

Color-changing and color-tunable photonic bandgap fiber textiles

B. Gauvreau¹, N. Guo¹, K. Schicker⁴, K. Stoeffler², F. Boismenu¹, A. Ajji³, R. Wingfield⁴, C. Dubois², M. Skorobogatiy^{1*}

¹ *Department of Engineering Physics, École Polytechnique de Montréal, C.P. 6079, succ. Centre-ville Montral, Qubec, Canada H3C 3A7*

² *Department of Chemical Engineering, École Polytechnique de Montréal, C.P. 6079, succ. Centre-ville Montral, Qubec, Canada H3C 3A7*

³ *Industrial Materials Institute, National Research Council, 75 de Mortagne, Boucherville, Qubec, Canada, J4B 6Y4*

⁴ *MA Design for Textile Futures, Central Saint Martins College of Arts and Design, University of the Arts, Southampton Row, London, UK WC1B 4AP*

maksim.skorobogatiy@polymtl.ca

[http://www.photonics.phys.polymtl.ca/](http://www Photonics.phys.polymtl.ca/)

Abstract: We present the fabrication and use of plastic Photonic Band Gap Bragg fibers in photonic textiles for applications in interactive cloths, sensing fabrics, signage and art. In their cross section Bragg fibers feature periodic sequence of layers of two distinct plastics. Under ambient illumination the fibers appear colored due to optical interference in their microstructure. Importantly, no dyes or colorants are used in fabrication of such fibers, thus making the fibers resistant to color fading. Additionally, Bragg fibers guide light in the low refractive index core by photonic bandgap effect, while uniformly emitting a portion of guided color without the need of mechanical perturbations such as surface corrugation or microbending, thus making such fibers mechanically superior to the standard light emitting fibers. Intensity of side emission is controlled by varying the number of layers in a Bragg reflector. Under white light illumination, emitted color is very stable over time as it is defined by the fiber geometry rather than by spectral content of the light source. Moreover, Bragg fibers can be designed to reflect one color when side illuminated, and to emit another color while transmitting the light. By controlling the relative intensities of the ambient and guided light the overall fiber color can be varied, thus enabling passive color changing textiles. Additionally, by stretching a PBG Bragg fiber, its guided and reflected colors change proportionally to the amount of stretching, thus enabling visually interactive and sensing textiles responsive to the mechanical influence. Finally, we argue that plastic Bragg fibers offer economical solution demanded by textile applications.

© 2009 Optical Society of America

OCIS codes: (060.2280) Fiber design and fabrication; (060.4005) Microstructured fibers; (060.5295) Photonic crystal fibers; (230.1480) Bragg reflectors.

References and links

1. P.S. Uskokovic, M. Miljkovic, M. Krivokuca, S.S. Putic, R. Aleksici, "An intensity based optical fibre sensor for flexural damage detection in woven composites," *Adv. Composites Lett.* **8**, 55-58 (1999).
2. P.S. Uskokovic, I. Balac, L. Brajovic, M. Simic, S. Putic, R. Aleksic, "Delamination detection in woven composite laminates with embedded optical fibers," *Adv. Eng. Mat.* **3**, 492-496 (2001).
3. E. D'Amato, "Stress-strain monitoring in textile composites by means of optical fibers," *Exp. Techniques & Design in Composite Mat.* **221**, 245-253 (2002).
4. K.S.C. Kuang and W.J. Cantwell, "Detection of impact damage in thermoplastic-based glass fiber composites using embedded optical fiber sensors," *J. Thermoplastic Composite Mat.* **16**, 213-229 (2003).
5. I. Zivkovic, L. Brajovic, P. Uskokovic, R. Aleksic, "Indentation damage detection in thermoplastic composite laminates by using embedded optical fibers," *J. Adv. Mat.* **37**, 33-37 (2005).
6. A. Kojovic, I. Zivkovic, L. Brajovic, D. Mitrakovic, R. Aleksic, "Low energy impact damage detection in laminar thermoplastic composite materials by means of embedded optical fibers," *Current Res. Adv. Mat. & Processes* **494**, 481-486 (2005).
7. M.A. El-Sherif, J.M. Yuan, A. MacDiarmid, "Fiber optic sensors and smart fabrics," *J. Intelligent Mat. Systems & Struct.* **11**, 407-414 (2000).
8. S. Ghosh, C. Amidei, K. Furrow, "Development of a sensor-embedded flexible textile structure for apparel or large area applications," *Indian J. Fibre & Textile Res.* **30**, 42-48 (2005).
9. Y.H. Zheng, N.P. Pitsianis, D.J. Brady, "Nonadaptive group testing based fiber sensor deployment for multiperson tracking," *IEEE Sens. J. Color Res. Appl.* **6**, 490-494 (2006).
10. J. Spigulis, D. Pfafrods, M. Stafekis, and W. Jelinska-Platace, "The 'glowing' optical fibre designs and parameters," *Proc. SPIE* **2967**, 231-6 (1997).
11. <http://www.lumigram.com/>
12. B. Selem, M. Rothmaier, M. Camenzind, T. Khan, H. Walt, "Novel flexible light diffuser and irradiation properties for photodynamic therapy," *J. Biomed. Opt.* **12**, 034024 (2007).
13. <http://www.lumitex.com/technologies.html>
14. A. Harlin, M. Makinen, A. Vuorivirta, "Development of polymeric optical fibre fabrics as illumination elements and textile displays," *AUTEX Res. J.* **3**, (2003).
15. R.M. Balachandran, D.P. Pacheco, N.M. Lawandy, "Photonic textile fibers," *Applied Optics* **35**, 91-1994 (1996).
16. O. Shapira, K. Kuriki, N.D. Orf, A.F. Abouraddy, G. Benoit, J.F. Viens, A. Rodriguez, M. Ibanescu, J.D. Joannopoulos, Y. Fink, "Surface-emitting fiber lasers," *Opt. Express* **14**, 3929-3935 (2006).
17. M. Hatcher, "France telecom debuts fiber screen," *Optics.org News*, Jul 2 (2002).
18. V. Koncar, "Optical fiber fabric displays," *Opt. Photon. News* **16**, 40-4 (2005).
19. A. Wakita, M. Shibutani, "Mosaic Textile: Wearable ambient display with non-emissive color-changing modules," *Proc. ACE 06*, (2006).
20. J. Berzowska and A. Banasik, "Very slowly animating textiles: Shimmering flower," *Proc. SIGGRAPH* (2004).
21. S.S. Hardaker and R.V. Gregory, "Progress toward dynamic color-responsive "chameleon" fiber systems," *MRS Bull.* **28**, 564-567 (2003).
22. T.Z.N. Sokkar, M.A. Kabeel, W.A. Ramadan, A.A. Hamza, "A contribution to the study of color of fabrics," *Color Res. & Application* **17**, 219-224 (1992).
23. B. Rubin, H. Kobsa, S.M. Shearer, "Prediction and verification of an iridescent synthetic fiber," *Appl. Opt.* **36**, 6388-6392 (1997).
24. M.M. Grasso, B.D. Hunn, A.M. Rewerts, "Effect of textile properties in evaluating a directional shading fabric," *Textile Res. J.* **67**, 233-247 (1997).
25. J. Schuster, M. Trahan, D. Heider, W. Li, "Influence of fabric ties on the performance of woven-in optical fibres," *Composites Part A - Appl. Science & Manufacturing* **34**, 855-861 (2003).
26. I. Maekawa, T. Gunji, T. Tsuboi, "Study on optical properties of silk-like fabrics," *J. Textile Machinery Soc. Japan* **30**, 18-27 (1984).
27. B. Rubin, H. Kobsa, S.M. Shearer, "Modeling the dependence of fabric reflectance on denier per filament," *Textile Res. J.* **64**, 685-689 (1994).
28. A. Sirikasmert and X. Tao, "Effects of fabric parameters on specular reflection of single-jersey knitted fabrics," *Textile Res. J.* **69**, 663-675 (1999).
29. S. Yamaguchi and H. Takanabe, "Fibers having fine concave and convex surface from silica hybrid polyester," *Sen-I akkaishi* **57**, 111-119 (2001).
30. H.Q. Zhang, W.D. Gao, H. Qiu, "Retro-reflection of round fibers," *Textile Res. J.* **73**, 965-970 (2003).
31. B. Rubin, "Tailored fiber cross sections," *Adv. Mat.* **10**, 1225-1227 (1999).
32. J.C. Knight, T.A. Birks, R.S.J. Russell, J.G. Rarity, "Bragg scattering from an obliquely illuminated photonic crystal fiber," *Appl. Opt.* **37**, 449-452 (1998).
33. K. Morikawa, T. Fujisawa, K. Saitoh, M. Koshiba, "Transmission characteristics of laterally illuminated photonic

- crystal fibers," *IEICE Electr. Express* **3**, 70-73 (2006).
34. K. Busch and S. John "Liquid-Crystal Photonic-Band-Gap Materials: The Tunable Electromagnetic Vacuum," *Phys. Rev. Lett.* **83**, 967-970 (1999).
 35. H. Fudouzi, Y.N. Xia, "Colloidal crystals with tunable colors and their use as photonic papers," *Langmuir* **19**, 9653-9660 (2003).
 36. T.T. Larsen, A. Bjarklev, D.S. Hermann, J. Broeng, "Optical devices based on liquid crystal photonic bandgap fibres," *Opt. Express* **11**, 2589-2596 (2003).
 37. S.D. Hart, G.R. Maskaly, B. Temelkuran, P.H. Pridaux, J.D. Joannopoulos, Y. Fink, "External reflection from omnidirectional dielectric mirror fibers," *Science* **296**, 510-513 (2002).
 38. G. Benoit, S.D. Hart, B. Temelkuran, J.D. Joannopoulos, Y. Fink, "Static and dynamic properties of optical micro-cavities in photonic bandgap yarns," *Adv. Mater.* **15**, 2053-2056, (2003).
 39. A. Dupuis, N. Guo, B. Gauvreau, A. Hassani, E. Pone, F. Boismenu, and M. Skorobogatiy, "Guiding in the visible with "colorful" solid-core Bragg fibers," *Opt. Lett.* **32**, 2882-2884 (2007).
 40. P.St.J. Russell, "Photonic crystal fibers," *J. Lightwave. Technol.* **24**, 4729-4749 (2006).
 41. G. Vienne, Y. Xu, C. Jakobsen, H. -J. Deyerl, J. Jensen, T. Sorensen, T. Hansen, Y. Huang, M. Terrel, R. Lee, N. Mortensen, J. Broeng, H. Simonsen, A. Bjarklev, and A. Yariv, "Ultra-large bandwidth hollow-core guiding in all-silica Bragg fibers with nano-supports," *Opt. Express* **12**, 3500-3508 (2004).
 42. A. Argyros, I. Bassett, M. Eijkelenborg, M. Large, J. Zagari, N.A. Nicorovici, R. McPhedran, and C.M. de Sterke, "Ring structures in microstructured polymer optical fibres," *Opt. Express* **9**, 813-820 (2001).
 43. M. Mignanelli, K. Wani, J. Ballato, S. Foulger, P. Brown, "Polymer microstructured fibers by one-step extrusion," *Opt. Express* **15**, 6183-6189 (2007).
 44. Y. Gao, N. Guo, B. Gauvreau, M. Rajabian, O. Skorobogata, E. Pone, O. Zabeida, L. Martinu, C. Dubois, M. Skorobogatiy, "Consecutive solvent evaporation and co-rolling techniques for polymer multilayer hollow fiber preform fabrication," *J. Mater. Res.* **21**, 2246-2254 (2006).
 45. M. Skorobogatiy, "Efficient anti-guiding of TE and TM polarizations in low index core waveguides without the need of omnidirectional reflector," *Opt. Lett.* **30**, 2991 (2005).
 46. S.G. Johnson, M. Ibanescu, M. Skorobogatiy, O. Weiseberg, T.D. Engeness, M. Soljacic, S.A. Jacobs, J.D. Joannopoulos, Y. Fink, "Low-loss asymptotically single-mode propagation in large core OmniGuide fibers," *Opt. Express* **9**, 748 (2001).
 47. <http://www.crystal-fibre.com/>
 48. <http://www.omni-guide.com/>
-

1. Introduction

Driven by the consumer demand of unique appearance, increased performance and multi-functionality of the woven items, smart textiles became an active area of current research. Various applications of smart textiles include interactive clothing for sports, hazardous occupations, and military, industrial textiles with integrated sensors or signage, fashion accessories and apparel with unique and variable appearance. Major advances in the textile capabilities can only be achieved through further development of its fundamental element - a fiber. In this work we discuss the prospectives of Photonic Band Gap (PBG) fibers in photonic textiles. Among newly discovered functionalities we highlight real-time color-changing capability of PBG fiber-based textiles with potential applications in dynamic signage and environmentally adaptive coloration.

As it stands from their name, photonic textiles integrate light emitting or light processing elements into mechanically flexible matrix of a woven material, so that appearance or other properties of such textiles could be controlled or interrogated. Practical implementation of photonic textiles is through integration of specialty optical fibers during the weaving process of textile manufacturing. This approach is quite natural as optical fibers, being long threads of sub-millimeter diameter, are geometrically and mechanically similar to the regular textile fibers, and, therefore, suitable for similar processing. Various applications of photonic textiles have been researched including large area structural health monitoring and wearable sensing, large area illumination and clothes with unique esthetic appearance, flexible and wearable displays.

Thus, optical fibers embedded into woven composites have been applied for in-service

structural health monitoring and stress-strain monitoring of industrial textiles and composites [1, 2, 3, 4, 5, 6]. Integration of optical fiber-based sensor elements into wearable clothes allows real-time monitoring of bodily and environmental conditions, which is of importance to various hazardous civil occupations and military. Examples of such sensor elements can be optical fibers with chemically or biologically activated claddings for bio-chemical detection [7], Bragg gratings and long period gratings [8] for temperature and strain measurements, as well as microbending-based sensing elements for pressure detection [9]. Advantages of optical fiber sensors over other sensor types include resistance to corrosion and fatigue, flexible and lightweight nature, immunity to E&M interference, and ease of integration into textiles.

Total Internal Reflection (TIR) fibers modified to emit light sideways [10] have been used to produce emissive fashion items [11], as well as backlighting panels for medical and industrial applications [12, 13]. To implement such emissive textiles one typically uses common silica [10] or plastic [14] optical fibers in which light extraction is achieved through corrugation of the fiber surface, or through fiber microbending. Moreover, specialty fibers have been demonstrated capable of transverse lasing [15, 16], with additional applications in security and target identification. Recently, flexible displays based on emissive fiber textiles have received considerable attention due to their potential applications in wearable advertisement and dynamic signage [17, 18]. It was noted, however, that such emissive displays are, naturally, "attention-grabbers" and might not be suitable for applications that do not require constant user awareness [19]. An alternative to such displays are the so called, ambient displays, which are based on non-emissive, or, possibly, weakly emissive elements. In such displays color change is typically achieved in the light reflection mode via variable spectral absorption of chromatic inks. Color or transparency changes in such inks can be thermally [19, 20] or electrically activated [21]. An ambient display normally blends in with the environment, while the display presence is recognized only when the user is aware of it. It is argued that it is in such ambient displays that the comfort, esthetics and information streaming is the easiest to combine.

Apart from photonic textiles, a vast body of research has been conducted to understand and to be able to design the light scattering properties of synthetic non-optical fibers. Thus, prediction of the color of an individual fiber based on the fiber absorption and reflection properties was discussed in [22]. Prediction of textile appearance due to multi-fiber redirection of light was addressed in [23, 24, 25]. It was also established that the shape of the individual fibers comprising a yarn bundle has a major effect on the appearance of the resultant textile [26, 27, 28, 29, 30], including textile brightness, glitter, color, etc. The use of the synthetic fibers with non-circular crosssections, or microstructured fibers containing air voids [31] running along their length became one of the major product differentiators in the yarn manufacturing industry.

Recently, novel type of optical fibers, called photonic crystal fibers (PCFs), has been introduced. In their crosssection such fibers contain either periodically arranged micron-sized air voids [32, 33], or a periodic sequence of micron-sized layers of different materials [37, 38, 39]. Non-surprisingly, when illuminated transversally, spatial and spectral distribution of scattered light from such fibers is quite complex. The fibers appear colored due to optical interference effects in the microstructured region of a fiber. By varying the size and position of the fiber structural elements one can, in principle, design fibers of unlimited unique appearances. Thus, starting with transparent colorless materials, by choosing transverse fiber geometry correctly one can design the fiber color, translucence and iridescence. This holds several manufacturing advantages, namely, color agents are no longer necessary for the fabrication of colored fibers, the same material combination can be used for the fabrication of fibers with very different designable appearances. Moreover, fiber appearance is very stable over the time as it is

defined by the fiber geometry rather than by the chemical additives such as dyes, which are prone to fading over time. Additionally, some photonic crystal fibers guide light using photonic bandgap effect rather than total internal reflection. Intensity of side emitted light can be controlled by choosing the number of layers in the microstructured region surrounding the optical fiber core. Such fibers always emit a certain color sideways without the need of surface corrugation or microbending, thus promising considerably better fiber mechanical properties compared to TIR fibers adapted for illumination applications. Additionally, by introducing into the fiber microstructure materials whose refractive index could be changed through external stimuli (for example, liquid crystals at a variable temperature), spectral position of the fiber bandgap (color of the emitted light) can be varied at will [34, 35, 36]. Finally, as we demonstrate in this work, photonic crystal fibers can be designed that reflect one color when side illuminated, while emit another color while transmitting the light. By mixing the two colors one can either tune the color of an individual fiber, or change it dynamically by controlling the intensity of the launched light. This opens new opportunities for the development of photonic textiles with adaptive coloration, as well as wearable fiber-based color displays.

So far, application of photonic crystal fibers in textiles was only demonstrated in the context of distributed detection and emission of mid-infrared radiation (wavelengths of light in a 3-12 μm range) for security applications [37, 38]; there the authors used photonic crystal Bragg fibers made of chalcogenide glasses which are transparent in the mid-IR range. Proposed fibers were, however, of limited use for textiles operating in the visible (wavelengths of light in a 0.38-0.75 μm range) due to high absorption of chalcogenide glasses, and a dominant orange-metallic color of the chalcogenide glass. In the visible spectral range, in principle, both silica [40, 41] and polymer-based PBG fibers [42] are now available and can be used for textile applications. At this point, however, the cost of textiles based on such fibers would be prohibitively high as the price of such fibers ranges in hundreds of dollars per meter due to complexity of their fabrication. We believe that acceptance of photonic crystal fibers by the textile industry can only become possible if much cheaper fiber fabrication techniques are used. Such techniques can be either extrusion-based [43], or should involve only simple processing steps requiring limited process control. To this end, our group has developed all-polymer PBG Bragg fibers [39, 44] using layer-by-layer polymer deposition, as well as polymer film co-rolling techniques, which are economical and well suitable for industrial scale-up.

This paper is organized as follows. We start, by comparing the operational principles of the TIR fibers and PBG fibers for applications in optical textiles. We then highlight technical advantages offered by the PBG fibers, compared to the TIR fibers, for the light extraction from the optical fibers. Next, we develop theoretical understanding of the emitted and reflected colors of a PBG fiber. Then, we demonstrate the possibility of changing the fiber color by mixing the two colors resulting from emission of guided light and reflection of the ambient light. After that, we present RGB yarns with an emitted color that can be varied at will. Then, we present light reflection and light emission properties of two PBG textile prototypes, and highlight challenges in their fabrication and maintenance. Finally, we study changes in the transmission spectra of the PBG Bragg fibers under mechanical strain. We conclude with a summary of the work.

2. Extraction of light from the optical fibers

The key functionality of a standard optical fiber is efficient guiding of light from an optical source to a detector. Currently, all the photonic textiles are made using the TIR optical fibers that confine light very efficiently in their cores. Due to considerations of commercial availability and cost, one frequently uses silica glass-based telecommunication grade fibers, which are even less

suitable for photonic textiles, as such fibers are designed for ultra-low loss transmission with virtually undetectable side leakage. The main problem for the photonic textile manufacturers, thus, becomes the extraction of light from the optical fibers.

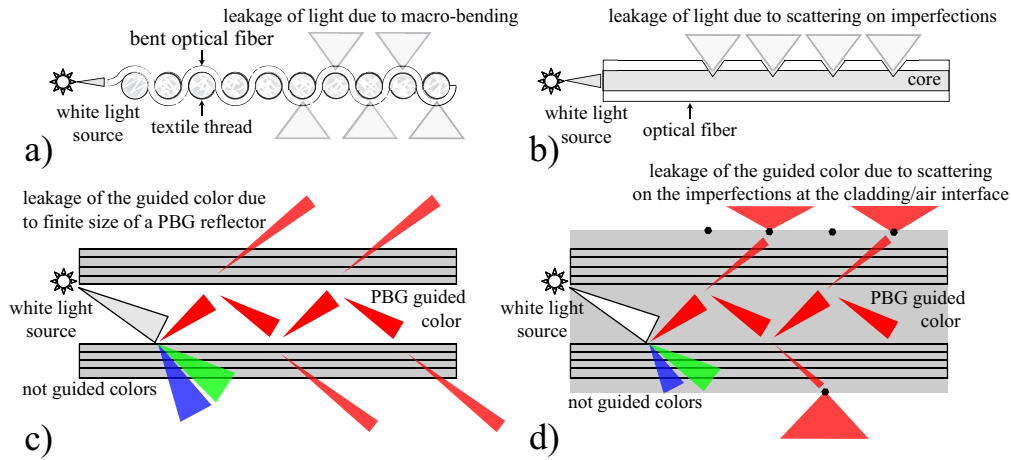


Fig. 1. Light extraction from optical fibers. a) Microbending in TIR fibers. b) Surface corrugation in TIR fibers. c) Leaky modes in straight hollow core PBG fibers. d) Leaky modes in straight low refractive index solid core PBG fibers with scatterers at the fiber/air interface.

Light extraction from the core of a TIR fiber is typically accomplished by introducing perturbations at the fiber core/cladding interface. Two most frequently used methods to realize such perturbations are macro-bending of optical fibers by the threads of a supporting fabric (see Fig. 1(a)), or scratching of the fiber surface to create light scattering defects (see Fig. 1(b)). Principal disadvantage of macro-bending approach is in high sensitivity of scattered light intensity on the value of a bend radius. Particularly, insuring that the fiber is sufficiently bent with a constant bending radii throughout the whole textile is challenging. If uniformity of the fiber bending radii is not assured, then only a part of a textile featuring tightly bend fiber will be lit up. This technical problem becomes especially acute in the case of wearable photonic textiles in which local textile structure is prone to changes due to variable force loads during wear, resulting in 'patchy' looking non-uniformly luminescing fabrics. Moreover, optical and mechanical properties of the commercial silica fibers degrade irreversibly when the fibers are bent into tight bends (bending radii of several mm) which are necessary for efficient light extraction, thus resulting in somewhat fragile textiles. Main disadvantage of scratching approach is that mechanical or chemical methods used to roughen the fiber surface tend to introduce mechanical defect into the fiber structure, thus resulting in weaker fibers prone to breakage. Moreover, due to random nature of mechanical scratching or chemical etching, such post-processing techniques tend to introduce a number of randomly located very strong optical defects which result in almost complete leakage of light at a few singular points, making photonic textile appearance unappealing.

In this work we demonstrate that using photonic bandgap fibers in place of TIR fibers eliminates many technological problems associated with light extraction from optical fibers, while also allowing additional functionalities. Although, the following discussion holds for any PBG fiber, we structure our presentation around hollow and solid core PBG Bragg fibers (see Fig 1(c), and (d)) that we fabricate in our laboratory. Hollow core Bragg fiber (Fig. 1(c)) consists

of an air-filled core surrounded by a periodic sequence of high and low refractive index layers forming a so-called Bragg reflector [46]. Distinguished feature of such a reflector is the presence of bandgaps - spectral regions of high reflector efficiency caused by the interference effects inside a periodic multilayer. In a Bragg fiber, light with frequency inside of a reflector bandgap can be effectively confined in the fiber hollow core through reflections from a surrounding periodic reflector. Effective refractive index of a core guided mode is typically somewhat smaller than that of air filling the core. In practice, due to finite number of layers in the multilayer, there is always tunnelling and leakage of light sideways across the reflector. By changing the number of reflector layers one can control the leakage rate. Thus, for energy transmission applications one wants to increase the number of reflector layers to suppress radiation loss, while for illumination applications one wants to choose a relatively small number of reflector layers to allow sizable sideways irradiation. Another characteristic feature of bandgap guidance is wavelength filtering. Particularly, when launching white light into a PBG fiber, only a particular color defined by the bandgap will be guided, while all the other colors will be irradiated out of the waveguide after the few cm of propagation (see Fig. 2(a)). The key advantage of the hollow core PBG fiber technology for photonic textiles is in the fact that such fibers can emit guided radiation sideways without the need of any mechanical deformations. Moreover, emission rate and the color of irradiated light can be controlled by varying the number of layers in the reflector, and the reflector layer thicknesses, respectively. Additionally, color emitted by PBG Bragg fiber is very stable as it is mostly defined by the geometry of a PBG reflector rather than spectral content and stability of the light source or chemical additives such as dyes.

As we have mentioned earlier, in the visible spectral range both silica [40, 41] and polymer-based hollow PBG fibers [42] have been recently demonstrated, with some of the PBG fibers even available commercially for the visible-near IR [47] and mid-IR ranges [48]. However, the cost of such fibers is in hundreds of dollars per meter due to challenges in their fabrication. To address this issue, our group has developed all-polymer low refractive index solid core PBG fibers (Fig. 1(d)) [39, 44], which are economical and well suitable for industrial scale-up. Such fibers are significantly easier to manufacture than hollow core PBG fibers, therefore their cost is expected to be much lower. Similar to the hollow core fibers, geometry of a solid core PBG fiber features periodic reflector made of a sequence of high and low refractive index layers. The reflector surrounds a low refractive index core, which is typically made of the same material as the low refractive index layers of a periodic reflector. Guidance in the low refractive index core of a fiber is enabled by the bandgap of a surrounding reflector, with non-guided colors leaking through the reflector and into the fiber cladding. Effective refractive index of a core guided mode in a solid core PBG fiber is somewhat smaller than that of a core refractive index, while larger than refractive index of air. Because of that, light that leaks from the fiber core and into the cladding will be contained in the fiber cladding material. In this respect, the fiber exhibits an overall TIR guidance and no sideways emission of light is expected. In practice, due to a large number of imperfections at the fiber cladding/air interface (dust, scratches, etc.), light in the cladding is always efficiently irradiated outside of the fiber.

It is important to note a significant difference in the complexity of light extraction in traditional TIR fibers versus low refractive index solid core Bragg fibers. In conventional TIR fibers one has to introduce perturbations at the core/cladding interface which is located well inside of the fiber structure, while in solid core Bragg fibers one only has to introduce perturbation at the outer fiber/air interface, which is significantly easier to accomplish. Moreover, in conventional TIR fibers, light emission rate is controlled directly through the average strength of the otherwise randomly distributed perturbations. In contrast, in solid core Bragg fibers, light emission

rate (from the core into the cladding) is controlled by the number of layers in the Bragg reflector, while for the emission from the cladding into air one only has to assure an efficient light scattering at the fiber/air interface. As a direct consequence of these differences, light emitted by the solid core Bragg fibers appears very uniformly distributed over the fiber length, and no bright spots are typically observed (see Fig. 2(a)).

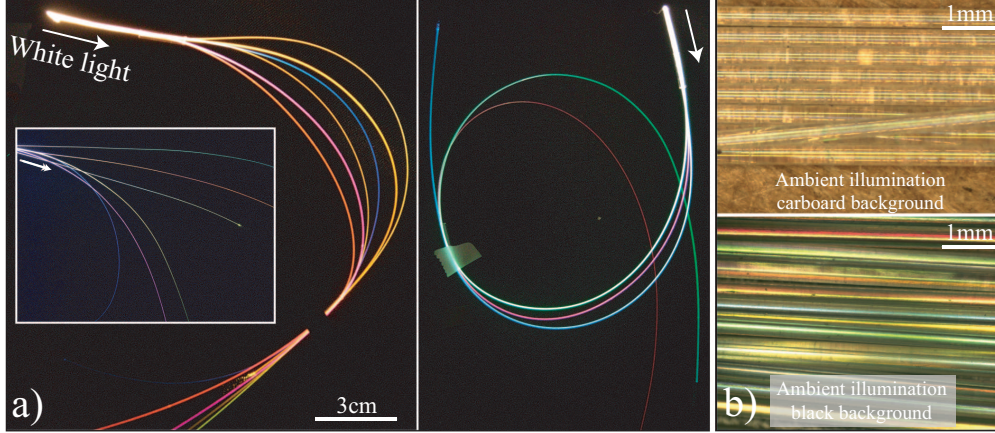


Fig. 2. Colorful PBG Bragg fibers. a) When launching white light into the Bragg fibers, after a few cm from the coupling end the fibers appear intensely colored. Color of an individual fiber is defined by the spectral position of the fiber reflector bandgap. b) Under ambient illumination, semi-transparent Bragg fibers appear colored again. Fiber color in reflection of the ambient light can be different from the color due to emission of guided light.

In Fig. 2(a) we present photographs of 20cm sections of various solid core Bragg fibers fabricated from the same preform, while drawn to different outside diameters. Under the injection of white light, the fibers are glowing uniformly along their lengths with reach distinct colors defined by the bandgaps of their corresponding Bragg reflectors. Moreover, even in the absence of guided light, the fibers appear colored when externally illuminated (see Fig. 2(b)), while remaining semi-transparent due to transparency of plastics used in the fiber fabrication.

3. Understanding the colors of PBG fibers

In our laboratory we fabricate solid and hollow core PBG Bragg fibers using layer-by-layer deposition of polymer films, as well as co-rolling of commercial and home-made polymer films around the core mandrel [39, 44]. Photographs of a typical solid core fiber preform and a resultant fiber are presented in Fig. 3(a). For fabrication of Bragg fibers we mainly use two material combinations, which are polystyrene (PS)/poly(methyl methacrylate) (PMMA) and polycarbonate (PC)/poly(vinylene difluoride) (PVDF) featuring the refractive index contrasts of 1.6/1.48 and 1.58/1.4 respectively. To describe guided states in such fibers one typically starts with finding the bandgaps of a Bragg reflector. In Fig. 3(b) we present a typical band diagram (frequency versus the propagation constant) of the guided modes of an infinite planar periodic reflector fabricated from PMMA/PS and having layers of equal thicknesses $d = 430nm$. Gray regions in the band diagram describe states delocalized over the whole periodic reflector. Such states are efficiently irradiated out of the fiber on the imperfections at the fiber/air interface. Thus, when launching white light into the fiber (see Fig. 2(a)), states delocalized over the whole fiber

cross-section are typically irradiated after the first few cm of propagation. Clear regions in Fig. 3(b) define regions of phase space where no delocalized states exist inside of the periodic reflector, these are the reflector bandgaps. Bragg reflector can, therefore, confine light in the fiber core if the frequency and angle of incidence (propagation constant) of guided light falls into the reflector bandgap. As the core size of Bragg fiber is very large (compared to the wavelength of operation), light propagation inside of the fiber core can be envisioned as a sequence of consecutive bounces of rays travelling at shallow angles with respect to the core/reflector interface. Effective refractive index of such rays is close, while somewhat smaller than that of a core material. Dispersion relation of the Gaussian-like fundamental core guided mode (shown in Fig. 3(b) as a solid red curve), therefore, appears inside of the Bragg reflector bandgap, and is positioned somewhat above the light line of a core material. Dispersion relations of the higher-order higher-loss core modes (not shown in Fig. 3(b)) are positioned further above the light line of the core material, while propagation of such modes within the fiber core is characterized by steeper incidence angles onto the core/reflector interface. The color guided by the fiber core is, therefore, defined by the spectral region corresponding to the intersection of a core material light line with the reflector bandgap. Spectral position of a reflector bandgap (guided color) can be varied at will by changing the thicknesses of the reflector layers, with thicker layers resulting in bandgaps positioned at longer wavelengths. Practically, layer thicknesses are varied by drawing the same preform to fibers of various diameters.

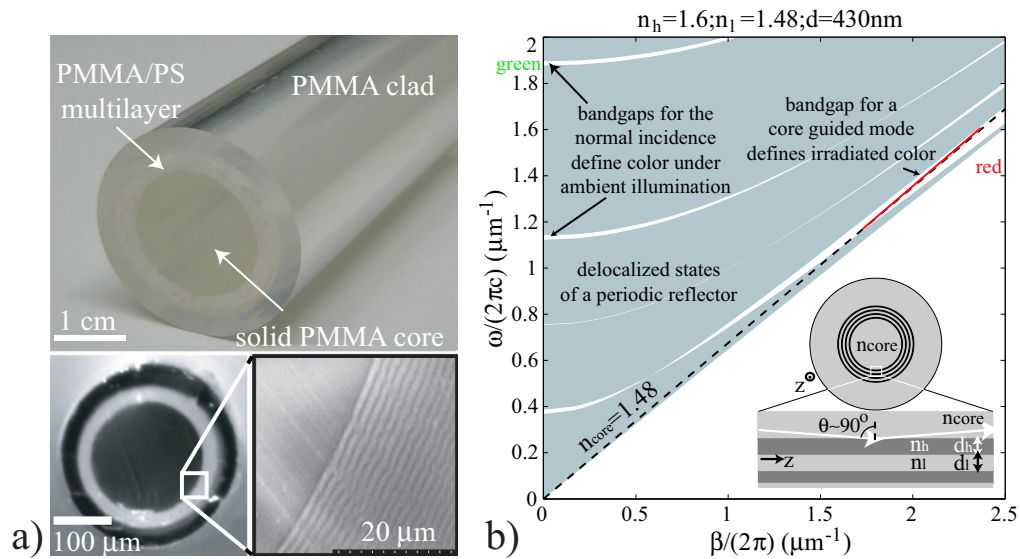


Fig. 3. a) Solid core plastic Bragg fiber preform and a resultant fiber. b) Band diagram of the modes of a solid PMMA core Bragg fiber with a PMMA/PS reflector. Colors of the emitted and reflected light from the Bragg fibers are determined by the positions of the fiber reflector bandgaps.

It is important to note that although bandgap position is determined solely by the geometry of a reflector, the color of guided light is rather determined by the intersection of the light line of a fiber core material with reflector bandgap (red solid line in Fig. 3(b)). From the basic theory of the low refractive index-contrast fibers [45] it follows that the center wavelength λ_c of the

reflector bandgap is given by:

$$\frac{\lambda_c}{2} = d_h \sqrt{n_h^2 - n_c^2} + d_l \sqrt{n_l^2 - n_c^2}, \quad (1)$$

where n_c is the core refractive index, $n_{h,l}$ are the refractive indices of the high and low refractive index layers in the fiber Bragg reflector, while $d_{h,l}$ are the corresponding layer thicknesses. As follows from Fig. 3(b) and expression (1), one can actively change the color of the guided light by either changing the thickness of the reflector layers, or by changing the value of the core refractive index. The former can be implemented by stretching the fiber. The latter can be implemented by filling the hollow core of a PBG Bragg fiber with a material whose refractive index can be changed by varying certain environmental parameters such as temperature or electric field. One class of such materials are liquid crystals that have already been successfully applied to tune bandgap positions in various PBG systems [34, 35, 36].

Additionally, even with no light travelling inside a fiber, while only under the ambient (external) illumination, the PBG Bragg fibers still appear colored (see Fig. 2(b)). Typically, the fiber color in the far field is determined by the reflection properties of the fiber Bragg reflector under the normal light incidence ($\beta=0$). From Fig. 3(b) it is clear that for low refractive index-contrast all-polymer Bragg fibers, the bandgap of a reflector at normal incidence is, generally, located at a different spectral position than the reflector bandgap that supports core guided mode. Therefore, the fiber color under ambient illumination is, generally, different from the fiber color due to irradiation of the core guided light. This opens an interesting opportunity of adjusting the overall fiber color by controlling the relative intensities of the ambient and propagating light. Finally, we note that when operating within higher order bandgaps of the fiber Bragg reflector, the color of guided light can be both of higher or lower frequency than the color of the fiber under ambient illumination.

4. Color-changing textiles under the variable ambient illumination

One of the unique properties of the PBG fiber-based textiles is their ability to change its overall color by mixing the color of reflected ambient light with the color of the irradiated guided light. Consider schematic of a hollow core PBG fiber shown in Fig. 4(a). As it was detailed in the previous section, when launching white light into such a fiber, only the color guided by the reflector bandgap will propagate along the fiber, while all the other colors will be lost to radiation in the first few cm of propagation. Due to finite number of layers in the reflector, guided color will slowly leak out of the fiber core and scatter on the imperfections at the fiber/air interface, thus resulting in fiber coloration. On the other hand, under ambient illumination, and in the absence of guided light, such fibers will again be colored (see Fig. 2(b)). This, however, is due to the reflection of a particular color by the reflector bandgap at close to normal angles of incidence of the ambient light (see Fig. 4(a)). As it was demonstrated in the previous section, color of the reflected ambient light is, generally, different from the color of the irradiated core-guided light. Therefore, when both the ambient illumination and guided light are present, the overall color of the fiber will be determined by mixing of the two colors in the radiation far field. This opens an interesting possibility of actively controlling the fiber color by controlling the relative intensities of the ambient and guided light.

In Fig. 4(b) we present practical demonstration of a color-mixing concept. In this experiment four fibers were suspended in air parallel to each other. The picture at the bottom left of Fig. 4(b) was taken in the dark with light going through the fiber, showing red coloration of the fiber. The picture at the top left of Fig. 4(b) was taken under the laboratory illumination and no

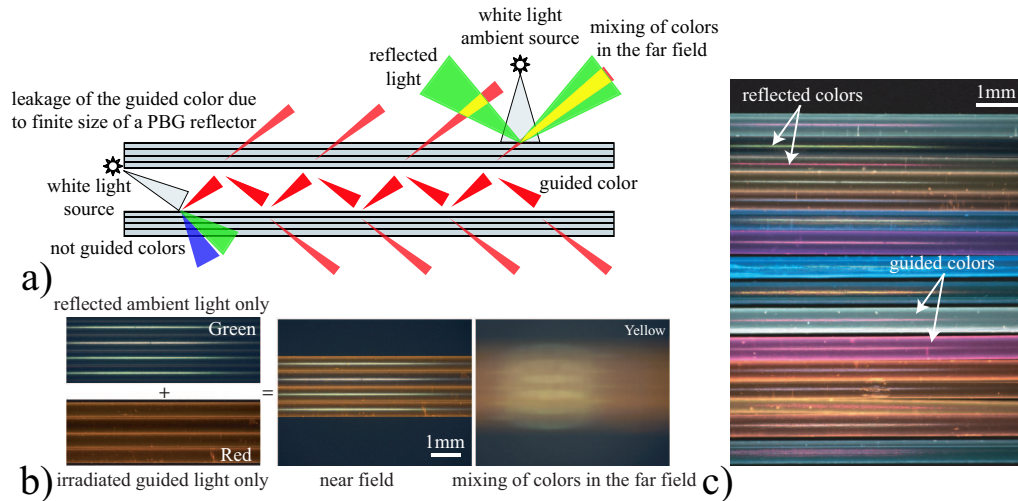


Fig. 4. a) Schematic of a color changing fiber. Color of a PBG fiber can be varied by mixing the emitted guided color with the reflected color from ambient illumination. b) Experimental demonstration of color mixing. c) A collection of lit fibers under strong ambient illumination. Both the emitted guided colors (especially visible at the fiber peripheries) and the reflected colors (especially visible along the fiber center lines) are visible.

light going through the fiber, showing green coloration of the fiber. When allowing both ambient illumination and guided light (middle picture in Fig. 4(b)), the resultant appearance of the fibers in the near field is a collection of green and red stripes. When defocusing the microscope from the fiber surface (right picture in Fig. 4(b)) we get, effectively, an image of the fibers in the far field, which reveals a resultant yellow color of the fiber bundle. Note that the backgrounds always appear black even for the photos captured under the laboratory illumination. This is due to the fact that to take the pictures of fibers we have used a 5x microscope. As the fibers were suspended in air, there was no reflective background in the field of view of a microscope, thus resulting in the black backgrounds in the photos. Finally, in Fig. 4(c) we show a collection of several randomly chosen lit fibers under ambient illumination with both the emitted and reflected colors clearly visible.

5. Color-on-demand textiles using RGB yarns

To implement a PBG fiber-based textile capable of changing its emissive color one can employ RGB yarns. Particularly, consider a braid made of 3 Bragg fibers having red (R), green (G) and blue (B) emissive colors (see Fig. 6(a)). The resultant color emitted by a RGB yarn can be adjusted by controlling the intensities of white light launched into the individual R, G or B fibers. In principle, one can use a single white light source with an unbalanced 1x3 splitter shown in Fig. 6(b). Advantage of this approach is that the color emitted by such a textile will be very stable over time and largely independent of the fluctuations in the intensity of a light source. Moreover, in the event of failure of a white light source one has to simply substitute it with a source of comparable emission spectrum with no re-calibration of the fiber color necessary. In comparison, traditional photonic textiles based on TIR fibers use three different light sources of R, G and B colors for adjusting the overall color of a textile. Relative intensities

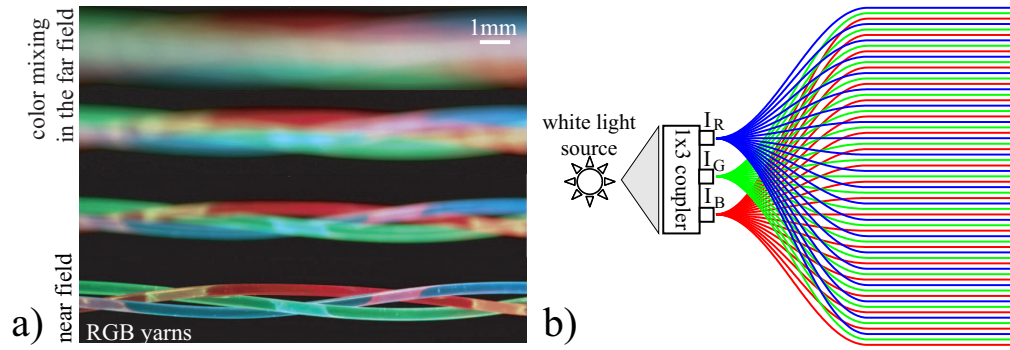


Fig. 5. a) RGB yarn in the form of a braid of three fibers of R, G and B colors. b) Schematic of a color-on-demand textile setup.

of the three light sources have to be monitored and maintained constant over time to avoid color drift. In the event of failure of one of the light sources one has to replace it and recalibrate the fiber color by adjusting the relative intensities of all the three sources.

Similarly, in the reflection mode, textile color can be designed by mixing in the proper proportion fibers of different reflected colors. Moreover, fibers having the same reflected color (for example, pink in Fig. 4(c)) can have different emissive colors (cyan, blue and pink in Fig. 4(c)). This opens an opportunity of designing a monochromatically colored textile under ambient illumination, which is, nevertheless, capable of having any resultant color through emission of R, G and B colors. Such color-changing textiles could find their use in uniforms, signage and machine vision. As no chemical colorants are used in the fabrication of the PBG fiber-based textiles, and as only white light sources are necessary to light them up, such textiles can prove to be more stable over the time and easier to maintain than their traditional counterparts.

6. Experimental realization of the PBG fiber-based textiles

In what follows we present two prototypes of the PBG fiber textiles.

6.1. Prototype I

In Fig. 6 we present photographs of the first 15cmx15cm textile prototype which was created by weaving the Bragg fibers into the matrix of white silk. About 200m of continuous colored Bragg fiber was created in a single draw. Fiber preform was fabricated by co-rolling of the two commercial $50\mu\text{m}$ thick PMMA and PS films around 1in diameter PMMA rod. The fiber diameter was varied in the range $100\mu\text{m}$ - $500\mu\text{m}$ during the production run to get the fibers of different colors. Fiber propagation loss for the fabricated batch was in the 10-20dB/m range (higher loss for smaller diameter fibers) in the visible, while the fiber numerical aperture (NA) in the visible varied between 0.15 and 0.38 with higher NA for the larger diameter fibers.

The sample was hand woven on a Dobby loom and specific weave structures were used to place as much of the optical fiber as possible on the white silk matrix, or ground cloth, so that the fibers could emit and reflect the maximum amount of light. As it is standard in textile manufacturing, several rows of tightly packed threads at the textile sides were used to hold the textile and fibers firmly together. Fibers on one end of a textile were extended outside of a sample for further connectorisation and light launching. Thus fabricated photonic textile appears col-

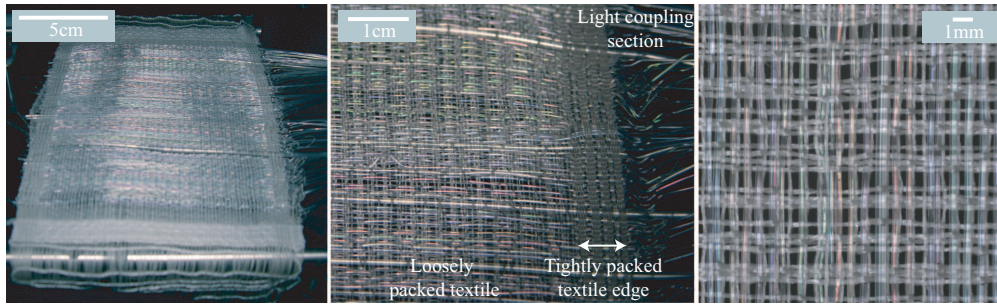


Fig. 6. PBG Bragg fiber-based textile with a white silk matrix. When externally illuminated the textile appears highly reflective showing stripes of different colors. When looked closely, the colored stripes are made of fibers of similar diameters; supporting silk ground cloth is visible through the transparent colored fibers.

ored and reflective when externally illuminated. When looked closer the textile shows colored stripes made of fibers with similar diameters and coloration. Finally, when looked even closer one distinguishes a white silk matrix visible through the semi-transparent colored fibers.

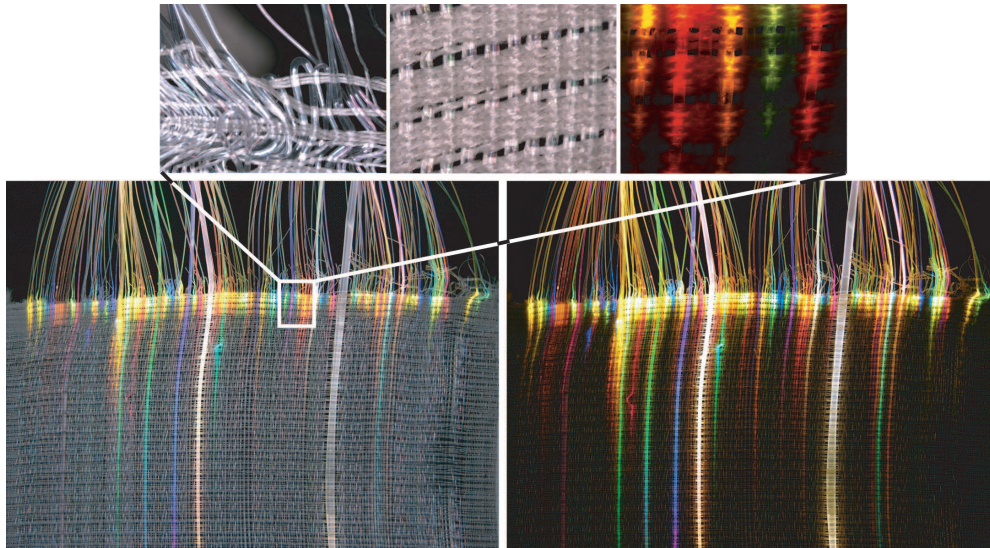


Fig. 7. Launching light into a PBG fiber-based textile under the medium ambient illumination and in the dark (view from the top). At the tightly weaved textile edge strong radiation loss is observed due to macro-bending of small diameter fibers. Thicker fibers persist into textile without too much bending at the edge, lighting up the sample with the guided color.

When launching white light into a textile sample (see Fig. 7) we note that light propagates easily through the coupling section containing mostly straight fibers, resulting in a collection of brightly lit fibers of every color. At the textile edge, the fibers are held by rows of tightly packed silk threads causing thinner fibers to experience strong macro-bending, and resulting in extensive light loss. In contrast, thicker fibers, which are less prone to bending, persist inside of

a textile and light it up through emission of guided color.

6.2. *Prototype II*

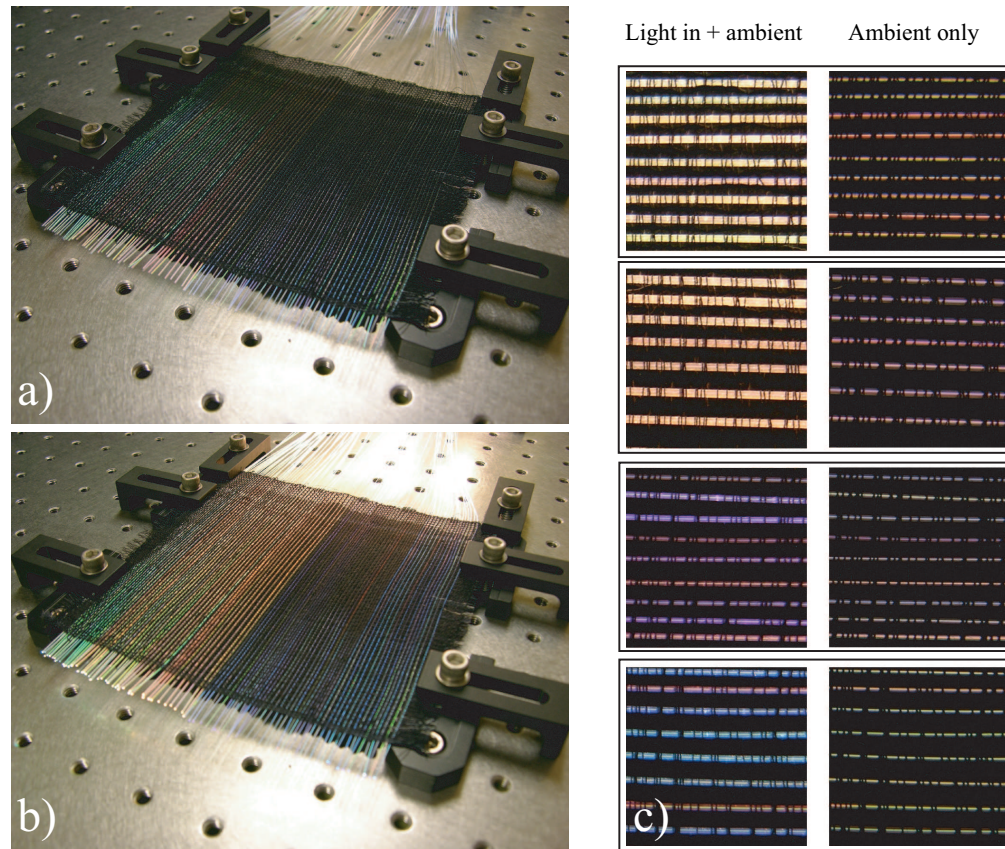


Fig. 8. PBG Bragg fiber-based textile with a black silk matrix. Before weaving, individual fibers were roughly sorted by their two colors in the reflection and emission modes. Therefore, both unlit and lit textile appears to be made of wide bands of distinct colors. a) Textile appearance under ambient illumination. b) Textile appearance when the white light is launch into it, while still under the ambient illumination. c) Colors of various textile patches under ambient illumination with or without the light going through the fibers.

In Fig. 8 we present photographs of a second 20cmx20cm textile prototype which was created by weaving the PBG Bragg fibers into the matrix of black silk. Before weaving, individual fibers were roughly sorted by their two colors in reflection and emission modes. Therefore, both unlit and lit textile appears to be made of wide bands of distinct colors. Fibers for the second prototype were made to have larger diameters to avoid the problem of excessive light loss due to textile induced fiber bending. Particularly, fiber preform was fabricated by co-rolling around a PMMA rod of the home-extruded PMMA and PS films each of less than $20\mu m$ of thickness. As we have started with thinner reflector layers in the preform, we needed smaller drawdown ratios (compared to that of the first prototype) to result in the same size of the reflector layers as in the

case of the first prototype. As a consequence, fibers in the second prototype were significantly larger and more mechanically robust than the fibers in the first prototype, while having similar colors both in reflection and emission modes. Overall, about 200m of continuous fiber was produced. Fiber diameter was varied in the range $300\mu\text{m}$ - $600\mu\text{m}$ during the production run to get the fibers of different colors. Fiber propagation loss for the fabricated batch was in the range of 5-10dB/m (higher loss for smaller diameter fibers) in the visible part of a spectrum.

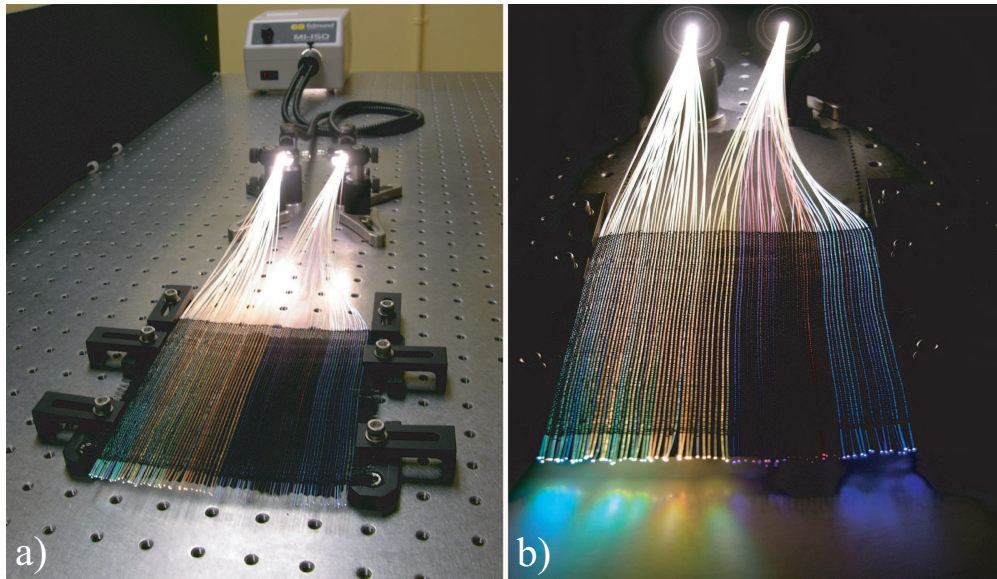


Fig. 9. PBG fiber textile and light coupling setup. a) Lit textile under the normal ambient illumination in the laboratory. b) Lit textile in the dark.

The second sample was also hand woven on a Dobby loom, however, unlike in the first prototype, care was taken not to create tightly packed threads at the textile sides in order to avoid an excess bending induced loss at the textile input and output edges. Fibers on one end of a textile were extended outside of a sample for further connectorisation and light launching. Thus fabricated photonic textile appears colored when externally illuminated (Fig. 8(a)). When looked closer the textile exhibits colored bands made of fibers with similar diameters and coloration. When launching white light into a textile sample (see Fig. 8(b)) light flows easily over the textile input edge, exhibiting a number of brightly lit wide bands of distinct colors.

In Fig. 8(c) we compare the appearances of various textile patches under the ambient illumination with or without the light going through the fibers. Note that the same patch looks differently depending on whether the textile is lit or not. This opens a possibility of controlling the resultant textile color by balancing the intensities of the guided and ambient light.

In Fig. 9(a) we present a complete view of a PBG fiber textile including the light coupling setup. Textile fibers are batched into two groups, each one is butt-coupled to one of the two fiber bundles coming out of the $\sim 100\text{W}$ Edmund Optics halogen lamp source. The picture is taken under the normal ambient illumination in the laboratory. The textile is lit, and the white light source is powerful enough so that the colors emitted by the textile are dominating the textile colors due to ambient illumination even under standard laboratory illumination. For

comparison, in Fig. 9(b) we present the same lit textile in the dark.

Finally, we note that as power leaks out of the fiber, the optical power carried along the fiber decreases exponentially with travelled distance, thus resulting in non-uniform brightness of a photonic textile. This problem is common to all fiber-based textiles. The simplest solution is to ensure that textile dimension is much smaller than a characteristic decay length of light in the fiber. In principle one can also resort to fabrication of non-uniform fibers to compensate for the decay in the transmitted light intensity by forcing more light to escape closer to the fiber end.

7. Optical response of plastic PBG fibers to mechanical stretching

Finally, we would like to discuss another interesting feature of plastic PBG fibers, which is change in their optical properties under mechanical influence. We have previously mentioned that scaling of Bragg fiber geometry leads to the shift in the reflector bandgap position, and as a consequence, to the change in the fiber transmitted and reflected colors. One would expect that under mechanical strain, fiber dimensions would vary, thus having an impact on both the fiber appearance and transmission spectrum.

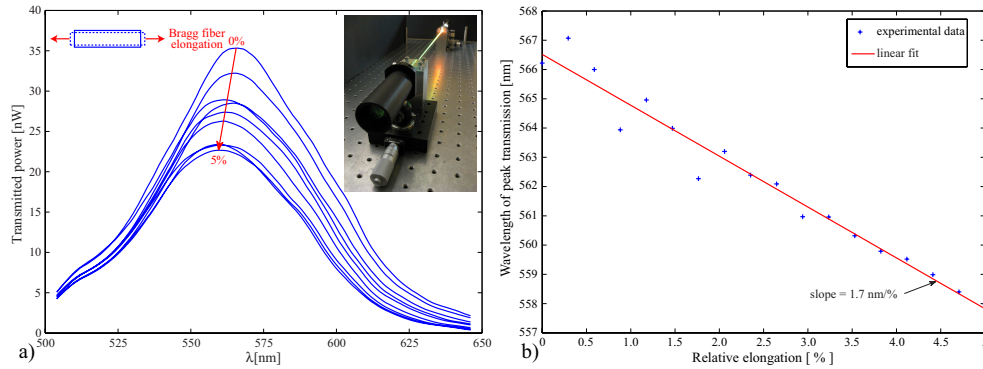


Fig. 10. Stretching of plastic Bragg fibers. a) Transmission spectra of a Bragg fiber sample subjected to longitudinal stretching. Fiber elongation results in the shift of the fiber transmission peak to shorter wavelengths due to Bragg reflector thinning. In the inset: photo of an experimental setup. Collimated beam of a supercontinuum white light source is injected into a Bragg fiber sample which is clamped at both ends to the rigid support blocks. b) Linear shift of the transmission peak wavelength with respect to the Bragg fiber elongation with a slope of $1.73 \frac{\text{nm}}{\%}$.

In order to verify this experimentally, a piece of Bragg fiber was attached to two rigid blocks, with one of the blocks (at the fiber output) being translated along the fiber axis using a linear stage, thus applying a measurable strain on a fiber sample (see inset in Fig. 10(a)). The linear stage at the output end also hosted a lens assembly for collimating the transmitted light (fiber output end placed at the focal plane of the lens). Optical transmission spectra were then acquired with the aid of a monochromator for various fiber elongations reaching up to 2.2cm with the initial distance between the fiber clamps of $\sim 43\text{cm}$. During the experiments we made sure that changes in the recorded spectra were not due to translation of the setup optics.

Measured transmission spectra are presented in Fig. 8(a). As fiber relative elongation progressively increases from 0 % to 5 %, fiber transmission peak shifts towards shorter wavelengths, while attenuation increases. We presume that shift of the fiber transmission peak is due

to spectral shift of the Bragg fiber bandgap. Particularly, we expect that due to fiber strain the fiber transverse crosssection contracts proportionally, thus resulting in a blue shift of a Bragg fiber bandgap. Decrease in the transmitted power can be explained in two ways. First, the two rigid clamps used to secure the fiber in place prevent about 2cm of fiber on each end to expand compared to the rest of the fiber. When strain is applied the clamped fiber will have a bandgap positioned somewhat differently from the one of a suspended fiber. This will amount to the increased loss as the transmission peak for a suspended fiber will be located closer to the bandgap edge of a clamped fiber. The net effect will be that of a transmission through a series of three somewhat mismatched narrow band filters. Another possible reason for the increase in fiber attenuation is the increase in the amount of the fiber structural defects due to applied strain.

Moreover, from the transmission data of Fig. 10(a) one can also deduce the dependence of the transmission peak wavelength with respect to the relative elongation of the Bragg fiber. Fig. 10(b) shows that transmission peak shift is linear with the fiber elongation having a slope of $1.73 \frac{nm}{\%}$. Thus, for the maximal fiber elongation of 5% we observe 8.5nm shift in the transmission peak position. Sensitivity of the fiber transmission and reflection spectra to the mechanical strain could lead to applications of such fibers as distributed sensors or indicators. Moreover, when fiber is left under strain for an extended time period, such a strain could become permanent in polymer fibers, thus allowing for tuning of the fiber color and transmission spectrum.

8. Conclusions

We have presented an implementation of a photonic textile based on plastic Photonic Band Gap Bragg fibers for potential applications in smart cloths, signage and art. It was established that under ambient illumination Bragg fibers appear colored due to optical interference in their microstructure. As Bragg fibers guide light in the low refractive index core by photonic bandgap effect they naturally emit sideways a portion of guided color without the need of mechanical perturbations, which is their key advantage over traditional TIR fibers. Moreover, we have demonstrated Bragg fibers that reflect one color when side illuminated, and emit another color while transmitting the light. We then showed that by controlling the relative intensities of the ambient and guided light the overall fiber color can be varied. General implementation of the color-on-demand textiles using RGB yarns in the form of tri-fiber braids was discussed. It was established that another key advantage offered by PBG fibers in application to photonic textiles is stability of the emitted color over time. Moreover, we showed that emitted color of the PBG fiber can be tuned by applying strain. Finally, compared to other existing PBG fibers, all-plastic Bragg fibers currently offer the most economical solution required by the textile applications.

9. Author contributions

Research group at the Department of Engineering Physics, Ecole Polytechnique de Montral (EPM) was responsible for the design and fabrication of the PBG Bragg fibers, as well as optical characterization of the photonic textiles. Groups at the Department of Chemical Engineering, EPM, and Industrial Materials Institute, NRC, were responsible for the materials preparation and extrusion of films for the fiber preform fabrication, as well as some drawing experiments. Group at the University of the Arts was responsible for weaving of the textile samples.