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Review

Highly Doped Phosphate Glass Fibers for Compact Lasers and Amplifiers: A Review

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Received: 27 October 2017; Accepted: 11 December 2017; Published: 13 December 2017

Abstract: In recent years, the exploitation of compact laser sources and amplifiers in fiber form has found extensive applications in industrial and scientific fields. The fiber format offers compactness, high beam quality through single-mode regime and excellent heat dissipation, thus leading to high laser reliability and long-term stability. The realization of devices based on this technology requires an active medium with high optical gain over a short length to increase efficiency while mitigating nonlinear optical effects. Multicomponent phosphate glasses meet these requirements thanks to the high solubility of rare-earth ions in their glass matrix, alongside with high emission cross-sections, chemical stability and high optical damage threshold. In this paper, we review recent advances in the field thanks to the combination of highly-doped phosphate glasses and innovative fiber drawing techniques. We also present the main performance achievements and outlook both in continuous wave (CW) and pulsed mode regimes.

Keywords: fiber laser and amplifier; phosphate fiber; all-fiber master oscillator power amplifier (MOPA); rare-earth-doped fiber

1. Introduction

Fiber lasers are nearly as old as the glass laser itself. The first demonstration of a fiber laser dated back to the 1960s, when E. Snitzer and C. J. Koester demonstrated laser action in a neodymium-doped fiber [1,2].

Nowadays, fiber lasers are not only one of the fastest growing photonic technologies, but they are also a sound industrial reality that is rapidly eroding the markets shares of other laser technologies. They find applications in a variety of fields ranging from industrial material processing, medical applications, semiconductor device manufacturing, remote sensing and scientific instrumentation.

The key advantages of fiber laser reside in their waveguide geometry. Indeed, a low threshold and a high conversion efficiency are possible thanks to the tight confinement of the pump and the generated signal. First of all the tight confinement of both pump and laser light results in a low threshold and a high optical conversion efficiency. Moreover, optical fibers exhibit an enhanced heat dissipation capability thanks to their high surface-to-volume ratio and the distribution of the thermal load over a considerably long length, which facilitates unprecedented power scaling capacity. The whole laser resonator can be realized using fiber components only, such as Fiber Bragg Gratings (FBGs) and fiber couplers. This all-fiber configuration avoids the use of free-space optics, thus allowing a robust and compact system design that facilitates the usability of fiber lasers outside the laboratory. Another advantage of fiber laser is that beam handling and beam deliveries become inherently simple thanks to the fiber based configuration [3,4].

Another important aspect of fiber laser technology is the fact that is extremely versatile and can be adapted to different laser applications, by customizing the output power, beam quality and dimension, spectral properties, output stability and temporal output properties. Moreover, the very large spectral bandwidths achievable from rare-earth (RE) ions in glass allow fiber lasers to operate from the continuous wave (CW) regime down to pulse durations of few femtoseconds.

The fiber geometry is indeed the origin of the main advantages of fiber lasers; however, it is also responsible for the main drawbacks of such devices. The enforcement of deleterious nonlinear effects, such as self-phase modulation (SPM), stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS), is due to the confinement of the laser radiation in a small area and to the long interaction length. These effects constitute the main restriction of RE-doped fiber laser systems [3].

Optical fibers for lasers and amplifiers are drawn from glasses and several glass systems suitable for photonic applications are well-known, with a variety of chemical, physical and optical properties [5]. However, most of the research work performed so far on fiber lasers has been performed on doped silica glasses, thanks to their outstanding properties. Silica is featured by the lowest propagation losses (0.2 dB/km), can withstand high temperatures and shows exceptional mechanical strength and chemical durability. However, a major drawback of silica glass is the poor solubility of RE ions, and the consequent tendency to cluster. This causes deleterious effects on the spectroscopic properties of the material.

Multicomponent phosphate glasses have demonstrated in last years to be a promising contender to silica glass as a fiber material, especially for the realization of compact active devices [6–8]. The main reason is that, thanks to the very open and disordered matrix structure [9,10], they can withstand very high doping level of rare earth-ions (up to 10^{21} ions/cm^3), typically about 50 times higher than in the more rigid glass matrix of silica glass. High concentrations of laser-active RE ions (like Erbium, Ytterbium and Neodymium) can thus be incorporated into the glass matrix without clustering, which is responsible to degrade the performance of the glass enhancing quenching effects [11–14]. Fiber laser length can be then substantially reduced, minimizing nonlinearities that grow with fiber length.

Moreover, phosphate glasses are substantially immune to photodarkening. It was demonstrated that the maximum concentration of Yb^{3+} ions allowed in a phosphate fiber before the onset of photodarkening at 660 nm was at least 56 times higher than a standard commercial silica fiber and 6 times higher than a highly Al-doped silica fiber [15].

In terms of thermo-mechanical properties, phosphate glasses have typically a low glass transition temperatures (400–700 °C), if compared to silica (1000–1200 °C), and also lower softening temperatures (500–800 °C instead of 1500–1600 °C) [10,16–18]. Although these thermal features present some advantages in terms of glass processing for fabricating the fiber preform, the drawback is that phosphate fiber can suffer from thermal degradation under high-power operation. Special care and subsequent cooling apparatus may therefore be required during high power laser operation. In addition, the characteristic temperatures difference between phosphates and silica, as well as the sharp difference in physical properties between standard commercial silica based fibers and phosphate ones, has slowed down the exploitation of these fibers due to the more challenging integration in all-fiber devices. Nonetheless, splicing of phosphate fibers to silica based fibers and fiber components (for example couplers and Fiber Bragg Gratings) is nowadays commonly employed, with relatively low loss (0.2 dB per joint) and high strength [19–21].

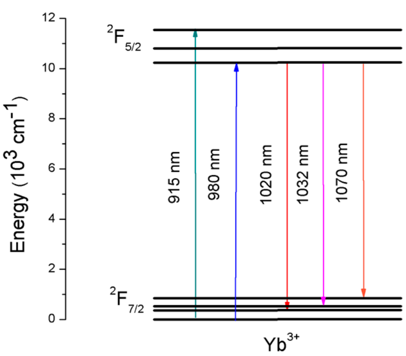
In the last decades, remarkable results in the field of phosphate based fiber lasers and amplifiers have been obtained in terms of high output power, new operating wavelengths, single-frequency operation, pulse duration and compact configurations. The aim of this paper is to review major results obtained in the field of phosphate fiber laser technology to highlight its complementarity to silica fiber technology and discuss its future prospect. The paper is organized as follows. In Section 2 a brief review of spectroscopic properties of main RE ions used for the development of phosphate fiber lasers and amplifiers is presented. Section 3 reports the current state of the art of CW phosphate fiber lasers and amplifiers. In Section 4 main results of CW single-frequency fiber lasers and amplifiers are reviewed. Pulsed single-frequency phosphate fiber lasers and amplifiers are addressed in Section 5.

2. Rare-Earth Active Ions for Phosphate Fiber Lasers

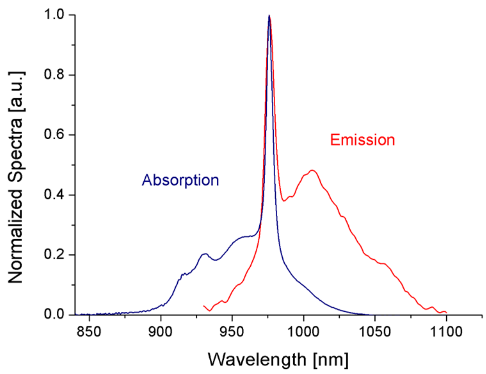
Among the different RE ions, Ytterbium is one of the most commonly used for the fabrication of phosphate fiber lasers. The electronic transition $^2F_{5/2} \rightarrow {}^2F_{7/2}$ (see Figure 1) can generate laser emission over a band of wavelengths ranging from ~970 to ~1200 nm, thus allowing a wide tuning ability of the output beam in the 1 µm window and short pulse amplification (down to fs regime) [22].

The absorption band is also very broad, from ~850 to ~1070 nm, and covers a range where laser diodes have their highest output power and efficiency. Since the pump wavelength is very close to the laser emission one, an Yb^{3+}-doped fiber laser displays always a small quantum defect, potentially allowing for very high power efficiencies and reduced overheating effects in high-power regimes [23].

Ytterbium is well-known for the simplicity of its energy level diagram, based on a simple two levels system that reduces the incidence of detrimental processes such as multiphonon relaxation and excited state absorption (ESA). Figure 1a shows a typical Yb^{3+} ions energy level diagram with indicative splitting of the Stark sublevels. This splitting allows the ion to work in a three or four levels system, according to the choice of the pump and lasing wavelengths. Figure 1b displays typical absorption and emission spectra of a multicomponent Yb^{3+}-doped phosphate glass. Table 1 summarizes the typical absorption and emission cross-sections reported in literature, alongside typical lifetime value of the $^2F_{5/2}$ excited state level.



(a)



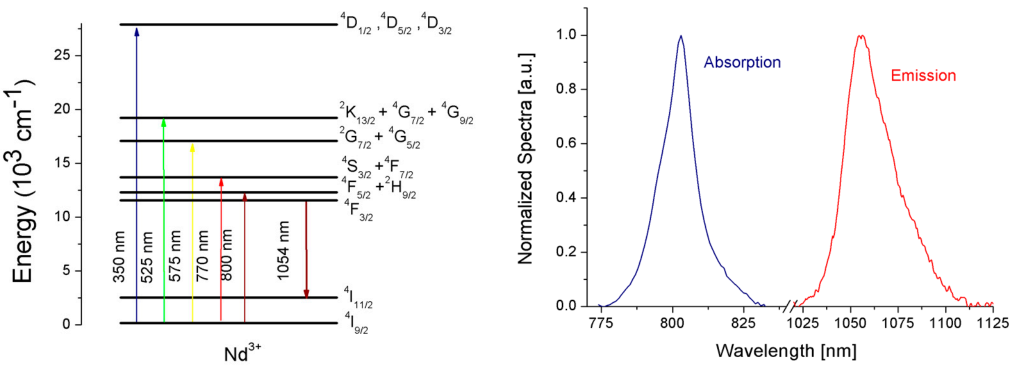
(b)

Figure 1. (**a**) Typical energy level diagram of Yb^{3+} ions in phosphate glasses; (**b**) Typical absorption and emission spectra of Yb^{3+} ions in an in-house fabricated phosphate glass.

The Neodymium is featured by a much more complex structure. Figure 2a reports the schematic of the energy levels of Nd^{3+} ions with the transitions of interest with respect to this review.

Although the radiative decay can occur to all the lower lying ^4I_J levels, the strongest transition is the one to the $^4I_{11/2}$ level, that leads to a maximum peak at a wavelength of 1053 nm in most phosphate glasses. Thanks to the numerous absorption bands in the visible and near-infrared, Nd could be pumped by flash lamps, which were the oldest and most common pumping solution for this ion in phosphate glass host. The first fiber laser in the 1960's was indeed demonstrated in a Nd-doped fiber excited by means of flash lamps [1,2]. More recently, with the availability of laser diodes at the requested wavelengths, a more efficient and compact pumping scheme has been achieved through the use of AlGaAs pump diode lasers operating at around 808 nm to excite the transition $^4I_{9/2} \rightarrow {}^2H_{9/2} + {}^4F_{5/2}$ (see Figure 2a). Despite the large number of closely spaced excited states, Nd^{3+} ion does not suffer from ESA. Even though the $^4F_{3/2} \rightarrow {}^2D_{5/2}$ ESA transition occurs, it is resonant with the photon energy of the 800 nm wavelength laser pump, it is negligible and does not significantly affect the 800 nm pumping [24]. Thanks to the several absorption bands in the visible, an unusual pumping scheme for Nd-doped phosphate lasers by solar radiation was also investigated in the framework of the research on solar pumped lasers [25,26].

Figure 2b reports typical absorption and emission spectra of Nd^{3+} ions in phosphate glasses. Typical cross-section values are reported in Table 1, along with lifetime of the $^4F_{3/2}$ excited state in phosphate glass.

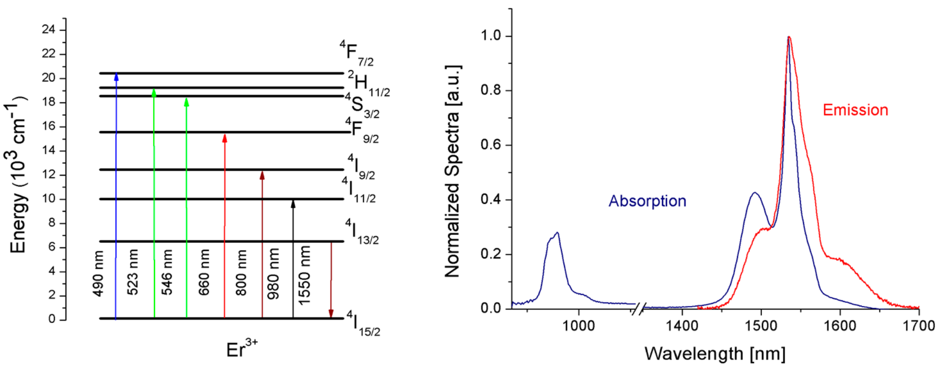


(**a**) (**b**)

Figure 2. (**a**) Typical energy level diagram of Nd^{3+} ions in phosphate glasses; (**b**) Typical absorption and emission spectra of Nd^{3+} ions in phosphate glasses (adapted from [27]).

The most common laser transition in Erbium is that from the $^4I_{13/2}$ manifold to the ground-state $^4I_{15/2}$ (see Figure 3a), centered at around 1.55 µm. This transition forms a three-levels system for which a high pump power is required to obtain a population inversion and thus reach the threshold. The most common pumping arrangement is based on the transition $^4I_{15/2} \rightarrow {}^4I_{11/2}$ with a wavelength of around 980 nm, although in-band pumping ($^4I_{15/2} \rightarrow {}^4I_{13/2}$, e.g., at 1.45 µm) is also possible [28,29]. This transition is widely exploited in Er^{3+}-doped fiber amplifiers (EDFAs).

In order to increase lasers and amplifiers efficiency, Erbium-doped fibers and amplifiers are often co-doped with Ytterbium, which exhibits larger absorption cross-section and broad absorption band (from ~850 to ~1070 nm). In this scheme Ytterbium, which acts as a sensitizer, strongly absorbs pump photons, and then resonantly transfers its energy to Erbium that acts as activator.



(**a**) (**b**)

Figure 3. (**a**) Typical energy level diagram of Er^{3+} ions in phosphate glasses; (**b**) Common absorption and emission spectra of Er^{3+} ions in phosphate glasses (adapted from [12]).

Phosphate glass is considered an excellent host for an Yb^{3+}-Er^{3+} co-doped system in virtue of its high emission cross-section, low accumulative energy transfer rates and low backward energy transfer [30]. In fact, in comparison to silicate glasses (~1100 cm^{-1}), the larger phonon energy in the phosphate host (~1200 cm^{-1}) increases the transition probability for $^4I_{11/2} \rightarrow {}^4I_{13/2}$ relaxation [31], which prevents the back energy transfer from Er^{3+} to Yb^{3+}. Furthermore, thanks to the large spectral overlap between the Yb^{3+} emission spectrum ($^2F_{5/2} \rightarrow {}^2F_{7/2}$) and Er^{3+} absorption spectrum ($^4I_{15/2} \rightarrow {}^4I_{11/2}$), the energy transfer efficiency from Yb^{3+} to Er^{3+} in phosphate glasses can reach 95% [11].

Typical absorption and emission cross-sections of Erbium ions in phosphate glasses, together with lifetime of the $^4I_{13/2}$ level, are reported in Table 1.

Table 1. Typical spectroscopic parameters of common rare-earth (RE) ions in highly doped phosphate glasses [8,11,14,25,32–35].

Parameter	Ytterbium	Neodymium	Erbium
Absorption cross-section (cm^2)	~1.6×10^{-20} $^2F_{7/2} \rightarrow {}^2F_{5/2}$	~2.0×10^{-20} $^4I_{9/2} \rightarrow {}^2H_{9/2} + {}^4F_{5/2}$	~1.5×10^{-21} $^4I_{15/2} \rightarrow {}^4I_{11/2}$ ~6.6×10^{-21} $^4I_{15/2} \rightarrow {}^4I_{13/2}$
Emission cross-section (cm^2)	1.4×10^{-20} $^2F_{5/2} \rightarrow {}^2F_{7/2}$	~2.4×10^{-20} $^4F_{3/2} \rightarrow {}^4I_{11/2}$	~7.0×10^{-21} $^4I_{13/2} \rightarrow {}^4I_{15/2}$
Doping level (ions/cm^3)	1.4×10^{21}	~2.7×10^{20}	4.0×10^{20}
Excited state lifetime (ms)	1.2 $^2F_{5/2} \rightarrow {}^2F_{7/2}$	0.3 $^4F_{3/2} \rightarrow {}^4I_{11/2}$	8.0 $^4I_{13/2} \rightarrow {}^4I_{15/2}$

3. CW Phosphate Fiber Lasers and Amplifiers

RE-doped glass fibers are excellent gain media for obtaining high power lasers with enhanced brightness. The large surface-to-volume ratio of active fibers favors heat dissipation to the surrounding, allowing active fibers to operate at very high powers. The heat dissipation further increases by using efficient RE dopants, such as Ytterbium, which allows operation with pump wavelengths close to the signal wavelength [23]. As a consequence, beam distortion is negligible and the beam quality is mainly affected by the fiber geometry.

In addition, the waveguide structure confines the pump light over the entire fiber length, enabling noticeably large single-pass gains to be achieved due to the long interaction path of the light with the active medium. This leads to a very efficient operation of the fiber lasers, showing very high gain and low pump threshold values.

Nowadays, high power fiber lasers and amplifiers are typically implemented using RE-doped double-cladding (DC) optical fibers, a concept which was introduced in 1988 by Snitzer et al. [36] and has allowed in last decades a significant enhancement in scaling fiber lasers to higher power levels. DC fibers consist in a RE-doped core surrounded by a much larger inner cladding, itself surrounded by an outer cladding (see Figure 4). The pump light is launched and confined into the inner cladding and spatially overlaps the core. The pump power is then absorbed over the entire length of the fiber through multiple interaction with the core, thus exploiting the fiber geometry. The benefit of this design resides in the possibility to use multi-mode high power laser diodes with relatively poor beam quality and to obtain a single-mode fiber radiation with outstanding beam quality.

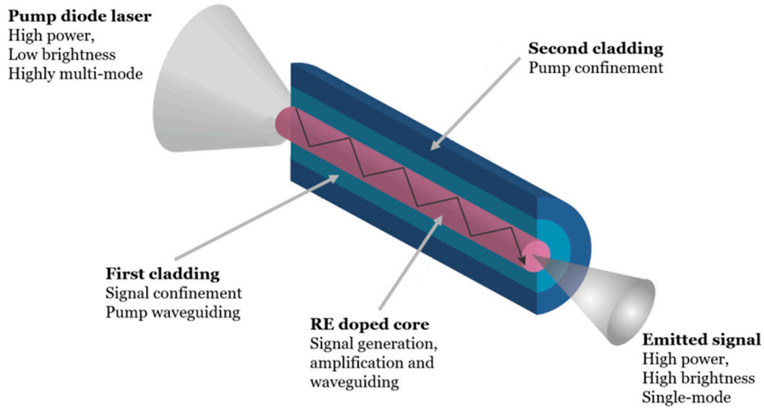


Figure 4. Schematic of cladding-pumped double-cladding fiber laser.

Thanks to DC fiber geometry, power scaling of silica-based fiber lasers has experienced noticeable progress in the last two decades, reaching 100 kW of output power in the 1 µm wavelength region from a multi-mode Yb^{3+}-doped fiber [37] and 10 kW from a single-mode fiber laser [38]. In eye-safe region, at 1.5 µm, 297 W from an Yb^{3+}-Er^{3+}-doped fiber laser was demonstrated [39], while at 2 µm 1 kW of emitted power was reported from a Tm^{3+}-doped fiber laser [40].

Power scaling of silica fiber lasers is ultimately limited by two main mechanisms: nonlinear effects (especially SBS) induced by the long path lengths of the tightly confined light in the fiber core and photodarkening. A different approach devoted to the fiber laser power scaling, which can overcome the above limitations, is indeed to employ phosphate glass instead of silica as fiber material. The higher solubility of RE ions in phosphate glass hosts allows the increase of RE ions concentration and thus to generate the necessary amplification over a much shorter fiber length as compared to silica fibers. The onset of the non-linear phenomena described above is then considerably limited. In addition, the higher photodarkening threshold in phosphate glasses eliminates the risk of power degradation over time in high power applications [15].

Another important advantage of phosphate glasses in power scaling of fiber lasers is related to the possibility to easily adjust the refractive indices [41]. Thus, DC optical fibers with a reduced core numerical aperture (NA) and hence a much larger single-mode core are feasible. Furthermore, thanks to a large glass forming region, it is possible to manufacture glasses with considerably large refractive index differences and thus realize a high NA pump waveguide with a glass based outer cladding instead of a low-index polymer coating, as widely used in DC silica fibers. These all-glass DC optical fibers offer a high degree of immunity to heat loading [8,42].

A typical configuration used to realize high power fiber lasers is the master oscillator power amplifier (MOPA) system: the high power laser is obtained by splitting it into a low-power signal generator (master oscillator) and an optical power amplifier that boosts the output power. Thus, the high-spectral qualities of the signal are preserved while simplifying the manufacturing constraints of the seed-laser. For this kind of device, an all-fiber structure without the use of free-space components is a better solution in order to simplify configurations while improving compactness and reliability.

Phosphate glasses main features, such as extremely high doping level, low SBS gain coefficient and absence of photodarkening, make them an ideal host to develop a MOPA system.

3.1. Yb-Doped Phosphate Fiber Lasers and Amplifiers

The first CW cladding-pumped Yb-doped single-mode phosphate fiber laser emitting in the 1 µm region was demonstrated in 2006 by Lee et al. [8] using a Large Mode Area (LMA) fiber with diameters of 10/240/355 µm for the core, inner cladding and outer cladding, respectively. In view of breaking the symmetry of the fiber design and thus increasing the pump absorption, the core of the fiber was offset from the center and an air hole parallel to the core was added to the inner cladding. With a length of 84.6 cm of this fiber, doped with 12 wt % of Yb_2O_3 and pumped with 80 W at 940 nm, an output power of nearly 20 W at 1.07 μm, with a slope efficiency of 25.8% against launched pump power, was demonstrated. With this very same fiber configuration, few years later, power scaling to 57 W was demonstrated with a slope efficiency of 50.6% by varying the pump wavelength to 977 nm, where Yb^{3+} absorption is much higher and quantum defect is lower [43]. In both reported Yb-doped fiber lasers, the slope efficiency was reduced by the quite high loss of the fiber, around 3 dB/m, which was measured to be mainly due to impurity absorption (77%) and scattering.

Recently, an Ytterbium-doped phosphate glass single-mode fiber laser with noticeably high slope efficiency of 66.6% in relation to the launched pump power was reported. The fiber consisted in a double-cladding fiber with a 19 μm diameter step-index core and a pump waveguide with a high numerical aperture due to the external air-cladding. An output power of 11.6 W was obtained by using 4 cm-long fiber sample pumped with a multi-mode laser diode. This is the best result, in terms of slope efficiency, ever reported for a phosphate single-mode fiber laser pumped with a multi-mode laser diode [44].

Concerning Yb^{3+}-doped phosphate fiber amplifiers, the first watt level Yb^{3+}-doped phosphate fiber MOPA was reported in 2009 [43] with an output power of 16.3 W corresponding to a gain of 27 dB with respect to the launched signal power (~0.36 dB/cm). The gain medium was a 74.5 cm-long single-mode double-cladding phosphate fiber doped with 12 wt % of Yb_2O_3.

3.2. Nd-Doped Phosphate Fiber Lasers and Amplifiers

As the first fiber laser was realized using a Nd^{3+}-doped fiber, in that case made of silicate glass [1], the first phosphate fiber laser reported in literature was also manufactured with a Nd^{3+}-doped phosphate fiber [45].

A length of 10 mm of single-mode and single-cladding optical fiber, manufactured by rod-in-tube technique and highly doped with 3 wt % of Nd_2O_3 (3.1×10^{20} Nd^{3+} ions/cm^3), was used to demonstrate laser emission at 1.054 μm, when core-pumped by an 808 nm laser diode. A low threshold of 1 mW and an efficiency of ~50% were measured. Lasing was also demonstrated at 1.366 μm, although with lower performance both in threshold and slope efficiencies, as expected for this less efficient neodymium emission.

In 1996 Griebner et al. [46] reported a core-pumped Nd-doped multi-mode phosphate fiber, although with a quite low output power of 130 mW at 1053 nm. An efficiency of 31% with respect to the launched pump power was achieved at 807 nm.

Concerning power scaling of CW Nd^{3+}-doped phosphate fiber lasers, in 2011 Zhang et al. [47] reported an output power of 2.87 W at 1053 nm from a length of 26 cm of heavily Nd^{3+}-doped (3.5×10^{20} Nd^{3+}/cm^3) DC fiber, with diameters of 14/285/360 μm for the core, inner cladding and outer cladding, respectively. Average slope efficiencies of 26.2% and 44.7% with respect to the launched and absorbed pump powers at 795 nm were obtained. The reported loss of 1.5 dB/m at 1053 nm is the lowest ever measured for a Nd^{3+}-doped phosphate fiber.

More recently [48], single-mode operation was reported in a cladding-pumped Nd^{3+}-doped fiber laser having an output power of 1.42 W and an efficiency of 34% with respect to the absorbed pump power at 808 nm. A 21 cm-long DC fiber was used, with a small core diameter of 5.3 μm to allow single-mode operation at 1.053 μm. In view of improving the coupling efficiency between the pump diode and the active fiber, a novel design for local cooling by fluid sealing of the coupling point was exploited.

In 2015 a Nd^{3+}-doped phosphate fiber laser was demonstrated by using a DC fiber with an hexagonal inner cladding made by a stack-and-draw technique, that is commonly used for the realization of microstructured optical fibers [42]. Single-mode operation was achieved with a core diameter of 35 μm, thanks to the low NA of the fiber core. A maximum output power of 2.87 W and a slope efficiency of 19% were achieved. The poor laser performance was due to the high propagation loss of the fiber, as high as 3.8 dB/m, and to the mismatch between the pump wavelength (793 nm) and the Nd-doped glass peak absorption (802 nm).

An alternative solution that was recently proposed for the power scaling of Nd^{3+}-doped fiber lasers and amplifiers relies in the use of short-length core/cladding canes as active elements. A 60 mm length of cane, with a core diameter of 270 μm and a cladding diameter of 800 μm, was able to emit 2 W of output power at 1054 nm with slope efficiencies of 30% and 40% with respect to the launched and absorbed pump powers, respectively. Caird's analysis revealed that a slope efficiency of 55% over the absorbed power could be achieved in optimal conditions, matching the highest results obtained so far [27]. Although the latter configuration did not operate in single-mode regime, similar cane configuration can be employed as a booster amplifier in a MOPA configuration to reach high power while preserving high beam quality [49].

Significant results have been obtained in last years from photonic crystal fibers (PCFs). In 2012 the first non-silica all-solid Nd^{3+}-doped PCF was demonstrated, with an hexagonal shaped inner cladding, to achieve high absorption coefficient of pump power [50]. An output power of 7.92 W and a slope efficiency of 38.1% were obtained but with unsatisfactory beam quality. In 2014 a single-mode multi-watt phosphate Nd^{3+}-doped all-solid PCF with core diameters of 30, 35 and 40 μm was reported [51]. An output power of 5.4 W and a slope efficiency of 31% were measured with a beam quality that is not degraded even at the highest power.

Higher emitted power was registered by using a complex photonic crystal fiber (PCF) containing seven different single-mode cores. This allowed achieving 15.5 W of emitted power over a fiber length of 25 cm, featuring a slope efficiency of 57% over the absorbed power [52].

3.3. Er and Yb/Er Co-Doped Phosphate Fiber Lasers and Amplifiers

Erbium-Ytterbium co-doped system received noticeable interest in the last two decades due to its use for optical communications and eye-safe laser applications.

In 2004 Qiu et al. reported 9.3 W CW 1535 nm multi-mode output from a 7.0 cm short-length single-cladding Er-Yb phosphate fiber [7]. The fiber featured a D-shaped cladding and an off-centered core 130 and 20 μm in diameter, respectively. A slope efficiency of 29% and a power per unit length (p.u.l.) as high as 1.33 W/cm were achieved. From another 7.1 cm of Er-Yb co-doped fiber laser, 4.0 W single transverse mode output was generated with lower power per unit fiber length (0.56 W/cm), due to the less efficient pump absorption exhibited by the smaller core.

In the early 2000's the first Er^{3+}-doped fiber amplifiers based on heavily Erbium-doped phosphate fibers were demonstrated [53,54]. They were core-pumped by single-mode laser diodes emitting at 980 nm. For example, Hwang et al. [54] reported a high concentration (3.5 wt %) Er^{3+}-doped phosphate fiber amplifier. An internal gain of 23 dB and a gain p.u.l. of 3 dB/cm were achieved in a 71 mm-long Er^{3+}-doped phosphate fiber core-pumped by a laser diode at around 980 nm. The fiber, manufactured by the rod-in-tube technique, displayed a single-mode behavior at 1.55 μm and showed a quite high loss of 0.28 dB/cm at 1.3 μm. The gain obtained was lower than that predicted by theoretical calculations, due to cooperative up-conversion phenomena between the Er^{3+} ions and the small absorption cross-section of Erbium at the pumping band of 980 nm. Thus, soon after the same group proposed the realization of the amplifier using a phosphate fiber doped with a lower amount of Er^{3+} (3 wt %) [55], to prevent Erbium concentration quenching, and with Yb^{3+} sensitization (2 wt %), to increase the pump absorption. An internal gain of 18 dB and a gain p.u.l. of 5 dB/cm were obtained for small-signal input at 1535 nm, using 3.6 cm-long co-doped fiber pumped at 980 nm in a co-propagating configuration.

In light of limiting the amplifier cost and power scale the output power, single-cladding phosphate fibers were replaced by DC fibers pumped by broad area high power multi-mode laser diodes instead of single-mode pump sources. Thanks to these improvements, in 2003 an Er^{3+}-doped phosphate fiber amplifier showing net gain values of 41, 27 and 21 dB at 1535 nm, 1550 nm and over the C-band, respectively, was demonstrated with only 8 cm-long fiber. The fiber was an all-glass single-mode DC fiber with a loss of 0.09 dB/cm at 1.3 μm [6], which was significantly lower compared to the previously fabricated fibers.

In 2008 5 cm-long single-mode heavily Yb^{3+}/Er^{3+} co-doped fiber was used to demonstrate optical amplification of signal in the range 1525–1565 nm [56]. The fiber, doped with 1 mol% of Er^{3+} and 2 mol% of Yb^{3+}, was dual-pumped by two 976 nm fiber pigtailed laser diodes. A peak net gain of 16.5 dB at 1534 nm was achieved, that corresponds to a gain p.u.l. of 3.3 dB/cm (internal gain p.u.l. of 9.1 dB/cm). The fiber loss was evaluated to be 0.06 dB/cm at 1.3 μm.

In 2015 novel high concentration Yb/Er co-doped phosphate glasses (1.08 mol% of Er_2O_3 and 1.08 mol% of Yb_2O_3) were employed to manufacture DC fibers for optical amplification. Core-pumped and cladding-pumped amplifiers were demonstrated, reaching gains p.u.l. of 4.0 and 2.3 dB/cm, respectively [57].

The main results obtained with highly RE-doped CW phosphate fiber lasers are summarized in Table 2.

Table 2. Main results obtained with continuous wave (CW) fiber lasers based on highly RE-doped phosphate glasses.

Fiber Type [Reference]	RE Doping Concentration	λ_{pump} (nm)	λ_{signal} (nm)	Output Power (W)	Slope Efficiency (%)	Gain Length (cm)
Yb^{3+}-doped multi-mode [8]	12 wt %	940	1064	20	34.4	84.6
Yb^{3+}-doped single-mode [43]	12 wt %	977	1064	57	56.7	71.6
Nd^{3+}-doped multi-mode [47]	3.5×10^{20} Nd^{3+}/cm^3	795	1053	2.9	44.7	26
Nd^{3+}-doped single-mode [48]	3.5×10^{20} Nd^{3+}/cm^3	808	1053	1.4	34.1	21
Nd^{3+}-doped single-mode PCF [52]	3 wt %	793	1053	15.5	57	25
Yb^{3+}/Er^{3+} co-doped multi-mode [7]	8.6×10^{20} Yb^{3+}/cm^3 1.1×10^{20} Er^{3+}/cm^3	976	1535	9.3	39	7.0
Yb^{3+}/Er^{3+} co-doped single-mode [7]	8.6×10^{20} Yb^{3+}/cm^3 1.1×10^{20} Er^{3+}/cm^3	976	1535	4.0	39	7.1

4. CW Single-Frequency Phosphate Fiber Lasers and Amplifiers

Fiber lasers considered in the previous Sections display relatively broad linewidth, usually in the 1–10 nm range. However, several applications such as interferometric gravitational-wave detection [58], coherent Light Detection and Ranging (LIDAR) [59], laser nonlinear frequency conversion [60], coherent beam combining [61] and laser spectroscopy [62] require laser emissions with narrower linewidth. This feature can be provided by single-frequency fiber lasers, which are lasers that operate with only a single-longitudinal mode and thus can emit quasi-monochromatic radiation with a very narrow linewidth and low noise.

Different configurations have been exploited to demonstrate single-longitudinal mode operation. One typical design is the distributed feedback (DFB) fiber laser, in which a FBG is directly written in the core of the active fiber and is responsible for the generation of a phase change in the middle of the grating area.

Another common configuration is the distributed Bragg reflector (DBR) fiber laser, in which the laser resonator is formed by the RE-doped fiber placed between two FBGs. This configuration is generally preferred for the fabrication of single-frequency fiber lasers thanks to its compactness and robustness [63].

When an output power higher than 1 W is demanded, a MOPA configuration is used, with a single-frequency seed laser followed by a series of amplifier stages to achieve the power amplification. This configuration is able to power scale the output power while preserving the spectral characteristics of the seed laser.

The use of highly doped phosphate glass fibers for the manufacturing of single-frequency fiber lasers is particularly advantageous since allows the realization of a short cavity that creates large longitudinal mode spacing, helping to maintain lasing on a single-longitudinal mode and thus a single-frequency behavior.

Power scaling of single-frequency fiber lasers is ultimately reduced by SBS and is much more arduous than that of a multi-longitudinal mode CW fiber laser. Several different methods have been implemented to limit the SBS in silica-based fiber lasers [64–66]. The use of phosphate glass-based optical fiber represents an alternative option to overcome this limitation.

CW single-frequency phosphate-based fiber lasers operating at 1 and 1.5 μm have reached a relatively high maturity level and are commercially available [67].

4.1. Yb-Doped Single-Frequency Phosphate Fiber Lasers

In 2004 Kaneda et al. [68] reported for the first time a DBR laser based on 1.5 cm-long Yb^{3+}-doped phosphate fiber that was fusion spliced with two FBGs to form the resonator. 200 mW of single-frequency output power at 1064.2 nm was achieved (gain p.u.l. equal to 2 dB/cm), with a linewidth of approximately 3 kHz.

In 2011 Xu et al. [69] demonstrated over 400 mW of emission at 1063.90 nm from a DBR Yb^{3+}-doped phosphate fiber laser based on 0.8 cm-long active fiber. The fiber was heavily doped (15.2 wt %) in order to obtain a very short resonator cavity and thus ensure laser operation on single-longitudinal mode. A slope efficiency of about 73% versus launched pump power was obtained, with a net gain coefficient p.u.l. of 5.7 dB/cm. This work reports the highest slope efficiency and output power obtained so far in this kind of single-frequency fiber lasers.

Besides the typical lasing wavelength at 1064 nm, Yb^{3+}-doped phosphate fibers have been successfully exploited to obtain single-frequency operation at more exotic wavelengths [20,70,71], thanks to the broad Yb^{3+} emission from 970 to 1200 nm.

In particular, during last years, interest for high power single-frequency lasers below 1 μm has increased, since they are excellent pump sources for second and fourth harmonic generation in the blue and deep UV, which have found several scientific and industrial applications [72]. Yb^{3+}-doped phosphate fibers have been successfully employed to achieve single-frequency laser emitting at 976 nm, through the transition from the lowest level of the excited state $^2F_{5/2}$ manifold to the lowest level of the ground state $^2F_{7/2}$ manifold (quasi-three-level operation) (see Figure 1a). Yb^{3+}-doped phosphate fibers, compared to Yb^{3+}-doped silica fibers, exhibit a larger difference between the absorption and emission cross-sections at shorter wavelengths, making them more suitable for short wavelength laser emission [73].

The first demonstration of an Yb^{3+}-doped phosphate fiber laser emitting at 976 nm was reported by Bufetov et al. [32] in 2006 using 2 cm-long highly doped fiber (1×10^{21} Yb^{3+} ions/cm^3). 250 mW of output power was achieved, with an efficiency versus launched pump power of about 40%.

In 2012 the first 976 nm single-frequency all-fiber DBR fiber laser was developed with a 2 cm-long highly (6 wt %) Yb^{3+}-doped phosphate fiber [20]. 100 mW of linearly polarized output power was generated with a linewidth of less than 3 kHz. By using this fiber laser as a seeder in a MOPA configuration, a single-frequency Yb^{3+}-doped phosphate fiber amplifier was realized. A linearly polarized output power of 350 mW was obtained by core-pumping a 4 cm-long polarization maintaining (PM) phosphate fiber [74]. The birefringence of the PM fiber was made possible by inserting two high stress elements around the fiber core. A small signal net gain of 25 dB, corresponding to a unit gain over 6 dB/cm, was achieved.

With the aim to investigate the power scaling of a single-frequency laser operating at 976 nm, Wu et al. fabricated an Yb^{3+}-doped phosphate fiber amplifier based on 7 cm-long Yb^{3+}-doped DC phosphate fiber cladding-pumped by high power multi-mode laser diodes. 3.41 W single-frequency output power was obtained, with a relatively low slope efficiency of ~7% due to the reduced spatial overlap of the pump and the doped fiber core in the cladding-pumped arrangement [73].

Single-frequency emission from an Yb^{3+}-doped phosphate fiber was also demonstrated at 1014 nm, which is an interesting wavelength for optical lattice clock applications [75]. A compact fiber laser of 5 mm was reported, with a CW single transverse and longitudinal mode characterized by an output power over 164 mW, low noise and a linewidth lower than 7 kHz. At the wavelength of 1014 nm Yang et al. [76] reported also a MOPA laser with over 1 W of single-frequency emission, obtained by amplifying a seed laser with a core-pumped one stage Yb^{3+}-doped phosphate fiber amplifier of 4 cm of length.

On the other hand, with Yb^{3+}-doped phosphate fibers, emission at longer wavelengths was also investigated. Low noise single-frequency single polarization fiber laser emitting at 1083 nm was reported from a 1.8 cm-long heavily (18.3 wt %) Yb^{3+}-doped phosphate fiber. 100 mW of output power was achieved, with a slope efficiency of almost 30% and a laser linewidth lower than 2 kHz [70].

4.2. Er and Yb/Er Co-Doped Single-Frequency Phosphate Fiber Lasers

The first single-frequency phosphate fiber laser emitting at 1.5 µm was reported in 2003 [77], with an output power of 100 mW and a very narrow linewidth of less than 2 kHz. It was a DBR fiber laser based on an heavily Yb^{3+}/Er^{3+} co-doped fiber (3 wt % of Yb^{3+} and 2 wt % of Er^{3+}) that displays very high optical gain per unit length of up to 5 dB/cm. The laser cavity was established by using two spectrally narrow passive FBGs that were fusion spliced to a 2 cm-long piece of active fiber.

In 2013 [78] a monolithic all-phosphate glass fiber laser was reported, with a laser cavity obtained by inscribing a FBG directly into an heavily Yb^{3+}/Er^{3+} co-doped phosphate fiber (8 wt % of Yb_2O_3 and 1 wt % of Er_2O_3) by using a femtosecond laser. Avoiding hybrid splices between phosphate and silica based fibers allowed for improving the laser stability and reducing the cavity loss. An output power of 550 mW was demonstrated with a slope efficiency of 12%.

Power scaling of a single-frequency fiber laser emitting at 1.5 µm was investigated in 2005 [79] by using a DC heavily Yb^{3+}/Er^{3+} co-doped phosphate fiber, cladding-pumped by multi-mode laser diodes at 976 nm. 1.6 W of single-longitudinal mode output power was reported from a 5.5 cm length of fiber, although the slope efficiency was limited at 5%.

The main results obtained with highly RE-doped CW single-frequency phosphate fiber lasers are summarized in Table 3.

Table 3. Main results obtained with CW single-frequency phosphate fiber lasers based on highly RE-doped phosphate glasses.

Fiber Type [Reference]	RE Doping Concentration	λ_{pump} (nm)	λ_{signal} (nm)	Output Power (mW)	Slope Efficiency (%)	Gain Length (cm)	Linewidth (kHz)
Yb^{3+}-doped [69]	15.2 wt %	976	1064	400	72.7	0.8	<7
Yb^{3+}-doped [20]	6 wt %	915	976	100	25	2	<3
Yb^{3+}-doped [75]	15.2 wt %	976	1014	164	21.9	0.5	<7
Yb^{3+}-doped [70]	18.3 wt %	976	1083	100	29.6	1.8	<2
Yb^{3+}/Er^{3+} co-doped [78]	8 wt % Yb_2O_3 1 wt % E_2O_3	975	1538	550	12	7	<60
Yb^{3+}/Er^{3+} co-doped [79]	8.6×10^{20} Yb^{3+}/cm^3 1.1×10^{20} Er^{3+}/cm^3	976	1550	1600	5	-	5.5

5. Pulsed Phosphate Fiber Lasers and Amplifiers

Pulsed fiber laser operation is generally obtained through modulation of the laser cavity using several Q-switching and mode-locking techniques. Owing to the very large spectral bandwidths achievable from RE ions in glass hosts, pulsed fiber lasers can operate in nanosecond, picosecond and even femtosecond regimes using chirped pulsed amplification techniques.

Q-switching is a technique mostly applied for the generation of micro and nanosecond pulses of high energy and peak power, while the mode-locking technique enables ultrafast laser pulses in the picosecond and femtosecond ranges.

In 1993 a Q-switched fiber laser based on a multicomponent Nd-doped phosphate glass was reported with 2.2 μJ, 2 ns duration pulses at up to 2 kHz repetition rate with only 22 mW of absorbed pump power at 812 nm from a laser diode [80]. Tunability over a 40 nm tuning range around 1060 nm was demonstrated thanks to the broad emission line of Neodymium in the phosphate glass.

More recently, in 2004 [81], a single-frequency all-fiber Q-switched laser at 1550 nm was reported with 25 W of peak power in 12 ns, 0.3 μJ pulses at a repetition rate of 80 kHz with 370 mW of pump power, without using an amplifier. The laser consisted of a 2 cm-long Yb/Er co-doped phosphate glass fiber fusion spliced between two FBGs inscribed in silica fibers. The fiber was actively Q-switched by fast stress-induced birefringence modulation, a technique that allows an all-fiber configuration, thus avoiding the use of bulk components in the cavity responsible for the growth of loss, size and complexity.

By using 2 cm-long highly (6 wt %) Yb^{3+}-doped phosphate fiber the first compact, single-frequency all-fiber Q-switched laser at 1 μm was reported in 2007 [82]. The fiber was actively Q-switched by fast stress-induced birefringence modulation [81], a technique previously demonstrated at 1.5 μm. A repetition rate up to 700 KHz was reported, with a maximum average power of 31 mW. A maximum average pulse energy of 0.4 μJ was obtained.

Concerning fiber lasers operating in the picosecond regime, mode-locking techniques are generally used. Passive mode-locking is usually preferred to avoid costly modulators in the laser cavity as those commonly employed in active mode-locking solutions. However, passive mode-locking of fiber lasers allows achieving low repetition rates (tens of MHz), as a results of the long cavity length. Thus, an attractive approach to push the pulse repetition rate into the GHz regime is the use of short Fabry–Perot lasers with high gain RE-doped phosphate fiber and a small saturable absorber that could be integrated with fiber-end.

In 2007 [83] a mode-locked short cavity 10 GHz phosphate fiber laser emitting at 1535 nm was reported using a 1 cm-long heavily Yb/Er co-doped phosphate fiber and a saturable absorber constituted by single-wall carbon nanotubes. Stable pulse trains with an output power as high as 30 mW and a repetition rate as high as 10 GHz were achieved.

In 2012 another solution for the integrated saturable absorber was proposed: a graphene film deposited on one tip of the active fiber [84]. The obtained laser operated in a stable mode-locked regime with fundamental repetition rate of 7 GHz but with an output power of only 1.2 mW.

In 2014 [85] a repetition rate of 12 GHz was demonstrated from a compact and stable all-fiber fundamentally mode-locked fiber laser based on an Yb/Er co-doped phosphate fiber and a semiconductor saturable absorbing mirror (SESAM). A short length of 0.8 cm of high gain (6 dB/cm at 1535 nm) PM fiber was used to form the laser cavity.

Several applications like coherent LIDAR, range finding or active remote sensing require, for high precision measurements, not only high peak power laser pulses in the nanosecond time regime but also a narrow linewidth. However, neither directly Q-switching a single-frequency fiber laser nor modulating a CW single-frequency fiber laser with an external modulator can deliver sufficient energy/power for practical applications [86]. A MOPA system is thus required to boost the power of a single-frequency low power seed laser.

Power scaling of narrow linewidth fiber laser and amplifiers using single-mode silica fibers is challenging due to the onset of nonlinearities in the fiber, primarily SBS, that build up strongly in case of pulses >1 ns [87].

Therefore, increasing SBS threshold for fiber amplifiers is crucial and several solutions have been proposed to fulfill this scope [88–90]. One possible approach is to focus on the optical fiber itself, with a reduction of the active fiber length and the increase of the core size, conditions that can be achieved more easily by using active fibers made of phosphate glass.

In 2009 Shi et al. [21] proposed the use of a single-mode PM large core highly Er/Yb co-doped phosphate fiber for engineering the final power amplifier stage of a monolithic all-fiber pulsed MOPA laser operating in the C band. Single-mode operation was achieved in such a large core (15 µm) thanks to the accurate control of the refractive indices of the core and the cladding obtainable in phosphate glasses (core NA = 0.053). The fiber length was 12 cm only, thanks to the high doping level used in the phosphate glass core (15% Yb and 3% Er). Pulse energy of 54 µJ and peak power of 332 W without SBS effects for 153 ns pulses at 1538 nm were demonstrated.

In 2010 the same research group, by using 15 cm of a new active fiber with larger single-mode core (25 µm, core NA = 0.0395) for the power amplifier section, was able to demonstrate a peak power of 1.2 kW for 105 ns pulses at 1530 nm, equivalent to a pulse energy of 0.126 mJ, with transform-limited linewidth and diffraction limited beam quality [91].

In 2012 a pulse energy of 0.38 mJ and a peak power of 128 kW were demonstrated using a multiple stage, short, large core Yb/Er co-doped phosphate fiber, in which a short pulse width of few nanoseconds was used to further enhance the SBS threshold [92]. In fact, SBS is an acousto-optic non-linear effect due to the interaction between photons and phonons in the fiber, therefore employing pulses with duration shorter then phonon lifetime, in applications in which this is allowed, is an additional method to increase the SBS threshold.

Further increase in power amplifier performances was reported in 2014 by NP Photonics [93]. An all-fiber pulsed MOPA system with 1 W average power, 200 µJ energy, >10 kW peak power and 20 ns of duration at 1550 nm was demonstrated using a seed phosphate single-frequency fiber laser, amplified by several Er-doped phosphate fibers, with a final power amplifier stage consisting in 11 cm of highly Yb/Er co-doped PM phosphate gain fiber.

The same group reported also a pulsed all-fiber MOPA system in the nanosecond regime emitting in the 1064 nm band. The architecture was similar to the one at 1550 nm, but in this case Yb-doped phosphate fibers were used. In particular, the power amplifier consisted in 25 cm of highly Yb^{3+}-doped PM phosphate fiber.

Both MOPA systems were packaged and shipped as an Original Equipment Manufacturer (OEM) product, just showing the maturity level achieved by phosphate fiber laser technology.

The main results obtained in the 1.5 µm region with high energy and peak power pulsed single-frequency all-fiber amplifiers are summarized in Table 4.

Table 4. Main results obtained in the 1.5 µm region with high energy, high peak power pulsed single-frequency all-fiber amplifiers based on highly Yb^{3+}/Er^{3+} co-doped phosphate glasses.

Reference	λ_{signal} (nm)	Pulse Energy (mJ)	Pulse Duration (ns)	Average Power (W)	Beam Quality (M^2)	Peak Power (kW)
[21]	1538	0.054	153	1.08	1.2	0.332
[91]	1530	0.126	100	-	1.2–1.4	1.2
[92]	1550	0.384	3	-	-	128
[93]	1550	0.200	20	1	-	>10

6. Conclusions

In the last decades, remarkable achievements in the field of phosphate based fiber lasers and amplifiers have been obtained thanks to the progress in the diode technology, advanced fiber fabrication technology and novel pumping techniques. In this review, we reported on current state-of-the-art CW, pulsed, and single-frequency fiber lasers and amplifiers based on phosphate glass optical fibers. Phosphate glasses main properties were also briefly discussed to give to the readers a general overview of this outstanding gain medium.

The reported results show that phosphate glass fiber lasers and amplifiers can be highly efficient in a short fiber laser arrangement and can thus represent a promising alternative for other glass lasers at medium output power performance. Thus, in future, phosphate based fiber lasers and amplifiers are expected to be extensively employed in different applications fields.

Author Contributions: This article has been written by Nadia Giovanna Boetti and revised by Diego Pugliese, Edoardo Ceci-Ginistrelli, Joris Lousteau, Davide Janner and Daniel Milanese.

Conflicts of Interest: The authors declare no conflict of interest.

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