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Historical Background of Polymeric Optical Fibers and Woven Fabrics Made of POFs

Can Esmercan[1], Füsun Doba Kadem[1]

[1]Department of Textile Engineering, Çukurova Üniversitesi, Türkiye

ORCID IDs of the authors: C.E. 0009-0007-6826-4415; F.D.K. 0000-0002-7764-5910

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Abstract

Polymeric optical fibers (POF) are mono-filaments that guide light and are primarily used for transmitting data over short distances, as well as for fiber-optic sensors and illumination purposes. These fibers are composed of polymers. Fiber production is inexpensive compared to glass fibers, and the products are more long-lasting than glass optical fibers (GOF). POFs can be classified into step-index fibers (SI-POF) and graded index profile fibers (GI-POF) based on their index profile. At first, only fibers with step-index were manufactured. The need for an augmentation in the potential data transmission rates has resulted in the creation of an index profile, GI-POF. POF materials are appropriate for transmitting data over short distances and can be integrated with textile structures. Because short-distance data transfer is sufficient when using POFs in textile structures, SI-POF is a more viable option than GI-POF due to its lower production cost and the required data transfer distance. The primary goal of incorporating POF material into textile fabrics is to facilitate media transmission, such as light. POFs can be readily incorporated into a fabric by weaving. The historical context of the production of POF in a step-index profile and the process of weaving POF has been extensively studied in the literature.

Keywords: Polymeric optic fiber, POF, SI-POF, weaving, woven, fabric

1. Introduction

Polymeric optical fibers (POF) are single filaments that guide light and are primarily used for transmitting data over short distances, as well as for fiber-optic sensors and illumination purposes. POF generally consists of circular fibers with a core-cladding structure. The core of the optical fiber is responsible for transmitting light. At the same time, the cladding is necessary to create a reflective interface with a consistent ratio of refractive indices, enabling total internal reflection.

POFs are used for data transmission, require extraordinary optical quality, and are produced using a highly specialized process. Regarding textile illumination using POF fabrics, the optical requirements for the POF are lesser significance. Nevertheless, the cost becomes crucial because of the substantial amount of POF needed for illumination [1]. Figure 1 displays the POF with woven fabric in the use of textile illumination.

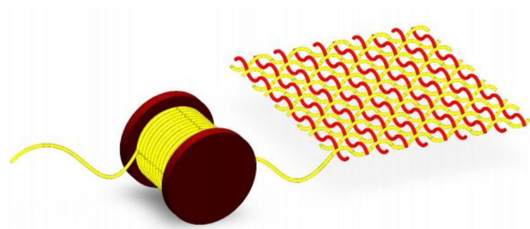

Figure 1. POF with woven fabric for textile illumination [1]

Address for Correspondence:
Can Esmercan, e-mail: cesmercann@gmail.com

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The predominant focus of POF literature revolves around communication. The uses of POFs go beyond data transmission. The illumination industry is one of the largest markets. POF is ideally suitable for integration into textiles. Several fabrics are comprised of POFs. Subsequently, these fibers can be employed for lighting, wearable sensors, or communication.

POFs with a pure step-index profile, also known as SI-POF, were the initial fibers developed. This implies that a straightforward optical cladding encompasses a uniform core. The routes within the fiber are determined similarly to a ray in geometric optics. Using step-index fibers, the ray's path is traced until it reaches the core interface and cladding interface. At this point, the ray's reflection is considered by recalculating the direction of propagation. When the reflection is optimal, the angle of incidence and the angle of reflection are identical. Over the past few years, there has been a significant emphasis on examining and advancing smart or intelligent textiles. As part of the intelligent textile category, POF textiles have attracted significant attention due to their pliability, lightweight nature, resistance to electromagnetic interference (EMI), ease of manipulation, straightforward connectivity, and compatibility with living organisms. POF can be integrated into textile structures by different techniques such as weaving, knitting and braiding [1].

The main objective of integrating POF into textiles is to facilitate light transmission. Light can illuminate fibers indivudually to achieve practical effects in fabrics, such as creating a pleasant atmosphere or enhancing safety in sports textiles. Light can be conveyed over long distances by travelling along an uncurved trajectory. Nevertheless, due to the phenomenon of refraction, the luminous power decreases over shorter distances when transmitted through undulating or looped structures. In order to take advantage of the benefits of POF material, the illuminated yarns within a fabric need minimal undulation or to be straight. Textiles can be produced from yarns with minimal undulation by weaving or braiding techniques. Both warp and weft knitting methods generate loop formation. They are susceptible to bending and mechanical strain. Weaving is the most widely regarded textile technique for transforming optical fibers into textile formations [1]. Figure 2 displays the luminous intensity of POFs depending on their different bent yarn paths.

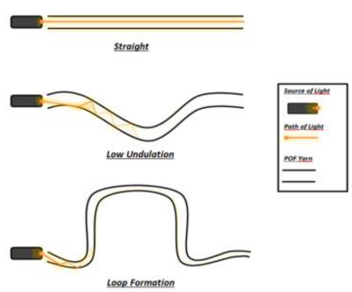

Figure 2. Diminution of luminous intensity resulting from refraction in differently bent yarn paths [2]

Since the 19th century, the production of POF has been initiated for industries. Initially, POF manufacturing was primarily used for data transmission, but it later expanded to include textile applications. SI-POFs are commonly employed in textile applications due to their limited data transmission range and reduced manufacturing expenses. In addition, during the 19th century, textile fabrics made from POF were manufactured for illuminating applications. These manuscripts are intended to demonstrate the historical background of both POF production and POF woven fabric to guide future trials and research.

2. Literature Review

2.1. Literature Review of Polymeric Optic Fibers

In the latter half of the 19th century, there was significant research interest in the idea of illuminating glass rods. This was because dentists needed technologies that could guide light to illuminate the entire mouth, as well as for other medical purposes such as imaging, spectroscopy, endoscopy, tissue pathology, blood flow monitoring, light therapy, biosensing, biostimulation, laser surgery, dentistry, dermatology, and health status monitoring. Optical fibers were first used in medicine to provide internal illumination during endoscopic procedures. In 1965, Manfred Borner developed the inaugural optical-data transmission system utilizing optical fibers at the Telefunken Research Laboratories in Ulm, Germany. The technology was granted a patent in 1966. Theodore Maiman's invention of the first laser system in 1960 marked a significant technological breakthrough [2,3].

The emergence of laser technology is the starting point for the development of long-distance operational glass fibers and POF. In the late 1960s, research on light-guiding fibers diverged into two branches: glass and polymer-based optical fibers, which had just been developed. During the latter decades of the 20th century and the early years of the 21st century, significant advancements in fabrication technology have led to a substantial reduction in fiber losses. POF applications are well-suited for data transfer, sensor technology, and the integration of fibers into functional textiles. These applications have significant market potential. The value of previously published works on POF is attributed mainly to the innovative features of current material selections, intelligent fabrics, and the market review [2].

Because the monomer materials used were not pure enough, the attenuation remained at approximately 1.000 dB/km. During the 1970s, it significantly reduced losses, approaching the theoretical limit of approximately 125 dB/km at wavelengths of 650 nm. During that period, there were ample supplies of glass fibers with shallow losses of less than 1 dB/km at wavelengths of 1,300 nm and 1,550 nm. However, these fibers were only available at a higher cost. Following the complete digitization of data communication for long-distance transmission in the 1990s, significant advancements in digital systems for individual users began. The annual international conference for POFs and applications, held since 1992, is a significant indicator of the advancements made in this specialized field [4].

POF provides substantial benefits compared to glass alternatives. More precisely, the substantial diameter of these connections, typically ranging from 0.25 to 1 mm, allows for the utilization of inexpensive plastic connections with lower levels of accuracy, resulting in a reduction in the overall cost of the system. Furthermore, POF stands out due to its enhanced adaptability, ability to withstand shocks and vibrations, and efficient light transmission from the light source to the fiber. As a result of these advantages, numerous POF applications have been created and commercialized [5].

Table 1. Historical development of the most significant SI-POF landmarks during the past 45 years [1]

Year	Organization	Milestone
1968	Dupont	First SI POF with PMMA core
1972	Toray	First SI POF with PS core
1976	Mitsubishi Rayon	Produced Eska™, a PMMA SI-POF: >300 dB/km @650 nm
1981	NTT	Low attenuation PMMA SI POF 55 dB/km at 568 nm
1982	NTT	First SI POF with deuterated PMMA core 20 dB/km at 650 nm
1983	Mitsubishi Rayon	Produced step-index PMMA-POF: 65 dB/km @570 nm
1991	Hoechst Celanese	SI PMMA "Infolite" POF 130 dB/km at 650 nm.
1993	Essex University	Transmission at 631 Mbps over 100 m by means of a PMMA-core SI POF and an equalizer circuit
1994	Asahi Chemical	First multicore SI POF for high speed transmission
1995	Mitsubishi Rayon,NEC	Transmission at 156 Mbps over 100 m by means of a low NA SI POF and a fast red LED
1997	POF Consortium of Japan	Standardization at ATM LAN 156 Mbps over 50 m of SI POF in the ATM Forum.
1997	POF Consortium of Japan	Standardization of the norm IEEE 1394 156 Mb/s over 50 m of SI POF.
1998		MOST Standard for Automobiles started
2006-2007		10 Mbps over 400 meters of 1 mm SI POF (4-PAM, 8-PAM
2006-2007		100 Mbps over 200 meters of 1 mm SI POF (4-PAM, 8-PAM)
2011	POF-PLUS	1 Gbps over 50 meters of SI PMMA
2011	Opto Marine Co., Ltd. /Korea	1 mm SI POF with data rates of 500 Mbps, 5 Gbps and 10 Gbps at 100 meters at 650 nm.
2013	KDPOF/Spain	1 Gbps of SI POF for Automotive Industry

The progression of SI-POF can be seen in Table 1. The primary focus of POF literature revolves around communication. POFs have a wide range of uses beyond just transmitting data. POF is highly compatible with integration into textiles. Many textiles consist of polymer fibers. Subsequently, these fibers can be employed to provide light, function as sensors that can be worn, or facilitate communication [2].

Digitalization is happening constantly, especially in industrial controls, consumer electronics, and automotive applications that need cheap, short-range connectivity and better performance. This will make the market for POF solid and stable in the future. POF has also capitalized on a vast market with diverse applications. The utilization of GOF primarily focuses on the communications and IT industries, whereas POFs are employed across a wide range of sectors, ensuring minimal risk of downturns. GOF did not penetrate the short-distance market due to its high cost, intricate design, and operating frequency. POF has a significant opportunity due to reduced prices, improved performance, and resistance to electromagnetic noise and interference [2].

2.2. Literature Review of Polymeric Optic Fiber Woven Fabrics

Weaving is the predominant technique for producing POF textile structures, surpassing the usage of knitting and embroidery methods. Incorporating POF into woven structures is essential for attaining a luminance effect. This can be accomplished by minimizing the bending of POF at a considerable [6].

The incorporation of POF into woven fabrics was first documented in the early 1960s. POFs are commonly used in weaving as weft yarns. Indeed, they can also be employed as warp yarns. This is typically the case for ribbon fabrics, as they are incredibly narrow. Standard multifilament or staple fiber yarns composed of cotton, PET, or other materials can be utilized for the second thread. Transparent yarns enhance the evenness of luminance by allowing the radial light emitted from the POF beneath them to pass through [7].

Before implementing beam warping, defining the application of POF is necessary. It has a great importance to know in which application POFs will be used. According to the application, also desired précised bending and illumaniton effects could be considered to use POFs as warp or weft POF used as weft yarn exhibits greater versatility compared to POF used as warp yarn. Predefining the patterning is unnecessary. Nevertheless, not all methods of inserting weft are suitable for processing POF [2].

In 1979, Maurice Daniel conducted research to develop a fabric that incorporates fiber optic illumination, with the fiber optic elements integrated into the fabric's threads. Another aim of this invention is to present a technique for illuminating apparel using fiber optic technology. The previous invention aimed to incorporate POF into a textile product in order to illuminate and display the light-transmitting section of the POF in relation to the textile product. However, the primary objective of this study was to demonstrate the consistency of illumination. The invention involved integrating POF as a substitute for traditional fabric yarns, such as warp and weft. The invention claimed to incorporate fiber optics into the fabric, enabling their use for purposes such as illumination, heat, or suntanning [8].

In 1988, Jeffery R. Parker conducted a study on enhancing the optical efficiency of a light-emitting panel and increasing its light output. Typically, when light enters one end of POF, it emerges from the other end but decreases the intensity. Nevertheless, light will be emitted at these locations if the surface of the optical fiber is scratched or deformed due to bending at specific points. The panel is optimally designed to serve as a backlight for a liquid crystal or similar device. It efficiently transmits light to the emitter surface from a distant light source through a cable or light conduit connected to either or both ends of the emitter surface [9].

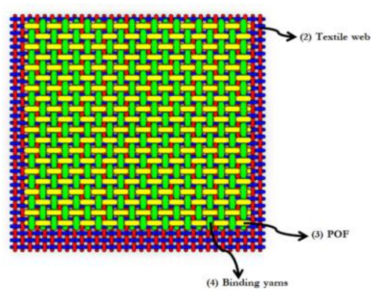

Figure 3. Textile web and POF [4]

Delphine Molhamme conducted a study in 2007 on a fabric web that consists of optical fibers woven with binding yarns. These optical fibers can emit light sideways. The illuminating assembly comprises a textile web (2) in which POF(3) is interwoven with binding yarns (4). The binding yarns (4) arrangement typically follows the warp direction, while the POF (3) is typically arranged in the weft direction, depending on the specific implementation. In order to improve the lighting properties of an illuminating structure that consists of a textile web (2), it is possible to locally weave binding yarns (4) with POF(3). The binding yarns, when interwoven in a "fabric" weave, can create empty spaces that enable the transmission of the optical fibers' luminous energy. The textile web is affixed to a rigid substrate and adhered using a bonding agent. POF (3) maintains constant communication with bonding intermediate in this scenario. The bonding intermediate facilitates the direct reflection of light emitted by POF. Figure 3 displays the presence of the textile web and POF [10].

The interior of the optical fibers can be made of one of the following materials: polymethyl-methacrylate (PMMA), polycarbonate (PC), or Cyclo-Olefin Polymers (COP). The yarns used for binding were woven from synthetic fibers.

In 2013, Thomas Franz et al. studied an illuminated fabric composed of glass fibers. The invention aims to create a radiant textile that exhibits exceptional lighting capabilities and maintains consistent brightness throughout its entire surface. Glass is a highly transparent substance to visible light. Utilizing glass fibers prevents light attenuation in the luminous woven fabric, thereby enhancing its optical efficiency and luminosity. The research shows that the luminous woven fabric is made up of glass yarns with a tex of 68 as the warp yarns and POF produced from PMMA/PTFE with a diameter ranging from 250 μm to 500 μm as the weft yarns. This combination of materials makes for good lighting levels. The woven textile supports are created using a 4, 8, and 12 harness satin weave, with a weft density ranging from 8 to 14 yarns per centimeter. The best lighting happens when optical fibers are 500 µm in diameter and have a density of at least 8 yarns/cm, preferably at least 10 yarns/cm, and ideally at least 12 yarns/cm are used in woven textile supports. Using specific-sized glass filaments as warp yarns increases the chances of increasing the density of optical fibers [11].

Also, in 2013, Hans-Joachim Kobek researched to develop a textile fabric with consistent luminosity throughout. The self-luminous fabric, which is already known, includes an additional layer of transparent yarns positioned directly above the second layer. This layer functions as a diffuser, dispersing light evenly. Given its established arrangement, the objective is to achieve consistent illumination across the entire surface of the self-luminous fabric. Controlling this configuration of either transparent or partially transparent fibers is challenging and relies on the specific type of light coupling. The luminosity of the light-emitting surface is insufficient due to the omnidirectional emission of light from the light-emitting yarns, which lack a specific direction of light emission. Currently, no structure can separate the emitted light in a way that allows it to be directed with a high level of brightness and a consistent brightness perception on the side where the light is emitted. The objective is accomplished by implementing a light decoupling structure where reflector elements are printed on at least one side of the luminescent textile's surface. These reflector elements are specifically designed to reflect light in a targeted manner and thus adhere to the light-guiding elements. This fabric utilizes the POF. One side of the luminescent textile contains flexible reflector elements that are distributed and bonded to the surface of the threads in a coating process. These reflector elements maintain the flexibility of the textile and are designed to reflect the light emitted into the fibers. Figure 4 displays the weft yarn as POF(1), the warp yarn(2), the reflector elements (10), and the crossing point of the weft and warp yarns (30). The invention primarily involves the creation of a uniformly bright and consistent surface [12].

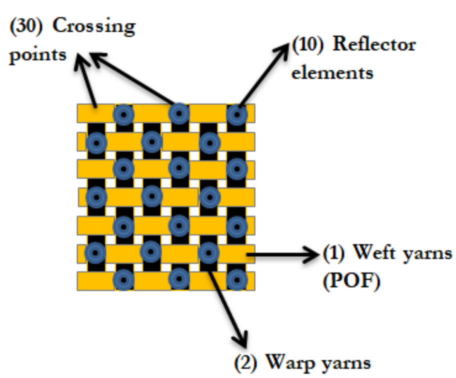

Figure 4. Fabric with reflector elements [12]

Zhou Leijing studied a flexible light-guiding optical fiber fabric in 2014 at Ningbo Jingzhi Electronic Technology Co. in Shenzhen, Guangdong, China. The invention uses a pliable fabric made of optical fibers that transmit light. The weft threads are formed by alternating PMMA optical fibers, while the warp threads consist of regular yarns. The diameter of the POF ranges from 0.2 mm to 0.8 mm. This fabric uses a sateen weave with 8 or 16 picks in the weft direction. The claims aspect of the application involves utilizing the flexible light-conducting POF fabric in domestic textiles and dress ornaments [13].

The comprehensive Table 2, which pertains to the information below regarding their region, active timespan, status, etc., is displayed.

Table 2. Historical background of weaving [14]

Year	Inventors	Main Claim	Landscape	Timespan	Status	Assignee
1967	Burton N.Derick	Luminous textile products	Delaware, ,USA	1967-1987	Expired	EIDP Ltd.
1979	Maurice Daniel	Fabric with fiber optic illumination	Ohio, USA	1979-1999	Expired	Individual
1988	Jeffrey R. Parker	Improve the optical efficiency of a light emitting panel	Ohio, USA	1988-2008	Expired	Lumitex Inc.
2007	Delphine Malhomme	Fabric web comprising warp and/or weft optical fibers	Villeurbanne,FR	2007-2009	Abandoned	Brochier Technologies
2013	Thomas Franz	Illuminated fabric which comprising glass fibers	Chambery,FR	2013-2016	Abandoned	Saint Gobain Adfors SAS
2013	Hans-Joachim Kobek	Uniformly luminous textile fabric	Traunreut, DE	2013-	Active	Motherson Innovations Lights GmbH
2014	Zhou Leijing	Flexible light-guiding optical fiber fabric	Guangdong,CN	2014-	Pending	Ningbo Jingzhi Electronic Technology Co. Ltd.
2015	Leng Jianjun Zhang Fang	Polymeric optical fiber, luminous fabric and its manufacture method	Jiangsu,CN	2015-	Active	Xuzhou Guohong Packaging Co., Ltd
2021	Benjamin Mohr Niklas Stracke	Device and method for preparing a fiber optic fabric	Bochum, DE	2021	Active	Munda Textile Lichtsysteme GmbH

In 2015, Leng Jianjun researched POF and luminous fabrics in Jiangsu, China. This undertaking produces luminous fabrics by intertwining weft yarns as POF. The POF within the fabric undergoes weaving on the loom, and the POF, after being bound and connected to a specific light source, creates a luminous POF fabric. The warp thread consists of man-made fibers with a line density ranging from 120 to 300 tex. The weft yarn is made of POF, and the light source is a 5 mm blue LED. The fabric possesses the subsequent attributes: The weft density and thickness are 250 per 10 cm. Due to the intricate weaving of POF, it possesses high durability, and the resulting luminous fabric exhibits exceptional brightness and longevity [15].

In 2021, Benjamin Mohr and Niklas Stracke conducted research on a device and technique for fabricating a fiber optic fabric. The objective of this invention is to offer a device and technique that allows for the preparation of a fiber optic fabric in the most straightforward and adaptable manner, enabling efficient, flexible, and controlled introduction of light into the fabric. The length of the exposed ends of the light-guiding fibers can vary across the width of the light-guiding fabric. The device based on the invention offers a notable benefit in that the level of exposure of the ends of the light-conducting fibers can be determined separately from the fabric. This determination can be achieved through the design of the combing device or by adjusting the relative movement of the combing element and the feed device [16].

3. Results and Discussion

The production of SI-POF has made significant advancements in reducing attenuation over the past 45 years. The advancement and tangible outcomes of POF manufacturing have generated significant prospects for textile lighting applications. The utilization of POF in textile illumination applications has yielded favourable outcomes, showcasing the weaving capabilities of POF through numerous examples. These trials have been conducted using various weaving patterns and methods to incorporate POF into woven textiles for illuminating textile applications.

4. Conclusion

POFs are utilized for both illumination purposes and data transmission. These enlightening applications are seamlessly incorporated into textile structures. POFs are required to exhibit reduced bending in order to facilitate their integration into textiles, as there is a risk of POFs breaking. POF for data-transmission must have a very high optical quality and are therefore manufactured through a very specialized procedure. When it comes to textile illumination with POF fabrics, the optical criteria for the POF are less important. In addition to the production of fibres, weaving is vital for the textile illumination. POFs are most effectively incorporated into textiles through the process of weaving. This manuscript serves as a guide by presenting the production and advancement of POF, a material that has experienced significant growth in recent years. It also discusses the incorporation of POFs into textile applications and the latest weaving applications of POFs for upcoming research and experimentation.

Acknowledgment

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