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FIBER OPTICS ENGINEERING: PHYSICAL DESIGN FOR RELIABILITY

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Abstract. *The review part of the paper addresses analytical modeling in fiber optics engineering. Attributes and significance of predictive modeling are indicated and discussed. The review is based mostly on the author's research conducted at Bell Laboratories, Physical Sciences and Engineering Research Division, Murray Hill, NJ, USA, during his tenure with Bell Labs for about twenty years, and, to a lesser extent, on his recent work in the field. The addressed topics include, but are not limited to, the following major fields: bare fibers; jacketed and dual-coated fibers; coated fibers experiencing thermal and/or mechanical loading; fibers soldered into ferrules or adhesively bonded into capillaries; roles of geometric and material non-linearity; dynamic response to shocks and vibrations; as well as possible applications of nano-materials in new generations of coating and cladding systems.*

The extension part is concerned with a new, fruitful and challenging direction in optical engineering- probabilistic design for reliability (PDfR) of opto-electronic and photonic systems, including fiber optics engineering. The rationale behind the PDfR concept is that the difference between a highly reliable optical fiber system and an insufficiently reliable one is "merely" in the level of the never-zero probability of failure. It is the author's belief that when the operational reliability of an optical fiber system and product is imperative, the ability to predict, quantify, assure and, if possible and appropriate, even specify this reliability is highly desirable.

Key words: fiber optics engineering, optical fibers, design-for-reliability, predictive modeling, probabilistic assessments

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1. PHYSICAL DESIGN-FOR-RELIABILITY IN FIBER OPTICS ENGINEERING

1.1. Fiber optics engineering (FOE)

Three major objectives are pursued in fiber optics engineering (FOE), as far as its short- and long-term reliability is concerned: 1) failure-free functional (optical) performance; 2) high physical (structural, mechanical) reliability; and 3) satisfactory environmental durability. The physical design for reliability (DfR) effort deals primarily with the second objective, but, to an extent, also with the other two as well. The DfR effort employs methods and approaches of Reliability Physics and Structural Analysis and is aimed at evaluating stresses, strains and displacements in fiber optics structures, carry out physical design of these structures, and assess and assure their short- and long-term reliability. Physical DfR effort treats fiber optics products as structures: the materials interaction, the size and configuration of the structural elements in the product, physical nature and magnitude of the applied loads, and the ability to quantify reliability are as important in this effort as the optical properties and characteristics of the employed materials.

The application of methods and approaches of DfR in FOE systems enables one to design, fabricate and operate a viable and reliable product [1]-[11]. Like traditional and much better developed branches of DfR, such as civil, aircraft, space, maritime, automotive, etc., DfR in FOE considers the specifics, associated with the properties of the materials used, typical structures employed, and the nature, magnitude and variability of the applied loads. Typical FOE structures are bare or composite (coated) rods and beams of various lengths and flexural rigidities. These structural elements could be soldered into ferrules, adhesively bonded into capillaries, or embedded into various materials and media. Typical materials are silica glasses; polymers (coatings, adhesives, and even polymer light-guides); semiconductors, including compound semiconductors; metals, and, first of all, solders, both “hard” (e.g., gold-tin) and “soft” (e.g., silver-tin) ones. Typical loads include internal (thermal) loads caused by dissimilar materials and/or by temperature gradients, and/or high- or low-temperature environments (temperature extremes); external (mechanical) loads due to the inevitable or imposed, but always critical, deformations; or possible dynamic loads caused by shocks, vibrations, acoustic noise or impact, etc. High voltage, electric current, ionizing radiation and/or extensive light output from a powerful laser source are also considered as loads (stressors, stimuli).

DfR in FOE pursues, but might not be limited to, the following major objectives:

1) Determine and idealize, for the sake of predictive modeling, the most likely loading conditions;

2) Evaluate the stresses, strains, displacements, and, when methods and approaches of fracture mechanics are applicable, also fracture characteristics of the fiber optics materials and structures;

3) Assure, typically on the probabilistic basis, that the acceptable strength and reliability criteria will remain, during the lifetime of the product, within the limits allowable from the standpoint of the product’s structural integrity, elastic stability, dependability, availability and normal operation.

While an optical engineer is and should be concerned, first of all, with the functional (optical) performance of the FOE product, an adequate performance of this product cannot assured, if its ability to withstand elevated stresses (physical reliability) and exhibit adequate environmental durability (ability to withstand degradation and aging at high temperature and/or humidity environments) is not taken care of. Accordingly, we consider the following stress-strain analysis problems encountered in FOE:

1) Role and attributes of, and challenges in, predictive modeling in FOE problems: the emphasis is on the analytical (mathematical) modeling;

2) Thermal stress in fiber optics structures: it is this stress and strains (displacements) that are the most typical and most detrimental in these structures;

3) Bending of bare fibers caused by the ends off-set;

4) Bare fibers under the combined action of bending and tension;

5) Role of the structural and materials nonlinearity;

6) Coated fibers and stresses that occur in the glass material during the design, fabrication, operation and proof-testing of such fibers;

7) Micro-bending of dual-coated fibers intended for long haul communication;

8) Solder materials and joints, and fibers soldered into ferrules;

9) Dynamic response of electronic and photonic systems, including optical fibers, to shocks and vibrations;

10) New nano-material and its applications in fiber optics, photonics and beyond;

11) Some special FOE problems: strain-free planar optical waveguides; apparatus and method for thermostatic compensation of temperature sensitive optical devices; stresses and strains in fused bi-conical taper couplers; “curling” phenomenon during drawing of optical fibers; effect of voids.

The extension part deals with a novel direction in “high-tech” engineering -probabilistic design for reliability (PDfR) of electronic and photonic systems, including optical fibers and interconnects. The objective of this direction is to provide quantitative probabilistic assessments of the likelihood of operational failures of OE materials, devices and systems. The PDfR direction is based on the rationale that when reliability is imperative, the ability to predict, quantify, assure, and, if possible and appropriate, even specify it, is highly desirable, or even a must.

1.2. Predictive modeling (PM) in fiber optics engineering (FOE): role, attributes, challenges

Modeling is the major approach of any science, whether pure or applied. Research and engineering models can be experimental or theoretical. Experimental models are typically of the same physical nature as the actual phenomenon or the object. They reproduce a notion or an object of interest in a simplified way and often on a different scale. Theoretical models represent real phenomena using abstract notions. The goal of a theoretical model is to reveal non-obvious, often even paradoxical, relationships hidden in the available intuitively obvious and/or experimentally proven input information [12]-[17]. A theoretical model can be either analytical or numerical (computational). Analytical models often employ more or less sophisticated mathematical methods of analysis. The today’s numerical models are computer-aided. The most widespread model in the stress-strain evaluations and physical design for reliability in FOE is finite-element analysis (FEA).

Experimental and theoretical models have their merits and drawbacks, their areas of application, and should be viewed as equally important and equally indispensable for the design of a viable, reliable, and cost-effective FOE product. One should always try to avoid to be blamed that because his/her only tool is a hammer, all the problems look like nails to him/her. Although the role of theoretical modeling, mostly computer-simulations based, has dramatically increased in FOE during the last two decades, the situation is still essentially different from the traditional areas of applied science.

The majority of studies dealing with the physical design and performance of FOE materials and products are experimental, and there are several reasons for that. First, experiments could be carried out with “full autonomy”, i.e. without necessarily requiring theoretical support. Unlike theory, testing can be, and is, in effect, used for final proof of the viability and reliability of a FOE product. That is why testing procedures are essential requirements of military and commercial specifications for such products. Second, experiments in the FOE field, expensive as they are, are considerably less costly than, e.g., hulls in naval architecture, or fuselages in the aerospace field, or objects in civil engineering, where "specimens" might cost millions of dollars. Third, FOE experimentations are much easier to design, organize, and conduct than in the macro-engineering world. Fourth, materials whose properties are unknown are often and successfully employed in various FOE applications. Lack of information about the properties of such materials is often viewed as an obstacle for implementing theoretical modeling. Finally, many of the leading specialists in FOE (experimental physicists, materials scientists, chemists, chemical engineers) traditionally use experimental methods as their major research tool. Some of them simply do not feel that adding theoretical modeling will make an appreciable difference in the state-of-the-art of what they do. It is not surprising that eleven out of twelve Bell Labs Nobel laureates were experimentalists.

On the other hand, the application of experimental modeling, unlike theoretical modeling, requires, as a rule, considerable time and is often associated with significant expense. What is even more important though is that experimental data inevitably reflect the effect of the combined action of a variety of factors affecting the phenomenon or the product of interest. This makes experimentation often insufficient to understand the behavior and the performance of an FOE material or a device. Such a lack of insight inevitably leads to tedious, time-consuming and costly experimental procedures. As a rule, the experimental data cannot be simply extended to new situations or new designs that are appreciably different from those tested. It is always easy to recognize purely empirical relationships obtained by formal processing of experimental data and not based on rational theoretical considerations reflecting the physical nature of the phenomenon of interest. Purely experimental relationships contain, as a rule, fractional exponents and coefficients, odd units, etc. Although such relationships may have a certain practical value, the very fact of their existence should be attributed to the lack of knowledge in the given area of applied science. Typical examples are a power law (e.g., the one used in proof-testing of optical fibers, when their delayed fracture, aka as “static fatigue”, is evaluated) or an inverse power law (e.g., numerous relationships of Coffin-Manson type used to evaluate the lifetime of solder joint interconnections).

In view of the above, here is what could be gained by using theoretical modeling:

1) Unlike experimentation, predictive modeling is able to shed light on the role of each particular parameter that affects the behavior and performance of the material, structure or a system of interest;

2) Although testing can reveal insufficiently robust elements, it is incapable to detect superfluously reliable ones; “over-engineered” (superfluously robust) objects may have excessive weight and be more costly than necessary; in mass production of expensive products, superfluous reliability may entail substantial and unnecessary additional costs;

predictive modeling might be able to reveal the “over-engineered” and, hence, cost-ineffective elements of a FOE design;

3) Theoretical modeling can often predict the result of an experiment in less time and at a lower expense than it would take to perform the actual experiment;

4) In many cases, theory serves to discourage wasting time on useless experiments; numerous attempts to build impossible heat engines have been prevented by a study of the theoretical laws of thermodynamics; while this is, of course, a classical and an outstanding example of the triumph of a theory, there are also numerous, though less famous, examples, when plenty of time and expense were saved because of prior theoretical modeling of a problem of interest;

5) In the majority of research and engineering projects, a preliminary theoretical analysis enables one to obtain valuable information about a phenomenon or an object to be investigated, and gives an experimentalist an opportunity to decide, what and how should be tested or measured, and in what direction success might be expected.

6) By shedding light on “what affects what”, theoretical modeling often serves to suggest new experiments: theoretical analyses of thermal stresses in bi-material assemblies (E. Suhir, ASME J. Appl. Mech., vol. 53, No. 3, Sept. 1986) and in semiconductor thin films (S. Luryi and E. Suhir, Applied Physics Letters, vol. 49, No. 3, July 1986) triggered numerous experimental investigations aimed at the rational physical design of semiconductor crystal grown assemblies;

7) Theory can be used to interpret empirical results and to bridge the gap between different experiments and can be used to extend the existing experience on new materials and products;

8) One cannot do without a good theory when developing rational (optimal) designs; the idea of optimization of structures, materials, functions and costs, although new in FOE, has penetrated many areas of modern engineering; no progress in this direction could be achieved, of course, without application of theoretical methods of optimization.

1.3. Analytical vs. numerical modeling

Analytical modeling [18]-[23] occupies a special place in the predictive modeling effort: it is able not only to come up with relationships that clearly indicate “what affects what”, but, more importantly, can often explain the physics of phenomena and especially paradoxical situations better than the FEA modeling, or even experiments, can. Although the basics of FEA modeling were known since mid-thirties or so, it is since mid-1950s, when high-speed and powerful computers have become available, FEA modeling has become the major research tool for theoretical evaluations in many areas of engineering. Since mid-1970s, FEA has become the major modeling tool in electronics and photonics as well. This can be attributed, first of all, to the developments of computer science and engineering and the availability of numerous powerful and flexible computer programs. These programs enable one to obtain, within a reasonable time, a solution to almost any stress-strain related problem.

Broad application of computers, however, has, by no means, made analytical solutions unnecessary or even less important, whether exact, approximate, or asymptotic. Simple and easy-to-use analytical relationships have invaluable advantages, because of the clarity and compactness of the obtained information and explicit indication of the role of various factors affecting the given phenomenon or the behavior of the given material or the device. These advantages are especially significant when the parameter under investigation depends on more than one variable. As to the asymptotic techniques, they can be successful in many cases, when there are difficulties in the application of computational methods, e.g., in various problems containing singularities. Such problems are often encountered in FOE, because of wide employment of assemblies comprised of dissimilar materials. But, even when application of FEA encounters no difficulties, it is always advisable to investigate the problem analytically before carrying out FEA analyses. Such a preliminary investigation helps to reduce computer time and expense, develop the most feasible and effective preprocessing model and, in many cases, avoid fundamental errors.

Let us indicated several attributes of the analytical modeling effort in comparison with the FEA:

1) FEA has been originally developed for structures with complicated geometry and/or with complicated boundary conditions (such as, e.g., avionics structures), when it might be difficult to apply analytical approaches. As a consequence, FEA has been especially widely used in those areas of engineering, in which structures of complex configuration are typical (aerospace, maritime and offshore structures, some civil engineering structures, etc.). In contrast, FOE structures are usually characterized by relatively simple geometries and can be easily idealized as cylindrical beams, flexible rods, rectangular or circular plates, various composite structures of relatively simple geometry, etc. There is an obvious incentive therefore for a broad application of analytical modeling in FOE.

2) The adjacent structural elements in FOE often have dimensions (thicknesses) that differ by orders of magnitude. Typical examples are dual-coated fibers, thin-film systems fabricated on thick substrates, and adhesively bonded assemblies, in which the bonding layer (or the primary coating) is, as a rule, significantly thinner than the bonded components (secondary coating). Since the mesh elements in a FEA model must be compatible, FEA of such structures often becomes a problem of itself, especially in regions of high stress concentration. Such a situation does not occur, however, when an analytical approach is used.

3) There is often an illusion of simplicity in applying FEA procedures. Some users of FEA programs believe that they are not even supposed to have any prior knowledge of structural analysis and materials physics, and that the ”black box" they deal with will automatically provide the right answer, as long as they push the right keys on the computer. At times, a hasty, thoughtless, and incompetent application of computers can result in more harm than good by creating an impression that a solution has been obtained when, actually, this "solution" is simply wrong. It is well known to those with hands-in experience with FEA that although it might be easy to obtain a FEA solution, it might be quite difficult to obtain the right solution. And how would one know that he/she obtained the right solution, if there is nothing to compare it with? In effect, one has to have good background in reliability and materials physics to develop an adequate, feasible, and economic preprocessing model and to correctly interpret the obtained information, and preliminary analytical modeling can be of significant help in that. Clearly, if the FEA data are in good agreement with the results of an analytical modeling (which is usually based on quite different assumptions), then there is a reason to believe that the obtained solution is accurate enough.

A crucial requirement for an effective analytical model is its simplicity and clear physical meaning. A good analytical model, which can be of real help in “high-tech” engineering, should produce simple, easy-to-use and physically meaningful relationships that clearly indicate the role of the major factors affecting a phenomenon or an object of interest. One authority in applied physics remarked, perhaps only partly in jest, that the degree of understanding of a phenomenon is inversely proportional to the number of variables used for its description.

Although an experimental approach, unsupported by theory, is "blind," theory, not validated by an experiment, is "dead." It is the experiment that forms a basis for a theoretical model, provides the input data for theoretical modeling, and determines the viability, accuracy, and limits of application of a theoretical model. Limitations of a theoretical model are different in different problems and, in the majority of cases, are not known beforehand. It is the experimental modeling therefore, which is the “supreme and ultimate judge” of a theoretical model.

A physical experiment can often be rationally included into a theoretical solution to an applied problem. Even when some relationships and structural characteristics lend themselves, in principle, to theoretical evaluation, it is sometimes simpler and more accurate to determine these relationships empirically. A good example is the spring constant of an elastic foundation provided by the primary coating in dual coated optical fibers.

1.4. Bending of bare fibers

Bending of bare fibers, idealized as a single span beams clamped at the ends and subjected to lateral and/or angular misalignment(s) was examined, based on the engineering beam theory, in application to the stress-strain evaluations in optical fiber interconnects [24]-[34]. Angular misalignments and lateral ends-offsets might be due to the inability of the given technology to ensure good alignment of the interconnect ends and/or end cross-sections, but might be also essential, and quite often even desirable, features of a particular design.

Elevated optical fiber curvatures, caused by misalignments, affect both functional (optical) performance and mechanical (structural) reliability of the fiber interconnects. These curvatures and the resulting bending stresses can be predicted and, if necessary, minimized for lower curvatures, thereby minimizing also the added transmission losses in, and structural reliability of, an interconnect. Sometime it might be particularly easy and effective to minimize the maximum curvatures by simply rotating the end cross-section of the interconnect. The directions and the angles of rotation could be predicted depending on the measured lateral misalignments [24], [25], [31]-[34].

An important factor in the assessment of the level of the reactive axial tensile forces in an interconnect experiencing ends off-set is the magnitude of the off-set for its given interconnect length (span). Reactive forces arise because the supports of the actual interconnect cannot move closer when the interconnect is subjected to the end’s off-set. In such a situation the interconnect experiences, in addition to bending, also reactive tension. This tension might be neglected nevertheless, if the misalignment is small compared to the interconnect length [26]. How small is “small” could be determined based on a more general, but still simple, predictive model that takes into consideration the possible occurrence of the appreciable tensile reactive forces [27]. If the reactive stresses are not negligible and have to be accounted for, this still could be done on the basis of the linear theory of bending of beams [27], although the level of the tensile forces is not proportional anymore to the level of the ends-offset. The situation is different if the interconnect experiences significant ends off- set [28]. If this is the case, the nonlinear Euler’s “elastic” theory can be employed to accurately predict the configuration of the misaligned fiber and the level of the tensile forces for the given (measured) ends off-set. For very large end off-sets the nonlinear stress-strain behavior of the silica material has to be accounted for (see section 1.6 below).

The effect of the ends-offset, as far as the bending and the reactive tensile stresses are concerned, depends on the flexural rigidity of the interconnect. It is different therefore for bare and coated fibers. The models suggested in Refs. [24], [25]-[34] can be employed also for coated interconnects, by just evaluating and using their increased flexural rigidity and then considering the distribution of the induced tensile force between the silica fiber and its coating.

Partially coated interconnects provide a particular challenge [26], as far as the ability to determine the induced stresses is concerned. If the highest stresses are expected to occur at the clamped ends of the interconnect, it might make a difference whether the interconnect is soldered or adhesively bonded into the support structures, and whether its coating becomes part of these structures: the lateral and/or the axial compliance of the clamped fiber at its support cross-sections might provide appreciable stress relief for the misaligned fiber and should be considered. In a conservative analysis, one could get away, however, assuming ideally rigid supports. Such an assumption will result in an overestimation of the actual stresses in bending and/or in (reactive) tension.

It is noteworthy that the occurrence of the tensile stress in an optical fiber of finite length subjected to a deliberately applied lateral off-set of its ends can be used in a unique and effective test vehicle for the evaluation of the tensile strength of the fiber, including its “static fatigue” (delayed fracture) [29]. Indeed, the developed models for the prediction of the tensile force in a fiber subjected to the given (imposed) ends offset enable one to develop a simple and an effective experimental setup. In fibers with significant ends off-set the bending stress is significantly lower than the tensile one, and could be neglected, especially if the ends of the fiber are allowed to rotate. Such a setup mimics well therefore the pull-test conditions.

While tensile loading on an optical fiber interconnect has always a negative effect on the state of stress in it, i.e., always leads to elevated stresses, especially in the presence of the ends off-set, moderate compression can have, strange as it may sound, a positive effect on the induced stresses [30], [31]. Even if the compressive force exceeds the critical (buckling) force, it can still be tolerated, as long as the distance between the interconnect ends is controlled and cannot be smaller than the distance determined by the thermal contraction mismatch of the supports (and this distance is determined by the thermal contraction mismatch between the optical fiber and its enclosure). The desired compression can be evaluated beforehand and then implemented into the actual design by choosing the most suitable material of the enclosure: when the structure is fabricated at an elevated temperature and is subsequently cooled down to a low (room) temperature, the thermal contraction mismatch between the materials of the fiber and the enclosure will lead to the desired (required) level of the compressive stress and the displacement in the fiber.

1.5. Pigtail configuration

Pigtails in laser package designs provide particular challenge, as far as their bending and optimized configuration is concerned. Various situations encountered when a pigtail is employed to connect a laser package to the “outside world” were addressed and analyzed [35]-[38]. It has been shown particularly [35] that by rotating the package inside the enclosure, one could reduce dramatically the induced curvatures. This should be done, however, with caution, since ideally straight pigtails cannot be recommended. This is because while the initial bending stress in them is indeed zero, the situation could be worsened dramatically if the structure with a high expansion enclosure is heated up, thereby leading to undesirable and significant tensile stresses in the pigtail. It is usually preferred that the pigtail is kept “loose” and, owing to that, is able to accommodate appreciable axial deformations in tension or compression without being stressed.

If a pigtail experiences two-dimensional bending on a plane [38], appreciable bending stress relief can be obtained by simply forcing the pigtail to be configured as a quarter of a circumference, so that all its points have the same curvature and, hence, experience the same bending stress. This stress can be appreciably lower than the maximum bending stress at the clamped end of a clamped-free pigtail.

More practical and more complicated situations take place when a pigtail is bent on a cylindrical surface [36], [37]. Such a design was considered for lasers intended for AT&T undersea long haul communication technologies. Achieving an optimized geometry of such a pigtail was certainly a challenge.

1.6. Consideration of structural and material nonlinearity

Consideration of the structural (geometric) and materials (physical) nonlinearity might be necessary, if the fiber experiences significant bending and/or axial deformations [39]-[48]. The effect of the structural nonlinearity, which is due to the significant bending deformations of optical fibers, takes place when the induced displacements are not proportional anymore to the applied forces. The stress-strain relationship might be still linear, however, i.e., Hooke’s law is still fulfilled. This is the case, e.g., of fiber interconnects with moderate end-offsets.

It has been established, however [39]-[43], that silica glasses exhibit highly non-linear, although still elastic, stress-strain relationships when the applied strains are not low enough. Young’s modulus in these materials becomes strain dependent. Experiments have indicated that it increases with an increase in the tensile stress and decreases with an increase in the compressive stress, even well below the stress that leads to buckling. When a silica fiber specimen is subjected to significant bending deformations, its neutral axis shifts at the given cross-section of the specimen, because of the non-linear stress-strain behavior of the material, in the direction of the layer subjected to tension. This phenomenon takes place, particularly, when the specimen is subjected to two-point bending tests [39]-[47]. Both the geometric nonlinearity caused by large bending deformations (the shape of the bent fiber) and material’s nonlinearity have to be considered, so that the maximum bending stress in the bent fiber is predicted in the most accurate fashion. If there is a need to establish the actual shape of the bent fiber, the Euler “elastica” approach might be necessary, and this shape is expressed in elliptic functions. Attributes associated with the role of fiber coating, if any, can be easily incorporated, if necessary, into the analytical stress model [48].

1.7. Thermal stress in coated fibers

Coated fibers, whether polymer coated or metalized or otherwise protected, are widely employed for better short- and long-term reliability of the silica material, which is both brittle and moisture-sensitive. The addressed problems encountered during design, manufacturing, testing, and reliability assessments for coated fibers include: evaluation of the effect of coating on the bending stresses; understanding the possible delamination modes and mechanisms; improving strippability of coated fibers; prediction of the magnitude and distribution of stresses occurring during proof (pull-out) testing, and others.

Thermal loading is responsible for many failures in photonics engineering, including optical fiber systems [49]-[61]. Such loading could be caused by the thermal expansion (contraction) mismatch of the dissimilar materials in the structure (and particularly of the fiber and its coating) and/or by the non-uniform distribution of temperature (temperature gradients) in the system. Steady-state or variable thermal loading takes place during the normal operation of optical assemblies and systems, as well as during their fabrication, testing, transportation and storage.

Thermal stresses, strains and displacements are the major contributor to the functional, structural and environmental failures of the optical equipment. This is true even for optical fiber systems, although optical fibers, unlike copper wires, do not dissipate heat. Creep and stress relaxation phenomena might lead to excessive and undesirable displacements in FOE systems. Complete loss in optical coupling efficiency can occur, because of the excessive displacements due to the lateral (often less than 0.2 micrometers) or angular (often less than a split of one percent of a degree) misalignment in the gap between two light-guides or between a light source and a light-guide. This could be caused particularly by the thermal stress related deformations and/or, e.g., by stress relaxation in the laser weld.

As is known, tiny temperature-induced changes in the distances between Bragg gratings written on an optical fiber can be detrimental to its functional performance. For this reason thermal control of the ambient temperature is sometime needed to ensure sufficient protection provided to an optical device sensitive to the change in temperature. The requirements for the structural (physical) behavior of the materials and structures in optoelectronics and photonics are often based therefore on the functional (optical) requirements and specifications, while the requirements for the structural reliability or for the environmental durability might be significantly less stringent. The importance of addressing thermal stresses in, and particularly of modeling of the physical behavior and performance of, coated optical fibers was addressed in Refs. 49-61, where a number of practically important fiber optics structures were considered and analyzed.

A simple analytical stress model has been recently developed for the prediction of thermal stresses in a cylindrical tri-material body [60], with application to silicon photonics technologies, when a metalized optical fiber is soldered into a silicon chip. The developed model is applicable also to situations when a fiber is soldered into a ferrule, or is adhesively bonded into a capillary. It is concluded particularly that the adequate bonding material (e.g., a “soft” tin-lead or a “hard” gold-tin solder) should be selected and its thickness should be established, for low enough thermally induced stresses in it, based on the developed model, so that the short- and long-term reliability of the materials, and, first of all, the solder material, is not compromised. Being analytical, rather than FEA based, this model is quite general and can be used in various other technologies and structures, even well beyond the field of photonics, when cylindrical tri-material bodies comprised of dissimilar materials and experiencing temperature excursions are employed.

In bi-material soldered or adhesively bonded assemblies, the bonding layer is much thinner than the bonded components and/or its Young’s modulus is considerably lower than Young’s moduli of the materials of the bonded components. Owing to that the CTE of the bonding material does not have to be accounted for, and the engineering predictive model can be developed for a bi-material assembly and made therefore relatively simple. However, when the intermediate (bonding) material is not thin and/or its Young’s modulus is not small, the material becomes “an equal partner” with the materials of the bonded components. Then a more complicated model has to be developed to account for the roles of all the materials in such a tri-material assembly. The development of such a model is particularly challenging for a cylindrical body, such as a silicon photonics assembly [60].

1.8. Coated fibers with low modulus coating at the ends

Interfacial thermally induced shearing and peeling stresses that are due to the interaction of the dissimilar materials in coated fibers are often the major cause of an insufficient short- and long-term reliability of the fibers. Since both categories of the interfacial stresses concentrate at the fiber ends and decrease with an increase in the compliance of the coating system [62]-[64], there is an obvious incentive for employing low modulus coating materials at the ends of optical fiber interconnects. Particularly, the maximum thermally induced interfacial shearing stresses at the ends of a jacketed fiber can be minimized, if the lengths of the end portions of the coating are established, for the given Young's modulus of the coating material and the given thickness of the coating layer, in such a way that the shearing stress at the fiber ends becomes equal to the shearing stress at the boundary between the mid-portion and the peripheral portions of the bonding layer. The maximum shearing stress in such an inhomogeneously coated fiber takes place at two locations: at the fiber ends and at the boundaries between the mid-portion and the peripheral portions of the coated fiber. This stress could be significantly lower than in a fiber with a homogeneous coating. Moreover, the maximum stresses in an inhomogeneously coated fiber will be even lower than in a fiber coated by a homogeneous layer whose Young's modulus is the same as the Young's modulus of the low modulus material at the peripheral portions of a fiber with an inhomogeneous coating. Such a paradoxical situation [65] is due to the fact that stiff mid-portions of bonded joints bring down the relative longitudinal interfacial displacements of the bonded materials not only in the fiber mid-portion, where the interfacial thermal stresses are low anyway, but also at the fiber ends, where the maximum interfacial stresses occur. These stresses decrease with a decrease in the peripheral displacements.

1.9. Micro-bending phenomenon in dual-coated fibers

Dual-coated optical fibers are fabricated at elevated temperatures and operated at low temperature conditions. It is imperative for coated fibers intended for long-haul communications remain stable at low temperatures, i.e., do not buckle (do not "micro-bend") within the primary coating as a result of the thermal contraction mismatch of the high expansion (contraction) secondary coating and the low expansion (contraction) fiber. Low-temperature micro-bending, while most likely harmless from the standpoint of the level of bending thermal stresses, can result in substantial added transmission losses [66]-[77]. The low-temperature micro-bending phenomenon is a good illustration of a situation, when it is the need for a failure-free functional (optical) performance, rather than the physical reliability, that determines the requirements for the adequate structural (physical) design of an optical fiber system. The simplest analytical models [67]-[74] suggest that the fiber prone to low temperature micro-bending is treated as an infinitely long beam lying on a continuous elastic foundation. This foundation is provided by the coating system, and, first of all, by the low-modulus primary coating.

As long as such a beam-on-elastic-foundation predictive model is considered, particular attention should be paid to how the spring constant of the elastic foundation is determined. In the early publications preceding the pioneering Vangheluwe's work [67] it was simply assumed that this constant was equal to the Young's modulus of the primary coating materials. Vangheluwe, using the plain strain theory-of-elasticity approximation, obtained, assuming ideally rigid secondary coating, a simple and physically meaningful formula for the spring constant. Vangheluwe's formula indicates that the spring constant of interest depends on both the elastic constants of the primary coating material (Young's modulus and Poisson's ratio) and its thickness. Vangheluwe's formula could result, however, in a considerable overestimation of the spring constant and, hence, in an overestimation of the critical (buckling) force, for some actual, not very stiff, secondary coating materials [69]. The more general formula [69] accounts for the finite rigidity of both the primary and the secondary coating. In the case of thick and not very high-modulus secondary coatings, the compliance of both coating layers should be considered.

Another significant finding, as far as the low-temperature micro-bending phenomenon is concerned, has to do with the role of the initial local curvatures [68]. While the initial curvatures do not change the magnitude of the critical force, they affect the pre-buckling behavior of the compressed fiber. When the compressive force increases, an initially straight fiber remains straight up to the very moment of buckling, while the localized curvatures in a fiber with such curvatures gradually increase with an increase in the compressive force. This could cause appreciable additional deflections of the glass fiber and, as the consequence of that, considerable added transmission losses even at moderately low temperatures, well below the buckling temperatures. It has been shown particularly that, from the standpoint of the pre-buckling behavior of a fiber, certain curvature lengths are less favorable than the others: a dual-coated fiber supported by an elastic foundation provided by the low-modulus coating behaves, with respect to the distributed localized initial curvatures, like a narrowband filter that enhances the curvatures, which are close to the post-buckling configuration of the fiber (regardless of whether buckling occurs or not), and suppresses all the other, 'non-resonant", curvatures. The developed analytical models are simple, easy-to-use, and clearly indicate the role of various factors affecting the pre-buckling behavior of the fiber. The obtained solutions indicate what could possibly be done to bring down, if necessary, the induced curvatures and the resulting added transmission losses in the fiber. The numerical examples are carried out for silicone/nylon coated systems extensively studied experimentally by Japanese engineers [66]. The theoretical predictions agree well with the experimental observations. It is noteworthy in this connection that it has been observed [76] that external (mechanical) periodic loading with a period of about 100nm can also cause appreciable micro-bending losses in dual-coated fibers, and therefore should be avoided in actual designs. This period is rather close to the predicted critical "periods" of initial curvatures in the low-temperature micro-bending situation.

1.10. Proof-testing of coated fibers

The stress-strain related problems that arise during proof-testing of coated optical fibers were addressed, based on the analytical predictive modeling, in Refs. 78-83. The considered problems include: the role of the lengths of test specimens in pull-testing [82]; the buffering effect of the coating on the acceptable length of the test specimens in pull (proof) [83] and in bending [80] tests; the magnitude and the distribution of the interfacial stresses during pull-out testing [81], as well as stresses in coated fibers stretched on a capstan during the manufacturing process [79]. In the brief discussion that follows we elaborate on some more or less important aspects of the physical phenomena associated with proof-testing of coated optical fibers.

It is well-known in materials science that if one intends to experimentally determine the Young's modulus of a material and/or its flexural strength through three- or four-point bending, the specimen should be long enough (say, its length should be at least 12-15 times larger than its height), so that lateral shearing deformations do not occur in the specimen and do not affect the test data [78]. A problem encountered during pull testing of a glass fiber whose one end is soldered or adhesively bonded (and is therefore rigidly or elastically clamped), and its other end is subjected to a pulling (tensile) force [82], although is somewhat different, of course, but has also to do with the intent to obtain clear information about testing. This could be done if the specimen is long enough, so that the tensile stresses prevail considerably over the bending stresses. Considering that the pulling force will always form a certain angle with the fiber axis, the question is what could be done to minimize the effect of the associated bending stresses? To answer this question, a simple analytical model has been developed for the evaluation of the bending stress caused by the misalignment of the ends of a glass fiber specimen soldered into a ferrule and subjected to tension during pull testing. It is shown that the bending stress can be reduced considerably by using sufficiently long specimens and how long such specimens should be, so that only the tensile stress could be accounted for. It is also shown how the uncertainty in the prediction of the inevitable misalignment of the fiber ends can be considered when establishing the appropriate specimen length.

The tensile force experienced by a dual-coated optical fiber specimen during its reliability (proof) testing is applied to the fiber's secondary coating and is transmitted to the glass fiber at a certain distance from the specimen's ends. Although it is true that, in accordance with the Saint-Venant's principle, the glass fiber will be subjected, at a certain distance from the specimen ends, to the same stress that it would experience if the external force were applied to both the fiber and the coating, it is also true that, because of the buffering effect of the coating, the effective length of the fiber under testing, when the testing force is applied to the coating only, might be reduced appreciably in comparison with the fiber's actual length. A simple analytical stress model for the evaluation of this effect was developed [83] and was used to establish the appropriate minimum length of a dual-coated test specimen, so that the experimental data would be consistent and physically meaningful. It has been found that it is the axial compliance of the secondary coating, which experiences the direct action of the external loading, and the interfacial compliance of the coating system that determine the buffering effect of this system. It was concluded that for any finite compliance of the coating, even a very low one, one could always employ a long enough specimen, in which the major mid-portion of the glass fiber would be loaded to practically the same level as in an infinitely long specimen, when the external force is distributed between the glass fiber and its coating proportionally to the axial rigidities of these structural elements. The developed model can be used for selecting the appropriate length of coated optical fiber specimens in reliability (proof) testing. It can be used also beyond the fiber optics technologies area, when composite structures of the type in question are employed and tested.

1.11. Elastic stability of optical fiber interconnects

Analytical models for the evaluation of the elastic stability of optical fiber interconnects have been developed

1) to understand the role of the nonlinear stress-strain relationship [84],
2) to assess the role of the hydrostatic pressure, if any [85],
3) to evaluate the role of the ends off-set [86],

4) to find out of there is sufficient incentive for using thicker coatings for higher elastic stability [87],

5) to investigate the role of the finite length of the interconnect [88], [91] on the critical stress, including the situation, when the interconnect is partially stripped off of its coating [89], and

6) to analyze the effect of the lateral compliance of the interconnect on the level of the buckling forces [90].

In the brief discussion that follows we indicate some important physical aspects of some of the phenomena associated with the above efforts.

The analysis of the effect of the nonlinear stress-strain relationship on elastic stability of optical glass fibers [84] has been carried out under an assumption that this relationship, obtained for the case of uniaxial tension, is also valid in the case of compression: just the sign in front of the nonlinear term in the formula for the strain-dependent Young's modulus should be changed. It is clear that since the critical force is proportional, in accordance with the well-known Euler formula, to the Young's modulus of the material, and this modulus reduces with an increase in the compressive force, an approach that ignores such a reduction will overestimate the magnitude of the critical force, and, hence, will not be conservative. In the studies addressing low-temperature micro-bending of infinitely long dual-coated fibers and elastic stability of short bare fibers the role of the nonlinear stress-strain relationship has been evaluated for strains not exceeding 5%, and therefore it has been indicated that future experimental research should include evaluation of the nonlinear stress-strain relationship, both in tension and compression, for higher strains and for high-strength fibers, such as, e.g., fibers protected by metallic coatings. The author of this review is not aware of whether such research has been conducted.

The analysis of the effect of the hydrostatic pressure in dual-coated optical fibers on the induced stresses in the fiber [85] has indicated that all the normal stresses in the fiber (radial, tangential, axial) are proportional to this pressure. It has been found also that hydrostatic pressure results in lower micro-bending losses.

Calculations of the elastic stability of coated fiber specimens subjected to compression were carried out using analytical modeling [86], [87] for 2mm and 5mm long interconnects for the cases of bare (uncoated) fibers, as well as for coated fibers with 62.5 μm and 187.5 μm thick coatings. The compressive, bending and the total stresses in the glass fiber at the pre-buckling, buckling and post-buckling conditions were computed with consideration of the non-linear stress-strain relationship in the silica material. It has been found that the stresses in the fiber are strongly dependent on its length and the coating thickness. The nonlinear stress-strain relationship plays, however, a minor role, unless the specimen is shorter than only 2mm.

The incentive for the evaluation of the effect of the length of a coated fiber, idealized as a beam lying on a continuous elastic foundation (provided by the coating system), on the critical stress in it [88], [90] is due to the fact that the critical (buckling) force for a beam, in the absence of an elastic foundation, is highly dependent on its length: in accordance with the Euler formulas, this force is inversely proportional to the beam's length squared and is proportional to the beam's flexural rigidity. On the other hand, the critical force for a long enough beam lying on a continuous elastic foundation is beam's length independent and, as is known from the theory of such beams, is proportional to the doubled square root of the product of the spring constant of the foundation and the beam's flexural rigidity. The following natural questions arise in this connection:

1) For what lengths both the beam's length and the spring constant of the foundation play a role and should be accounted for? In other words, if the beam on an elastic foundation is not long enough, how does its finite length affect, if at all, the critical force?

2) What role, if any, the arrangements of the beam's supports at its ends play, as far as the critical force is concerned, and is this role dependent of the beam's length? In other words, is the above mentioned well known formula for the critical force for a long enough beam calculated as the doubled square root of the product of the spring constant of the elastic foundation and beam's flexural rigidity, valid for any long enough beam lying on an elastic foundation, regardless of the arrangements of its end supports, or it is not always the case?

The developed analytical model enabled one to obtain answers to these questions and, as a by-product, to provide practical guidance for designers of coated fiber interconnects. An easy to use and physically meaningful diagram [90] based on the developed analytical models has been suggested to determine stability/instability zones for the given compressive force, the spring constant of the foundation, the length of the beam (fiber) and its flexural rigidity. Both the mechanical and thermally induced compressive forces were considered. It has been shown also that the critical force for a long enough beam with a free (unsupported) end is half of the magnitude of the force in a beam with both ends supported. The obtained solution has been extended for a fiber with a stripped-off coating at its end portion, when the stripped off end of the fiber interconnect (connector) is subjected to compression [89]. A situation when the critical force for the coated portion of the fiber is equal to the critical force for its stripped off portion was particularly addressed and the recommendations for the corresponding length of the elastically stable stripped off portion have been suggested.

The model developed for a cantilever beam lying on a continuous elastic foundation and subjected to the combined action of the concentrated compressive and lateral forces at the free end of the beam (coated fiber) [90] was used to explain the effect of the lateral compliance of such a beam (i.e., its propensity to deflect under the action of the given lateral force) on its elastic stability. It is clear that the flexural rigidity of the beam and the presence of a compressive or a tensile force are equally important when assessing the role of the lateral compliance. Indeed, while the tensile axial force results in an increased effective flexural rigidity of the beam, the compressive force results in its lower flexural rigidity. In an extreme situation, when the compressive force is significant and becomes equal to its critical value, the beam buckles, i.e., its effective flexural rigidity becomes zero. In another extreme case, when the tensile force is large, the beam's effective flexural rigidity increases, and a significant lateral force is needed to bend the beam. These phenomena can be used in fiber optics to increase, if necessary, the elastic stability (the critical force) by applying a tensile force to the fiber. This could be done, e.g., by placing the fiber into an enclosure whose CTE is even lower than that of the fiber, say, in an enclosure built of carbon nano-tubes (CNTs). As is known, at low and room temperatures, the CTE for single wall CNTs in axial direction could be even negative. On the other hand, if one intends to increase the lateral compliance of the fiber, a high expansion enclosure could be used. Such an enclosure will apply compression to the silica fiber. The modeling technique could be similar to the one used in [30] where a fiber with an initial ends off-set was considered.

1.12. Solder materials and joints, and fibers soldered into ferrules

Solder materials and joints are as important in photonics and, particularly, in FOE, as they are in microelectronics [92], [93]. There are, however, specific requirements for the solder materials and joints used in photonics. These requirements are associated with the ability to achieve high alignment, high yield stress, propensity to low creep, etc. It has been shown [92] that low expansion enclosures with good thermal expansion (contraction) match with silica is not always the right choice (solution) from the standpoint of the thermally induced stresses in metalized fibers soldered into ferrules, and in the solder material itself. Indeed, the low expansion enclosures result in tensile radial stresses in the solder ring, and could lead to the delamination of the metallization from the fiber and/or to the excessive tensile radial deformations in the solder. On the other hand, high expansion (contraction) enclosures might result in high compressive stresses in the solder material, and in unfavorable low cycle fatigue conditions during temperature cycling of the joint. The most feasible material of the enclosure and/or the thickness of the solder ring, and/or the physical properties of the solder material could and should be found based on the developed model.

1.13. Dynamics response of optoelectronic structures to shocks and vibrations

Numerous problems associated with the dynamic response of electronic and photonic structures to shocks and vibrations were addressed in Refs. [94]-[106]. The major findings, conclusions and recommendations could be summarized as follows:

1) The maximum acceleration is typically used in electronics and photonics engineering as the major reliability criterion. It is suggested that this criterion can be indeed used in this capacity, when functional (electrical, optical, thermal) performance of the product is evaluated. It could be misleading, however, when structural (physical) reliability is critical [95]. It is the dynamic stress, and not the maximum accelerations (decelerations) that should be used as a suitable and an adequate criterion of the dynamic strength of the material or a device. This stress may or may not be proportional to the maximum acceleration.

2) Drop tests are often replaced in electronics and photonics engineering by shock tests, which are simpler to design and conduct, and whose results is easier to interpret. It has been found that such a replacement can be justified, if the dynamic response of the device under test is as close to an instantaneous impact, as possible [97], [98], [103];

3) Electronic and opto-electronic systems are often tested “on the board level”. The model [99] contains is an exact solution to a highly nonlinear equation for the principal coordinate for the dynamic response of a board to an impact (shock) loading. The model can be used to evaluate the dynamic response characteristics of the board (with surface mounted devices on it) that experiences highly nonlinear vibrations as a result of the shock impact applied to the board’s support contour in drop or shock tests. The model has been developed under an assumption that the size of the surface-mounted devices in the x-y plane is small, so that the surface mounted devices do not change the flexural rigidity of the board, but contribute significantly to its mass and, hence, to the inertial forces.

4) Electronic and photonic systems often experience periodic impacts that could be idealized and modeled as a train of instantaneous impulses [101]. The developed model enables one to evaluate the dynamic response of such systems to a train of periodic impacts, including the situation, when such shocks generate quasi-chaotic vibrations in the system. Smoluchowski’s (Fokker-Planck) equation is used to describe and to characterize the quasi-random vibrations caused in such a nonlinear system by periodic impulses.

1.14. New nano-particle material (NPM) and its applications in fiber-optics

An advanced technology for making nano-particle material (NPM) based optical silica fiber coatings has been developed under grants from DARPA/Navy [107]-[116]. 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 metallized fibers, as well as a potential that the NPM has for various commercial and military applications in micro- and opto-electronics and related areas. It can have many attractive applications also well beyond the "high-tech" field. This NPM-based coating has all the merits of polymer and metal coatings, but is free of the majority 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:

1) low Young's modulus,
2) immunity to corrosion,
3) good-to-excellent adhesion to adjacent material(s),
4) non-volatile,
5) stable properties at temperature extremes (from -220 ^{0}C to +350 ^{0}C),
6) very long (practically infinite) lifetime,
7) "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;
8) 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 that are most important for the pursued application. The 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 lightguide. It is always 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.

The following NPM applications are viewed as the most attractive ones.

1) NPM is able to hermetically seal packages, components and devices, such as laser packages, MEMS, displays and plastic LEDs;

2) NPM can be used as an effective protective coating for various metal and non-metal surfaces, well beyond the area of micro- and opto-electronics: 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);

3) The NPM can be added in the formulation of various coatings such as paints, thereby providing protective benefits without changing the application techniques;

4) 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 preform will consist of a single (undoped and, hence, less expensive) silica material;

5) 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 bio-medicine, 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;

6) 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;

7) Yet 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, e.g., 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 structural reliability of the light-guide will be improved dramatically compared with the conventional systems;

8) Ultra-thin planar light-guides are yet 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.

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:

1) 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;

2) The conducted mechanical tests have demonstrated remarkable strength (up to 7.5Gpa=765kgf/mm.sq.=1088kpsi) 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;

3) 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;

4) 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;

5) 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.

1.15. Some special FOE problems

1. Application of the mechanical approach to the evaluation of low-temperature added transmission losses in single-coated (jacketed) optical fibers [117] enables one, based on the developed analytical stress model, to evaluate the threshold of such losses from purely structural (mechanical) calculations, without resorting to optical evaluations or measurements. The model has been confirmed, however, by optical measurements. The model is based on the experimentally obtained evidence that the temperature threshold of the elevated added transmission losses coincides with the threshold of the elevated thermally induced ("hoop") stresses applied by the polymer jacket to the silica fiber. The suggested model enables one to predict the threshold of interest by stress calculations, instead of resorting to much more complicated optical calculations or measurements. The model sheds light on the physics of the losses in question. The model can be used also to assess the incentive for employing a dual coated system, in which the thermally induced pressure on the glass fiber will be reduced.

2. Analytical models [118]-[120] were used to predict the thermal stresses in fused bi-conical taper (FBT) light-wave couplers. The stresses are caused by the thermal contraction mismatch of the high-expansion coupler and its low-expansion substrate. The challenge in the modeling is due to the non-prismaticity of the FBT structure and the non-linear stress-strain relationship of the FBT material.

3. Elevated lateral gradients of the CTE's and Young's moduli (in direction of the fiber diameter) can be possibly responsible for the fiber "curling" during drawing of optical silica fibers [121]. The analysis was carried out on the basis of both analytical and FEA modeling, and an excellent agreement of the analytical modeling and FEA data has been observed.

4. Apparatus and method for thermostatic compensation of temperature change sensitive opto-electronic devices [122] was also based on analytical modeling. In accordance with the invention, temperature-sensitive devices are mounted within a thermostatic structure that provides temperature compensation by applying compressive or tensile forces to stabilize the performance of the device across a significant operating temperature range. In a preferred embodiment, an optical fiber refractive index grating is thermostatically compensated to minimize changes in the reflection wavelength of the grating. Various methods and devices are known in the art to compensate for temperature induced thermal expansion. The patent [122] provides the simplest and most effective solution to the thermal compensation problem, when regular and readily available materials can be used to solve the problem.

2. PROBABALISTIC DESIGN FOR RELIABILITY IN FIBER OPTICS ENGINEERING

2.1. Qualification testing (QT)

The short-term goal of a particular opto-electronic device manufacturer is to conduct and pass the established QT, without questioning if they are adequate. The ultimate long-term goal of opto-electronic industries, whether aerospace, military, or commercial, regardless of a particular manufacturer or a product, is to make their deliverables reliable in the actual operations. It is well known, however, that today's electronic devices that passed the existing QT often fail in the field (in operation conditions). Are the existing opto-electrionic QT specifications adequate? Do opto-electronic industries need new approaches to qualify their devices into products? Could the existing QT specifications and practices be improved to an extent that if the device passed the QT, there is a quantifiable way to assure that its performance will be satisfactory?

At the same time, there is a perception, perhaps, a substantiated one, that some electronic products "never fail". It is likely that such a perception exists because these products are superfluously durable, are more robust than is needed for a particular application and, as the consequence of that, are more costly than necessary. To prove that it is indeed the case, one has to find a consistent way to quantify the level of the opto-electronic product robustness in the field. Then one could establish if a possible and controlled reduction in the reliability level could be translated into a significant cost reduction.

2.2. Probabilistic design for reliability (PDfR)

The probabilistic design for reliability (PDfR) concept enables one to provide affirmative answers to the above questions. The concept suggest that one

1) conducts a highly focused and highly cost-effective failure-oriented accelerated testing (FOAT),

2) carries out simple and physically meaningful predictive modeling (PM) to understand the physics of failure;

3) predicts, using the results of the carried out FOAT and PM, the probability of failure (PoF) in the field;

4) carries out sensitivity analyses (SA) to establish the acceptable PoF;

5) revisits, reviews and revises the existing QT practices, procedures, and specifications; and

6) develops and widely implements the PDfR concept, methodologies and algorithms, considering that "nobody and nothing is perfect", that the probability of failure is never zero, but could be predicted and, if necessary, minimized, controlled, specified and even maintained (assured) at an acceptable level. In effect, the only difference between a highly reliable and an insufficiently reliable product is "merely" in the level of the operational PoF.

Very popular today prognostication and health monitoring (PHM) approaches and techniques could be very helpful at all the stages of the design, manufacturing and operation of the product. The reliability evaluations and assurances cannot be delayed, however, until the device is made (although it is often the case in many current practices). Reliability should be "conceived" at the early stages of the device design; implemented during manufacturing; qualified and evaluated by (electrical, optical, environmental and mechanical) testing at the design, product development and the manufacturing stages checked (screened) during production (by implementing an adequate burn-in process) and, if necessary and appropriate;

monitored and maintained in the field during the product's operation, especially at the early stages of the product's use by employing, e.g., technical diagnostics, prognostication and health monitoring (PHM) methods and instrumentation.

Three classes of engineering products, including opto-electronic and particularly fiber optics products, should be distinguished from the reliability point of view:

1) *Class I* includes some military or aerospace objects, such as warfare, military aircraft, battle-ships, space-craft. Cost is important, but is not a dominating factor;

2) *Class II* includes objects like long-haul communication systems, civil engineering structures (bridges, tunnels, towers), passenger elevators, ocean-going vessels, offshore structures, commercial aircraft, railroad carriages, cars, some medical equipment. The product has to be made as reliable as possible, but only for a certain specified level of demand (stress, loading);

3) *Class III* includes consumer products, commercial electronics, agricultural equipment. The typical market is the consumer market.

2.3. Reliability, cost effectiveness and time to market

Reliability, cost effectiveness and time-to-market considerations play an important role in the design, materials selection and manufacturing decisions in commercial electronics, and are the key issues in competing in the global market-place, at least for Class III products. A company cannot be successful, if its products are not cost effective, or do not have a worthwhile lifetime and service reliability to match the expectations of the customer. Too low a reliability can lead to a total loss of business. Product failures have an immediate, and often dramatic, effect on the profitability and even the very existence of a company. Profits decrease as the failure rate increases. This is due not only to the increase in the cost of replacing or repairing parts, but, more importantly, to the losses due to the interruption in service, not to mention the losses due to reduced customer confidence and acceptance. These make obvious dents in the company's reputation and, as the consequence of that, affect its sales. Each business, whether small or large, should try to optimize its overall approach to reliability. "Reliability costs money", and therefore a business must understand the cost of reliability, both "direct" cost (the cost of its own operations), and the "indirect" cost (the cost to its customers and their willingness to make future purchases and to pay more for more reliable products).

2.4. Failure oriented accelerated testing (FOAT)

It is impractical and uneconomical to wait for failures, when the mean-time-to-failure for a typical today's electronic device (equipment) is on the order of hundreds of thousands of hours. Accelerated testing (AT) enables one to gain greater control over the reliability of a product. AT has become a powerful means in improving reliability [3], [4]. This is true regardless of whether (irreversible or reversible) failures will or will not actually occur during the FOAT ("testing to fail") or the QT ("testing to pass").

In order to accelerate the material's (device's) degradation and/or failure, one has to deliberately "distort" ("skew") one or more parameters (temperature, humidity, load, current, voltage, etc.) affecting the device functional or mechanical performance and/or its environmental durability. AT uses elevated stress level and/or higher stress-cycle frequency as effective stimuli to precipitate failures over a short time frame.

The "stress" in RE does not necessarily have to be mechanical or a thermo-mechanical: it could be electrical current or voltage, high (or low) temperature, high humidity, high frequency, high pressure or vacuum, cycling rate, or any other factor (stimulus) responsible for the reliability of the device or the equipment. AT must be specifically designed for the product under test. The experimental design of AT should consider the anticipated failure modes and mechanisms, typical use conditions, and the required or available test resources, approaches and techniques.

Some of the most common AT conditions (stimuli) are: high temperature (steady-state) soaking/storage/ baking/aging/ dwell; low temperature storage; temperature (thermal) cycling; power cycling; power input and output; thermal shock; thermal gradients; fatigue (crack propagation) tests; mechanical shock; drop shock (tests); random vibration tests; sinusoidal vibration tests (with the given or variable frequency); creep/stress-relaxation tests; electrical current extremes; voltage extremes; high humidity; radiation (UV, cosmic, X-rays, alpha particles); space vacuum.

2.5. Qualification testing (QT) and failure oriented accelerated testing (FOAT)

QT is a must. Industry cannot do without QT. Its objective is to prove that the reliability of the product-under-test is above a specified level. QT enables one to "reduce to a common denominator" different products, as well as similar products, but produced by different manufacturers. QT reflects the state-of-the-art in a particular field of engineering, and the typical requirements for the product performance.

However, if a product passes the today's QT for opto-electronic products, it is not always clear why it was good, and if it fails the tests, it is usually equally unclear what could be done to improve its reliability. Since QT is not failure oriented, it is unable to provide the most important ultimate information about the reliability of the product – the reliability physics behind the failure and the PoF after the given time in service under the given operation conditions.

FOAT on the other hand, is aimed, first of all, at revealing and understanding the physics of the expected or occurred failures. That is why it could be referred to as knowledge oriented testing. Unlike QTs, FOAT is able to detect the possible failure modes and mechanisms. FOAT end points are cycles or durations that are scaled to the use environments. Another possible objective of the FOAT is, time permitting, to accumulate failure statistics. Thus, FOAT deals with the two major aspects of the RE– physics and statistics of failure.

Adequately planned, carefully conducted, and properly interpreted FOAT provides a consistent basis for the prediction of the PoF after the given time in service. Well-designed and thoroughly implemented FOAT can facilitate dramatically the solutions to many engineering and business-related problems, associated with the cost effectiveness and time-to-market. This information can be helpful in understanding what should be changed to design a viable and reliable product. This is because any structural, materials and/or technological improvement can be "translated", using the FOAT data, into the PoF for the given duration of operation under the given service (environmental) conditions. FOAT should be conducted in addition to the QT.

There might be also situations, when FOAT can be used as an effective substitution for the QT, especially for new products, when acceptable qualification standards do not yet exist. While it is the QT that makes a device into a product, it is the FOAT that enables one to understand the reliability physics behind the product and, based on the appropriate PM, to create a reliable product with the predicted or even specified PoF.

2.6. Burn-in testing (BIT) as a special type of failure oriented accelerated testing (FOAT)

Burn-in ("screening") testing (BIT) is widely implemented to detect and eliminate infant mortality failures. BIT could be viewed as a special type of manufacturing FOAT. BIT is needed to stabilize the performance of the device in use. BIT is supposed to stimulate failures in defective devices by accelerating the stresses that will cause these devices to fail without damaging good items. The bathtub curve of a device that undergone BIT is supposed to consist of a steady state and wear-out portions only.

The rationale behind the BIT is based on a concept that mass production of electronic devices generates two categories of products that passed QT:

1) robust ("strong") components that are not expected to fail in the field and

2) relatively unreliable ("week") components ("freaks") that, if shipped to the customer, will most likely fail in the field.

2.7. Failure oriented accelerated testing (FOAT): predictive modeling (PM)

FOAT cannot do without simple and meaningful predictive models. It is on the basis of such models that one decides which parameter should be accelerated, how to process the experimental data and, most importantly, how to bridge the gap between what one "sees" as a result of the accelerated testing and what he/she will possibly "get" in the actual operation conditions. By considering the fundamental physics that might constrain the final design, PM can result in significant savings of time and expense and shed additional light on the physics of failure.

PM can be very helpful to predict reliability at conditions other than the FOAT and can provide important information about the device performance. Modeling can be helpful in optimizing the performance and lifetime of the device, as well as to come up with the best compromise between reliability, cost effectiveness and time-to-market.

A good FOAT PM does not need to reflect all the possible situations, but should be simple, should clearly indicate what affects what in the given phenomenon or structure, be suitable/flexible for new applications, with new environmental conditions and technology developments, as well as for the accumulation, on its basis, the reliability statistics. The scope of the model depends on the type and the amount of information available. A FOAT PM does not have to be comprehensive, but has to be sufficiently generic, and should include all the major variables affecting the phenomenon (failure mode) of interest. It should contain all the most important parameters that are needed to describe and to characterize the phenomenon of interest, while parameters of the second order of importance should not be included into the model.

The most widespread FOAT PM are: power law (used when the physics of failure is unclear); Boltzmann-Arrhenius' equation (used when there is a belief that the elevated temperature is the major cause of failure) and its numerous extensions; Coffin-Manson's and related equations; crack growth equations (used to assess the fracture toughness of brittle materials); Miner-Palmgren's rule (used to consider the role of fatigue when the yield stress is not exceeded); creep rate equations; weakest link model (used to evaluate the MTTF in extremely brittle materials with defects); stress-strength interference model, which is, perhaps, the most flexible and well substantiated model.

2.8. Safety factor (SF)

Direct use of the probability of non-failure is often inconvenient, since, for highly reliable items, this probability is expressed by a number which is very close to one, and, for this reason, even significant than in the item's (system's) design, which have an appreciable impact on the item's reliability, may have a minor effect on the probability of non-failure. In those cases when both the mean value, $<\psi>$, and the standard deviation, $\hat{s}$, of the margin of safety (or any other suitable characteristic of the item's reliability, such as stress, time-to-failure, temperature, displacement, affected area, etc.), are available, the safety factor_(safety index, reliability index) SF can be used as a suitable reliability criterion. If the probability distribution density $f(\psi)$ of the random safety margin ψ for the TTF is anticipated or established, then the mean value $\lhd \psi \rhd$ and the standard deviation S_ψ of this margin can be determined as $\lhd \psi \rhd = \int_0^\infty f(\psi)\psi d\psi$, and $S_\psi = \sqrt{\int_0^\infty f(\psi)(\psi - \lhd \psi \rhd)^2 d\psi}$, and the corresponding SF can be evaluated as $SF = \lhd \psi \rhd / S_\psi$. The SF establishes both the upper limit of the reliability characteristic of interest (through the mean value of the corresponding margin of safety) and the accuracy with which this characteristic is defined (through the corresponding standard deviation).

The structure of the SF indicates that it is acceptable that a system characterized by a high mean value of the safety margin (i.e., a system whose bearing capacity with respect to a certain stress/reliability-characteristic, is significantly higher than the level of loading) has a less accurately defined deviation from this mean value than a system characterized by a low mean value of the safety margin (i.e., a system whose bearing capacity is much closer to the possible level of loading). In other words, the uncertainty in the evaluation of the safety margin should be smaller for a more vulnerable design.

2.9. Do opto-electronic (OE) industries need new approaches to qualify their devices into products?

It should be widely recognized that the probability of a failure is never zero, but could be predicted and, if necessary, controlled and maintained at an acceptable low level. One effective way to achieve this is to implement the existing methods and approaches of PRM techniques and to develop adequate PDfR methodologies. These methodologies should be based mostly on FOAT and on a widely employed predictive modeling effort. FOAT should be carried out in a relatively narrow but highly focused and time- effective fashion for the most vulnerable elements of the design of interest. If the QT has a solid basis in FOAT, PM and PDfR, then there is reason to believe that the product of interest will be sufficiently robust in the field. The QT could be viewed as "quasi-FOAT," as a sort-of the "initial stage of FOAT" that more or less adequately replicates the initial non-destructive, yet full-scale, stage of FOAT.

We expect that the suggested approach to the DfR and QT will be accepted by the engineering and manufacturing communities, implemented into the engineering practice and be adequately reflected in the future editions of the QT specifications and methodologies. The PDfR-based QT will still be non-destructive. Such QTs could be designed, therefore, as a sort of mini-FOAT that, unlike the actual, "full-scale" FOAT, is non-destructive and conducted on a limited scale. The duration and conditions of such "mini-FOAT" QT should be established based on the observed and recorded results of the actual FOAT, and should be limited to the stage when no failures in the actual full-scale FOAT were observed.

Prognostics and health management (PHM) technologies (such as "canaries") should be concurrently tested to make sure that the safe limit is not exceeded. It is important to understand the reliability physics that underlies the mechanisms and modes of failure in electronics and photonics components and devices. No statistics is able to replace understanding of reliability physics underlying a particular design and modes of failure. Statistical assessments could and should be conducted when there is a good reason to believe that an adequately reliable product is on the way. As to the FOAT, it should be thoroughly implemented, so that the QT is based on the FOAT information and data. PDfR concept should be widely employed. Since FOAT cannot do without predictive modeling, the role of such modeling, both computer-aided and analytical, in making the suggested new approach to product qualification practical and successful.

3. CONCLUSION

The application of the methods and approaches of methods and approaches of materials physics and structural analysis can be very helpful in creating a viable and reliable fiber optics products and networks. The probabilistic design for reliability (PDfR) concept enables one to design and fabricate a viable and reliable optoelectronic product.

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