Optical Materials 53 (2016) 39–43

Contents lists available at ScienceDirect

Optical Materials

journal homepage: www.elsevier.com/locate/optmat

A silica optical fiber doped with yttrium aluminosilicate nanoparticles for supercontinuum generation

Tonglei Cheng [a], Meisong Liao [b,*], Xiaojie Xue [a], Jiang Li [c,*], Weiqing Gao [a], Xia Li [d], Danping Chen [d], Shupei Zheng [d], Yubai Pan [c], Takenobu Suzuki [a], Yasutake Ohishi [a]

[a] Research Center for Advanced Photon Technology, Toyota Technological Institute, 2-12-1 Hisakata, Tempaku, 468-8511 Nagoya, Japan
[b] College of Science, Shanghai Institute of Technology, 201800 Shanghai, China
[c] Key Laboratory of Transparent Opto-Functional Inorganic Materials, Shanghai Institute of Ceramics, Chinese Academy of Sciences, 200050 Shanghai, China
[d] Key Laboratory of Materials for High Power Laser Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, 201800 Shanghai, China

ARTICLE INFO

Article history:
Received 24 September 2015
Received in revised form 6 January 2016
Accepted 8 January 2016
Available online 13 January 2016

Keywords:
Yttrium aluminosilicate nanoparticles
Optical fiber
Supercontinuum generation
Multiple solitons and dispersive waves

ABSTRACT

We design and fabricate a silica optical fiber doped with yttrium aluminosilicate (YAS, Y_2O_3–Al_2O_3–SiO_2) nanoparticles in the core. The optical fiber is drawn directly from a silica tube with YAG ($Y_3Al_5O_{12}$) ceramics and silica powders (the molar ratio 1:18) in the core at the temperature of ~1950 °C. The YAS nanoparticles are formed during the optical fiber drawing process. Supercontinuum (SC) generation in the optical fiber is investigated at different pump wavelength. At the pump wavelength of ~1750 nm which is in the deep anomalous dispersion region, SC spectrum evolution is mainly due to multiple solitons and dispersive waves (DWs), and three pairs of multiple optical solitons and DWs are observed. When the pump wavelength shifts to ~1500 nm which is close to the zero-dispersion wavelength (ZDW), flattened SC spectrum with ±7 dB uniformity is obtained at the wavelength region of ~990–1980 nm, and only one obvious soliton and DW are observed. At the pump wavelength of ~1100 nm, a narrow SC spectrum from ~1020 to 1180 nm is obtained in the normal dispersion region due to self-phase modulation (SPM) effect.

1. Introduction

Nanoparticles present novel optical and electrical properties because they take the dimensions between the size of molecules and that of bulk [1–4]. Up to now, nanoparticles have been widely used for various applications, such as biodiagnostics [5], the stabilization of enzyme [6,7], drug delivery in diseases [8,9] and protein detection analytes [10]. Optical fibers provide another attractive platform for nanoparticle application [11–13], because the development of numerous optical devices demands optical fibers with high nonlinearity, and doping nanoparticles into the optical fibers is an effective way to enhance the nonlinear effects.

Yttrium aluminosilicate (Y_2O_3–Al_2O_3–SiO_2, YAS) glasses have been of great interest for many years due to their high linear and nonlinear refraction indice [14,15], elastic modulus and high hardness [16,17] as well as excellent chemical durability [18,19]. These properties have led to various applications in modern technology, for example, as a host material in laser and amplifier applications, for bonding of silicon nitride ceramics, and a matrix for storage of long-lived actinides [20–22]. If we could produce YAS nanoparticles and dope them into the optical fibers, it may lead to some interesting result.

In this work, a silica optical fiber doped with YAS nanoparticles in the core was designed and fabricated. The optical fiber was drawn directly from a silica tube containing YAG ($Y_3Al_5O_{12}$) ceramics and silica powders (the molar ratio 1:18) in the core at the temperature of ~1950 °C, and YAS nanoparticles with the random shape were formed during the drawing process. Supercontinuum (SC) generation in the optical fiber was investigated at different pump wavelength. At the pump wavelength of ~1750 nm which was in the deep anomalous dispersion region, SC generation by multiple solitons and dispersive waves (DWs) was obtained. Decreasing the pump wavelength to ~1500 nm which was close to the zero-dispersion wavelength (ZDW), flattened SC spectra were observed at the average pump power of ~500 mW. Furthermore, decreasing the pump wavelength to ~1100 nm, a narrow SC spectrum was obtained in the normal dispersion region due to self-phase modulation (SPM) effect.

* Corresponding authors.
E-mail addresses: liaomeisong@siom.ac.cn (M. Liao), lijiang@mail.sic.ac.cn (J. Li).

http://dx.doi.org/10.1016/j.optmat.2016.01.018
0925-3467/

2. Fabrication and properties

The silica optical fiber doped with YAS nanoparticles in the core was fabricated directly in the tower, as shown in Fig. 1. First, the YAG ceramics and silica glass were milled to micron-size powders and filled in a silica tube with the center hole diameter of ~3 mm and the outer diameter of ~10 mm, as shown in Fig. 1(a). The molar ratio of YAG and silica powders was 1:18. Then, the silica glass tube was inserted into another silica tube with the center hole diameter of ~11 mm and the outer diameter of ~60 mm in order to decrease the core diameter. Finally, the silica tube was elongated in the tower at the temperature of ~1950 °C to produce the optical fiber of which the diameter was ~120 μm. During the fiber-drawing process, the center hole was filled with a negative pressure of nitrogen gas which was ~4–6 kPa lower than the standard atmospheric pressure to avoid the interstitial hole formation. YAG reacted with silica in the core to produce Y_2O_3–Al_2O_3–SiO_2 nanoparticles, and the insert of Fig. 1(b) was an image of the fabricated optical fiber.

In order to confirm YAS nanoparticles in the core, the overall structural features of the optical fiber were revealed by the scanning electron microscopy (SEM) and the transmission electron microscopy (TEM) characterization. In Fig. 2(a) the core diameter was measured to be ~6.1 μm, and in Fig. 2(b) the core-cladding interface can be easily distinguished. Fig. 2(c) shows the enlarged TEM image of the core region, and the dark spots are YAS nanoparticles with the random shape. The nanoparticle dimension is from ~10 to 40 nm and the background is silica glass. The TEM image was further enlarged to check the existence of crystal structure in YAS and none was found. Furthermore, a sample of silica glass doped with YAS nanoparticles was produced under the same condition with the fabrication of the silica optical fiber. We investigated both the silica glass sample and the YAG ceramics by X-ray powder diffraction (XRD) using a LabX XRD-6100 X-ray diffractometer. The result, which is shown in Fig. 2(d), also confirms that no crystal structure exists in the nanoparticles. Additionally, the size distribution of the YAS nanoparticles in the fiber core was analyzed by the scanning transmission electron microscopy (STEM), and the images are shown in Fig. 2(e) and (f). The former is the bright field STEM (BF-STEM) and the latter is the dark field STEM (DF-STEM). Both dark regions in BF-STEM and bright regions in DF-STEM are YAS nanoparticles.

Fig. 3(a) was the DF-STEM image under high magnification. Based on it, the elemental mapping was carried out by the energy dispersive X-ray (EDX) spectroscopy. Fig. 3(b) was for the aluminum element (bright region) and Fig. 3(c) was for the yttrium element (bright region), both of which corresponded well with Fig. 3(a), indicating that Al and Y mainly accumulated within the YAS nanoparticles. Fig. 3(d) was for the silicon element (bright region), and the bright/dark contrast was less obvious, suggesting that there was Si both within the nanoparticles and throughout the background, only the ratio was different. To further reveal the distribution of the constituent atoms, a spot each from the nanoparticle region (Spot 003) and background region (Spot 004) was selected to carry out the EDX examination, as shown in Fig. 3(e) and (f). The atomic ratio of Al, Y, O and Si was 3.63%, 2.69%, 61.96% and 31.71% for the YAS nanoparticles, and 0.18%, 0.14%, 62.63% and 37.05% for the silica background.

Fig. 4(a) shows the linear material refractive index of the silica glass sample doped with YAS nanoparticles, which was measured at different wavelength from 1000 nm to 1800 nm using prisms. Fig. 4(b) shows the chromatic dispersion curve of the optical fiber, which was calculated by a commercial software (Lumerical MODE Solution) using the full-vectorial mode solver technology. We can see that the ZDW is ~1360 nm. Furthermore, a 10 m-long fiber was used to measure the loss by the cutback technique and at the wavelength of ~1550 nm, and the loss was ~0.7 dB/m. The nonlinear response of the optical fiber is related to the anharmonic motion of bound electrons under the influence of an applied field. The YAS nanoparticles in the core can improve the fiber nonlinearity [15], which can be used in the high power fiber lasers and the nonlinear optical devices. The physical mechanism for the improved nonlinearity can be explained from two aspects: one is that the nonlinear refractive index of YAS is larger than that of silica [23]. The other is that the nanoscale itself can improve the nonlinear coefficient [13]. Moreover, compared with the silica optical fibers doped with noble metal nanoparticles, the scatting loss in this optical fiber is lower because the YAS is glass.

3. SC generation

To investigate SC generation of the silica optical fiber doped with YAS nanoparticles, an optical parametric oscillator (OPO, Coherent Inc.) with a pulse width of ~200 fs and a repetition rate of ~80 MHz was used as the pump source. The experimental setup was shown in Fig. 5. The idler wavelength of the OPO could be tuned from ~1800 to 3200 μm and the signal wavelength could be tuned from ~1060 to 1440 nm. The output beam was linearly polarized. After a neutral density (ND) filter, the pulse was coupled into a 50 cm-long optical fiber by lenses: the one for the signal wave had a focal length of ~3.1 mm and a numerical aperture (NA) of ~0.68 (THORLABS, C330TME-C, 1050–1800 nm), while the other for the idle wave had a focal length of ~4.0 mm and an NA of ~0.56 (THORLABS, C036TME-D, 1800–3000 nm). The output signal was then butt-coupled into a 0.3 m long large-mode-area

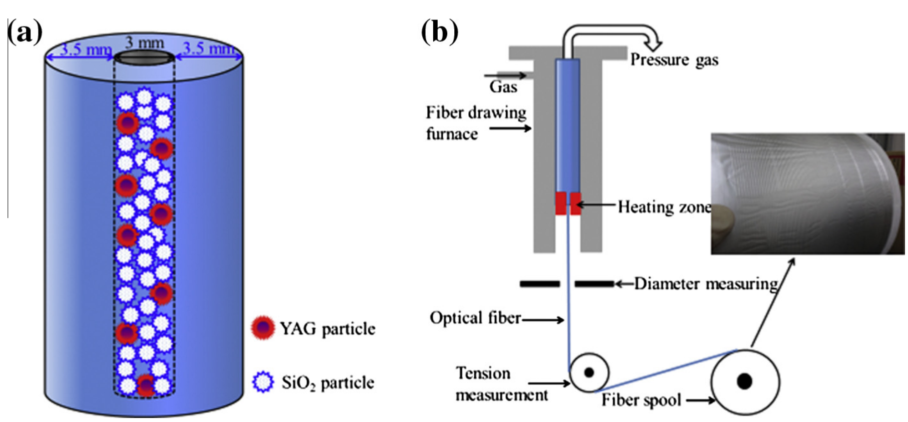

Fig. 1. (a) Silica tube with the YAG ceramics and silica powders in the core. (b) Schematic illustration of the fabrication process. Insert was the fabricated optical fiber.