reflective cover or even by a mirror formation when films are deposited on the crystal faces.

## 5. Conclusions

The computation method of the sensing head efficiency, can be successfully applied to various categories of fluorescence optical fibre sensors, as e.g. chemical and biological sensors. Using this method, it is possible to get the value of the efficiency of the critical component for the optical section of the sensor and indicates ways for its improvement, the sensing head being the element of the optical section of sensors using fluorescence, with the lowest efficiency.

The computation method plays an important role in the sensor design process. It is possible to calculate the global efficiency of the optical section, thus offering the possibility of an entire ensemble of optimised design that contains the optical source, the fibres, the active zone and the photodetector. The general result is obviously a minimum price of the sensor, under required performance.

The method can be used for every geometry of the sensing head, if the corresponding equivalent model is generated.

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