# Tellurite photonic crystal fiber with $Er^{3+}$-$Tm^{3+}$ for broadband optical amplifier in 1550nm

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## ABSTRACT

$Er^{3+}$-$Tm^{3+}$ co-doped tellurite photonic crystal fiber was fabricated via a stack-and-draw procedure and without using extrusion in any stage. The final fiber presents a 187 nm bandwidth of amplified spontaneous emission (ASE) intensity around 1550nm when pumped with 790nm. In this manuscript a soft-glass tube fabrication technique, using the centrifugation method, is also shown.

**Keywords:** Tellurite Photonic Crystal Fiber, optical amplifier, Erbium-Thulium fiber, centrifugation.

## 1. INTRODUCTION

Since the first Photonic Crystal Fiber (PCF) was demonstrated as a new type of optical waveguide in 1996[1] there is a great interest for using PFC's in telecommunications, including rare earth-doped PCF's. For this particular application, amplification, gain and bandwidth are some of the most important parameters. Bandwidths of 45 nm in the 1550 nm band (1520-1565 nm) for $Er^{3+}$- doped silica fibers and 30nm in the 1470 nm band (1450-1480 nm) for $Tm^{3+}$- silica doped fiber are usually obtained. An ASE spectra broader than 90nm, ranging from 1460 to 1550 nm, was already demonstrated with a 20 m long $Er^{3+}$ and $Tm^{3+}$ co-doped silica fiber pumped at 980nm[2]. n the other hand, tellurite glasses are better hosts than silica for rare earth doping due to its broader gain bandwidth, higher solubility and low cross relaxation. Indeed, a 187 nm emission bandwidth with a 15cm long $Er^{3+}$ and $Tm^{3+}$ co-doped tellurite core/clad standard fiber, pumped at 790 nm, was recently reported[3]. Microstructured fibers can, therefore, improve the design flexibility and performance of optical amplifiers.
To fabricate a PCF one first need to prepare a mm or cm-thick preform with the desired structure which is then drawn down, on a fiber-drawing tower, greatly extending its length while reducing its cross-section. The silica-based PCF's preforms are usually made by stacking capillaries and rods by hand[4,5]. This technique, however, is in general, not the best one for soft glass fibers due to the difficult of preparing high quality tubes and capillaries. The standard procedure in this case is the fabrication of the preform by extrusion, where the softened glass is forced against a dye with the desired geometry. Tellurite[6],SF6[7] and SF57[8] glasses extruded PCF's were produced in the last years. Contamination problems, the difficulty to prepare fibers with different glasses and/or complex geometries and the importance of properly designing the dye are just some of the drawbacks of this technique.
This letter reports the successful fabrication of $Er^{3+}$-$Tm^{3+}$ co-doped tellurite PCF by the stack-and-draw technique and the demonstration of a 187 nm amplified spontaneous emission bandwidth around 1550nm of a 15 cm long fiber pumped at 790nm.

## 2. FIBER DESIGN AND FABRICATION

The Tellurite-PCF structure consists of a stacking of four Erbium (5000 ppm wt%) and Thulium (5000 ppm wt%) co-doped tellurite capillaries that surrounds a central rod of the same composition. The whole set lays inside an un-doped tellurite glass tube with 4.5mm internal diameter.
The rod was prepared by vacuum sucking the melted $71TeO_2$-$22.5WO_3$-$5Na_2O$-$1.5Nb_2O_5$ (%mol) tellurite glass inside a 10 mm internal diameter silica tube, where it quickly solidifies as a solid rod. This 10 mm external diameter tellurite rod with 12 cm length can then be drawn down until 0.7 mm diameter forming what will be the central core in our preform.

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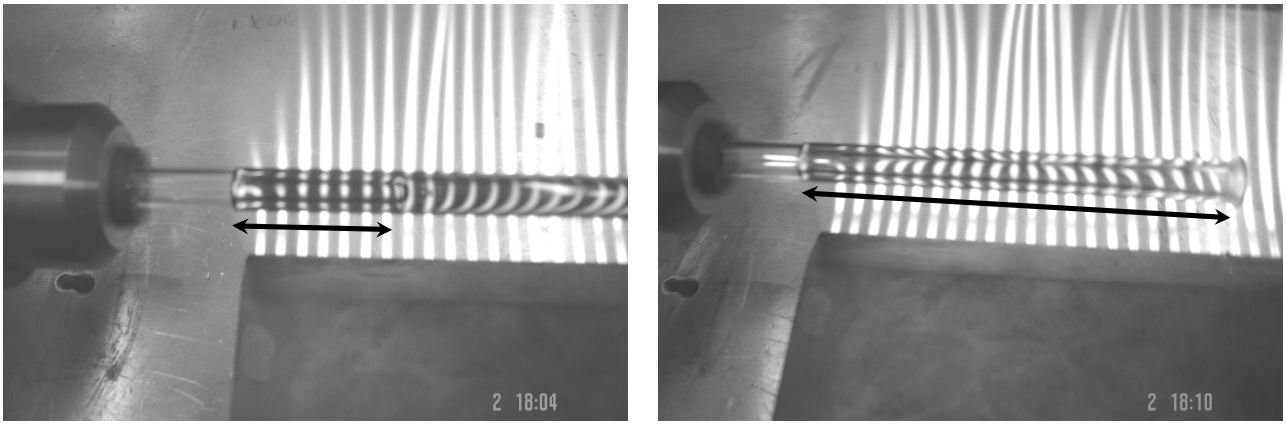
To prepare the tubes the process starts as the previous one, sucking the melted glass inside a silica tube. The second stage consists in exposing the silica plus tellurite tube to a planar flame with uniform distribution. The tube rotates at high speed in order to homogenize the heating distribution and helps the tube formation. In figure 1A it is observed the initial part of the centrifugation step where the chuck rotates at 750 rpm and the inner tube (tellurite) starts to form, what can be seen in the left hand side of the picture (arrow region). Figure 1B shows the final stage (1800 rpm) when the tube is fully prepared.



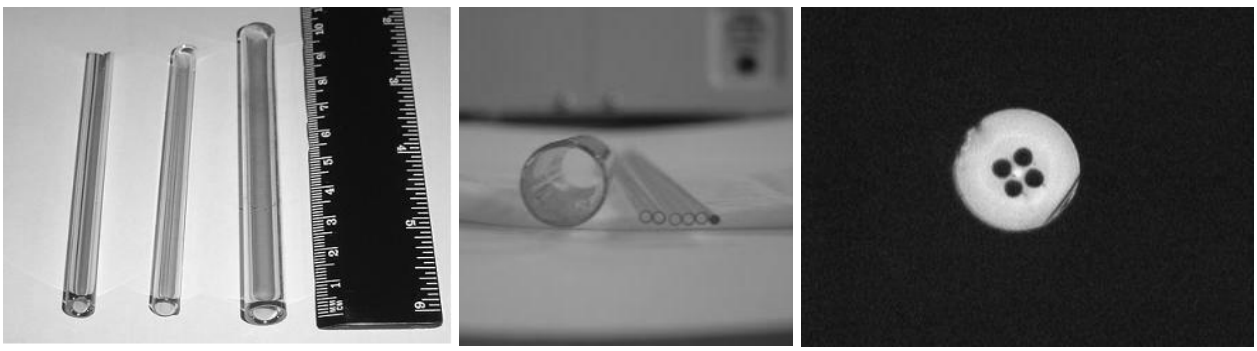

**(A)** **(B)**

Figure 1 Tellurite tube fabrication by a centrifugation method

This centrifugation process is realized between the drawing and the onset crystallization temperatures. The tube thickness can be controlled via the rotational speed and the sample temperature. Tellurite tubes with 7, 10 and 12 mm external tube diameter were obtained using the process mentioned above. The 1.8 mm external diameter capillaries were drawn from the 10 mm tubes and these were stacked, together with the central solid rod, to form the preform.

The preform was drawn down to fiber using the same tower and with furnace temperatures between 430 and 450 Celsius degrees. Figure 2A shows some tubes prepared while figure 2B presents the capillaries and central rod as well. The cross section of the final tellurite $Er^{3+}$ - $Tm^{3+}$ co-doped fiber, 125 μm thick, 14 μm diameter core, can be seen guiding white light in figure 2C.

Although it is a simple geometry with high confinement loss, it presents a high quality structure. Future work will focus on improving the loss by both increasing the number of holes that surrounds the core and thinning the bridges between them.



**(A)** **(B)** **(C)**

Figure 2 Tubes (A and B), capillaries and central rod (B) of $71TeO_2$-$22.5WO_3$-$5Na_2O$-$1.5Nb_2O_5$ (%mol) tellurite glass prepared by centrifugation method. (C) Fiber cross-section optical micrograph.

## 3. OPTICAL CHARACTERIZATION

For the Amplified Spontaneous Emission intensity (ASE) measurements, the $Er^{3+}$-$Tm^{3+}$ co-doped Tellurite-PCF fiber was excited with a cw Ti:Sa (400 mW, 790 nm) or with a diode laser (120 mW, 980 nm). The optical setup to measure the ASE intensity is shown in figure 3 for the 790 nm pump source. The light was coupled using microscope lenses ($L_1$, $L_2$ and $L_3$) and micro-translators. The light after the fiber is collected with a multimode standard optical fiber (MF) and fed into an optical spectrum analyzer (OSA) set to 10 nm resolution. It is used a long wavelength pass-band filter (F RG1000) to improve the signal-to-noise ratio. For ASE intensity measurements using the 980nm pump laser we butt-coupled the laser and PCF fibers.

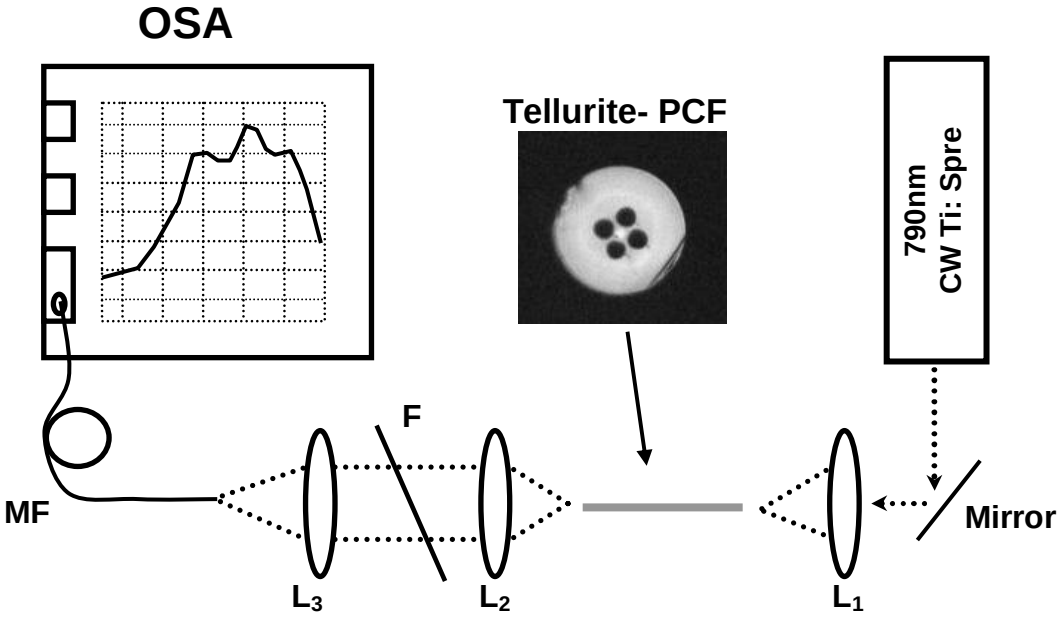



Figure 3 Set-up experimental for ASE intensity measurements with 790nm pump laser. $L_1$, $L_2$ and $L_3$ are microscope lenses and F is a RG1000 filter.

## 4. RESULTS AND DISCUSSIONS

Figure 4A shows the ASE spectra of 15, 30, 50 and 110 cm long tellurite-PCF fibers pumped with 120 mW at 980 nm pump laser. The contributions for the ASE intensity spectra arise mainly from the $Er^{3+}$ $^4I_{13/2} \rightarrow {}^4I_{15/2}$ (~1550 nm) and $Tm^{3+}$ $^3F_4 \rightarrow {}^3H_6$ (~1750nm) bands. The broader spectrum appears with the 30cm-long fiber where the ASE has a 100 nm amplification bandwidth (measured at -3dB level of ASE maximum intensity).

Figure 4B shows the ASE intensity spectra of 15, 24 and 50 cm long Tellurite-PCF fibers pumped with 400 mW at 790 nm. In this case the addition of the $Tm^{3+}$ $^3H_4 \rightarrow {}^3F_4$ (~1465 nm) band extends the amplification bandwidth to 187 nm (15 cm long fiber).

While the 790 nm pump can directly excite both ions, $Er^{3+}$ ion from $^4I_{15/2}$ ground state to $^4I_{9/2}$ excited state and $Tm^{3+}$ from $^3H_6$ ground state to $^3H_4$ excited state, the 980nm pump can only excites the $Er^{3+}$ ion from the ground state to $^4I_{11/2}$ excited state. Due to this fact, when a $Er^{3+}$-$Tm^{3+}$ co-doped tellurite-PCF is pumped with 980nm laser the $Tm^{3+}$ $^3H_4 \rightarrow {}^3F_4$

transition is not observed although the $Tm^{3+}$ $^3H_4$ and $^3F_4$ levels can be populated by energy transfer processes ($ET_1$ and $ET_3$) from the $Er^{3+}$ $^4F_{9/2}$ and $^4I_{13/2}$ levels respectively.

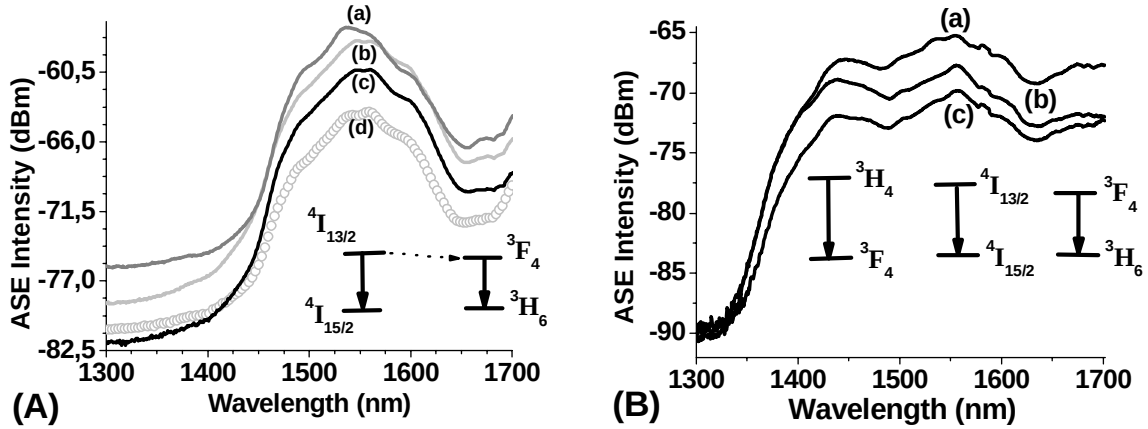



Figure 4 (A) ASE spectra obtained for 980 nm pump laser and different fibers lengths: (a) =15, (b) = 30, (c) = 50 and (d) =110 cm. (B) 790nm pump laser and different fibers lengths: (a) = 15, (b) = 24 and (c) = 50cm.In both cases the main bands are presented.

The 980nm pump laser allows the $^3H_4$ level to be populated by $ET_1$ and $ET_2$ processes and the $^3F_4$ level to be populated by $ET_3$ process. $ET_3$ is, however, very efficient compared with $ET_1$ and $ET_2$, which avoids the $^3H_4 \rightarrow {}^3F_4$ transition as observed in figure 5.

However, 790nm pump laser allows the $^3H_4$ and $^4I_{9/2}$ levels to be populated directly and consequently the $^3H_4$ level to be populated more than $^3F_4$ level for 5000ppm (in weight) $Tm_2O_3$ concentration, which allow $^3H_4 \rightarrow {}^3F_4$ transition favorable for bandwidth increase, as observed in figure 5 additionally with dashed lines.

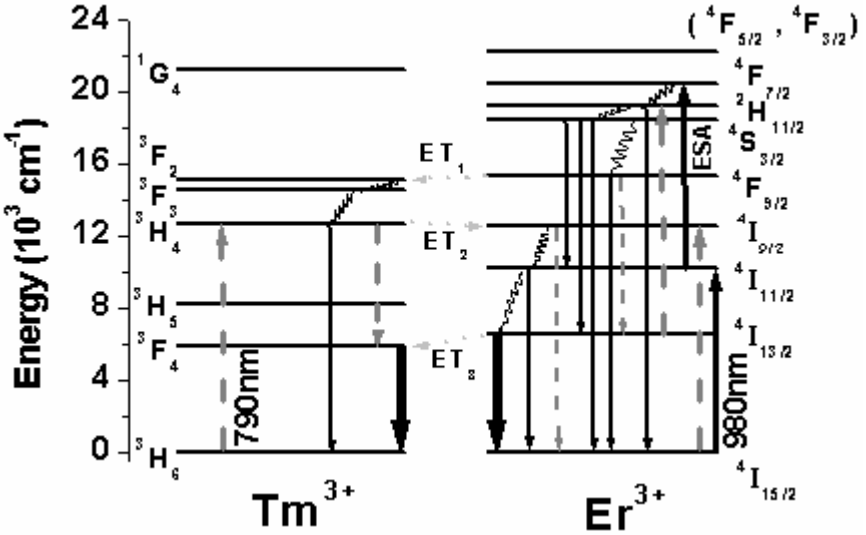



Figure 5 Energy levels diagram showing the absorption, emission and energy transfer processes in the $Er^{3+}$ -$Tm^{3+}$ co-doped tellurite fiber. The solid arrows represent the transitions when the tellurite fiber is pumped with a 980 nm laser and the dashed arrows are indicative of the transitions for the 790 nm laser pumping.

## 5. CONCLUSIONS

This work shows a successful fabrication of a co-doped tellurite photonic crystal fiber where extrusion was not used in any step of the fabrication. The preform was prepared by the powerful stack-and-draw technique being the capillaries drawn from high quality (both optical and geometrical) tubes prepared by a centrifugation method. Soft-glass PCF´s with complex geometries, doped regions or several composition glasses fibers are then easier to fabricate. In this case we present a co-doped $Er^{3+}$-$Tm^{3+}$ fiber that has an ASE spectrum as broad as 187 nm at 1550nm when pumped with a 790nm laser.

## 6. ACKNOWLEDGMENTS

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## 7. REFERENCES

**[1]** J. C. Knight, T. A. Birks, P. St. J. Russel and D. M. Atkin.: " All-silica single-mode optical fiber with photonic crystal cladding", Opt. Lett, 1996, 21, pp. 1547-1549

**[2]** H. Jeong, K.Oh, S. R. Han, T.F. Morse, "Characterization of broadband amplified spontaneous emission from an $Er^{3+}$-$Tm^{3+}$ -codoped silica fiber", Opt. Lett, 2003, 367, pp. 507-511

**[3]** E. F. Chillcce, E. Rodriguez, A. A. R. Neves, W. C. Moreira, C. L. César, L. C. Barbosa, "$Er^{3+}$-$Tm^{3+}$ co-doped tellurite fibers for broadband optical fiber amplifier around 1550 nm band", Opt. Fiber Technol., 2005, article in press

**[4]** P. Russell, "Photonic crystal fibers", Science, 2003, 299, pp. 358-362

**[5]** J. C. Knight, "Photonic crystal fibers", Nature 2003, 424, pp 847-851

**[6]** V.V. Ravi Kanth Kumar, A.K. George, J.C. Knight and P.St.J. Russell, "Tellurite photonic crystal fiber", Opt. Exp, 2003, 20 pp. 2641-2645

**[7]** V.V. Ravi Kanth Kumar, A.K. George, W.H. Reeves, J.C. Knight and P.St.J. Russell, F.G. Omenetto and A.J. Taylor, "Extruded soft glass photonic crystal fiber for ultrabroad supercontinuum generation", Opt. Exp, 2002, 10 (25), pp. 1520-1525

**[8]** K. M. Kiang, K. Frampton, T. M. Monro, R. Moore, J. Tucknott, D. W. Hewak, D. J. Richardson and H. N. Rutt, "Extruded singlemode non-silica glass holey optical fiber", Electron. Lett, 2002, 38(12), pp. 546- 547