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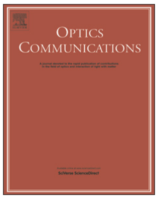

Numerical simulation for optimizing mode shaping and supercontinuum flatness of liquid filled seven-core photonic crystal fibers

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ABSTRACT

A seven-core photonic crystal fiber filled with commercial index-matching liquids is designed to optimize mode shaping and supercontinuum flatness. Numerical simulation of supercontinuum generation in these liquid-filled seven-core PCFs is conducted at 25 °C. The definition of spectral flatness measure is used to quantitatively describe SC flatness. Numerical simulations are performed to study the propagation of femtosecond pulse in the liquid-filled seven-core PCFs. Results show that mode shaping and supercontinuum flatness can be easily optimized and modified using the index-matching liquids in seven-core PCF without varying the structure of the air rings around the guiding cores. Simulations also show that 50 fs pulses with a center wavelength of 1064 nm generate relatively flat SC spectra in the 25 cm-long liquid-filled PCF. A flat spectral bandwidth of 400 nm (900–1300 nm) is achieved with an applied pump power of 30 kW. The simulation results demonstrate that using index-matching liquids to fill the inner ring of the seven-core PCF optimizes mode shaping and generates flat SC spectrum in specified wavelength region. Results further demonstrate that the SC flatness increased with increasing PCF dispersion corresponding to pump wavelength, on the premise that generated enough spectrum width, when the pump worked in the normal dispersion region. Temperature barely affects the spectrum flatness, but can affect spectrum broadening.

1. Introduction

Supercontinuum (SC) generation has become an active research topic over the last few years [1–7] because of its unique application in diverse fields. Photonic crystal fibers (PCF) are ideal medium for SC generation because of design flexibilities in its dispersion and nonlinear properties. The design and manufacture technology of PCF have been improved in the past 10 years.

For a further upscaling the performance of SC fiber lasers, the multicore photonic crystal fiber (MCPCF) has become an attractive topic because such fibers provide larger mode areas that can reduce thermo-optical damage and stress-induced beam distortion in high-power fiber lasers and amplifiers [8–14]. The coherent beam combining technology requires every combining beam to have the same phase. Given that the in-phase supermode in a MCPCF can be achieved when individual core outputs are phase locked [15], the broad use of MCPCF in fiber lasers is impeded by difficulties in suppressing high-order supermodes, which significantly lower the far-field beam quality of the fiber-laser output. A great amount of research [14–22] has been aimed at making MCPCF operate in a particular in-phase supermode. Spectrum flatness is another critical factor for specified SC applications; e.g., time-resolved measurements, amplification of SC pulses in parametric processes or for few-cycle or single-cycle pulse generation [4]. Researchers have found that soliton dynamics could be avoided when pumping occurs entirely in the normal dispersion regime and changing the pump parameters could generate flat spectrum. Given that the dispersion curve and the shape of in-phase supermode could be controlled and modified by varying the structure of air holes around the guiding cores, most of the previous methods [18,23–26] proposed to optimize the structure parameters for better beam quality in MCPCF. Although the structural parameters of MCPCF could affect the mode shape in principle, controlling the MCPCF structure parameters in micrometer dimensions while preserving the cross-sectional structure is not trivial. Meanwhile, researchers [27–29] have found that MCPCF could generate a mode similar to in-phase supermode

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when the seven-core cores are separated by high refractive index solid rods, which translates into Gaussian-like beam profile in the far field.

In the present paper, a seven-core PCF filled with commercial refractive index liquids was designed to optimize the in-phase supermode shaping and flatness of SC. Initially, the Finite Difference Time Domain (FDTD) was applied to simulate mode shaping of the liquid-filled seven-core PCF. Numerical simulation of flat SC generation in the liquid-filled seven-core PCFs was the performed. The spectral flatness measure (SFM) was used to quantitatively describe SC flatness. The influences related to the filled rings, index of filled liquids, and temperatures were analyzed in detailed.

2. Theoretical analysis of modes in the seven-core PCF

The use of seven-core PCF with air holes having the same diameter ($d=1.47\ \mu m$) and pitch ($\Lambda=3.26\ \mu m$) was proposed to analyze the effects of filling liquids in the air rings of the seven-core PCF. The concept of the scheme is depicted in Fig. 1. The inner rings of the air holes can be filled with liquid by fusing the outer rings of air holes with fusion splicing technique, and then immersing one end of the fiber in a liquid reservoir and applying vacuum to the other end of the fiber [30]. According to Reference [31], the seven-core PCF could operate in single mode from 900 nm to 1300 nm wavelength.

According to the coupled mode theory, the electric field distribution of each core when existing alone is given by [16],

$$E_m(x, y)exp(i\beta_m z) \tag{1}$$

m is the mth core. Assuming that a core only couples to its nearest neighbors, the complex field of core E_m, which is the sum of the electric field in the core and the electric field coupled from the nearest neighbors, can be expressed by the following equation [32,33]:

$$\frac{dE_m(z)}{dz} = -i\beta_m A_m(z)e^{-i\beta_m z} + \sum_n k_{m,n}A_n(z)e^{-i\beta_n z} \tag{2}$$

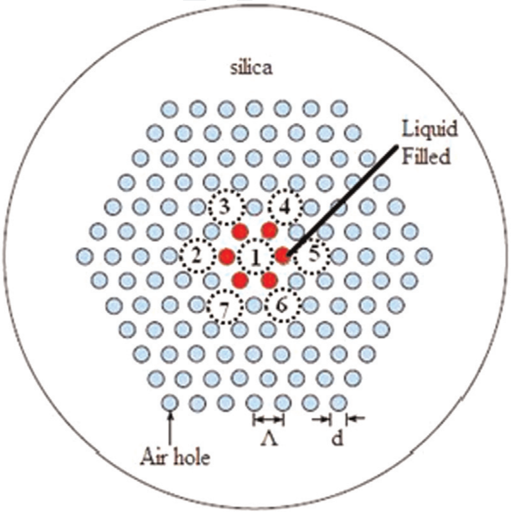

Fig. 1. Cross-sectional view of the seven-core PCF with triangular lattice consisting six hexagonal rings of air holes. PCF inner ring filled with liquid ($\Lambda=3.26\ \mu m$, $d=1.47\ \mu m$).

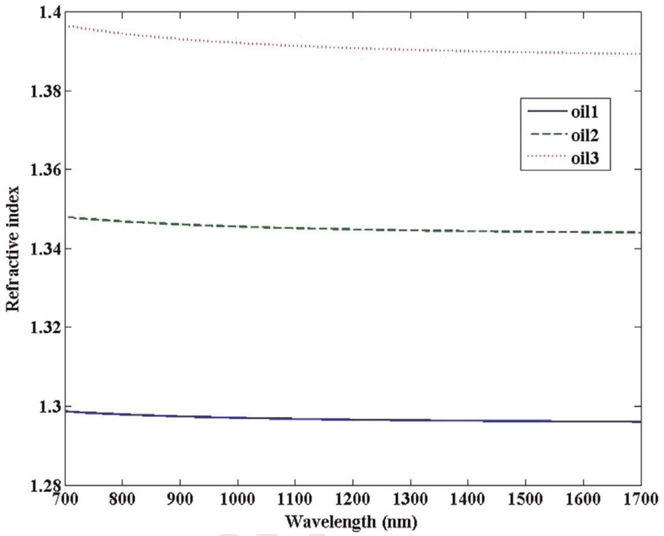

Fig. 2. Variation of refractive index with wavelength for Cargille refractive index liquids [30,39].

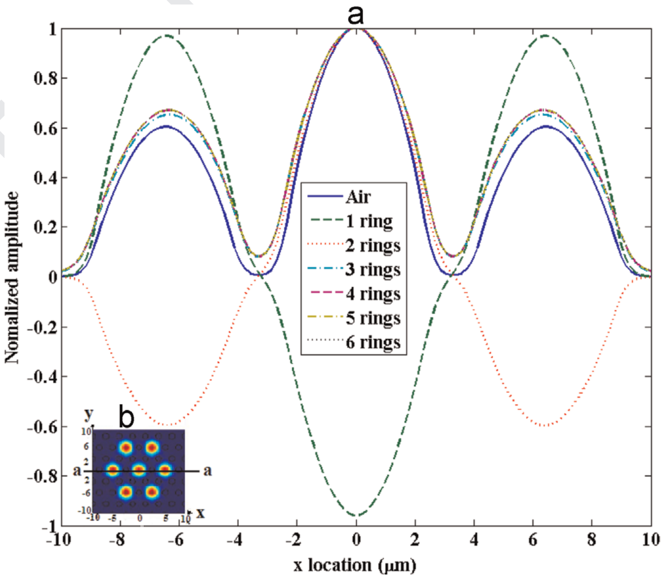

Fig. 3. Mode of different liquid filled rings in the seven-core PCF. (a) Cross profile of the mode in (b) along the X direction at $Y=0$.

where $A_m(z)$ is the amplitude of the field in the mth core, n is the number of the nearest neighbor cores, and k and β are the coupling coefficient and propagation constants, respectively. k can be calculated as follows [33,34]:

$$k_{m,n} = \frac{k_0^2}{2}\int[n^2(x, y) - n_m^2(x, y)]\varepsilon_n(x, y)\varepsilon_m(x, y)dxdy \tag{3}$$

where $\varepsilon_m(x,y)$ or $\varepsilon_n(x,y)$ is the normalized electric field distribution when only the mth or nth core is present, $k_0=2\pi/\lambda$ is the wave vector in the free space, λ is the free space wavelength, $n(x,y)$ is the refractive index distribution of the whole PCF, and $n_m(x,y)$ is the refractive index distribution when only the mth core is present. The complex amplitude distribution across the whole multicore fiber is given by

$$E(x, y, z) = \sum\nolimits_m A_m(z)E_m(x, y)\exp\left(i\beta_m z\right) \tag{4}$$

The coherent beam combining technology requires every combining beam to have the same phase so that the output beam can achieve high power and optimum beam quality. The in-phase supermode, where all cores have the same phase, is the most desired operation mode in MCPCF.

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