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Broadband supercontinuum generation in hollow-core photonic crystal fibers infiltrated with chloroform

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The chloroform-infiltrated square lattice photonic crystal fibers (PCFs) are designed with the difference of the air hole diameters in the cladding to improve chromatic dispersion and nonlinear properties. Based on numerical simulation results, two optimal structures with flat dispersion, high nonlinear coefficient, and small confinement loss are used for supercontinuum (SC) generation. The first fiber has an all-normal dispersion regime, a nonlinear coefficient of $486.355\,\mathrm{W^{-1}.km^{-1}}$ generating an SC spectrum of 640.3 nm within 30 dB levels at a pump wavelength of $0.945\,\mu$m with peak power as low as 1.44 kW. With anomalous dispersion properties, the second fiber gives a very broad SC spectrum of 1471.8 nm within 30 dB levels at a $1.4\,\mu$m pumping wavelength with a peak power of 20 kW. All-fiber SC sources operating with low-power pump lasers can use these fibers to effectively replace glass-core fibers.

Keywords: PCF; $CHCl_3$ infiltration; broadband supercontinuum generation; low peak power; all-normal dispersion; anomalous dispersion.

1. Introduction

In recent years, different approaches to photonic crystal fibers (PCFs) in numerical simulation as well as in experiment have been implemented to obtain high supercontinuum (SC) generation efficiency and enhance its applicability in practice. Many new nonlinear materials have been developed, diversifying the non-silica-based fiber technology.[1–8] However, silica-based PCFs have always been attractive to research groups because they are a traditional optical fiber material, suitable for practical fiber fabrication despite limitations in extending the SC spectrum. Furthermore, the

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advancement of fiber fabrication technology has made it possible to fabricate silica fibers with many new designs. Therefore, every attempt to enhance the nonlinear performance of silica fibers[9–12] and widen the scope of SC applications has been verified in many publications.[12–17] One of the ways of interest is to fill the hollow core of the PCF with a highly nonlinear liquid. The advantages offered by these PCFs include controllable dispersion properties, improved nonlinear properties, broad spectrum SC generation, and experimentally fabricable fibers. The diverse dispersion properties including all-normal (ANDi) and anomalous dispersion regimes are obtained in the PCFs.[18–20] Flat dispersion, small value, even ultra-flat, and near-zero in a wide wavelength range has been found in some recent studies.[21,22] Moreover, the nonlinearity of PCF is significantly improved i.e. one achieves a high nonlinear coefficient, small effective mode region, and low confinement loss, which can be beneficial for the SC process.[23–25] Unlike silica, nonlinear fluids show high nonlinearity and hence can generate a broad SC spectrum in a very short length of optical fiber with relatively lower input power.[26,27] In the experiment, highly nonlinear liquids were filled into the cores of PCFs by integrating a microfluidic pumping system using a thermal fusion splicer or laser writing technique.[28] These fibers can be easily fabricated by the conventional stack-and-draw method.[20]

The way in which nonlinear effects occur to govern the SC spectrum expansion and generate new frequency components as the laser pulse propagates in a highly nonlinear liquid-infiltrated PCF is strongly dependent on its dispersion profile. When the input pulse is excited in the normal dispersion mode, the soliton dynamics and related nonlinear effects can be avoided, but the spectral bandwidth is not significantly broadened. ANDi PCF with a convex dispersion regime, flattened near the pump wavelength, can produce a highly coherent, flat-top SC spectrum due to the dominance of self-phase modulation (SPM) effect, followed by optical wave breaking (OWB) but pump wavelength is higher than that of conventional.[20,25,29] The soliton dynamics[30] including soliton fission (SF), soliton self-frequency shift (SSFS), and blue-shifted dispersive waves (DWs) are responsible for the SC spectrum expansion when the input pulse is excited in the anomalous dispersion regime. The spectral bandwidth is significantly broadened with lower pump power but the spectrum is noisy.[19,27]

So far, there have been only a few publications on the generation of SC using silica-based PCFs filled with hollow-core by chloroform ($CHCl_3$). The high nonlinearity of these fibers implies that SC with broadband can be generated with low peak power pump pulses in a short-length fiber. SC spectrum expansion to 1100 nm with a peak power of 2 kW and within a short propagating distance of only 5 mm was observed in $CHCl_3$-infiltrated PCFs into the air core.[31] The highly coherent spectrum, with a bandwidth of 1020 nm, is testified in $CHCl_3$-filled PCF with appropriate geometric parameters. Although the nonlinear coefficient of the PCF is quite small, $640\,W^{-1}\cdot km^{-1}$, it still allows the propagation of the laser pulse in the 1 cm-long fiber with a peak power of 47 kW.[32] Meanwhile, the work[33] shows that the SC spectrum can be achieved with broadband 660 nm and 800 nm within two fibers with an all-normal and anomalous dispersion regime with 2.5 kW peak power. The nonlinear coefficients of the fibers are $1290\,W^{-1}\cdot km^{-1}$ and $440\,W^{-1}\cdot km^{-1}$, respectively.

$CHCl_3$ can become a typical choice for use in highly nonlinear liquid-core PCFs due to some of its interesting characteristics. Although the nonlinearity of $CHCl_3$ ($n_2 = 1.64\times10^{-19}\,m^2\cdot W^{-1}$)[34] is lower than that of toluene (C_7H_8) ($n_2 = 16\times10^{-19}\,m^2\cdot W^{-1}$) and carbon disulfide ($CS_2$) ($n_2 = (4.3-5.1)\times10^{-18}\ m^2\cdot W^{-1}$), which might be equivalent to carbon tetrachloride (CCl_4) ($1.53\times10^{-19}\,m^2\cdot W^{-1}$) but it is one order of magnitude higher than fused silica (SiO_2) ($n_2 = 2.74\times10^{-20}\,m^2\cdot W^{-1}$).[35] This allows the electromagnetic field modes to be better confined in the core of the PCF. In practical applications, the toxicity of liquids infiltrating PCF is a safety concern. The advantage of $CHCl_3$ is its negligible toxicity when compared with CS_2 and C_7H_8.[36] To design single-mode silica PCFs efficiently, coupling with the standard silica fibers used in the all-fiber pump laser system is extremely important. Fortunately, the linear refractive index of $CHCl_3$ is only about 0.012 lower than that of silica. This enables the fabrication of $CHCl_3$-infiltrated silica fibers in practice to achieve higher coupling efficiency.[37]

Some research results on SC generation through hollow-core PCF filled with other liquids such as tetrachlorethylene (C_2Cl_4), ethanol (C_2H_5OH), benzene (C_6H_6) and nitrobenzene ($C_6H_5NO_2$) are presented in Table 1.

In the experiment, square-lattice PCF can be performed with a standard fabrication process, stack, and draw. It is also useful in the integrated optical devices

Table 1. Overview of SC generation in several liquids-infiltrated PCFs.

Structures	Liquids	Fiber length (cm)	Pump wavelength (μm)	Dispersion regime	SC range (nm)	Input peak power (kW)	Refs.
Hexagonal (#F_1)	C_2Cl_4	5	1.56	all-normal	1180	16.67	18
Hexagonal (#F_2)		10	1.56	anomalous	1000	16.67	
Hexagonal (#F_3)		10	1.03	anomalous	1700	20.83	
Hexagonal (#F_1)	CCl_4	30	1.35	anomalous	1300	2.67	20
Hexagonal (#F_2)		30	1.064	all-normal	350	2.67	
Hexagonal	C_2H_5OH	20	1.55	anomalous	1000	50	22
Circular (#F_1)	C_7H_8	1	1.064	all-normal	800	0.45	23
Circular (#F_2)		10	1.55	anomalous	1100	0.56	
Hexagonal (#F_1)	C_6H_6	1	1.55	all-normal	1300	55	25
Hexagonal (#F_2)		1	1.55	anomalous	2000	37	
Hexagonal (#F_3)		1	1.55	anomalous	2900	37	
Hexagonal (#L0.3)	C_7H_8	10	1.55	all-normal	575	7.14	27
Hexagonal (#L0.35)		10	1.55	anomalous	750	6.67	
Hexagonal (#F_1)	$C_6H_5NO_2$	5	1.03	anomalous	1000	0.83	29
Hexagonal (#F_2)		5	1.56	all-normal	1300	5.56	
Hexagonal (#F_3)		5	1.56	anomalous	1000	0.67	
Hexagonal	$CHCl_3$	0.5	0.8	anomalous	850	2	31
Hexagonal	$CHCl_3$	1	1.06	anomalous	1020	47	32
Hexagonal (#F_1)	$CHCl_3$	10	0.92	all-normal	660	2.5	33
Hexagonal (#F_2)		10	1.03	anomalous	800	2.5	
Hexagonal	CS_2	14	1.56	anomalous	640	560	38

of a rectangular or a square cross-section with pig-tail fibers.[39] Some publications show that high birefringence, dispersion compensation, low confinement, and large mode area for data transmission can be achieved by introducing defects into square-lattice PCFs.[40] It can be seen that square-lattice PCF has not yet been extensively investigated in fiber fabrication experiments and other promising applications of SC generation. The results of our study illustrate the potential of the selected optimal structures for applications involving low peak power and broadband SC. In this report, we investigate $CHCl_3$-infiltrating PCF-based SC with a square lattice for the first time. The fibers' chromatic dispersion and nonlinear properties are investigated in detail based on numerical simulation results. The ability to generate a broad SC spectrum with low peak power is also verified for two optimal fibers. With a nonlinear coefficient as high as $486.355\,W^{-1}\cdot km^{-1}$, the first fiber emits a broad SC spectrum of 640.3 nm within 30 dB levels in an all-normal dispersion regime with a low peak power of 1.44 kW. The cause of the spectral expansion is attributed to the SPM effect. The soliton dynamics enable the SC spectrum to be broadened to 1471.8 nm at 30 dB levels with a peak power of 20 kW using a second fiber with an anomalous dispersion regime. Although this fiber has a nonlinear coefficient about nine times smaller than the first fiber, the low dispersion of −1.631 ps/nm.km at the pump wavelength is an advantage for the SC spectrum expansion.

2. Numerical Modeling of the PCFs

At the center of the PCF is a hollow core filled with $CHCl_3$, eight regularly arranged layers of air holes surrounding the core in a square lattice. Defects are reasonably introduced to optimize the dispersion and nonlinear properties of the fiber. The geometric cross-sections of the PCFs are described in Fig. 1(a). The work[41] demonstrated the effect of dispersion improvement, including zero-dispersion wavelength (ZDW) shift when modifying the size of the innermost layer. The attenuation of the fundamental mode and even the higher modes is also affected by the size of the remaining layers. Inspired by this, we designed PCFs with a filling factor d_1/Λ varying from 0.3 to 0.8 with a step of 0.5 (d_1 being the diameter of the air holes of the first layer near the core) while d_2/Λ is kept 0.95 constant (d_2 is the diameter of the other layer's air holes). The distance from the center of the core to the air holes and between the air holes is called lattice pitch Λ, Λ changes by 1.0, 1.5, 1.8, and 2.0 μm. The core diameter of the PCF is also an essential structural parameter because the size of the core affects its ability to be confined in light modes. It is always important to keep the core size as consistent as possible because it is small enough to enable dispersion engineering by designing photonic cladding and large enough to reasonably match the PCF-mode field diameters with the telecommunication single mode fiber. Our PCFs with core diameters determined by the formula $D_c = 2\Lambda - 1.1d_1$ ensure an effective guide index with reasonably large-mode field diameters. This improves dispersion to match conventional femtosecond laser pumps. The electromagnetic field modes are well confined in the PCF core, as shown in Fig. 1(b).