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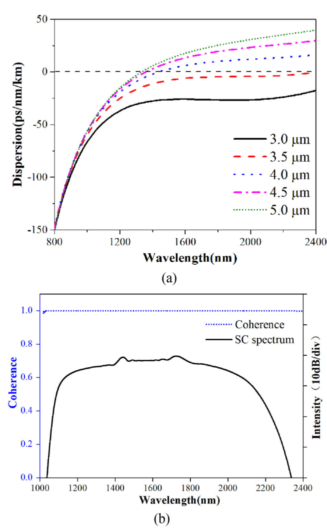

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A Step-Index Silicate Nonlinear Fiber With All Normal Flattened Dispersion for Coherent Supercontinuum

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Abstract: A step-index silicate fiber with all normal flat dispersion was fabricated. Coherent supercontinuum (SC) spectrum spanning 1200 to 2000 nm was generated in a 5 cm silicate fiber pumped at 1560 nm. The numerical simulation result agreed with the experiment result. Also, highly coherent SC spectrum spanning from 1100 to 2100 nm with flatness $<$7 dB generated in the fiber with 57 kW pumping power according to simulation. The step-index silicate fiber is not only easy to prepare but also a promising candidate to achieve all-fiber structure for coherent SC.

Index Terms: fiber design and fabrication, nonlinear fiber, coherent supercontinuum, all normal dispersion.

1. Introduction

Supercontinuum (SC) generation in optical fibers have attracted widespread attentions owing to its numerous applications in ultra-short pulse generation [1], frequency combs [2], and optical coherence tomography [3], [4]. However, the noise of the SC limits the precision or resolution of these applications [5]. Therefore, high coherence becomes one of the key properties of SC, which is determined by pump source and broadening mechanism of the SC. Stable pump source with short pulse width is preferable for achieving high coherent SC [6]. Commonly used method, nowadays, to generate SC is pumping at anomalous dispersion region of the fiber, which can fully broaden the spectrum. However, soliton-related dynamics and modulation instability (MI) are main broadening mechanism in these cases, leading to the amplified noise of SC [7]. An alternative approach to get highly coherent SC is to use the fiber with all normal dispersion (ANDi) as the nonlinear media to avoid the soliton-related dynamics and MI [8]–[10]. In these cases, the broadening mechanism is dominated by self-phase modulation (SPM) and optical wave breaking (OWB) [11], which ensure a deterministic phase relation between the newly generated wavelengths and pump pulse [12].

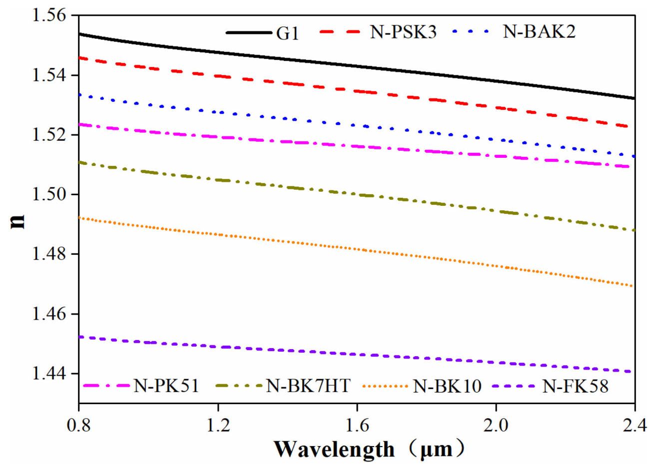

Fig. 1. Refractive indices of core and cladding glasses.

Microstructured optical fibers (MOFs) can flexibly tailor the dispersion of the fibers by carefully controlling the structure of the fibers. Hooper *et al.* demonstrated a photonic crystal fiber (PCF) with ANDi for highly coherent SC and pulse compression [13]. Also, all-solid PCF with ANDi were fabricated by standard stack-and-draw technique to generate over an octave coherent SC [12]. More recently, Huang *et al.* proposed and fabricated an all-solid Asterisk-shaped MOF which exhibits a low, ultra-flat and all-normal dispersion, and an octave spanning coherent SC was generated from the fiber pumped by 0.5 ps pulses at 1.55 μm [14]; Huang *et al.* fabricated an all-solid MOF with ANDi to generate highly coherent SC and pulse compression [15]. Although the dispersion of the MOFs can be flexibly designed, the MOFs are more difficult to prepare than the step-index fiber due to the precisely control of the air-hole and periodic structure.

In the step-index fibers, the dispersion of the fiber with various core sizes can be tailored provided that the refractive index difference between core and cladding glass is sufficiently large. The step-index tellurite fibers with ANDi were fabricated for coherent mid-infrared SC [16], [17], in which the NA of the tellurite fibers are 0.7 and 0.607, respectively. However, silica or silicate fibers are more suitable to generate near infrared SC because of higher strength and lower spliced loss than tellurite fibers. Sufficiently large refractive index difference can be achieved in the silicate glasses with matched thermal properties due to its multi-components and gradual viscosity-temperature property [12]. Therefore, the step-index silicate fibers with ANDi can be alternative candidates to generate highly coherent SC. To the best of our knowledge, the step-index silicate fibers with flat ANDi for highly coherent SC generation have not been reported yet.

In this work, dispersion-engineered step-index silicate fiber with flat ANDi was fabricated for highly coherent SC. The fiber with ANDi can be achieved when the core size of the fiber is less than or equal to 3.5 μm. A flat coherent SC spanning from 1100 to 2150 nm with flatness $<$7 dB can be generated from the fiber. The step-index silicate fiber with flat dispersion is easier to fabricate and splice than MOFs, therefore the fiber is a promising candidate to achieve all-fiber coherent SC source.

2. Fiber Fabrication and Characterization

The ANDi of the step-index silicate fibers with various refractive index difference are calculated without thermal properties in consideration. Figure 1 shows the refractive indices of core and cladding glasses. The composition of the core glass (G1) is (60$\sim$70SiO_2-10$\sim$15CaO-3$\sim$8Na_2O-3$\sim$8BaO-1$\sim$5TiO_2-2$\sim$7K_2O-1$\sim$5ZnO-0$\sim$2Al_2O_3, mol. %), and the refractive index of the glass is 1.55 at 1014 nm. The cladding glasses (Schott) are N-PSK3, N-BAK2, N-PK51, N-BK7HT, N-BK10

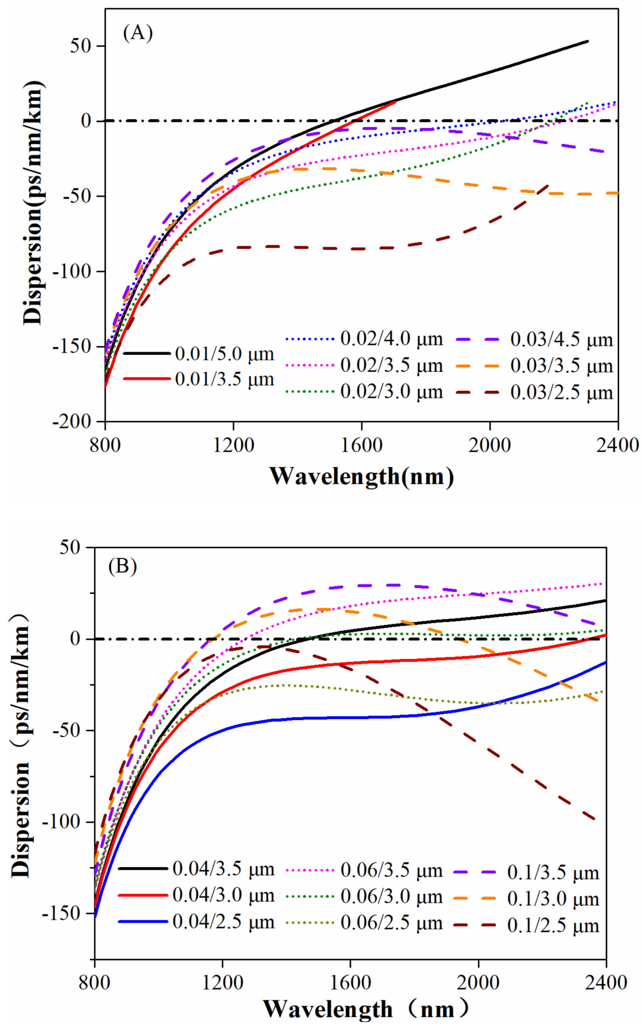

Fig. 2. Dispersion spanning from 800 nm to 2400 nm of the fibers with various core sizes and refractive index differences: (A) 0.01~0.03; (B) 0.04~0.1.

and N-FK58, respectively. Refractive index differences between core and cladding glass at 1014 nm are about 0.01, 0.02, 0.03, 0.04, 0.06 and 0.1, respectively.

Figure 2 shows the dispersion spanning from 800 nm to 2400 nm of the fibers with various refractive index differences and core sizes. When the refractive index differences are 0.01 and 0.02, the mode cannot be confined in the small core of the fibers at long wavelength band, which make it hard to achieve ANDi up to 2400 nm. When the refractive index difference is 0.03 or more than 0.03, the fibers can achieve ANDi spanning from 800 nm to 2400 nm. As the refractive index difference increases from 0.03 to 0.10, the fibers need a smaller core diameter from 4.5 μm to 2.5 μm to achieve ANDi. In addition, when the refractive index difference increases to 0.1, the absolute value and slope of the dispersion of the fiber become larger, which are unfavorable for SC broadening in the normal dispersion regime. As a result, step-index silicate fibers with refractive index difference between 0.03 and 0.06 are promising candidates for coherent SC generation.

In order to obtain silicate fiber with ANDi, the thermal properties of the core and cladding glasses must be considered in addition to the difference of refractive index. The silicate glass which is labeled as G2 (80~90SiO_2- 5~10K_2O- 7~13Na_2O- 0~2BaO, mol. %).) was selected to prepared the step-index fiber. The thermal properties of the glasses were shown in the Table 1. T_g, T_s and α are the

TABLE 1
Thermal Properties of Core and Cladding Glasses

Glass	T_g (℃)	T_s (℃)	α (10^{-7}/K)
G1	586	657	88
G2	558	610	99

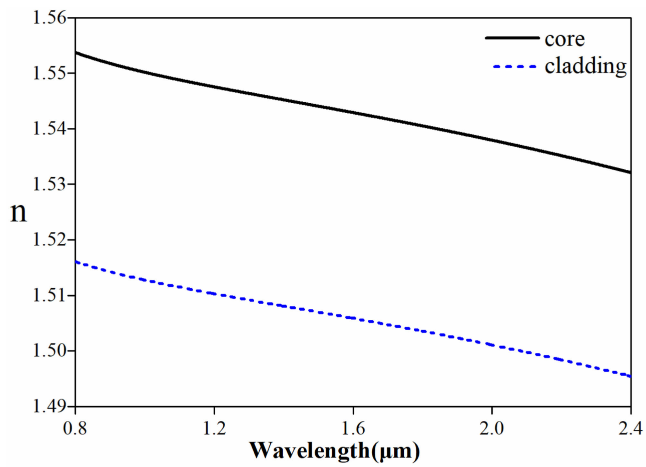

Fig. 3. The refractive indices of the core and cladding glasses.

transformation temperature, the softening point and the thermal expansion coefficient (100∼300 °C) of the glasses, respectively. Although the softening point of the core glass is 40 °C larger than that of the cladding glass, no crystallization phenomenon was observed during the process of fiber fabrication owing to good thermal stability and gradual viscosity-temperature property.

The refractive indices of the glasses are shown in the Figure 3. The refractive indices of the core and cladding glasses, measured at 1014 nm, are 1.55 and 1.513, respectively. The three-term Sellmeier equation was used to fit and calculate the refractive indexes of the glasses [18]. As mentioned above, the refractive index difference of 0.037 between core and cladding glasses is sufficient for achieving ANDi in the step-index silicate fibers.

Figure 4(A) shows the dispersion of the step-index silicate fiber as a function of wavelength for the fundamental mode between 800 and 2400 nm. The zero-dispersion wavelength shifts from 1350 nm to a longer wavelength exceeding 2400 nm as the diameters of the fiber is varied from 5 to 3 μm. ANDi between 800 to 2400 nm can be achieved when the core diameter of the fiber is 3.5 μm or less than 3.5 μm. With the core diameter decreasing from 3.5 to 3 μm, the dispersion of the fiber at 1560 nm decreases from −6.5 to −25.7 ps/nm/km, which is unfavorable for broadening of SC in the normal dispersion region. The step-index silicate fiber whose core diameter is 3.5 μm is selected to be prepared. The V-parameter of the selected fiber is calculated to be 2.37 at 1560 nm, so the step-index silicate fiber is single mode at 1560 nm. The fundamental mode of the fiber is presented in the Figure 4(B), and the mode filed of the designed fiber is calculated to be 10.4 μm^2 at 1560 nm.

The silicate fiber was fabricated by rod-in-tube and stack-and-draw method. The designed core diameter of the fiber is 3.5 μm, so the fiber needs to be drawn twice to reduce the core to such a small size. First, the cladding glass was processed and polished into a tube, and the outer and inner diameters of the cladding tube are 18 mm and 6.5 mm, respectively. The core glass was processed into a rod with 6.5 mm outer diameter. Then, the core rod and cladding tube were drawn to 1 mm

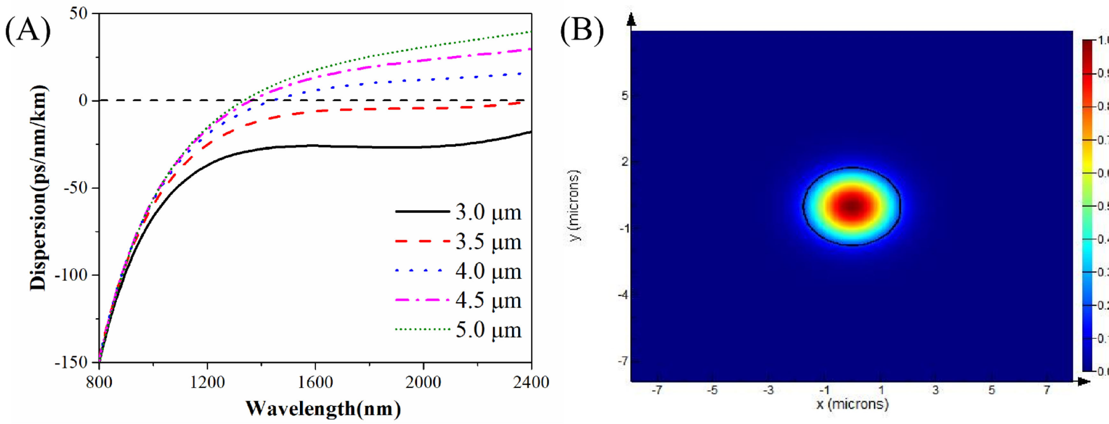

Fig. 4. (A) Wavelength-dependent dispersion of the step-index silicate fiber with varying core diameter 3.0, 3.5, 4.0, 4.5 and 5.0 μm; (B) Mode filed of the designed fiber whose core diameter is 3.5 μm.

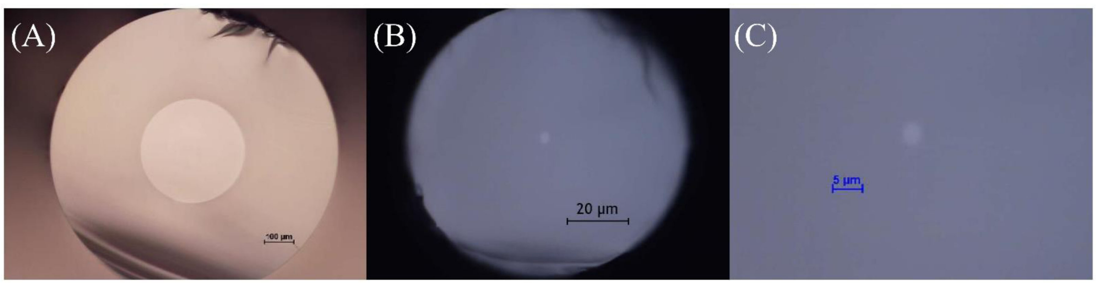

Fig. 5. Optical photograph of the cross-section of the fiber.

cane by rod-in-tube method. Next, the cladding glass was processed to a rod with 18 mm outer diameter and then was drawn to 1 mm cane. Finally, the core-cladding cane and cladding cane were drawn to the fiber. Figure 5(A) shows the cane of the step-index silicate fiber, and the diameter of the cane is 1 mm. Figure 5(B) shows the cross-section of the fiber. The outer diameter of the fiber is 100 μm, and the core of the fiber shows a little ellipse with diameter of 3.2 $\times$ 3.5 μm. Figure 5(C) is the zoom of the fiber core. The nonlinear refractive index is used as 3.9 $\times$ 10^{-20} m^2 W^{-1} in this work [19], and the nonlinear coefficient of the silicate fiber with core size of 3.5 μm was calculated to be 15 km^{-1} W^{-1} at 1560 nm. The loss of the fiber was 4.5 dB/m at 1560 nm measured by cut-back method.

3. SC Generation

A 1560 nm femtosecond laser with a pulse width of 88 fs, a maximum average power of 2.26 W and a repetition rate of 80 MHz was used to pump the fiber. A mounted rochester aspheric lens (Thorlabs, C430TM-C) was used to focus the laser. The focused laser was coupled into a 5 cm long step-index silicate to generate SC. The spectrometers (Yokogawa) was used to detect the spectrum of the SC from 1200 to 2400 nm. Figure 6 shows the dependence of the measured SC spectrum on the average pumping power. With increasing pumping power to 2.26 W, SC spectrum spanning 1200–2000 nm was achieved. When the pumping power increasing from 0.89 W to 2.26 W, the SC spectrum broadens symmetrically. The results show that the broadening mechanism is mainly dominated by SPM.

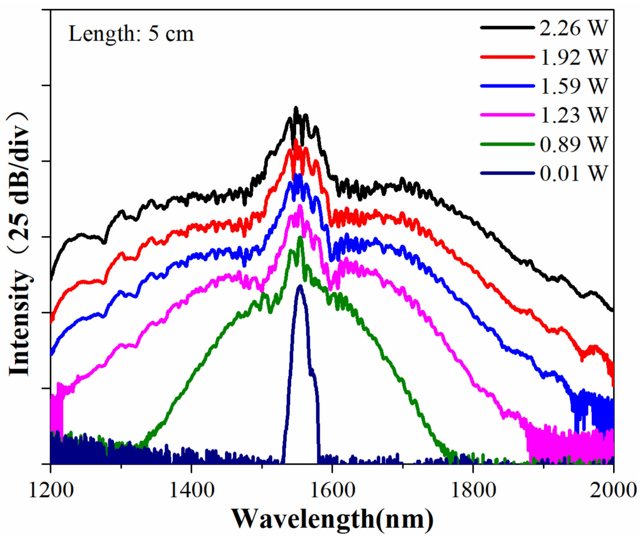

Fig. 6. Dependence of the measured SC spectrum from 5 cm step-index silicate fiber on the pumping power.

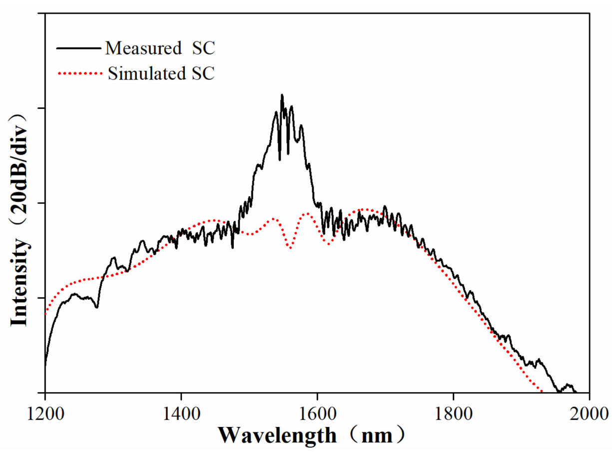

Fig. 7. Comparison of the simulated (the red solid curve) and measured (the black dotted curve).

To verify the experimental result, the generalized nonlinear Schrodinger equation was used to simulate the SC generated from the silicate fiber. Nonlinear coefficient was used as mentioned above, and the dispersion of fiber with 3.5 μm was used in the simulation. The parameters of Raman response were derived from the [20], and τ_1, τ_2 and f_R were 5.5 fs, 32 fs and 0.3, respectively. The measured and simulated SC were shown in the Figure 7, and the SC spectrum of simulation with pumping power of 0.2 W agree well with the experiment with pumping power of 2.2 W. The result indicates that coupling efficiency is about 10% which is comparable with the coupling efficiency of [15].

The degree of coherence of the SC was studied by calculating the spectrum with random noise seeds for 108 times [21]. In addition to fiber length and pump peak power, the simulated parameters were the same as mentioned above. In order to generate wider SC from the fiber, the pumping power and fiber length were set as 0.4 W and 0.3 m, respectively. Figure 8 shows that the SC spectrum has high flatness with deviations of less than 7 dB ranging from 1100 to 2100 nm, and the

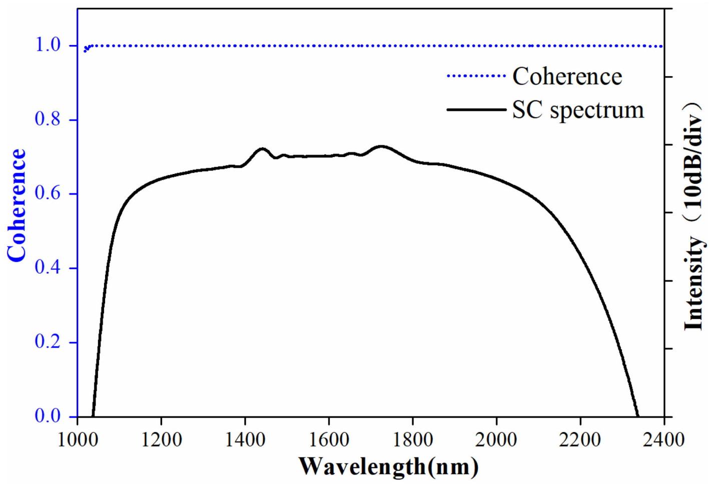

Fig. 8. Coherence and spectrum of the SC for 57 kW pump conditions.

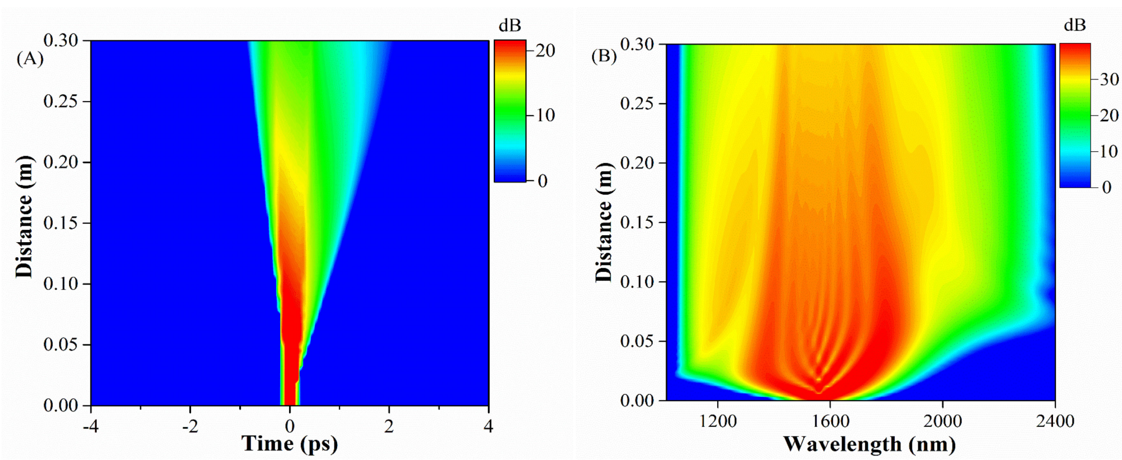

Fig. 9. The temporal (A) and spectral (B) evolution processes of the SC along the propagation distance.

coherence of the SC is 1. The results indicate that a highly coherent SC spectrum covering from 1100 to 2100 nm can be generated using a 30 cm ANDi step-index silicate fiber with peak pumping power of 57 kW. So, the ANDi step-index silicate fiber is a promising candidate for coherent flat SC.

In order to further investigate the SC generation, the spectral and temporal evolution processes of the SC along the propagation distance are simulated. Figure 9 illustrate the simulation results, the spectral and temporal evolutions are mainly dominated by SPM in the initial propagation of the ultra-short pulse. At the beginning of the 5cm fiber length, the spectral evolution is oscillatory, which is a feature of SC governed by SPM. With further propagation, new frequencies of the SC are generated via OWB, and the SC broadens further and becomes flatter. These broadening mechanisms do not amplify the noise of the SC. So, a near-zero and flat ANDi is conducive to generate SC with high coherence.

4. Conclusions

Two thermally matched silicate glasses with refractive index contrast of 0.037 were selected, and a step-index silicate fiber with all normal dispersion was fabricated. 1560 nm femtosecond fiber laser was used to pump the fiber with length of 5 cm, coherent SC spectrum spanning 1200 to 2000 nm was generated. The numerical simulation result agreed with the experiment. The simulation result also shows that coherent SC spectrum spanning from 1100 to 2100 nm with flatness $<$7 dB can generate from 30 cm the silicate fiber with 57 kW pumping power. The step-index silicate fiber is easier to fabricate and splice than MOFs, so the step-index silicate fiber with ANDi is a promising candidate to achieve all-fiber structure for coherent SC.

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