Volume 52, Number 3, 2011

ACTA TECHNICA NAPOCENSIS
Electronics and Telecommunications

DISTRIBUTED BENDING MEASUREMENT SENSOR

Ramona V. GALATUS, Lorant SZOLGA, Emil VOICULESCU
Technical University of Cluj-Napoca
Address: G. Baritiu 26-28, Cluj-Napoca, Romania, tel./fax +4 0264 592 055, Email: ramona.galatus@bel.utcluj.ro

Abstract: **The paper introduces an improved bendable distributed optical fiber used into an all-optical power-up system. The contribution highlights the high sensibility of the large mode area (LMA) fiber, designed with the most powerful higher-order mode rejection. The considered LMA were used in conjunction with MOFA power-up configuration scheme. Setup has a master oscillator fiber amplifier (MOFA) configuration for large scaling of the output power, meant for a linear sensing accuracy of the order of microns. A power variation of the fundamental mode was measured in order to discern the proportional rate for bending radius. The signal was 1550nm, typical to assure compatibility with telecommunication links. The performance is optimized by varying the bending radius, index/ doping profile, the LMA fiber custom profile and core diameter.**

Keywords: *Fiber Optic Sensor, Bending Measurement, EDFA(Erbium Doped Fiber Amplifier), LMA, Highly Doped Fiber, MOFA*

I. INTRODUCTION

In the context of *Smart factories* development, intelligent sensor-based systems respond to the conditions of safety and security for cost saving, diagnostics and quality assurance in dynamic monitoring of the efficient fabrication process. The intelligent sensor-based systems contribution aims to improve the efficiency, adaptability and sustainability of manufacturing systems, based rather on the load history monitoring than on the working hours (guaranteed operational life), as well as their better integration within business processes in an increasingly globalised industrial context.

The photonic sensor and in particular optical fiber sensors technology can be easily adapted to specific applications that asks for their advantageous features such as: telecom compatibility, fast response, immunity to electromagnetic interference generated by electrical instruments in the operating environment (no electromagnetic shield is necessary), multiple sensing capabilities. Therefore they have compact sizes (small size even 0.25mm diameter, and small weight) that enable them to be located in usually inaccessible sites (from sea-bottom to cell-level applications), or to be embedded within most composite structures without adverse impact. The trend toward miniaturization offers single-based optical sensors with distributed, multiple parameter sensing capabilities. Also different types of optical sensors (bending, temperature, pressure, strain, torsion etc.) can be linked together using a combination of fibers and wavelength-division multiplexing is used to distinguish their respective signals.

In terms of accuracy and sensor drift, optical sensors often have superior level of performances compared to electrical miniature sensors. Low loss and large bandwidth enables transmission of data over long distances (reducing network complexity by using optical amplifier and multiplexing technology), without the need for any additional electronic devices.

The technology brings benefits to a wide range of real-life applications from in situ sensors for monitoring important parameters, through to distributed measurements. The system allows quickly adapting to global competitive pressures by improving the technological base of manufacturing and also responding to the requirements of providing *energy-efficient information*, reduction the power consumption per circuit/function. The great potential of fiber sensors is well known for many years, but the market penetration has been slower than expected [1]. The main reason is the lack of standard (to establish what measurements they should be used for) and this keep another barrier of growth, the high cost – context dependent.

According to [2] various techniques have been developed for specific applications with various measurands. Papers related to *bending and displacements* have a distribution of around 3.5% from the total types of optical fibre sensors applications.

This paper deals with a design process to obtain a suitable optimized bending sensor, acting as position transducer meant for a sensing accuracy of the order of microns. The sensor sensitivity can be set at a specific value according to the requirements of the measurement condition. Connected with multiplexed sensing processing schemes, the sensor array may find an application in the real-time monitoring and damage detection of large and critical engineering structures.

The fiber optic technology can be used to sense position and displacement by means of maintaining the near-total internal reflection of light accepted at the input along their

Manuscript received September 4, 2011; revised October 20, 2011

length acting as a distributed intrinsic sensor. The design of an optical fiber sensor suitable for power-up applications was studied, using different optical fiber profiles and an improved all-fiber MOFA configuration. It was analyzed the impact of macro bending on the transmitted signal using bending loss formula for optical fibers with an axially symmetric arbitrary-index profile, proposed by Sakai & Kimura [3]. Using the experience from [4],[5], for special LMA fiber designed with most powerful higher-order mode rejection, and three categories of optical fiber acting as a bending sensor were studied: SM (single mode with core radius: 6-9 µm, step index profile), MM (multi-mode with core radius: 65µm, step and graded index profile) and LMA (Large Mode Area) doped fiber, using different relative index profile (Δ) and core diameter 50-100 µm with cladding diameters of up to 400 µm [6]. This paper deals with different single or double clad index profile geometry LMA (figure 1), with different depressed position in order to optimize the linearity and sensibility of bending sensor suitable for specific applications where the rate cost-efficiency(precision) is optimized. Also an improved MOFA configuration setup (figure 7) is proposed, suitable for power-up applications. The theoretical results were validated using a setup containing OTDR, bending equipment and EDFA used in telecommunication systems (figure 4). Fibers were simulated at a wavelength of 1064 for Yb and 1550 nm for the rest of the fibers, to provide compatibility with optical telecommunication applications. The light monitoring in fiber setup, with an OTDR (Optical Time Domain Reflectometer) shows the corresponding diagram for the cases of power losses proportional with bending radius.

II. SENSOR DESIGN

In order to obtain a single-mode operation of LMA fibers, with higher order modes rejection concurrently with magnifying the light coverage of the core (effective area in the fundamental mode/ MFD) six index profiles with increased core diameter ranging from 50 µm to 100 µm were chosen. Using the bending loss formula for optical fibers with an axially symmetric arbitrary-index profile, proposed by Sakai & Kimura [3] comparative results were depicted in figure 2, for a *passive fiber system*. The high sensitivity fiber is demonstrated by high power loss in bending process between 5…20 mm bending radius (depicted in figure 2).

Choosing fibers with better results (3,5,6), they are integrated into an *active system*, acting as a fiber amplifier. By combining the optical gain of rare earth ions (Er, Yb) with parabolic doping concentration with the large optical confinement available in a single mode optical fiber, these fibers offer an environment for producing devices that are both very small and extremely efficient, called EDFA (erbium doped fiber amplifier) and respectively YDFA (ytterbium doped fiber amplifier) acting as compact and practical laser devices that require lower drive power provided by a simple, inexpensive laser diode at 980nm for Er and 976nm for Yb. To obtain such a custom index profile, the manufacturer use Direct Nanoparticle Deposition (DND) technology.

Because of their efficiency, compactness, mechanical and thermal stability, and excellent coupling to single mode communication fibers these amplifiers, based on LMA fiber can be included into an optical communication sensing system. To obtain high gain and low noise and to avoid gain saturation, the simulation indicates the optimal length of the fiber, as it is depicted in figure 3. For the 1µm difference a power variation of the fundamental mode increases, comparative with step index fiber, in excess of 48µW.

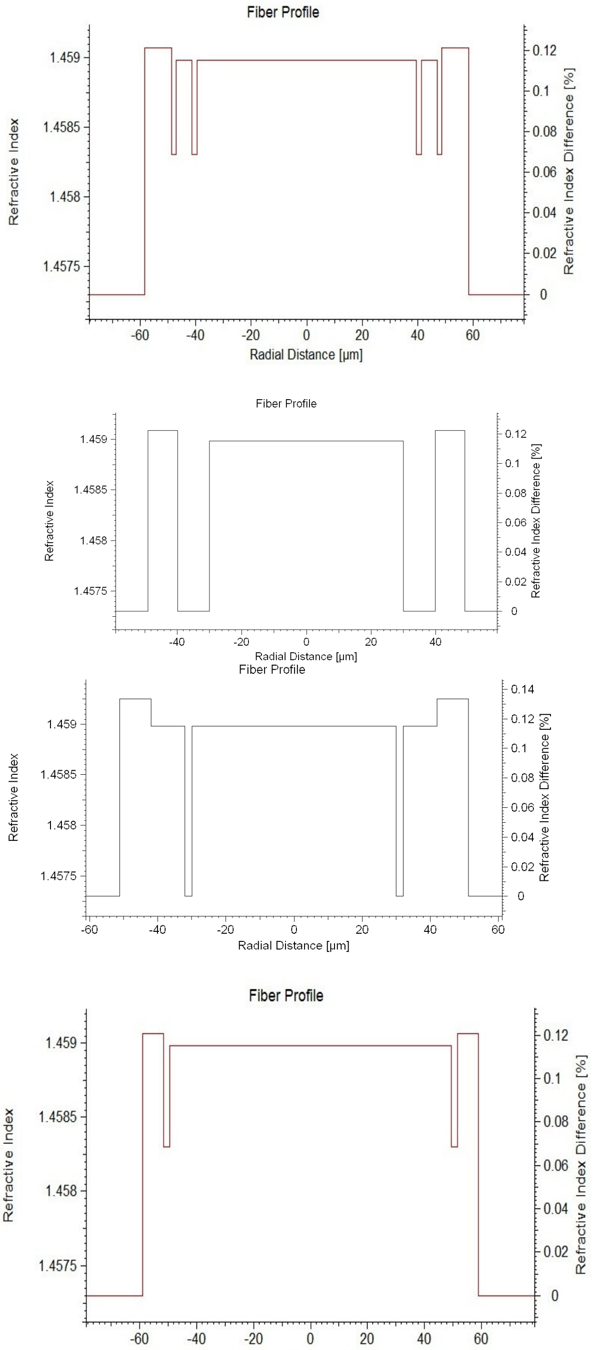

Figure 1. Custom index profile for LMA fibers (fiber1,3,5,6 profile index)

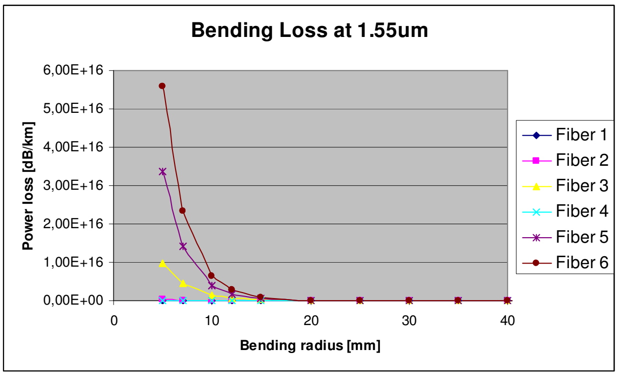

Figure 2. Power bending loss (dB/km) for optimized index profile, LMA fiber

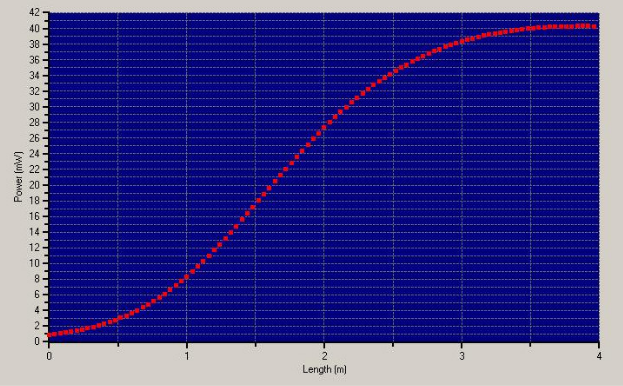

Figure 3. Power gain saturation at 3.7m

The model of the transducer has been validated by comparing numerical data and experimental data of bending loss at a signal of wavelength 1550nm for the compatibility with the telemetry systems. The results are partially validated by using a setup like in figure 4 and 5. A metal cone is used for bending radius variations, and a micrometer to vary the step-radius. The OTDR (optical domain reflectometer) shows a diagram which permits to calculate the bends at every discrete elements along the length. Each individual radius shape on the cone can be considered as sensing elements. The sensor density can be integrated to reconstruct the shape of the fiber.

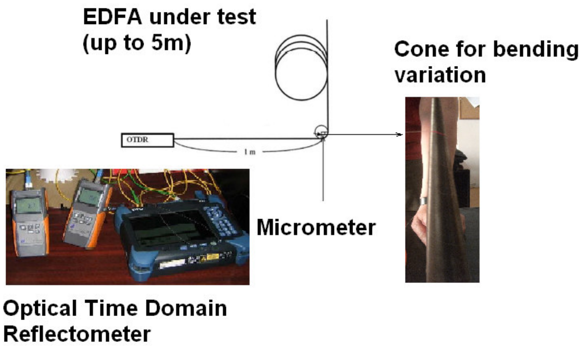

Figure 4. Schematic view of the set-up used for the validation of the theoretical results

Figure 5. Radius variation measurement on the bending cone.

III. SENSOR SYSTEM

To permit the scaling of the output power of the transducer a MOFA (master oscillator fiber amplifier) configuration is used is depicted in figure 7. Because MOFA can be sensitive to back-reflections, which are amplified again, a Faraday isolator between first and second stage is used, but in this case is obtained a *one-directional sensor*. The first stage consists of simple fiber Bragg grating-based Fabry-Perot Cavity, which is often used to increase power levels ranging from a few mW to tenth even hundred of watts. To obtain a higher power levels this first stage is used in combination with a second stage consisting in a LMA fiber (with fiber profile 3,5or 6 from figure 1 and a fiber length of 3.7m), which offers a flexibility to reach the required performance in terms of linewidth, polarization control, beam quality or pulse duration if the required power is very high (reaching about 7.5 W power level in this simulation model). Despite of the fact that the complexity of the setup is higher, the polarization control, necessary for bending sensor is an advantage.

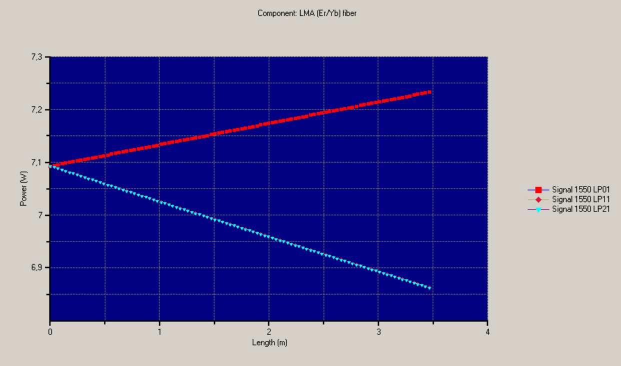

Figure 5. Power gain for selected first three modes of the LMA fiber(at 3.7m, high modes are considerable attenuated)

The superior modes at the output of the LMA fiber, acting as a bending sensor, are much attenuated, and fiber can be considered to work very similar like monomode amplifier.

With the input power of 0,3W, the *output power is about 8W*, with the pumping power of 40W. The output power attenuation, for 1 µm bending radius variation is quite well discerned (> 8µW). This power difference is depicted in figure 6.

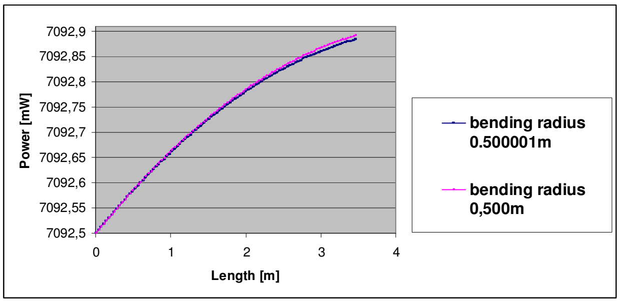

Figure 6. Power variation, after 3,7m LMA length, for 1 µm bending radius variation

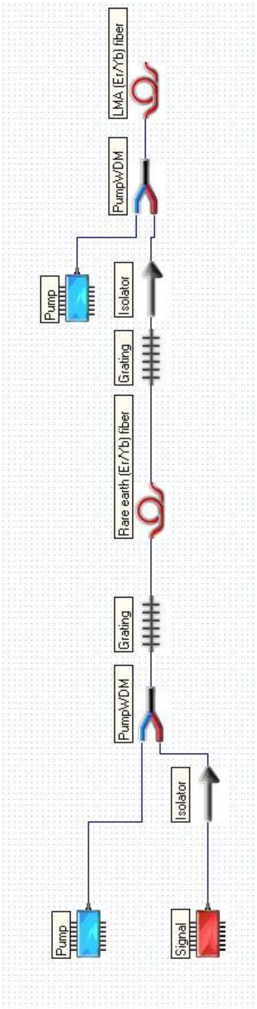

Figure 7. MOFA configuration (Liekki LAD 4.0, UTCN License).

III. CONCLUSIONS

This paper reports simulation results obtained using a MOFA configuration, acting as a low-cost optical bending sensor in a power-up condition. The MOFA configuration is used for scaling the output power. The high-power single-mode operation (figure 5) in a rare-earth-doped LMA fiber is obtained by using fiber Bragg grating (FBG)-based Fabry–Pérot cavity in the first stage of the amplifier in series with a large mode area doped fiber with depressed clad index profile, acting as an amplifier in the second stage. The large mode area fiber from the second stage acts as a distributed bending transducer. The original contributions refers to design a powerful micrometer sensor using the advantages of a power up scaling MOFA general configuration, combined with the improved particular index profile geometry of LMA fibers, to obtain a monomod operations needed to optimize the linearity and sensibility of bending sensor. The alternative of using LMA fibers instead of conventional high numerical aperture, small MFD (mode-field diameter fiber) designs inherited from the telecommunications industry was considered. Using LMA fibers with larger cores, lower NA (numerical aperture) and increased size of the mode field (MFD) made it possible to succeed against nonlinear limitations associated with high intensities in conventional fibers.

The results point out that such kind of sensor may be very useful in applications related to safety, automatic control, with telecom compatibility, where the precision of distributed sensing of 1µm bending radius difference need to be quite well discerned. Different bending operation windows are obtained by playing with the index profile, dopant concentration, core radius (Large Mode Area fiber) in applications that offers compatibility with the telecom operating window and require a power-up configuration.

ACKNOWLEDGMENTS

This paper was supported by the project "Development and support of multidisciplinary postdoctoral programmes in major technical areas of national strategy of Research - Development - Innovation" 4D-POSTDOC, contract no. POSDRU/89/1.5/S/52603, project co-funded by the European Social Fund through Sectoral Operational Programme Human Resources Development 2007-2013.

The authors thank to TeleDataNet SRL for their support in realizing the bending set-up measurements.

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