Jacquard-Woven Photonic Bandgap Fiber Displays

I. Sayed[1], J. Berzowska[2] and M. Skorobogatiy[1*]
[1]Ecole Polytechnique de Montréal, Montréal, Canada, maksim.skorobogatiy@polymtl.ca
[2]XS Labs, Concordia University, Montréal, Canada, joey@xslabs.net
http://www.photonics.phys.polymtl.ca/
http://xslabs.net/karma-chameleon/

ABSTRACT

We present an overview of photonic textile displays woven on a Jacquard loom, using newly discovered polymer photonic bandgap (PBG) fibers that have the ability to change color and appearance when illuminated with ambient or transmitted light. The photonic fiber can be thin (smaller than 300 microns in diameter) and highly flexible, which makes it possible to weave in the weft on a computerized Jacquard loom and develop intricate double weave structures together with a secondary weft yarn. We demonstrate how PBG fibers enable a variety of color and structural patterns on the textile, and how dynamic imagery can be created by balancing the reflected ambient light and emitted light. Finally, a possible application in security wear for low visibility conditions is described as an example.

Keywords: Photonic Displays, Electronic Textiles, Photonic Bandgap Fibers, Jacquard Loom

1. Introduction

In recent years, electronic textiles have become a major multi-disciplinary area of research with applications in health, security and safety, communication, and culture industries. Although the field is growing and developing at an accelerated rate, the predominant implementation model usually still consists of layering electronic or mechatronic functionality on top of a textile substrate. Prior work exists in the domain of stitching, weaving, or knitting with conductive yarns to create structures such as electrodes, sensors, or communication lines, and subsequently attaching electronic components to that substrate. Few functional yarns (other than conductive or resistive yarns) are currently available commercially to enable functionality such as the display of information, sensing, or energy harnessing in a textile. The ability to integrate the desired functionality on the fundamental level of a fiber remains one of the greatest technological challenges in the development of smart textiles. In this review, we consider photonic fibers as an example of functional yarns that integrate several optical functionalities at the fiber level.

As indicated by their name, photonic textiles integrate light emitting or light processing elements into the mechanically flexible matrix of a woven material, so that the appearance or other properties of such textiles can be controlled or sensed with light. One of the practical implementation of photonic textiles is, for example, 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 regular textile fibers, and therefore, suitable for similar processing. Various applications of photonic textiles have been researched, including large area structural health monitoring, wearable sensing, large area illumination, garments with unique aesthetics, as well as flexible and wearable displays.

Traditional fiber optic textiles use commercial total internal reflection (TIR) optical fibers developed for the telecommunication industry. Such fibers are made of transparent materials, such as glass or polymers, and optimized for low loss information transmission. TIR optical fibers

---

[*] Corresponding author. Tel.: 1 (514) 340-4711 (3327); Fax: 1 (514) 340-3218
E-mail address: maksim.skorobogatiy@polymtl.ca

embedded into woven composites have been applied for in-service structural health monitoring and stress-strain monitoring of industrial textiles and composites (Uskokovic et al., 1999; D'Amato, 2002; Kuang & Cantwell, 2003).

Integration of optical fiber-based sensor elements into wearable apparel allows real-time monitoring of bodily and environmental conditions, which is important to various hazardous civil occupations, including the security and military sector. Examples of such sensor elements can be optical fibers with biologically or chemically activated claddings for bio-chemical detection (El-Sherif, 2000), Bragg gratings and long period gratings (Ghosh et al., 2005) for temperature and strain measurements, as well as microbending-based sensing elements for pressure detection (Zheng et al., 2006).

Advantages of the optical fiber sensors over other sensor types include resistance to corrosion and fatigue, flexible and lightweight nature, immunity to electricity and magnetism (E&M) interference, and ease of integration into textiles.

TIR optical fibers modified to emit light sideways (Spigulis et al., 1997) have been used to produce emissive fashion items (Lumigram) as well as backlighting panels for medical and industrial applications (Salem et al., 2007; Lumitex).

To implement such emissive textiles, one typically uses common silica (Spigulis et al., 1997) or plastic (Harlin et al., 2003) optical fibers in which light extraction is achieved through corrugation of the fiber surface or fiber microbending. Moreover, specialty fibers capable of transverse lasing (Balachandran et al., 1996; Shapira et al., 2006) have been demonstrated, 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 for wearable advertisements (Koncar, 2005).

It was noted, however, that such emissive displays are only visible in certain lighting conditions and function as "attention-grabbers" which makes them less suitable for applications that do not require constant user awareness (Wakita & Shibutani, 2006).

An alternative to such displays are ambient displays, which are based on non-emissive or weakly emissive elements. An ambient display normally blends in with the environment and is recognized only when the user is aware of it. It is argued that such ambient displays most successfully combine comfort, aesthetics and information streaming capability.

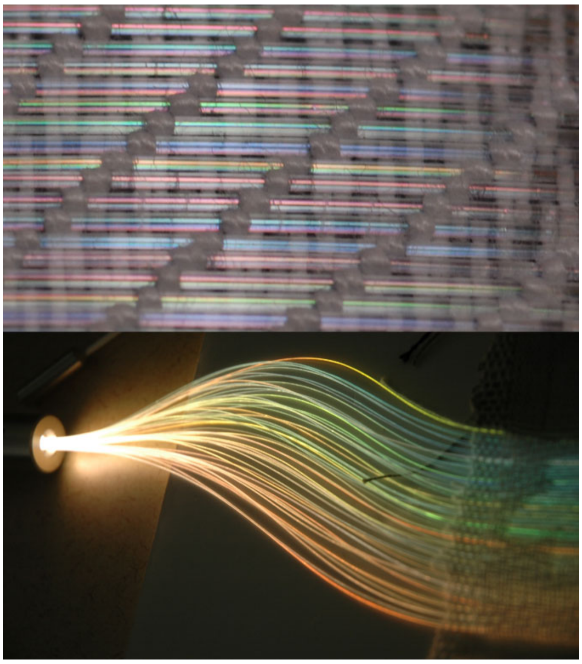

Fig. 1. Top: PBG fibers under ambient illumination show colors due to light interference in their nanostructure. No dyes are used to color the fibers.
Bottom: when launching white light into PBG fibers, after a few cm from the source, individual fibers become strongly colored by rejecting non-guided colors at the input end.

In this paper, we will deal with a subclass of photonic textiles, specifically the one based on a novel type of optical fibers, called photonic crystal fibers (PCFs). In their cross section, PBG fibers contain either periodically arranged micron-sized air voids (Knight et al., 1998) or a periodic sequence of micron-sized layers of different materials (Hart et al., 2002; Dupuis et al., 2007).

When transversally illuminated, the 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 correctly choosing the transverse fiber geometry, one can design the fiber color, translucence and iridescence. This holds several manufacturing advantages, namely that color agents are no longer necessary for the fabrication of colored fibers and the same material combination can be used for the fabrication of fibers with very different designable appearances. Moreover, the fiber appearance is very stable over time as it is defined by the fiber geometry rather than chemical additives, such as dyes, which are prone to fading over time. Some PCFs guide light using the PBG effect rather than total internal reflection. The intensity of side-emitted light can be controlled by choosing the number of layers in the microstructured region which surrounds the optical fiber core. Such fibers always emit a certain color sideways without the need for surface corrugation or microbending, thus promising considerably better fiber mechanical properties compared to TIR fibers adapted for illumination applications. By introducing materials whose refractive index could be changed through external stimuli into the fiber microstructure (for example, liquid crystals at a variable temperature), the spectral position of the fiber bandgap (color of the emitted light) can be varied at will (Larsen et al., 2003).

Finally, as we demonstrate in this work, PCFs can be designed to reflect one color when side illuminated and emit another color while transmitting the light. By mixing the two colors, one can either tune the color of an individual fiber, or dynamically change it 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, one application of PCFs in textiles has been 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 (Hart et al., 2002).

The authors used photonic crystal Bragg fibers made of chalcogenide glasses which are transparent in the mid-IR range. The proposed fibers are, however, of limited use for textiles operating in the visible spectrum (wavelengths of light in a 0.38-0.75 μm range) due to the high absorption of the chalcogenide glasses, and their dominant orange-metallic color. In the visible spectral range, both silica (Knight et al., 1998) and polymer-based PBG fibers (Arguros et al., 2001) are now available and can be used for textile applications. Currently, however, the cost of textiles based on such fibers would be prohibitively high, as these fibers range in hundreds of dollars per meter due to the complexity of their fabrication. We believe that the acceptance of PCFs by the textile industry will only come if much cheaper fiber fabrication techniques are used. Such techniques can be either extrusion-based (Mignanelli et al., 2007), or should involve simple processing steps that require limited process control. To this end, our group has developed all-polymer PBG Bragg fibers (Dupuis et al., 2007; Gao et al., 2006) using layer-by-layer polymer deposition and polymer film co-rolling techniques, which are economical and well suitable for industrial scale-up. In this paper, we overview the latest advances of our group in the fabrication of PBG fiber-based textile panels and review their many intriguing properties (Gauvreau et al., 2008; Gauvreau & Schicker et al., 2008).

2. Photonic Band Gap Fiber

In our research, we have been fabricating and weaving PBG fibers on a computer-controlled electronic Jacquard loom, in order to produce textile displays with dynamic appearances. In their cross section, PBG Bragg fibers feature periodic sequence of 100s of nano-sized layers of two distinct plastics. Under ambient illumination (Fig. 1, top), the fibers appear colored due to optical interference in their nanostructure. Importantly, no dyes or colorants are used in the fabrication of such fibers, thus making the fibers resistant to color fading. In addition, Bragg fibers guide light in the low refractive index core by the PBG effect (Fig. 1, bottom), while uniformly emitting a portion of guided color without the need for mechanical perturbations, such as surface corrugation or microbending (which is the case in traditional photonic textiles (Lumigram, Lumitex)), thus making such fibers mechanically superior to standard light emitting fibers.

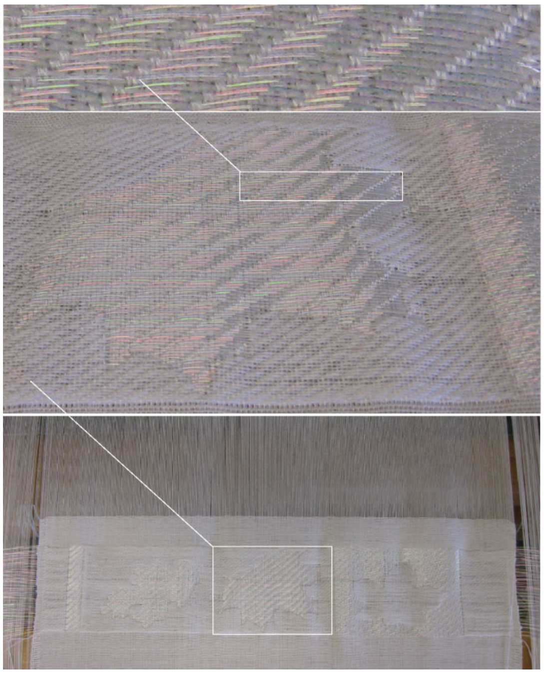

Fig. 2. Textile that features a leaf pattern made of cotton thread (warp and weft) and PBG fiber (weft). Leaves are made either with PBG fibers on a cotton background (top left), or cotton threads on a PBG fiber background (top right).

The intensity of side emission is controlled by varying the number of layers in a Bragg reflector. Under white light illumination, the emitted color is very stable over time as it is defined by the fiber geometry rather than spectral content of the light source. Moreover, Bragg fibers can be designed to reflect one color when side illuminated and emit another color when transmitting light. By controlling the relative intensities of the ambient and guided light, the overall fiber color can be varied, thus enabling color changing textiles.

Fabrication of solid-core PBG fibers involves layer-by-layer deposition of polymer films, or co-rolling of commercial polymer films around a plastic core rod followed by drawing of these preforms at elevated temperatures (Dupuis et al., 2007; Gauvreau et al., 2008). Material combination of the poly methyl methylacrylate (PMMA) and polystyrene (PS) plastics with refractive indices of 1.48 and 1.6, respectively, was used. The core was made of PMMA, while the cladding is a multilayer containing 100s of nano-sized layers (200-1000 nm in thickness) of PMMA/PS which act as a color selective all-dielectric mirror. The resultant fiber diameter can be varied between 300 and 700 microns. As the fiber color is a result of interference in the reflector layers, it can be adjusted by drawing the same preform into fibers of different diameters.

3. Textile Reflective Properties Under Ambient Illumination

PBG fibers are highly reflective and have the appearance of colored metallic mirrors. A straight PBG fiber exposed to ambient light can "sparkle" when the incidence angle and the angle of observation are properly chosen (see Fig. 2). The sparkling effect can be enhanced by introducing bends into the fiber. The appearance of the reflective textile can be dramatically varied by using different weave patterns, such as the ones enabled by a computerized Jacquard loom. A Jacquard loom allows the weaver to individually address each warp thread so as to create complex weave structures, including double weaves. Double weave is a type of woven cloth in which two warps and two sets of weft yarns are interwoven to form a two layered cloth. We used a white cotton warp. We also used a white cotton weft and a PBG fiber weft to create individual illuminated designs in the textile display.

To systematically study the reflection from PBG fiber textiles, we prepared a textile sample with a three leaf pattern, each using a variety of weft face double weave structures. We wove the pattern twice, using two different diameters of PBG fibers, 500 and 300 microns. The first sample, shown in Fig. 3(a), is woven with thicker PBG fibers which used a double weave where the warp yarns were separated into two layers so as to bring the PBG fibers to the surface in the leaf pattern and weave them in the back layer in the area around the leaf. In the leaf featured in Fig. 3, the PBG fiber is woven in a 1/7 twill structure in the front layer, while the cotton yarn is woven in a 2/2 pocket weave structure in the back layer. The two layers are connected by reversing the positions of the two layers outside the leaf pattern, but are not connected inside the leaf, which is also known as pocket cloth or pocket weave, since it creates pockets between the two layers. The leaf structure features relatively long sections of straight fiber (1-2 cm) placed on the surface of white cotton. When reflecting daylight, textile sections that have Bragg fibers show a warm red color and have a "sparkly" appearance (Fig. 2).

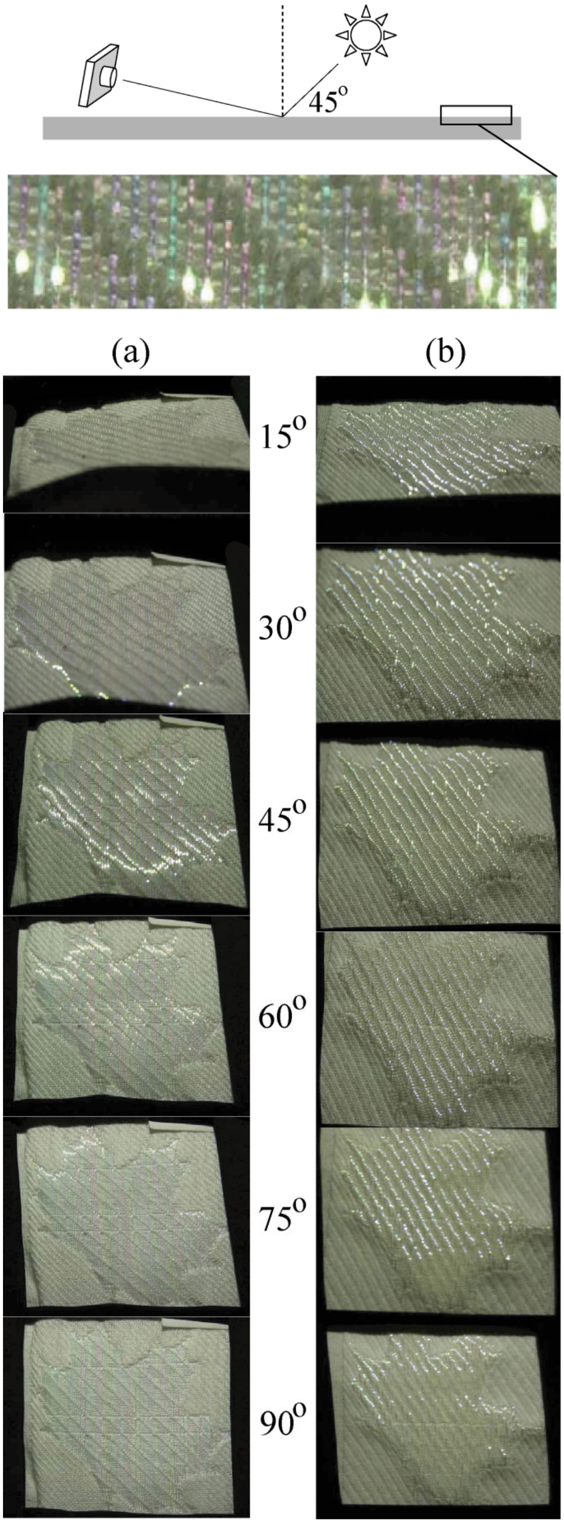

Fig. 3. Reflection of ambient light from a PBG fiber-based textile as a function of the angle of observation. The angle of incidence of ambient light is 45°.
(a) Sample that features relatively straight sections of PBG fibers.
(b) Sample that features strongly bent and curled PBG fibers.

To study textile reflection properties under controlled conditions, we used artificial illumination provided by a Luxeon cool-white light-emitting diode (LED) source (LXK2-PW14-T00 model) placed 60 cm from the textile surface at a 45° inclination, see Fig. 3(a). We positioned the photo camera 60 cm from the center of a sample and took images at 15°, 30°, 45°, 60°, 75°, and 90° inclinations with respect to the textile surface. From the photographs, we see that the reflection of ambient light from this textile sample is very directional, and that the observed reflection is the strongest when the angle of observation matches the angle of incidence. Note from Fig. 3 that the color of the reflected LED light appears white, in stark contrast to the color of the reflected daylight (see Fig. 2) which appears red. Moreover, when inspecting the same textile sample under magnification in the LED light (see the top part in Fig 3) and in daylight (see the top part in Fig. 2), one clearly sees that the individual strands are colored in both cases, while the overall hues are different. The main reason for the difference in perceived appearances of the same textile under different illumination conditions takes root in the spectral differences of the two illumination sources. Thus, a cool-white spectrum of an LED source features the main maximum in the blue region and a secondary much smaller maximum in the green-red region, while the spectrum of daylight has a much stronger red component.

A second sample, shown in Fig. 3(b), uses thinner PBG fibers, while having similar weave structures as the first one. One difference is that since the fibers are thinner, we used a stitched double cloth instead of a pocket cloth. As before, the PBG fiber in the leaf is woven in a 1/7 twill structure in the front layer, while the cotton yarn is woven in a 2/2 pocket weave structure in the back layer. Since the PBG fiber is thinner, it did not provide the same structural rigidity in the pocket structure and we needed to stitch the two layers together by lifting a back end over a face pick in a 1/7 twill pattern, aligned to the 1/7 twill structure in the front layer. This caused increased intersections between the cotton warp yarns and the PBG weft fibers. The tension placed on the weft by the warp threads exerts pressure, which can bend the weft threads. As a result, the thinner PBG fibers are strongly bent at the point of contact with the cotton thread in this weave structure. As seen in Fig. 3(b), this sample scatters light differently from the sample shown in Fig. 3(a). Due to the presence of many tight bends in the PBG textile layer, the intensity of the reflected light becomes largely independent of the angle of observation.

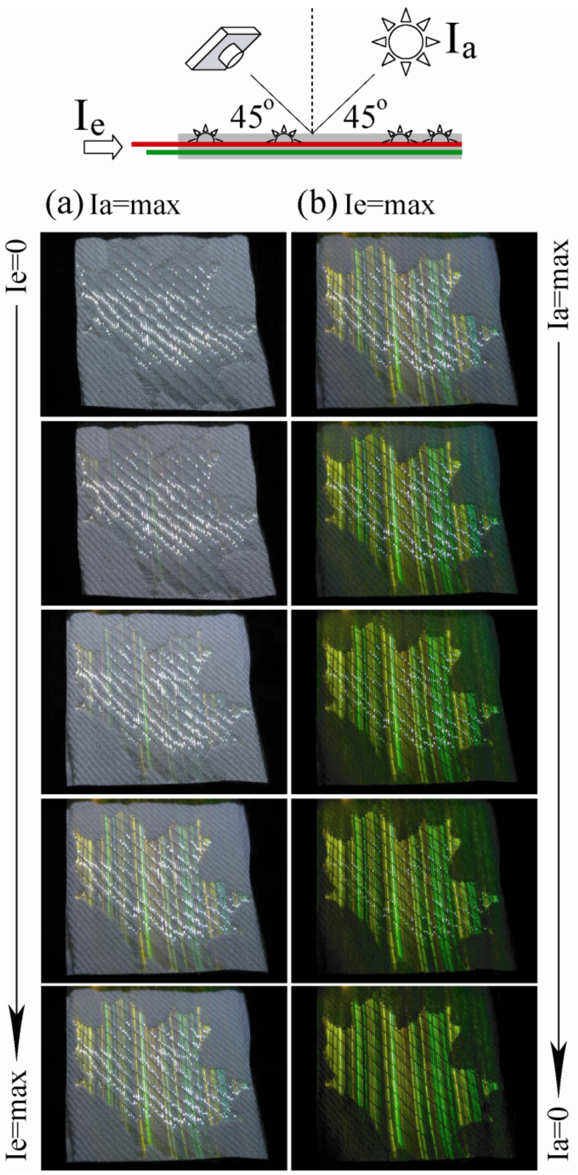

Fig. 4. Mixing reflection of the ambient light with emission of the guided light. Left: LED ambient light is at maximum, while intensity of the guided light is varied from zero to its maximal value. Right: intensity of the guided light is at its maximum, while intensity of the LED ambient light is reduced from its maximal value to zero.

4. Dynamic Animated Textile Appearance Using Mix of Ambient and Emitted Lights

To explore variations in textile appearance produced by changes in the relative intensities of the ambient illumination and the emitted radiation, we performed the following experiment. The sample under study is a textile panel shown in Fig. 3(a). It was illuminated with a cool-white LED at a 45° angle with intensity Ia, and at the same time, light was launched into the textile with intensity Ie. In Fig. 4(a), we show a sequence of photos which were taken at a fixed intensity of ambient light Ia=const and a variable intensity of light launched into a textile Ie=0→max. We observed that when the intensity of the emitted light is small, the overall appearance of a textile panel is determined by the reflected light. When intensities of the emitted and reflected lights are comparable, the textile appearance becomes strongly affected (compare the top and the bottom pictures in Fig. 4(a)). Another experiment reflected in a series of photos in Fig. 4(b) was performed by keeping the light launched into a textile at the maximal intensity, while gradually reducing the intensity of the ambient light. Note remarkable dynamics both in color, warmth, iridescence, etc. of the textile provoked by changes in the illumination conditions.

5. Potential Applications in Worker Wear for Low Visibility Conditions

One scenario of using PBG textiles relates to a civil worker safety garment that operates at low light (night) conditions (Fig. 5).

In this scenario, the worker is operating at night time, and s/he is wearing an emissive textile panel (see Fig. 5). When no external illumination source is present, one detects a colorful emission from the worker garment. When a car (with headlights turned on) approaches from a distance, the textile appearance starts changing. As the car comes closer, the reflected light in the garment becomes stronger. As the overall appearance of a textile is strongly sensitive to the balance between intensities of the emitted and reflected lights (see previous section), we expect strong changes in the textile appearance under this scenario. In Fig. 5, we demonstrate the results of an experiment in which a camera and a lit camera-mounted LED were placed at various distances from a lit photonic textile panel. All the pictures were taken with the same shutter speed and an aperture.

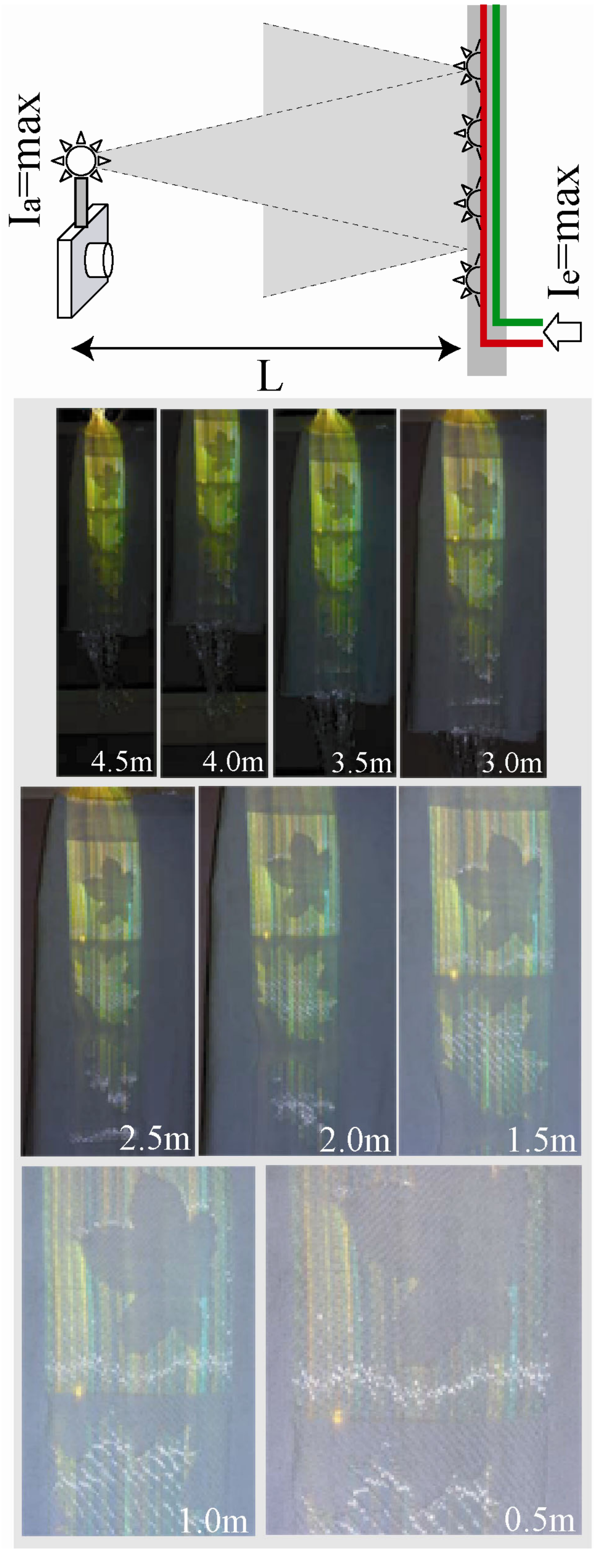

Fig. 5. Changes in the textile appearance under a night time scenario of an approaching car with turned on headlights. The emissive textile panel represents a worker operating at night. Worker appearance considerably changes when a bright illumination source (car headlights) approaches.

When an LED and a camera are placed far from a textile panel (L>4.0 m), the camera could only register light emitted from the photonic textile. When moved closer towards the textile panel, the reflection of the LED light becomes more pronounced. At a distance of L~1.5 m, the intensities of the reflected and emitted lights become comparable, while at shorter distances, the textile appearance is dominated by reflections. As the human eye is most sensitive to detection of changes in the appearance of objects, a PBG fiber-based photonic textile panel will be highly noticeable in the night time environment.

6. Note on Durability of the PBG Textiles

The photonic textile prototype presented in this paper has been extensively used as a technology demonstrator at various conferences and workshops for a period of over 3 years. During all this time, we did not have a single optical fiber breakage, nor see any polymer yellowing or degradation of the fiber optical properties due to exposure to the UV light. The outstanding mechanical stability of the PBG fibers can be attributed to two factors. First, there is the highly elastic all-polymer material combination of the PBG fibers that positively contrasts with a much more rigid polymer-glass combination of a standard optical fiber. Second, there is the laminate structure of the PBG fiber cladding made of hundreds of layers of two different plastics. Laminated fibers, in general, are known to tolerate much greater stresses than monofilaments before they show signs of mechanical damage. For example, when tying a knot with a regular optical fiber, the fiber breaks when the knot size is around 5 mm. With a PBG fiber, one can make a complete tight knot with the knot size only limited by the thread size. We would also like to note that as it is the case with many synthetic yarns, plastic PG fibers can be sensitive (yellowing, for example) to prolonged exposure to UV radiation. To address this problem, one would use the same standard approaches that are used with other synthetic yarns. Among others, those include a stricter control over the quality of the original plastics (low content of the unreacted monomer during polymer synthesis) used in PBG multilayer plastics that are more resistant to UV light, and other methods.

7. Conclusion

We have presented examples of novel PBG fiber-based textiles for potential applications in smart cloths, signage and art. It has been established that under ambient illumination, such textiles appear colored due to optical interference in the microstructure of constitutive optical fibers, with no color dyes needed. Moreover, when launching white light into PBG fibers, all but a single color are rejected, while the remaining color is guided and gradually emitted along the textile length. Note that PBG fibers naturally emit sideways, a portion of guided color, without the need of any mechanical perturbation, which favorably differentiates them from the competing standard optical fibers. We have also demonstrated that PBG fibers can reflect one color when side illuminated, and emit another color while transmitting light. We then demonstrate that by controlling the relative intensities of the ambient and guided lights, the overall textile appearance (color, warmth, iridescence, etc.) can be strongly varied. Finally, we have explored the possibility of using PBG fiber-based textiles in safety worker wear for operation at night time. We have demonstrated that when an external light source, such as car headlights, approaches an emissive PBG fiber-based textile panel, the textile appearance can dramatically change, thus being highly noticeable.

Acknowledgements

We would like to thank the Hexagram Research Center for giving us the access to the Jacquard loom, Ronald Borshan for helping photograph the textiles, Francis Boismenu for his continuing technical support, and Damir Cheremisov and Helene Gingras for weaving assistance. We would like to acknowledge the NSERC Media Arts Initiative and Canada Art Council for their financial support of this project.

REFERENCES

[1] Argyros, A., Bassett, I., Eijkelenborg, M., Large, M., Zagari, J., Nicorovici, N.A., McPhedran, R. & de Sterke, C.M. 2001, ‘Ring structures in microstructured polymer optical fibres’, *Opt. Express*, vol. 9, pp. 813-820.

[2] Balachandran, R.M., Pacheco, D.P. & Lawandy, N.M. 1996, ‘Photonic textile fibers’, *Applied Optics*, vol. 35, pp. 91-94.

[3] D'Amato, E. 2002, ‘Stress-strain monitoring in textile composites by means of optical fibers’, *Exp. Techniques & Design in Composite Mat.*, vol. 221, pp. 245-253.

[4] Dupuis, A., Guo, N., Gauvreau, B., Hassani, A., Pone, E., Boismenu, F. & Skorobogatiy, M. 2007, ‘Guiding in the visible with ‘colorful’ solid-core Bragg fibers’, *Opt. Lett.*, vol. 32, pp. 2882-2884.

[5] El-Sherif, M.A., Yuan, J.M. & MacDiarmid, A. 2000, ‘Fiber optic sensors and smart fabrics’ *J. Intelligent Mat. Systems & Struct.*, vol. 11, pp. 407-414.

[6] Gao, Y., Guo, N., Gauvreau, B., Rajabian, M., Skorobogata, O., Pone, E., Zabeida, O., Martinu, L., Dubois, C. & Skorobogatiy, M., 2006, ‘Consecutive solvent evaporation and co-rolling techniques for polymer multilayer hollow fiber preform fabrication’, *J. Mater. Res.*, vol. 21, pp. 2246-2254.

[7] Gauvreau, B., Guo, N., Schicker, K., Stoeffler, K., Boismenu, F., Ajji, A., Wingfield, R., Dubois, C. & Skorobogatiy, M. 2008, ‘Color-changing and color tunable photonic bandgap fiber textiles’, *Opt. Express*, vol. 16, pp. 15677.

[8] Gauvreau, B., Schicker, K., Guo, N., Dubois, C., Wingfield, R. & Skorobogatiy, M. 2008, ‘Color-on-demand photonic textiles’, *The Textile Journal*, vol. 125, pp. 70-8.

[9] Ghosh, S., Amidei, C. & Furrow, K. 2005, ‘Development of a sensor-embedded flexible textile structure for apparel or large area applications’, *Indian J. Fibre & Textile Res.*, vol. 30, pp. 42-48.

[10] Harlin, A., Makinen, M. & Vuorivirta, A. 2003, ‘Development of polymeric optical fibre fabrics as illumination elements and textile displays’, *AUTEX Res. J.*, vol. 3.

[11] Hart, S.D., Maskaly, G.R., Temelkuran, B., Prideaux, P.H., Joannopoulos, J.D. & Fink, Y. 2002, ‘External reflection from omnidirectional dielectric mirror fibers’, *Science*, vol. 296, pp. 510-513.

[12] Knight, J.C., Broeng, J., Birks T.A. & Russell, P.J. 1998, ‘Photonic band gap guidance in optical fibers’, *Science*, vol. 282, pp. 1476-1478.

[13] Koncar, V. 2005, ‘Optical fiber fabric displays’, *Opt. Photon. News*, vol. 16, pp. 40.

[14] Kuang, K.S.C. & Cantwell, W.J. 2003, 'Detection of impact damage in thermoplastic-based glass fiber composites using embedded optical fiber sensors', *J. Thermoplastic Composite Mat.*, vol. 16, pp. 213-229.

[15] Larsen, T.T., Bjarklev, A., Hermann, D.S. & Broeng, J. 2003, 'Optical devices based on liquid crystal photonic bandgap fibres', *Opt. Express*, vol. 11, pp. 2589-2596.

[16] Mignanelli, M., Wani, K., Ballato, J., Foulger, S. & Brown, P. 2007, 'Polymer microstructured fibers by one-step extrusion', *Opt. Express*, vol. 15, pp. 6183-6189.

[17] Selem, B., Rothmaier, M., Camenzind, M., Khan, T. & Walt, H. 2007, 'Novel flexible light diffuser and irradiation properties for photodynamic therapy', *J. Biomed. Opt.*, vol. 12, 034024.

[18] Shapira, O., Kuriki, K., Orf, N.D., Abouraddy, A.F., Benoit, G., Viens, J.F., Rodriguez, A., Ibanescu, M., Joannopoulos, J.D. & Fink, Y. 2006, 'Surface-emitting fiber lasers', *Opt. Express*, vol. 14, pp. 3929-3935.

[19] Spigulis, J., Pfafrods, D., Stafekis, M. & Jelinska-Platace, W. 1997, 'The 'glowing' optical fibre designs and parameters', *Proc. SPIE*, vol. 2967, pp. 231-6.

[20] Uskokovic, P.S., Miljkovic, M., Krivokuca, M., Putic, S.S. & Aleksici, R. 1999, 'An intensity based optical fibre sensor for flexural damage detection in woven composites', *Adv. Composits Lett*, vol. 8, pp. 55-58.

[21] Wakita, A. & Shibutani, M. 2006, 'Mosaic Textile: Wearable ambient display with non-emissive color-changing modules', *Proc. ACE.*

[22] www.lumigram.com

[23] www.lumitex.com

[24] Zheng, Y.H., Pitsianis, N.P. & Brady, D.J., 2006, 'Nonadaptive group testing based fiber sensor deployment for multiperson tracking', *IEEE Sens. J. Color Res. Appl.*, vol. 6, pp. 490-494.