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Publication details:
Proceedings of SPIE Volume 5595
pp. 138-152
0819455482 (ISBN)

Event details:
Optics East Conference on Active and Passive Optical Components for WDM Communications IV
Philadelphia, PA, USA

Publication Date:
2004

DOI:
https://doi.org/10.26190/unsworks/646

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ABSTRACT

Novel special polymer optical fibres and devices have been developed by several research groups around the world. Special polymer optical fibres and devices have great potential in a range of photonic applications. These polymer optical fibres, including both single-mode and multimode, could be made laser-active, photosensitive, photorefractive or optically nonlinear, either by incorporating functional materials into the fibre cores or by fabricating specially structured fibre cross sections. In this presentation we will report on the progress in developing special polymer optical fibres and also discuss a few prospective device applications of these fibres.

1. INTRODUCTION

With the rapid implementation of optical fibre trunk links (exclusively silica fibres) around the world, overall telecommunication capacity has been increasing at an unprecedented rate. The fast development of the Internet-World-Wide-Web (WWW), Multimedia, and the forthcoming digital services to the home such as digital radio, high definition television and digital video, would require hundreds even thousands of times of more capacity than presently available. Obviously, as the world is fast moving into a digitised information era, ever greater challenges are waiting for telecommunications in the 21 century. The most important one is the need for a new-generation of networks that would underpin the future high-capacity telecommunication infrastructure. It is anticipated that future networks will include (1) High speed (1Gbits/s (10^9 bits/sec) or greater) Local Area Networks (LANs); and (2) Ultra-high speed (1Tbit/s --10^{12} bits/sec or greater) Wide Area Networks (WANs).

Presently a great number of terrestrial and transoceanic links with substantial trunk communication capability have been installed worldwide. The bottleneck in telecommunication infrastructure is now shifting toward metropolitan area networks, and eventually toward the user end networks, e.g. LANs and computer data links. The present LANs using metal wires or cables simply cannot provide the capacity and quality required. Hence future high-speed LANs have to use optical fibre and to choose the most appropriate fibre from two most attractive candidates: silica optical fibres and polymer optical fibre (POF).

According to their specific applications, polymer optical fibres may be classified into two main categories, viz. for communication applications and for other photonic applications. There has been a significant increase of research and development of polymer optical fibre for communication applications in the decade [1-4]. The primary drive of these activities is an emerging market of high-speed (broadband) local area networks where optical fibre is required and especially where polymer optical fibre could be advantageous over conventional silica optical fibre [5]. At the same time, remarkable progresses have also been made in developing special polymer optical fibres and devices for photonic applications in recent years.

Here we first briefly summarise the background development of polymer optical fibres for communications applications. Then we will review the recent development of special polymer optical fibres and devices for photonic applications.

Active and Passive Optical Components for WDM Communications IV, edited by
Achyut K. Dutta, Abdul Ahad S. Awwal, Niloy K. Dutta, Yasutake Ohishi, Proc. of SPIE
Vol. 5595 (SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.575908

2. DEVELOPMENT OF POF FOR COMMUNICATION

In contrast to long distance links where attenuation and dispersion are of prime importance, short distance networks are usually more concerned with flexibility, ease of handling and low-cost connection. In these systems multimode optical fibre with large core size is preferred over single mode fibre. The large core diameter is essential for ease of handling, large alignment tolerance and low connection cost. However, conventional multimode silica glass fibre cannot have a very large core size, because large fibre becomes very brittle and inflexible. In contrast to silica fibre, POF is very elastic. For example, PMMA-based POF is so elastic that it recovers up to 13% strain and remains flexible for very large core sizes (typically 0.25 ~ 1mm in diameter). These properties are important for fibre interfaces within optoelectronic systems where space is usually limited. Also POF can have larger numerical aperture (up to 0.6) than silica fibre (up to 0.3) and this means better power transmission capability. As a whole, in addition to similar attributes to those of silica optical fibre, e.g. electromagnetic interference (EMI) free and high bandwidth, POF has advantages, such as great flexibility, large power transmission capability and low material cost that make it very competitive with silica optical fibre.

Hence a significant part of POF development has been targeted for high bandwidth, short haul information and communication systems, including in high speed LANs. For example, AT&T Bell Laboratories reported their success in a high speed POF system transmitting at 11Gbit/s over a 100m link [6]. The ATM Forum adopted POF for networks operating at 155 Mbits/s. Now a number of Japanese companies are offering commercial POF systems operating at 200 Mbits/s or higher. Clearly POF can be used in various data networks including Fast Ethernet, Token Ring, FDDI to ATM-LANs. Moreover, POF based systems are emerging across a broad spectrum of applications including multimedia, automotive and aerospace, entertainment systems, lighting and architectural design, and point to point links. In Europe, automobile manufacturers are installing POF entertainment systems.

Recent developments in the home network front are very significant to POF system application. It is envisaged that the digital revolution will create a great market for home networking --the interconnection of personal computer, consumer electronics, and video-audio equipment at home. This has been identified as an ideal market for POF system applications. The IEEE has defined the standard 1394 which sets a benchmark speed up to 400Mbit/s for home networks. Now the IEEE is in the process of approving a newer version -the 1394B standard defined at a higher speed up to 3.2Gbit/s. It is obvious that a POF system would have all the important attributes necessary for these applications: high data rate (up to 10Gbit/s), sufficient coverage (up to 100m), electrical isolation, EMI free, flexibility, ease of installation and, most important of all, low cost.

Step-index multimode POF

Conventional commercial POFs are dominantly step-index multimode (SI-MM) fibres made from extrusion. These commercial POFs typically have 1mm outer diameter with a core diameter of 980µm. As an example, the properties of a 1 mm diameter SI-MM POF (ESKA CK40) made by Mitsubishi Rayon in Japan are summarized in Table 1 (Source: Ref.[7]). As we will discuss later, there are activities to develop novel POFs smaller size and lower numerical aperture with higher bandwidth.

Table 1. Specification of a SI-MM POF (ESKA CK40) [7]

	Core	**Cladding**
Material	PMMA	Fluorinated polymer
Diameter (typical)	980 μm	1000 μm
Young's modulus	3.09 GPa	0.68 GPa
Poisson's ratio	0.3	0.3
Refractive index	1.492	1.405
Yield strength	82 MPa	
Transmission loss (@ 650 nm)	200 dB/km	
Maximum operating temperature	70 °C	
Approximate weight	1 g/m	

Graded-index multimode POF

In addition to traditional step-index multimode fibres, graded-index multimode (GI-MM) POFs with both low loss and high bandwidth have been developed with well-tailored index profiles [8]. Since early 1990s, intensive research has been carried out to produce a graded-index POF which would have significantly larger bandwidth-length product. One significant advance in POF was made by Keio University when they developed a graded-index POF with a bandwidth-length product of 2GHz·km [9]. This graded-index polymer optical fibre is produced using a photo copolymerisation process. The original process involves a glass tube filled with two or three different monomers, and specific amounts of initiator and chain transfer agent. The tube was then rotated about its axis while under exposure to UV light. As a result, a copolymer phase was first formed on the inner wall. Since each constituent monomer has a different refractive index and also different activity with initiator and chain transfer, the final polymer rod was solidified with a graded refractive index profile. This technique was subsequently refined by replacing the glass tube with a polymer tube such as PMMA. The mixture of monomers dissolved the polymer on the inner wall and a gel layer at the interface was formed. Since the polymerisation in the gel phase is faster than that in the liquid phase due to the "gel effect", the polymerisation occurs from the interface toward the centre.

Special Material POF

POFs can be made from a range of different materials, poly-methyl metracrylate (PMMA), polystyrene (PS), polycarbonate (PC), etc. Most of conventional polymer optical fibres are made from low-loss PMMA. The PMMA-based POF typically has attenuation ranging from 80dB/km to 120dB/km in its transmission window around 650nm. These figures are significantly higher than that of silica fibre, although they are not far from the theoretically expected values.

In PMMA-based POFs, the attenuation in the visible and IR wavelength range comes largely from the overtone absorption of C-H (carbon-hydrogen) bond vibration. However, the spectrum of infrared vibration absorption can be modified by atomic substitution. Since hydrogen is the lightest atom, the fundamental vibration of C-H occurs at a relatively short wavelength. For example, in PMMA, the fundamental vibration of C-H bond corresponds to wavelength 3.2μm. As a result, its second to eighth overtones are distributed in the range of 0.4μm ~ 1.6μm. These overtones give rise to large absorptions within the communications spectrum. By substituting hydrogen with a heavier atom, the wavelength of fundamental IR vibration will increase and consequently the wavelength of a certain overtone will also increase. This in turn reduces the absorption in the communications spectrum where lower order overtones are replaced by higher order overtones. The fundamental vibration of a C-D (carbon-deuterium) bond is at about 4.5μm. The fundamental vibrations of C-F (carbon-fluorine) and C-Cl (carbon-chlorine) bonds are at even longer wavelengths, 7.6~10μm and 11.7~18.2μm respectively, which are comparable to or better than that of the Si-O (silicon-oxygen) bond; typically 9~10μm in silica glass. Because of the longer wavelengths of the molecular vibrations of C-D, C-F and C-Cl bonds, deuteration, fluorination or chlorination will significantly reduce attenuation in the visible and near infrared (600nm -1500nm). The deuterated PMMA as a core material was suggested and demonstrated by Schleinitz to reduce the IR vibration absorption [10]. Kaino et al at NTT, Japan, developed techniques to make POF with a deuterated PMMA core and the lowest loss they achieved was 20dB/km at 680nm [11,12]. However, the deuteration of PMMA is very expensive and it may not be practical for communication POFs.

Fluorinated POF technology has made remarkable progress in recent years. Polymer optical fibres based on perfluorinated polymers have been made with very low loss [13-15]. The fluorinated polymer has the similar excellent chemical, thermal, electrical and surface properties as conventional fluoropolymers such as teflon. In addition, it has low optical attenuation. The most attractive feature of this material is its very broad transmission window, ranging from 650nm right up to 1300nm. Within this window, graded-index POF has been made with loss less than 40dB/km. The minimum loss is about 10dB/km at around 1000nm [14]. It has been predicted that the material would have a theoretical attenuation limit of 0.3dB/km; comparable to that of silica glass [16].

OFS laboratories (previously one of the Bell Laboratories in USA) proposed and produced a series of fluorinated GI-POFs. Different from the fluorinated GI-POF technology reported by Keio University and Asahi Glass, the low loss GI-POFs reported by OFS researchers have been made using the conventional extrusion method [17]. The main features of these fibres are summarized in Table 2 [17]. New POFs are made in a variety of sizes to improve the bandwidth in POF systems.

Table 2 Fluorinated GI-POFs proposed by OFS Laboratories [17]

Cladding Diameter (µm)	Core Dia.(µm)	Attenuation @850 nm (dB/km)	Bandwidth (MHz-km)
750	500	40	150-300
490	200	40	150-400
490	120	33	188-500
250	62.5	33	188-500

While fluorinated GI-MM POFs do have significant advantages, such as low loss, high bandwidth, high thermal and chemical stabilities, the cost of the fluorination of polymer materials remains very high at the moment and further development is necessary.

In Figure 1, we compare the typical attenuation spectra of polymer optical fibres based on different materials and processes. The fluorinated POF results from the preform method developed by Asahi Glass Co. and Keio University produces lower loss than the extrusion method developed by OFS. However, the extrusion method would be more desirable for mass production and lower fabrication cost.

The physical properties of POFs are of interest for practical applications. POFs may suffer undesirable changes in their optical, thermal and mechanical properties when aged by means of high temperature, humidity and UV exposure. In particular, the temperature range of operation of POF is important for industrial environments. Conventional PMMA POFs are typically fine up to 85°C. However, the long term performance remains an issue. Under accelerated aging tests equivalent to environmental effects of typical temperature and humidity of about 10 years, considerable spectral changes in transmission have been observed [18]. GIPOF doped with triphenyl phosphate (TPP) demonstrates high thermal stability at high humidity (80°C, 80% RH) [19]. The refractive index profiles of GI-POF could be stable at 85°C over 5000 h. New dopants for GIPOF under investigation with T_g (glass transition temperatures) greater than 90°C have been found to be stable after 600–700 h.

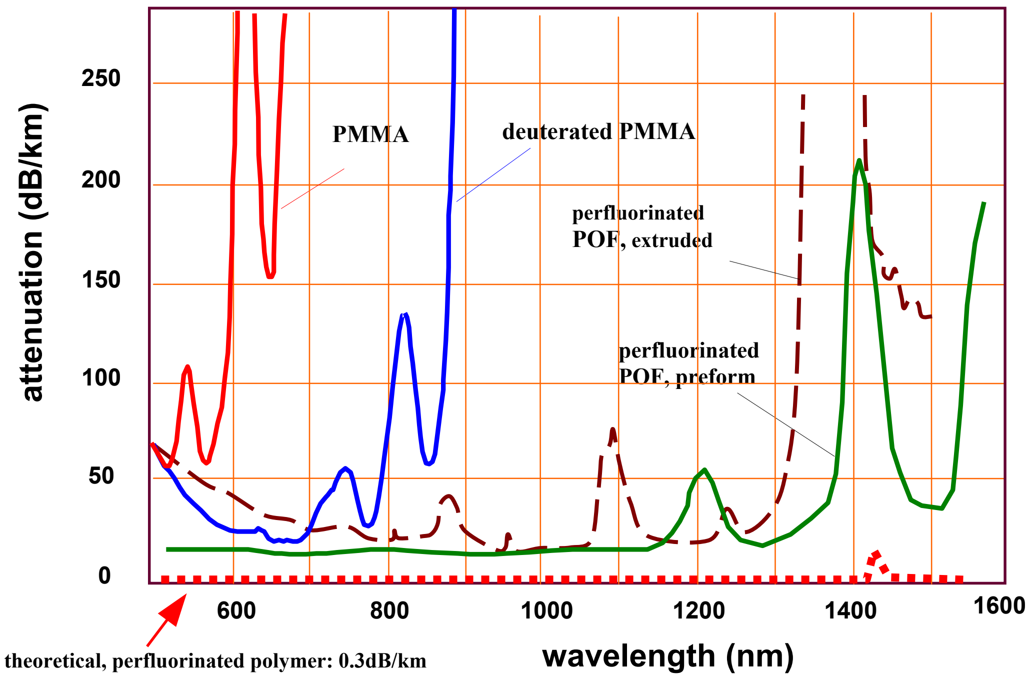


Figure 1 Characteristic attenuation spectra of polymer optical fibres based on (1) PMMA; (2) deuterated PMMA, (3) perfluorinated polymer and (4) extruded perfluorinated polymer..

3. DEVELOPMENT OF SPECIAL POF

Conventional POFs are developed for communication applications where the attenuation and bandwidth of fibre are always of great concern. However, for many other photonic applications, the special properties or functionalities of polymer optical fibres such as flexibility, elasticity, laser activity, electro-optical nonlinearity, photosensitivity and refractivity, etc are of greater interest. It is well known that many of nonlinear optical organics and laser dyes possess outstanding qualities including high and fast nonlinearities, high quantum efficiency and broad spectral range, etc. These materials usually have good compatibility with polymer fibre materials. Hence polymer optical fibres are advantageous in incorporating these functional molecules when they are compared with its better known counterpart --silica optical fibre. Also the low processing temperature of polymer fibres allows to incorporate a wide range of organic materials of special properties and, at the same time to retain their special functionalities.

Different types of non-conventional or special polymer optical fibres are being developed by a number of research groups around the world. These include single-mode POFs [20,21], twin-core POFs [22], nonlinear POFs [23], dye-doped POFs [24-26], electro-optical POFs [27], photosensitive POFs [28,29] and photorefractive POF [30]. These fibres are made single-moded, laser-active, photosensitive, photorefractive or optically nonlinear, depending on the designs of fibre or the incorporation of specific functional materials into the fibres.

Single-mode POF

The development of single-mode POFs was started in early 1990s [20,21]. Single-mode POF have been reported for nonlinear optical effects and POF Bragg Gratings [22,31]. Recently using single-mode polymer optical fibres for fibre sensor application has also been proposed and reported [32,33]. Single-mode POF could be advantageous for use in fibre-optic nonlinear devices and fibre sensors. Single-mode POFs is advantageous for nonlinear optical effects because of their small effective core areas and long interaction lengths, together with higher nonlinearities achieved by doping nonlinear organics. Single-mode POFs is also advantageous for sensor application, especially interferometer-based fibre sensors, because the low Young's modulus of polymer materials. The Young's modulus of polymer fibre materials is typically many times less than that of silica glass. This property could be very significant for strain-related sensing applications. Since a strain ε is related the applied stress σ by $\varepsilon = \frac{\Delta L}{L} = \frac{\sigma}{E}$, with E the Young's modulus of material, under a certain stress, a much lower Young's modulus of polymer fibre means much higher strain and thus much higher sensitivity. Also, the breakdown strain of POF is typically much larger than that of its silica counterpart. For strain sensing in civil engineering or composite structures, this larger breakdown strain could mean higher dynamic range. Moreover, it is possible to tailor the Young's modulus and elasticity of a polymer fibre with readily available synthesis techniques or to select appropriate materials with desirable Young's modulus or elasticity from a wide range of optical polymer materials. This is another important feature that makes polymer optical fibres better candidates for sensing in various liquid and elastic material environments, duly covering a wide range of strain-related sensor applications.

Table 3 briefly summarises the relevant characteristics of typical silica and polymer fibres [34]:

Table 3 Comparison of relevant parameters of silica and polymer optical fibres [34]

Property	Silica fibre	Polymer fibre
Attenuation (dB/km)	0.2~3	10 ~ 100
Young's modulus (GPa)	100	3
Breakdown strain (%)	1~2	5 ~ 10

Segmented cladding POF

Chiang et al proposed a new type of segmented cladding fibres [35]. A segmented cladding fibre is a novel fibre design that a core of high refractive index is surrounded by a cladding with alternate regions of high and low refractive indices in the radial direction. The fibre design was proposed as an alternative of the holey fibre structures for single-mode operation over an extended wavelength range. Due to the difficulties in silica fibre fabrication, initial attempt to make silica segmented cladding fibres was not successful.

Taking advantage of the flexibility in POF fabrication, Yeung et al [36] successfully fabricated segmented cladding POF by following the approach described in Ref.[22]. Both 4-segment and 8-segment POF have been fabricated, as shown in Figures 2 and 3. These fibres have been shown to have a large range of single mode wavelength operation for large core diameters.

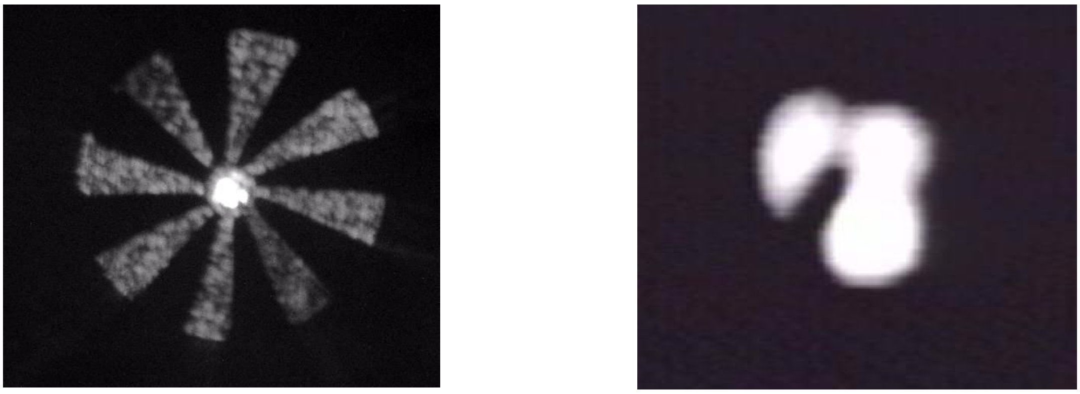


Figure2 Near-field patterns of a 35-μm-core 8-segment fiber. Left: multimode at 0.633 μm; Right: few moded at 1.548 μm [36].

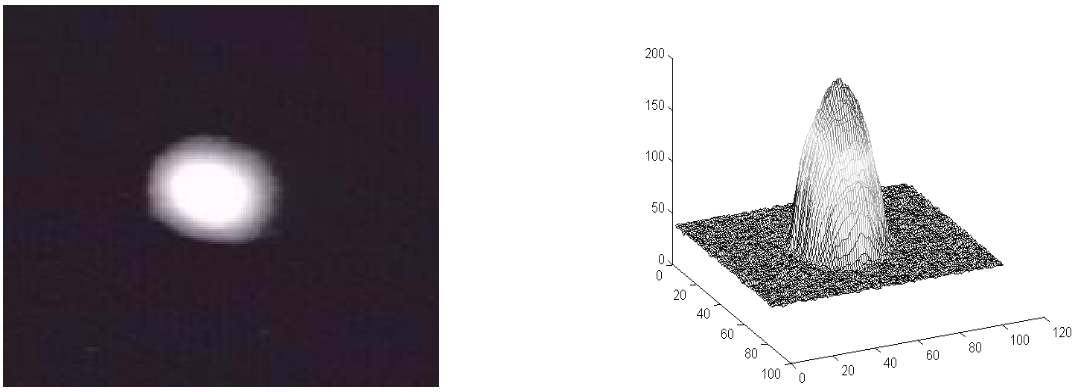


Figure 3 Near-field patterns of a 20-μm-core 4-segment fibre, single-moded at 1.548 μm with a spot of ~15 μm in diameter [36].

Nonlinear POF and Electro-optic POF

Optical fibre is perhaps the most effective medium for devices based on nonlinear optical effects. Nonlinear optical effects can be optimised with high intensity and long interaction length in optical fibre. It is well known that many optical organics are highly nonlinear and have a fast response. Incorporating these materials into an optical fibre would render it optically nonlinear. One unique advantage of POF is its relatively low process temperature (typically less than 250°C). This allows a wide range of functional optical materials to be incorporated into the POF, which would be otherwise be impossible in silica-based fibre. The process temperature of silica fibre is so high (typically

1800°C~2000°C) that those useful organic materials would simply be destroyed. Another advantage of POF is its good compatibility with these functional polymer materials, and this means that various synthesis techniques and materials can be used to produce functional POFs for various applications.

Electro-optic (EO) POF has been developed by Kuzyk et al for optical switching and modulation [27]. EO POFs could have great potential for applications such as voltage and electric field sensors.

We have also reported β-carotene doped POFs for all-optical switching [37]. We have also fabricated electro-optic organic material or dye-doped twin-core POFs for nonlinear optical applications. Figure 4 shows two of our nonlinear POF designs.

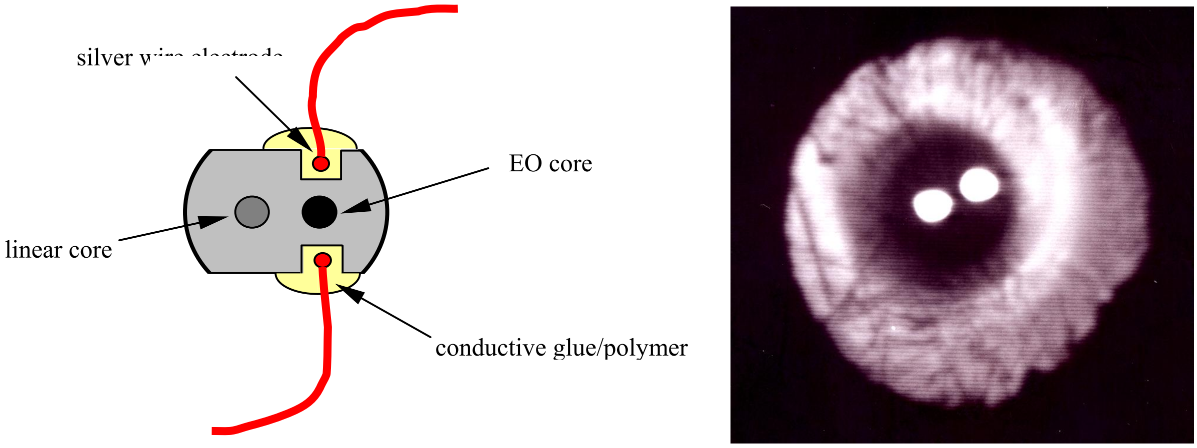


Figure 4 Nonlinear POF designs. Left: a twin-core electro-optic POF; Right: the near-field of a doped twin-core nonlinear optical POF

Laser Dye-Doped POF

Laser dyes are highly efficient media either for laser sources with high power, short pulse width and wide tunable range or for optical amplifiers with high gain, high power conversion efficiency and broad bandwidth. Laser dyes captured in a solid matrix are easier and safer to handle than their counterpart in liquid form. For this reason, solid-state dye gain media have attracted considerable research interest. It is considered that the dye-doped polymers could achieve better efficiency and beam quality, and superior optical homogeneity.

Many dye-doped POFs, either doped in the core or cladding, have been developed for fibre amplifier, laser and sensor applications [38,39]. A wide range of fibre sensors can be built on dye-doped POFs. For example, Muto et al reported dye-doped POFs for humidity sensing [40-42]. Laguesse developed a noncontact sensor using dye-doped POFs for detecting defects in thin-film sheet strips consisting of opacity variation, holes, cracks, and rendings or thickness variation of transparent film [43]. Also scintillating POFs are developed for measurement of nuclear radiation that is useful in detecting radiations and tracking charged and high-energy particles in nuclear physics [44,45].

Also various dye-doped POFs have been developed for fibre lasers and optical amplifiers since early 1990s. Koike et al reported an active POF with laser dyes as dopants [46,47]. Peng et al have also developed laser dye-doped POFs for active components applications [25,26]. Dye-doped POFs can be used for fibre amplifiers and lasers that operate at wavelengths other than the 1300 and 1550 nm used in silica-based fibre lasers. Many well-known laser dyes, including rhodamine 6G, rhodamine B, pyrromethane 650 and fluorescein, can be used to make dye-dope POFs. Moreover, novel organic laser-active optical chromophores can be synthesized. As an example shown in Figure 5, two novel organics, chiral *S*(1)-*N*-[*p*-(4-nitrostyryl) phenyl] prolinol (NSPP-1) and non-chiral [*p*-(4-nitrostyryl) phenyl] piperdine (NSPP-2), were developed as potential laser-active dyes for photonic applications [48]. Both have been observed to be laser active as shown in Figures 6 and 7.

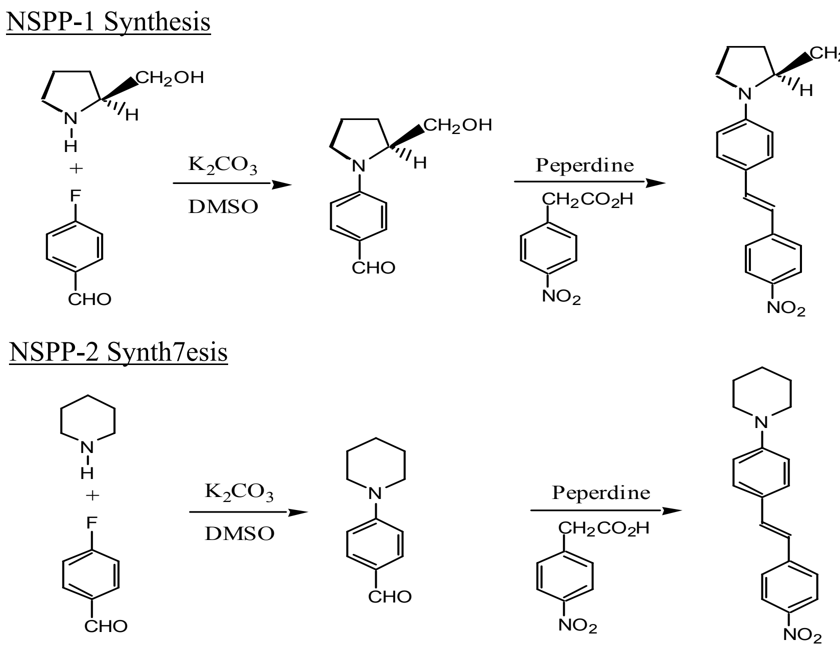


Figure 5 The synthesis of novel laser-active chromophores [48].

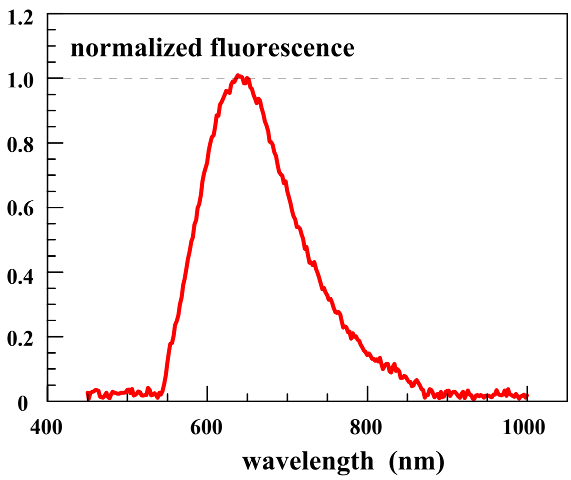


Figure 6 Fluorescence of NSPP-1-doped POF [48].

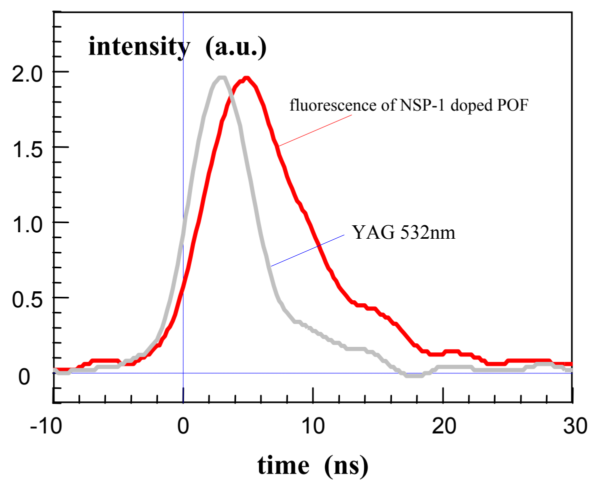


Figure 7. Fluorescence response of NSPP-1-doped POF [48].

Microstructured POF

A new class of special fibres has been investigated in recent years. These fibres can also be made in POFs and are usually referred as microstructured POFs [49]. The light guiding mechanism in microstructured POFs can be quite different from conventional POFs.

In a holey microstructured POF, as shown in Fig.2, a range of microscopic air holes produces an averaged refractive index distribution equivalent to the conventional refractive index distribution of a fibre.

Large et al has made MPOFs from drilling patterned holes in commercial PMMA rods, as the electron microscope photos show in Figure 9 [49]. These commercially available extruded PMMA rods are not of good optical quality. They reported the attenuation of a raw fibre to be about 32 dB/m at a wavelength of 632.8 nm. From the photos, it can be seen that the air hole microstructure consists of four rings of holes in a hexagonal pattern embedded in an outer sleeve. Small deformations in the hole diameters and shapes are obvious. Compared to the preform that the fibre was drawn from, the hole structure in the fibre has a slightly reduced ratio of hole diameter (d) to hole spacing (D), d/D= 0.46, whereas in the preform the ratio d/D=0.67.

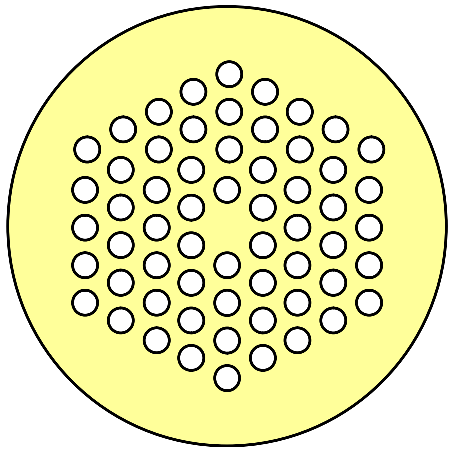


Figure 8 A design of 4-layer holey microstructured POF.

The specially structured pattern of holes in a POF introduces novel properties similar to those of microstructured silica optical fibres. These novel properties include the possibility to realize single-mode operation with large effective core / mode areas or to guide the light in air rather in fibre materials. The novel properties certainly are significant for fibre sensor applications. For example, being able to have the guiding mechanism realized by means of an air microstructured band-gap POF is of great significance in gas or chemical sensor applications.

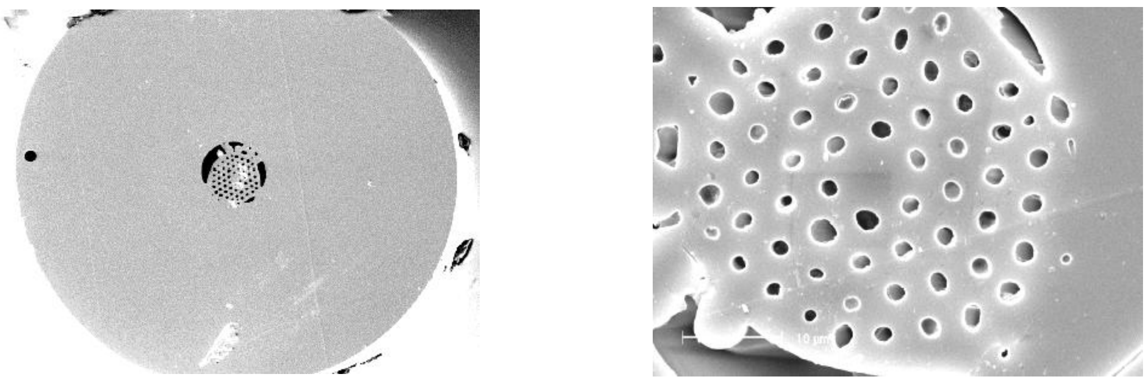


Figure 9 A holey microstructured POF with a sleeve. [49].

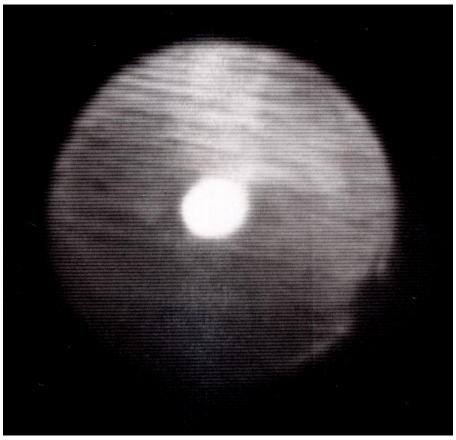
4. DEVELOPMENT OF SPECIAL POF DEVICES

For their great advantages in material related properties that complement those of silica fibres, special polymer optical fibre devices could be very useful and important in an extended range of applications. Considerable research efforts as well as remarkable progress have been made in recent years and a number of POF based device including amplifier, laser, grating , etc have been developed.

POF amplifier

The optical amplification in dye-doped polymer optical fibre was first reported by researchers of Keio University in Japan [44]. Using a dye-doped gradient-index (GI) POF, a of 27 dB was achieved at 591 nm wavelength with high pump power (11 kW) and with a 10~15% energy conversion efficiency. Researchers in University of New South Wales developed a novel and simple technique for fabricating special polymer optical fibres. Using this technique, step-index laser dye-doped polymer fibres of good optical quality have been produced. They have achieved high optical gain (23 dB), high energy conversion efficiency (40%~60% varying with input signal power) and broad gain bandwidth [45]. More importantly, by achieving higher concentration of the laser dye and smaller core size, high gain and high efficiency optical amplifications have been realised with substantially reduced pump power. The significance in achieving lower pump operation is remarkable. Firstly, lower pump power relaxed the constraints in applications. Secondly, the reduced pump power is important to extend the lifetime of the gain medium. Their observation showed a very promising stability of more than 360000 shots of 5 ns pulse under high incident optical intensity of over 120 MW/cm^2. This demonstrated that the polymer fibre has improved stability compared with previously reported results in similar material systems.

Figure 10 shows the cross-section and optical amplification record of a dye-doped POF made in University of South Wales. This POF is Rodamine B-doped and multi-moded with step-index profile. The traces in the photo on the right show the signal with and without the pump. Figure 11 shows the gain spectra of a short piece POF (69cm) [26]. The net gain achieved in this case is about 22dB while the maximum change of gain achieved is 28dB.



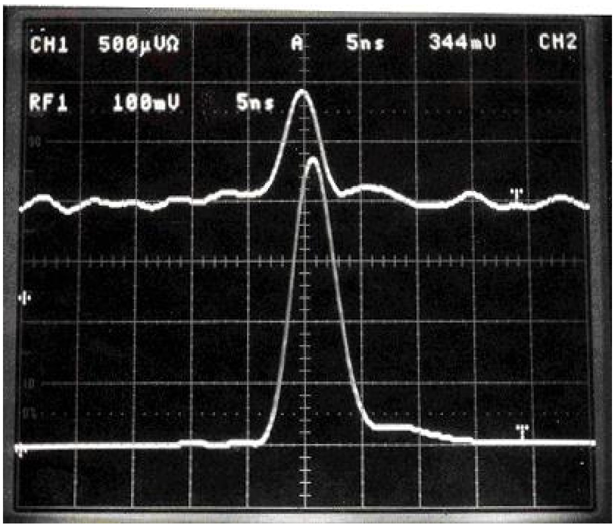


Figure 10 A multimode Rodamine B-doped POF (left) and its use in optical amplification (right; top trace: signal level not amplified, at 500μV/div ; lower trace: signal amplified, at 100mV/div).

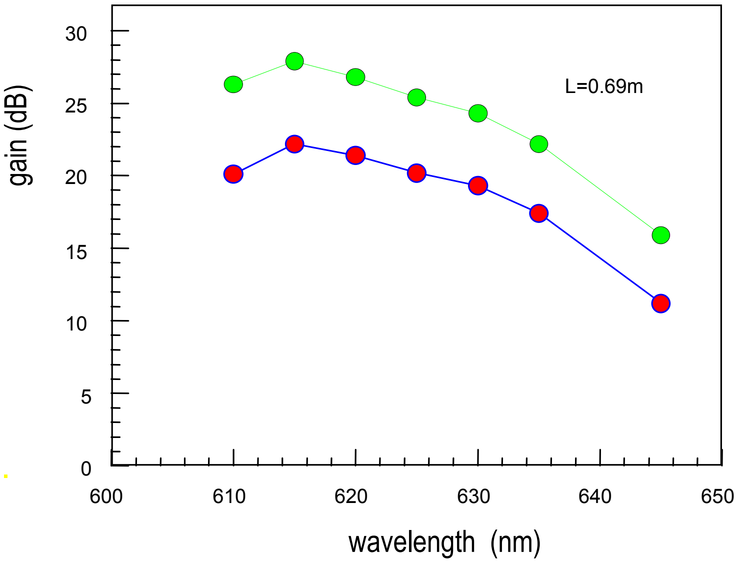


Figure 11 Optical gain spectrum of a Rhodamine B-doped POF of 0.69m length. The upper curve is the change of gain, while the bottom curve denotes the net gain [26].

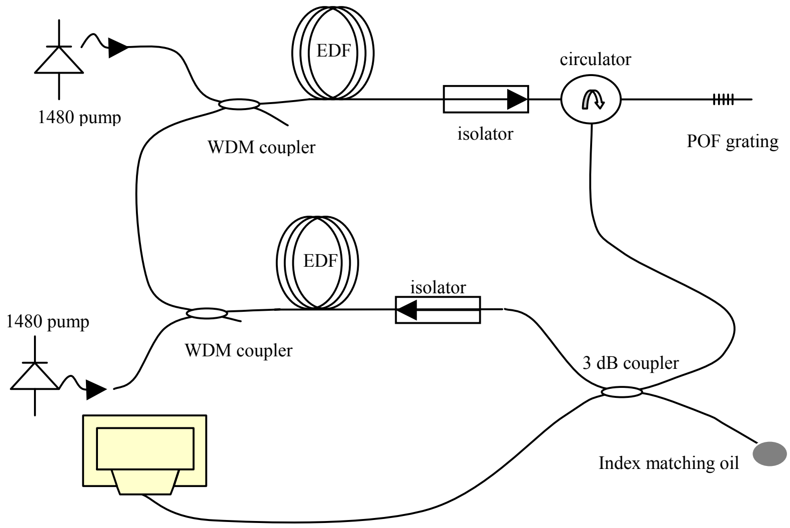
POF FBG & tunable fibre laser

Fibre Bragg grating (FBG) is a very useful component for applications in optical fibre communications and fibre sensor systems. FBG made in silica fibres has been very successful and commercialized. Silica FBG has been useful for a number of its great attributes. However, the wavelength tuning of the silica optical fibre grating is both hard and limited because the silica glass has large Young's modulus and is rigid.

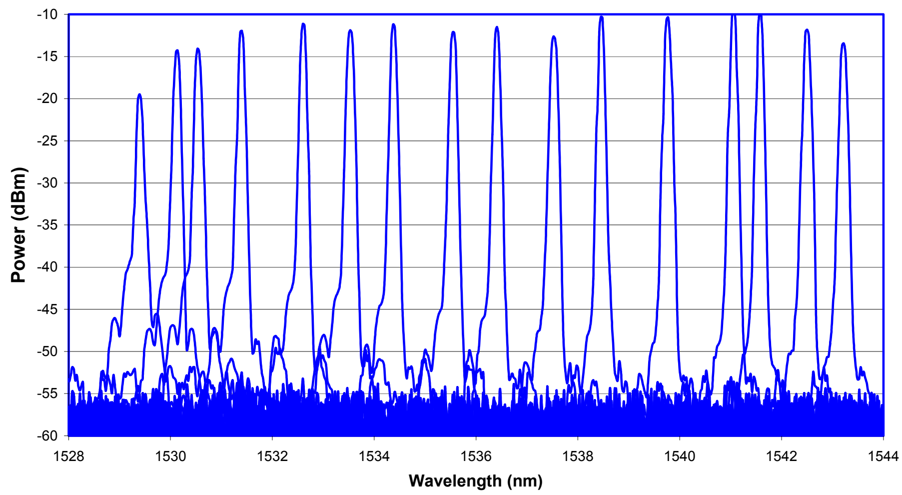
FBG in POF has been developed only in recent years [28]. One of the most attractive features of a POF grating is its wavelength tunability because a polymer material is intrinsically very elastic. This would make it possible to construct highly tunable fibre devices. POF FBG has been reported to achieve a wavelength tuning range of 70 nm.

Tunable FBG could be an important element for building tunable fibre lasers. A tunable laser is desirable to offer large tunable range, compact size, high coherence and low noise. Tunable fibre laser is attractive because it has most of these attributes and also because of its compatibility to the existing telecommunication systems and relative ease of fabrication. Numerous tunable fibre lasers have been reported. However, most of these tunable lasers require complicated tuning mechanisms. For example, a widely S-band tunable fibre ring laser based on thulium-doped fluoride fibre has been demonstrated recently by Chen et al [50]. A grating-based bulk-optic band pass filter was used to realize wide range tuning.

Taking advantage of the wide wavelength tuning range of POF FBG, a tunable fibre laser can be easily constructed. A POF FBG-based tunable fibre ring laser, as shown in Figure 12, has been demonstrated recently [51].



(a) Schematic diagram of the fibre ring laser.



(b) Tuning output of the fibre laser.

Figure 12 A POF FBG-based fibre ring laser [51].

5. FINAL REMARKS

Due to their simplicity in fabrication and flexibility in material selection, a wide range of special application-specific POFs can be made for many different photonic applications. POFs with special functionalities have been developed including laser-dye doped POFs, scintillating POFs, electro-optic POFs, rare-earth doped POFs and would find great application opportunities in future.

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