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# Spectrum Broadening of Supercontinuum Generation by fill Styrene in core of Photonic Crystal Fibers

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In this paper, a new photonic crystal fiber with hollow core filled by styrene (PCFS) has been designed for coherent supercontinuum generation. Its main optical characterisitcs are simulated for different lattice microstructure. The $PCFS_{2,0.3}$ with lattice pitch Λ=2 μm, filling factor d/Λ=0.3 and styrene core of diameter of 3.34 μm, owning the flat and anomalous dispersion in the near infrared range from 1.33 μm, lower confinement loss, higher effective refractive index at pump wavelength, and smaller effective mode area is chosen to invetigate the supercontinuum spectrum (SC). The spectrum broadening of SC depending on the fiber's length, pump duration and pump energy is simulated and discussed in comperison to that obtained in the photonic crystal fibers with hollow core filled with toluene ($PCFT_{2,0.3}$).

**Keywords:** Photonic crystal fibres, Fibre dispersion, Supercontinuum generation

## 1 Introduction

A breakthrough in the fiber-optic technology that was in 1996, P. Russell and his colleagues discovered a new kind of optical fibers called photonic crystal fiber (PCF)[1]. Up to now, a series of PCFs have been designed and its properties are studied and improved[2-7]. Recently, the PCF infiltrated liquids are attracted the attention of scientists around the world both in theory and experiment, because of their potential applications and prospect in the fiber optic technology. Theoretical studies have been focusing into two main interesting fields. The first, the most attentions are focused on the solid-core PCF infiltrated liquids into air holes that could control the zero dispersion wavelengths (ZDW)[8], effect of temperature and concentration of liquid on ZDW[9], effect of temperature on the dispersion characteristics of PCF[10], which is seen as the proposals for the dispersive technology[11] and high sensitivity sensor equipment[12]. The second has been focusing on the PCF with hollow core filled gas to use as Raman laser medium[13-15] and liquids to use as the optical sensor[16-23], to generate supercontinuum[24-27].In previous work[27], the toluene ($C_7H_8$) is permeated into the core of PCF, resulting two optimal structures with lattice constant $\Lambda$=2μm, filling factors $d/\Lambda$=0.3 and 0.35, which is applied to create SC.

However, we have also shown the limitations of PCFT as that the effective mode area is large, the bandwidth of ZDW is too large and the confinement loss is high. With above mentions, we suggest using styrene ($C_8H_8$) to replace toluene ($C_7H_8$) and hope that the PCFS can overcome those limitations.

In this paper, we present the obtained results investigate optical properties of the PCFS. The geometry structure, effective index, effective mode area, and dispersion are simulated and discussed to choice the suitable structure for SC generation. The influence of some parameters on the spectrum broadenning of SC is investigated and finally, we discuss all obtained results in comparison to that of PCFT.

## 2 Optical properties of PCF with core filled styrene

A new PCF structure is proposed to designed with a silica substrate and the cladding consists of eight rings of air-holes that ordered in a hexagonal lattice with hollow core infiltrated $C_8H_8$, which is illustrated in Fig. 1. The diameter of the core is determined as $D_c = 2\Lambda - 1.1d$, where $\Lambda$ is the lattice pitch and $d$ is the diameter of the air holes.

In the hollow-core PCF can be fabricated using the conventional stack-and-draw method[28]. Then, it is selectively filled liquid into the core using thermal fusion splicer[29], or laser writing technique[30], next, is integrated with a microfluidic pump system to fill liquid into the core[29].

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The main materials in the structure of PCFS are styrene[31], and fused silica[32]. Their refractive index is a function of the wavelength described by the Sellmeier formula shown in Eq. 1:

$$n^2(\lambda) = B_0 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \quad \ldots (1)$$

Table 1 — Dispersion parameters of Styrene[28] and fused silica[29]

| Parameter | Value |
|---|---|
| *Styrene* | |
| $B_0$ | 1 |
| $B_1$ | 1.2542 |
| $C_1$ | 0.013862 μm$^2$ |
| *Fused silica* | |
| $B_0$ | 1 |
| $B_1$ | 0.6694226 |
| $B_2$ | 0.4345839 |
| $B_3$ | 0.8716947 |
| $C_1$ | 4.4801×10$^{-3}$ μm$^2$ |
| $C_2$ | 1.3285×10$^{-2}$ μm$^2$ |
| $C_3$ | 95.341482 μm$^2$ |

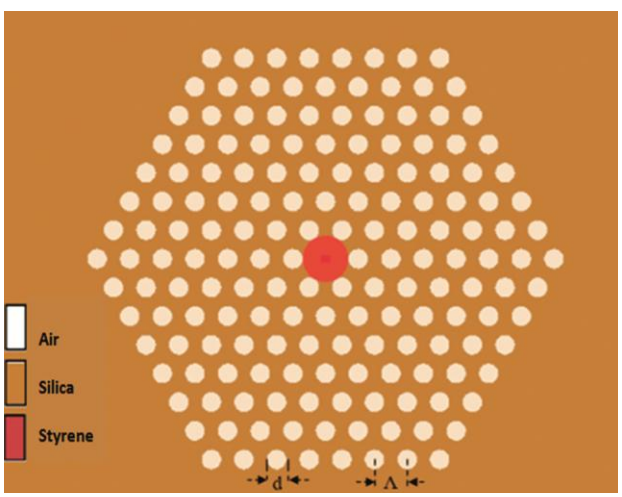


Fig. 1 — The geometry structure of the PCF with core filled styrene

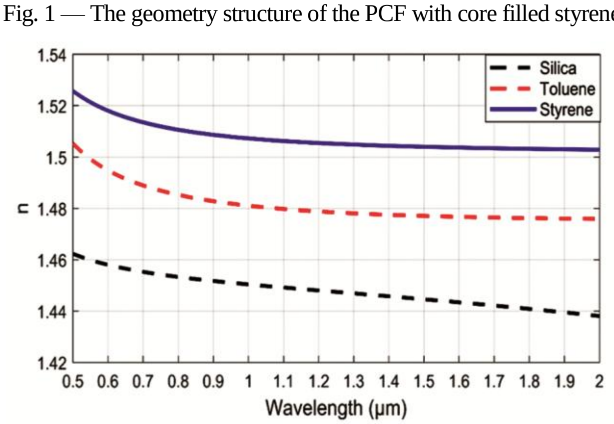


Fig. 2 — Real part of $n$ vs. $\lambda$ of styrene, toluene[27] and silica

Where λ if the pump wavelength and the parameters $B_0 \ldots B_3$ and $C_1 \ldots C_3$are listed in the Table 1.

The real parts of the refractive index of styrene and fused silica are shown in Fig. 2.

As it is shown in figure, the refractive index of the styrene is higher than that of toluene and sillica. That means, the hollow core PCFS will be more effective for index guidancein comparison to PCFT[27,33], resulting the SC generation could be more efficient.

Using the expressions of the effective refractive index, $n_{\text{eff}}$[34], effective mode area, $A_{\text{eff}}$[35], dispersion, $D$[36] and confinement loss, $L_c$[37], the main optical properties of PCFS are numerically analysed for structures with $\Lambda$=2.0 μm and different filling factor, $d/\Lambda$ of 0.3 to 0.8 by the Lumerical Mode solution software and presented in Figs. 3-6.

From Fig. 3-6, we see that all optical properties of PCFS change as well as conventional PCF. However, there is an important feature of PCFS, that the main

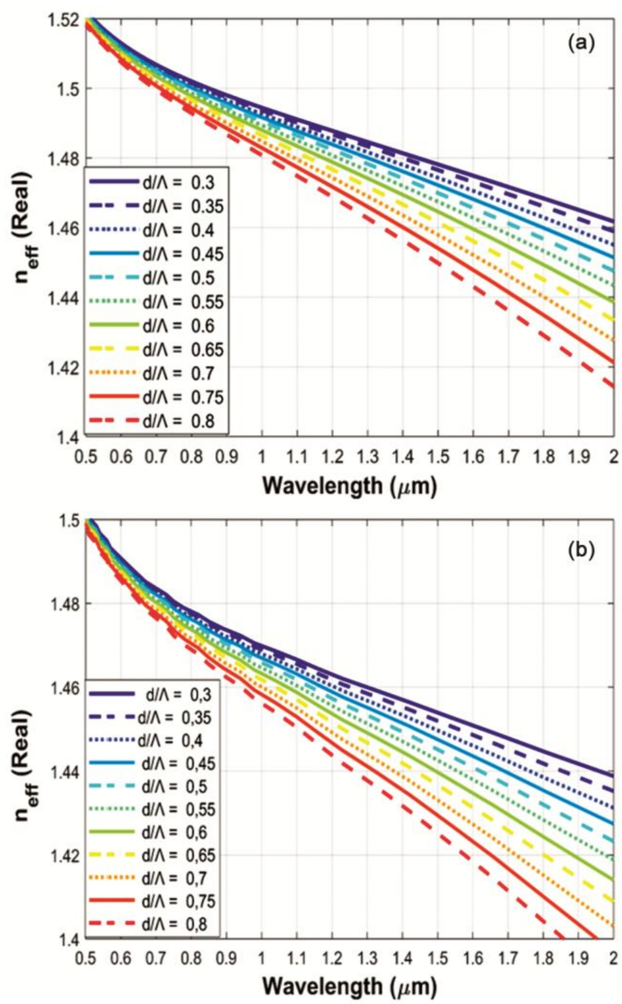


Fig. 3 — The real part of $n_{eff}$ vs. $\lambda$ for PCFS (a) and PCFT (b)

properties as the confinement loss, effective mode area, and dispersion significantly improve in comparison to that of PCFT. In detail, the confinement loss is lower, the effective mode area is smaller, and especially, the bandwidth of ZDW in PCFS is narrower than that of PCFT (see Fig. 6), that is in good agreement to our hope. This important feature of PCFS is caused by its high effective refractive index.

The main difference between PCFS and PCFT is that the ZDW appears at λ=1.33672μm for the $PCFS_{2,0.3}$, but exists not for $PCFT_{2,0.3}$ (see Fig. 6). It is an advantage to use the pump wavelength in the near infrared region for SC generation in PCFS.

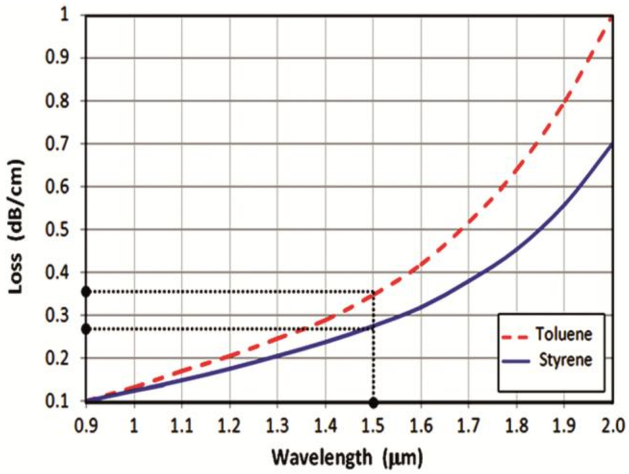


Fig. 4 — The $L_c$ vs. $\lambda$ calculated for $PCFS_{2,0.3}$ (blue-solid) and $PCFT_{2,0.3}$ (red-dash).

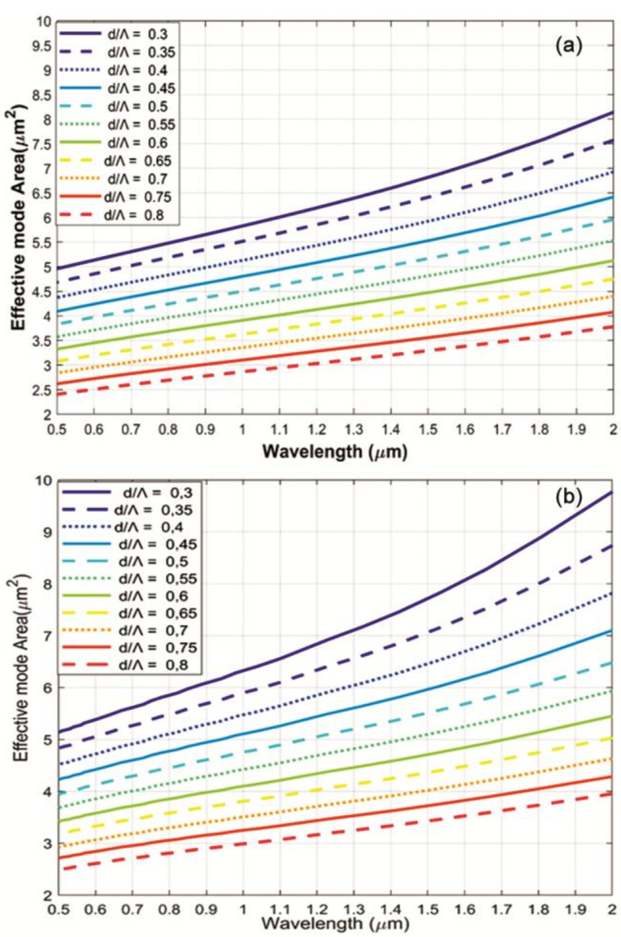


Fig. 5 — The $A_{eff}$ vs. $\lambda$ with $\Lambda$= 2μm and different $d/\Lambda$ for PCFS (a) and PCFT (b)

## 3 Supercontinuum generation

The optical properties of the $PCFS_{2,0.3}$ simulated and compared with that of the $PCFT_{2,0.3}$ are seen as a suggestion to use it for the SC generation. First, the effective refractive index is higher, the confinement loss is smaller, consequently, the effective mode area smaller ($A_{eff}$≈$6.3\times10^{-12}$$m^2$), resulting the pump energy will be much larger storaged in the core. In addition, the nonlinear refractive index coefficient of the styrene belong to asene ogranic solvents is about

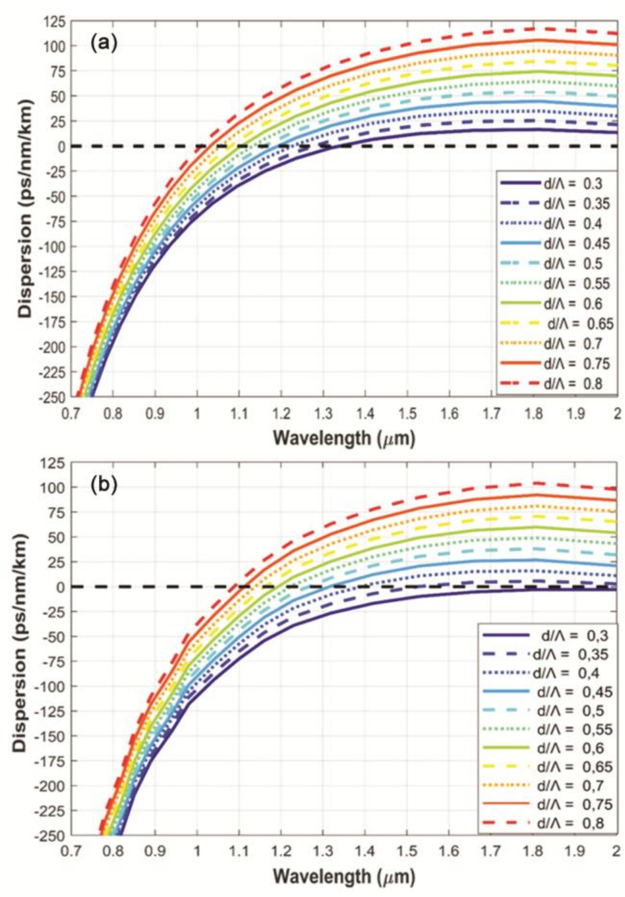


Fig. 6 — The D vs. λ for some stuctures of PCFS (a) and PCFT (b)

$2\times10^{-18}m^2/W$[38], resulting nonlinear coefficient at pump wave length of $\lambda$=1.55μm,

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \approx 1246 W^{-1} km^{-1}$$

high enough[39] for the nonlinear effects as the soliton fission, induced Raman scattering[13-15], four wave mixing, self-phase modulation, cross-phase modulation[39-40], which will be more effective in the PCFS $_{2,0.3}$.

Using all optical parameters received above we have simulated SC generated in the $PCFS_{2,0.3}$ for fundamental mode. To receive SC we have solved the generalized nonlinear Schrödinger equation using split-step fourier method[27,34,39]. We have analyzed the SC for 1.55 μm laser pump pulse with different widths, energies propagating along different length of $PCFS_{2,0.3}$.

The spectrum evolution along length of 1 cm of $PCFS_{2,0.3}$ (Fig. 7a) and spectrogram of broadened pulse (Fig. 7b). The spectrum evolution map is similar to that of $PCFT_{2,0.3}$ (in set) as well as Fig. 8a in previous work[27]. As it is shown in Fig. 7c, there is a different point that the SC spectrum for the $PCFS_{2,0.3}$ with anomalous dispersion (see Fig. 6b) is broadened from 1.2 to 1.85μm at power level of -55dBm/nm, *i.e.*, the broadband spectrum is 600 nm, meanwhile for the $PCFT_{2,0.3}$ with all-normal dispersion the broadband is 500 nm, only. The spectrum broadening on both sides of pump wavelength is remarkable for length 10 cm of $PCFS_{2,0.3}$ (see Fig. 8c). Although, the SC power is slightly reduced by absorption for longer distance, butits spectrum is more broadened from 0.9 to 2.5μm at power level -80 dBm/nm.

But at power level of -60dBm/nm, the spectrum width of SC for $PCFS_{2,0.3}$ is 1.5 time broader than that of $PCFT_{2,0.3}$ .

Moreover, at power level higher - 55dBm/nm, the spectrum is flat. The flatness of spectrum is enhanced for the fiber length longer than 4cm (Fig. 9a) and with increasing of the pump pulse width (Fig. 9b). The spectrum is wider with increasing of the pump energy (Fig. 9c).

It is clear that the spectrum broadening in PCFS is more intense in comparison to that of PCFT.

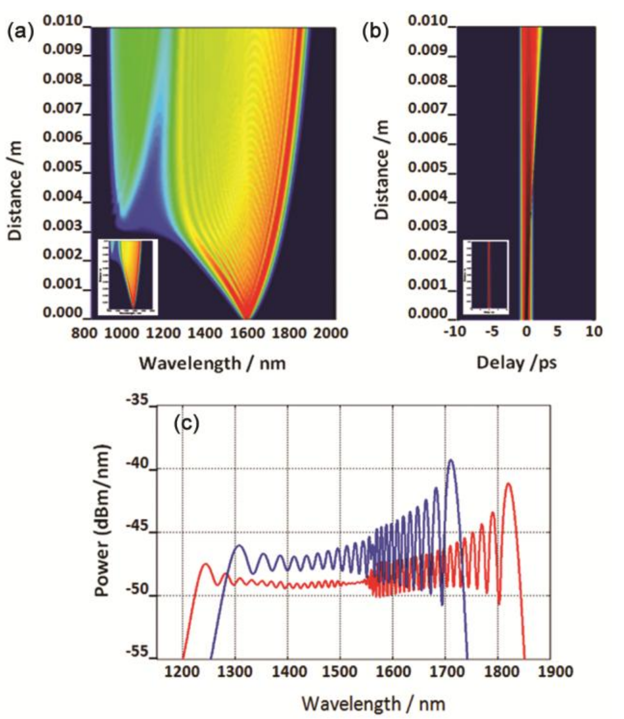


Fig. 7 — Spectrum evolution along fiber length of 1 cm (a: $PCFS_{2,0.3}$, inset: $PCFT_{2,0.3}$); spectrogram of broaden pulse (b: $PCFS_{2,0.3}$ , inset: $PCFT_{2,0.3}$); c: Supercontinuum spectrum estimated for length 1cm of $PCFS_{2,0.3}$ (red) and $PCFT_{2,0.3}$ (blue). The input pulse had width of 350fs and energy of 2nJ.

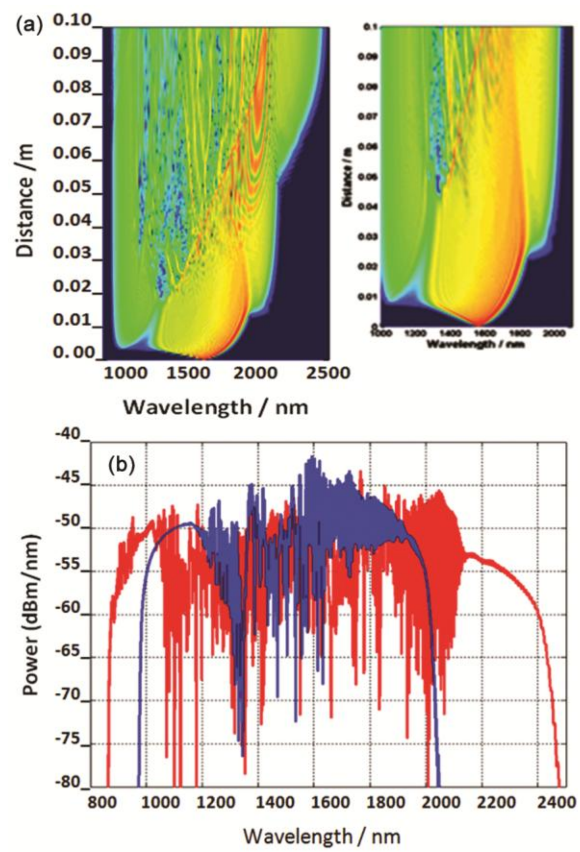


Fig. 8 — a) Spectrum evolution of $PCFS_{2,0.3}$ (a) and $PCFT_{2,0.3}$ (inset) andb) SC spectrum estimated for length 10cm of $PCFS_{2,0.3}$ (red) and $PCFT_{2,0.3}$ (blue).The input pulse had a width of 350fs and energy of 2nJ.

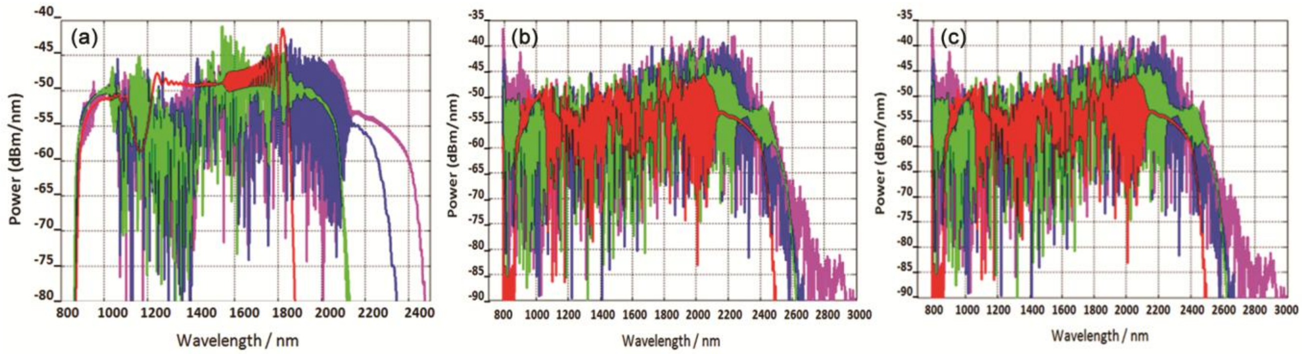


Fig. 9 — Supercontinuum spectrum of $PCFS_{2,0.3}$ simulated for length 1cm (red), 4cm (green), 7cm (blue) and 10cm (magenta) with pump energy E = 2nJ, width T = 350fs (a); for length 10cm, with pump energy 2nJ and width T = 50fs (magenta), 150 fs (green), 250fs (blue) and 350fs (red) (b); and for length 10cm with pump width T = 350fs and energy E = 2nJ (red), 4nJ (green), 6nJ (blue) and 8nJ (magenta) (c).

Moreover, the spectrum broadening is more effective when the length is longer, the pump duration is shorter and pump energy is higher, that enhances the nonlinear process in PCFS. Particulally, the nonlinear processes assoliton fission, self-phase modulation, and group velocity dispersion, non-solitonic radiation (or phase-matched four wave mixing) and induced Raman scattering will replace many times in the long PCFS with high nonlinearity relating to short pump pulse and high pump energy.

## 4 Conclusion

Some optical parameters of microstructured optical fiber designed from silica substrate with cladding consisting of eight rings of air-holes ordered in a hexagonal lattice and hollow core filled styrene are numerically analyzed. Due to high refractive index of styrene, the PCFS has high effective refractive index. For all mentioned structures, the anomalous dispersion regime always appears in PCFS. The optimal$PCFS_{2,0.3}$ for that the dispersion is flat and closed to ZDW, specially, its confinement loss and effective mode area are smaller than that of $PCFT_{2,0.3}$[27].

The supercontinuum generation in $PCFS_{2,0.3}$ was numericaly simulated for pump pulse with different energy, duration and different length of fiber. The obtianed SC spectrum is remarkable broadened. The obtained broadband spectrum of 600 nm is stable at power level of -55dBm/nm in infrared wavelength range to 2.5μm for $PCFS_{2,0.3}$ of length 1cm, but it can be broadened to 1400 nm for the long fiber, short pump pulse and high pump energy. The broadband spectrum of SC in PCFS is flat, wider and enhanced with increasing of fiber length, energy and decreasing of pump duration. Althougth loss of $PCFS_{2,0.3}$ is till high that can cut the spectrum shorter for long fiber, but because of small effective mode area, high effective index and high nonlinearity of $PCFS_{2,0.3}$, the broadband spectrum keeps flat and stable for length of centimetres. The $PCFS_{2,0.3}$is suitable for SC generation which needs the pump pulse with relatively long duration low energy. The obtained results could be a hint towards the experimentally design of a PCFS and theoretically investigate SC in PCF filled with higher nonlinnear liquid. We hope PCFS could be used as a wavelength division multiplexing source with flat and wide spectrum in the furture.

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