SPECIALTY OPTICAL FIBRES FOR A SENSING APPLICATION

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Key words: optical fibres sensors, OFS, advantages of OFS, application area of OFS, sensing application

Abstract: Development of the optical fibre sensor (OFS) becomes an important real practical task due to a number advantages of a such sensors. The main are : the immunity to external influences, flexibility and long distance operation, high stability and sensitivity to various measurands, high resistance to a harsh environmental , possibility of nonelectrical operation and other. The application area for OFS is very wide and roughly could be divided in the following general categories: sensing of temperature; mechanical stress and displacement; acoustics waves; chemical and biosensing, electromagnetic fields. Some OFS could control only point data, other could measures many points over a fibre length simultaneously – these are called distributed type OFS. The development of OFS requires many types of optical fibres with very wide range of parameters and design are needed. In the present paper some more common speciality types optical fibre are described and several examples are given, based on researches made by author group.

Uporaba posebnih optičnih vlaken za zaznavanje

Kjučne besede: optična vlakna, optični senzorji, prednosti optičnih senzorjev, uporabna področja optičnih senzorjev, zaznavne aplikacije

Izvleček: razvoj senzorjev na osnovi optičnih vlaken (OFS) postaja pomembna naloga zaradi številnih njihovih prednosti, ki jih nudijo. Glavne prednosti so: imunost na zunanje vplive, prilagodljivost, delo na daljave, visoka stabilnost in občutljivost na različne merjene veličine, visoka odpornost na kruto okolje, možnost delovanja brez elektrike in druge. Aplikacijsko območje OFS je zelo široko in ga lahko grobo razdelimo v naslednje splošne kategorije: zaznavanje temperature, merjenje mehanskih obremenitev in premikov, zvočni valovi, kemično in biološko zaznavanje, elektromagnetna polja. Nekateri optični senzorji lahko kontrolirajo samo točkovne podatke, drugi lahko hkrati merijo več točk po celi dolžini vlakna-tem pravimo porazdeljeni OFS. Razvoj OFS zahteva veliko različnih vrst optičnih vlaken s širokim razponom parametrov in oblik. V članku je opisanih nekaj vrst posebnih optičnih vlaken in podanih je nekaj primerov, ki temeljijo na raziskavah, ki jih je opravila avtorjeva skupina.

1 Introduction

The speciality types optical fibre (SOF) were developed practically just after the development of telecommunication types optical fibre- i.e. at the end of 70th years. There are several types of SOF, but 2 main groups are an active, or lasing types optical fibres and fibres for sensing application. The last one is the topic of present paper, reviewing the main applications areas and designs of SOF for fibre optical sensors (OFS).

Development of the OFS becomes an important real practical task due to a number advantages of a such sensors. The main are : the immunity to external influences, flexibility and long distance operation, high stability and sensitivity to various measurants, high resistance to a harsh environmental , possibility of nonelectrical operation and other. OFS at present penetrates to many real application areas, but only few of them are really big commercial values. Probably the most bright example is the OFS for angular rotation control, often called as a gyro sensor /1/. Thus , real value of the total market for OFS is not easy to specify and one of a recent market estimation gives a value of about 1 bln $ (see Fig.1 /2/) . It is significantly less than telecom one, but grows quickly and has a big potential.

The application area for OFS is very wide and roughly could be divided in the following general categories: sensing of temperature; mechanical stress and displacement; acoustics waves; chemical and biosensing, electromagnetic fields. Some OFS could control only point data, other could measures many points over a fibre length simultaneously – these are called distributed type OFS. Principles of operation of OFS are also very different and most common are : interferometer schemes, Raman and Brillouin scattering , in- fibre Bragg gratings, small scale infibre resonators, amplitude modulation of light in a fibre under external influence and other.

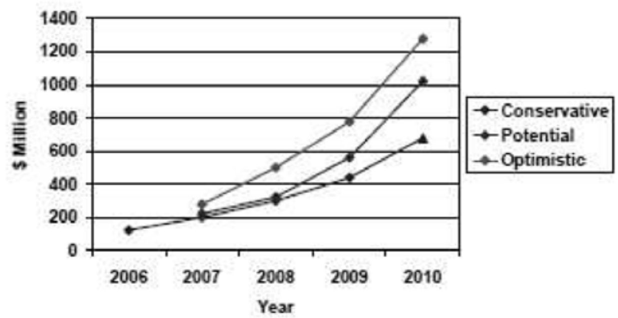


Fig.1: OFS market estimation (from /2/). Lower curve- conservative, upper- optimistic

It is clear that OFF should have a very wide range of the design and optical characteristics to fit the particular OFS application goal and engineering parameters. This is in a contrast with requirements for optical fibres for telecom applications where tight specification and unification as well as very low price are related with mass production conditions. Some main requirements for optical fibres are given in a Tab.1, of course this is a general consideration and can't be applied for absolutely all applications.

Table 1: Comparison of main parameters of the telecom fibres and SOF for sensors.

Parameter	Telecom fibre	SOF
Optical loss	< 0.5 dB/km	1-100 dB/km
Outer diameter	125 µm	40-2000 µm
Core diameter	10,50,62.5 µm	1-2000 µm
Mode dispersion	As low as possible	Could be very high for
		polarization types
Numerical aperture	0.1- 0.15	0.07- 0.6
Geometry	Circular (perfect)	Could be shaped in different forms
	0.2-	
Coating	Standard polymers	Standard, silicone, PI, metal
Sample length	10^4-10^5 m	1-10^4 m
Typical price	< 0.5 Eu/m	0.5-500 Eu/m
Operating temperature	-40 ÷ 80 C	-270 ÷ 700C

Below in section 2 we give a short description of most common types of SOF, based on their application for different physical values and measurement conditions. An example the optical fibre current transformer having a very high accuracy of about 0.1% , stability and wide dynamic range is considered. Such OFS is developed in our research group and uses a several types of SOF, including an advanced microstructured type fibre. It should be noted, that the question of SOF manufacturing process is not discussed in this paper, and one interesting in this could be referred to /3/.

2 Main types of SOF

2.1 SOF for chemical and bio-medical sensing

The basic principle of such OFS is the measurement of changing of some optical parameters (color, losses, polarization) of sensing element under presence of specific materials. Normally the SOF in such schemes must supply and collect light to/from sensing elements –such FOS are called as extrinsic sensors. Main demand to a fibre in this case is a core size and NA to collect enough light and medical compatibility of a fiber coating for medical applications. The typical examples of such FOS is given e.g. in /4/. The sensing elements could be placed at fiber endface or at outer surface, in later case it is necessary to modify fiber geometry to force the optical field to come out of boundary. This can be achieved e.g. by tapering of optical fibre or by making it D-shaped. Recently another approach was suggested for a such SOF, based on a new type of fiber – so called holey, or photonic crystal fibre /5/. Operation principle in this case is the high fraction of evanescent field (field out of fiber core) due very small core size – about wavelength. Thus the field propagating in a cladding, which is really an air holes, could be affected by the material penetrating to these holes. Simplest case of course is a gas, filling a holes. Typical structures of such SOF are presentaed at Fig.2: left is a common suspended core structure, with the core being placed between 3 holes (dark areas) and core size is less than 1 µm; right one shows the co-called " open" structure, where one holes is open to surrounding atmosphere. It gives a possibility to make gas penetration much faster and decrease time response of OFS. Another similar approach is to use the air hole core photonic crystal fibre /6/ and now a number of researches is made to optimize a design of OFS.

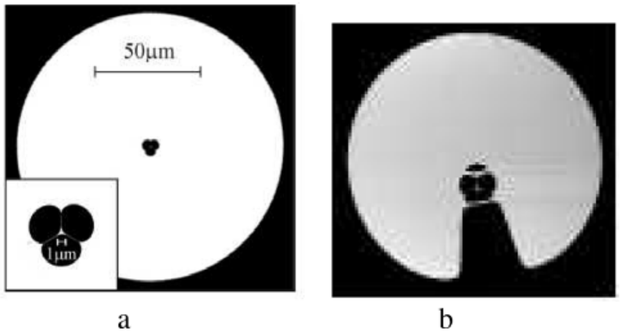


Fig. 2: Structures of holley type SOF for gas sensing a- suspended core structure, b-"open" hole structure.

2.2 Temperature sensors and high temperature applications

OFS for temperature measurements is probably the most wide type of sensors, at least in a number of units and operation principles. They use e.g. change of light transmission amplitude, color, polarization, as well as Fabry-Perot resonator and Bragg grating frequency shift or change of luminescence decay time constant with a temperature change. The review of such sensors is not a goal of paper and we should only point out that for all above design a telecom type fibres could be used with only a moderate modification for optimization sensors parameters. But situation changes dramatically if OFS should be used or measure the high temperature, say above 150 °C. This is because standard polymer coatings resist only a temperature about 100 °C and not higher. So even silica itself could work up to 1000 °C, damage of coating gives in result very quick mechanical damage of a fibre. For a temperature about 300 °C there is an alternative version with PI (polyimide) coating /7/, but for many application higher temperature is needed. We performed a research for applying of metal coating and investigation of high temperature behavior of SOF with metal coating. Two types of coatings were tested – Al and Cu based alloys. The gold coating also looks very promising with technical point of view, but a current gold price makes such experiments problematic. Shortly main results are the following. There are 2 reasons for loss increment in metal coated SOF- absorption and scattering due to microbending. Absorption increase depends on a preform and fibre design and environmental condition and is significantly higher for Al coated fibre /8/ (see Fig.3) Typical diagram for microbending induced losses for Cu coated fibre is presented at Fig.4

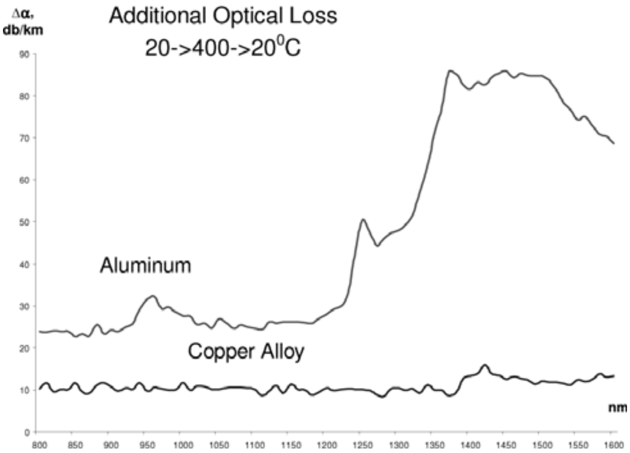


Fig. 3: Additional losses induced in Cu-alloy (lower curve) and Al coated fibre after heat cycling To 400 ^{o}C and back

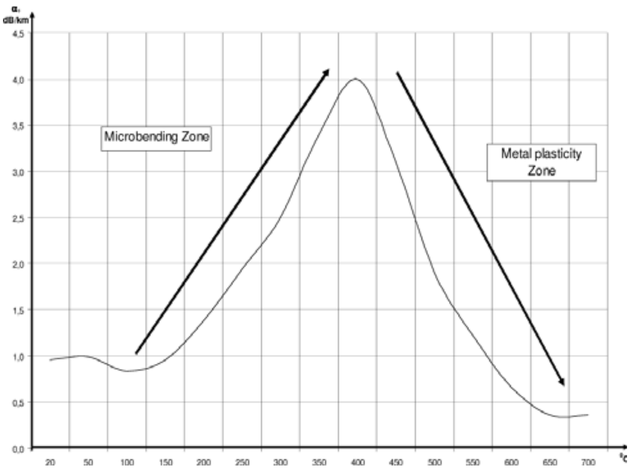


Fig. 4: Microbending induced losses at 1300 nm in optical fibre with Cu alloy coating .

It should be mentioned one application of a metal coated fibre- OFS for high temperature based on a fibre Bragg grating (FBG). As it is known the normal FBG written in GeO_2 fibre destroyed at high temperature /9/, but it was found that doping with N could resolve this problem and FBG in such fibre operates at rather high temperature, over 500 ^{o}C /10/. We combine N doped fibre with a Cu coting and obtain in this way a sensitive element for high temperature OFS /11/- example is given at Fig.5 and comparison of GeO_2 and N doped FBG behavior under high temperature annealing at Fig. 6

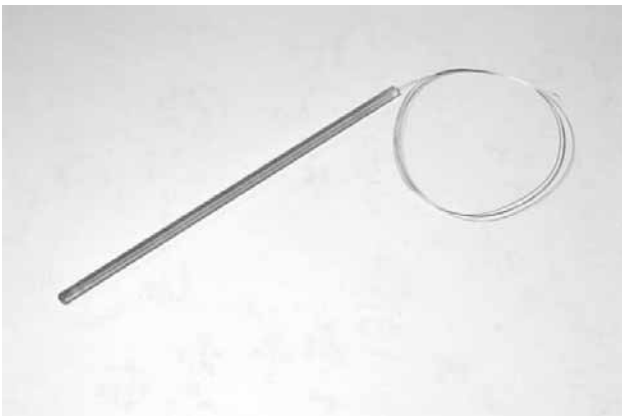


Fig. 5: High temperature Bragg type sensing element with N-doped and Cu coated fibre

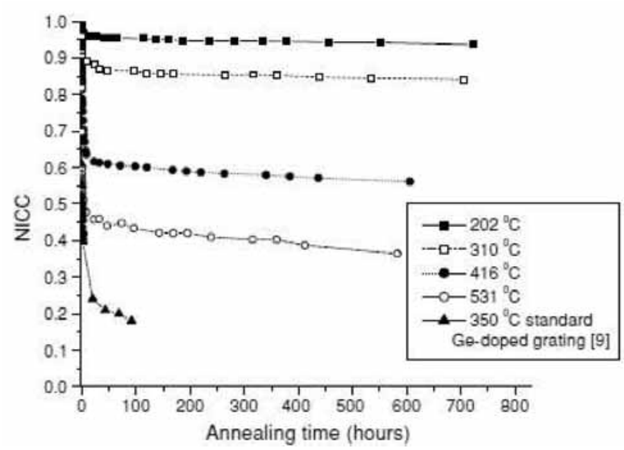


Fig. 6: Isothermal annealing of FBG written in an N-doped fibre compared with that of a Ge-doped.

Here NICC parameter (normalized integrated couple constant) defined as NICC $=\tanh^{-1}(\sqrt{R})/\tanh^{-1}(\sqrt{R_0})$ where , R_0 and R are the initial and current reflection coefficients of the grating at the resonance wavelength, respectively.

2.3 SOF for stress and displacement monitoring systems

The fibers used for this application are very similar to the fibers for temperature sensing because physical phenomena are practically the same for these sensors. For example, shift of central wavelength of FBG, resonator frequency or fiber interferometer phase shift depend both on temperature and stress in a fiber and separation of different influences is a common problem for OFS design. Of course some OFS measure the single measurand – e.g. Raman scattering or luminescence based sensors affected by temperature only, but from fiber point of view differences of the two OFS are very small. May be the remarkable one is related with the object of monitoring of the stress and deformation. As a rule it is a long haul and big in size objects –e.g. bridge, oil hole, gas or oil pipe, etc. and hence normally one have to control the distributed or multipoint parameters. For many of engineering objects the hard environmental conditions are also proper. Thus, SOF for monitoring system normally must be strong enough at length up to several km, resists relatively high temperature, in some cases (e.g. in oil mines) be hermetical to avoid H penetration. Some of these parameters could be achieved by using SOF with combined coating : carbon layers plus PI layers / 7/, but in general the problem needs more effort to develop SOF adequate to practical problems and advanced types of modern opto-electronic measuring devices, such as Raman, Brillouin or polarization reflectometers /12/.

2.4 Polarization types SOF. Optical fibre current transformer

The interest to polarization type SOF was generated in a first turn by the development of angular velocity OFS, often called as gyro sensor /1/. For such an OFS the fibre preserving linear polarization state (HB fibre) was necessary and several types were successfully designed – PANDA type, bow-tie, elliptical stress jacket, elliptical core. Basic design and principle of operation of these SOF are described in a classic paper /12/, and in many more modern papers, e.g. / 3/. Shortly, two main mechanisms could lead to strong linear birefringence and hence to polarization holding property. First is the creation of anythotropic mechanical stress due to adding an elements or making an uncercular internal regions in the fibre with big thermoelastic coefficient, second is making uncercular core shape and obtaining of waveguiding birefringence. The properties of HB fibres are now investigated in details, including relation between fibre design and birefringence value and its temperature dependence. An example of most common type HB fibre- PANDA fibre is presented at Fig7 a. Bright area in a center corresponds to a core, and two black circulars to stress applying rods.

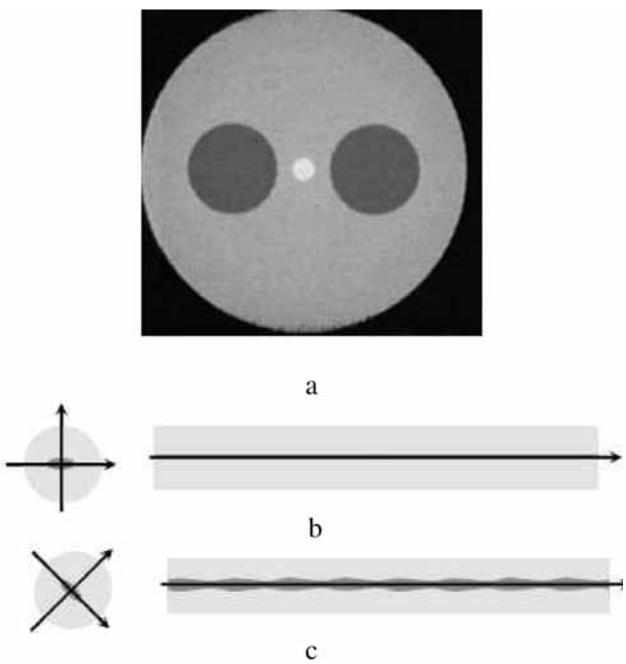


Fig. 7: Cross section of a typical HB SOF PANDA type (a) and comparison of HB (b) and SPUN (c) fibres structures.

The fibre, preserving elliptical ("circular like") polarization states is not so common and isn't investigated in all details. On our opinion this fibre has at least the same importance as HB fibre as they could be used for creation of optical current sensors or optical current transformer (OCT) based on a Faraday effect. Such OCT could have an extremely high characteristic and are very perspective for application in electro energetic and some other industrial areas /13/. The SOF using for Faraday OCT is made by fast rotation of a fibre during its drawing and as a result the birefringence axes rotated along a fibre length in a spiral manner. As a starting preform we use a HB type preform in this case and the fibre obtained in this way is called SPUN type fibre. Schematically, the difference between HB and SPUN fibres is clear from Fig.7 b and c.

The principle scheme of OCT is given at Fig.8. It is interesting to point out that such OFS uses 6 different SOFs in a real design. They are:

- Active Er-doped optical fibre wide spectrum light source at 1550 nm
- Polarizing fibre
- Delivery fibre PANDA type (up to 1 km)
- Fibre phase modulator
- Fibre quarter wavelength thermo stable plate
- Sensitive SPUN type fibre

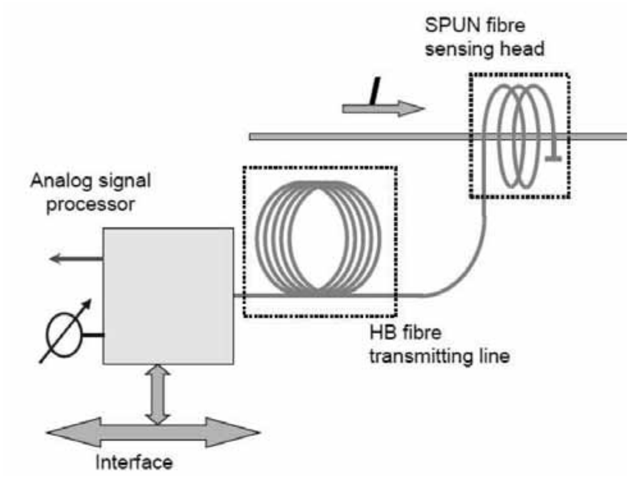


Fig. 8: Principle scheme for OCT,using SPUN fibre. I- electrical current coming through sensing fibre coil.

Characteristics of developed OCT based on a " classical" SPUN type fibre are very high: accuracy of measurement is better than 0.2 % over a 1000 °C range, dynamic range is better than 10^5, maximal current – up to 10^5 A, high linearity and total immunity to electromagnetic interference.

We show recently /13,14/ that replacing of a "classical" SPUN fibre by an advanced holey type SPUN fibre open it out that parameters could be further improved. First, it is possible to make a coil with up to 10^5 fibre turns without degradation of optical parameters (loss and magneto-optical sensitivity) and also thermal stability becomes higher due to fact of very high insensitivity of holey SPUN fibre to temperature. The cross section of advanced SPUN fibre is given at Fig.9 a . Also shown are sensitive coils with 10^2 and 10^5 turns number (Fig.9 b,c)

We think that now it is obvious that holey fibre could be used in a many modern practical OFS. Another fact confirming it is for example a value of linear birefringence- in our fibre we achieve a value of about $2x10^{-2}$, what is about 20 times higher than for best PANDA type fibre /14/.

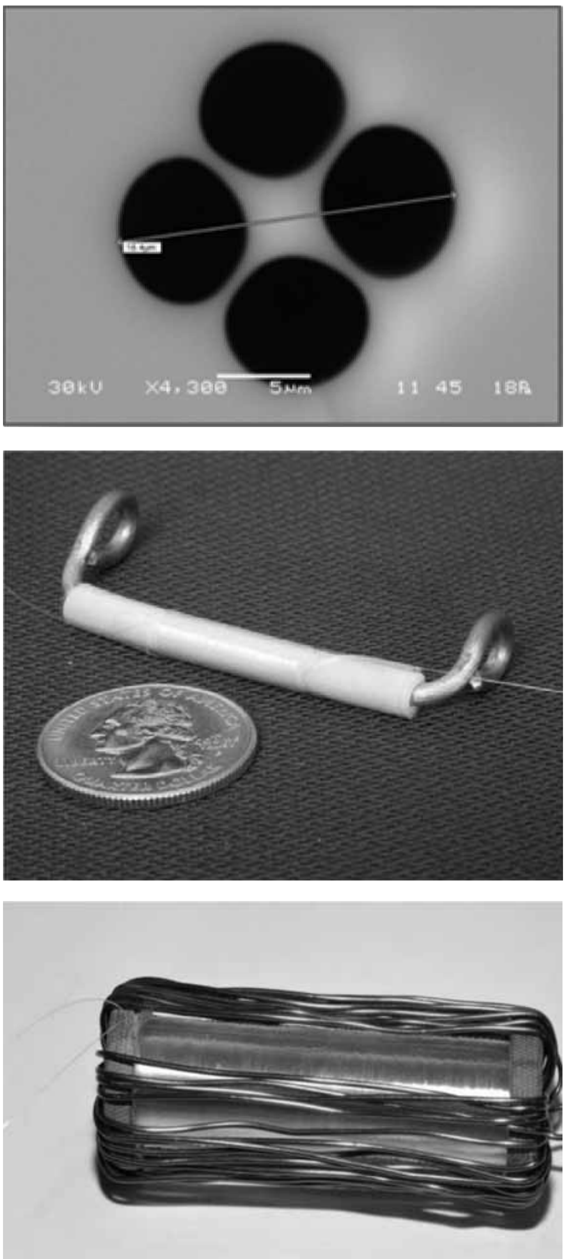
a
b
c


Fig. 9: a-Cross section of central region of holey SPUN fibre, 4 dark regions- air holes, inside-core region; b- SPUN holey fibre sensitive coil with 100 turns; c-the same but with 10000 turns.

3 Conclusions

The brief review of main types of SOF for sensing applications is presented. Developed SOF could tolerate to a very wide spectrum of OFS differing by physical operation principles, measured parameters and design. Probably the most important type of SOF which needs a further serious development is the SOF for very high temperature and harsh environmental conditions. OFS with such fibre could be used in multiple monitoring systems – smart oil holes, engine, engineering structures and have a big commercial potential. Application of a new advanced holey or photonic crystal fibres gives a possibility for remarkable improvement of OFS parameters.

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References

/1/ B. Culshaw, "Optical fibre sensor technologies: Opportunities and perhaps pitfalls", J. Lightwave Technol., 22, No 1, pp. 39-50, 2004

/2/ P. E. Sanders, D. A. Krohn, "Market Opportunities for Photonic and Optical Fiber Sensors", OFC/NFOEC 2007, Workshop: Future of Fiber Optic Sensors, 2007

/3/ A.Mendez, T.F.Morse "Speciality Optical Fibers Handbook", Elsevier AP, 2007.

/4/ F. Baldini, "Advanced biomedical optical fibre sensors", 20th International Conference on Optical Fibre Sensors, Proc. of SPIE Vol. 7503, 75030Q, 2009

/5/ E. P. Schartner, R. T. White, S. C. Warren-Smith, T. M. Monro, "Practical sensitive fluorescence sensing with microstructured fibres", 20th International Conference on Optical Fibre Sensors, Proc. of SPIE Vol. 7503, 75035X, 2009

/6/ T. Ritari, J. Tuominen, H.Ludvigsen, J. Petersen, T. Sřrensen, T. Hansen, H.Simonsen, "Gas sensing using airguiding photonic bandgap fibers," Opt. Express, 12, pp. 4080-4087, 2004.

/7/ C.Wang, A.Soufiane, I. Majid, K. Wei, "High reliability hermetic optical fiber for oil and gas application", Proceedings of the SPIE, Volume 5855, pp. 563-566, 2005.

/8/ V. V. Voloshin, I. L. Vorob'ev, G. A. Ivanov, V. A. Isaev, A. O. Kolosovskii,S. M. Popov*, and Yu. K. Chamorovskii," Effect of Metal Coating on the Optical Losses in Heated Optical Fibers", Technical Physics Letters, Vol. 35, No. 4, pp. 365–367, 2009

/9/ D. Razafimahatratra, P. Niay, M. Douay, B. Poumellec , I.Riant " Comparison of isochronal and isothermal decays of Bragg gratings written through continuous-wave exposure of an unloaded germanosilicate fiber" Appl. Opt.39 pp.1924–33, 2000

/10/ O.V. Butov, E.M. Dianov, K. M. Golant, " Nitrogen- doped silica-core fibres for Bragg grating sensors operating at elevated temperatures", Meas. Sci. Technol. 17 pp.975–979, 2006

/11/ O.V. Butov, K.M. Golant, Yu.K. Chamorovsky, V.A. Isaev, I.L. Vorobjev, V.V. Voloshin, A.O. Kolosovsky, Ya. V. Gusev, I.V. Sokolov "In fiber Bragg graiting for sensor application at high temperatures" // Proc.. OFC-2004, Los Angelos, Febr. 22-27, đ.Fc5, 2004.

/12/ M.N.Alahbabi, Y.T.Cho, T.P.Newson, "Simultaneous temperature and strain measurement with combined spontaneous Raman and Brillouin scattering", Optics Letters , V.30(11) pp.1276-1278, 2005

/13/ Yu K Chamorovsky, N I Starostin, S K Morshnev, V P Gubin, M V Ryabko, A I Sazonov, I L Vorob'ev, "Spun microstructured optical fibres for Faraday effect current sensors", QUANTUM ELECTRON , 39 (11), pp.1074–1077, 2009

/14/ / Yu.K. Chamorovskiy, N.I. Starostin, M.V. Ryabko, A.I. Sazonov, S.K. Morshnev, V.P. Gubin, I.L. Vorob'ev, S.A. Nikitov, "Miniature microstructured fiber coil with high magneto-optical sensitivity", Optics Communications, V. 282, 23, pp. 4618-4621, 2009

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