SUPERCONTINUUM GENERATION IN THE CLADDING MODE OF PHOTONIC CRYSTAL FIBER WITH HOLLOW CORE

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Abstract. In this paper, we have investigated the supercontinuum generation of propagation in the cladding modes of the photonic crystal fiber PCF 5C_6B with hollow core. As a result, this mode achieved a supercontinuum spectrum with a higher spectral power density that would achieve only when core-pumping the fiber.

I. INTRODUCTION

Supercontinuum generation is a phenomenon that involves the spectral expansion of a narrow laser pulse of high intensity when propagated in a nonlinear medium [1-3]. This is the result of nonlinear effects such as self-modulation, Raman scattering, four-wave mixing, and dispersion characteristics of a nonlinear medium [4, 5]. SC has been created in a variety of nonlinear environment [6, 7] which includes being produced in a chalcogenide waveguide [8], a silicon nitride waveguide [9], and a silica waveguide [10]. Although supercontinuum generation has been produced in various nonlinear environment, photonic crystal fiber (PCF) has emerged as the most common nonlinear medium for supercontinuum generation due to the technical feasibility of changing the dispersion characteristics as well as the nonlinearity [2, 5].

In recent years, simulation studies have shown that if light is confined to the PCF core, it can be easily applied for supercontinuum generation in optical fibers. However, when conducting experiments, we have found that it is difficult to confine light to be only propagated in the core. Light not only propagates at the fiber core, but it also propagates in the cladding mode of the PCF.

Several studies have shown the application of cladding modes to supercontinuum generation in PCFs such as the experimental measurement and numerical analysis of group velocity dispersion in cladding modes of an endlessly single-mode PCF [11] and the investigation of supercontinuum generated in the cladding of highly nonlinear PCF [12]. In the most recent study, scientists have analyzed the contributions of the cladding modes in endlessly single-mode fiber for application to supercontinuum generation [13]. The results indicated that supercontinuum generation performed using the cladding modes of endlessly single-mode fiber had a higher spectral power density that could be achieved only when core-pumping the fiber.

In this paper, we proceed to study the contributions of the cladding modes to the supercontinuum generation process of a PCF 5C_6B with hollow core. We investigated the supercontinuum generation in the cladding modes using Ti:sapphire femtosecond laser

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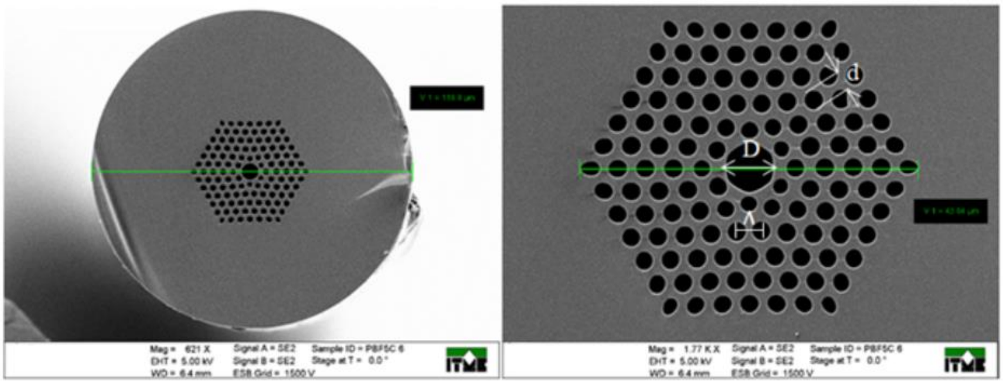
pulses with a central wavelength of 800 nm and with light confined in the core and obtaining the maximum spectral width.

II. THEORY AND EXPERIMENT SYSTEM

2.1. Structure of photonic crystal fiber PCF 5C_6B with hollow core



a) **b)**

Fig. 1. *a) SEM image showed structure of the fiber PCF 5C_6B with magnification 621 times; b) SEM image showed structure of the fiber PCF 5C_6B with magnification 1770 times.*

In this paper, we used PCF 5C_6B with hollow core whose geometric structure is shown in the SEM image in Fig. 1. The substrate material is silica, and the cladding consists of 6 rings with circularly arranged air holes that form an even hexagonal lattice that surrounds the central core of the fiber. The diameter of the fiber is $118.8\ \mu m$. The diameter of each air hole is $d = 2\ \mu m$, and the lattice constant (the distance between the two closest air-hole centers) is $\Lambda = 3.85\ \mu m$. The diameter of the fiber core is calculated by the formula $D = 2\Lambda - 1.1d = 5.5\ \mu m$.

2.2. Supercontinuum generation

We solved the general nonlinear Schrodinger equation (GNLSE) in the frequency domain [4] wherein the GNLSE used is given by:

$$\partial_z \tilde{A} - \sum_{k\geq 2} \frac{i^{k+1}}{k!} \tilde{\beta}_k(z) \frac{\delta^k A}{\delta r^k} + \frac{\tilde{\alpha}(\omega)}{2}\tilde{A} = i\gamma\left(1+\frac{\omega-\omega_0}{\omega_0}\right)\tilde{A}\mathcal{F}\left[\int_{-\infty}^{+\infty} R(T')|A(T-T')|^2 dT'\right] \quad (1)$$

where $\tilde{A}(z,\omega)$ is Fourier transform of the amplitude of a pulse $A(z,T)$, and $R(T)$ is Raman response function.

The left side of Eq. (1) describes linear propagation effects with $\tilde{\alpha}$ and $\tilde{\beta}$ related to attenuation and dispersion of the fiber, respectively. The right side of the equation models the nonlinear effects, which depend on the nonlinear properties of silica. Nonlinear response function $R(T)$ consist of an instantaneous part originating from the electronic bound contribution and a non-instantaneous contribution induced by molecular vibrations. The response function is of the form:

$$R(T) = (1 - f_R)\delta(T) + f_R h_R(T) \quad (2)$$

where $f_R = 0.18$ is the fractional contribution of delayed Raman response, $\delta(T)$ is Dirac delta function, and $h_R(T)$ represents the retarded response.

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In Fig. 2, we used the commonplace Ti:sapphire lasers with a central wavelength of around 800 nm to confine the light tightly to the core, increase the nonlinearity of the fiber, and obtain a maximum spectral width. The input beam is coupled to the survey fiber using the 40X objective (MO1). The output beam is directed to a 10X objective (MO2) to bring the output light into the large-core multimode fiber integrated with the spectrophotometer. For the same pump power capacity, we used the YOKOGAWA-AQ370D spectrum analyzer (range: 600 – 1700 nm) and the Czerny-Turner Ocean Optics Red Tide compact spectrometer (range: 350 – 1000 nm) to record the SC spectrum of Mode 1 and some other basic modes to see the optimization of mode 1 over other modes in the fiber coupling process.

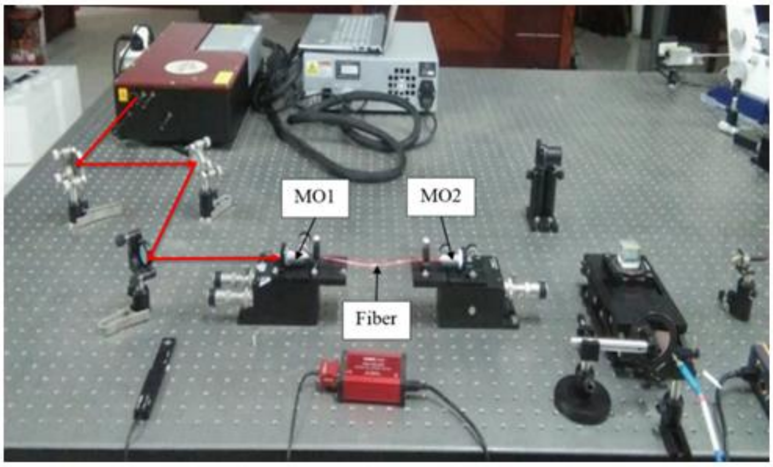
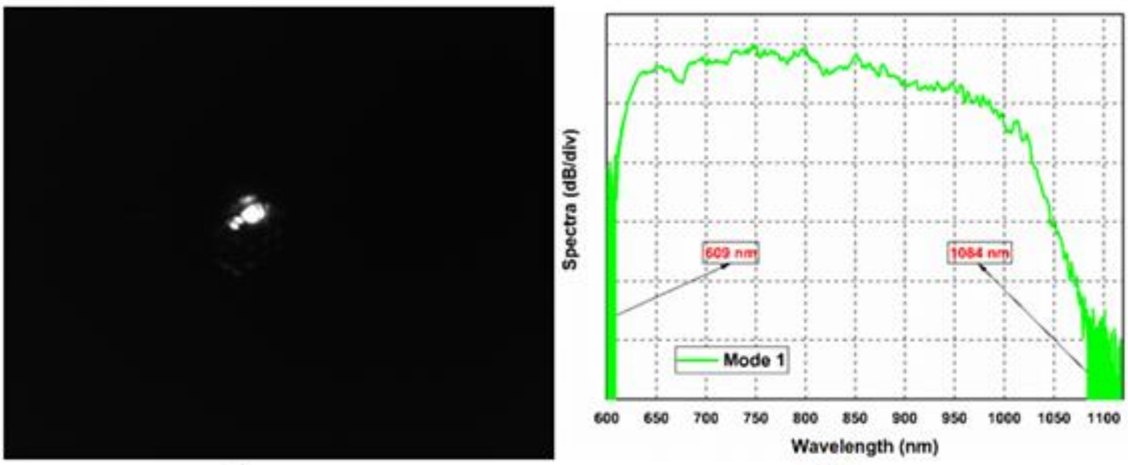


Fig. 2. *Experimental system investigated the supercontinuous generation process in the cladding mode of the photonic crystal fiber with hollow core PCF 5C_6B.*

III. RESULTS AND DISCUSSION

3.1. Supercontinuum in the cladding modes



a) b)

Fig. 3. *a) Mode 1; b) Output spectrum of mode 1.*

Through the experimental system, we investigated the supercontinuum generation process of the photonic crystal fiber with hollow core PCF 5C_6B. We obtained the supercontinuum generation spectrum of the cladding mode and other basic modes shown in Figs. 3, 4, 5, and 6.

First, Fig. 3a is a representation of mode 1, and Fig. 3b shows the dependence of the output spectral intensity with respect to wavelength. For mode 1, we obtained a relatively flat, highly coherent supercontinuum spectrum in a wavelength range from 609 nm to 1084 nm.

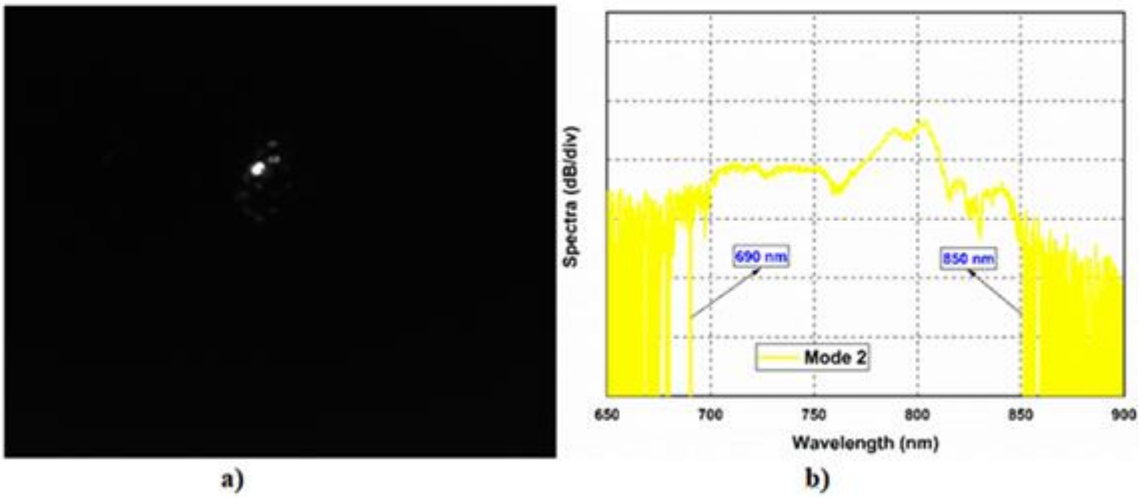


Fig. 4. *a) Mode 2; b) Output spectrum of mode 2.*

Second, Fig. 4a is a representation of mode 2, and Fig. 4b shows the dependence of the output spectral intensity with respect to wavelength. For mode 2, we obtained supercontinuum spectrum in a wavelength range from 690 nm to 850 nm.

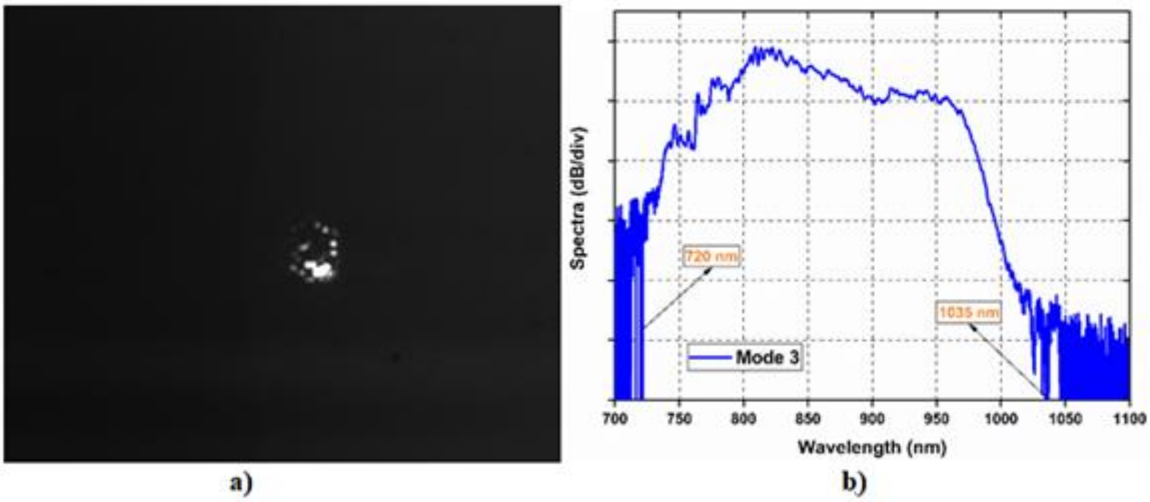


Fig. 5. *a) Mode 3; b) Output spectrum of mode 3.*

Third, Fig. 5a is a representation of mode 3, and Fig. 5b shows the dependence of the output spectral intensity with respect to wavelength. For Mode 3, we obtained supercontinuum spectrum in a wavelength range from 720 nm to 1035 nm.

Next, Fig. 6a is a representation of Mode 4, and Fig. 6b shows the dependence of the output spectral intensity with respect to wavelength. For mode 4, we obtained supercontinuum spectrum in a wavelength range from 665 nm to 864 nm.

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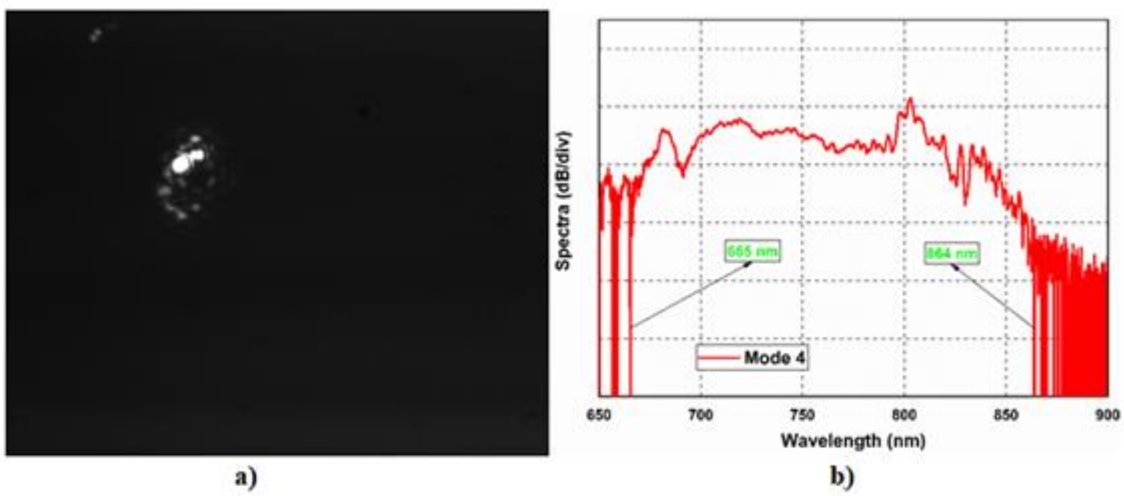

Fig. 6. *a) Mode 4; b) Output of spectrum of mode 4.*

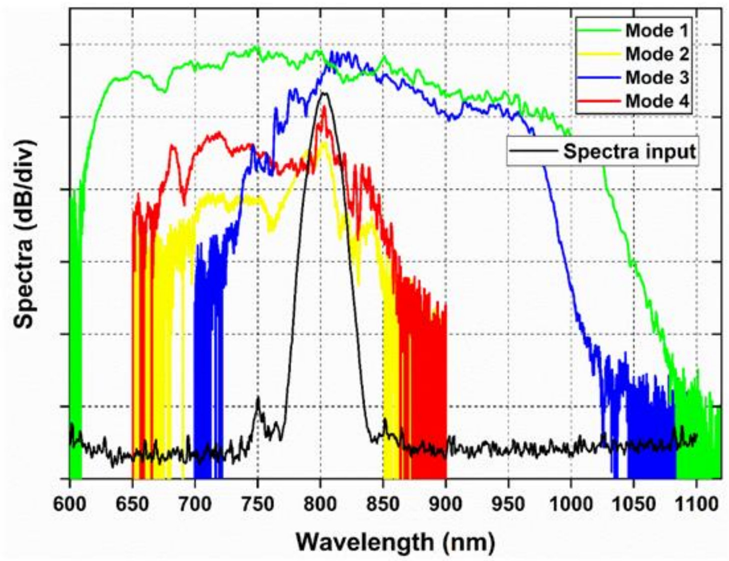

Fig. 7. *Input spectrum of pump laser and output spectrum of modes in the fiber PCF 5C_6B.*

Finally, Fig. 7 shows the dependence of the laser pump source input spectrum and the output spectrum of the modes in PCF 5C_6B with hollow core. We have found that when the laser pump has the same input power at 800 nm, mode 1 obtained a fairly flat, highly coherent, supercontinuum output spectrum expanded than the basic modes 2, 3, and 4. This result shows that Mode 1 is the most optimal mode (off-core) for fiber coupling process.

IV. CONCLUSION

In this paper, we used a femtosecond Ti:sapphire laser with a central wavelength of 800 nm to investigate the supercontinuum process of the cladding mode in PCF 5C_6B with hollow core. The results showed that when the laser pump had the same input power at 800 nm, mode 1 obtained a fairly flat, highly coherent output spectrum wherein the output spectrum is expanded than the basic modes 2, 3, and 4. This is the most optimal mode (off-core) for fiber coupling process.

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