Research Article

Effect of Ge Nanoparticles in the Core of Photonic Crystal Fiber on Supercontinuum Generation

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The effect of Ge nanoparticle (Ge NP) incorporation in the germanosilicate glass core of the photonic crystal fiber (PCF) on supercontinuum generation (SCG) was investigated. The Ge NP-doped germanosilicate glass core PCF was fabricated by using the modified chemical vapor deposition (MCVD) and the stack-and-draw processes. The average diameter of Ge NPs embedded in the core of the PCF was 4.2 nm. The absorption peaks at 480 nm and 515 nm and the band from 600 to 800 nm were attributed to the Ge NPs in the core of the PCF. SCG of the 490 nm bandwidth (598 nm~1088 nm) with a conversion efficiency of 31% was obtained by pumping at 800 nm with the Ti:sapphire femtosecond laser of 160 mW with 35 fs pulse at 1 kHz repetition rate, resulting from the enhanced optical nonlinearity from Ge NPs as well as the PCF structure of the fiber.

1. Introduction

Supercontinuum generation (SCG) is a spectral broadening phenomenon to yield a broadband output when a narrow-band incident laser pulse goes through an optically nonlinear medium. A broadband supercontinuum laser source generated by injection of high-power ultrashort pulses into a nonlinear medium has much attention in the applications including optical coherence tomography, time-resolved spectroscopy, optical frequency metrology, and optical communications [1–12]. Particularly, SCG based on highly nonlinear optical fiber has been of interest due to its low optical loss and high stability and reliability. Recently, various types of optical fibers were used for the SCG: conventional highly nonlinear fiber, photonic crystal fiber (PCF), tapered fiber, and specialty fibers incorporated with the nanoparticles

(NPs) of semiconductors, heavy metals, and oxides [1–6, 13–18]. Among these nonlinear optical fibers, the PCFs and the small core fibers have turned out to be interesting because of their very large nonlinearity and controllability of chromatic dispersion. Recently, our group has reported the SCG with a spectral bandwidth of 400 nm using the specialty optical fiber incorporated with Si NPs in the core [14]. It is well known that group IV semiconductor NPs such as Si and Ge have a large optical nonlinearity due to the formation of non-bridging oxygens (NBOs) and defects and due to the strong quantum confinement effect of the NPs [14, 18–23]. Particularly, Ge NPs have stronger quantum confinement and higher optical nonlinearity than Si NPs resulting from its direct-gap semiconductor nature [20, 23–26]. Therefore, in this paper, we fabricated the germanosilicate glass core PCF incorporated with Ge NPs

and investigated its SCG characteristics upon pumping with the femtosecond laser.

2. Experiments

The Ge NP-doped core PCF was fabricated by using the modified chemical vapor deposition (MCVD), which is based on the high temperature oxidation of reagents inside a rotating silica glass tube by heating using an external heat source, and the stack-and-draw methods [27, 28]. The schematic diagram of the fabrication steps of the Ge NP-doped core PCF is shown in Figure 1. Porous germanosilicate layers were deposited onto the inner surface of a silica glass tube by the MCVD process using primarily silicon tetrachloride (SiCl_4) and germanium tetrachloride (GeCl_4). Then, the silica glass tube with the deposited layers was dried and partially sintered. To incorporate Ge NPs in the porous core layers, the tube was soaked with a Ge-doping solution prepared by dissolving 0.1 mole of high purity Ge powders (45 μm under, Kojundo, GEE05PB) in deionized water for two hours. Then, the Ge NP-doped glass tube was collapsed into a rod as a fiber preform. And the cladding part of the fiber preform was removed by etching with a hydrofluoric acid solution to obtain the core part of the Ge NP-doped glass with a diameter of 2 mm from the preform.

To fabricate a PCF preform with the Ge NP-doped glass core of 2 mm diameter, capillary tubes of silica glass with the same diameter of 2 mm (1.4×2 mm diameters) were prepared by drawing a silica glass tube (19×25 mm diameters). The 60 capillary silica glass tubes were stacked 5 layers around the core rod in a hexagonal pattern, and it was jacketed with a large silica glass tube (19×25 mm diameters) into a first PCF preform (PCF preform 1). Then, the first PCF preform was drawn into a cane with a diameter of 2 mm, and the cane was jacketed again with a silica tube (2×6 mm diameters) into a second PCF preform (PCF preform 2). After all, this second PCF preform was drawn into a final PCF fiber of 125 μm diameter with a Ge NP-doped glass core. Note that the pressure was applied to keep the air hole circular during the drawing process. The diameter of the core and the air hole, and the hole-to-hole distance (pitch, Λ) of the fabricated Ge NP-doped core PCF were 4.1 μm and 2.9 μm , and 5.2 μm , respectively (Figure 1). For a comparison, a PCF with the pure silica glass core and a PCF with the germanosilicate glass core without Ge NPs were also fabricated. The diameter of the core and the air hole, and the hole-to-hole distance (Λ) of the pure silica core PCF were 6.0 μm and 1.9 μm , and 4.3 μm , respectively. And those of the PCF with the germanosilicate glass core without Ge NPs were 4.2 μm and 3.3 μm and 5.1 μm , respectively.

To verify the existence of Ge NPs in the core of the PCF, the fabricated fiber was examined by the Cs-corrected scanning TEM (JEOL, JEM-ARM200F). The optical absorption of the fiber was also measured by the cut-back method using the optical spectrum analyzer (OSA; Ando, AQ 6315B) and white light source (WLS; Ando, AQ 4303B). Note that the cut-back method is done by comparing the optical power transmitted through a long fiber to that transmitted through a short piece of the fiber after cutting the long fiber without

variation of the input signal. Furthermore, to find optimum experimental condition for SCG, the chromatic dispersion and the nonresonant optical nonlinearity such as the nonresonant nonlinear refractive index coefficient, n_2 , and the effective nonlinear parameter, γ , were obtained by using the optical dispersion analyzer (ODA; AGILENT, 86038B) and the continuous wave self-phase modulation (cw-SPM) method, respectively. A detail measurement method and the result of the PCF fiber were described in reference [2]. The estimated nonresonant nonlinear refractive index, n_2 , and the effective nonlinear parameter, γ , of the Ge NP-doped core PCF were found to be $4.74 \times 10^{-20} \text{ m}^2/\text{W}$ and $14.41 \text{ W}^{-1} \text{ km}^{-1}$, respectively [27]. And the n_2 and the γ of the pure silica core PCF and the germanosilicate glass core without Ge NPs were $2.56 \times 10^{-20} \text{ m}^2/\text{W}$ and $3.67 \text{ W}^{-1} \text{ km}^{-1}$, and $2.62 \times 10^{-20} \text{ m}^2/\text{W}$ and $7.82 \text{ W}^{-1} \text{ km}^{-1}$, respectively. The n_2 and γ of the Ge NP-doped core PCF were larger than those of the PCFs with the pure silica core and the germanosilicate glass core without Ge NPs. The specifications of the fabricated PCFs are summarized in Table 1.

SCG was obtained by pumping the 5 m long fiber with the Ti:sapphire femtosecond laser (Spectra-Physics, Spitfire Ace) at 800 nm with the power of 160 mW and the pulse width of 35 fs at 1 kHz repetition rate. The output spectrum of the SCG was measured by using the optical spectrum analyzer (OSA: ANDO, AQ-6315B). Note that the pumping laser was directly launched onto the fiber core using a focusing lens.

3. Results and Discussion

Figure 2 shows the TEM image and the size distribution of Ge NPs embedded in the germanosilicate glass core of the PCF. It clearly shows the existence of the roughly spherical crystalline Ge NPs even after the high temperature drawing process of over 1950°C. The average diameter of Ge NPs was measured to be about 4.2 nm with the range of 3.4 nm~5.4 nm. Despite the multiple high temperature drawing processes (the 2 mm rod drawing, the cane drawing, and the final fiber drawing), Ge NPs were well retained in the core of the PCF. The existence of Ge NPs in the core of the PCF was also verified by absorption spectrum analysis. As shown in Figure 3(a), two absorption peaks appeared at 480 nm and 515 nm, and an absorption band appeared centering at 650 nm, and these are attributed to Ge NPs in the core of the PCF [23, 27]. An absorption peak at 1380 nm is due to the presence of OH ion impurities.

To estimate an optimum wavelength for the SCG of the PCF, the chromatic dispersion of the Ge NP-doped core PCF was measured and shown in Figure 3(b). The measured zero-dispersion wavelength was 1246.3 nm, a little shorter than the simulated zero-dispersion wavelength of 1361.0 nm by using the finite element method- (FEM-) based COMSOL program [27]. Even though pumping for an efficient SCG must be carried out near the zero-dispersion wavelength, the actual pumping was done at 800 nm (normal dispersion of $D \approx -1238.9 \text{ ps/nm/km}$) by using the available commercial high-power femtosecond laser [16]. The laser

FIGURE 1: Fabrication process and fabricated cross-section image of the Ge NP-doped core PCF.

TABLE 1: Specifications of the fabricated PCFs.

Fiber	Solid core diameter	Air hole diameter	Hole-to-hole distance (pitch)	Chromatic dispersion coefficient @ 800 nm	Nonlinear refractive index	Effective nonlinearity
Symbol	—	—	Λ	D	n_2	γ
Unit	(μm)	(μm)	(μm)	(ps/nm/km)	(m^2/W)	($\text{W}^{-1} \text{km}^{-1}$)
Pure silica core PCF	6.0	1.9	4.3	-932.5	2.56×10^{-20}	3.67
Germanosilicate glass core PCF (without Ge NPs)	4.2	3.3	5.1	-1073.5	2.62×10^{-20}	7.82
Ge NP-doped germanosilicate glass core PCF	4.1	2.9	5.2	-1238.9	4.74×10^{-20}	14.41

was launched onto the core of the 5 m long PCFs at the pump power of 160 mW with 35 fs pulse width at 1 kHz repetition.

Figure 4 compares the output powers of the PCFs upon pumping with the Ti:sapphire femtosecond laser at 800 nm. All the PCFs showed the SCG from 600 nm to 1100 nm after pumping with the laser. The SCG bandwidth of the Ge NP-doped core PCF was wider than that of the pure silica glass core PCF and the germanosilicate glass core PCF. The bandwidth at the output power of -60 dBm of the SC spectrum (full width at half maximum, FWHM) of the pure silica core PCF and the germanosilicate glass core PCF at the same output power were 393 nm (650 nm~1043 nm) and 414 nm

(640 nm~1054 nm), respectively. But that of the Ge NP-doped core PCF was 490 nm (598 nm~1088 nm). The average power from the SC spectrum of the Ge NP-doped core PCF was 49.6 mW with a power conversion efficiency of 31%. It is known that when the PCFs are pumped at wavelengths of normal dispersion region (shorter than zero-dispersion wavelength), which is our case, spectral broadenings are narrow and smooth, and it is due to the self-phase modulation only. On the other hand, when the PCFs are pumped at wavelengths of anomalous dispersion region (longer than zero-dispersion wavelength), dominant nonlinear processes became modulation instability and

FIGURE 2: (a) TEM image and (b) size distribution of Ge NPs in the core of the Ge NPs-doped core PCF.

FIGURE 3: (a) Optical absorption spectrum and (b) chromatic dispersion of the Ge NP-doped core PCF.

solitonal dynamics, and thus, the output spectral bandwidth are wide and rough [16].

Particularly, the expansion of the SCG bandwidth of the Ge NP-doped core PCF compared to the others (from 393 and 414 nm to 490 nm) demonstrates the role of Ge NPs to the large optical nonlinearity. The nonresonant optical nonlinearity of the Ge NP-doped core PCF may be caused by the hyperpolarizabilities of NBOs formed by the incorporated Ge NPs, and this NBOs have higher ionicity and are easily distorted by the applied optical field [23, 27]. In the viewpoint of the PCF structure, the germanosilicate core PCF has a broader SC spectrum than the pure silica core PCF because the small core diameter causes an increase in optical nonlinearity [29]. Note that as shown in Table 1, the γ of the germanosilicate glass core PCF was larger than that of the pure silica glass core PCF because of the core size difference while the n_2 of both PCFs was almost the same.

4. Conclusions

The effect of Ge NP incorporation in the germanosilicate glass core of the PCF on SCG was investigated. Three types of PCFs, the Ge NP-doped germanosilicate glass core PCF, the germanosilicate glass core PCF, and the pure silica glass core PCF, were fabricated by using the MCVD process and the stack-and-draw technique. The diameters of the core and the air hole, and the hole-to-hole distance (Λ) of the fabricated Ge NP-doped core PCF were 6.0 μm and 1.9 μm , and 4.3 μm , respectively. The average diameter of Ge NPs embedded in the core of the PCF was 4.2 nm (3.4 nm~5.4 nm). The absorption peaks appearing at 480 nm and 515 nm and the band centering at 650 nm were attributed to the Ge NPs in the core of the PCF. The measured zero-dispersion wavelength and the normal dispersion at 800 nm were at 1246.3 nm and -1238.9 ps/nm/km, respectively. And the nonresonant nonlinear refractive index (n_2) and the effective

FIGURE 4: Supercontinuum generation of the PCFs upon pumping with the femtosecond laser at 800 nm.

nonlinear parameter (γ) of the Ge NP-doped core PCF measured by the cw-SPM method were $4.74 \times 10^{-20} \text{ m}^2/\text{W}$ and $14.41 \text{ W}^{-1} \text{ km}^{-1}$, respectively. SCG was obtained by pumping into the fiber core at 800 nm with the Ti:sapphire femtosecond laser of 160 mW with 35 fs pulse at 1 kHz repetition rate. The SCG bandwidth at the output power of -60 dBm of the Ge NP-doped core PCF was 490 nm (598 nm~1088 nm) with a conversion efficiency of 31%, resulting from the enhanced optical nonlinearity from Ge NPs as well as the PCF structure of the fiber.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they do not have conflicts of interest.

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