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Fiber Optics Structural Mechanics and Nano-Technology Based New Generation of Fiber Coatings: Review and Extension

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7.1. INTRODUCTION

This chapter consists of two parts—review and extension.

The review part deals with typical fiber optics structures (bare, single- and dual-coated fibers; fibers experiencing low temperature micro-bending; fibers soldered into ferrules or adhesively bonded into capillaries; role of the non-linear stress–strain relationship, etc.) subjected to thermally induced and/or mechanical loading in bending, tension, compression, or to various combinations of such loadings. The emphasis is on the state-of-the-art in the area of optical fiber coatings and the functional (optical), mechanical and environmental problems that occur in polymer-coated or metalized fibers. The solutions to the examined problems are mostly obtained using analytical methods (predictive models) of structural mechanics. The review is based primarily on the author's research conducted at Bell Laboratories, Murray Hill, NJ, during his eighteen years tenure with this company.

The extension part addresses a new generation of optical fiber coatings and deals with the application of a newly developed (by the ERS/Siloptix Co.) nano-particle material (NPM) that is used as an attractive substitute for the existing optical fiber coatings. This NPM-based coating has all the merits of polymer and metal coatings, but is free of many of their shortcomings. The developed material is an unconventional inhomogeneous "smart" composite material, which is equivalent to a homogeneous material with the following major properties: low Young's modulus, immunity to corrosion, good-to-excellent adhesion to adjacent material(s), non-volatile, stable properties at temperature extremes (from −220°C to +350°C), very long (practically infinite) lifetime, "active" hydrophobicity—the material provides a moisture barrier (to both water and water vapor), and, if necessary, can even "wick" moisture away from the contact surface; ability for "self-healing" and "healing:" the NPM is able to restore its own dimensions, when damaged, and is able to fill existing or developed defects (cracks and other "imperfections") in contacted surfaces; very low (near unity) effective refractive index (if needed). NPM can be designed, depending on the application, to enhance those properties most important. NPM properties have been confirmed through testing. The tests have demonstrated the outstanding mechanical reliability, extraordinary environmental durability and, in particular applications, improved optical performance of the light guide.

7.2. FIBER OPTICS STRUCTURAL MECHANICS

Fiber-Optics Structural Mechanics (FOSM) deals with the application of methods and approaches of Structural Engineering (Structural Analysis), as well as of Engineering and Applied Mechanics, to the stress/strain evaluations, and physical design for reliability of fiber-optics structures and systems. FOSM considers the specifics, associated with the properties of the materials used, typical structures employed, as well as the nature, magnitude and variability of the applied loads. FOSM treats an optical fiber system as a structure. In other words, it examines hardware systems, in which the materials' interaction, their size and configuration, and the loads, whether thermally induced or "mechanical," are as important as the characteristics of the employed materials. The main objectives of FOSM have to do with physical design for reliability of fiber optic systems and could be defined as follows:

- determine the loading conditions (which could be due to the thermal expansion mismatch of materials, lateral and angular misalignments, test loads, dynamic loads due to shocks and vibrations, etc.),
- evaluate stresses, strains, and fracture characteristics of the photonics structure, and
- ensure that the chosen strength and reliability criteria will remain, during the lifetime of the structure, within the limits acceptable from the standpoint of structural integrity, elastic stability, dependability, and normal operation, both mechanical (structural) and functional (optical), of the system.

The application of the methods and approaches of FOSM can be very helpful in creating a viable and reliable fiber optics products and networks. In this review we examine a number of practically important problems of the mechanical behavior and structural ("physical") design of bare or coated optical fibers, experiencing thermal, mechanical or dynamic loading. The following major topics are addressed: (1) bending of bare silica fibers, (2) fibers under the combined action of bending and tension, (3) large deflections of fibers, (4) effect of material's nonlinearity, (5) mechanical behavior of polymer coated or metalized fibers, (6) elastic stability and low temperature microbending of optical fibers, (7) solder materials and joints employed in fiber optics, and (8) dynamic response of optical fibers to shocks and vibrations.

7.2.1. Review

The state-of-the-art in the application of methods of materials, mechanical and reliability engineering to photonics structures, including optical fibers, with an emphasis on analytical modeling, design for reliability, and application of probabilistic methods, can be found in the [1–15]. A brief review of the major directions in Fiber Optics Structural Mechanics is given in [4]. Thermal loading is responsible for many failures in photonics engineering. The state of the art in this area is outlined in [5,9,11]. Methods and approaches in evaluating structural reliability of fiber optics systems, including stress/strain analyses and accelerated life testing were addressed in [3,12,14].

Bending of bare fibers, idealized as a single span beams clamped at the ends and subjected to both lateral and/or angular misalignment, was examined, based on the elementary beam theory (see, for instance, [1]), primarily in application to the mechanical behavior of optical fiber interconnects [16–31]. In optical fiber interconnects, angular misalignments and ends offsets are typically due to the inability of the given technology to ensure good alignment of the interconnect ends and/or end cross-sections. In other cases, misalignments are essential, and quite often even desirable, features of a particular package design. In many cases, elevated optical fiber curvatures, caused by various misalignments, can be responsible for both its functional (optical) performance and mechanical (structural) reliability. These curvatures and the resulting bending stresses can be predicted [17–19] and, if necessary, successfully minimized [18,21–24] for lower curvatures. These are responsible for both added transmission losses and mechanical reliability.

Three- or four-point bending is often used to experimentally evaluate the Young modulus of the silica material and its ultimate flexural strength. If such testing is conducted, it is important to make sure that the test specimen is long enough so that the effect of shear would not have to be considered [16].

Elevated lateral gradients of the coefficients of thermal expansion and Young's moduli (in direction of the fiber diameter) can be responsible for the fiber "curling" during drawing of optical silica fibers [19]. The analysis, reported in [19], was carried out on the basis of both analytical ("mathematical") and numerical (finite element) modeling.

Bare fibers under the combined action of bending and tension were examined in connection with proof testing of optical fibers soldered (epoxy bonded) into ferrules (capillaries) [25]. It has been shown that the fiber under testing should be long enough so that the inevitable end misalignment would not result in appreciable bending stresses. The effect of these stresses should be accounted for, if the test specimen cannot be made sufficiently long and/or if a sufficiently good alignment could be achieved. If the lateral misalignment of an optical fiber interconnect is not very small, and the interconnect ends cannot move closer when it experiences substantial bending deformations, then reactive tension occurs. The resulting tensile stresses can be analyzed on the basis of a linear theory. This could be done, if bending deformations are large enough to produce appreciable reactive tensile stresses, but still small enough not to necessitate the application of a nonlinear approach [27,28]. Tensile stresses are highly undesirable in silica fibers. In combination with surface cracks and moisture, such stresses can lead to a rapid rupture of a silica fiber. On the other hand, elevated compressive stresses can lead to fiber buckling, thereby producing tensile stresses due to bending. In some cases, the thermal contraction mismatch between the silica fiber enclosure and the fiber itself can be effectively used to minimize the tensile stress in an optical fiber interconnect subjected to both end misalignment and thermally induced compression [28,29].

Consideration of the structural ("geometric") and materials ("physical") nonlinearity might be necessary, if the fiber experiences large bending and/or axial deformations [32–44]. The effect of the structural nonlinearity, which is due to the significant bending deformations of optical fibers, and the materials nonlinearity, caused by the nonlinear stress-strain relationship in silica materials subjected to tension, has been analyzed by many investigators (Cowap and Brown [36], France et al. [35], Krause et al. [34], McMullin and Freeman [37], Murgatroyd [32], Sinclair [33], Suhir [38–40], Muraoka [44]). The combined effect of the materials nonlinearity and the nonprismaticity of a fused biconical taper (FBT) optical coupler on the induced thermally induced stresses was analyzed in [41].

Optical fiber "pigtails" often experience three-dimensional bending deformations. Substantial relief in the induced bending stresses and curvatures can be achieved by optimizing the "pigtail's" configuration [42,43].

Coated fibers, whether polymerically coated (see, for instance, Devadoss [48], Gebizioglu and Plitz [47], King and Aloisio [54]) or metalized (see, for instance, papers published in [1]), are widely employed for better short- and long-term reliability of the silica material, which is both brittle and moisture-sensitive. Problems encountered during design, manufacturing, testing, and reliability assessments for dual-coated glass fibers include: evaluation of the effect of coating on the bending stresses [45,46], understanding the delamination mechanisms and improving strippability [46,49,52], prediction of the magnitude and distribution of stresses occurring during proof (pull-out) testing [49–62], etc.

Understanding and optimizing the interaction of "global" and "local" thermally induced stresses in optical glass fibers adhesively bonded or soldered at the ends into capillaries or ferrules is important for the "physical" design of, and reliability assessments for, these structures. This can be done on the basis of a simplified analytical stress model developed for a cylindrical b-material assembly adhesively bonded at the ends [56].

Elastic stability and microbending of optical fibers is important primarily in connection with the added transmission losses associated with these phenomena (Cocchini [71], Ostojic [76], Shiue [66–68,70,72–75,79,80], Suhir [63–65,69,77,78,81,82]). In metalized fibers, however, the high Young modulus of metalization can cause significant strength problems for both the metalization and the fiber [62]. Therefore the application of "hard" metalization should be carried out with caution, unless no appreciable thermal deformations of the interconnect are expected.

It has been noticed [77] that external periodic loading with the period of about 100 nm can cause appreciable microbending losses in dual-coated fibers, and therefore should be avoided in actual designs. It has been noticed also [65] that the threshold of elevated low temperature transmission losses in polymer-coated fibers corresponds to the temperature at which the stresses at the coating/glass interface start to increase rapidly. This circumstance enables one to predict this threshold by stress calculation; instead of much more complicated optical calculations or measurements.

Voids in the solder joints and adhesives in soldered or adhesively bonded fiber optic assemblies cause natural concerns of fiber optics designers. Effect of voids in epoxy-bonded fibers was analyzed in [78] for different void size, configurations, locations, etc.

Solder materials and joints are as important in photonics and, particularly, in fiber optics, as they are in microelectronics. There is, however, a number of specific requirements for the solder materials and joints used in photonics: ability to achieve high alignment, requirement for a very low creep, etc. [84]. Thermally induced stresses in optical fibers soldered into various ferrules were addressed in [83]. It has been shown that low expansion enclosures is not always the right choice from the standpoint of the thermally induced stresses in optical fibers soldered into ferrules, as well as the stresses in the solder material itself.

Dynamic response of fiber optic structures to shocks and vibrations was examined in [85–90]. The ability to predict and possibly minimize the dynamic stresses in fiber-optic systems is of obvious practical importance. It has been shown, particularly, that the application of the maximum acceleration as the criterion of strength of a structural element in a microelectronic or photonic design can be misleading [87].

7.3. NEW NANO-PARTICLE MATERIAL (NPM) FOR MICRO- AND OPTO-ELECTRONIC APPLICATIONS

7.3.1. New Nano-Particle Material (NPM)

A new advanced nano-particle material (NPM) has been developed by the ERS/Siloptix Co. [91–95]. This material has many attractive applications in micro- and opto-electronic packaging. Particularly, an effective practical technology for making NPM-based optical silica fiber coatings has been developed under grants from DARPA/Navy. The developed technology enables one to create ultra-thin, highly cost-effective, highly mechanically reliable, and highly environmentally durable coatings for silica light-guides. The obtained results have demonstrated the performance superiority of the developed technology over polymer-coated and metalized fibers, as well as a potential that the NPM has for various commercial and military applications in micro- and opto-electronics packaging and related areas. It can have many attractive applications also well beyond the "high-tech" field. NPM is an unconventional inhomogeneous "smart" composite material. It is equivalent to a "hypothetical" homogeneous material with the following major properties:

- Low Young's modulus
- Immunity to corrosion
- Good adhesion to the adjacent material
- Non-volatile
- Stable properties at temperature extremes (from +350°C to as low as −220°C)
- Very long (practically infinite) lifetime
- Strong hydrophobicity (against both water and water vapor)
- Ability for "self-healing:" ability to restore its dimensions and initial structure when damaged
- Ability for "healing" the surfaces of the adjacent materials, i.e., to fill in the existing and/or the developed defects (surface cracks, flaws, and other imperfections) and to slow down their propagation and/or even to "arrest" them completely
- Very low effective refractive index (if needed)
- High dielectric constant (if needed).

The NPM can be designed, depending on the particular application, in such a way that its most important particular properties are enhanced. The conducted tests have confirmed these properties. In general, it is desirable to provide application-specific modifications of the NPM to master/optimize its properties and performance. Because it is a nano-material, its surface chemistry and its performance depend a lot upon the contact materials and surfaces. With this in mind, the following applications are viewed as the most attractive ones.

- NPM is able to hermetically seal packages, components and devices, such as laser packages, MEMS, displays and plastic LEDs.
- NPM can be used as an effective protective coating for various metal and non-metal surfaces, well beyond the area of micro- and opto-electronic packaging: in cars, aerospace structures, offshore and ocean structures, marine vehicles, civil engineering structures (bridges, towers, etc.), tubes, pipes and pipe-lines, etc. These

applications benefit because the material is actively hydrophobic, does not induce additional stresses (owing to its low modulus), is inexpensive, is easy-to-apply, has practically infinite lifetime, and is self-healing. Application of this material can result in a significant resistance of a metal surface to corrosion, and, in addition, in substantial increase in the fracture toughness of the material, both initially and during the system's operation (use).

- The NPM can be added in the formulation of various coatings such as paints, thereby providing protective benefits without changing the application techniques.
- Because of a low refractive index, the NPM can be used, if necessary, as an effective cladding of optical silica fibers. The use of the NPM cladding eliminates the need to dope silica for obtaining light-guide cores. The new perform will consist of a single (undoped and, hence, less expensive) silica material.
- A derivative application is flexible light-guides. Multicore flexible fiber cables employing NPM are able to provide high spatial image resolution. As such, they might find important applications, when there is a need to provide direct high-resolution image transmission from secluded areas. Possible applications can be found in biomedicine, nondestructive evaluations, oil and other geological explorations, in ocean engineering, or in other situations when an image needs to be obtained and transmitted from relatively inaccessible locations. In such applications, the plane ("butt") end of the fiber bundle (cable) will play the role of a small size pixel array. The transmitted image can be concurrently or subsequently enlarged to a desirable size, as needed.
- Another derivative application is a multicore fiber cable. Ultra-small diameter glass fibers with an NPM-based cladding/coating can be placed in large quantities within a NPM medium ("multiple cores in a single cladding"). In addition, owing to a much better inner-outer refractive index ratio in the NPM-based fibers, such cables will be characterized by very low signal attenuation.
- Another derivative application is sensor systems. The NPM-based fibers can be used in optical sensor systems that employ optical fibers embedded in a laminar or a cast material. Such systems are used, for instance, in composite airframes. With the NPM used as a cladding or, at least, as a coating of the silica optical fiber, the optical performance and the mechanical reliability of the light-guide will improve dramatically compared with the conventional systems.
- Ultra-thin planar light-guides are another derivative application of the NPM. In the new generation of the planar light-guides, NPM can be used as the top cladding material. It will replace silicon or polymer claddings, which are considered in today's planar light-guides. All the advantages of the NPM cladding material discussed above for optical fibers are equally applicable to planar light-guides. These are thought to have a "bright" future in the next generation of computers and other photonic devices.

7.3.2. NPM-Based Optical Silica Fibers

A modification of the NPM has been developed and tested as an attractive substitute for the existing hermetic and non-hermetic optical fiber coatings. The following major activities were undertaken and the following results were obtained:

- The drawing (manufacturing) process and the drawing tower were adequately retrofitted to adjust them to the characteristics of the developed NPM and to the NPM layer application procedure
- The conducted mechanical tests have demonstrated remarkable strength (up to 7.5 GPa = 765 kgf/mm sq = 1088 kpsi) and attractive quality (low strength variability) of the manufactured NPM-based fibers. Such high strength characteristics have been never achieved before, even in the lab conditions.
- The environmental tests have shown that even at the humidity level of 100% (samples were immersed into water for 24 hours) the mechanical strength of these fibers is on the order of the strength of the best quality fibers at the "dry" conditions in the previous tests. There is reason to believe that the achieved performance is still not a limit of the NPM-based technology and that the higher fibers strengths and better environmental stability are feasible by further "fine tuning" and further optimization of the NPM and the drawing procedure.
- The optical performance of the NPM-based fibers (in terms of the attenuation level) is almost two-fold better than the optical performance of the reference (existing) samples. The estimated lower limit of the NPM based optical fibers with silica glass core and stepwise refractive index change, can potentially get a record values for the tested type of multi-mode fibers (getting even below 1 dB/km in a specific spectral "window").

The obtained results clearly demonstrated the performance superiority of the developed technology and a great potential (scientific, technological and commercial) of the future products, which makes the project attractive for the commercialization. The commercialization phase of the project will allow one to broaden the scope and the range of the NPM compounds modeling leading to much more "smarter" and better "self-programmable" claddings/coatings, including transparent and other special properties NPM materials for claddings and coatings. Some NPM coated samples are shown in Figures 7.1 and 7.2. Figures 7.3 and 7.4 illustrate the significant advantages, in terms of the

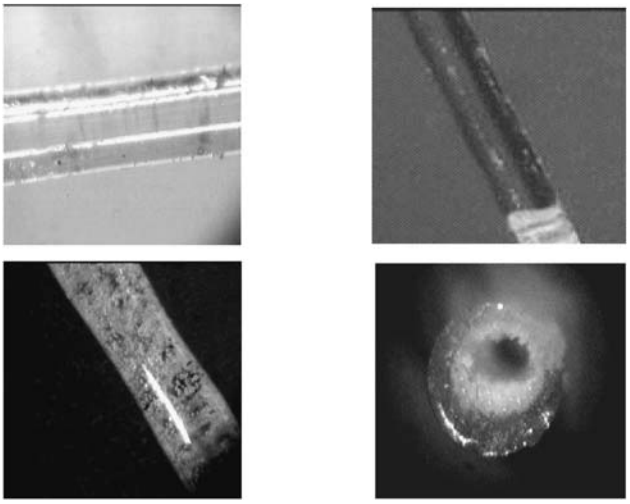
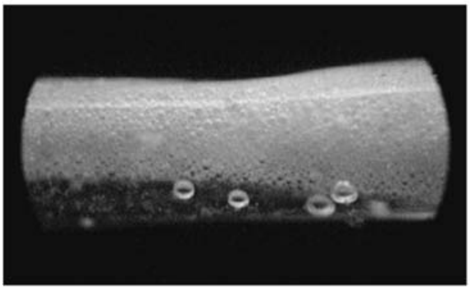


FIGURE 7.1. NPM coated samples.



Advantages of this structure are:

- **Good strippability**
- **Tensile and twisting stresses applied to the fiber are, actually, applied to the coating only**
- **Reduced bending stresses applied to the core/cladding for the same bending radii**

FIGURE 7.2. NPM-based containing structures-1.

Strength Distributions of NPM -Coated (Blue) and Reference (Red) Fibers

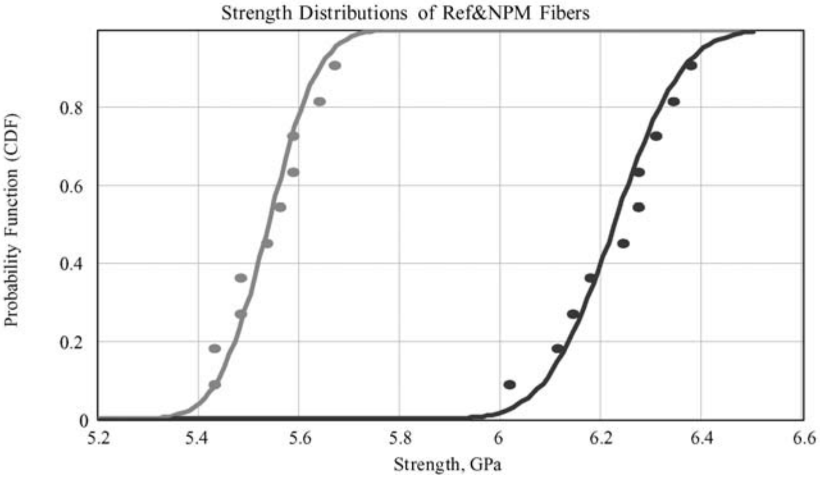
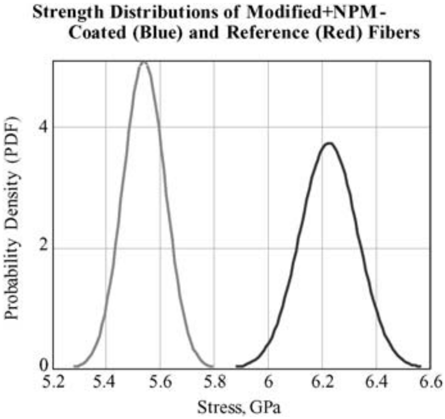


FIGURE 7.3. Samples manufactured using improved technology environmental tests (RH = 100%).



At a high humidity level, the gap between the strengths of the NPM-coated and the reference population is even greater: the weakest NPM-coated sample turned out to be substantially stronger than the strongest reference fiber sample

FIGURE 7.4. Samples manufactured using improved technology.

fiber strength, of the NPM-based coating technology over the conventional, polymer-based, optical fiber coatings.

7.4. CONCLUSIONS

The following conclusions can be drawn from the carried out study:

- The application of the methods and approaches of Fiber Optics Structural Mechanics (Structural Analysis of fiber optics systems) can be very helpful in creating a viable and reliable fiber optics products and networks.
- A viable and effective advanced technology for drawing optical silica fibers with the NPM-based coatings has been developed. This technology has many important advantages over the existing “non-hermetic” (polymer) and “hermetic” (metalization, carbon, etc.) coating materials.
- The conducted mechanical tests have demonstrated remarkable strengths (up to 7.5 GPa) and attractive quality (low local strength variability) of the manufactured NPM-Coated fibers.
- Environmental tests showed that even at the humidity level of 100% (samples were immersed into water for 24 hours) the mechanical strength of these fibers is on the order of the strength of the best quality fibers at dry conditions in the previous tests.
- There is a reason to believe that the achieved performance is still not a limit of the NPM coating technology and that the higher fibers strengths and environmental stability are feasible by further “fine tuning” and optimization of the NPM coating compound content and the drawing procedure.
- The achieved results clearly demonstrated the performance superiority of the developed technology and a great potential (scientific, technological and commercial) of the future products, which makes the project extremely attractive for commercialization.

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