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PREFACE

The 7th Academic Conference on Natural Sciences for Young Scientists, Masters and PhD. Students from ASEAN countries (CASEAN-7) has been successfully held both online and offline on 14-17 October 2021, for a while the Covid situation in Vietnam and neighboring countries is complicated. The CASEAN-7 takes place at two locations, in Ha Noi and Vinh City, Nghe An Province, Vietnam.

The main purpose of the Conference is to provide a good opportunity for young scientists, Master and PhD. students, coming from universities and institutes in ASEAN countries to develop regional exchange activities, mutual understanding and cooperation as well as stimulate scientific training and education.

There were about 200 participants in different fields of natural sciences and from Cambodia, Laos, Malaysia, Myanmar, Philippines, Thailand, and Vietnam. More than 120 scientific reports were presented at the conference. Furthermore, some senior scientists and professors (from China, India, Japan, South Korea, New Zealand,...) were invited to give their talks. The Conference created favorable conditions for all participants to establish new cooperative linkages and also strengthen our friendship.

The CASEAN-7 Proceedings book has published the papers which were presented in the conference and selected by the editorial committee with a standard referee procedure.

We have to say that the success of the CASEAN-7 Conference was resulted from active contributions of all the conference committees, the session chairmen and the participants.

On this occasion, we express our deep thanks to the ASEAN Co-Organizers and Co-Sponsors. Specially, we sincerely thanks to International Centre of Physics (ICP), Institute of Physics (IOP), Vietnam Academy of Science and Technology (VAST) and Vinh University for all its wonderful cooperation and great contribution to CASEAN-7.

We would like to thank the conference secretariat and technicians for their dedication and hard works./.

CASEAN-7 Co-Chairmen

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NUMERICAL SIMULATION SUPERCONTINUUM GENERATION IN ALL-NORMAL DISPERSION SUSPENDED-CORE FIBER INFILTRATED WITH ETHANOL AROUND 1064 NM

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Abstract. In this work, we optimized the structure of suspended-core fiber and filled air holes with ethanol to change the dispersion characteristic to all-normal dispersion for supercontinuum generation. The fiber with a 2.2 μm core diameter filled with ethanol operates in all-normal dispersion region. The SC spectral is formed with the spectrum range from 717 nm to 1700 nm by using a pump pulse with a central wavelength of 1064 nm, pulse width 50 fs, and power of 30 kW.

I. INTRODUCTION

Supercontinuum (SC) generation in all-normal dispersion fiber is studied for its fascinating applications and properties. They have been studied and used in fields such as ultra-short pulse generation [1] and optical coherence tomography [2]. The SC generated in normal dispersion regimen is generated by optical wave breaking (OWB) and self-phase modulation (SPM) [3] mechanisms. Therefore, the SC generation in normal dispersion has the potential for high temporal coherence and flat [4]. For broadband SC generation, numerous efforts have been devoted to extending the spectral width and flatness over wavelength broadband. To achieve this, the initial laser pulse properties should be optimized in terms of pulse duration, pump power, pump wavelength, and input energy [5-6]. Besides, the fiber requires special optical-wave-guiding designs to produce both flat all-normal dispersion and high-nonlinearity properties.

A promising approach is to use suspended core fibers (SCFs) that are fibers composed of small cores, suspended on thin glass bridges [7]. The light is strongly confined in the core of these fibers resulting in high nonlinear coefficient γ [8]. Some articles presenting SCG in silica and soft glasses-based SCFs have been published [9].

In recent years, a promising way to control the dispersion characteristics of SCFs is to infiltrate liquids into the holes of the SCFs. Experimental results of SCFs infiltrated with water have been reported in [4]. In addition, ethanol is also an attractive candidate for SCFs infiltrated with liquids because of its lower refractive index than fused silica, which ensures a modified total internal reflection (M-TIR) mechanism.

In this article, we optimize the dispersion curve of SCFs by infiltrating holes with ethanol. We assume a fiber structure with the core suspended over six thin bridges glass and the background material is fused silica and solved the general nonlinear Schrodinger equation (GNLSE) to demonstrate the SC generation for our optimized fiber structure. We discuss about this structure.

II. MODELING STRUCTURE AND THE STUDY METHOD

The general structure of the investigated fibers is presented in Fig. 1. The background material of the fiber is made of fused silica and consists of six thin glass bridges.

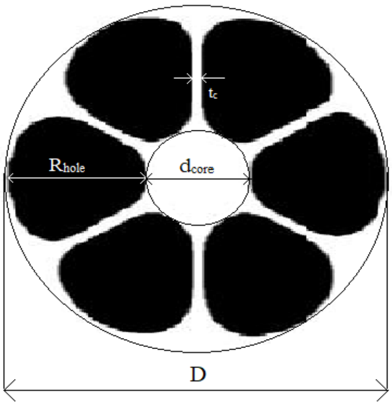

Fig. 1. *The cross-section of simulated SCFs, d_{core} is the core diameter. White area is illustrated fused silica and black area is air or ethanol.*

For modeling, we use the commercial software Lumerical Mode Solution (LMS) on the eigenmode solver method [10]. The refractive indices of the material as a function of wavelength are given by the Sellmeier equation below:

$$n^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \tag{1}$$

where constant B_i and C_i are given in Table 1.

Table 1. *The Sellmeier coefficients of fused silica and ethanol.*

Sellmeier coefficients	**Materials**	
	Fused silica	Ethanol (C_2H_5OH)
B_1	0.6694226	0.83189
C_1 (μm²)	4.4801×10^{-3}	0.0093
B_2	0.6694226	-0.15582
C_2 (μm²)	1.3285×10^{-2}	-49.452
B_3	0.8716947	0
C_3 (μm²)	95.341482	0

We also numerically modeled SCG in the investigated fibers to analyze the nonlinear processes responsible for spectral broadening. We solved the general nonlinear Schrodinger equation (GNLSE) to achieve these goals [11]:

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2}A - \sum_{k\geq 2}\frac{i^{k+1}}{k!}\beta_k\frac{\partial^k A}{\partial T^k} = i\gamma\left(1 + i\tau_{shock}\frac{\partial}{\partial T}\right)\times\left(A|z,t|\int_{-\infty}^{\infty}R(T')\left|A(z,T-T')\right|^2 dT'\right) \tag{2}$$

where α is the total fiber loss, z is the spatial coordinate along fiber and β_k is the *k-th* order of dispersion. The GNLSE in our modeling accounts for dispersion terms β_k up to the 9th order. In our simulations, the pump pulse was Gaussian-shaped, the centered wavelength at 1064 nm.

The fiber's mode effective areas were approximated with fixed values of their core areas. The Raman scattering spectra of the fiber were comparable to the fused silica; hence the Raman response function identical to fused silica was used in both simulations, according to:

$$R(T)=(1-f_R).\delta(T)+f_R\frac{\tau_1^2+\tau_2^2}{\tau_1\tau_2^2}\exp(-T/\tau_2)\sin(T/\tau_1)\Theta(T) \tag{3}$$

where f_R =0.18 is the delayed Raman contribution, τ_1=12.2 fs, τ_2=32 fs, $\Theta(T)$ is the Heaviside step function, δ(T) is the Dirac delta function.

In the numerical simulation of SC generation, we used the split-step Fourier method to solve the GNLSE in the frequency domain for input femtosecond pulse. The analysis is simulated with the following parameters: fiber length 15 cm, pulse width 50 fs, and pump wavelength 1064 nm.

III. RESULTS AND DISCUSSION

In our work, we aim at designing a new suspended-core fiber that allows for low chromatic dispersion inside the all-normal regime, which is employed for a commecial pulse laser at central wavelength of 1064 nm.

We analyze how the diameter of the core affects the linear characteristics of the SCFs, especially the effective dispersion for precise shaping and a wide range of wavelengths in the completely normal mode. In all investigated cases, we only consider the SCF's fundamental mode, as shown in Fig. 2.

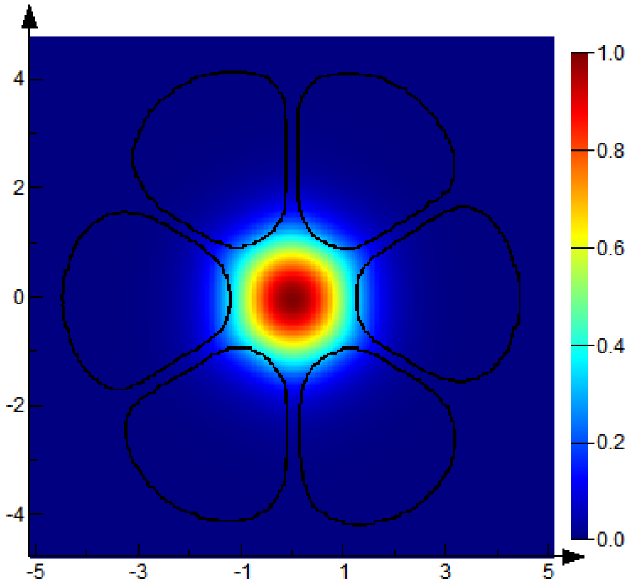

Fig. 2. *Numerically calculated intensity distribution of the fundamental mode of the SCFs.*

To optimize the fiber structure, we first simulate the influence of the diameter core from 4.4 µm to 2.2 µm. The resulting dispersion curves for the fundamental modes are depicted in Fig. 3. Decrease the core diameter leads to increase in dispersion value.

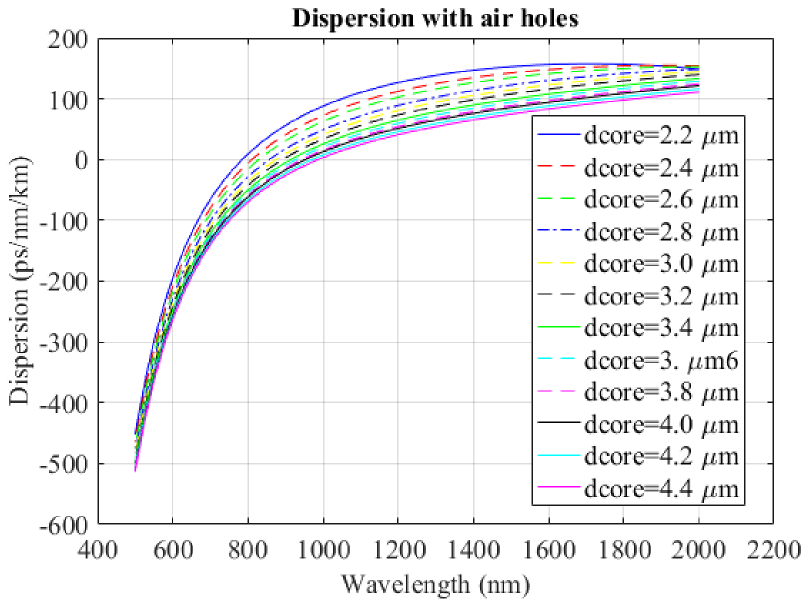

Fig. 3. *Dispersion characteristics of the fundamental mode with air holes.*

In the next step, we filled six air holes with ethanol and Fig. 4 is depicted the dispersion characteristics for different diameters of the core with holes filled ethanol. In the case of fiber filled with ethanol, when the core diameter is reduced from 4.4 microns to 2.2 microns, the dispersion curve changes from anomalous dispersion to normal dispersion.

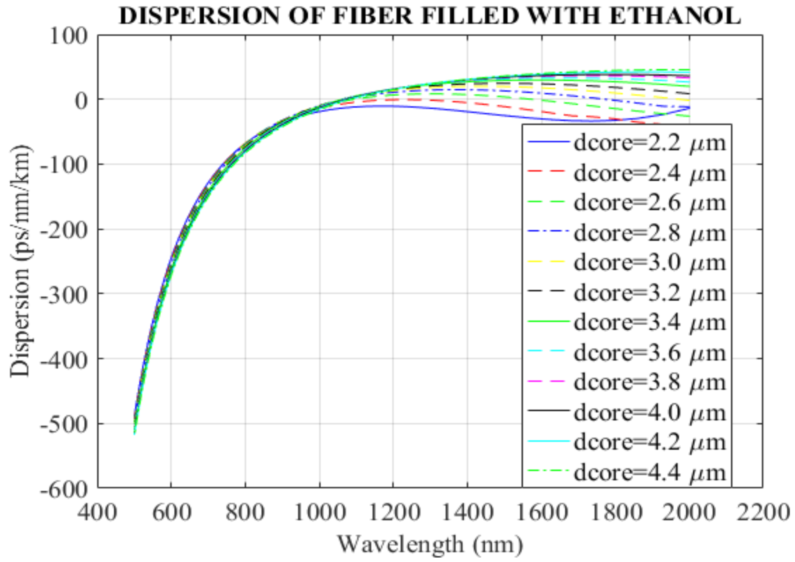

Fig. 4. *Dispersion characteristics of the fundamental mode with ethanol holes.*

Figure 5 shows the different in dispersion characteristics of fiber with 2.2 microns core diameter when the holes filled with ethanol and the air holes. This fiber has optimum dispersion curve for SC generation because it has all-normal dispersion. Where, the dispersion characteristic of fiber with air holes is anomalous dispersion, ZWD is 790 nm, dispersion at 1064 nm is 103.078 ps/nm/km.

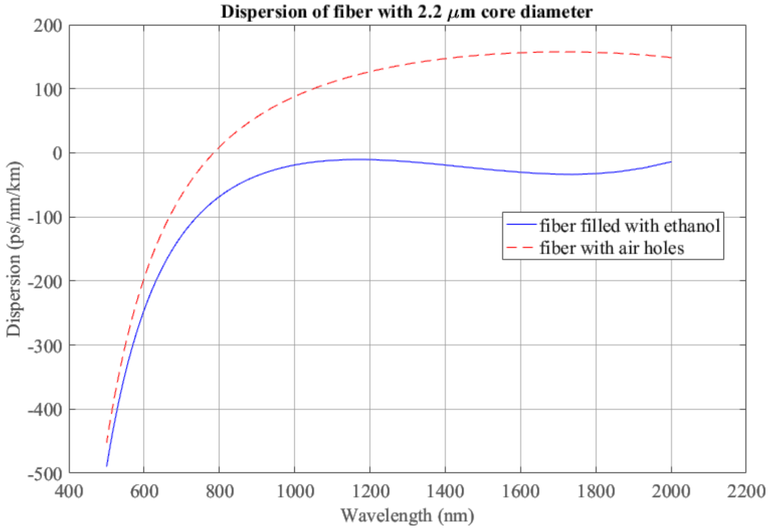

Fig. 5. *Dispersion characteristics of fiber with 2.2 microns core diameter.*

Fig. 6 shows the non-linear coefficient and effective mode area of optimal structure. The non-linear coefficient decrease with wavelength and the effective mode area of fundamental mode increase with wavelength. At wavelength 1064 nm, the non-linear coefficient equal 0.3997 μm^2 and the effective mode area of fundamental mode equal 4.032 W^{-1}m^{-1}. Where, the effective mode area is small because the core diameter is small.

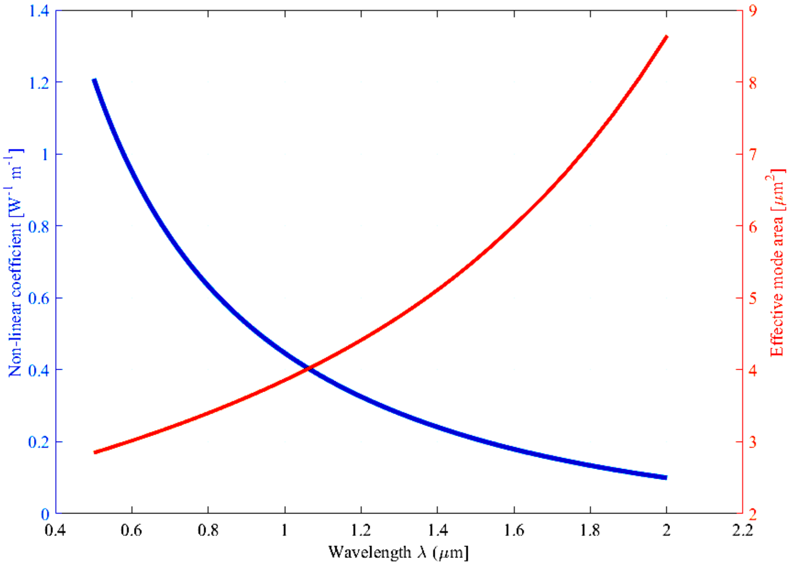

Fig. 6. *Non-linear coefficient and effective mode area of optimal structure SCF.*

In Fig. 7a, the output spectral with difference powers at the 15 cm length of fiber. With pump power of 30 kW, the spectrum range from 717 nm to 1700 nm. Fig. 7b illustrated the spectral of the pulse along the propagation distance with difference powers.

Meanwhile, Fig. 8 shows the spectral and temporal evolution of the pulse along the propagation distance with an input power of 30 kW. The broad spectrum is asymmetric because different frequency components usually have different velocities, the time delay between different frequencies becomes larger with longer propagation.

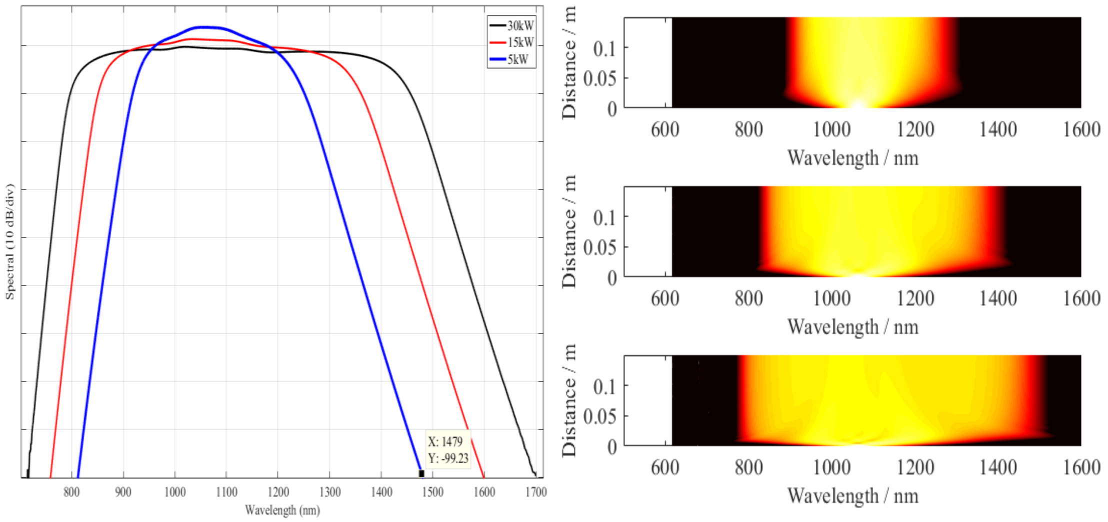

Fig. 7. *a) The output spectrum calculated at distance 15 cm with difference powers, b) Numerical calculations of the output spectral of the pulse along the fiber filled with ethanol.*

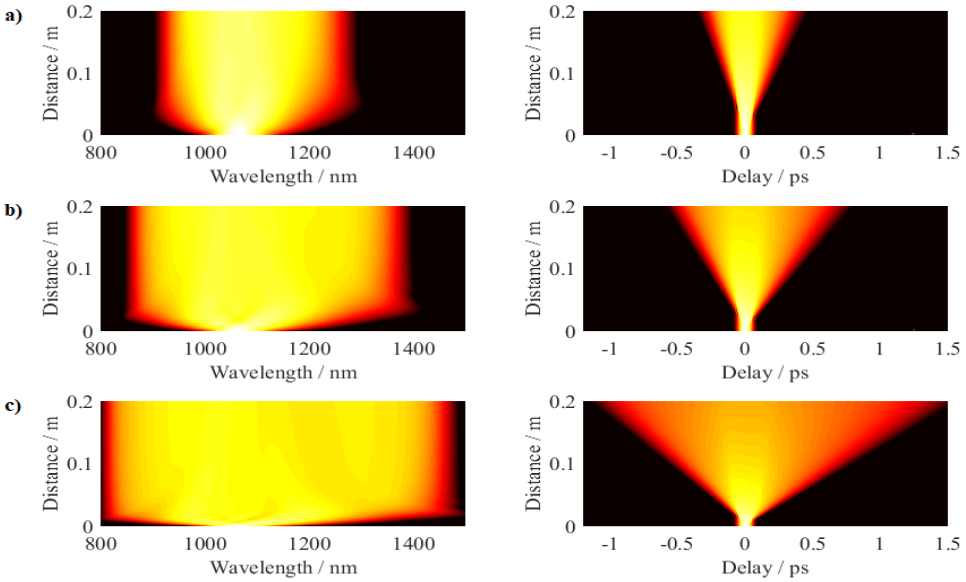

Fig. 8. *Numerical calculations of the spectral and temporal evolution: a) 5 kW; b) 15 kW; c) 30 kW.*

IV. CONCLUSSION

In this paper, we used numerical method on the optimum structure SCFs with background material is fused silica and filled with ethanol. The dispersion characteristic of optimum structure are flat and located in all-normal dispersion for SC generation with pumping at 1064 nm, the optimum structure with 2.2 µm core diameter.

In our result, by using pulses with a central wavelength of 1064 nm, pulse width 50fs and pump power of 30 kW, we obtain output spectrum in the range from 717 nm to 1700 nm. Further increasing the width of the spectral can be expected if we increase input pulse power. The output SC spectral is flat, which has the potential for high temporal coherence.

REFERENCES

[1] Heidt A. M., Rothhardt J., Hartung A., Bartelt H., Rohwer E. G., Limpert J., et al., High quality sub-two cycle pulses from compression of supercontinuum generated in all-normal dispersion photonic crystal fiber, *Optics Express*, 2011, **19**(15), 13873-13879.

[2] Povazay B., Bizheva K., Unterhuber A., Hermann B., Sattmann H., Fercher A. F., et al., Submicrometer axial resolution optical coherence tomography, *Optics Letters*, 2002, **27**(20), 1800-1802.

[3] Heidt A. M., Hartung A., Bosman G. W., Krok P., Rohwer E. G., Schwoerer H., et al., Coherent octave spanning near-infrared and visible supercontinuum generation in all-normal dispersion photonic crystal fibers, *Optics Express*, 2011, **9**(4), 3775-3787.

[4] Trung Le Canh, Van Thuy Hoang, Hieu Le Van, Dariusz Pysz, Van Cao Long, Thuan Bui Dinh, et al., Supercontinuum generation in all-normal dispersion suspended core fiber infiltrated with water, *Opt. Mater. Express*, 2020, **10**, 1733-1748.

[5] Medjouri A., Abed D., Ziane O., Simohamed L. M., Design and optimization of As_2S_5 chalcogenide channel waveguide for coherent mid-infrared supercontinuum generation, *Optik*, 2018, **154**(2018), 811-820.

[6] Hansen K. P., Dispersion flattened hybrid-core nonlinear photonic crystal fiber, *Optics Express*, 2003, **11**(13), 1503-1509.

[7] P. Kaiser, E. A. J. Marcatili, and S. E. Miller, A new optical fiber, *Bell Syst. Tech. J.,* 1973, **52**(2), 265-269.

[8] S. Afshar V., W. Q. Zhang, H. Ebendorff-Heidepriem, and T. M. Monro, Small core optical waveguides are more nonlinear than expected: experimental confirmation, *Opt. Lett.*, 2009, **34**(22), 3577-3579.

[9] Bo Wu, Zheming Zhao, Xunsi Wang, Youmei Tian, Nan Mi, Peng Chen, Zugang Xue, Zijun Liu, Peiqing Zhang, Xiang Shen, Qiuhua Nie, Shixun Dai, and Rongping Wang, Mid-infrared supercontinuum generation in a suspended-core tellurium-based chalcogenide fiber, *Opt. Mater. Express*, 2018, **8**, 1341-1348.

[10] LumericalSolutions, Inc., https://www.lumerical.com/products/mode/.

[11] J. C. Travers, M. H. Frosz, and J. M. Dudley, Nonlinear fiber optics overview, Supercontinuum Generation in Optical Fibers, J. M. Dudley and R. Taylor, Eds., Cambridge University, 2010, 32-51.