Silica Nano-Structured Fiber for Illumination

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***Abstract*—This paper describes a novel fiber designed to produce uniform illumination in angular space along its length. The mechanism of light extraction from the silica glass guiding region is due to nano-sized gas filled voids formed during fiber preform consolidation and fiber draw process. The resulting effect creates an aesthetically pleasing line or string of light which provides a long, thin, and flexible illumination tool for a variety of designs or functional applications. The rate of light extraction is determined by size and number of the formed these elongated voids features. The scattering material in the secondary coating modifies the scattering distribution function to make it uniform in angular space. The rate of the scattering efficiency can be controlled by drawing conditions and light launch conditions from the light source. The spectral efficiency of scattering is very high due to use of pure silica and low-absorbance coating materials from UV through IR. The use of color conversion materials placed outside the secondary coating can be used to generate a wide range of colors using a blue wavelength light pump, including pure white colors with a color temperature ranging from 3000 to 10000 K. Finally, a range of aesthetic and functional illumination applications for this fiber are also discussed.**

***Index Terms*—Flexible illumination, lighting, light-diffusing fiber, optical fiber, optical wavelength conversion.**

I. Introduction

THE use of glass optical fiber as a means to transmit light across long distances with little loss of light power has revolutionized many facets of our world and played a major role in the rapid pace of technical advancement in telecommunication that we know today. As such, manufacturing a glass fiber fit for long distance/low loss light propagation requires a robust knowledge of the materials science of the light-carrying fiber core, the cladding material used to confine the light to the core and the polymeric coatings that protect and permit handling of the fiber. One may carry this knowledge a step further by realizing that this material science understanding may be extended to controlling the light exiting from not merely the other end of the fiber, but also via a controlled release of the light through the clad layer and polymeric coatings. This paper describes the efforts we have made to generate an orderly, consistent loss of light through the sides of the fiber, at various lengths, and the extension of this ability to wavelengths outside the visible region from the UV thru IR spectra. There are a few known ways to create fibers with controlled scattering loss along the length. One possibility is the introduction of scattering features into the core, clad, or core clad interface [1]–[4]. Important requirements of this approach are that additional modifications will not introduce absorption losses, and that the loss can be precisely controlled. In addition, when one wants to create the illumination with fiber along the length in UV or IR region, the absorption properties of the polymer coating now become increasingly important. In this paper we describe an approach to prepare illumination fiber based on the introduction of voids into the silica core or clad of the fiber to create efficient scattering of light. In this case, absorption losses are minimal due to the high quality of the glass and the low absorption cross-section of gas filled voids.

Earlier reports demonstrated that light can be guided in a fiber with randomly distributed air holes in the cladding [5] which served as a negative down-dopant for the fiber clad. One method of making hole-assisted optical fibers is the use of the nanoStructures technology, involving the formation of randomly distributed voids in the nano-engineered region of the fiber using traditional optical fiber manufacturing methods such as the Outside Vapor Deposition (OVD), Vapor Axial Deposition (VAD), or Modified Chemical Vapor Deposition (MCVD) processes, thereby making the technology ideal for large-scale manufacturing. Created voids exhibit a very large index contrast relative to the surrounding glass and serve as strong efficient scattering features. When a majority of the void structures are placed in the high light intensity region of a waveguide, the loss of the light due to scattering may be well controlled [6]. This paper describes the efforts that we have made to generate an orderly, consistent loss of light down optical fibers of various lengths through the sides of the fiber and the extension of this ability to wavelengths outside the visible region to the UV and IR ranges. Optical properties of such fibers are described in detail, and applications of such illumination fibers are also discussed.

II. Materials and Methods

A. Fiber Making

Nano-structured (NS) fiber is made by using Corning's standard optical fiber manufacturing process, the Outside Vapor Deposition (OVD) process used to make telecommunications fiber, but with one key difference: we intentionally make voids in the core of the fiber preform. The NS fiber needs a core and cladding to guide light, and scattering elements to disturb the light guidance in a controlled fashion, scattering the light out of the fiber on lengths ranging from <1 mm to over

Manuscript received January 14, 2019; revised May 17, 2019; accepted July 10, 2019. Date of publication July 23, 2019; date of current version November 15, 2019. *(Corresponding author: Stephan L. Logunov.)*

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Digital Object Identifier 10.1109/JLT.2019.2928697

ten meters. While there are multiple ways to accomplish this [7], [8], the following will describe the most commonly employed method. Flame hydrolysis is used to convert $SiCl_4$ plus O_2 into SiO_2 soot particles, which are captured on a cylindrical target, the resulting soot body is then sintered in the presence of a void forming gas to capture holes thus generating a fiber preform with a controlled size and number of voids. Void forming gasses are not soluble in silica and commonly include N_2, Ar, Kr, $C0_2$, 0_2, air, $S0_2$, Cl_2, CF_4, and mixtures thereof. By controlling the starting pore size distribution in the soot preform and ratio of void forming gas to non-void forming gas (Helium), the number and the size of the voids can be controlled. This void filled core preform can then be either taken directly to the fiber draw process, if using a low index polymer cladding, or may be over-clad with a lower index glass cladding to produce a core-clad structure. Glass-clad fibers are more robust when high optical power is required at light launch, and offer easier termination methods, but typically suffer from lower NA (numerical aperture). Polymer clad fibers are produced by replacing the typical primary acrylate coating with a low index fluoro-acrylate coating. Care must be taken when terminating these fibers as the polymer cladding cannot be removed, or the fiber will no longer guide light, if a higher index coating or material is re-applied at the connector.

At the fiber draw, the time and temperature history that the void filled blank is exposed to also impacts the light diffusing properties and thus provides additional approach to control light loss. For example, if the viscosity of the glass is sufficiently low and two voids are close enough, they will coalesce into a single larger void. By drawing the same blank at a higher temperature, larger voids result leading to greater scattering and thus a shorter diffusion length.

Control of the scattering rate can also be achieved by changing the distribution and size of the scattering voids. The voids can be distributed uniformly across the entire core with varying counts per unit area to make high versus low scattering fibers or use material with a constant count per unit area and vary the percentage of the core covered by voids to get a similar effect.

The number of voids, their diameter, and length can be designed by initial blank filling with gas and draw conditions. The scattering is most efficiently affected by start and stop positions of the elongated voids and their size and concentration. The void-containing region can contain over 1,000,000 voids in the cross-sectional slice of the preform wherein the voids can be approximately 1 to 10 microns in average diameter and from a few mm to a few m in length. These voids are typically discrete and isolated spheroid shapes surrounded by silica, therefore each void is non-continuous in the axial or radial position along the length of the optical preform. When the preform is drawn into optical fiber, the voids are stretched along the fiber axial direction, thereby forming the non-continuous voids in the nano-engineered region of the optical fiber [8]. The core size and NA target of the fiber are varied in conjunction with the NA and spot size of the light source to enable high coupling efficiency between source and fiber.

A secondary coating with scattering elements is added at the fiber draw and applied on top of the primary coating. The secondary scattering elements help make the light scattered out of the core appear more uniform by re-scattering it.

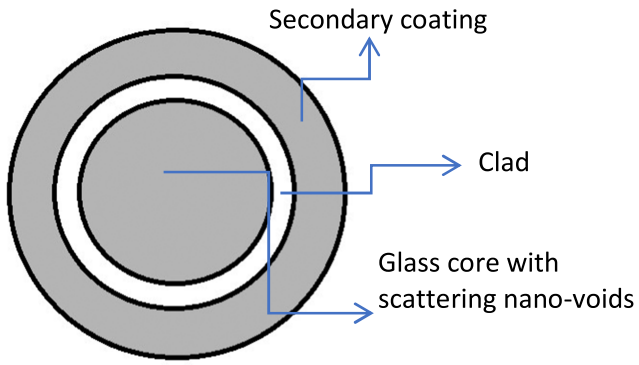

Fig. 1. Design of NS fiber with nano-voids filled core, clad with fluorine doped glass or fluorinated polymer, and acrylate based secondary coating filled with scattering particles.

The general design of the NS fiber is shown in Figure 1, where the core of the fiber is filled with nano-voids, the primary coating can be either glass with fluorine doping to reduce refractive index or fluorinated polymer, secondary coating is scattering particles filled acrylate coating. Typical NA of the fiber with glass clad is 0.2, while with fluorinated coating ~0.5.

Glass core diameter can be varied from 80 to 200 microns providing excellent flexibility to the fiber.

B. *Fiber Characterization Efficiency Test*

One of the key factors that determines the performance of illumination fiber is how much light is lost due to internal absorption during operation. This energy loss due to internal absorption is equal to a loss of radiometric efficiency. Therefore, to understand product performance it is essential to develop metrology tools/procedures for accurately measuring absorption loss.

The absorption loss of NS fiber was measured for broad ranges of wavelength from 300 to 1700 nm using a calibrated integrating sphere system attached to a spectrometer. Different light sources and different spectrometers were used for different spectral ranges. For the UV- visible range we used a plasma fiber coupled source (Energetiq Technology) with a visible fiber coupled spectrometer (SpectraNet). For the NIR range we used a femtosecond supercontinuum fiber source and OSA analyzer. The efficiency is measured by placing a long piece of NS fiber (exceeding length where attenuation is more than 10 dB) inside an integrating sphere, the size of which is large enough in comparison to fiber surface. The detector reading is then compared to the reading of the same fiber with same light coupling conditions when the fiber is cut to very short (2–3 cm) lengths. NS fiber emission efficiency (η) is given by the following equation:

$$\eta(L) = \frac{P_2}{P_1}, \tag{1}$$

where total emission inside of the integrating sphere for the short fiber length is P_1, emission for the long fiber is P_2, and L is the difference in length between long and short fibers with the same light coupling conditions. Length L is selected to be

where attenuation of the intensity at the output of the fiber is about 10 dB. The efficiency may be somewhat different for long and short NS fiber depending on rate of scattering loss.

1) Angular Distribution of Illumination: The measurements are performed on an optical setup for angular scattering distribution in wide angular ranges of 30–150 degrees. The fiber under study is placed on the black steel plate with a groove, and covered by one mm long aperture, so only small section of the fiber is open. The angular distribution is measured as the detector moves in a semi-angular motion in a plane of the fiber. Due to the geometrical constraints, the useful angular range is 30–150 degrees. All laser sources used are fiber coupled laser diodes (450, 520, and 630 nm) with the laser output modulated at ∼400 Hz and data collected by a lock-in-amplifier. The average power in the fiber is kept at ∼1 mW level to provide reasonable signal to noise ratio.

Similar measurements targeting radial distribution of the intensity showed very symmetric distribution in the plane perpendicular to the fiber.

2) Diffusion Length Test Bench: Distribution of the intensity vs. length of the fiber was measured on a bench with detector positioned perpendicular to fiber and moving along the length of the fiber from the launch point. The setup is based on measurements of the light intensity radiated by the fiber at ∼90 degrees to its surface. The fiber is positioned straight with different launch conditions at one end, such as lower or higher NA input relative to fiber NA. Different wavelength sources are used for this test such as blue, green and red wavelengths. The detector used is a silicon photodiode.

3) Spectral Attenuation: Spectral attenuation based on the cutback method was used to access the spectral dependence of the loss in these fibers. We used broad band source (Ando-6317B) with a spectral range of 350–1700 nm and a wide band spectral analyzer (Ando AQ-4303B) for detection. Depending on the attenuation cutback, the section of the measured fiber varied from approximately 10–20 meters to a fraction of a meter.

III. Results

During fiber draw the gas filled voids can coalesce together to form voids of different shapes due to effects of heating and draw conditions. Due to the stretching of the preform, different distributions of the tapers in the void region can be formed as well. All these factors affect the scattering efficiency of the light in the fiber and its wavelength dependence. This can be seen in Figure 2, where the same fiber preform was drawn at different conditions. At condition one, nano features with diameter ∼600–1000 nanometers as measured with SEM (scanning electron microscopy) were formed with higher efficiency of scattering, but fewer numbers. At condition two, larger number of scattering sites were created, but with diameter 150–300 nanometers. Different wavelength dependence of fiber attenuation due to scattering was observed, and it is very different from the small feature size scattering typical for Rayleigh scattering as shown also in Figure 2. Changing draw conditions such as furnace temperature dynamically can produce variable scattering along the length of the fiber, which can cause non-exponential decay of the intensity.

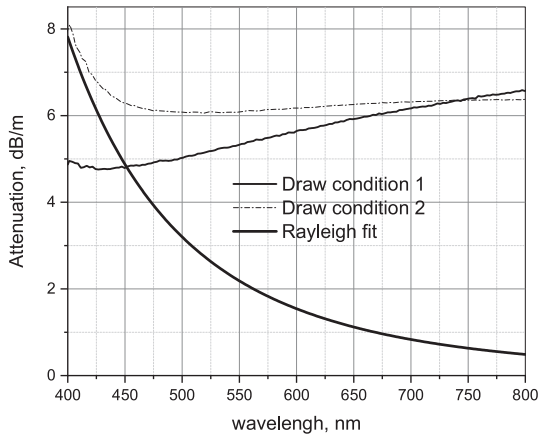

Fig. 2. Shape of spectral loss for preform drawn at different draw conditions. Dashed line – draw condition 1, which has higher loss and Y scale was reduced by 5x, thin solid line –draw condition 2, and thick solid line is Rayleigh scattering curve.

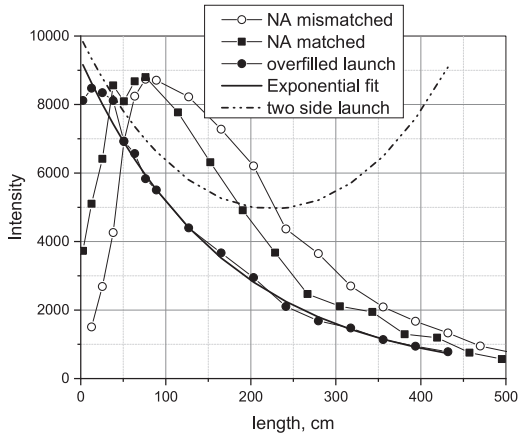

Fig. 3. Intensity distribution along the length of NS fiber with different launch conditions: "NA mismatched" (NA of the source is less than NA of NS fiber), NA matched "(NA of the source is matched to NA of the NS fiber), "overfilled launch" (NS fiber is overfilled), "two side launch" is condition when two light sources from opposite sides of the fiber were used. The starting measurement position is immediately after re-usable connector, which is ∼20–25 mm long.

Typical intensity variation along the length of the NS fiber with 10 dB attenuation at about 5 m is shown in Figure 3. While one expects to see simple exponential decay for constant attenuation or constant scattering loss in the fiber, experimentally we found that results are strongly dependent on light launch conditions. At distance more than 5 m decay was following exponential function, but at shorter distances we observed deviation from exponential decay. The typical light source that we use for efficient coupling is a multimode laser diode (LD) with focusing lens, making excitation spot size on the fiber core less than 100 um in diameter and NA of 0.2. NA of the fiber is significantly larger, close to 0.5, and not all radiation modes are excited in the fiber if normal launch conditions are used, as seen in Figure 3. It takes some distance depending on number of scattering nano-features in the core to populate all the modes, and after this propagating distance is reached, scattering intensity reaches a maximum value. To reduce this distance,

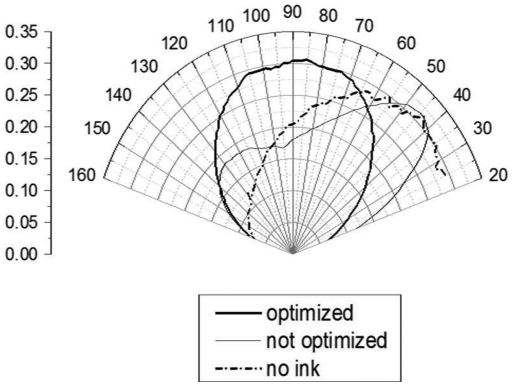

Fig. 4. Angular distribution of the NS fiber with different design of secondary coatings.

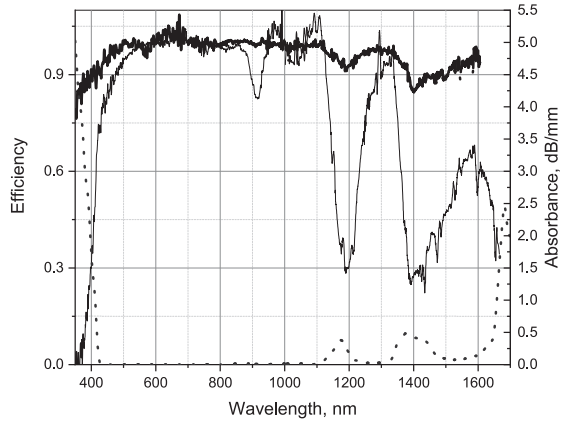

Fig. 5. Spectral efficiency of the NS fiber with TiO_2 doped acrylate secondary coating (thin solid line), fluorinated secondary coating and alumina particles dispersed in primary coating (thick solid line), and spectral attenuation for acrylate secondary coating doped with TiO_2 (dotted line).

one could increase NA on the launch light and to make the induction zone shorter as shown in Figure 3. Another option is to overfill this fiber or alternatively use launch light at an angle, so all high order modes are excited in this waveguide. Thus, the induction zone is eliminated, and the fiber intensity follows exponential decay. This property of illumination fiber can be used to create different intensity profiles. In addition to this, one could use excitation from both sides, or attach a reflection mirror on another side of the fiber to deviate the scattering profile from exponential as shown in Figure 3. The angular distribution of different versions of light diffusion fiber were tested as well and the results are shown in Figure 4. The fiber, which only has a nano-structured core section and no scattering material in secondary coating, produces a very forward-directed angular distribution curve ("no ink" curve in Figure 4). This creates a non-uniformity in intensity brightness, when the viewer observes the fiber at different angles relative to direction of light propagation. This happens since scattering centers are comparable to, or larger than, the wavelength of light.

Moreover, if the input light is not monochromatic, different wavelengths may have different scattering angular distributions. To overcome this problem, we added a scattering material ("ink") to the secondary coating. The secondary coating serves to optically de-couple from the propagation region, and it has a higher refractive index than the primary coating. As a result, all light scattered from the core is directed to the secondary coating region, where it can be trapped and partially scattered and /or partially absorbed due to the lower optical quality of the material for secondary coating than glass. If the scattering particles are present in the secondary coating, it changes the angular distribution of the scattered light curve ("optimized" curve in Figure 4) and prevents light from becoming trapped in the secondary coating, thereby improving overall scattering efficiency. Optimized conditions look preferable to what was reported earlier for other illuminating fibers [9]. A wide range of scattering materials can be used for secondary doping and in this example we used TiO_2 particles directly dispersed into the secondary coating. The number of particles was optimized to afford a reasonable scattering diagram.

For example, a smaller amount of scattering particles or different refractive index contrast particles create a somewhat improved diagram vs. non-doped fiber, but are not exactly the ideal diffuser ("non-optimized" in Figure 4).

To understand scattering efficiency of the light diffusing fiber, we studied scattering efficiency as described above. It is known that silica is a low absorbance material across a wide spectral range of 250–1700 nm [10], and that the gas filled scattering voids also have low absorbance. Therefore, the main absorption loss may be expected to originate from the polymer coating used in the fiber and scattering centers placed in secondary coating.

The results of these efficiency tests are shown in Figure 5 and discussed in the following paragraph. Curve one (thin solid line) depicts a fiber with a polymer clad and TiO_2 doped secondary coating with a significant drop in near UV and NIR wavelength range. While UV attenuation can be attributed to both primary coating absorption and TiO_2 absorption, NIR peaks at 910 nm, 1200 nm, and 1400 nm are mainly attributed to C-H overtones stretches absorption peaks. The dotted line represents absorbance spectrum of the acrylate coating doped with TiO_2. It shows positions of the C-H peaks and TiO_2 absorbance in UV wavelength range. However, for the visible wavelength range efficiency is very close to 100%. To obtain higher efficiency in the UV and NIR ranges, modification to the fiber design would be needed and this will be discussed in a later section.

Comparison of the efficiency and attenuation curves for the same fiber shows that position of NIR peaks is about the same as expected, but the relative magnitude is not similar. While the attenuation test shows the overall amount of the light lost, the efficiency measurement shows light which was not absorbed in the fiber. Higher impact from the 910 nm and 1200 nm bands in the efficiency curve suggests that this dropping efficiency is caused by secondary coating absorption.

IV. Improvement With Coating Modifications for UV and NIR

In order to optimize NS fiber for non-visible applications, it is important to focus on the spectral range optimization of

all components of the fiber and its design. As stated earlier, voids responsible for scattering are not UV or NIR absorbing, but other components of the fiber are. UV attenuation for both the polymer clad (which is made from a fluorinated polymer with RI $\sim$ 1.38) and the secondary coating, (which is a UV curable acrylate) is significantly below 420 nm. TiO2, which is used as scattering material in the secondary coating, also has a significant absorption below 420 nm and it would also affect absorption losses in the NS fiber.

To overcome this problem, we developed two solutions. One intermediate solution is shown in Figure 1. In this case, no modifications are done to the fiber design except replacing scattering particles in the secondary coating from TiO_2 to other non-absorbing particles. This is a non-trivial task since in order for a particle to be efficient at scattering, the refractive index difference between the matrix and the material of the particle needs to be as large as possible. TiO_2 is an ideal material since its refractive index is 2.6 at 0.58 um, while the polymer refractive index is $\sim$1.5. We considered the use of aluminum oxide, RI = 1.77, silica RI = 1.46, Barium sulfate, RI = 1.636 and other materials dispersible in the polymer and available in small particle form. For practical reasons we selected aluminum oxide. Even though the index contrast is lower than TiO_2, it provided a reasonable scattering function without penalty for UV attenuation down to 300 nm. Figure 4 shows the scattering diagram for fiber with alumina (15% wt.) ("non-optimized" curve).

A more radical solution is to completely replace the polymer coatings. In this case, there is no polymer clad in fiber, fluorine-doped (F-doped) silica glass serves as a clad, and a hard polymer with good UV transmission serves as the coating protecting the fiber. The F-doped glass, however, can't have an index lower than $\sim$1.42–1.43, i.e., numerical aperture (NA) for this fiber can be significantly lower than for the first version of NS fiber described above (0.2 vs. 0.53). This is not a significant problem for light coupling, but makes the lower NA fiber more bend sensitive (light loss due to bends). The presence of a primary polymer coating with even lower index creates a "double clad design", where in tight bends light can escape to the glass clad, but is guided there without escaping and creation of bright spots. The preferred materials are high OH silica for the core, high OH-F-doped silica for the clad, and Teflon type (Tefzel or similar) based material for the coating. Tefzel material has low refractive index $\sim$1.31–1.32, so silica particles may serve as scattering material, which are transparent down to 200 nm. Fluorinated polymer materials such as PTEF (Polytetrafluoroethylene), PET (Polyethylene terephthalate), FEP (fluorinated ethylene propylene), PFA (perfluoroalkoxy), PEEK (polyetheretherketone), Nylon, and other fluorinated extrudable polymers could work as a protective coating. We selected a solution where we use F-doped glass clad, place a UV-curable primary coating (thin layer $\sim$10–15 um) doped with scattering particles as primary coating, and hard thermally curable coating as a secondary coating. The efficiency curve for this solution is shown in Figure 5. As a polymer with low absorption in UV, which can be UV curable with mercury lamp, we selected cycloalphatic epoxy. The photo-initiator used for UV cure is bleached during cure and the polymer itself has low absorption in UV. Aluminum oxide was added as scattering particles to the coating. Clearly every step shows improvement in efficiency in UV range. Regular NS fiber will not be efficient at wavelengths <410 nm, alumina replacement for TiO_2 shows a significant improvement around 405 nm, and placing a glass clad layer provides even further improvement (405 nm version fiber). This type of fiber is acceptable for 405 nm applications, where high power non-expensive laser diodes are available. The improvements in UV region were also noticeable in NIR due to lower CH content in the fiber coatings.

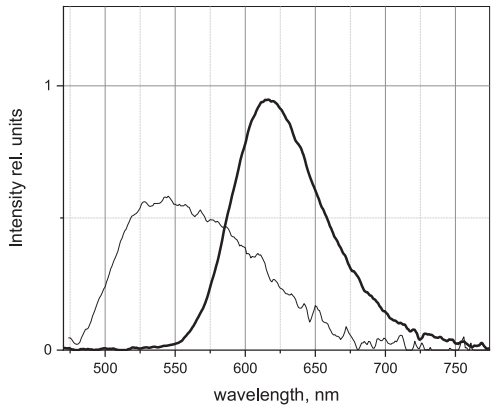

Fig. 6. Luminescence for "yellow" Ce-YAG phosphor (thin line) and "red" nitride based phosphor (thick line) with 450 nm LD excitation.

V. Color Generation With Color Converting Phosphors

The effect of phosphors combined with NS fiber was shown [6] to change the color of the output light vs. the input light. The diffused light from the fiber core can be converted by active luminescence material placed in the secondary coating. The easiest way to generate a white color of a given color temperature is to use a 450 nm LD and use either single or combinations of a few phosphor materials to achieve the color desired. Since the angular distribution of diffused light, in absence of the additional scattering material, may have a forward directed diagram, the color point may differ in different viewing directions relative to the light propagation. This is because the amount of scattered blue light will be angularly dependent, and the final color point depends on the amount of 450 nm light leaking thru the phosphor coating. To compensate for this effect either another wavelength needs to be used such as 405 nm with three phosphor materials for blue, green, and red colors or angular distribution of the scattered light needs to be homogenized. If an improved scattering diagram fiber is used as shown in Figure 4, the color point dependence on the viewing angle is negligible. Achieving a desired white color point is possible with combination of just two phosphor materials, Figure 6.

However, only one true white color point can be obtained since all color points, depending on thickness of the phosphor layers, will be aligned along one line of the CIE 1931 color chart, Figure 7.

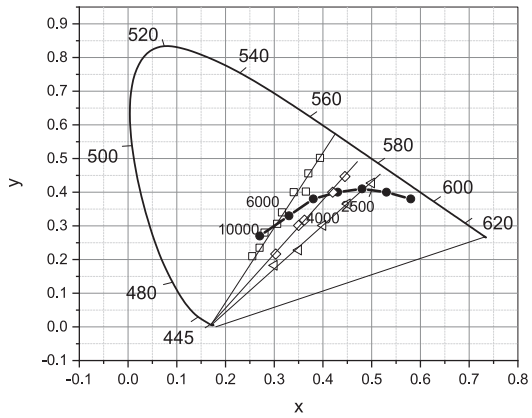

Fig. 7. Position of the colors for different NS fiber made with different combinations of two phosphors (yellow and red) and different thickness of the phosphor layer. To optimize the color to be as close as possible to Planckian locus, thickness of the coating was fine tuned.

For a specific mix of phosphors all the points for a different phosphor layer thicknesses will move along one single line as shown in Figure 7.

The placement of a color converting phosphor can be on top of the secondary coating on the surface of the fiber or in a jacket around the fiber. The amount of the phosphor material needed can also be modified by the addition of a scattering material mixed with the phosphor.

The presence of additional scattering material effectively increases pathlength of the blue 450 nm light interaction with color converting particles. A potential drawback of this approach is back scattering by additional particles toward the fiber core, but since it is a non-absorbing material in this geometry, all scattered light will be utilized. Mixing phosphor materials with scattering materials is a more efficient use of these materials, which are quite expensive.

With moderate concentrations of the phosphor and TiO_2 as a scattering material, the thickness of the color converting layer was $\sim$200 microns. Luminous efficiency measured for 6000 K color correlated temperature CCT was about 240 lm/W.

VI. Applications

Numerous applications of illuminating fibers were previously reported [11]–[16]. Most of them related to the decorative lighting [12]–[14] or to medical applications [15], [16]. The reported fiber in this paper clearly can be used for the same applications; it can be used as a single fiber with moderate NA source like LD, or in a bundle of fibers connected to a large aperture source like an LED. In addition to that, due to low absorption relatively long length of illuminating fibers are possible, up to a few 100 s of meters.

As shown in Figure 5, NS fiber can operate across a wavelength spectrum ranging from UV to IR. This broad range of wavelength capability for that fiber enables applications across a wide range of markets. These applications range from consumer electronics, wearables, safety, architecture, design, automotive, medical and defense.

Fig. 8. Examples of NS fiber knitted or woven into a fabric and then lit up with a red (635 nm) laser.

NS fiber, by nature of its thinness, flexibility and uniformity of light emission, lends itself well to areas like consumer electronics, gaming, and wearables to differentiate product offerings through design. Commercially available headsets and illuminated charge cables create a fun consumer experience as well as visibility at night for runners. As gaming PC's and laptops continue to get thinner, it is becoming more challenging to route alternative lighting solutions into these platforms offering a competitive advantage for illuminating fiber-based lighting systems. NS fiber can also be placed in water to illuminate pools, aquariums, and ponds as well as removing the electronic and light source from the light delivery path for added safety.

Designers and architects value differentiation through new forms of lighting experiences. NS fiber provides a unique aesthetic look for OEMs and building owners. For example, interior and exterior automotive lighting designs where the thin lighting can create new designs and strengthen brand recognition. With higher power laser sources, one can deliver NS fiber solutions that span over 100 m, opening applications in architecture that span lobbies, signage, wayfinding, and exterior lighting. Figure 8 is an example of NS fiber integrated into a fabric using industrial knitting and weaving processes. This demonstrates the possibility of integrating light, fiber, and sensors into products and garments that give visual feedback based on their environment and users condition or needs.

Because NS fiber can deliver light in the IR spectral range, a fiber illuminated with an IR LD can be a light-weight system used in combination with night vision sensors or detectors for identifying people or objects. Applications in law enforcement, military, drones as well as in VR/AR can benefit from this thin line IR capability. Additionally, because of its cylindrical symmetry, NS fiber can be used to transilluminate many luminal tissues and structures for surgical identification using red or IR light and Photodynamic Therapy.

It is well known that UV wavelengths, particularly UV-C, can be used to kill bacteria [17]. The ability for NS fiber to operate in the UV spectrum opens up new opportunities for optical disinfection where other UV light sources cannot be used due to geometry or mechanical constraints. Additionally, blue-violet light has been shown to kill bacteria and be less harmful to eukaryotic cells versus UV light [18]. From a medical perspective, the ability to integrate NS fiber into a catheter or tube combined with 405 nm light could significantly reduce hospital inquired infections in patients and decrease the use of antibiotics.

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