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Evanescent wave sensor based on permanently bent single mode optical fiber

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ABSTRACT

A novel refractive index sensing scheme based on evanescent wave interaction through locally and permanently bent single mode optical fibers is proposed. Local and permanent bends in single mode optical fibers enable significant power coupling between core and cladding modes. Order and number of excited cladding modes depend on bend features and determine the field profile at the output of the bent region. This in turn constitutes a simple mechanism to tailor the field distribution in single mode optical fibers useful for spatial light modulation. Moreover, since guided cladding modes are strongly influenced by the surrounding refractive index (SRI), the power transmitted at the output of the bent region as well as its dependence on the optical wavelength are strongly sensitive to the SRI opening new scenarios in sensing applications.

1. Introduction

Fiber optic evanescent wave sensors are ideal candidates for in-line remote detection in dangerous locations and industrial process control. In standard single mode optical fibers (SMFs), the light propagates into the core by total internal reflection at the core/cladding interface while evanescent field is produced in the medium surrounding the core (cladding). To access the evanescent field, fiber structure necessitates of being properly modified [1,2]. To this aim, approaches based on polishing or chemical etching of cladding layer have been proposed. However, these approaches often favor the weakening of the final device causing the lack of robustness for their exploitations in practical applications. Alternatively, it is possible to use evanescent wave of cladding modes which extends in the medium surrounding the cladding region. To this aim, it is necessary to provide power coupling mechanisms between core and cladding modes. The most used approach involves long period gratings or tilted fiber gratings which are able to selectively couple light from the core mode to cladding modes [3,4]. On this line of argument, here, we propose a novel and simple solution provided by the use of permanently bent fibers [5].

Theoretical and experimental investigation of the bending characteristics of single- and multi-mode fibers have been the purpose of optical fiber research for many years since bends cause the power propagating through guided core modes to be lost by coupling to leaky and guided cladding modes [6,7]. To investigate and quantify such a behavior, different approaches have been presented, mainly based on perturbation methods from the properties of the straight fiber to determine power losses and field shift [8].

Recently, Schermer presented a comprehensive study of the bending features in step index fiber that favors modal transition to whispering gallery modes (WGMs) [9]. Starting from similar considerations, Yao et al. demonstrated that low bend loss occurs in tightly bent optical fibers by winding the fiber around a mandrel designed to follow an adiabatic transition path into the bend [10]. In particular, light is smoothly transferred from the fundamental core-guided mode to a single cladding mode of the bent fiber, and back to the core mode as it leaves the bent region again.

Moreover, the power coupling or modal transition induced by a local bend in single- and multi-mode fibers attracted the researchers' attention to develop new in-fiber components. For instance, Tomita et al. proposed a simple water sensor based on detection of bend power losses [11]. When water is absorbed by a properly selected absorbent material, its volume increases. This pushes a movable bender against the fiber with consequent increase in optical loss. Nam and Yin [12] proposed a new mechanism for high-temperature sensing based on WGM resonance in bent optical fibers. The interference fringes between the core mode and WGMs were induced by bending a cladding-thinned fiber whereas peak shifts as a function of temperature were measured.

It is worth noting that the mentioned works deal with not-permanently bent optical fibers (single- or multi-mode) while the bend is forced by wrapping the fibers around proper holders. Differently, only few works involving permanently bent optical fibers are present in literature [13,14]. In these works, U-shaped fibers were fabricated via flame treatment in order to enhance evanescent

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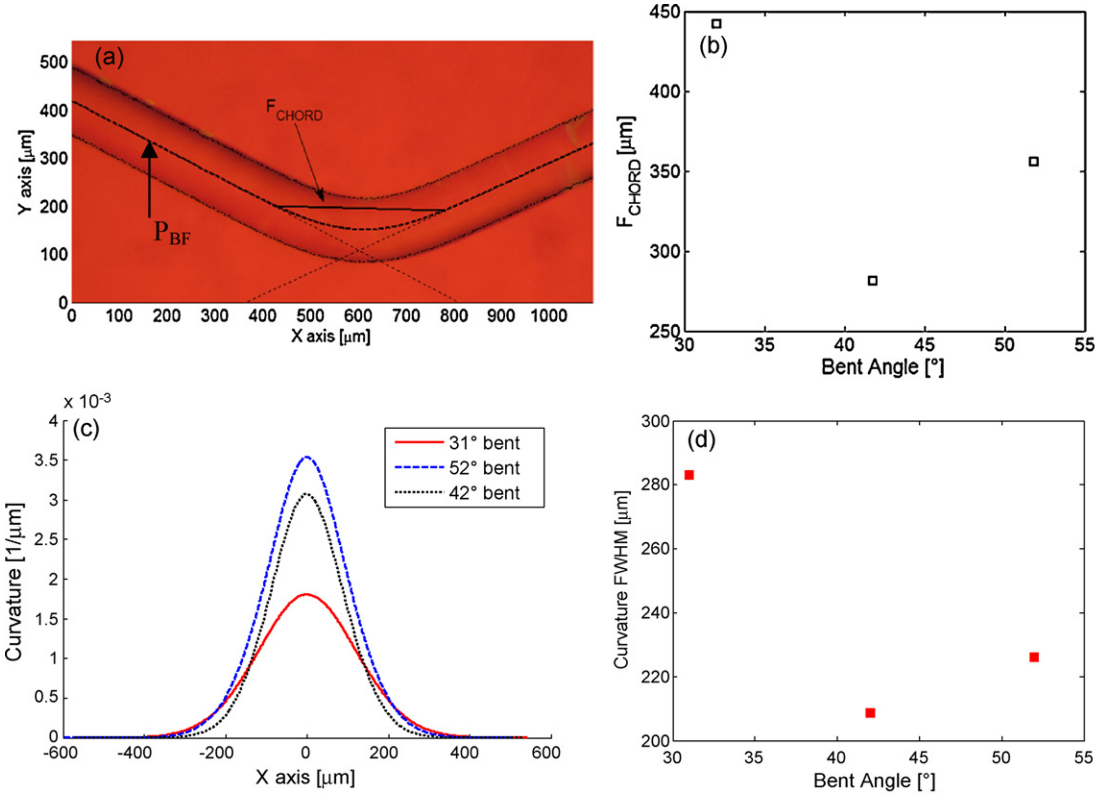

Fig. 1. (a) Optical image of the 52° bent fiber, (b) F_{CHORD} versus the bent angle, (c) curvature of the bent fiber samples versus the *x*-axis (centered on the curvature maximum value), and (d) curvature FWHM versus the bend angle.

wave sensing mechanism in plastic-clad multi-mode fiber where the cladding layer was preventively removed [13]. U-shape fiber has been also combined with gold layer for biosensing applications [15].

In this paper, we present a detailed experimental analysis of field distribution in permanently bent SMFs pointing out their sensing performance in terms of surrounding refractive index (SRI) sensitivity. Local and permanent bends in SMFs, in fact, induces significant power coupling from guided core mode to guided and leaky cladding modes depending on bend features (mainly bending angle and radius). While leaky modes soon attenuate far from the bent region, the final field distribution along the optical fiber (as the fiber is kept coating less) is dominated by the contributions of guided core and guided cladding modes in proportions strongly depending on the bend characteristics. This simple mechanism first allows to completely tailor the field distribution in SMFs. Second, it acts as novel in-fiber sensing scheme based on evanescent wave for SRI measurements.

2. Permanently bent single mode optical fibers

Here, local and permanent bends on SMFs have been induced by local thermal treatments via electric arc-discharge (EAD) while a bending state is locally forced along the fiber. EAD-based technology has been selected in light of its well-exploited capabilities for silica-fiber manipulation [16].

In particular, the EAD approach has been carried out by using a commercial fusion splicer (Fujikura FSM-50S). To induce correct bending state along SMF in correspondence of the arc electrodes two plastic holders were properly designed to be hosted on the splicer clamps. Besides, fine bending state adjustment is achieved by acting on the distance between holders and electrodes controlled by the motorized stages of the splicer machine. In addition, a correct setting of EAD current and duration is necessary, in our cases the best performances have been obtained with 17.1 mA and 400 ms, respectively. During the arc discharge operation, localized thermal treatment combined with the forced bending state, is able to induce a permanent bend in the region of the optical fiber close to the splicer electrodes. By acting on the bending state forced during the EAD procedure, permanent bend angles in the range 2–60° can be readily obtained. In the current analysis 31°, 42° and 52° bent fibers have been considered. Fig. 1a reports the optical image of the 52° bent optical fiber. For each sample, the fiber chord (F_{CHORD}), defined as the distance between the bent region ends in the bending plan, is also measured to better explore the bending features. In Fig. 1b, the values of F_{CHORD} related to the investigated samples are plotted as function of the bent angles. The smallest value is related to the 42° bent fiber: note that F_{CHORD} parameter yields information about the length of the fiber region involved in the bending procedure. However, to completely characterize the bent fiber geometry in the bending plan, the samples curvature has been evaluated through the profiles of the bent fiber region P_{BF} (see for example Fig. 1a). The local fiber curvatures (C) have been estimated according to Ref. [17]:

$$C = \frac{P''_{\mathrm{BF}}}{\left(1+{P'_{\mathrm{BF}}}^{2}\right)^{3/2}} \tag{1}$$

where P'_{BF} and P''_{BF} are the first and second order derivative of P_{BF} versus the x-axis, respectively. Fig. 1c shows the curvature versus the x-axis (centered on the curvature maximum value). As observable, the curvature maximum value – corresponding to the minimum curvature radius ($R = 1/C$) – exhibits a monotonic behavior versus the bend angle. In practice, for the investigated samples the curvature maximum value is strictly related to the bend angle: the higher is the bend angle, the higher is the curvature maximum value and the lower is the curvature radius minimum value. Dif-

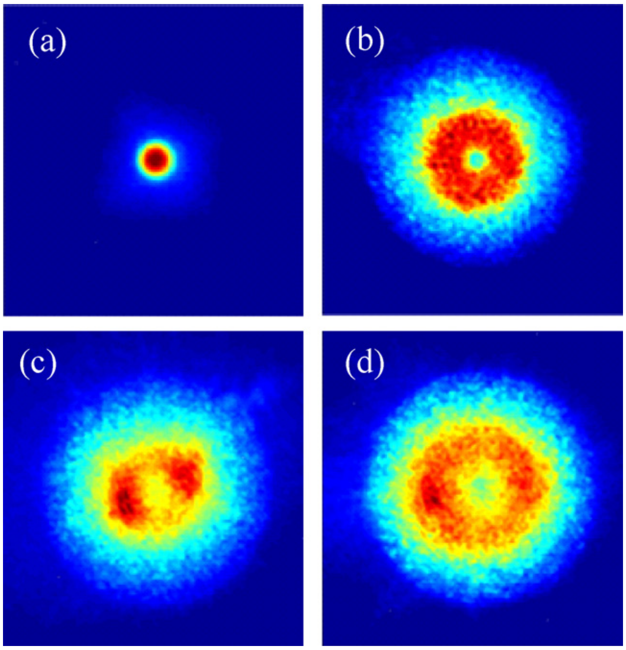

Fig. 2. Far field patterns of the (a) straight fiber, (b) 31°, (c) 52° and (d) 42° bent fibers in air at 1550 nm.

ferently, according to F_{CHORD} definition, the curvature full width half maximum (FWHM) is not monotonic with the bend angle and assumes the minimum value for the 42° case as shown in Fig. 1d, definitively confirming that F_{CHORD} depend on the fiber length involved in the bending procedure. Finally, the geometrical analysis in the bending plan of the investigated samples highlighted that only two distinct parameters can be adopted to characterize the bent fibers: the bend angle (or equivalently the curvature maximum value) and the F_{CHORD} parameter (or equivalently the curvature FWHM).

The analysis of the optical field distribution changes induced by the local bent region has been carried out in transmission mode through an infrared Vidicon camera (Hamamatsu C2741-03). In particular, fiber samples kept without protective coatings and with different bend angles have been cut approximately 25 mm after the bent region. This way, by using a tunable narrowband laser source accordable in the range 1520–1620 nm, the emerging far field from the cut end of the fiber is collected through the IR camera.

Fig. 2a shows the far field pattern of a standard SMF at 1550 nm exhibiting the typical Gaussian-like shape of the field associated to the fundamental core mode. For comparison, Fig. 2b–d, instead, show far field patterns of 31°, 52° and 42° bent fibers, respectively, at 1550 nm. As observable, the introduction of a permanent bend along the fiber enhances the field portion within the cladding region, reducing in turn the optical field associated to the fundamental core mode. It can be retrieved that 31° (Fig. 2b) and 52° (Fig. 2c) bent fibers exhibit a FWHM in the field diameter approximately 4.0 and 4.6 times larger than the fundamental mode, respectively. It is worth noting that in both cases far field emerging from the samples exhibits a ring-shape whereas the light intensity in the core region results strongly weakened. On the other side, the far field profile of the 31° bent fiber exhibits good azimuthal symmetry (intensity variation within 8%) whereas the field profile of the 52° bent fiber exhibit light intensity variation up to 30%. This means that different coupling regime in terms of order and number of involved cladding modes can be achieved by properly modulating the bend features. In particular, the pronounced asymmetry showed by the far field profile of the 52° bent fiber is probably due to physical and/or geometrical asymmetry induced along the bent fiber region during the EAD procedure, leading to the excitation of azimuthal asymmetric cladding modes. Note that the geometrical analysis reported above is able to characterize the bent fiber geometry in the bending plan, but it is unable to describe eventual torsion or elliptical shaping of the bent fiber region during the EAD procedure: such geometrical parameters also need to be investigated in the future. Finally, also in the 42° bent fiber (Fig. 2d) the far field assumes a ring-shaped profile. However the enlargement in cladding region increases exhibiting FWHM approximately 5.5 times larger than the fundamental mode. This means that the power carried by the fundamental mode is coupled towards higher order cladding modes in correspondence of the permanent bent region. Note that the lower is the F_{CHORD} parameter, the higher is the order of the excited cladding modes (see Fig. 1b). This means that the different coupling regimes are influenced by both bend angle and F_{CHORD}, but this last parameter is the main responsible of the order of the excited cladding modes. A deeper analysis about the influence of these two parameters on the mode coupling along the bent region is currently in progress and will be reported in a future publication.

Based on the reported results, it is easy to argue that permanently bent single mode optical fibers can be properly designed to tailor the field profile for specific applications. In particular, a complete power transfer between the core and cladding modes is possible by properly selecting the bend geometry. Moreover, since cladding modes distribution is dependent on the fiber outer medium via evanescent wave, further field manipulation is possible by acting on the SRI.

3. SRI sensitivity

To investigate the dependence of the field distribution on the SRI, fluids with different refractive indices have been used to surround 5 mm long fiber region located between the bent region and the fiber tip. To obtain different refractive indices, glycerin has been mixed with water in different ratios and the resultant solutions have been characterized by an Abbe refractometer with a refractive index resolution of 10^{-4}.

Fig. 3a–e shows the far field patterns of the 31° bent fiber for SRI = 1, 1.33, 1.3465, 1.3598 and 1.3655, respectively at an operating wavelength of 1550 nm. As observable, when the SRI increases the light intensity as well as the FWHM of the field gradually decreases. This can be attributed to the gradual approaching of the cut-off condition for the cladding modes as the SRI increases, depending on the mode order. As the SRI moves from air to 1.33, 1.3465 and 1.3598, the total transmitted power decreases of 3%, 31% and 83%, respectively, as compared with air case. Further increase of SRI (1.3655) induces complete attenuation of all cladding modes involved in the power coupling, and the far field profile is not longer dependent on the SRI value. It is worth noting that when SRI increases up to values higher than the silica refractive index, the light intensity in the fiber center (core) is approximately unchanged due to the presence of core mode (not dependent on SRI).

A similar behavior is also observable in the 52° bent fiber case. The correspondent far field distributions for the same SRI values are plotted in Fig. 3f–l. In this case, the transmitted power decreases of 14%, 70% and 83% as the SRI moves from air to 1.33, 1.3465 and 1.3598, respectively. This means that higher bend angle (52°) is able to excite higher order cladding modes compared to the 31° bent case with a cut-off for the cladding modes occurring for lower SRI values. A further SRI increase (Fig. 3l) attenuates almost completely the optical power demonstrating that the optical power carried from core mode is completely coupled to cladding modes.

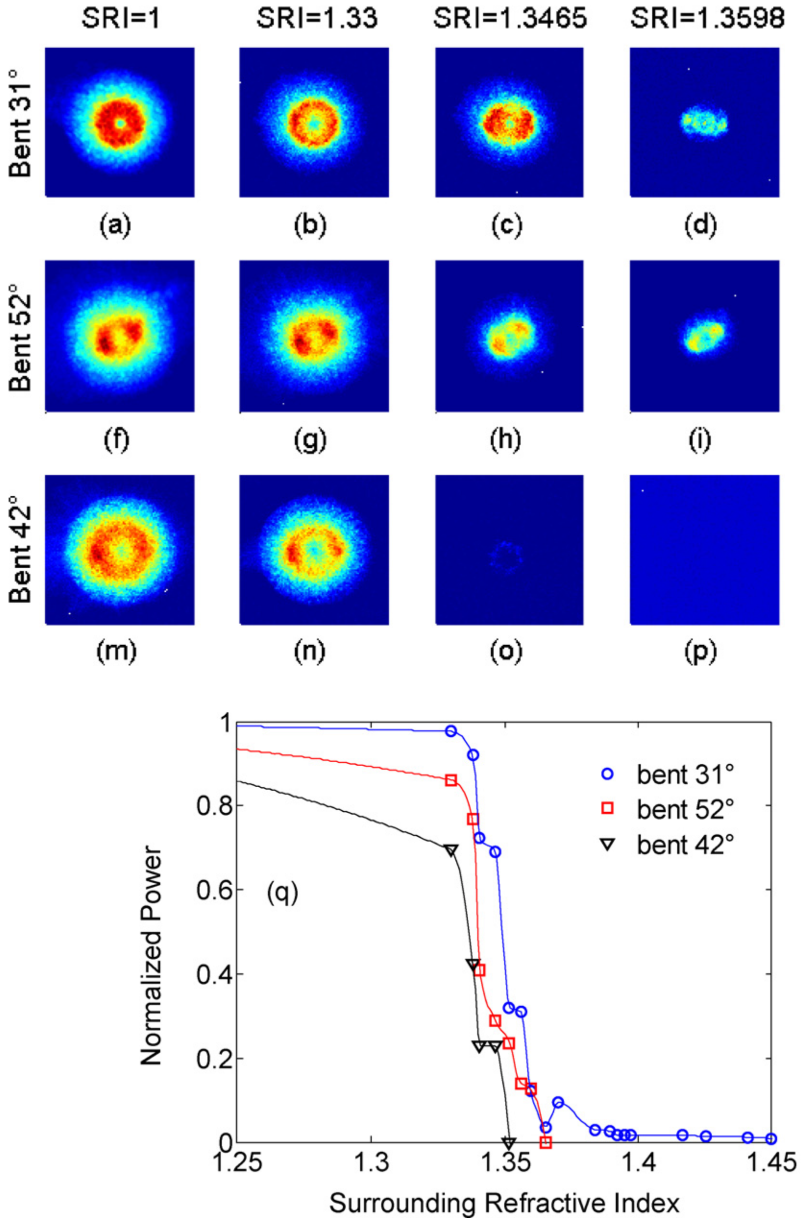

Fig. 3. Field profiles of the 31° (a)–(e), 52° (f)–(l), and 42° (m)–(p) bent fibers for different SRIs; (q) normalized power of the 31°, 52°, and 42° bent fibers versus the SRI.

Finally, the same analysis was repeated with regards the 42° bent fiber. Fig. 3m–p shows the far field patterns for SRI = 1, 1.33, 1.3465 and 1.3598, respectively. Total power decreases of 30% and 77% as SRI moves to 1.33 and 1.3465, respectively. As expected, the 42° bent fiber excites higher order cladding modes due to lower bending radius. Consequently, cut off conditions for the coupled cladding modes occur for lower SRI values if compared with the 31° and the 52° bent fibers. Higher SRI values, Fig. 3p, attenuate completely the optical power demonstrating a negligible residual optical power carried from the core mode.

Fig. 3q shows the behavior of the total transmitted optical power versus SRI (markers) for the investigated samples. It is evident that the transmitted light intensity can be used for high sensitivity refractive index change measurements also in water environmental where evanescent wave based optical sensor are usually not optimized. Intensity sensitivity versus SRI of approximately 9.7%/RIU, 12.2%/RIU and 36.6%/RIU (in terms of percentage of light intensity) for 31°, 52° and 42° bent fibers in case of SRI very close to water refractive index.

The reported results readily suggest a simple interrogation scheme for the proposed low cost sensor. It would be possible to face the fiber termination just after the bent region to a photodiode to detect the amount of power transmitted through the bend.

Nevertheless, light intensity measurements are rather affected by fluctuations in the optical power levels along the optical chain requiring properly designed compensation methods. To overcome this issue, we investigated the spectral dependence of the transmitted intensity in the range 1520–1620 nm. Fig. 4a plots the optical power versus the operating wavelength as function of the SRI for the 31° bent fiber. As expected, for a given operating wavelength, the optical power decreases as well as the SRI increases. This suggests also a sensitivity optimization method through the tuning of the operating wavelength in correspondence of the largest variation observed in the transmitted optical power. Moreover, for a fixed SRI value, the light intensity decreases as well as the operating wavelength exhibiting a slightly sub-linear behavior. It can be attributed to different mechanisms: (i) dependence of core and cladding modes distribution and their power coupling on the oper-

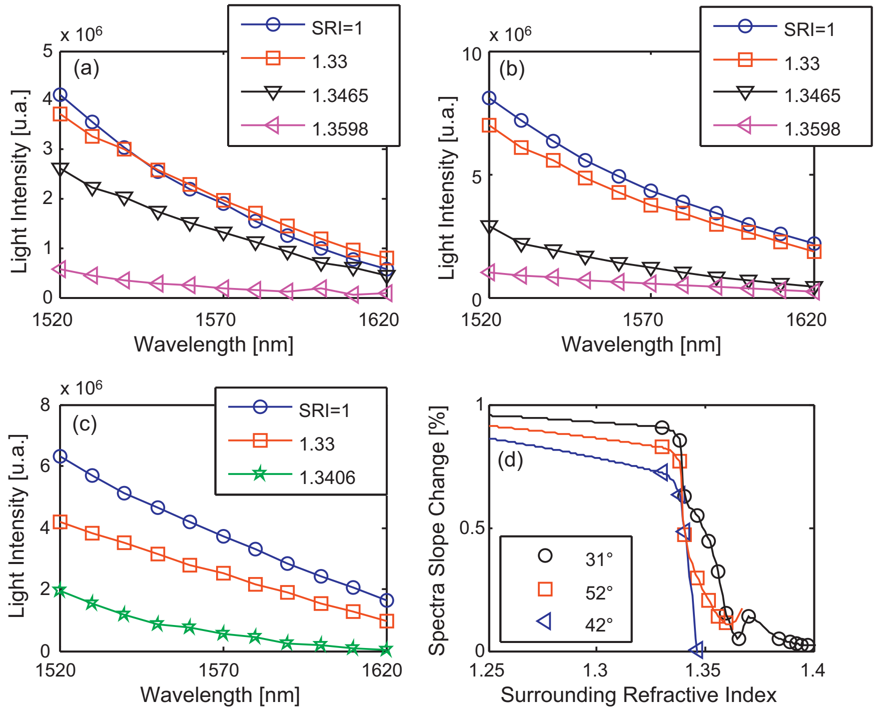

Fig. 4. (a)–(c) Spectra of the 31°, 52°, and 42° bent fibers for several SRIs; (d) changes in the spectral slopes.

ating wavelength; (ii) dispersion coefficient of the surrounding medium. As matter of fact, changes in number and order of radiated cladding modes due to variation of SRI induce a different spectral behavior in terms of slope of the spectral curve versus wavelength. From these considerations, detections of SRI changes are also possible by exploring the spectral changes in the light transmitted through a permanently bent optical fiber.

When SRI reaches 1.3655, all cladding modes are in cut off regime and spectrum is not more dependent on SRI. The same mechanism is experienced in the case of the 52° and 42° bent fiber (see Fig. 4b and c) where maximum spectral changes are expected for lower SRI. To better understand the potential approach of such spectral measurements, in Fig. 4d the percentaged changes in the decreasing spectra slopes versus the SRI are shown for an operating wavelength of 1550 nm. As SRI moves from air to 1.33 the spectra slope decreases of 9%, 18% and 28% for 31°, 52° and 42° bent fibers, respectively.

From these results, permanently bent fibers represent an attractive solution to achieve novel high sensitivity and low cost in fiber evanescent wave based sensor tuned for the specific application through a proper selection of the bend characteristics and thus on the excited cladding modes.

4. Conclusion

In conclusion, the capability of locally and permanently bent SMF to properly manipulate the field distribution by adopting core to cladding mode coupling has been experimentally demonstrated. By acting on the bend characteristics, the number, the order of excited cladding modes as well as the power transfer efficiency can be easily modified. This also leads to a different dependence of the field distribution on the SRI. Experimental results in fact demonstrate the feasibility to use the proposed structures as high sensitivity SRI sensor especially for SRIs close to 1.33 where common optical evanescent wave sensors are not optimized. Moreover, spectral analysis offers new insights on the light manipulation capability of permanently bent optical fibers opening new scenarios in sensing and optoelectronic applications.

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Biographies

Agostino Iadicicco was born in 1974 in Italy. He received the electronic engineering degree cum laude at the Second University of Naples, Italy, in 2002 and the Ph.D. degree in the Information Engineering at the University of Sannio, in 2005. Currently he has a permanent position as assistant professor at the University of Naples "Parthenope", Italy. His field of interest is in the area of fiber-optic devices. In particular he is mainly involved in the design and prototyping of novel devices based on fiber Bragg gratings and long period gratings in standard and new generation optical fibers for sensors and communications application.

Domenico Paladino was born in Sapri, Salerno, Italy, in 1980. He graduated with honors in *Ingegneria delle Telecomunicazioni* (Telecommunications Engineering) at University of Naples "Federico II", Italy, in 2005. In 2009, he received the Ph.D. degree in Information Engineering (tutor: Prof. Antonello Cutolo) from University of Sannio, Benevento, Italy, discussing a thesis titled "Photonic Band-Gap Engineering in Fiber Grating Structures". During his Ph.D. course, on August/September 2008 he carried out his research activity with Prof. Wojtek J. Bock at the Centre de Recherche en Photonique, Université du Québec en Outaouais, Gatineau, Canada. Since December 2008, he is a Project Researcher for Centro Regionale Information Communication Technology (CeRICT) scrl and carries out his research activity at the Engineering Department, University of Sannio, Benevento, Italy. His current research interests are in the area of optical fiber devices, including grating structures, for sensing and communication applications. In particular, his attention is focused on the local micro- and nano-structuring of different optical fiber technological platforms as well as on the effects of depositing coatings with proper optical, geometrical and physical features along such fibers.

Stefania Campopiano is Associate Professor of Electronics and Optoelectronics at the University of Naples "Parthenope", Italy. She received the Electronic Engineering degree cum laude at the University of Naples Federico II, Italy, and the Ph.D. degree in Electronic Engineering from the Second University of Naples, Italy, in 1999 and 2003, respectively. In 2002, she worked at DIMES (Delft Institute of Microelectronics and Submicrontechnology), Technical University of Delft, The Netherlands. Her research activity is focused on the field of optoelectronic devices for sensing and telecommunication applications. She is author and co-author of several international publications including international journals and conferences, co-author of several patent and reviewer for IEEE, OSA and Elsevier journals. She has been cooperating on scientific arguments with several universities and companies in Italy and abroad.

Dr. Wojtek J. Bock received the M.Sc. degree in Electrical Engineering and the Ph.D. degree in Solid State Physics from the Warsaw University of Technology, Poland, in 1971 and 1980, respectively. Since 1989 he is a full professor of Electrical Engineering at the Université du Québec en Outaouais (UQO), Canada. Since 2003 Dr. Bock is Canada Research Chair Tier-I in Photonic Sensing Technologies and Director of the Photonics Research Center at UQO. His research interests include fiber optic sensors and devices, multisensor systems, and precise measurement systems of non-electric quantities. His current research program centers around developing a variety of novel fiber-optic device solutions and sensing techniques with a view to acquiring better performing photonic sensing components, devices and systems for applications in sectors of national importance to Canada. He has authored and co-authored more than 280 scientific papers, patents and conference papers in the fields of fiber optics and metrology which have been widely cited. Dr. Bock is a Fellow of IEEE, and Associated Editor of IEEE/OSA Journal of Lightwave Technology and International Journal of Optics. He is also Chairman of the upcoming International Optical Fiber Sensor Conference (OFS21) to be held in Ottawa in May 2011.

Antonello Cutolo received the Laurea Degree cum Laude in Electronic Engineering from the University "Federico II" of Napoli in 1978 after a six months stage at the Fiat Reasearch Center working on online characterization of mirrors for high power laser systems. After serving for one year the Italian Air Force, he spent one year at the Applied Mathematical Physics Dept. of the University of Copenaghen, working on propagation in non-linear structures, soliton interaction and Josephson structures. In particular, he found the theoretical limit of the bandwidth of finite size josephson oscillators. Then, in 1982, he worked at the National Laboratories of Frascati (Rome) to build a free electron laser on the Adone Storage Ring, where he was in charge of the design and the construction of the optical resonator. In 1983, he was appointed Researcher at the Electronic Dept. of the University of Napoli. In 1983–1986 he worked at the Photon Research Lab. and at the Stanford Linear Accelerator S.L.A.C. of the Stanford University (California) and at the Physics Dept. of the Duke University (North Carolina) where he designed and constructed a set of novel devices for increasing the peak power (cavity dumpers and mode lockers) and the tunability range (broadband output couplers and higher harmonic generators) of a free electron laser. He was appointed, in 1987, Associate Professor of Quantum Electronics at the University of Napoli and, in 1998, full professor of electronics and optoelectronics at the University of Sannio. He has founded and directed two laboratories of optoelectronics finalized to contactless characterization of electronics devices and materials, optical fiber sensors, non-linear optics and nanophotonics applications. Many of the results have founded practical applications in several industrial applications. Professor Cutolo has been the main advisor of many research project in both basic and industrial research which lead to many patents with large and small companies. He has been the tutor of several students working for their PhD program. He has published some books, more than 300 papers on international technical journals and conference proceedings and filed more than 20 patents both in Europe and U.S. He was cofounder in 2005 of the spin-off company "OptoSmart S.r.l.", finalized to the production of optical fiber sensor arrays for environment, structural health monitoring, railway security, harbor surveillance and food quality control application. In addition, he created the Optosonar Consortium finalized to the application of optical fibers to underwater security and monitoring. He has been member of the Scientific Committee of the consortium Corista and he is member of the scientific committee of Confindustria. Prof. Cutolo has been chairmarn or cochair of several national and international technical conferences and he is the referee of several international scientific publications. His research interest involve: optoelectronic modulators and switching, optical characterization of semiconductor devices and materials, laser beam diagnostic, and non-linear optical devices.

Andrea Cusano was born on May 31, 1971, in Caserta. He received his Master degree cum Laude in Electronic Engineering on November 27, 1998 from University of Naples "Federico II", Italy and his Ph.D. in "Information Engineering" from the same university, with tutor Professor Antonello Cutolo. He is actually Associate Professor at the University of Sannio, Benevento. From 1999 his activity is focused in the field of optoelectronic devices for sensing and telecommunication applications. He was cofounder in 2005 of the spin-off company "OptoSmart S.r.l." and in 2007 of the spin-off company "MDTech". He published over 100 papers on prestigious international journals and more than 150 communications in well known international conferences worldwide; he has 4 international patents currently in charge of prestigious industrial companies (Ansaldo STS, Alenia WASS, Optosmart and MdTEch) and more than 10 national patents. He is also referee of several scientific international journals. He is associate editor of Sensors and Transducers Journal, Journal of Sensors (Hindawi), The Open Optics Journal (Bentham), The Open Environmental & Biological Monitoring Journal (Bentham) and the International Journal on Smart Sensing and Intelligent Systems. He is a member of the technical committee of several international conferences such as IEEE Sensors, ICST, EWSHM, EWOFS. Andrea Cusano was principal investigator and scientific responsible of several national and international research projects. He is coauthor of more than 10 chapters published in international books and invited papers in prestigious scientific international journals. He is coeditor of 2 Special Issues (Special Issue on Optical Fiber Sensors, IEEE Sensors 2008, and Special Issue on "Fiber Optic Chemical and Biochemical Sensors: Perspectives and Challenges approaching the Nano-Era", Current Analytical Chemistry, Bentham, 2008 and of 3 scientific international books. He is also consultant for big companies of the Finmeccanica group such as Ansaldo STS and Alenia WASS. He has also collaborations with CERN in Geneva where he is working on the development of innovative sensors for high energy physics applications.