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High power fiber lasers and amplifiers/Lasers et amplificateurs à fibre de puissance

Photonic crystal fibres for lasers and amplifiers

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Abstract

Air Silica microstructure fibres, often improperly named Photonic Crystal Fibres (PCFs), offer singular propagation properties because of the multiple possible interactions between the guided fields and the heterogeneous structure. We propose a short review of the various PCFs fields of applications while showing, through various examples of fibre structures, how these properties are exploited and which are the most significant results. ***To cite this article: Ph. Roy et al., C. R. Physique 7 (2006).***
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Résumé

Les fibres microstructurées pour applications aux lasers et aux amplificateurs. Les fibres microstructurées Air Silice, souvent improprement baptisées Fibres à Cristal Photonique, offrent des propriétés de propagation tout à fait singulières du fait des multiples interactions possibles entre les champs guidés et la structure hétérogène. Nous proposons un tour d'horizon rapide des différents domaines d'applications de ces fibres en montrant, à travers divers exemples de réalisations, comment sont exploitées ces propriétés et quels sont les principaux résultats obtenus. ***Pour citer cet article : Ph. Roy et al., C. R. Physique 7 (2006).***
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Keywords: Photonic Crystal Fibres; Fibre lasers; Fibre amplifiers; High power lasers; Nonlinear frequency conversion; Liquid core fibres; Hollow core fibres

Mots-clés : Fibres microstructurées ; Lasers à fibre ; Amplificateurs à fibres ; Lasers de puissance ; Conversion Non Linéaire de fréquence ; Fibres à cœur liquide ; Fibre à cœur creux

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Version française abrégée

Au cours des dernières années, les fibres microstructurées Air Silice également appelées Fibres à Cristal Photonique (PCFs) ont démontré de nombreuses propriétés peu usuelles du fait de l'interaction entre les trous d'air (espacement Λ et diamètre d) et le champ électrique des modes guidés. Grâce à la grande différence d'indice de réfraction entre la silice et l'air, des fibres dopées aux terres rares à petit cœur (diamètre $\approx \lambda$) et à forte ouverture numérique peuvent être fabriquées. Un petit diamètre de champ de mode (MFD) conduit alors à l'obtention d'une efficacité de gain très

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élevée [1]. Au contraire, des fibres à faible proportion d'air peuvent guider un mode unique quelle que soit la longueur d'onde même lorsque le rayon de champ du mode guidé est grand (diamètre $\approx 40\lambda$) [2]. En outre, la dispersion de vitesse de groupe est très sensible aux paramètres opto-géométriques de la fibre. Des sources d'impulsions ultra courtes ou à large spectre peuvent être conçues grâce à l'emploi de fibres à zéro de dispersion chromatique décalé vers les courtes longueurs d'onde ou encore de fibres à dispersion faible et aplatie sur une large bande. Enfin, pour atteindre les bandes de longueur d'onde indisponibles avec les terres rares, la conversion de fréquence par des processus non linéaires peut être réalisée en utilisant des PCFs à cœur creux remplis de gaz ou de liquides fortement non linéaires. La méthode « d'assemblage–étirage », utilisée pour la fabrication des fibres PCF peut être appliquée à des fibres composées de verres très non linéaires utilisables aussi pour la conversion de fréquences.

Pour des applications exigeant un pompage à distance (liens de transmission sans répéteur ou amplification d'un signal faible émis par un capteur ou un dispositif de surveillance en milieu explosif), de faibles puissances de pompe sont disponibles. Dans ce cas, une amplification efficace et large bande ne peut être réalisée qu'en utilisant la technologie des PCFs [3]. L'utilisation d'un cœur hexagonal conduit à des facteurs de recouvrement élevés entre le cœur dopé, la pompe et le signal. L'amplification sur une courte longueur de fibre peut donc être obtenue conjointement avec de faibles effets non linéaires grâce à un plus grand rayon de champ de mode et à la valeur élevée du coefficient de gain [4]. L'émission d'impulsions femtosecondes pour la spectroscopie, le traitement de matériaux ou la femto-chimie peut être obtenue par la mise en œuvre de lasers à PCFs dopées aux ions ytterbium dont la dispersion chromatique est anormale aux longueurs d'onde courtes (en-dessous de 1.3 µm) [5] et [6].

Depuis que les fibres à double gaine ont été proposées [7], la puissance moyenne émise par les lasers ou les amplificateurs à fibre est passée de quelques centaines de milliwatts [8] à plusieurs centaines de watts [9]. La forte puissance émise par des diodes de pompe très multimodes est convertie en un faisceau puissant de grande qualité. Pour des niveaux de puissance de pompe élevés, le revêtement externe fait de polymère bas indice de réfraction peut être endommagé, ce qui entraîne la rupture de la fibre. En utilisant la technologie des PCFs, les fibres à gaine d'air suppriment l'interaction entre la puissance de pompe et le polymère. Les propriétés mécaniques et thermiques sont améliorées et l'ouverture numérique peut atteindre des valeurs supérieures à 0,6 alors qu'elles sont au plus égales à 0,48 avec un revêtement polymère. De plus, les plus grands diamètres de champ de mode obtenus dans des fibres usuelles sont d'environ 25 µm. Si toute la fibre est microstructurée, il est alors possible d'atteindre des diamètres de champ de mode de plus de 40 µm [11,12]. Pour toutes ces raisons, les seuils d'apparition des effets non linéaires sont augmentés et le risque d'endommager la fibre réduit. Les PCFs sont par conséquent des candidates idéales pour la réalisation de lasers fibrés transversalement monomodes, puissants (>1 kW), fonctionnant en régime d'émission continu. Enfin, ces fibres dont on peut contrôler à la fois l'aire effective et la dispersion chromatique ont des qualités évidentes pour l'émission d'impulsion de forte puissance crête [13–15].

Beaucoup de longueurs d'onde sont indisponibles avec des sources laser conventionnelles. Dans le domaine des sources basées sur l'exploitation des processus non linéaires tels que la conversion paramétrique ou l'effet Raman, les PCFs ont suscité une attention considérable au cours des dernières années. D'une part, des oscillateurs paramétriques fonctionnant en régime continu ont été conçus grâce à des fibres à dispersion chromatique contrôlée favorisant les échanges paramétriques [16]. D'autre part, un faisceau laser puissant peut être fortement confiné dans une fibre PCF à cœur creux guidant par effet de bande interdite photonique. L'interaction sur une grande longueur, entre divers matériaux bas indice à fort coefficient de gain Raman (certains gaz ou liquides) et une forte puissance de pompe est alors possible, menant à de nouvelles conversions de longueur d'onde [17–21].

1. Rare-earth doped PCFs: low mean power applications

The efficient amplification of weak signals from sensing/monitoring devices in explosive areas or in remote pumping transmission links must be operated with low input pump power. Highly efficient amplification, requiring a strong confinement of both the pump and the signal in the doped region is then necessary. For achieving such a strong confinement in step index fibres, the numerical aperture must be increased by heavily doping the core with germanium. The available amplification bandwidth is then dramatically reduced compared to that in alumino-silica host material.

To overcome this drawback, the unique features of PCFs can be used. With a large air filling fraction and a small pitch, Er/Al doped core fibre amplifiers with both a high NA and a small effective area of the fundamental mode (A_{eff}) can be designed. Due to the stack and draw manufacturing process, the erbium doped region is limited to $\Lambda/2$. For example, Hougaard et al. report a PCF amplifier ($d \approx 0.58$ µm, $\Lambda \approx 0.73$ µm) providing a 15 dB gain at $\lambda = 1.55$ µm with less than 0.7 mW pump power at 980 nm [3]. However, let us note the high 8 dB splicing loss of the fibre with a standard single mode fibre, and the low nonlinear effects threshold due to the small A_{eff} of the signal mode ($\sim 3.7\ \mu\mathrm{m}^2$).

With the PCF depicted in Fig. 1(a) ($d = 1\ \mu\mathrm{m}$, $\Lambda = 2\ \mu\mathrm{m}$) whose silica core is codoped with Al and Er, Furosawa et al. obtained a 8.6 dB/mW gain coefficient at 1533 nm with a 2.5 m long fibre [1]. Laser operation with 0.5 mW laser threshold was achieved over a 100 nm broad tuning range of wavelengths.

To enhance Er-doped amplifiers efficiency, we proposed a new PCF structure with an enlarged core (Fig. 1(b)). When manufacturing the preform, the central rod and the first ring of capillaries are replaced by a hexagonal erbium-doped rod to maximise dimensions of the doped area (inset Fig. 2(a)). The geometrical parameters were chosen for optimising the overlap factors between the doped area and both the pump ($\lambda = 980$ nm) and signal ($\lambda = 1550$ nm) transverse distributions that were calculated by numerically solving the Maxwell equations in the structure by means of a vectorial finite element method (FEM). It was found that, with $d = 0.6\ \mu\mathrm{m}$ and $\Lambda = 2\ \mu\mathrm{m}$, the propagation remains single mode at both wavelengths. In Fig. 2(a) the overlap factor in this PCF is plotted together with that of a typical erbium doped step index fibre (doped zone radius: 1.5 µm, $\Delta n = 21 \times 10^{-3}$). It can be seen that, at the two wavelengths, it remains higher than 90% in the PCF whereas it decreases from 86% to 55% in the standard doped one.

These data were used to compare the amplifier performances of the two fibres. The parameters of the simulation were the following: erbium concentration = 150 ppm, pump power = 190 mW and signal power = −10 dBm, equally

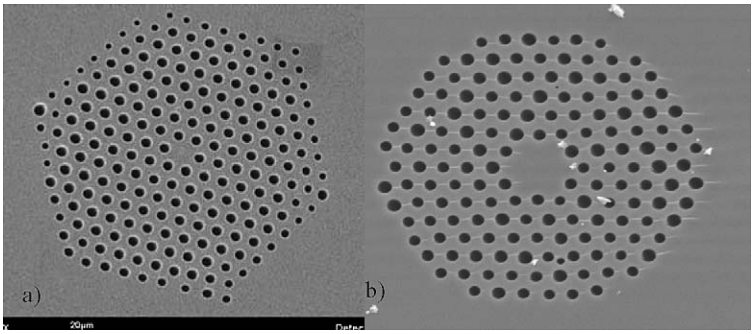


Fig. 1. Cross section of PCFs (a) with a 8.6 dB/mW gain efficiency [1], (b) with a large hexagonal doped core.

Fig. 1. Sections transverses de PCFs (a) présentant une efficacité de gain de 8.6 dB/mW [1], (b) avec un cœur hexagonal dopé.

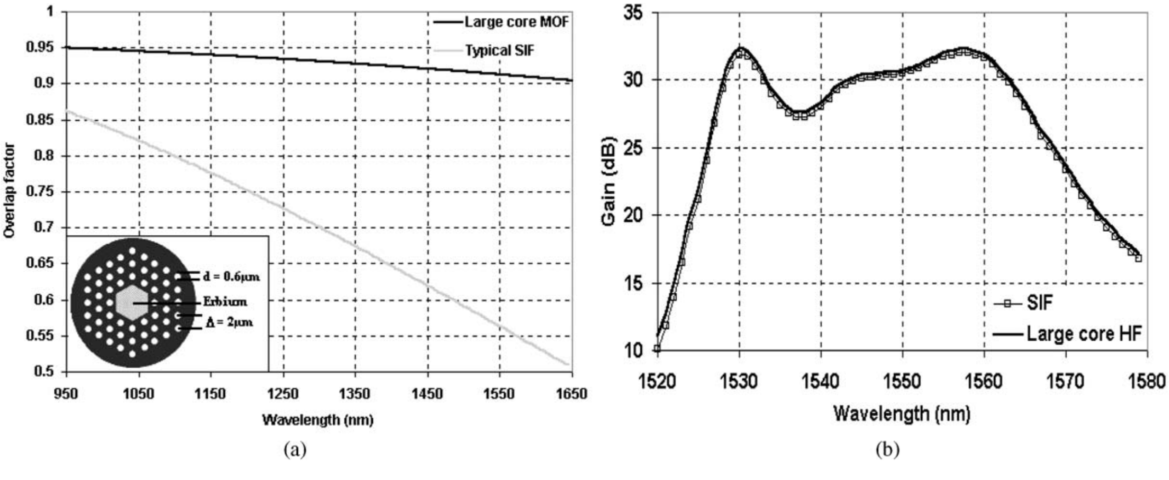
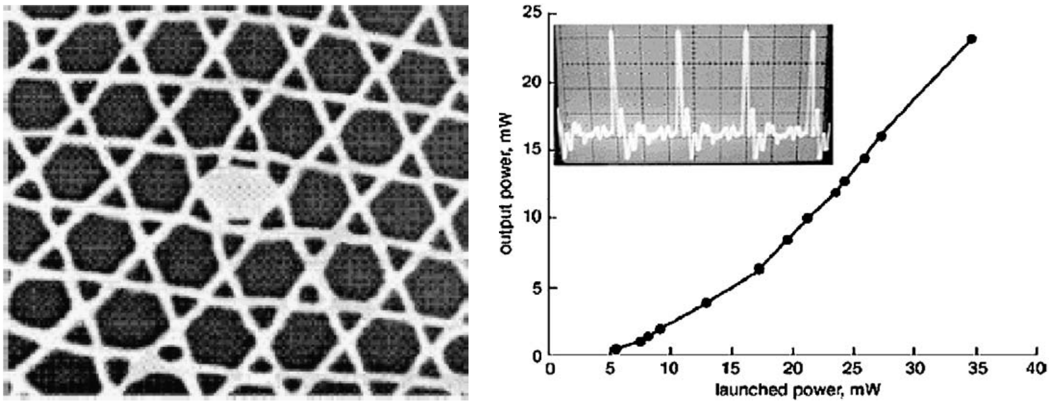


Fig. 2. (a) Overlap factor of typical SIF and large core PCF (inset: transverse structure of the large core PCF), (b) gain curves for the SIF and the large core PCF amplifiers with 40% off in fibre length.

Fig. 2. (a) Facteurs de recouvrements typiques d'une SIF (step index fibre) et d'une PCF à coeur hexagonal (insert : structure transverse d'une PCF à coeur hexagonal), (b) courbes de gain d'un amplificateur à fibre SMF comparée à celle d'un amplificateur à PCF utilisant une fibre 40% plus courte.



(a) (b)

Fig. 3. (a) Scanning electron microscope picture of an Yb doped PCF [5], (b) laser output power at 1038 nm against launched 966 nm pump power and typical oscilloscope picture of pulses trains in inset [5].

Fig. 3. (a) Image MEB de la PCF dop ée Yb [5], (b) puissance de sortie à 1038 nm en fonction de la puissance de pompe à 966 nm et oscillogramme typique représentant le train d'impulsions en insert [5].

distributed over 60 channels from 1520 to 1580 nm. The lengths of both fibres were optimised for providing a gain shape with a flatness verifying the standard condition $(G_{\max} - G_{\min})/G_{\max} \sim 21\%$. As shown in Fig. 2(b), very similar gain curves were obtained. However, the necessary length of PCF is 40% shorter than that of step index fibre (31 and 52 m respectively), that is attractive for designing efficient short length cavity lasers [4]. The nonlinear effects threshold is also increased thanks to the larger effective area of the modes (21 and 25 μm^2 at 980 and 1550 nm respectively) and the shorter interaction length.

Novel designs of Ytterbium doped PCFs have also been developed for mode locked laser application [5] and tunable femtosecond pulses [5]. For example, the PCF whose scanning electron microscope picture is shown in Fig. 3(a) is characterised by a large numerical aperture (up to 0.8) with a 2000 ppm codoped Yb/Al/Si elliptical core ($\sim 2.6 \times 1.5$ μm). The fibre is highly birefringent (beat length of 0.3 mm at 1.54 μm) due to the elliptical core. The fundamental mode is characterised by a very small effective area (around 2.5 μm^2) at 1.55 μm and an anomalous dispersion at 1 μm. A mode locked fibre laser based on this fibre provides 15 ps pulses with a 0.1 nm spectral bandwidth (Fig. 3(b)). With the same fibre, a 1.06 to 1.33 μm tunable soliton source (duration: 67 fs) has also been demonstrated [6]. This kind of source is of great interest for ultra fast spectroscopy, material processing, optical chemistry and nonlinear optics [5,6].

2. Rare-earth doped PCFs: high power applications

At the end of the 1990s, double-clad fibres were proposed [7] in order to enable the guidance of pump energy in a large multimode region known as inner cladding, thus allowing us to use low brightness high power multimode laser diodes as pump sources. In this way, the mean power emitted by fibre lasers or amplifiers is increased from few hundred milliwatts to several hundred watts [8], and even to 1.36 kW [9]. The slope efficiency can be higher than 75% and the output laser beam quality close to the diffraction limit. Moreover double-clad fibres offer the advantage of being easily manufactured, thanks to the standard and well-controlled step index technology, with different possible inner cladding geometries for better pump absorption [10] (Fig. 4). However, the low refractive index polymer used to form the outer cladding causes two problems: first, it restricts the inner cladding numerical aperture to 0.48 and, second, it can be damaged (degradation or even burning) when handling high pump power level, reducing fibre reliability.

Using the PCF technology, air-clad fibres have been proposed in order to overcome these problems by replacing the polymer by an arrangement of air holes (Fig. 5). Thus mechanical and thermal properties are improved, since the interaction between pump power and polymer is suppressed. Moreover, thanks to the use of very thin silica bridges between the holes, a large air filling factor can be achieved in the cladding, leading to numerical aperture values up to 0.8. This improves the coupling efficiency of the multimode pump source into the fibre and the fibre length can be consequently shortened, considering a given pump absorption level. The limitations due to unwanted nonlinear effects can thus be avoided, giving more flexibility in the design of very high power systems.

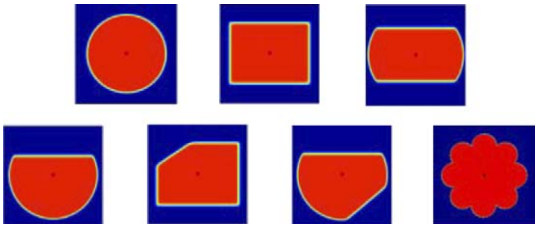


Fig. 4. Different inner cladding geometries proposed to enhance pump absorption in double-clad fibres.

Fig. 4. Différentes géométries de gaine interne proposées pour améliorer l'absorption de la puissance de pompe.

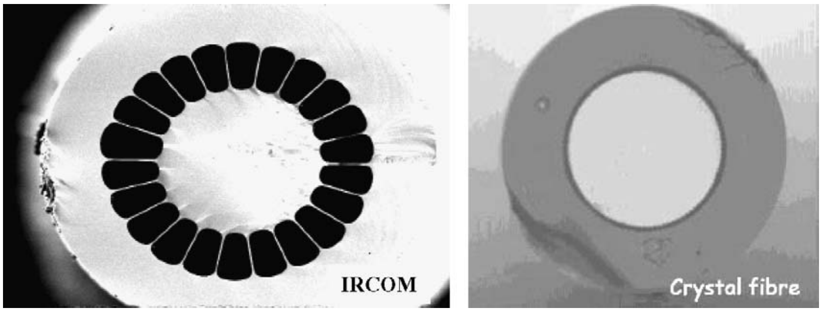


Fig. 5. Examples of air-clad structures.

Fig. 5. Exemples de structures à gaine d'air.

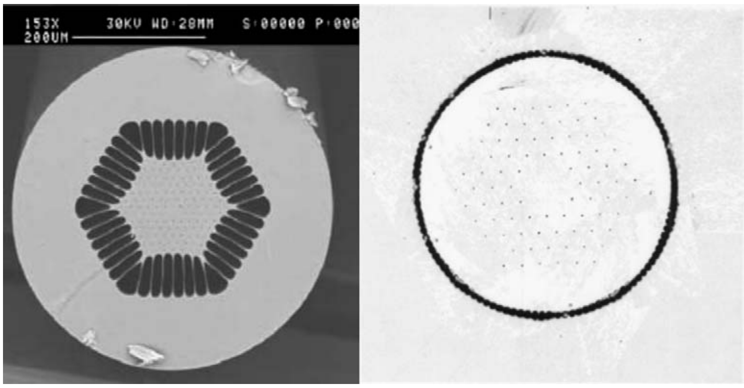


Fig. 6. Examples of PCFs combining air-clad and LMA structures (from Crystal Fibre AS).

Fig. 6. Exemples de PCFs à gaine d'air et gaine interne microstructurée à grand cœur de type LMA (Crystal Fibre AS).

Another attractive feature of PCFs consists in combining the air-clad technology with a Large Mode Area (LMA) structure, which allows one to increase the active core area and subsequently the nonlinear optical effects penalty and material damage thresholds. Indeed, when the central core and the inner cladding are manufactured by the standard index doping technology, the Mode Field Diameter (MFD) upper limit for singlemode propagation is around 25 µm. Moreover, if both inner and outer claddings are made of well designed air-silica structures (Fig. 6), larger MFD (more than 40 µm) are available [11,12]. In addition, LMA-structures initiate endlessly singlemode propagation (i.e., the transverse pattern is singlemode whatever the wavelength is), with a very low mode effective area dependence to the wavelength. PCFs are therefore great candidates to perform high power (>1.5 kW) continuous wave emission together with high beam quality ($M^2 < 1.2$). Finally, the combination of high pump power level, control of both effective area and chromatic dispersion make such slightly nonlinear fibres also good solutions for high peak power pulse emission [13–15], as shown in Fig. 7.

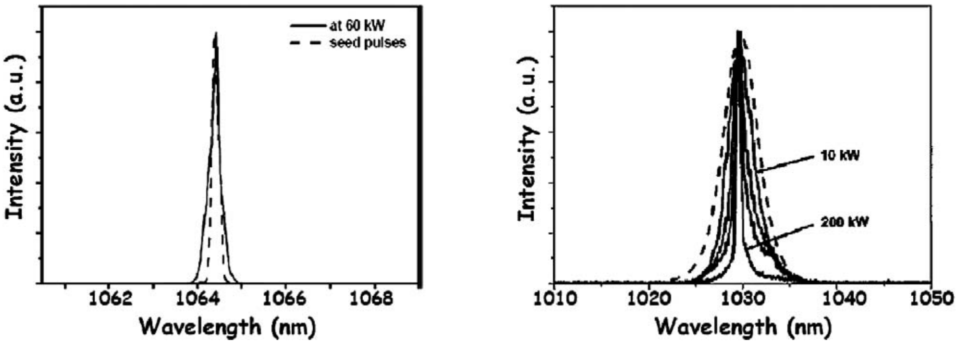


Fig. 7. Use of air-clad LMA PCFs for high peak power ps emission (spectra from [13]).

Fig. 7. Spectres d'impulsions ps puissantes émises par une fibre à gaine d'air incluant un coeur de grande section [13].

3. Photonic crystal fibre for new wavelength emission

3.1. Gas or liquid filled hollow-core photonic crystal fibres

Nonlinear effects could be used to realise optical sources at unconventional wavelengths. To optimise the efficiency of the nonlinear process, a trade-off has to be made between the nonlinearity of the medium, the interaction length and the pump intensity. It is well known that silica is a low-nonlinear medium. The nonlinear efficiency may be enhanced by using gas or liquids rather than silica. The simplest way to implement nonlinear processes in such low-index media is the use of filled capillary. Unfortunately, this solution is somewhat unattractive since this structure is a very leaky waveguide and can not lead to long interaction lengths. Moreover, reducing the propagation loss in such capillary waveguide necessitates to enlarge the hole diameter. Hence the pump intensity is lowered. One other attractive feature of PCFs, is the possibility to efficiently guide light in a low-index medium. For instance, the microstructuration of the holey cladding allows one to decrease the cladding index. Hence, waveguides exhibiting a low-index-liquid core can be realised. These waveguides operate thanks to total internal reflection at the liquid/cladding interface. The theoretical and experimental cross-sections of such a fibre are shown in Fig. 8(a), (b). When the innermost hole is filled with ethanol ($n = 1.3528$ at $\lambda = 830$ nm), light is mainly guided in the liquid core thanks to the low-index high-air-filling-fraction microstructured cladding [17] and [18]. Fig. 3(c) shows the spatial distribution of light in the fibre.

Thanks to the strong confinement of light in the core, such an ethanol-core fibre has been proved to be an efficient Raman converter [18].

Hollow-Core PCFs guiding by photonic bandgap effect can simultaneously offer tight confinement of laser light and long interaction lengths in gaseous cores. In such waveguides, light is guided thanks to Bragg reflection off a

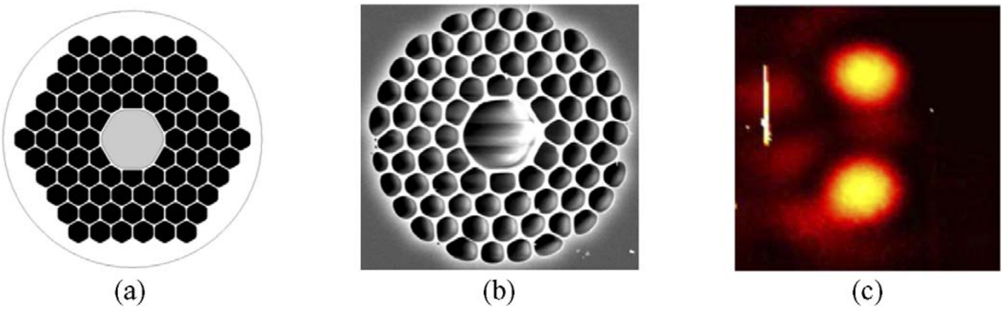


Fig. 8. Ethanol-Core Photonic Crystal Fibre: (a) Theoretical cross-section of the filled HC-PCF; (b) SEM photograph of the fabricated HC-PCF; (c) Observed near-field intensity distribution in the fabricated fibre when core filled with ethanol ($\lambda = 830$ nm).

Fig. 8. Fibre microstructurée à coeur liquide (ethanol) ; (a) Section transverse théorique de la fibre HC-PCF ; (b) Image MEB de la fibre HC-PCF fabriquée ; (c) Distribution d'intensité du champ proche observé lorsque le cœur est rempli d'éthanol ($\lambda = 830$ nm).

photonic crystal consisting of air holes in a silica matrix. The defect trapping the light is the core of the fibre. The transverse cross-section of such a fibre is similar to that shown in Fig. 8(a) except a higher air-filling fraction and a larger number of hole layers. Such a complicated periodic structure is needed to efficiently guide light in air thanks to the bandgap effect. In HC-PCFs total internal reflection does not occur and the core index may be smaller than the average surrounding index. Recently the propagation loss in HC-PCFs has been decreased down to 1.2 dB/km opening the way to very long interaction length in gaseous medium [19].

The efficient interaction between gas with high Raman gain coefficient and high power pump laser is consequently obtainable, leading to new laser wavelength conversions [20]. Vibrational stimulated Raman scattering in hydrogen-filled hollow-core PCF has been demonstrated. The results showed a threshold energy of 800 nJ (with a 532 nm pump source and pulse duration of ~6 ns). This value represents a decrease in the required pump power by a factor of more than 100 times in comparison with any conventional technique using either focusing or multi-pass cells. For pure rotational SRS, the photonic crystal may be optimized in order to reduce the bandwidth to 150 nm allowing for the efficient filtering of the unwanted vibrational SRS [20,21]. In this case, 92% quantum conversion efficiency and threshold energies as low as 3 nJ (more than 10^6 times lower than previously reported) have been reported. Moreover, compact, stable and hermetic gas-cells may be realised by splicing the filled HC-PCF to two solid-core standard fibres [21].

3.2. Soft glasses photonic crystal fibres

Promising glasses different from silica are studied to get new laser wavelengths conversion: the main ones are chalcogenide glass and telluride glass.

Chalcogenide glasses have many unique optical properties such as a large transmission in the near, middle and out into the far IR depending on the glass composition (Fig. 9) [22]. Recent studies [23] have shown that the Raman gain coefficient of As–Se fibre is more than 300 times higher than the Raman gain coefficient of silica at a wavelength of 1.5 μm, as is shown in Fig. 10. These two properties show a great potential for the development of Raman fibre lasers and amplifiers in the whole IR region.

Telluride fibres are also studied for Raman amplification because of their useful properties not possessed by silica: the transmission window of Te–X glasses is ranging from 1 to 18 μm and they have a high refractive index and a high optical nonlinearity. Moreover they are more stable than fluoride glasses and have higher rare-earth solubility than chalcogenide glasses. Fig. 11(a) shows a scanning electron microscope (SEM) picture of a PCF made of telluride glass manufactured by extrusion technique [24]. A strong stimulated Raman scattering (first and second order Stokes

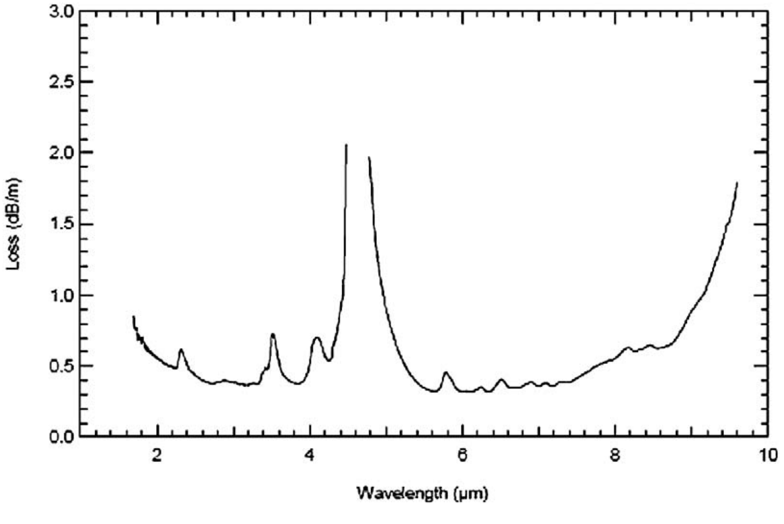


Fig. 9. Typical loss spectrum of an As–Se fiber taken with a Fourier transform IR spectrometer [22].

Fig. 9. Spectre de pertes typiqued'un fibre As–Se relevé à l'aide d'un spectroscape IR à transformée de Fourier [22].

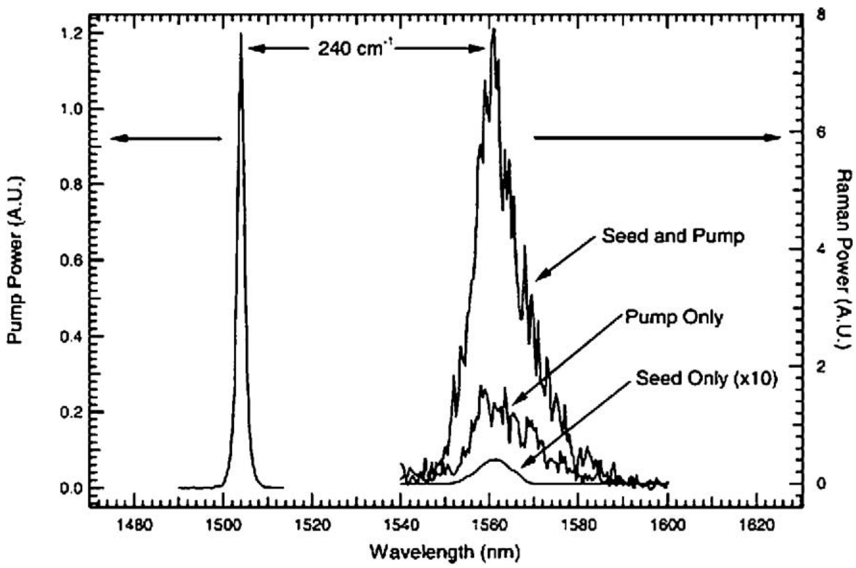
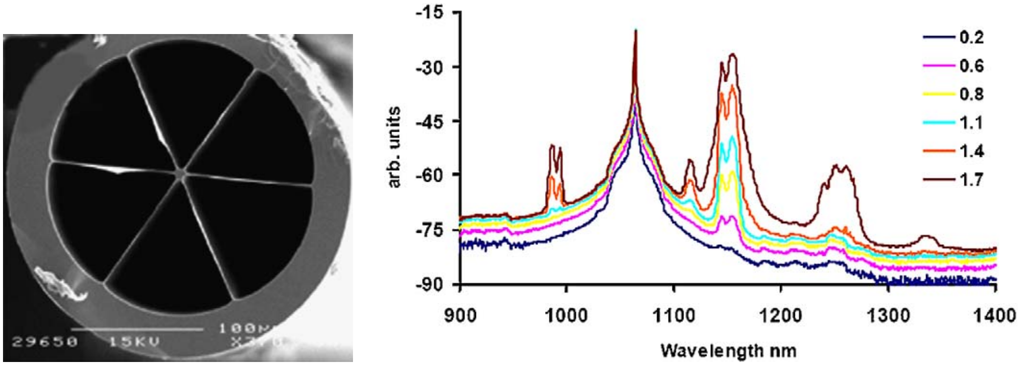


Fig. 10. Raman amplification of a 1.56 µm diode laser in a small core As–Se fiber [23].

Fig. 10. Amplification Raman dans une fibre As–Se à petit coeur [23].



(a) (b)

Fig. 11. (a) SEM picture of a tellurite PCF. (b) Stimulated Raman spectra from a PCF (lenght: 1.02 m).

Fig. 11. (a) Image MEB de la fibre en verre de tellure. (b) Spectre Raman stimulé en sortie de 1,02 m de fibre PCF en verre de tellure.

as well as an anti-Stokes peak) is observed using a microchip laser at a wavelength of 1064 nm (Fig. 11(b)). Further work is now planed to extend the use of this kind of fibre in all the IR range.

4. Conclusion

In this article, although only a brief overview, we have shown how PCFs properties are used in the field of amplifiers and lasers applications. Highly efficient amplifiers and low threshold lasers have been reported thanks to the strong mode confinement proffered by high numerical aperture PCFs. Concerning high power fibre lasers and amplifiers, rare-earth doped PCF with air-clad and very large doped core demonstrated laser operation up to 1.5 kW continuous wave. Nonlinear limitations have been rejected due to particular fibre design. Finally, as PCFs have been used as the favoured media to enhance interactions between pump light and unusual solid, liquid or gas media, new wavelength generation is available, opening a new field of investigations.

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